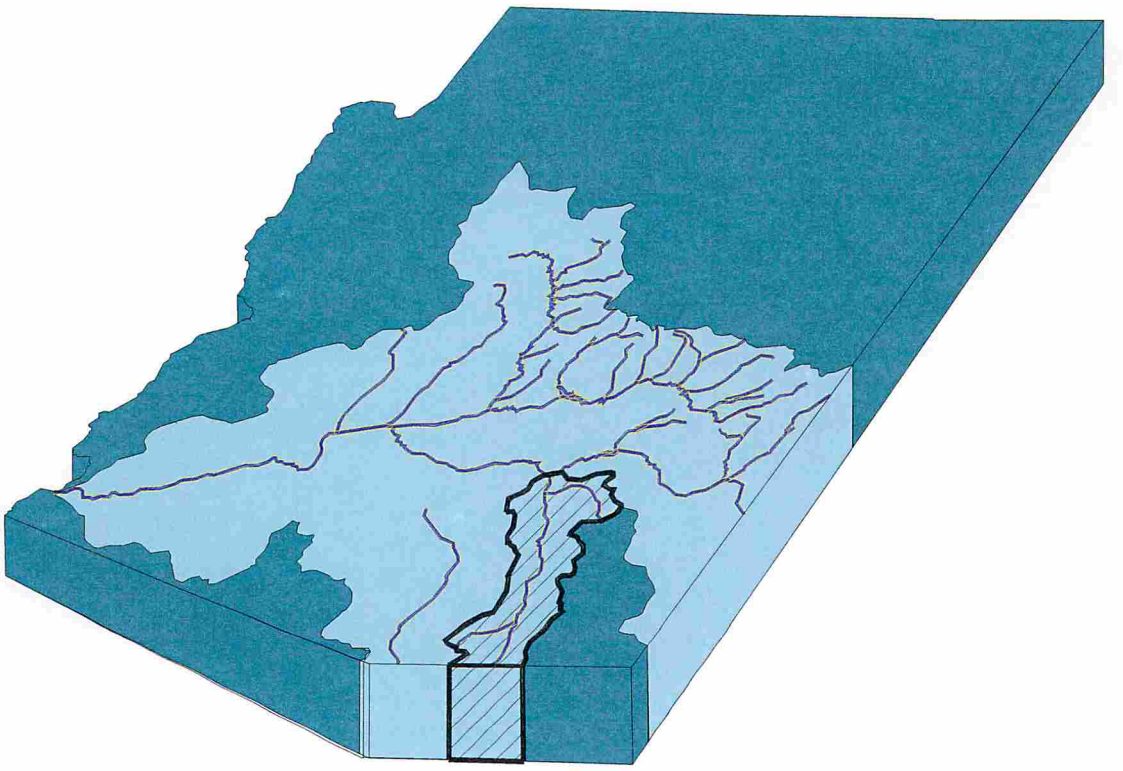
SUBFLOW TECHNICAL REPORT
SAN PEDRO RIVER WATERSHED

In Re The General Adjudication Of The
Gila River System And Source



Arizona Department of Water Resources

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CHAPTER 1: INTRODUCTION

This report has been prepared by the Arizona Department of Water Resources (Department) at the request of the trial court in the general adjudication of the Gila River System and Source (Gila River adjudication). Minute Entry, Jan. 9, 2002. It addresses issues relating to the distinction between surface water and groundwater that have been before the trial court as well as the Arizona Supreme Court on four separate occasions between 1988 and 2000.

Water rights in Arizona are subject to a bifurcated system that differentiates groundwater from surface water. Surface water is subject to the doctrines of prior appropriation and beneficial use, whereas percolating groundwater is not appropriable and may be pumped by the overlying landowner subject to the doctrine of reasonable use, and the federal reserved water rights doctrine. *In re the Adjudication of all Rights to Use Water in the Gila River System and Source,* 198 Ariz. 330, 334, 9 P.3d 1069, 1074 (2000) (*Gila IV*). Arizona's bifurcated system is complicated by the fact that there is no clear distinction between surface water and groundwater in certain areas close to streams.

Arizona's bifurcated system has generated several years of litigation within the context of the Gila River adjudication. Simply because water is located below the surface, it may not necessarily be groundwater but instead may be appropriable subflow. Since 1931, courts have recognized that pumping water from wells may have a direct and appreciable impact on stream flows if those wells are in the vicinity of the stream. *Maricopa County Municipal Water Conservation Dist. No. One v. Southwest Cotton Co.*, 39 Ariz. 65, 4 P.2d 369 (1931) (*Southwest Cotton*). Identifying those wells has been problematic.

Early in the Gila River adjudication, the issue of identifying wells pumping appropriable subflow was before the trial court to determine whether those wells should be included in the adjudication. In 1987, the trial court held hearings on the relationship between surface water and groundwater, and in 1988 the trial court concluded that certain wells withdrawing water from the younger alluvium of a stream basin should be presumed to be pumping appropriable subflow if the volume of stream depletion was 50% or more as the result of 90 days of continuous pumping. In 1993, the Arizona Supreme Court determined that the trial court erred in adopting the 50%/90 day test, and

the matter was remanded to the trial court "to take evidence and, by applying the principles contained in this opinion, determine the criteria for separating appropriable subflow from percolating groundwater." *In re the Adjudication of all Rights to Use Water in the Gila River System and Source,* 175 Ariz. 382, 394, 857 P.2d 1236, 1248 (2000) (*Gila II*).

Upon remand from the Arizona Supreme Court, the trial court engaged in a lengthy hearing process, involving expert testimony on complex hydrogeologic principles, that culminated in a 66-page detailed order with 36 additional pages of exhibits. *Gila IV,* 198 Ariz. at 336, 9 P.3d at 1075. The trial court applied the criteria described in *Gila II* and concluded that the saturated floodplain Holocene alluvium was the "most credible" subflow zone, that wells located outside the subflow zone could also pump subflow if their cones of depression intercepted the subflow zone, and that wells should be subject to a *de minimis* standard even though they may be pumping subflow. Trial Court Order, June 30, 1994 at pp. 58-62. The matter was again taken before the Arizona Supreme Court, and in 2000 the Court affirmed the trial court's June 30, 1994 order after remand "in all respects." The Court stated:

> We affirm the trial court's order after remand in all respects. The subflow zone is defined as the saturated floodplain Holocene alluvium. DWR, in turn, will determine the specific parameters of that zone in a particular area by evaluating all of the applicable and measurable criteria set forth in the trial court's order and any other relevant factors. See ¶¶ 33-35, *supra*. All wells located in the lateral limits of the subflow zone are subject to this adjudication. In addition, all wells located outside the subflow zone that are pumping water from a stream or its subflow, as determined by DWR's analysis of the well's cone of depression, are included in this adjudication. Finally, wells that, though pumping subflow, have a de minimus [*sic*] effect on the river system may be excluded from the adjudication based on rational guidelines for such an exclusion as proposed by DWR and adopted by the trial court.

Gila IV, 198 Ariz. at 344, 9 P.3d at 1083.

By Minute Entry dated January 9, 2002, the trial court requested that the Department prepare a report that identifies and describes "the procedures and processes that it proposes to use to establish the limits of the subflow zone within the San Pedro River watershed." As directed by *Gila IV*, the trial court requested that the report address

the following: procedures for determining the lateral limits of the subflow zone, a test for determining if a well's cone of depression is withdrawing water from the subflow zone, and rational guidelines for determining whether a particular well, though pumping subflow, has a *de minimis* effect on the river system. In response to the trial court's request, the Department prepared this report.

There are six chapters in this report. The methodologies that the Department proposes to use are described in Chapters 2, 3 and 4. In Chapter 2, the Department discusses steps for delineating the lateral limits of the jurisdictional subflow zone. In Chapter 3, the Department discusses steps for implementing a cone of depression test. In Chapter 4, the Department recommends guidelines for addressing *de minimis* uses within the adjudication. In Chapter 5, the Department summarizes its recommended approaches, and discusses how they may be implemented in the future. In Chapter 6, the Department lists the technical references cited in this report.

CHAPTER 2: SUBFLOW ZONE

This chapter describes the Department's proposed methodology for delineating the jurisdictional subflow zone within the San Pedro River watershed. As required by the Arizona Supreme Court in *Gila IV*, this methodology uses those criteria geologically and hydrologically appropriate for a subflow determination in this watershed. And, as requested by the trial court, this methodology "addresses the appropriate use, if any, of each of the criterion listed in Gila IV, as well as any other relevant factors that will be helpful in insuring that ADWR's subflow zone determination is completed using all reasonable means to arrive at results that are as accurate as possible."

The trial court also requested that the Department include a method to include "both perennial and intermittent streams as part of the subflow analysis, including streams that historically contained perennial or intermittent flows, but which now are ephemeral due to development and other human initiated actions." Additionally, the trial court requested that the Department include "effluent fed" streams. These streams are included in the Department's analysis.

The Department proposes to use five steps to delineate the jurisdictional subflow zone for San Pedro River watershed. The Department will determine the location of:

- Perennial streams;
- Intermittent streams;
- Effluent fed streams;
- Lateral extent of the floodplain Holocene alluvium; and
- Saturated portion of the floodplain Holocene alluvium.

Each of these steps is described below. These steps may be applied for all watersheds within the Gila River adjudication, including the San Pedro River watershed.

2.1 LOCATION OF PERENNIAL STREAMS

To determine the location of perennial streams under both predevelopment and current conditions, the Department conducted an extensive literature search to identify Arizona streamflow maps. A total of eleven published streamflow maps were identified

that cover all or portions of the Gila River adjudication area. A list of the maps identified by the Department and the data sources that were used to delineate stream reaches are presented in Appendix A.

The published streamflow maps identified by the Department can be divided into two general groups, those that identify predevelopment perennial streams and those that identify recent perennial, intermittent, or effluent fed streams. To determine the location of the predevelopment perennial reaches, the Department proposes to use the U.S. Geological Survey (USGS) Hydrologic Investigations Atlas entitled *Predevelopment Hydrologic Conditions in the Alluvial Basins of Arizona and Adjacent Parts of California and New Mexico*. This atlas was published in 1986, and was prepared by G.W. Freethey and T.W. Anderson as part of the Southwest Alluvial Basins, Regional Aquifer Systems Analysis (Swab/RASA) Project. One of the goals of the Swab/RASA Project was "an overall assessment of hydrologic conditions that existed prior to man's activities that might have altered the natural hydrologic systems." The atlas is comprised of three maps that, when combined, cover the entire Gila River adjudication area as well as minor areas outside of the adjudication. Copies of the maps are provided in this report as Plates 1, 2 and 3.

The USGS atlas shows the location of predevelopment perennial streams as well as predevelopment water level contours. These predevelopment hydrologic conditions were based on a variety of sources including:

- Historic accounts;
- Field data collected by the USGS and other agencies from the early 1900s to about 1940 "which precedes the period of greatest development;"
- Recent data "for basins where development is minor and long term changes in water levels can be assumed to be small and negligible;" and
- Numerical ground water models.

A list of references used in preparation of the USGS atlas is provided on Plate 2.

The Department is aware that perennial stream reaches currently exist in the adjudication area that are not shown on the USGS predevelopment maps, either because they did not exist under predevelopment conditions or they were not identified by the USGS. To identify these reaches, the Department proposes to use a 1993 perennial stream map prepared by Valencia and others of the Arizona Game and Fish Department

(AGFD) as part of the Statewide Riparian Inventory and Mapping (SRIM) Project. The perennial reaches identified by the AGFD are shown in Figure 1, and a copy of the accompanying technical report is included in Appendix B. Included in the 1993 AGFD report are definitions for perennial, intermittent, and ephemeral streams that were used by the Department for this report.

The 1993 AGFD map is based on a 1981 AGFD perennial stream map by Brown and others that was later revised based on consultation with the Department, U.S. Forest Service (USFS), Bureau of Land Management (BLM), Arizona Department of Environmental Quality (ADEQ), private sector hydrologists, and academicians. Using Graphic Information System (GIS) technology, the Department proposes to overlay the recent AGFD perennial stream map on the USGS predevelopment maps. The recent perennial reaches would then be combined with the predevelopment perennial reaches to create a perennial stream map.

2.2 LOCATION OF INTERMITTENT STREAMS

Due to a lack of historical data, the Department was unable to identify a published map that depicts the location of *predevelopment* intermittent streams. However, the Department did identify a 1997 map by Wahl and others of the AGFD that shows the recent location of intermittent streams in Arizona. This map was prepared during the last phase of the SRIM Project and was based on the identification of intermittent streams on topographic maps by staff of the BLM, USFS, National Park Service (NPS), and AGFD. Some of the intermittent reaches depicted on the AGFD map are questionable and believed by the Department to actually be ephemeral based on recent data from USGS stream gages. As the adjudication proceeds into those areas, the Department recommends that the location of current intermittent reaches be further evaluated. The intermittent reaches identified by the AGFD are shown in Figure 2, and a copy of the accompanying technical report is provided in Appendix C.

The Department is aware that intermittent stream reaches currently exist that were not previously identified as perennial, and that are not currently perennial. The Department proposes that these recent intermittent reaches be identified by overlying the 1997 AGFD map onto the perennial map prepared under section 2.1. The end product

would be a composite map that shows the predevelopment perennial stream reaches identified by the USGS combined with recent perennial and intermittent stream reaches identified by the AGFD.

2.3 LOCATION OF EFFLUENT FED STREAMS

A list of the major and minor effluent fed reaches in Arizona was developed by the ADEQ as part of its surface water quality rules (A.A.C. R18-11-113, Effluent Dependent Waters). A copy of the rule is presented in Appendix D. According to the ADEQ, there are three major effluent fed stream reaches located within the Gila River adjudication area:

- Santa Cruz River below the Nogales International Waste Water Treatment Plant (WWTP);
- Santa Cruz River below Tucson's Roger Road WWTP; and
- Gila River below Phoenix's 91st Avenue WWTP.

Except for the reach below Tucson, the USGS predevelopment maps indicate that the entire length of these effluent fed streams was perennial during predevelopment conditions. In addition to the major reaches listed above, ADEQ identified several minor effluent fed streams that occur below the WWTPs of several towns including Mt. Lemmon and Tombstone that are located in the San Pedro River watershed. The location and length of the effluent fed reaches are shown in Figure 3 based on GIS data the Department received from the ADEQ. The Department proposes to compare this figure with the composite stream map prepared under section 2.2, and those effluent fed reaches not already identified as perennial or intermittent would be added to the map and designated accordingly.

It should be noted that not all effluent fed streams would necessarily have a jurisdictional subflow zone adjacent to and beneath them. One of the characteristics of the jurisdictional subflow zone is the existence of a hydraulic connection between the subflow and the stream. Due to the elevated nutrient and/or organic content of most effluent, it is common for low permeability "clogging layers" to form along the bed of effluent fed streams. These layers can restrict the seepage of streamflow and, as a result, can cause the sediments beneath the stream to be unsaturated. Under these conditions,

effluent would seep downward as unsaturated flow until it reaches an underlying saturated zone. The area adjacent to and beneath such streams would not, by definition, be characteristic of a jurisdictional subflow zone due to the lack of a hydraulic connection between the subflow and the stream.

Bouwer (1978) states the following regarding clogging layers at page 289 in his textbook on hydrology:

> Clogging is primarily caused by settling of sediment, straining of suspended material as water moves through the sediment layer and into the soil, and bacterial and other biological action... When sediment begins to accumulate on top of the soil...the fine particles no longer move into the bottom material but are strained out on top of the sediment layer where they contribute to the hydraulic resistance of the clogging layer. Clogging thus is primarily a surface phenomenon that rarely extends more than 10 cm into the soil and often is restricted to the top centimeter or less... Continued clogging eventually reduces infiltration rates to only a fraction (one tenth or less, for example) of the original infiltration rate... Rice (1974) reported serious clogging with infiltration of secondary sewage effluent if it contained more than 10 mg/l suspended solids.

Further discussion of clogging layers is found in the hydrology textbook by Todd (1980).

Detailed geologic and hydrologic data are needed to confirm the presence or absence of clogging layers along effluent fed streams, and the occurrence of unsaturated flow beneath these streams. The Department believes these data are generally unavailable at this time and would require considerable time and resources to collect in the future. Two of the three major effluent fed streams in the Gila River adjudication were previously perennial and would already be included in the composite map following the methodology described in section 2.1. For the effluent fed streams that were not previously perennial, or recently perennial or intermittent, the Department proposes that it be assumed that the sediments immediately beneath these reaches are unsaturated due to clogging layers. These reaches would, therefore, not be included in the methodology to determine the jurisdictional subflow zone.

2.4 LOCATION OF LATERAL EXTENT OF THE FLOODPLAIN HOLOCENE ALLUVIUM

Defining the lateral extent of the floodplain Holocene alluvium requires several steps. The first step would be to identify and obtain copies of published surficial geology maps for the areas with perennial and intermittent streams. The second step would be to review the identified maps and determine those which delineate floodplain Holocene alluvium. The third step would be to evaluate the adequacy of the Holocene maps using a set of predefined criteria. Based on this adequacy evaluation and professional judgment, the fourth and final step would be to select the best available Holocene map to define the lateral extent of the floodplain Holocene alluvium. Further discussion of these steps is provided below along with an example of how the steps would be applied to the Sierra Vista subwatershed of the San Pedro River watershed.

The Department proposes to use two primary data sources to identify published surficial geology maps, the Arizona Geological Survey (AGS) and the USGS. Both of these agencies have developed computerized databases of Arizona geology maps. At the Department's request, the AGS searched its database and identified approximately 400 maps in the Gila River adjudication area that it believed could have useful data on the floodplain Holocene alluvium. The USGS map database is available on-line at http://ngmdb.usgs.gov and can be easily searched by inputting the coordinates of an area of interest. Although the USGS website provides a ready source of geology maps, the maps identified on-line would need to be reviewed to determine whether they provide Holocene data.

Using the map databases of the AGS and the USGS, the Department next proposes to develop a list of all published Holocene maps for a given area. Published maps are subject to peer review, which improves the reliability of the maps. The adequacy of the listed maps for the purpose of this report would then be evaluated using four criteria:

- Field work;
- Map coverage;
- Dating methods; and
- Map scale.

The reasons for selecting these criteria are described below.

In general, the Department believes a Holocene map is more adequate for defining the jurisdictional subflow zone if field work was conducted by its author; if it covers the entire subwatershed or watershed being adjudicated; if a variety of methods were used to date the floodplain Holocene alluvium; and, if it was mapped at a relatively small scale (typically less than 1:150,000). Field work is important to identify floodplain Holocene alluvium, particularly in areas where the floodplain is relatively wide and topographic maps and aerial photography are less useful in differentiating geologic units. Regarding map coverage, the use of a single map for a particular study area avoids the potential for inconsistencies in mapping methods used by different geologists. A summary of methods that can be used to date Holocene deposits and the applicability, age range, and optimal resolution of these methods are presented in Plate 4, which was published by the Geological Society of America. The Department believes that, other factors being equal, the greater the variety of dating methods employed by the geologist to map the Holocene alluvium, the more adequate the map. Finally, regarding map scale, the smaller the scale of a map, the finer its resolution and generally the more accurate the location of boundaries between geologic units. The Department recommends that these criteria be used to select the best available Holocene map to determine the lateral extent of the floodplain Holocene alluvium.

To demonstrate the process described above, the Department evaluated the adequacy of ten geologic maps that delineate the lateral extent of floodplain Holocene alluvium along the San Pedro River within the Sierra Vista subwatershed. These maps were identified in the AGS and USGS databases. Table 1, included at the end of this chapter, lists the authors of these maps, and the criteria used in the Department's adequacy evaluation.

The Sierra Vista subwatershed is located in southeastern Arizona within the San Pedro River watershed. The subwatershed covers approximately 950 square miles and extends from the international border with Mexico to about 27 miles north near Fairbanks. This reach of the San Pedro River was determined by the USGS to be perennial during predevelopment conditions, and more recently by the AGFD to be either perennial or intermittent.

Figure 4 is a composite map prepared by the Department that shows the various boundaries of the floodplain Holocene alluvium delineated on the ten maps for the Sierra

Vista subwatershed. A review of the boundaries illustrates that there are several factors that affect the mapping of the floodplain Holocene alluvium. First, when the original map scale is large (*e.g.*, the 1:1,000,000 scale maps by Richard and others, 2000 and Reynolds, 1988), the location of the Holocene boundary may be found to be inaccurate when plotted on a smaller scale. Second, when the map scale is small (*e.g.*, the 1:24,000 scale maps by Demsey and Pearthree, 1994 and Moore, 1991), the location of the Holocene boundary is more irregular than when mapped at a larger scale. Also, small-scale maps are less commonly available and, in this example, the two 1:24,000 scale maps each cover less than half of the area being evaluated. Third, where the floodplain is relatively narrow (*e.g.*, between Hereford and Charleston), the different maps show remarkably similar boundaries for the floodplain Holocene alluvium. On the other hand, where the floodplain is relatively wide (*e.g.,* south of Hereford and north of Charleston) the different maps show a wide range of boundaries for the floodplain Holocene alluvium. The Department used the criteria described above to select the most suitable map.

The Department determined that the map prepared by Pool and Coes (1999) was the best available for delineating the extent of the floodplain Holocene alluvium along the San Pedro River within the Sierra Vista subwatershed. This map has a relatively small scale (approximately 1:135,000), it covers the study area completely, the floodplain Holocene alluvium was identified and field mapped by researchers referenced by the authors, and a variety of methods were used to date the Holocene deposits. Figure 5 is a map prepared by the Department that shows the lateral extent of the floodplain Holocene alluvium along the San Pedro River based on the map by Pool and Coes (1999). It should be noted that this map was printed by the Department at a scale of approximately 1:144,000. Maps used for the actual delineation of the floodplain Holocene alluvium would be evaluated at their original scale, which, in this case, is approximately 1:135,000.

2.5 LOCATION OF THE SATURATED PORTION OF THE FLOODPLAIN HOLOCENE ALLUVIUM

The next and final step in delineating the jurisdictional subflow zone is to determine that portion of the floodplain Holocene alluvium that is saturated. Determination of the saturated portion of the floodplain Holocene alluvium requires data on two subsurface conditions:

- The thickness of the floodplain Holocene alluvium; and
- The depth to the water table beneath the floodplain.

Knowing these two conditions, the portion of the floodplain Holocene alluvium that exists beneath the water table (the saturated portion) can be determined.

However, the two conditions indicated above cannot be determined with reasonable means in the San Pedro River watershed or elsewhere in the Gila River adjudication area. The thickness of the floodplain Holocene alluvium and the depth to the water table beneath the floodplain are highly variable, both spatially and temporally, and this makes the determination of saturation difficult. In many areas of the Gila River adjudication, detailed subsurface data for the floodplain simply do not exist or are limited, and additional data would have to be collected and analyzed at considerable cost and time. In the few areas where extensive subsurface data have been collected, it is often still difficult to define variations in the thickness of the Holocene alluvium across the floodplain and changes in the elevation of the water table over time. Based on these factors, and in light of the trial court's request to consider predevelopment streamflow conditions, the Department recommends that the entire lateral extent of the floodplain Holocene alluvium be assumed to be saturated for the purpose of delineating the jurisdictional subflow zone.

An example of the inherent difficulty in defining the saturated portion of the floodplain Holocene alluvium is provided below for an area that has been extensively studied. The Sierra Vista subwatershed has been, and continues to be, one of the most studied areas in Arizona by geologists and hydrologists. Plates 5 and 6, from the 1999 USGS report by Pool and Coes, illustrate the subsurface geologic data that has been collected recently by the USGS from this subwatershed.

In order to construct hydrogeologic cross-sections along the San Pedro River within the Sierra Vista watershed, the USGS drilled several new boreholes in the floodplain Holocene alluvium and logged the drill cuttings to supplement existing

information from well driller's logs. A variety of geophysical data were also collected from the floodplain Holocene alluvium including:

- Surface resistivity measurements from four survey lines and over 20 sounding areas;
- Seismic readings from four survey lines; and
- Subsurface geophysical logs from at least two boreholes.

Using these lithologic and geophysical data, four hydrogeologic cross sections were constructed, three oriented perpendicular to the San Pedro River and one oriented parallel to it. In order to construct these cross sections, it was necessary to extrapolate subsurface conditions between data points. For the cross section oriented parallel to the river, the distance between data points was greater than 1 to 2 miles, and the three sections oriented perpendicular to the river were separated by more than 5 miles. The work by the USGS just described was very costly, and was partially funded by the Department. The Department has very limited resources available to continue to fund this type of work.

Based on these data, the USGS divided the floodplain Holocene alluvium in the Sierra Vista subwatershed into two stratigraphic units consisting of the older, pre-entrenchment alluvium and the overlying post-entrenchment alluvium. From their study, Pool and Coes (1999) concluded that "deposits of pre-entrenchment Holocene alluvium are as much as 20 feet thick" but "unfortunately the distribution of pre-entrenchment Holocene alluvium is not well known." Regarding the post-entrenchment Holocene alluvium, Pool and Coes (1999) stated that its thickness ranges between "only a few feet" and "less than 20" feet. Thus, even with very sophisticated and expensive geophysical and lithological data, the actual thickness of the Holocene alluvium could not be determined with any degree of certainty.

In the remainder of the San Pedro River watershed and most of the Gila River adjudication area, well driller's logs will likely be the only source, if any, of subsurface geologic data for the floodplain. The accuracy of this data is questionable. For example, relying on an interpretation of subsurface lithology from well driller's logs, Roeske and Werrell (1973) of the USGS had previously concluded that the floodplain Holocene alluvium along the San Pedro River "generally is from 40 to 100 feet thick but may be as much as 150 thick in places." The more recent subsurface data collected by the USGS in the Sierra Vista subwatershed suggests that the thickness of the floodplain Holocene

alluvium in this area may be considerably less. This lack of reliable data prevents the thickness of the floodplain Holocene alluvium from being determined with any certainty.

In addition to the lack of reliable subsurface geologic data, there is a lack of reliable data concerning the depth to the water table. On this subject, Pool and Coes (1999) state at page 23:

> Water-level changes also have occurred near the San Pedro River, but water level data have not been routinely collected in the area. As a result, relations between the ground-water flow system and flow in the river before the mid-1990's are difficult to define in detail.

This lack of data is further exacerbated by the dynamic nature of the floodplain aquifer system as demonstrated by Plate 6 from Pool and Coes (1999). Plate 6 includes long-term (greater than 30-year) hydrographs for two wells, and short-term (less than 5-year) hydrographs for six wells completed in the floodplain Holocene alluvium within the Sierra Vista subwatershed. Review of the hydrographs suggests that the aquifer system beneath the floodplain is dynamic, with the water table sometimes changing rapidly in response to storm runoff events and evapotranspiration by plants, and sometimes changing slowly due to the effects of droughts and wet periods, seasonal differences, and pumping. Based on the two long-term hydrographs on Plate 6, the depth to the water table beneath the floodplain of the San Pedro River may vary by as much as 10 to 15 feet. This is a significant amount considering that the total thickness of the floodplain Holocene alluvium in this area may be only 20 to 30 feet.

Due to variations in the depth of the water table, the portion of the floodplain Holocene alluvium that is saturated changes over time, making the determination of the jurisdictional subflow zone difficult. And these variations are not unique to recent times, but apparently also occurred during predevelopment conditions. In his description of vegetation changes and arroyo cutting in southeastern Arizona, Hastings (1959) states at page 61:

> Variation occurs from one area to another during the same season; variation occurs from one season to another; wide variation can occur from one season to the same season in a different year. By way of historical illustration two descriptions of the junction of Sopori Creek with the Santa Cruz River can be cited.

One, written by Major Fergusson in 1862, talks of the "good grass" there and the "permanent water (Fergusson, 1863).

Another by J. Ross Brown in 1864, describes the same spot this way:

> There was not so much as a pool left in the Santa Cruz River from which we could satisfy our own thirst, much less water our animals... The grass is crisped, the trees are withered, the bed of the river is dry, the sap of life seems to have deserted the place...

The same point in space, then, varies in time.

Hastings and Turner (1965) at page 37 further describe variations in predevelopment hydrologic conditions for arid and semiarid regions:

> In summary, the valleys were wetter and more open than today, and relatively unchanneled. But the precise conditions varied from place to place and probably from time to time. As the tributary washes dumped greater or less *[sic]* amounts of debris, depending upon where heavy summer rains may have struck, the rivers had to transport varying loads of sediment at different points along their course. Channeling and filling, aggradation and degradation – all may have been going on simultaneously, in various stages of development along various parts of the stream. If this dynamic situation existed, one can be sure that the vegetation reflected it. At a given time there may have been mesquite invading, where a temporary trench had sliced through the old flood plain, draining it; mesquite dying where the plain was aggrading and marshes being developed. The old accounts present a picture that is neither homogeneous, nor static. By postulating a dynamic situation one can reconcile the variety of conditions that evidently existed.

The variety of conditions discussed above were present in the San Pedro River watershed during both predevelopment and recent times making a determination of the water levels only possible at a particular point in time.

In summary, the Department believes that an accurate determination of the saturated portion of the floodplain Holocene alluvium is impractical for three reasons:

- Difficulties in defining the thickness of the floodplain Holocene alluvium;
- The general lack of detailed and long-term water level data from the floodplain; and
- The dynamic nature of the floodplain aquifer system.

The Department, therefore, recommends that the entire lateral extent of the floodplain Holocene alluvium be assumed to be saturated for the purpose of delineating the jurisdictional subflow zone. This recommendation is consistent with the inclusion of predevelopment perennial streams in the Department's methodology for delineating the jurisdictional subflow zone as requested by the court. By definition, floodplain Holocene alluvium was saturated at some point in predevelopment time.

The five steps described above will allow the Department to identify the lateral extent of the saturated floodplain Holocene alluvium by "using all reasonable means to arrive at results that are as accurate as possible" as requested by the trial court. These steps also address "the appropriate use, if any, of each of the criterion listed in Gila IV" as further requested by the trial court.

With respect to the other criteria in *Gila IV*, they are either already addressed by the preceding steps, or cannot be determined using "reasonable means." Regarding the location of saturated floodplain, the locations of perennial and intermittent streams during both predevelopment and recent times provide an indication there was a hydraulic connection between the subflow zone and the stream, and that the floodplain alluvium at those locations was saturated. However, it is not possible to determine the depth of saturation due to limited data. Regarding the flow direction, water level elevations, gradations of water level elevations, chemical composition, and lack of hydraulic pressure from tributary aquifer and basin fill recharge, these factors were already taken into account by the trial court when it concluded that the subflow zone should be determined by the lateral extent of the saturated floodplain Holocene alluvium.

> After consideration of flow direction, water level elevation, the gradation of water levels over a stream reach, the chemical composition if available, and lack of hydraulic pressure from tributary aquifer and basin fill recharge which is perpendicular to stream and "subflow" direction, the Court finds the most accurate of all the markers is the edge of the Holocene alluvium.

Gila IV, 198 Ariz. at 337, 9 P.3d 1069 at 1076 (2000). It would not be practicable for the Department to revisit the trial court's determination, which was based on a ten-day evidentiary hearing, a two-day 600-mile trip within the San Pedro River watershed, testimony by several experts in hydrology and geology, and a two-day supplemental

evidentiary hearing. *Gila IV*, 198 Ariz. at 336, 9 P.3d at 1075 (2000). It is the Department's opinion that the methodology described in this chapter satisfies the criteria discussed by the trial court and the Arizona Supreme Court in *Gila IV*, and that this methodology may be used for all watersheds within the Gila River adjudication.

TABLE 1

PUBLISHED MAPS SHOWING EXTENT OF FLOODPLAIN HOLOCENE ALLUVIUM ALONG SAN PEDRO RIVER IN SIERRA VISTA SUBWATERSHED

REFERENCE	FIELD WORK	METHODS USED TO DATE FLOOPLAIN HOLOCENE ALLUVIUM									SUBWATERSHED COVERAGE	MAP SCALE
		Historic Records	Dendrochronology	Radiocarbon	Rock Varnish/ Weathering	Soil Chemistry	Soil Profile Development	Geomorphic Position	Stratigraphy	Fossils and Artifacts		
Richard and others (2000)	U	U	U	U	U	U	U	U	U	U	Complete	1:1,000,000
Pool and Coes (1999)[1]	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Complete	1:35,000 (approx.)
Demsey and Pearthree (1994)	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Partial	1:24,000
Moore (1991)	Yes	U	U	U	U	U	U	U	U	U	Partial	1:24,000
Reynolds (1988)[2]	U	U	U	U	U	U	U	U	U	U	Complete	1:1,000,000
Roeske and Werrell (1973)[3]	U	U	U	U	U	U	U	U	U	U	Complete	1:127,000 (approx.)
Brown and others (1966)[3]	Yes	U	U	U	U	U	U	U	U	U	Partial	1:62,500
Hayes and Landis (1964)	U	U	U	U	U	U	U	U	U	U	Partial	1:48,000
Gilluly (1956)	U	U	U	U	U	U	U	U	U	U	Partial	1:253,000 (approx.)
Heindl (1952)	U	U	U	U	U	U	U	U	U	U	Complete	1:453,000 (approx.)

Notes:

'U' indicates documentation was unavailable for ADWR to make a determination.

[1] Floodplain Holocene alluvium was identified and field mapped by other researchers referenced by authors.

[2] Age of floodplain alluvium shown on map was determined to be Holocene to Late Pleistocene.

[3] Age of floodplain alluvium shown on map was determined to be Quarternary and, therefore, may include Holocene and pre-Holocene (Pleistocene) deposits.

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CHAPTER 3: CONE OF DEPRESSION

This chapter describes the Department's proposed methodology for determining whether pumping from a well located outside of the jurisdictional subflow zone has created a cone of depression that intercepts and withdraws water from the subflow. Quoting with approval from the trial court, the Arizona Supreme Court stated that:

> "[w]ells located outside the lateral parameters of the defined 'subflow' zone" may be included in the adjudication if "it is proven that their 'cones of depression' reach the 'subflow' zone and the drawdown from the well affects the volume of surface and 'subflow' in such an appreciable amount that it is capable of measurement." In other words, the trial court ruled, a well may be subject to the adjudication if its " 'cone of depression' caused by its pumping has now extended to a point where it reaches an adjacent 'subflow' zone, and by continual pumping will cause a loss of such 'subflow' as to affect the quantity of the stream."

In re the General Adjudication of all Rights to use Water in the Gila River System and Source, 198 Ariz. 330, 342-343, 9 P.3d 1069, 1082-1083 (2000) *(Gila IV)*. The trial court requested that the Department include a cone of depression test in this report.

A cone of depression is a funnel-shaped area, often irregular, around a well where the withdrawal of groundwater by the well has lowered the water table. Determining the size of a well's cone of depression and how it changes over time with pumping is a relatively complex and data intensive task involving subsurface conditions. The Department believes that the following information needs to be known to determine whether a well currently outside of the jurisdictional subflow zone is pumping subflow by virtue of its cone of depression:

- *Distance* between the well and the jurisdictional subflow zone;
- *Time* that the well has been pumped and at what *discharge rate*;
- *Well construction* details; and
- Local *hydrogeologic conditions*.

With the exception of the distance between the well and the jurisdictional subflow zone, these conditions will often be either unknown or poorly known, and will need to be estimated. Conducting cone of depression tests requires numerous assumptions and

considerable judgment and, in many cases, the test results will only provide a rough approximation of actual field conditions.

The courts have provided little guidance on how to proceed with cone of depression tests. In *Gila IV*, the Arizona Supreme Court left the development of a suitable test to the Department.

> The trial court did not attempt to establish a test for determining a well's cone of depression because the court lacked pertinent evidence on that issue. Instead, the court recognized that each well must be separately evaluated "to compute drawdown at the 'subflow' zone" and that 'whatever test ADWR finds is realistically adaptable to the field and whatever method is the least expensive and delay-causing, yet provides a high degree of reliability, should be acceptable."

198 Ariz. at 343, 9 P.3d at 1082. Although the Department has established a cone of depression test as anticipated by the Arizona Supreme Court, and as requested by the trial court, such a test has inherent difficulties and presents many challenges.

Before the Department describes its proposed methodology for conducting cone of depression tests, three related issues should be discussed. First, the Department does not currently have the resources to conduct cone of depression tests across wide areas of the Gila River adjudication. As noted by the court in *Gila IV*, a cone of depression test requires an evaluation of each well. Within the San Pedro River watershed alone, it is estimated that several hundred cone of depression tests would have to be performed. Even if the trial court were to proceed with the adjudication of smaller areas, such as subwatersheds, the Department would still face resource issues.

Second, results from cone of depression tests are time-sensitive. A well whose cone of depression does not intercept the jurisdictional subflow zone today may intercept it next week or several years from now. This is reason, along with the Department's limited resources, to wait to conduct cone of depression tests until a particular area is ready to be adjudicated as determined by the trial court.

And third, the methodology described in this chapter is limited to determining whether a well has a cone of depression that intercepts the jurisdictional subflow zone and is potentially pumping subflow. Additional data would be needed and new procedures developed to determine the *quantity* of appropriable water pumped from such

a well. This would be a difficult task. As described in *Gila II*, most wells whose cones of depression have intercepted the jurisdictional subflow zone will not be pumping subflow alone, but rather, a mixture of subflow and tributary aquifer water.

> [I]f the cone of depression of a well has extended to the point that it intercepts a stream bed, it almost certainly will be pumping subflow. At the same time, however, it may be drawing water from the surrounding alluvium. Thus, part of its production may be appropriable subflow and part of it may not. Even though only a part of its production is appropriable water, that well should be included in the general adjudication.

In re the General Adjudication of all Rights to Use Water in the Gila River System and Source, 175 Ariz. at 382, 391, 857 P.2d 1236, 1245 (1993) (*Gila II*). Appendix F provides copies of three journal articles that further discuss streamflow depletion by wells and recent attempts by researches to quantify the effects. If the quantity of subflow that a well is pumping can be accurately quantified, a further issue may be whether this quantity has its own *de minimis* threshold.

Keeping the previous issues in mind, the Department proposes that the following steps be taken to conduct cone of depression tests:

- Determine well location, elevation, and distance from jurisdictional subflow zone;
- Determine pumping history;
- Determine frequency of pumping;
- Determine how the well was constructed;
- Characterize local hydrogeologic conditions;
- Define local aquifer properties;
- Construct a conceptual model of the aquifer system;
- Select a mathematical model;
- Input data and run a simulation using mathematical model;
- Analyze model output; and
- Determine whether a well should be adjudicated.

Although the Department recommends that cone of depression tests be conducted on a well-by-well basis, several of the steps listed above may be combined under suitable conditions and used for different wells in the same general area. These steps include characterization of local hydrogeologic conditions and aquifer properties, construction of a conceptual model, and selection of a mathematical model. Further discussion of these and the other steps proposed to conduct cone of depression tests is provided below.

3.1 WELL LOCATION, ELEVATION, AND DISTANCE FROM JURISDICTIONAL SUBFLOW ZONE

The well location should be determined by using a hand-held Global Position Satellite (GPS) unit. The distance between the well and the jurisdictional subflow zone can then be measured by plotting the well location and the edge of the jurisdictional subflow zone on a 7.5-minute series (1:24,000 scale) U.S. Geological Survey (USGS) topographic map using GIS technology. The well's elevation could then be estimated using coordinates from the GPS unit and Digital Elevation Model (DEM) software available through the USGS.

3.2 PUMPING HISTORY

The date that pumping began, and the average quantity of water pumped annually since that time, should be listed on the Statement of Claimant (SOC) filed by the well owner in the adjudication. If the SOC does not list the date that pumping began, the date of well completion could be used, as provided in the well driller's report filed with the Department. If the SOC does not list the quantity of water pumped, that amount may be estimated using one or a combination of the following:

- Pump capacity;
- Power records; and/or
- Claimed type of use.

Pump capacity is often listed in well registration documents and could be used to estimate the quantity pumped if the frequency of pumping were also known. Power records, if available, provide another means of estimating the quantity pumped, but this requires that the type of pump and the distance that the pump lifts the water be known. The quantity

of water pumped could also be estimated based on the claimed type of use. For example, water use by an irrigation well could be estimated using records of cropped acreage and by assuming a water duty that is representative of the crop and irrigation system.

3.3 FREQUENCY OF PUMPING

Some wells, particularly those used in agricultural production, are only pumped during part of the year or during dry periods. Depending on the period that the well is used, the quantity of water pumped, and local aquifer conditions, the cone of depression may expand and contract over time.

For those wells believed not to have been pumped continuously, the Department recommends that the well owner be contacted for additional pumping information. Alternatively, power records could be used to determine seasonal water use. If further information is not available on the frequency of the well pumping, the Department proposes that it be assumed that the well has been pumped continuously throughout the year at a rate based on the annual pump volume.

3.4 WELL CONSTRUCTION

Well construction records (*i.e.* total well depth, screen or perforation zone, and location of annular seals) are needed to determine which geologic unit(s) supply water to the well. This information may be found in the well driller's report or other records maintained by the Department, such as construction reports filed in Active Management Areas (AMAs), and in applications filed with the Department for assured water supply (AWS) and water adequacy determinations, and for recharge purposes. However, even if available, these data may not necessarily be reliable. If reliable well construction records cannot be located, the Department proposes that it be assumed that the well is screened across its entire depth.

3.5 LOCAL HYDROGEOLOGIC CONDITIONS

To illustrate the hydraulic connection between the well and the jurisdictional subflow zone, hydrogeologic cross sections should be constructed that show the subsurface geology and location of saturated zones. In areas where the geologic units are highly stratified and/or laterally discontinuous, more cross sections may be needed to adequately illustrate the subsurface conditions. However, the number of cross sections that can be constructed and the area that they cover will ultimately be limited by data availability and resources.

The Department proposes that hydrogeologic cross-sections be constructed using available lithologic logs, geophysical measurements, and water level data from a variety of sources. These sources may include, but are not limited to:

- Well driller and construction reports (Department);
- AWS, water adequacy, and recharge program files (Department);
- Ground Water Site Inventory database (Department);
- Hydrographic Map Series (Department); and
- Published water supply and hydrogeologic studies (Department, USGS, Arizona Department of Environmental Quality, Arizona Geological Survey, Bureau of Land Management, United States Forest Service, and National Park Service).

3.6 LOCAL AQUIFER PROPERTIES

Aquifer properties for the geologic unit(s) that supply water to the well need to be defined next. In addition to the thickness and lateral extent of each unit, which would be based on the hydrogeologic cross sections, the unit's ability to transmit water under a hydraulic gradient (hydraulic conductivity) and yield water due to a change in head (storage coefficient) must be determined.

Adequate characterization of aquifer properties is perhaps the most difficult and the most important task in conducting cone of depression tests. As stated by T.N. Narasimhan (1998) at page 44 in his paper on the history of hydraulic characterization of aquifers, reservoir rocks, and soils:

> Looking purely from the viewpoint of science, it may appear as though what stands between us and satisfactory characterization is adequate data. Often we are limited by resource availability for data gathering, be it a research venture or engineering venture. Even in those situations where sufficient resources are available, one must consider whether the wells or boreholes themselves may compromise the integrity of the site. Constrained by these practical concerns, we need to recognize that the Earth's subsurface is difficult to assess. Consequently, our methods of hydraulic characterization are only capable of yielding estimates, and we function on the reasonable premise that the estimates become more reasonable with better information and fewer assumptions in the interpretation process.

A copy of Narasimhan's paper is provided in Appendix G.

Also in Appendix G is a copy of a 1996 water supply paper prepared by the USGS that describes how the hydraulic characteristics and yield of aquifers beneath the Ak-Chin Indian Community were determined. This work was conducted pursuant to the Ak-Chin Indian Community Water Rights Settlement Act, Public Law 95-328. Review of the USGS report demonstrates that, even when substantial time and resources are available to collect data, interpretation of aquifer conditions is not straightforward and requires considerable professional judgment.

To conduct cone of depression tests, the Department proposes that representative values for hydraulic conductivity and storage coefficient be taken from published water supply and hydrogeologic studies, preferably completed in the area where the well was drilled. If available, pump test data previously collected by the well owner, such as specific capacity data, may also be useful in defining local aquifer properties. Due to the spatial variability in aquifer properties, it may be necessary to define a reasonable range of values for each unit screened by the well.

3.7 CONCEPTUAL MODEL OF AQUIFER SYSTEM

To simulate how the cone of depression has formed and changed over time, a conceptual model of the aquifer system needs to be constructed. A conceptual model provides a verbal and graphical description of an aquifer system and the stresses on that system. The development of a conceptual model is usually the first step in the modeling process. The Department proposes that this simplified representation of an actual aquifer

system be based on available information on local hydrogeologic conditions and aquifer properties and include the following components:

- Type of aquifer (unconfined, confined, or leaky);
- Aquifer geometry (uniform or irregular);
- Aquifer matrix (porous or fractured media, homogenous or heterogeneous, and isotropic or anisotropic);
- Aquifer boundaries (recharge, discharge, impermeable, constant head, water table, etc.);
- Mode of flow (2-dimensional horizontal or 3-dimensional);
- Initial flow conditions;
- Aquifer penetration by the well (fully or partially penetrating well); and
- History of well pumping (continuous or discontinuous, constant or variable rate).

The design of a conceptual model requires professional judgment and depends, to a large degree, on the availability of field data and the ingenuity of the modeler to estimate subsurface conditions based on limited or incomplete data.

3.8 MATHEMATICAL MODEL

The next step in the modeling process would be to transform the conceptual model into a mathematical model. Mathematical models are a set of flow equations whose solutions yield a simulation of the dynamic behavior of an aquifer system in response to aquifer stresses. Depending on how the flow equations are solved, these models can be broadly grouped into two categories, analytical or numerical.

The Department proposes that analytical models be used to evaluate a well's cone of depression where, based on the conceptual model, the aquifer system is less complex and the flow equations can be solved directly using calculus. It is important to note that the modeler can make several simplifying assumptions so that even relatively complex aquifer systems can be evaluated using analytical models. These simplifying assumptions are summarized by Walton (1989) and include corrections or adjustments to account for the following complexities:

- Irregular aquifer geometry (principle of equal area);

- Heterogeneous aquifers (incremental approximation technique);
- Anisotropic aquifers (principle of equivalent section);
- Aquifer boundaries (image well theory and the principle of superposition);
- Partially penetrating well (Hantush method); and
- Discontinuous pumping and variable pumping rates (principle of superposition).

Analytical models can be constructed relatively quickly using a variety of commercially available computer software. The Department recommends that the program THWELLS (version 4.01, 1996) be used for analytical modeling. This program was developed by P.K.M. van der Heijdge of the International Ground Water Modeling Center and is widely distributed. A copy of the manual for THWELLS is provided in Attachment H and includes a description of the program's development, verification, and testing and solutions to example problems. The Department currently uses THWELLS in evaluating applications for AWS designations and to conduct well impact analyses in AMAs.

The Department recommends that numerical models, instead of analytical models, only be used to evaluate the cone of depression of a well in special circumstances where, based on the conceptual model, the aquifer system is exceedingly complex and the flow equations can only be solved by recasting them in algebraic form. These recast equations are numerical approximations and their solutions are also approximations. Several computer programs have been written to solve numerical flow equations; the most widely used being the USGS finite-difference code MODFLOW. A fact sheet describing MODFLOW and a summary of the model's development are included in Appendix I. A copy of the software and additional information are available on-line at the USGS website http://water.usgs.gov/software/ground_water.html.

Although use of MODFLOW has been simplified by increases in computing speed and through development of user-friendly pre- and post-processing software, development of numerical models is still a very time consuming process that requires substantial field data to justify its use and to properly calibrate. The Department currently uses MODFLOW primarily to model impacts on large, regional aquifer systems. For most, if not all, cone of depression tests, the benefits of a more realistic numerical model would be outweighed by the difficulty and expense of collecting the

data necessary to adequately define the numerical model and then run the computer simulation.

3.9 SIMULATIONS USING MATHEMATICAL MODEL

The data required to run the mathematical model would need to be compiled and entered into the selected computer program (THWELLS or MODFLOW). Depending on the complexity of the conceptual model, the model input may include several of the following:

- Model area (domain) and model grid;
- Location, aerial extent, and thickness of all aquifer and aquifer confining layers;
- Location and type of aquifer boundaries;
- Aquifer properties and their variation across the model domain;
- Initial position of the water table (unconfined aquifer) and/or potentiometric surface (confined aquifer) before pumping began (pre-development conditions);
- Location and quantity of natural aquifer recharge and discharge;
- Location and quantity of artificial recharge (*e.g.* infiltration of effluent and irrigation return flow);
- Location, depth, and open interval of cone of depression and image wells; and
- Rate and schedule of well pumping.

The model area and model grid would be determined by the complexity of the local aquifer system and the distance between the pumping well and the jurisdictional subflow zone. The spatial characteristics of the aquifer, confining layers, and aquifer boundaries would be based on hydrogeologic cross sections that the Department proposes be constructed in Section 3.5. Aquifer properties and their variability across the model area would be based, as proposed in section 3.6, on data from published water supply and hydrogeologic studies and, if available and reliable, on existing pump test data from the well. To determine the initial position of the water table and/or potentiometric surface before pumping began, the Department proposes to use the USGS predevelopment maps described in Chapter 2 and presented in Plates 1 through 3. Like aquifer properties, the

occurrence of aquifer recharge and discharge between the pumping well and the jurisdictional subflow zone would be based on published water supply and hydrogeologic studies. Data on well location and construction would be collected following the procedures outlined in sections 3.1 and 3.4. And finally, the rate and schedule of well pumping would be based on information described in sections 3.2 and 3.3.

3.10 MODEL OUTPUT

Model output would be used to prepare a map that shows the simulated cone of depression and its relation to the jurisdictional subflow zone. If ranges of model inputs were evaluated, a series of cone of depression maps would be prepared. To evaluate whether the maps are reasonable, the Department proposes that, at a minimum, the simulated depth to water in the well be compared to past and current pumping levels, if available. Based on these comparisons, it may be necessary to adjust the model input (calibrate) to better reflect actual water level conditions and then rerun the mathematical model.

3.11 ADJUDICATION OF WELL

The Department proposes that a well be included in the adjudication only if, *at the time of the modeling*, two conditions are met. The first condition is that the simulated cone of depression has reached the edge of the jurisdictional subflow zone and drawdown at that point is greater than or equal to 0.1 foot, an amount that can be accurately measured in the field using standard water level measuring equipment. The second condition is that the water level in the well is *below* the water level in the jurisdictional subflow zone during pumping. If the water level in the well is *above* the water level in the jurisdictional subflow zone during pumping, the well cannot be pumping subflow.

It is important to remember that the accuracy of model simulations will in most, if not all, cases be far less accurate that the ability to measure drawdown in the field. Simulated water levels from even the most carefully calibrated MODFLOW models are typically no closer than $\pm$ 5 to 10 feet from the actual water levels measured in the field. And, unless water level data are available at the pumping well and at the edge of the

jurisdictional subflow zone, it will be difficult to determine if the model simulations are overestimating or underestimating the true drawdown at these points.

3.12 THWELLS MODEL SIMULATIONS

This chapter concludes with two examples that demonstrate how THWELLS can be used to conduct cone of depression tests. The examples are hypothetical and the data used to run the model simulations were assumed to be readily available. As described earlier in this chapter, information needed to conduct cone of depression tests will often be unknown or only poorly known, requiring that data be estimated.

EXAMPLE 1

The first hypothetical example involves a municipal well located 10,000 feet (1.9 miles) upgradient of a jurisdictional subflow zone. The SOC filed by a water company who owns the well indicates it has been pumped since 1962 at a rate of 200 acre-feet per year. Assuming the well is pumped continuously, this equates to a discharge of approximately 124 gallons per minute (gpm).

Water adequacy documents filed with the Department include a completion log that shows that the well is 300 feet deep, sealed from 0 to 50 feet, and screened from 50 to 250 feet. Also in the Department's file were lithologic logs indicating that the well obtains water from a relatively uniform layer of silty sand that extends from the jurisdictional subflow zone to an area 3 miles upstream of the well. Based on predevelopment water level data from the USGS, the saturated thickness of the silty sand layer is about 200 feet and the municipal well completely penetrates the aquifer.

Previous work on a regional ground water model of the area found that the silty sand aquifer is relatively homogenous and isotropic with a hydraulic conductivity of 10 feet/day (ft/d) and a storage coefficient of 0.08. The unconfined aquifer is bounded at the base by low permeability clay deposits and at the top by a water table that slopes at a regional gradient of 0.2%.

Appendix J includes a printout of the input used in THWELLS to simulate the cone of depression around the municipal well and output from the model simulations. The model output shows that after 40 years of pumping, drawdown at the well is

estimated to total about 23 feet. This compares favorably to the 27 feet of drawdown currently measured in the well. After only four years of pumping, the simulated drawdown at the edge of the jurisdictional subflow zone exceeds 0.1 feet, and the simulated water level in the pumping well was below the simulated water level at the edge of the jurisdiction subflow zone. Based on these model results, it is likely that the well is pumping subflow and should be included in the adjudication.

EXAMPLE 2

The second hypothetical example involves an irrigation well located 3,500 feet (0.7 miles) upgradient of a jurisdictional subflow zone. The SOC filed by a farmer who owns the well does not indicate how long the well has been pumped or at what rate. The farmer was contacted and it was learned that the well was installed in the spring of 1996 and has been used since that time to irrigate a small (1.5-acre) field of grapefruit trees. Meter records provided by the farmer indicate that the well is used throughout the year and the discharge has averaged 5 gpm, or 8.1 acre-feet per year.

The driller's report states that the irrigation well is 50 feet deep and screened from 30 to 50 feet. No information was provided on well seals, so it was assumed the well is unsealed. A log included in the driller's report indicates that the well obtains water from a 10-foot layer of "sand and gravel" overlain by 30 feet of "dry silt" and underlain by 10 feet of "tight clay". Based on predevelopment water level data from the USGS, the sand and gravel layer identified by the driller was previously completely saturated and the well completely penetrates this aquifer.

The only information on the hydraulic characteristics of the sand and gravel layer is found in a 1960 USGS water supply paper describing the availability of water in the region for agriculture. Pumping tests conducted by the USGS near the irrigation well found the aquifer has a hydraulic conductivity of 50 ft/d and a storage coefficient of 0.2. This unconfined aquifer is regionally extensive and bounded at the base by low permeability clay deposits and at the top by a water table that slopes at a regional gradient of 0.5%.

Appendix J includes a printout of the input used in THWELLS to simulate the cone of depression around the irrigation well and output from the model simulations. Model output shows that after six years of pumping, drawdown at the well is estimated to

total 3.4 feet. This compares favorably to the 5 feet of drawdown currently measured in the well by the farmer. The simulated drawdown at the edge of the jurisdictional subflow zone never exceeds 0.1 feet after six years of pumping. Based on the model results, it appears that the well is not pumping subflow and should not be included in the adjudication at this time.

This chapter has presented a discussion of the steps required to implement a cone of depression test for wells located outside of the subflow zone. These steps are resource intensive and time sensitive. Accordingly, the Department recommends that they not be initiated until the trial court determines that a particular watershed or subwatershed is ready for adjudication.

CHAPTER 4: *DE MINIMIS* USES

This chapter describes methodologies for developing guidelines to determine whether a given well, though pumping subflow, has a *de minimis* effect on the river system, and further describes the Department's recommendations for addressing *de minimis* uses within the adjudication. Extensive proceedings have already been conducted by the special master in the San Pedro River watershed concerning *de minimis* uses, and the matter is now before the trial court for review. *In re Sands Group of Cases (W1-11-19) and Other Related Cases (Consolidated)* (Group 1 Cases). Discussed below are the special master's decision in the Group 1 Cases, and the Department's recommendations regarding *de minimis* uses.

4.1 GROUP 1 CASES

The Group 1 Cases have a long history beginning in 1993 when six consolidated cases were first organized for trial by Special Master Thorson. After a seven-day trial, and several months of post-trial briefing, the special master entered a memorandum decision in November 1994 (1994 Memorandum Decision). In February 1995, the special master granted the State of Arizona's motion for reconsideration, and modified the 1994 Memorandum Decision (1995 Modified Memorandum Decision). Between 1995 and 2001, objections were filed by the parties to the special master's 1994 and 1995 decisions in the Group 1 Cases. Objections were not filed by neighboring stockwatering, stockpond or domestic users, but rather by users below the mouth of the San Pedro River (1994 Memorandum Decision, p. 19). The matter was argued before the trial court on September 27, 2001 and now awaits decision.

In the special master's 1994 Memorandum Decision, the special master recommended definitions for stockwatering, stockpond and domestic *de minimis* uses. Because the vast majority of domestic uses are supplied by wells, the special master's definition for *de minimis* wells provides useful guidance. Although the Department disagrees with the special master's approach, the Department believes that the special master's definition of domestic *de minimis* use is acceptable. The appropriate definition will be decided by the trial court.

In the special master's 1994 Memorandum Decision, the special master engaged in a rigorous analysis to address the following questions:

> Are stockwatering, stockponds, or domestic water uses in the San Pedro River watershed *de minimis* in the context of the Gila River adjudication? If these uses are *de minimis*, what are the appropriate summary procedures for adjudicating them? What procedures should be followed to adjudicate any stockwatering, stockponds, or domestic uses not determined in this proceeding to be *de minimis* uses?

(1994 Memorandum Decision, p. 7.) The special master entered 64 findings of fact and 31 conclusions of law that addressed the total water supply of the San Pedro River watershed; the number of stockwatering, stockpond, and domestic uses within the watershed; the extent and impact of these uses on outflows from the watershed; the costs and benefits of a summary adjudication of these small uses; and appropriate procedures for summary adjudication of these uses. The special master concluded that the cumulative impact of depletions from stockwatering uses on flows at the mouth of the San Pedro River was a *de minimis* amount, but that neither the cumulative impact of depletions from stockponds nor the cumulative impact of depletions from domestic uses was a *de minimis* amount (1994 Memorandum Report, pp. 31, 33). However, based on the resources required to individually adjudicate these uses[1], as well as the difficulty of administering these uses post-decree, the special master further concluded that stockwatering, stockpond and domestic uses should be considered *de minimis*.

Part of the analysis undertaken by the special master included a determination of the cumulative impacts from stockponds, and the cumulative impacts from domestic uses, on the amount of water available at the mouth of the San Pedro River. Although not required for stockponds, the special master's analysis of domestic uses necessarily involved water supplied by wells. In Finding of Fact No. 22, the special master found that only about 3% of the domestic uses in the San Pedro River watershed were supplied by surface water, while 97% were supplied by wells (1994 Memorandum Decision, p.

[1] In Findings of Fact No. 58 and No. 59, the special master found that the pre-trial process alone resulted in the expenditure of $42,000 by the parties, and that it could require eleven years to complete a detailed, individual adjudication of each of the stockwatering, stockpond, and domestic uses in the San Pedro River watershed (1994 Memorandum Decision, pp. 29, 30). These uses totaled approximately 5,800 and comprised about 85% of all of the potential water rights included in the San Pedro River Watershed Hydrographic Survey Report (1994 Memorandum Decision, pp. 18, 26).

19). The calculations used by the special master to determine cumulative depletions from domestic uses have not been the subject of objections by the parties.

The special master's calculations in both the 1994 Memorandum Decision and the 1995 Modified Memorandum Decision relating to the amount of water available at the mouth of the San Pedro River have been the subject of considerable debate. The ratio between the amount of domestic use depletions and the amount of water available at the mouth of the San Pedro River led the special master to conclude that the cumulative impact of domestic uses could not be considered a *de minimis* amount. However, as indicated above, the special master concluded that these uses should still be subject to a summary adjudication process (1994 Memorandum Decision, p. 33).

In anticipation of trial in the *Group 1 Cases*, the special master requested that the Department prepare a technical report on the magnitude of *de minimis* uses in the San Pedro River watershed. In response to this request, the Department prepared a technical report entitled *Technical Report on De Minimis Adjudication of Domestic, Stockpond and Stockwatering Uses in the San Pedro Watershed* (ADWR, 1993), which was subsequently admitted into evidence at trial (1994 Memorandum Decision, p. 7). Based on information in the San Pedro River Watershed Hydrographic Survey Report (San Pedro HSR), the Department's analysis of impacts on the river system included approximately 3,000 domestic uses, 3% of which were supplied by surface water, with the remaining 97% supplied by domestic wells located throughout the entire San Pedro River watershed (ADWR, 1991). By assuming that withdrawals from these wells would have an instantaneous effect on reducing surface water supplies, the Department made a conservative calculation of the impact of domestic uses on the available water at the outflow of the watershed based on a undepleted flow analysis. This analysis involved a water budget that evaluated the impact of cultural uses on streamflow, and accounted for natural losses (evaporation and riparian use) that occur regardless of other uses. The Department concluded that the impact from domestic uses was only 1% of the watershed outflow amount.

The special master adopted the Department's 1993 Technical Report only in part. Although the special master accepted the Department's undepleted flow analysis for domestic uses in Finding of Fact No. 64, the special master did not agree with the Department's determination of the amount of water available at the mouth of the San

Pedro River (1994 Memorandum Decision, p. 31.) Instead of the 1% impact found by the Department, the special master concluded that there was between a 23% and 66% impact on water availability at the outflow of the watershed (1995 Modified Memorandum Decision, p. 14). The parties have challenged the special master's calculations supporting this conclusion.

Regardless of the impacts from domestic uses on the river system, the special master concluded that certain domestic uses should be treated as *de minimis*. The special master defined *de minimis* domestic uses as individual domestic uses for single residences, serving household purposes and associated outdoor activities on adjoining land not exceeding 0.2 acres. As part of the summary adjudication process, these *de minimis* uses would be quantified in an amount "not to exceed 1 acre-foot/year," and would be referred to as "self-supplied residential domestic rights."[2] Remaining domestic uses would be adjudicated separately in the normal course of the adjudication (1994 Memorandum Decision, p. 33). The special master's proposed definition of *de minimis* domestic uses with a uniform quantification has not been challenged by any of the parties. The Department also believes that this is an acceptable definition.

4.2 THE DEPARTMENT'S RECOMMENDATIONS

The special master's 1994 and 1995 decisions are currently before the trial court upon objections filed by the parties. It does not appear that any of the parties have challenged the special master's definition of *de minimis* uses, or the special master's determination that these *de minimis* uses should be summarily adjudicated with water rights characteristics. Based on a recent decision by the Arizona Supreme Court, the Department disagrees with the special master on the latter issue.[3]

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[2] The Department's undepleted flow analysis assumed a domestic use amount of 0.5 acre-feet per year, of which 80% was depleted (ADWR, 1993). Although the special master adopted the Department's undepleted flow amount, the special master disagreed with the Department's assumption regarding the quantity of each domestic use. The special master concluded that 1 acre-foot/year was the appropriate quantification amount (1994 Memorandum Decision, p. 33).

[3] Some of the parties raised related issues. See *e.g.* "United States Reply to Responses to Objections to Special Master's De Minimis Uses Report" (Jan. 11, 2001); "ASARCO Incorporated's Supplemental Objections to the Special Master's Memorandum Decision, Findings of fact, and Conclusions of Law for Group 1 Cases Involving Stockwatering, Stockponds, and Domestic Uses" (Sept. 6, 2001); "Response to Objections to Special Master's Report Re: Treatment of Stockwatering, Stockpond and Domestic Uses in the San Pedro River Watershed" (Nov. 9, 2000) filed by the Salt River Project Agricultural Improvement and Power District and the Salt River Valley Water Users' Association (SRP).

The special master's decision in 1994 to summarily adjudicate *de minimis* uses rather than to exclude them from the adjudication is called into question by an Arizona Supreme Court decision that was entered six years after the special master's first decision in the Group 1 Cases. By decision of 2000, the Arizona Supreme Court set forth three tests, including a subflow zone test, a cone of depression test, and a *de minimis* test, to determine whether a well should be included within the adjudication. The Court stated:

> All wells located within the lateral limits of the subflow zone are subject to this adjudication. In addition, all wells located outside the subflow zone that are pumping water from a stream or its subflow, as determined by DWR's analysis of the well's cone of depression, are included in this adjudication. *Finally, wells that, though pumping subflow, have a de minimus [sic] effect on the river system may be excluded from the adjudication based on rational guidelines for such an exclusion, as proposed by DWR and adopted by the trial court.*

In re the General Adjudication of all Rights to use Water in the Gila River System and Source, 198 Ariz. 330, 344, 9 P.3d 1069, 1083 (2000) (*Gila IV*) (emphasis added).

The above-quoted language reaffirms a prior Arizona Supreme Court decision. The Arizona Supreme Court previously stated:

> We believe that the trial court may adopt a rationally based exclusion for wells having a de minimis effect on the river system. Such a de minimis exclusion effectively allocates to those well owners whatever amount of water is determined to be de minimis. It is, in effect, a summary adjudication of their rights. A properly crafted de minimis exclusion will not cause piecemeal adjudication of water rights or in any other way run afoul of the McCarran Amendment. Rather, it could simplify and accelerate the adjudication by reducing the work involved in preparing the hydrographic survey reports and by reducing the number of contested cases before the special master.

In re the General Adjudication of all Rights to use Water in the Gila River System and Source, 175 Ariz. 382, 394, 857 P.2d 1236, 1248 (1993) (*Gila II*). Although the Court in *Gila II* stated that an exclusion of *de minimis* uses is "in effect, a summary adjudication of their rights," the Court also stated that it neither intended the Department to include those uses in the Department's hydrographic survey reports, nor intended that the special

master litigate those uses as part of a contested case. Rather, the exclusion of *de minimis* uses would "simplify and accelerate the adjudication by reducing the work involved." Furthermore, such an exclusion would not "run afoul of the McCarran Amendment." The Department does not believe that the special master's approach to *de minimis* uses is consistent with *Gila II* and *Gila IV*.

In light of *Gila II* and *Gila IV*, the Department makes the following recommendations regarding *de minimis* uses. The Department recommends that *de minimis* domestic well uses be listed under a *de minimis* domestic use category in both the San Pedro HSR and in the court's decree.[4] The *de minimis* category would list the name of the present well owner, the well location to the nearest ¼ ¼ ¼ section, the type of use (domestic *de minimis*), the place of use, and the quantity of use. As long as these catalogued domestic uses continued to satisfy the definition of a *de minimis* use adopted by the trial court, these uses would not be subject to post-decree administration or enforcement.[5] In the Department's opinion, this approach would satisfy the directives of the *Gila II* and *Gila IV* that the adjudication be simplified and accelerated, while at the same time satisfying the McCarran Amendment.[6]

This chapter has set forth the Department's recommendation for addressing *de minimis* uses in the adjudication. The Department believes that the special master's definition of *de minimis* domestic uses is acceptable. However, based on decisions by the Arizona Supreme Court, the Department believes that these uses should not be summarily adjudicated with water rights characteristics. Rather, they should be excluded from the adjudication and catalogued in the decrees. The Department believes that this approach is consistent with both *Gila II* and *Gila IV*.

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[4] Another potential *de minimis* category would be for stockwatering uses supplied by wells. These wells were not addressed by the special master in the Group 1 Cases.

[5] In Finding of Fact No. 58, the special master stated: "Administration of individual domestic uses is generally not feasible in terms of making water available to downstream users." (1994 Memorandum Decision, p. 29.)

[6] The McCarran Amendment gives consent to suits against the United States in state court adjudications of rights to use water in a river system or other source. 43 U.S.C. ∋ 666(a).

CHAPTER 5: SUMMARY AND IMPLEMENTATION

In Chapters 2, 3, and 4 of this report, the Department describes methodologies for delineating the jurisdictional subflow zone within the San Pedro River watershed; for determining whether pumping by a well located outside the jurisdictional subflow zone has created a cone of depression that intercepts and withdraws water from the subflow zone; and, for developing guidelines to determine whether a given well, though pumping subflow, has a *de minimis* effect on the river system together with the Department's recommendations regarding *de minimis* uses. The Department summarizes these chapters below, and indicates how the methodologies described in those chapters may be implemented in the future.

CHAPTER 2

In Chapter 2, the Department describes the methodologies it proposes to use to delineate the jurisdictional subflow zone of the San Pedro River. These methodologies are summarized below.

As part of the preparation of this report, the Department has already conducted an extensive literature search to identify published streamflow maps that cover all or portions of the Gila River adjudication area. Based on this search, the Department identified two streamflow maps. One of the maps used was published by the U.S. Geological Survey (USGS) for predevelopment perennial reaches, and the other was published by the Arizona Game and Fish Department (AGFD) for recent perennial reaches. The Department proposes that these maps be combined to create a composite map of perennial streams. The Department was unable to identify published maps that depict predevelopment intermittent stream reaches. Therefore, the Department proposes to use only a map published by AGFD for recent intermittent stream reaches that may then be combined with the composite map of perennial reaches.

The Department also identified major and minor effluent fed streams based on information from the Arizona Department of Environmental Quality. However, the Department does not recommend that they be included on the streamflow maps. Two of the three major reaches are already included on the USGS predevelopment perennial map selected by the Department, and, for most other reaches, a hydraulic disconnect may often exist between the subflow and the stream.

The Department next proposes to identify and obtain copies of published surficial geology maps for the areas with perennial and intermittent streams. For the San Pedro River within the Sierra Vista subwatershed, the Department has already identified ten maps that delineate the lateral extent of the floodplain Holocene alluvium from map databases developed by the Arizona Geological Survey (AGS) and the USGS. The Department evaluated these maps and selected a map by Pool and Coes (1999) as the best available for this example.

For the last step, the Department attempted to determine the saturated portion of the floodplain Holocene alluvium. However, there is lack of readily available and reliable data that may be obtained by reasonable means to determine either the thickness of the alluvium, or the depth to water beneath the floodplain. Because of this limitation, and because streamflow conditions for predevelopment times have already been taken into account as part of the mapping steps described above, the Department recommends that the entire lateral extent of the saturated floodplain Holocene alluvium be assumed to be saturated for the purpose of delineating the jurisdictional subflow zone.

The Department believes that it has the necessary resources to determine the jurisdictional subflow zone using the steps outlined above. The Department anticipates that it would require approximately four to six months to implement these steps for *each* of the seven watersheds in the Gila River adjudication, including the San Pedro River watershed.

CHAPTER 3

In Chapter 3, the Department describes proposed methodologies for determining whether pumping from a well located outside of the jurisdictional subflow zone has created a cone of depression that intercepts and withdraws water from the subflow zone. Analysis of the size of a well's cone of depression and how it changes over time with pumping is a complex and data intensive task involving subsurface conditions that are difficult to determine.

The Department recommends that the following steps be undertaken. First, the well location, elevation, and distance from the subflow zone should be determined. The pumping history and frequency of pumping should then be established, and well construction records should be reviewed. Local hydrogeologic conditions and aquifer properties should also be established. After these steps are completed, a conceptual model of the aquifer system should be created which can then be transformed into an analytical or numerical mathematical model. For less complex aquifer systems, the Department recommends use of the computer program

THWELLS, an analytical model, and for more complex aquifer systems, the computer program MODFLOW, a numerical model. The Department further recommends that the model output be used to prepare a map depicting the simulated cone of depression and its relation to the jurisdictional subflow zone. If the model indicates that the drawdown at the edge of the jurisdictional subflow zone is greater than or equal to 0.1 foot, *and* the water level in the pumping well is below the water level in the jurisdictional subflow zone, then the Department recommends that the well be included in the adjudication.

The Department has limited resources to accomplish the steps described above. Ideally, these steps should be implemented on a well-by-well basis, but it may be possible to combine several of these steps and use them for different wells in the same general area. By using available data, and making certain assumptions based on professional judgment, the THWELLS analytical model could be run for each well, or group of wells in the same general area, within a watershed. For complex aquifer systems, the MODFLOW numerical model could also be used, but the necessary input data would be difficult and expensive to obtain.

Within the San Pedro River watershed alone, it is estimated that several hundred cone of depression tests would have to be performed. It has been the Department's experience that it takes one person working full time to make about 50 to 60 model runs using THWELLS in one year. Without sufficient resources, it could take several years to run the necessary models at the end of which the input data could be stale.

Because of the intensity of the resources required to conduct cone of depression tests, and because much of the data used for these tests is time sensitive, the Department recommends that the cone of depression analysis be delayed until a watershed is ready to be litigated. At that time, in order to provide timely analyses, additional resources will need to be devoted by either the Department or the parties.

CHAPTER 4

In Chapter 4, the Department describes the methodologies it proposes for developing guidelines to determine whether a given well, though pumping subflow, has a *de minimis* effect on the river system. This chapter also includes the Department's recommendations regarding *de minimis* uses.

The special master has already conducted extensive proceedings concerning guidelines related to *de minimis* uses, and the matter is currently before the trial court for review. *In re*

Sands Group of Cases (W1-11-19) and Other Related Cases (Consolidated) (Group 1 Cases). In the Group 1 Cases, the special master concluded that three categories of uses should be summarily adjudicated as *de minimis* uses, including stockwatering from streams, stockponds, and domestic uses. The majority of the domestic uses are supplied by wells. The special master defined a *de minimis* domestic use as an individual domestic use for single residences that serves household purposes and associated outdoor activities on adjoining land not exceeding 0.2 acres with a quantification of not to exceed 1.0 acre-foot per year. Because this definition has not been challenged by the parties, the Department recommends that the trial court use this definition as a guideline to determine *de minimis* uses.

The Department further recommends that *de minimis* uses be listed under a *de minimis* domestic use category in both the San Pedro River Watershed Hydrographic Survey Report and in the court's decree. The list would include the name of the present well owner, the well location, the type of use, the place of use, and the quantity of use. Under the Department's proposal, these uses would not receive a decreed water right and would not be subject to post-decree administration or enforcement.

The Department recommends that *de minimis* uses supplied by wells be identified within each watershed after the Department determines the lateral extent of the subflow zone using the steps described in Chapter 2 of this report. In order to implement this process, the Department would obtain appropriate remote sensing imagery, review existing records regarding well location and uses supplied by those wells, and conduct field investigations as necessary. Assistance in obtaining additional information from well owners could be obtained through a public notice process.

The Department recommends initiating these steps as each watershed is designated by the trial court for litigation. The time required would be a function of the number of domestic wells within each watershed. The Departments estimates that the following amounts of time would be required for each of the watersheds within the Gila River adjudication:

- Two to four months for the Upper Agua Fria River watershed;
- Two to four months for the Upper Santa Cruz River watershed;
- Four to six months for the San Pedro River watershed;
- Four to six months for the Upper Salt River watershed;
- Six to ten months for the Verde River watershed;

- Six to twelve months for the Lower Gila River watershed; and
- Ten to twelve months for the Upper Gila River watershed; and

IMPLEMENTATION SEQUENCE

In this report, the Department has described proposed methodologies for determining the jurisdictional subflow zone, for applying a cone of depression test, and for addressing *de minimis* uses. For each watershed, the Department recommends that the jurisdictional subflow zone be identified first, followed by the identification of those uses which qualify as domestic *de minimis* uses. This will minimize the number of wells that will be subject to the costly and resource intensive cone of depression test, which depends upon time-sensitive data. The identification of *de minimis* uses and implementation of the cone of depression test should only be implemented when the watershed is ready to be litigated, and sufficient resources have been identified to conduct the necessary analyses in a timely manner in advance of the commencement of litigation.

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RECENT PERENNIAL STREAMS

Based on 1993 Arizona Game and Fish Department Report

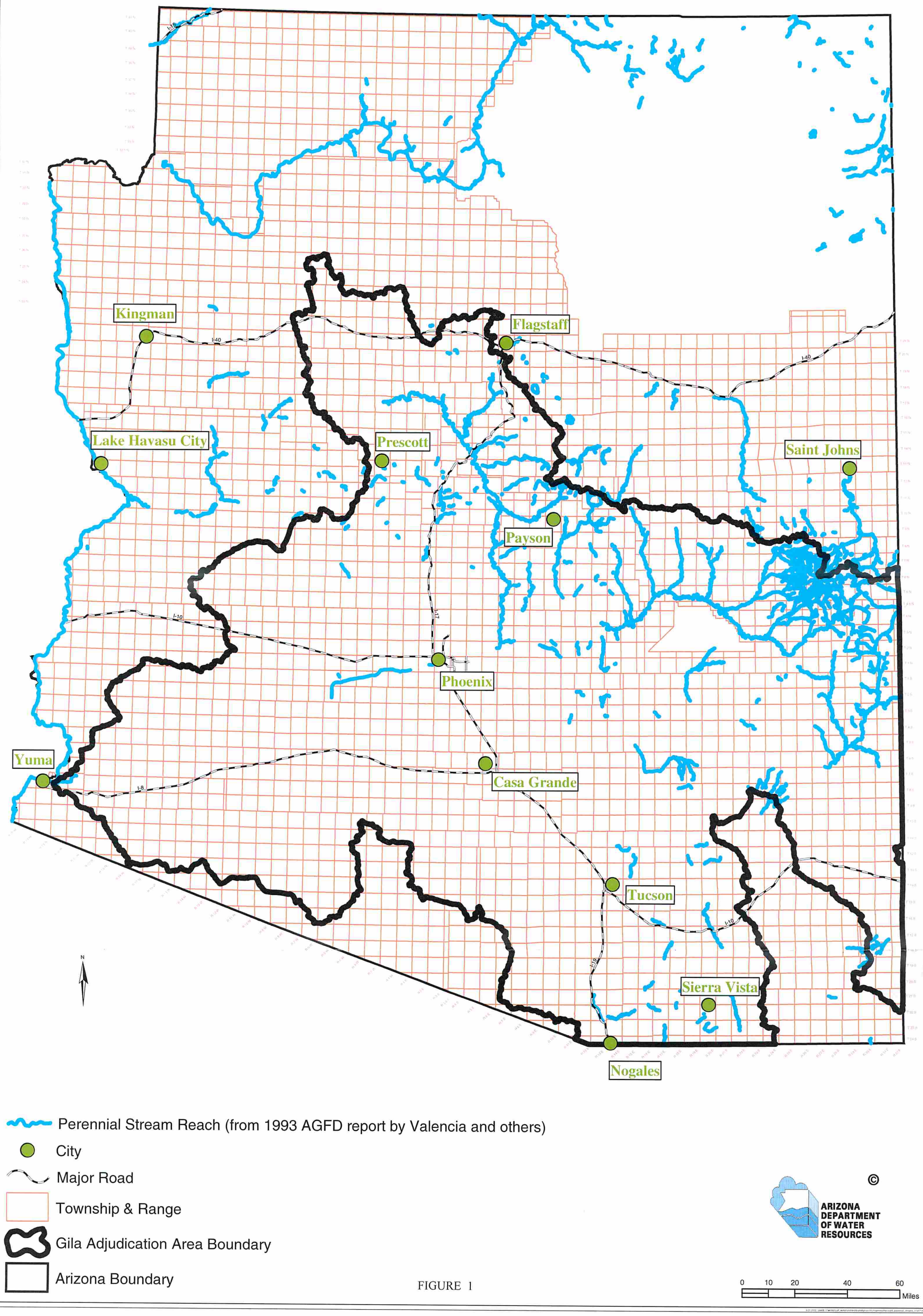
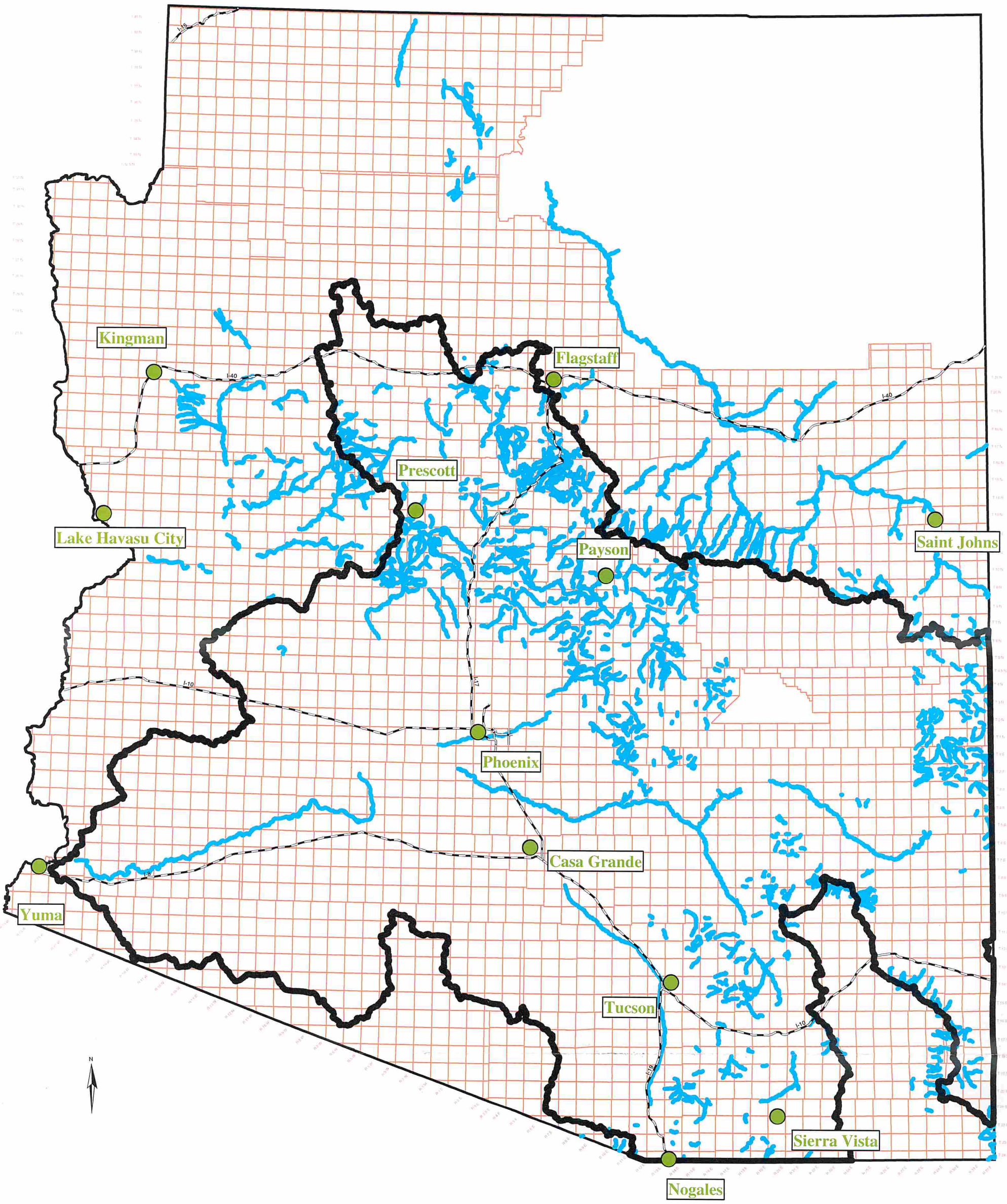


FIGURE 1

RECENT INTERMITTENT STREAMS

Based on 1997 Arizona Game and Fish Department Report



Intermittent Stream Reach (from 1997 AGFD report by Wahl and others)

City

Major Road

Township & Range

Gila Adjudication Area Boundary

Arizona Boundary

FIGURE 2

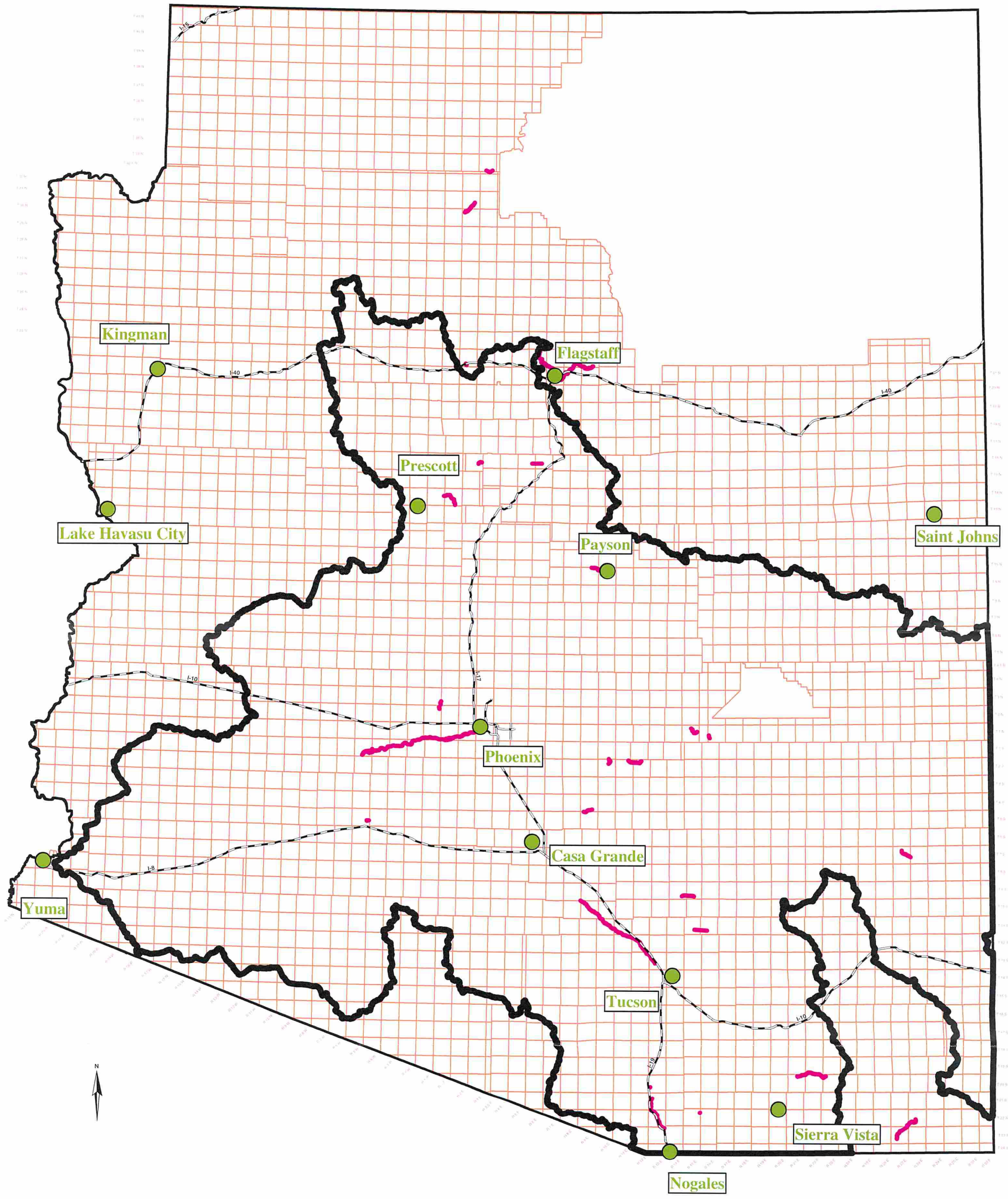
©

ARIZONA DEPARTMENT OF WATER RESOURCES

0 10 20 40 60 Miles

EFFLUENT FED STREAMS

Based on Arizona Department of Environmental Quality's Classification of Effluent Dependent Waters (A.C.C. R18-11-113)



Effluent Fed Stream Reach (ADEQ's 2002 GIS coverage of effluent dependent waters)

City

Major Road

Township & Range

Gila Adjudication Area Boundary

Arizona Boundary

©

ARIZONA DEPARTMENT OF WATER RESOURCES

FIGURE 3

0 10 20 40 60 Miles

PUBLISHED MAPS DELINEATING FLOODPLAIN HOLOCENE ALLUVIUM ALONG SAN PEDRO RIVER WITHIN SIERRA VISTA SUBWATERSHED

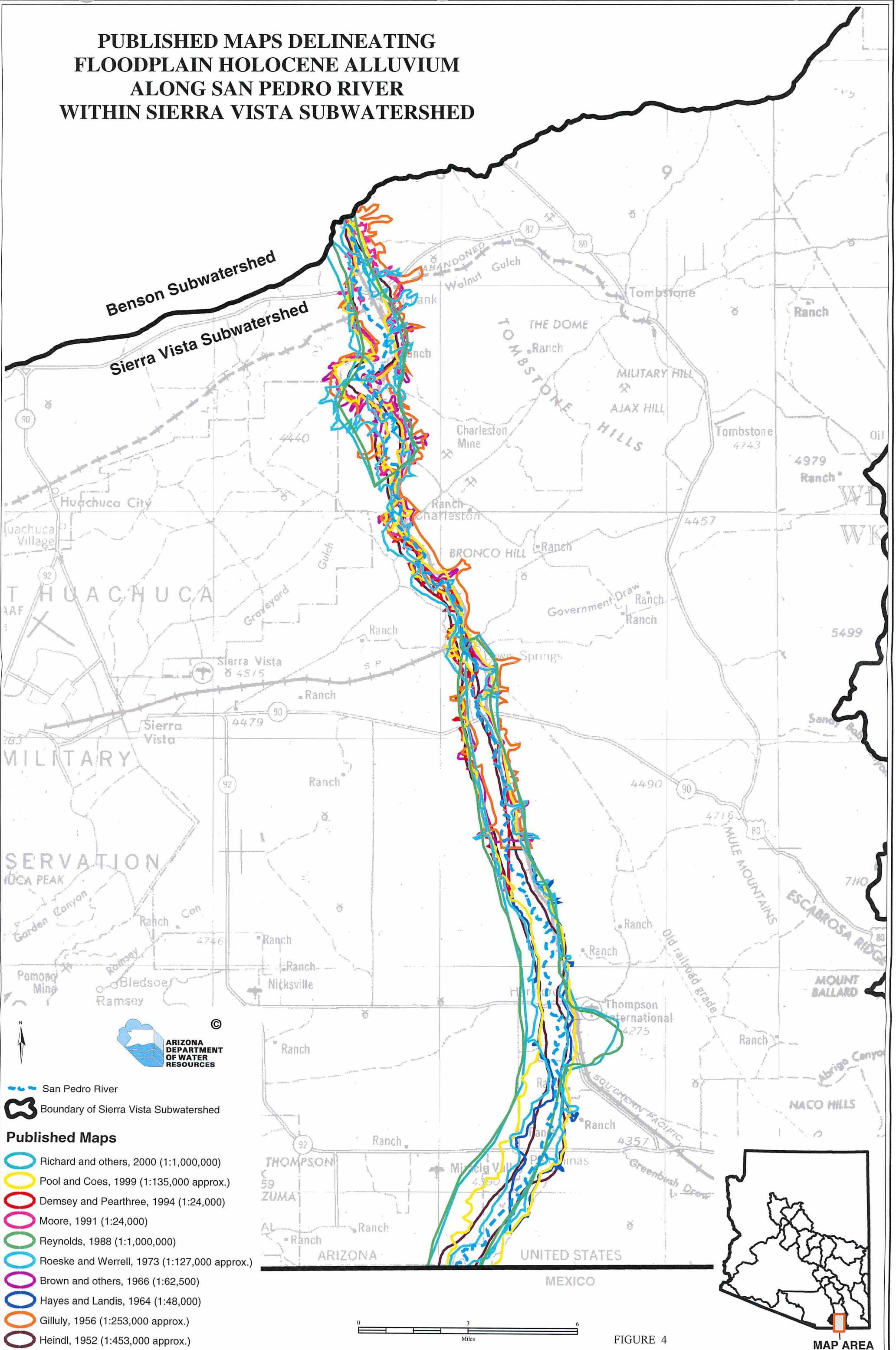


FIGURE 4

POOL AND COES (1999) DELINEATION OF FLOODPLAIN HOLOCENE ALLUVIUM ALONG SAN PEDRO RIVER WITHIN SIERRA VISTA SUBWATERSHED

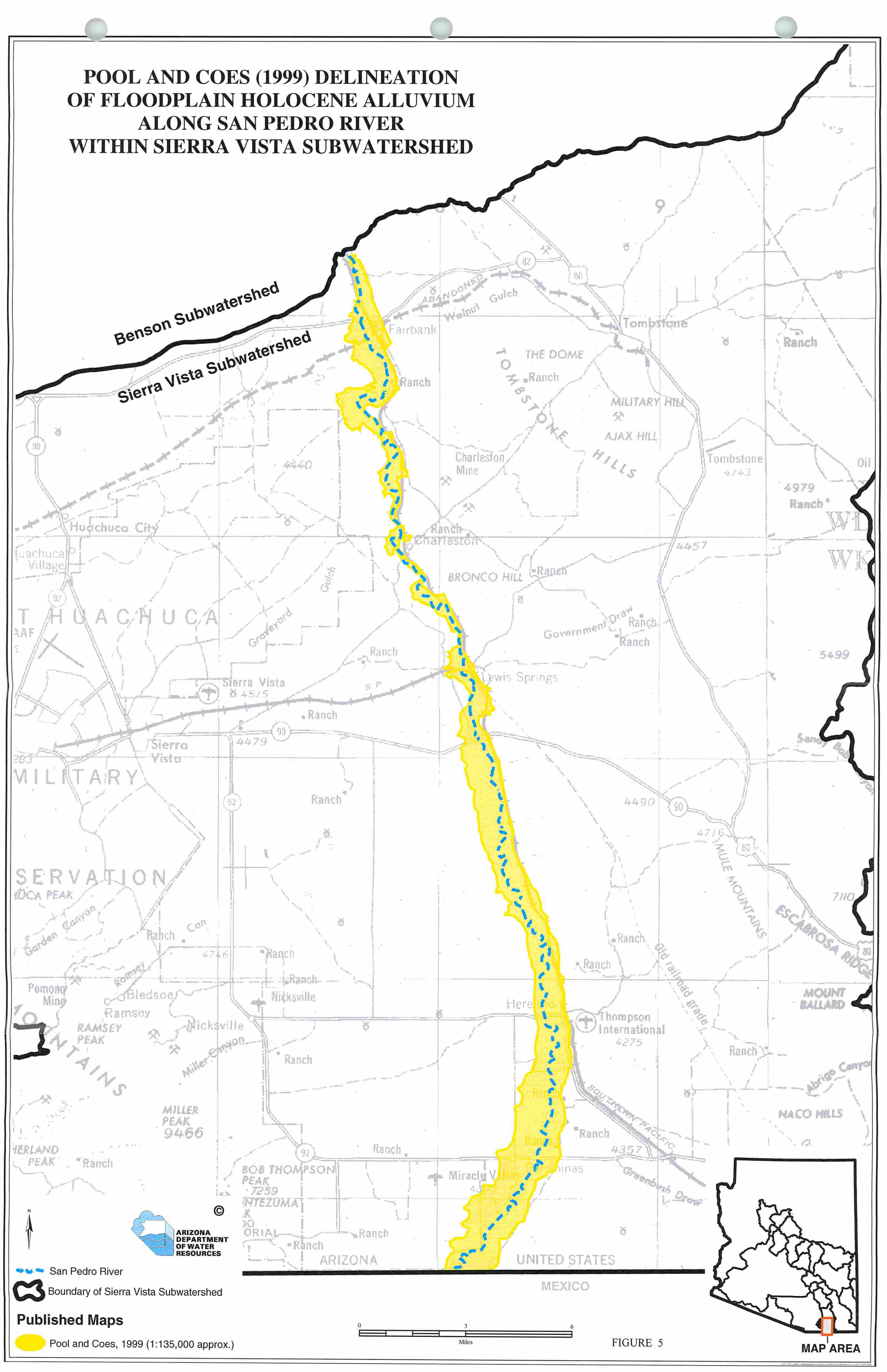
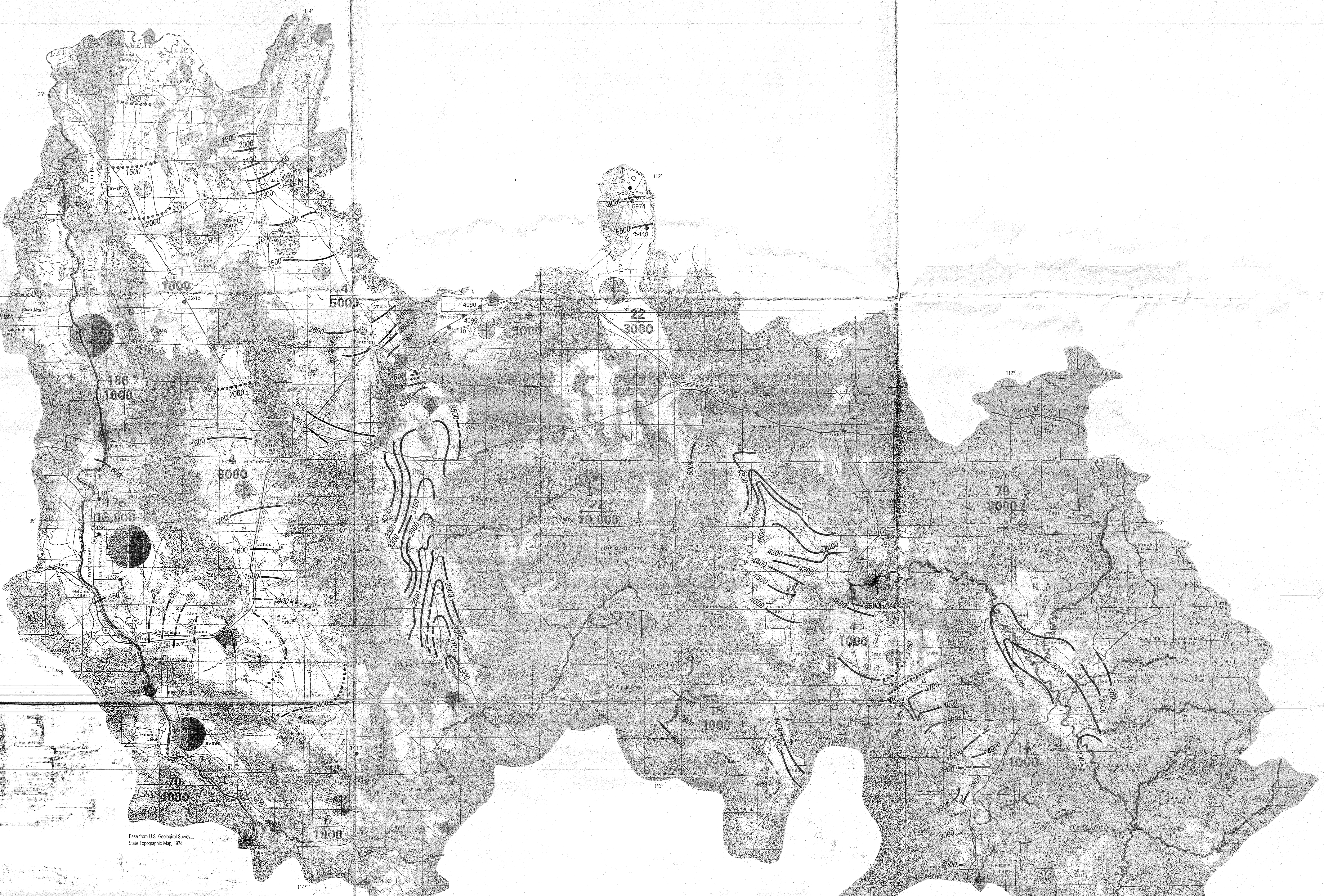


FIGURE 5



Base from U.S. Geological Survey, State Topographic Map, 1974

Geology modified from Wilson and others (1969)

INTRODUCTION

The objectives of the Southwest Alluvial Basins, Regional Aquifer-System Analysis (Swab/RASA) Project included an overall assessment of the hydrologic conditions that existed prior to man's activities that might have altered the natural hydrologic systems. Prior to development, the ground-water systems were assumed to be in equilibrium—long-term inflow was equal to long-term outflow and no change in storage occurred. The purpose of this atlas is to summarize the predevelopment hydrologic conditions using available data and hydrogeologic knowledge.

The data presented in this atlas represent a conceptual model of the predevelopment hydrologic system of the entire area and each individual basin. The quantities of inflow and outflow and the volume of water in storage were estimated from field data, numerical modeling, and transfer of selected parameter values from basins for which data were available to basins for which data were not available. The transfer of information was based on known similarities in physiography and hydrology and assumed similarities in lithology of the basin-fill sediments between adjacent or nearby basins.

GEOHYDROLOGIC FRAMEWORK

The study area includes about 82,000 mi² and is divided into 72 subareas or basins that represent, for the most part, separate ground-water systems (fig. 1). The area is characterized by sharply rising mountains separated by broad alluvial basins. The basins are filled with a sequence of permeable sediments that represent different depositional environments. The basin-fill deposits, which constitute the aquifer system of the area, generally are several thousand feet thick and store large quantities of water. The bedrock of the mountains is relatively impermeable.

The specific flow components of the hydrologic system within each basin differ in quantity because of different topographic, climatic, hydrologic, and geologic characteristics. Components of inflow to the aquifers include ground-water underflow from adjacent basins, mountain-front recharge, and infiltration of streamflow along the major drainages. Components of outflow include ground-water underflow to adjacent basins, discharge to streams, and evapotranspiration losses (fig. 2). Owing to the aridity of the area, values for the flow components commonly are small, especially in comparison to the vast quantities of water that are stored in the basin-fill deposits.

WATER-LEVEL CONFIGURATION AND IMPLICATIONS

The water-level contours represent the altitude at which water stood in wells finished in the unconfined aquifers in the basins prior to development. An exception is the configuration *shown for the San Simon-Bowie area* near the Arizona-New Mexico State boundary. Because the data for the unconfined aquifer in the northern part of the basin were inadequate, the contours represent the potentiometric surface of the confined aquifer system in this area. The water table generally follows the trend of the topographic surface overlying it but is less steep. The depth to water therefore is shallowest in the topographic low area of the basin and gradually increases away from the basin axis and toward the topographic high areas (fig. 2).

The contours were based on water-level data obtained from reports and data files of the U.S. Geological Survey and other agencies. Recent water-level data were used for basins where development is minor and long-term changes in water level can be assumed to be small and negligible. Data from the early 1900's to about 1940, which precedes the period of greatest development, were used for highly developed basins. In places, water-level contours were based on the location and altitude of perennial streams (Brown and others, 1981) and descriptions of the streams given in historical accounts of the Gila River drainage system. In a few basins for which data are practically nonexistent, the water-level contours were estimated on the basis of available water-level or perennial-stream altitude and known or assumed similarities between basins.

The predevelopment water-level contours can be interpreted to indicate the general ground-water movement. Ground water flows from areas of high head to areas of low head. The individual basins are linked together to varying degrees in a dendritic pattern to form a regional flow system. The shapes of the water-level contours generally indicate areas of inflow and outflow. Basins in which contours are U-shaped and nearly parallel to the mountain fronts probably receive a significant amount of mountain-front recharge. Basins in which contours are relatively straight and nearly perpendicular to the mountain fronts receive little or no mountain-front recharge. Significant variations in water-level gradients indicate changing physical or hydraulic properties of the aquifer.

The contours shown are assumed to represent the head throughout the entire aquifer thickness. On a regional basis, this assumption is probably valid. Minor head differences, both greater and lesser with depth, occur in places in the study area but are not known to be extensive or mappable. Areas in which this assumption may not be valid are in zones of inflow and outflow where vertical-flow components may be significant.

VOLUME OF GROUND WATER IN STORAGE

The volume of recoverable ground water in storage in the saturated zone that extends to 1,200 ft below the land surface is estimated to be 900 million acre-ft in the study area prior to development. This value, which was estimated using a specific yield ranging from 0.03 to 0.25 and estimated aquifer volumes, is less than previously estimated (Brown, 1976). Water-quality constraints were not imposed on the estimates, although all the water is not necessarily potable or usable. As a result of the Swab/RASA study, new information was developed on the lateral extent of the aquifer and the specific yield of the aquifer materials. A depth-to-bedrock map (Oppenheimer and Sumner, 1980), which was developed using gravity-modeling techniques, provided an estimate of the geometry of each basin. Regional and vertical patterns of specific yield were developed using empirical values of specific yield for particular sediment types and a computerized integration technique. The estimated areal patterns were used and evaluated in numerical models of several basins. The most significant lithologic feature that influences the estimates of recoverable ground water in storage is the presence of thick, extensive fine-grained facies in the basin fill in the central parts of most basins. The fine-grained facies typically contain more than 50 percent of sediments that are less than 0.0625 mm in diameter. Calibration of transient ground-water flow models of basins with areally extensive fine-grained facies required specific-yield values ranging from 0.05 to 0.13. This range of values is lower than those used in previous estimates of ground water in storage.

The ratio of the annual inflow to each basin to the estimated volume of water in storage within each basin is shown on the maps. The ratio ranges from about 1:5 to 1:14,000. The low value represents a basin with a small extent of basin-fill deposits and thus a small volume of water stored within it. The high value represents a basin in which the annual inflow is small and the volume of water in storage is large. The typical range for the major developed basins is from about 1:200 to 1:2,000.

GROUND-WATER BUDGET

The development of a ground-water budget for each of the 72 basins of the study area resulted from an iterative process of balancing inflow and outflow components for adjacent basins. Components that were reliably known were considered fixed; unknown components were estimate by balancing the water budget for the basin. All unknown components were maintained within the general limits indicated by knowledge of that component in similar basins. The reliability of each estimated was considered when adjusting components to balance the regional budget.

Previously reported estimates of various components, which included stream base flow and ground-water underflow, were compiled. Estimates of evapotranspiration were obtained from reports, and the areal extent of riparian vegetation was compiled from 1936 aerial photomosaics. Estimates of recharge were based on previous studies and on precipitation-recharge relations developed as part of this study. Results of previous and ongoing ground-water modeling studies were used extensively. Reports from which particular flow-component estimates and water-level information were obtained are listed in "Selected References."

The individual components shown in the ground-water-budget diagrams should not be considered exact values for a specific basin. The values represent an approximation of each component derived by balancing the entire regional water budget. The diagrams represent a means of comparing the magnitude of the total budget and the individual components between basins and parts of the study area.

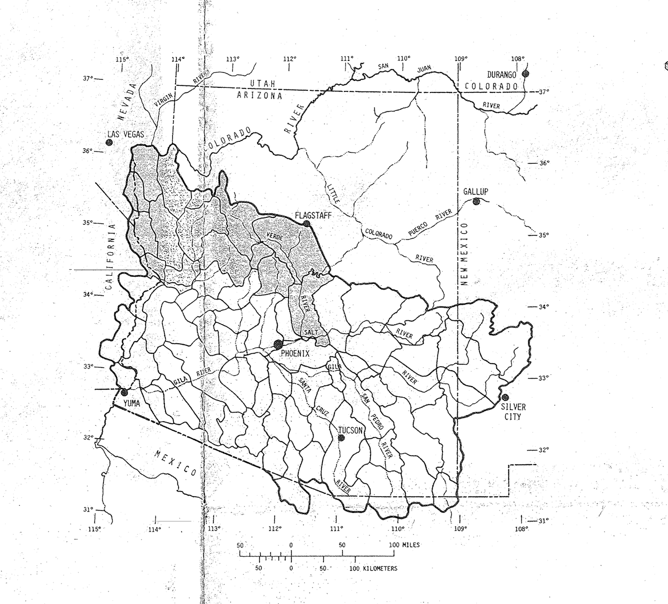


FIGURE 1.—*Study area and basins.*

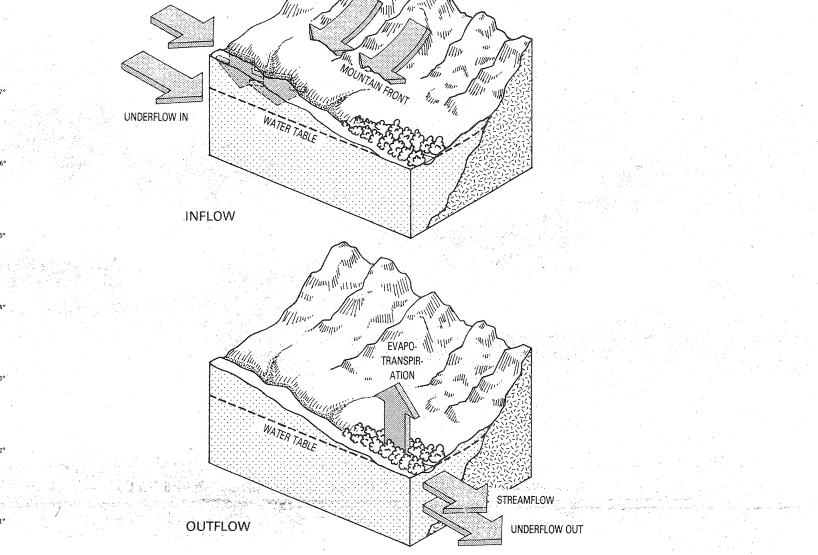


FIGURE 2.—*Mechanisms of natural inflow and outflow in typical basins in the study area.*

EXPLANATION

—500— WATER-LEVEL CONTOUR—Shows altitude of the water level prior to development. Dashed where based on meager data; dotted where approximately located. Contour interval, in feet, is variable. National Geodetic Vertical Datum of 1929

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SCALE 1:500 000

10 0 10 20 30 40 MILES

10 0 10 20 30 40 50 60 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

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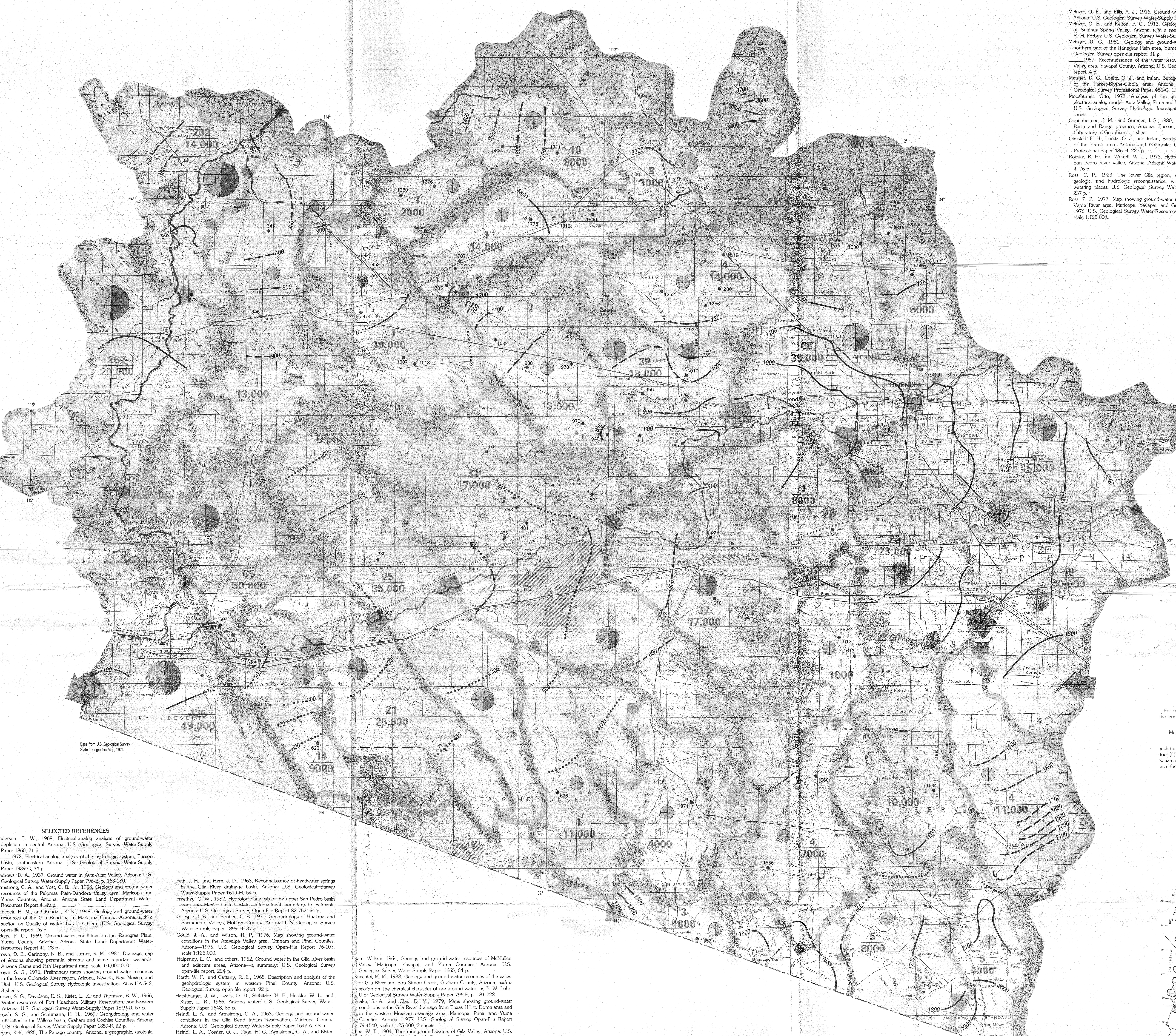

Base from U.S. Geological Survey State Topographic Map, 1974

Geology modified from Wilson and others (1969)

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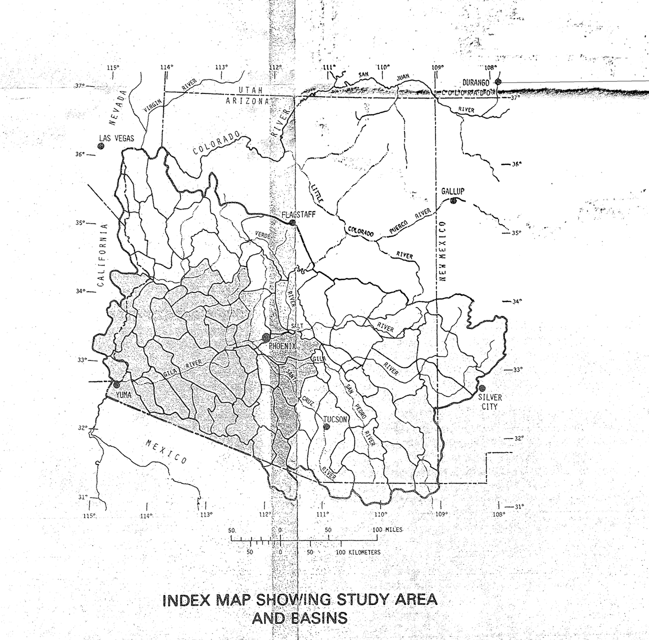

INDEX MAP SHOWING STUDY AREA AND BASINS

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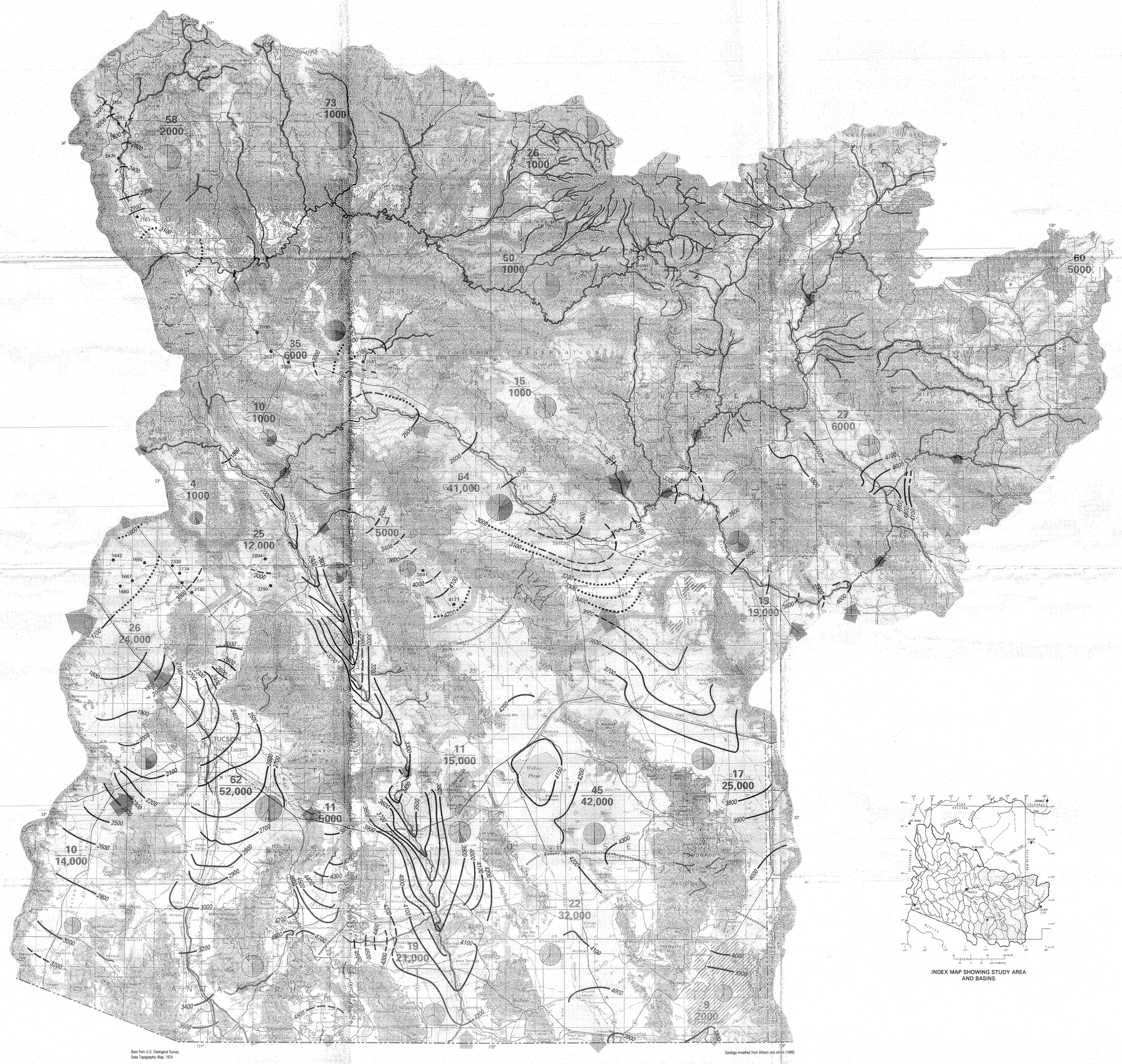
CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929



Base from U.S. Geological Survey
State Topographic Map, 1974

Geology modified from Wilson and others (1969)

INDEX MAP SHOWING STUDY AREA AND BASINS

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA.—1986—4964(6)

PREDEVELOPMENT HYDROLOGIC CONDITIONS IN THE ALLUVIAL BASINS OF ARIZONA AND ADJACENT PARTS OF CALIFORNIA AND NEW MEXICO

By
Geoffrey W. Freethey and T. W. Anderson

1986

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SUMMARY TABLE OF QUATERNARY DATING METHODS

[Modified from Colman and Pierce (1977, reference 66). See Rosholt and others (this volume) for short discussion and classification of methods and explanation of references. Asterisks indicate methods covered in that chapter].

Prepared by S. M. Colman and K. L. Pierce
Approved by the Director,
U.S. Geological Survey
July 28, 1986

TYPE OF RESULT	TYPE OF METHOD	METHOD	APPLICABILITY[1] (GLACIAL, MARINE, LACUSTRINE, ALLUVIAL, EOLIAN, VOLCANIC)	AGE RANGE (YRS) AND OPTIMUM RESOLUTION[2] (10^2 10^3 10^4 10^5 10^6)	BASIS OF METHOD	REMARKS
NUMERICAL-AGE	SIDEREAL	1. Historical records			Requires preservation of pertinent records. (2,4,12)	Applicability depends on quality and detail of records. Limited to several hundred years in North America.
		2. Dendrochronology			Requires either direct counting of annual rings in live trees or overlapping chronologies correlated between individual trees by changes in annual ring growth. (1,3,13)	Restricted to areas where trees of the required age and (or) environmental sensitivity grow or have been preserved.
		3. Varve chronology			Requires either direct counting of varves back from the present sediment surface or correlation of overlapping successions of continuously varved sediments. (1,14,15)	Subject to errors in matching separate sequences, to misidentification of annual layers, and to undetected hiatuses.
	ISOTOPIC	4. Radiocarbon*		?	Based on incorporation and decay of radiogenic ^{14}C (produced by cosmic radiation) to ^{14}N. Depends on availability and preservation of carbon. (1-5,16-19)	Subject to errors due to contamination by younger carbon, particularly in older deposits, and by older carbon, particularly in hard water. Carbonate material, such as mollusk shells, marl, and soil carbonate is readily contaminated.
		5. Uranium series*			A variety of isotopes of the U-decay series are used: $^{230}Th/^{234}U$ (<350 ka; most common method, described at left), $^{234}U/^{238}U$ (<600 ka), $^{231}Pa/^{235}U$ (10-150 ka), U-He (0-2 Ma), and $^{226}Ra/^{230}Th$ (<10 ka). (1-6,20,21)	Used to date coral, mollusks, bone, cave carbonate, and carbonate coats on stones. Has been used in dating travertine and soil carbonate. Errors due to open chemical systems and incorporation of secondary uranium are common problems, especially in mollusks, bones, and soils.
		6. Potassium-argon* and argon-argon			Based on decay of ^{40}K to ^{40}Ar. Requires K-bearing phases such as feldspar, mica, glass, and others. (1-4,22,23)	Directly applicable to igneous rocks and glauconite. Subject to errors due to excess argon, loss of argon, and contamination. The associated ^{40}Ar-^{39}Ar method produces dates analogous to K-Ar dates; the step-heating ^{40}Ar-^{39}Ar method can be used on small samples, on those with excess argon, or on those which have lost argon due to reheating.
		7. Uranium trend*			Based on the uranium-series decay system and the open-system flux of uranium through sediment and soil. (4,6,24)	Measurements of ^{238}U, ^{234}U, ^{230}Th, and ^{232}Th made on samples (usually five or more) from a given age of deposit. The samples must have different isotopic compositions so that an isochron can be constructed. The method must be calibrated with independent age estimates.
		8. Lead-210			Based on the accumulation and decay in sediments of ^{210}Pb produced in the atmosphere by the decay of ^{222}Rn. (2,3,25)	Subject to uncertainty in flux, accumulation, and bioturbation rates, and limited to lacustrine and marine sediment less than about 100 years old.
		9. Cosmogenic isotopes other than ^{14}C and ^{210}Pb		? ? ? ?	Based on the accumulation and decay of cosmogenic isotopes (half-life in 10^3 yr in parentheses) ^{32}Si (0.3), ^{41}Ca (13), ^{36}Cl (30.8), ^{26}Al (73), ^{10}Be (1500), ^{129}I (16000), and ^{53}Mn (3700); artificially produced ^{137}Cs (0.03) can be used in a similar way. (2-5,26-28)	Dating based on either atmospheric flux rates or on in-place production on surfaces. Requires knowledge of the generation rates, flux rates, and retention efficiency of the material being dated. These radioisotopes occur in very low abundances and are measured by accelerator mass spectrometry.
CALIBRATED-AGE	RADIOGENIC	10. Fission track*			Based on the formation of fission tracks (strained zones) during uranium fission; requires uranium-bearing material such as zircon, sphene, apatite, or glass. (1,3-5,7,29)	Directly applicable to igneous rocks, including volcanic ash. Subject to errors due to misidentification and annealing of tracks.
		11. Thermoluminescence*			Based on displacement of electrons in parent atoms by alpha, beta, and gamma radiation. Electrons accumulate in energy traps following heating or exposure to light. Amount of light released during laboratory heating is compared with that released after known radiation dose. (3-5,8,30-31)	Mainly applicable to quartz and feldspar in sediments and carbonate in soils. Filtered light may also be used to release luminescence. For ceramics in 0.4-10 ka range, TL precision is better than indicated.
		12. Electron spin resonance			Based on displacement of electrons in parent atoms by alpha, beta, and gamma radiation. Electrons accumulate in energy traps following heating or exposure to light. ESR measured as microwave energy absorbed when electrons change spin direction as they are released from traps. (4,5,32)	Applicable to a wide range of geologic and archaeologic materials. Methodology largely experimental.
RELATIVE-AGE	CHEMICAL AND BIOLOGICAL	13. Amino acid* diagenesis			Based on release of amino acids from protein and subsequent inversion of their stereoisomers. Requires shell, skeletal, or other organic material. (1-5,9,33)	Shells tend to be more reliable than bone, wood, or organic-rich sediment. Strongly dependent on other variables, especially temperature and leaching history. Commonly used as a relative dating or correlation technique, but yields numerical ages when calibrated by other techniques.
		14. Obsidian hydration			Based on thickness of the hydrated layer along obsidian crack or surface formed during an abrasion or cooling event. Age proportional to the square of the thickness of the hydrated layer. (2-4,10,34-35)	May also be used on volcanic glass in tephra. Calibration depends on experimental determination of hydration rate or independent dating. Subject to errors due to temperature history and variation in chemical composition.
		15. Tephra superhydration			Based on the progressive filling of bubble cavities with water in glass shards. Requires volcanic ash. (2,36)	Subject to the same limits as obsidian hydration, plus others, including variations due to the thickness of bubble walls.
		16. Lichenometry			Based on systematic growth of lichens; lichen thallus diameter is proportional to age. Requires exposed, stable rock suitable for lichen growth. (2-3,37-38)	Mainly useful in alpine and arctic regions. Subject to errors due to climatic differences, lichen kill, misidentification of species, and limits on useful age ranges, which vary with climate and rock type.
		17. Rock varnish chemistry			Based on the systematic changes in chemistry of rock varnish, primarily cation composition. Color and thickness used as a relative-age indicator. (39-40)	Mostly used in desert environments, although rock varnish has a wide distribution. The relation of most physical features, such as color and thickness, to time is poorly known, but chemical methods show a progressive leaching of cations with time.
		18. Soil chemistry			Based on changes in soil chemistry, especially the accumulation of secondary products in soils, with time. Chemical measurements of calcium carbonate, iron oxyhydroxides, pH, phosphate, nitrogen, and organic carbon are most common (2-5,41-43)	Rates of change of soil chemistry are dependent on other variables in addition to time (parent material, climate, organisms, topography). Most effective when these other variables are held constant or can be evaluated. Comparisons with independent age estimates suggests that age precision within 20 percent may be possible
	GEOMORPHIC	19. Soil-profile development			Encompasses a number of soil properties that systematically develop with time through weathering, translocation of materials, and additions to and losses from soil. (2-5,41-46)	All properties are dependent on other variables in addition to time (parent material, climate, organisms, topography). Most effective when these other variables are held constant or can be evaluated. Comparisons with independent age estimates suggests that age precision within 30 percent may be possible.
		20. Rock and mineral weathering			Based on rock and mineral-weathering features that systematically develop with time as a result of near-surface weathering processes. (2-5,11,41,45,47-48)	Includes many features, such as thickness of weathering rinds, solution of limestone, etching of pyroxene, and grussification of granite. Has the same basic limitations as soil development. Precision varies with the weathering feature measured.
		21. Progressive landform modification			Based on reconstruction of original landform and modeling of processes such as gullying and colluviation that result in change of landforms. (3,4,49-54)	Rates and forms strongly affected by climate and lithology in addition to time. Includes emprirical and theoretical models of degradation of fault, terrace, and wave-cut scarps.
		22. Rate of deposition		? ? ? ?	Based on sediment thickness between horizons dated by other methods. (2-3)	Assumes relatively constant rate of sedimentation over time intervals considered. Rates particularly variable in alluvial deposits.
		23. Geomorphic position		? ?	Based on relative level or position in an age sequence of landforms. (2)	Has similar limitations to those of landform modification, and is commonly used to determine age sequence. Only useful for certain types of landforms, such as terraces, moraines, alluvial fans, and pediments.
		24. Rate of deformation		? ?	Based on amount of tectonic deformation compared to an average deformation rate. (4,55)	Depends on assumption of constant deformation either as an interpolation between dated events, or as an extrapolation beyond dated events. Best results obtained at plate boundaries, where nearly constant rates may be valid for intervals of millions of years.
CORRELATED-AGE	CORRELATION	25. Stratigraphy		RESOLUTION DEPENDS ON RECOGNITION AND INDEPENDENT DATING OF FEATURE	Based on geologic sequence and physical properties of units; depends on the establishment of time equivalence of units. (2,4)	Deposition of Quaternary units commonly occurs in response to cyclic climatic changes on timescales of 1 to 100 ka.
		26. Tephrochronology			Requires volcanic ash (tephra) and unique chemical or petrographic identification, along with independent dating of the ash or related eruption. (4-5,7,56-57)	Very useful in correlation because ash eruptions represent virtually instantaneous geologic events, and because ash deposits are commonly widespread.
		27. Paleomagnetism*			Depends on correlation of magnetic properties (magnetic vector or polarity, or a sequence of vectors or polarity) with a known chronology of magnetic variation. Requires material with stable remanent magnetism. (1,3-5,58-61)	Very useful in dating or correlating terrestrial and marine sequences, including those in deep-sea and lake cores. Subject to errors due to chemical or viscous magnetic overprinting and physical disturbance.
		28. Fossils and artifacts			Requires fossils (including pollen) and (or) artifacts. (1-4,62)	Resolution depends on the rate of evolution or change of organisms or cultures and on calibration by other techniques. Subject to errors due to misidentification, interpretation, and inclusion of older materials.
		29. Stable isotopes			Depends on correlation of a sequence of changes in stable isotopes (most commonly oxygen and carbon isotopes) with an age-controlled master chronology. (1,61,63-64)	Oxygen-isotopic record is especially useful in deep-sea and icecap cores, and perhaps in cave deposits.
		30. Orbital variations			Based on correlation of deposits or events related to large-scale climatic changes with the known timing of variations in the earth's orbit. Orbital changes have been shown to be a primary forcing function for climatic change. (61,63-64)	Subject to uncertainties in relating deposits or events to orbitally induced climatic change and to errors due to leads and lags of the climatic system in relation to timing of orbital variations.
		31. Tektites and microtektites			Requires identification and dating of glassy material (tektites) formed and scattered over large areas by impact of extraterrestrial masses. (65)	Includes the Australo-Asian tektite field, which was deposited about 0.7 Ma.

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[1]APPLICABILITY TO DEPOSITS OF THE PROPER AGE RANGE

- VERY OFTEN APPLICABLE
- OFTEN APPLICABLE
- SOMETIMES APPLICABLE
- SELDOM OR NEVER APPLICABLE

[2]OPTIMUM RESOLUTION (magnitude of error)

- <2 %
- 2-8 %
- 8-25 %
- 25-75 %
- 75-200 %

Plate 2. Summary table of Quaternary dating methods
Quaternary Nonglacial Geology: Conterminous U. S.
Vol. K-2 of The Geology of North America (GNA-K2)

PLATE 4

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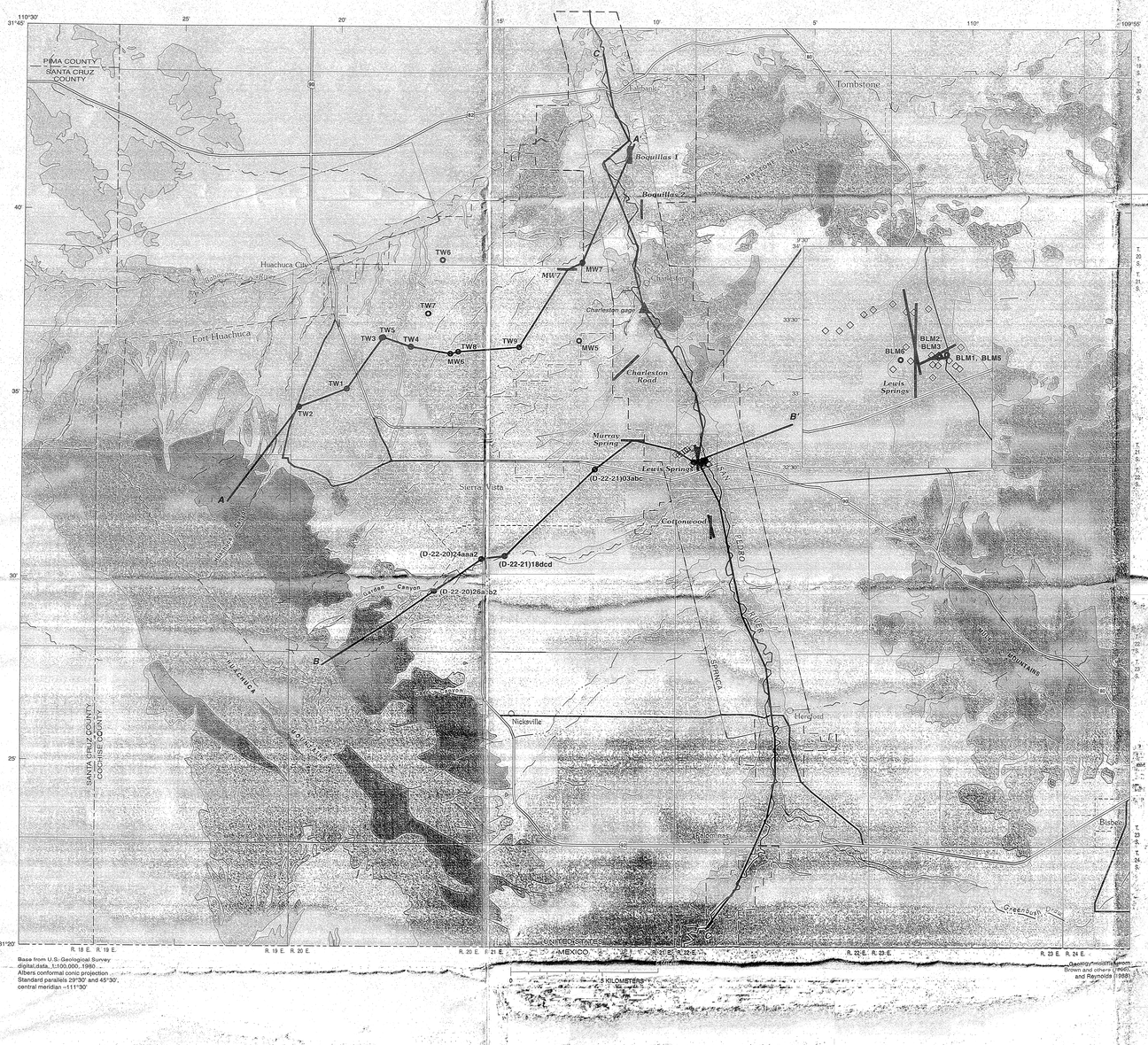
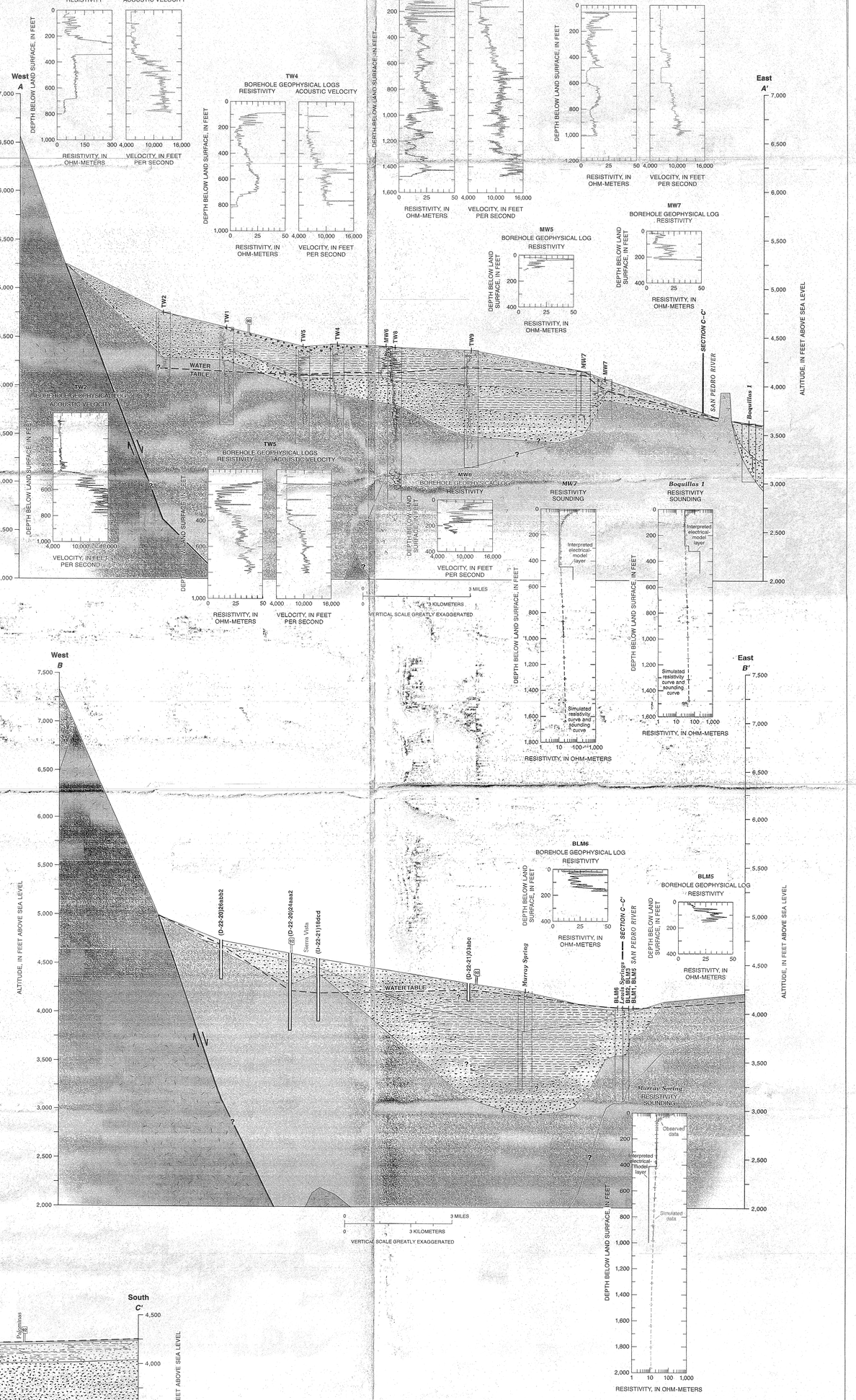
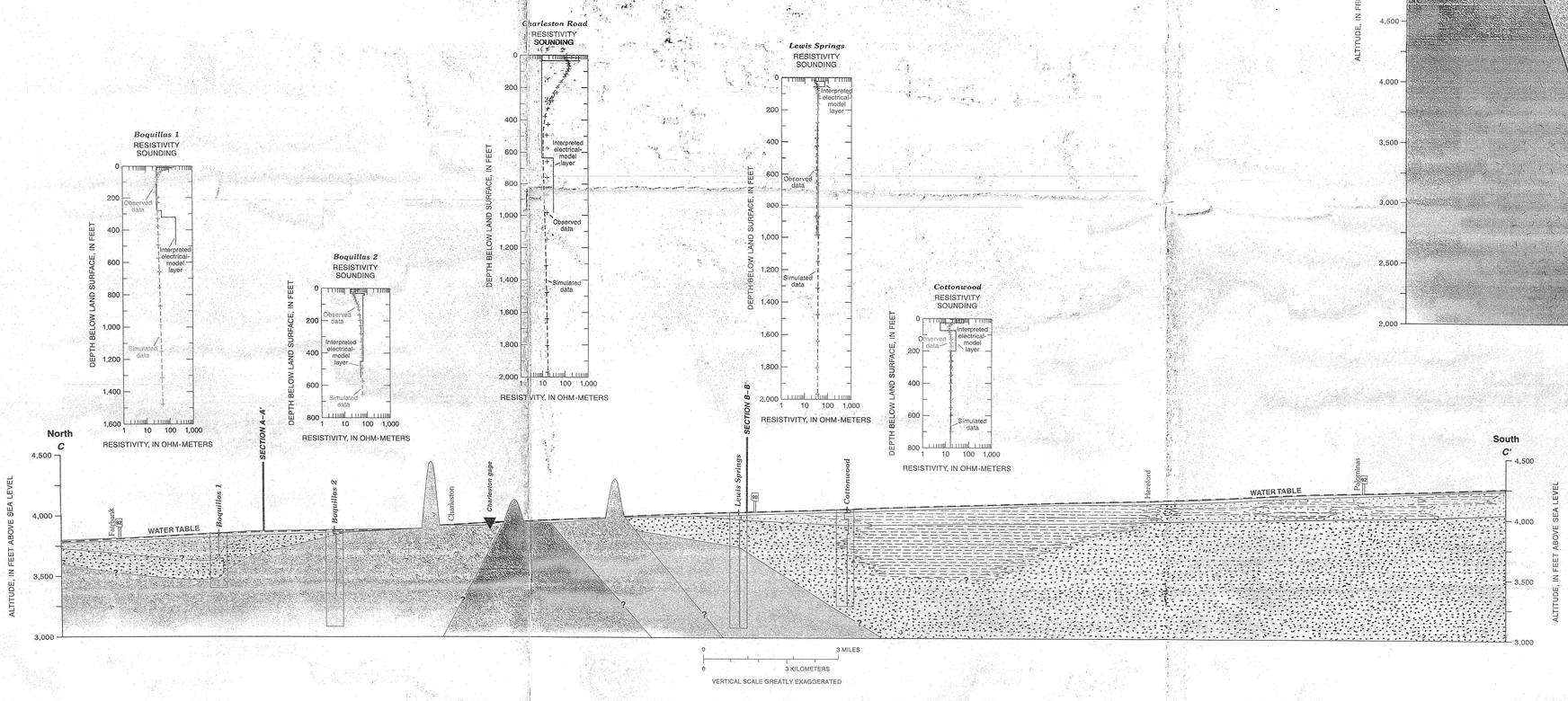


Base from U.S. Geological Survey digital data, 1:100,000, 1980
Albers conformal conic projection
Standard parallels 29°30' and 45°30', central meridian –111°30'

Geology modified from Brown and others (1991) and Reynolds (1988)





EXPLANATION

SAND AND GRAVEL
SILT AND CLAY
UPPER BASIN FILL
SAND AND GRAVEL
SILT AND CLAY
LOWER BASIN FILL
HOLOCENE ALLUVIUM
TERRACE DEPOSITS
BASIN FILL
PANTANO FORMATION
SEDIMENTARY ROCKS
VOLCANIC ROCKS
GRANITIC ROCKS

CONTACT—Queried where uncertain
FACIES CHANGE—Queried where uncertain
B B' TRACE OF HYDROGEOLOGIC SECTION
BOUNDARY OF SAN PEDRO RIPARIAN NATIONAL CONSERVATION AREA (SPRNCA)
SEISMIC SURVEY LINE
RESISTIVITY-SOUNDING SURVEY LINE

RESISTIVITY-SOUNDING DATA
WELLS WITH SUBSURFACE INFORMATION
ELECTROMAGNETIC-SOUNDING SITE
WELL WITH DRILLER'S LOG
FAULT—Arrows indicate direction of throw

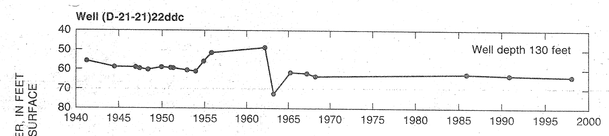
MAP SHOWING GEOLOGY, LOCATIONS OF HYDROGEOLOGIC SECTIONS AND GEOPHYSICAL DATA-COLLECTION SITES IN THE SIERRA VISTA SUBWATERSHED OF THE UPPER SAN PEDRO BASIN, COCHISE COUNTY, SOUTHEAST ARIZONA

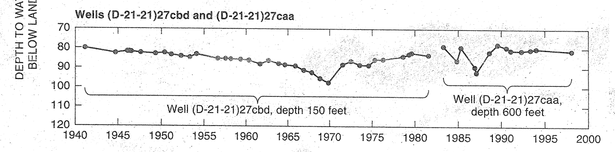
By D.R. Pool and Alissa L. Coes

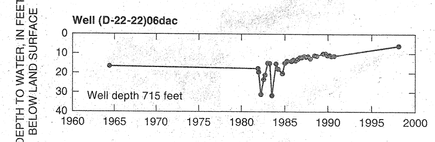
1999

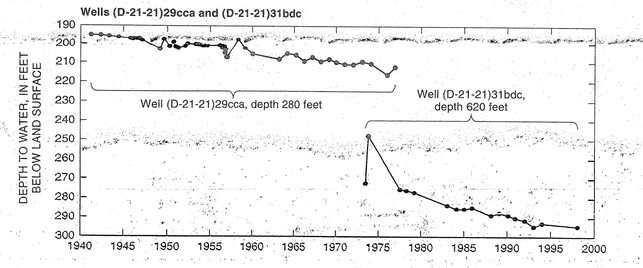
PREPARED IN COOPERATION WITH THE
ARIZONA DEPARTMENT OF WATER RESOURCES AND COCHISE COUNTY

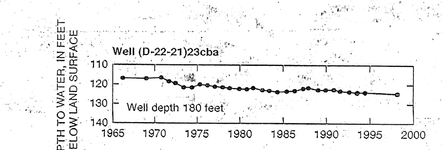
PLATE 6

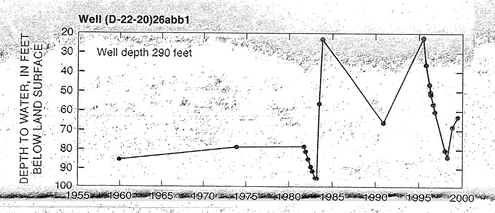


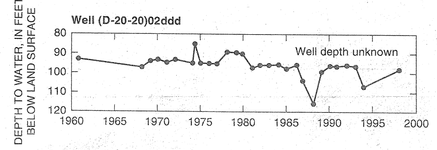


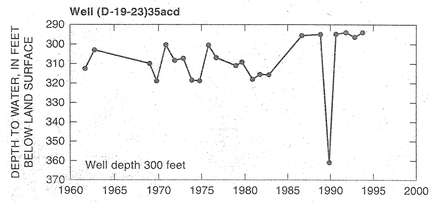


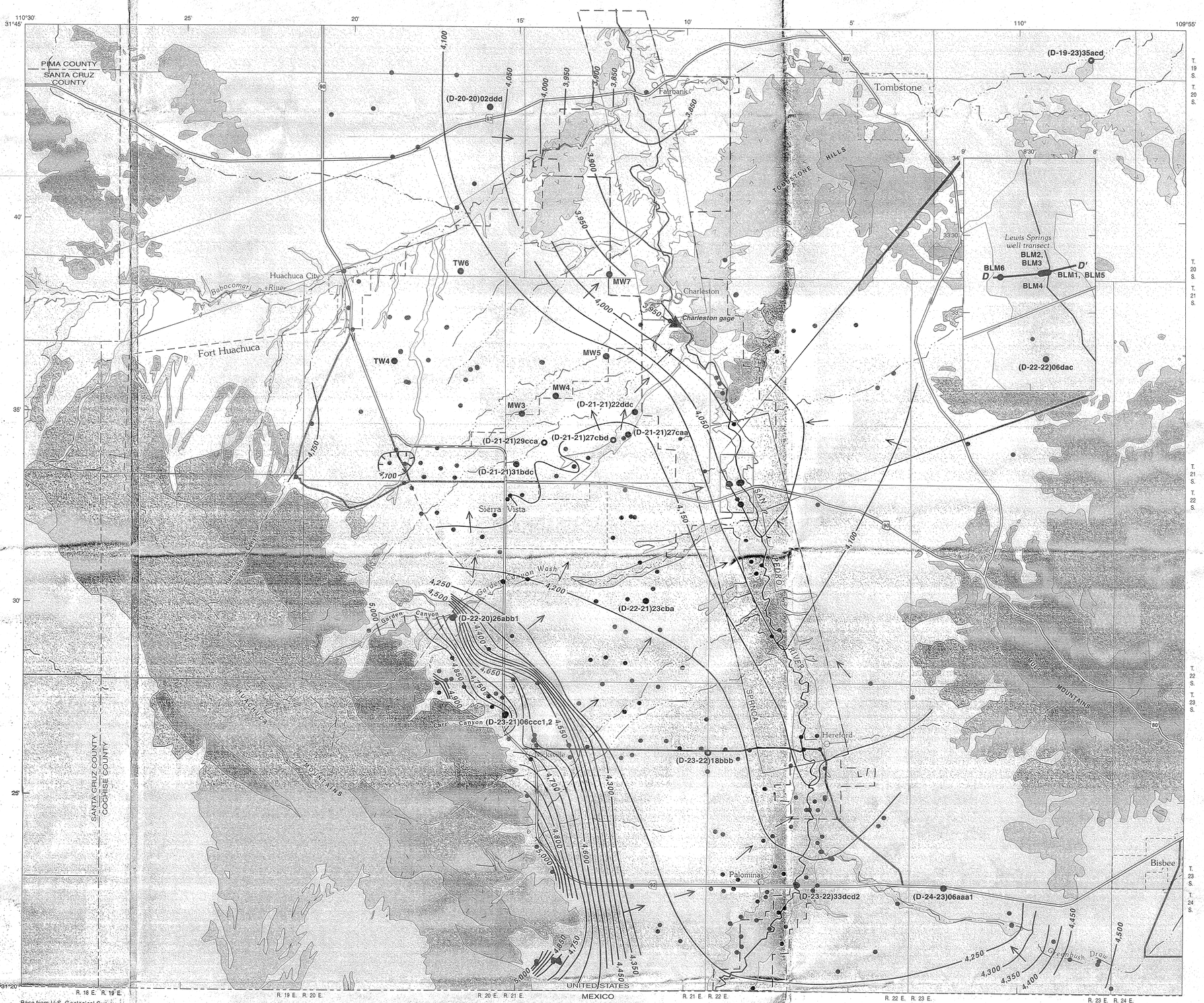






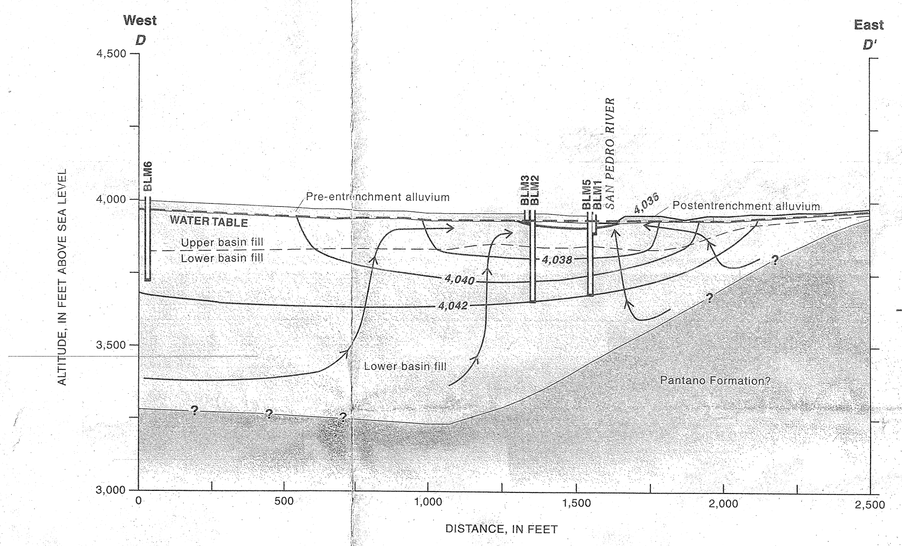






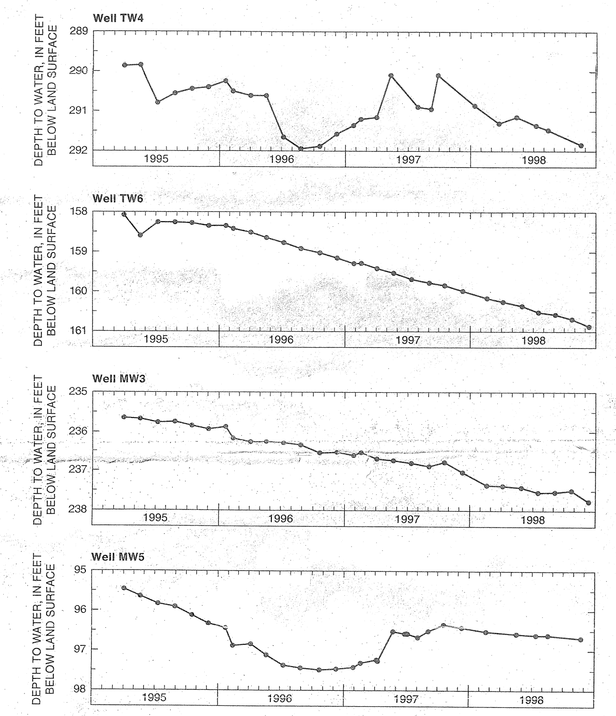
Base from U.S. Geological Survey digital data, 1:100,000, 1980
Albers conformal conic projection
Standard parallels 29°30' and 45°30', central meridian —111°30'

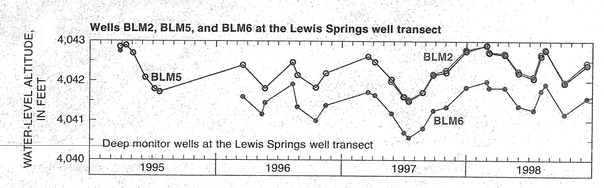
Geology modified from Brown and others (1966), and Reynolds (1988)

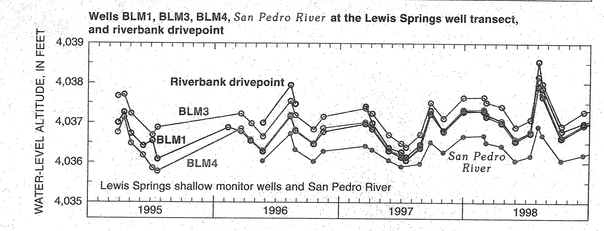


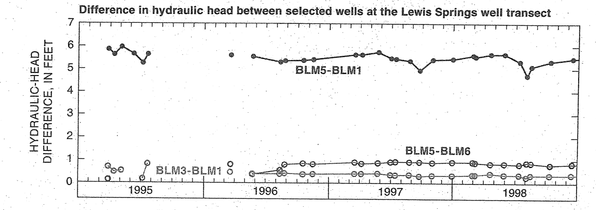
EXPLANATION

- HOLOCENE ALLUVIUM — Pre-entrenchment; Postentrenchment
- BASIN FILL
- PANTANO FORMATION
- 4,040 — POTENTIOMETRIC CONTOUR—Shows the altitude at which the water level would have stood in a tightly cased well, March 1995–October 1998, in feet above sea level. Contour interval, 2 feet
- DIRECTION OF GROUND-WATER FLOW



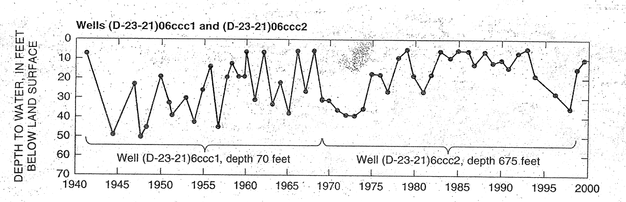


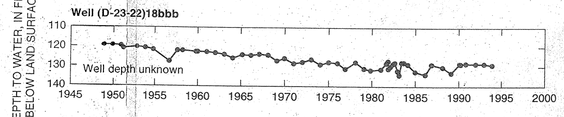


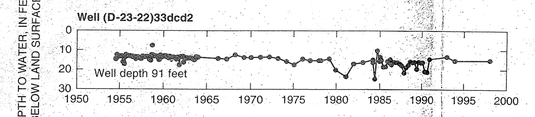


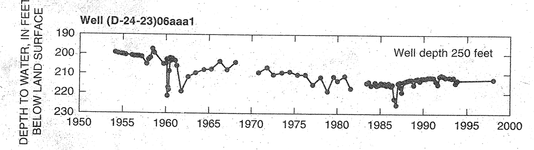
EXPLANATION

- HOLOCENE ALLUVIUM
- BASIN-FILL AND TERRACE DEPOSITS
- PANTANO FORMATION
- SEDIMENTARY ROCKS
- VOLCANIC ROCKS
- GRANITIC ROCKS
- BOUNDARY OF SAN PEDRO RIPARIAN NATIONAL CONSERVATION AREA (SPRNCA)
- 4,300 — EQUIPOTENTIAL CONTOUR—Shows altitude of ground-water equipotential, January 1998, in feet above sea level. Contour interval 50 feet
- DIRECTION OF GROUND-WATER FLOW
- MW5 — WELL WITH HYDROGRAPH AND WELL DESIGNATION
- WELL WHERE WATER-LEVEL ALTITUDE WAS MEASURED IN 1998
- SPRING WHERE WATER-LEVEL ALTITUDE WAS MEASURED IN 1997









MAP SHOWING GROUND-WATER FLOW SYSTEM, WATER-LEVEL ALTITUDE IN WELLS DURING JANUARY 1998, AND HYDROGRAPHS OF WATER LEVELS IN SELECTED WELLS IN THE SIERRA VISTA SUBWATERSHED OF THE UPPER SAN PEDRO BASIN, COCHISE COUNTY, SOUTHEAST ARIZONA

By D.R. Pool and Alissa L. Coes

1999

APPENDIX A

SUMMARY OF MAPS DELINEATING ARIZONA STREAMFLOW CONDITIONS

I. PREDEVELOPMENT PERENNIAL STREAMS –

Freethey, G.W. and T.W. Anderson, 1986. *Predevelopment Hydrologic Conditions in the Alluvial Basins of Arizona and Adjacent Parts of California and New Mexico.* U.S. Geological Survey Hydrologic Investigations Atlas HA-664, 3 sheets (1:500,000).

Data Sources – Historic accounts; field data collected by the U.S. Geological Survey (USGS) and other agencies from the early 1900's to about 1940 "which precedes the period of greatest development"; recent data "for basins where development is minor and long term changes in water levels can be assumed to be small and negligible", and, numerical ground water models. Among the numerous reports referenced by the authors is the map by Brown and others (1981).

Brown, D.E., N.B. Carmony and R.M. Turner, compilers, 1981. *Drainage Map of Arizona Showing Perennial Streams and Some Important Wetlands.* Arizona Game and Fish Department, 1 sheet (1:1,000,000).

Data Sources – Information provided by the Arizona Game and Fish Department (AGFD), USGS, U.S. Forest Service (USFS), National Park Service (NPS), private citizens, and extensive list of publications. The latter included recent and early USGS reports on geology, surface water, and ground water; historic diaries and personal journals; modern review of historic accounts; historic and recent irrigation reports; early government land surveys and engineering reports; studies describing geomorphic changes in Arizona and the Southwest; and, recent wildlife and vegetation inventories.

Brown, D.E., N.B. Carmony and R.M. Turner, compilers, 1978. *Drainage Map of Arizona Showing Perennial Streams and Some Important Wetlands.* Arizona Game and Fish Department, 1 sheet (1:1,000,000).

Data Sources – Same as Brown and others (1981).

II. RECENT PERENNIAL, INTERMITTENT, AND EFFLUENT FED STREAMS –

A. Recent Perennial Streams

Pima County Flood Control District, 2001. *Riparian Habitat Maps*. 103 sheets (each covers a township), viewable on Web at www.dot.co.pima.az.us/flood/riparian/.

Data Sources – Aerial photos and limited field verification of riparian habitat within unincorporated areas of Pima County expected to be affected by development.

Sonoran Desert Conservation Plan, 2000. *GIS Coverage of Perennial Streams, Intermittent Streams, and Areas of Shallow Groundwater.* Pima Association of Governments, 33 pp. plus appendices.

Data Sources – GIS coverages of Pima County were based on existing reports, theses, dissertations, and local publications; maps and aerial images; input from technical advisory committee and general public; and, "very limited" field verification. Technical advisory committee included personnel from the Pima County Flood Control District, U.S. Fish and Wildlife Service, University of Arizona (U of AZ), Arizona Department of Environmental Quality (ADEQ), AGFD, and environmental organization (The Nature Conservancy) and a private consultant (Dames and Moore). Staff from the USFS and Bureau of Land Management (BLM) reportedly provided extensive information.

Habitat Branch of Arizona Game and Fish Department, 1998. *Untitled Map Showing Perennial Streams and Wetlands in Arizona*. 1 sheet (1:1,000,000).

Data Sources – Maps by Brown and others (1981) and AGFD (1994?).

Harbour, T., G. Bushner, T. McCraw, and T. Carr, primary authors, 1994. *Arizona Riparian Protection Program Legislative Report*. Arizona Department of Water Resources, 459 pp. with appendices and plates.

Data Sources – Valencia and others (1993).

Valencia, R.A., J.A. Wennerlund, R.A. Winstead, S. Woods, L. Riley, E. Swanson and S. Olson, 1993. *Arizona Riparian Inventory and Mapping Project.* Arizona Game and Fish Department, 134 pp.

Data Sources – Map by Brown and others (1981) revised based on additional riparian mapping by AGFD and consultation with USFS, BLM, ADEQ, ADWR, private sector hydrologists and academicians.

Arizona Land Resource Information System (ALRIS), 1988. *Geographic Information System (GIS) Data on Streams.* Viewable on Web at www.land.state.az.us/alris/.

Data Sources – USGS Line Graph (DLG) topographic maps (1:100,000) revised by "several Arizona agencies" and U.S. Environmental Protection Agency (EPA).

Brown, D.E., N.B. Carmony and R.M. Turner, compilers, 1981. *Drainage Map of Arizona Showing Perennial Streams and Some Important Wetlands.* Arizona Game and Fish Department, 1 sheet (1:1,000,000).

Data Sources – Information provided by the AGFD, USGS, USFS, NPS, private citizens, and extensive list of publications. The latter included recent and early USGS reports on geology, surface water, and ground water; historic diaries and personal journals; modern review of historic accounts; historic and recent irrigation reports; early government land surveys and engineering reports; studies describing geomorphic changes in Arizona and the Southwest; and, recent wildlife and vegetation inventories.

Brown, D.E., N.B. Carmony and R.M. Turner, compilers, 1978. *Drainage Map of Arizona Showing Perennial Streams and Some Important Wetlands.* Arizona Game and Fish Department, 1 sheet (1:1,000,000).

Data Sources – Same as Brown and others (1981).

B. Recent Intermittent Streams

Sonoran Desert Conservation Plan, 2000. *GIS Coverage of Perennial Streams, Intermittent Streams, and Areas of Shallow Groundwater.* Pima Association of Governments, 33 pp. plus appendices.

Data Sources – GIS coverages of Pima County were based on existing reports, theses, dissertations, and local publications; maps and aerial images; input from technical advisory committee and general public; and, "very limited" field verification. Technical advisory committee included personnel from the Pima County Flood Control District, USFWS, U of AZ, ADEQ, AGFD, an environmental organization (The Nature Conservancy) and a private consultant (Dames and Moore). Staff from the USFS and BLM reportedly provided extensive information.

Wahl, C.R., S.R. Boe, J.A. Wennerlund, R.A. Winstead, L.J. Allison, and D.M. Kubly, 1997. *Remote Sensing Mapping of Arizona Intermittent Stream Riparian Areas.* Arizona Game and Fish Department Technical Report 112, 58pp.

Data Sources – Intermittent stream reaches identified on topographic maps by BLM, USFS, NPS, and AGFD staff.

C. Effluent Fed Streams

Arizona Department of Environmental Quality, 2002. *GIS Cover of Effluent Dependent Waters.*

Data Source – A.C.C. R18-11-113 (Effluent Dependent Waters).

Habitat Branch of Arizona Game and Fish Department, 1998. *Untitled Map Showing Perennial Streams and Wetlands in Arizona.* 1 sheet (1:1,000,000).

Data Sources – Maps by Brown and others (1981) and AGFD (1994?).

Valencia, R.A., J.A. Wennerlund, R.A. Winstead, S. Woods, L. Riley, E. Swanson and S. Olson, 1993. *Arizona Riparian Inventory and Mapping Project.* Arizona Game and Fish Department, 134 pp.

Data Sources – Map by Brown and others (1981) revised based on additional riparian mapping by AGFD and consultation with USFS, BLM, ADEQ, ADWR, private sector hydrologists and academicians.

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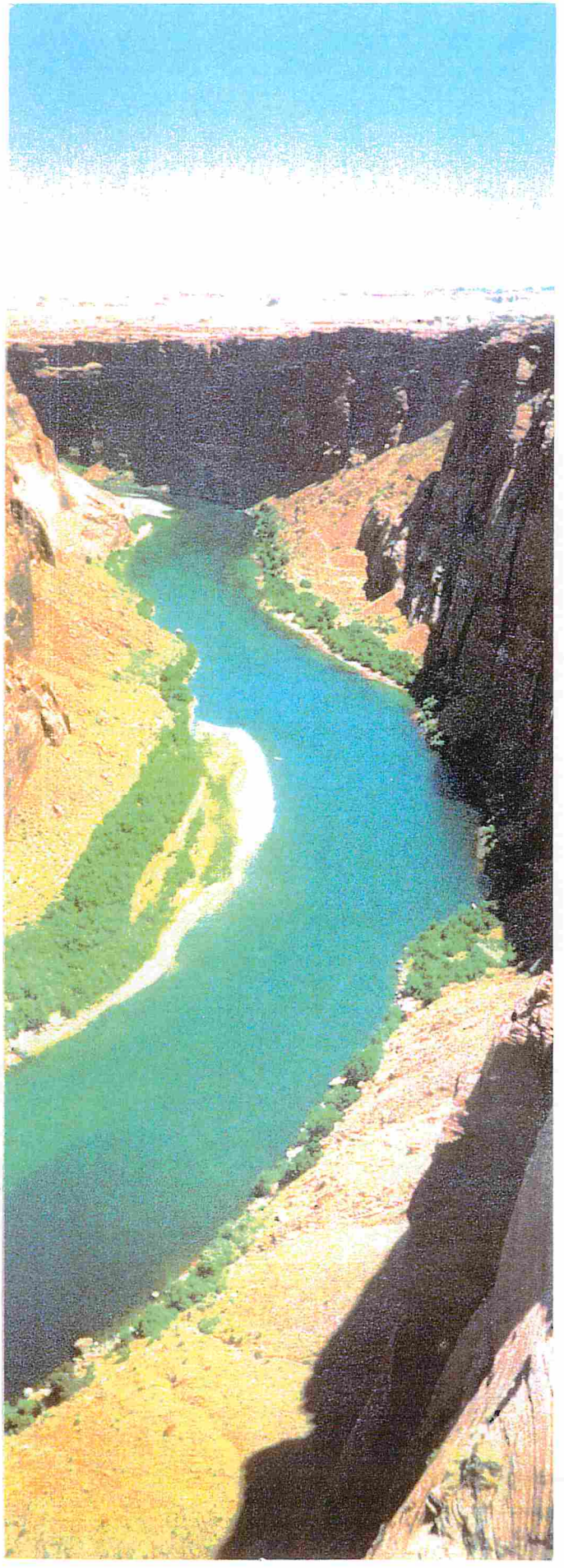
Data Sources – Same as Brown and others (1981).

APPENDIX B



Arizona Riparian Inventory and Mapping Project

December 1, 1993

Arizona Game and Fish Department
2221 West Greenway Rd.
Phoenix, Arizona 85023-4312

Cover Photo by Jeff Sorenson.

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Arizona Riparian Inventory and Mapping Project.
Arizona Game and Fish Department. pp. 134

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Other Arizona Game and Fish Department Funds were used for support of this project.

Arizona Riparian Inventory and Mapping Project

A report to the Governor, President of the
Senate and Speaker of the House

Arizona Game and Fish Department

Director
Duane L. Shroufe

Commissioners
Larry Taylor, Chairman
Beth T. Woodin, Vice Chairman
Arthur Porter
Nonie Johnson
Michael M. Golightly

December 1, 1993

ARIZONA GAME AND FISH DEPARTMENT
ARIZONA RIPARIAN INVENTORY AND MAPPING PROJECT

AUTHORS

Ruth A. Valencia, Project Leader	Ecosystems Program Manager, Nongame Branch
Jennifer A. Wennerlund	Senior GIS Specialist, Research Branch
Richard A. Winstead	Ecosystems Field Project Coordinator, Nongame Branch
Scott Woods	GIS Specialist, Research Branch
Larry Riley	Environmental Compliance Supervisor, Habitat Branch
Eric Swanson	Aquatic Habitat Coordinator, Habitat Branch
Susan Olson	GIS Specialist, Research Branch

TECHNICAL OVERSIGHT COMMITTEE

Bruce D. Taubert, Chair	Assistant Director, Wildlife Management Division
Susan Miller	Executive Staff Assistant, Wildlife Management Division
Terry B. Johnson	Chief, Nongame Branch
Dennis Kubly	Section Supervisor, Nongame Branch
Jim deVos	Chief, Research Branch
Denny Haywood	Research Program Supervisor, Research Branch
Jim Burton	Chief, Habitat Branch
Larry Riley	Environmental Compliance Supervisor, Habitat Branch

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EXECUTIVE SUMMARY

This report is submitted to the Governor, the President of the Senate, the Speaker of the House of Representatives and the Riparian Area Advisory Committee in response to the requirements of the Waters - Riparian Protection Program signed into law in 1992, amending ARS 45-101. The act directs the Arizona Game and Fish Department (AGFD) to conduct investigations relating to Arizona's riparian areas and to report on its findings by December 1, 1993. Specifically, it mandates the following:

(1) development of a system for classifying riparian areas including physical and ecological criteria to be used to develop riparian designations consistent with the definition prescribed in this statute. A hierarchical designation system is to be developed according to relative functions and values;

(2) identification, classification and mapping of riparian areas in the state, giving priority to those riparian areas associated with perennial waters;

(3) identification and mapping of land ownership of identified riparian areas according to the general categories of Indian, federal, state and private lands and mapping of current land uses of those areas, and;

(4) identification of existing options for protecting riparian areas in each ownership category that may be available under existing state and federal laws (Section 5, Chapter 298, Laws 1992).

Our choice of classification system was based on the desire to identify geographic areas that represent ecological units. The classification system applied to this project was devised by Brown, Lowe and Pase (1979). This system provides an ecological basis for the location of plant and animal communities in the American Southwest and arranges them within a hierarchical structure.

Our primary charge was to identify, classify and map riparian areas which are defined by "the presence of deep-rooted plant species that depend on having roots in the water table or its capillary zone" (ARS 45-101.6). AGFD contracted with Dr. Lee Graham through the Arizona Cooperative Fish and Wildlife Research Unit at the University of Arizona to formulate a methodology to identify and map riparian vegetation. Graham devised an innovative remote sensing technique combining satellite imagery and aerial videography. The resulting maps show the extent of riparian vegetation along perennial stream corridors in Arizona. The methodology chosen was determined to be the best technology available to map riparian vegetation on a statewide basis given the time requirements of the project.

Products of this riparian inventory include riparian vegetation maps, numerous Geographic Information System (GIS) databases and aerial videotapes. Examples of some of the maps are presented in this report, along with a summary of findings. These examples are intended to give

the reader an idea of (1) the types of maps that can be produced, and (2) the types of data contained within these GIS databases.

The identification, classification and mapping of riparian vegetation is being completed in a phased approach. In this first year, priority was given to mapping riparian areas associated with perennial waters. We will begin to map riparian areas associated with intermittent waters in the state once we have met the accuracy standards set for maps associated with perennial waters.

We devised a method to assess the accuracy of the riparian vegetation maps through ground verification. Stream corridors in the southeastern portion of the state were investigated during this first year of the project. Results of that effort are presented. Although maps are not yet at a level of accuracy we would like, we will continue to verify and modify maps until our accuracy expectations are met. This should be completed by June 1994.

Riparian vegetation maps are the result of a broadly applied remote sensing process. However, precision of data can often be a problem. Therefore, data should always be field verified. That means the site represented on a map should be visited to ensure the information is correctly represented. The maps are a representation of the general location and type of riparian vegetation that existed in an area at the time the satellite images were created. The process was not intended to create maps that delineate each tree and shrub in the riparian corridor. In fact, any attempt to create statewide maps on this scale would be futile. Riparian vegetation is subject to many disturbances, primarily flood events. By the time one portion of the state is completed, other riparian areas in the state may have been severely altered. Therefore, it is important to realize that these maps are best used (1) for collecting general data on the amount of riparian vegetation existing at a given time in the state, (2) for determining the general location and percentage of various riparian vegetation community types, and (3) for change analysis studies (comparing general trends or changes between years). The suitability of these maps for regulation can only be evaluated at a later date.

The inventory covered 4,628.95 miles of streams and mapped 266,786.39 acres of riparian vegetation. Portions of the Colorado River and its tributaries that are within Grand Canyon National Park have not yet been inventoried because of flight restrictions. This portion represents an additional 393.52 miles of regulated river.

Total miles of perennial streams inventoried	**4,628.95 miles**
Total miles of perennial streams identified	5,022.47 miles
Flow unregulated	3,961.26
Flow regulated	972.95
Effluent dominated	88.26

Based on the methods as described in this document, riparian vegetation associated with perennial streams comprises approximately 0.4% of the total land area of the state. Vegetation associated with most lakes and wetlands (marshes, cienegas) and with the excluded portions of the Colorado River are not represented in these numbers. **It should be noted that not all riparian vegetation, as defined by legislation was mapped during this first phase of the inventory.** A great deal of riparian vegetation is supported by intermittent waters in Arizona, but, these areas have not yet been inventoried.

Miles of perennial waters by land ownership category*

	Miles	Percent of Total Mapped
Total Federal	2,510.79	49.99
National Forests	1,573.50	31.33
National Parks	611.90	12.18
BLM	289.07	5.76
Wildlife Refuges	28.26	0.56
Military	8.06	0.16
Total State & Municipal	254.58	5.07
State trust/state sovereign	156.06	3.11
State & municipal parks	82.40	1.64
AGFD lands	16.12	0.32
Total Private	856.67	17.06
Total Tribal	1,408.80	28.05

**NOTE: These figures exceed 100% of the total miles of perennial streams because there are instances where landownership is different on each bank of a given length of stream. In those cases, stream mileage is included in both landownership categories.*

This inventory revealed seventeen (17) riparian vegetation community types (series level), and approximately 85 vegetation associations in Arizona. Accuracy on vegetation data is still being verified and should be completed by June 1994. Conversion of vegetation classes to the Brown, Lowe and Pase (1979) system is currently underway. The following table shows riparian vegetation community types as a percentage of the total amount of riparian vegetation mapped during this phase of the inventory. Although the inventory is not complete, these percentages begin to give a picture of the relative amounts of the various riparian vegetation community types found in Arizona. More detailed data on vegetation classifications will be available from AGFD when all components have been verified.

Relative amounts of riparian vegetation communities associated with perennial waters in Arizona.

Total acres of riparian vegetation associated with perennial waters as inventoried by AGFD in 1992-1993: 266,786.39 acres

Vegetation Community	Percent	Vegetation Community	Percent
Tamarisk	20.3	Russian olive	<1.0
Mesquite	17.5	Reed	<1.0
Arrowweed	14.8	Sacaton grass	<1.0
Conifer	11.2	Mixed canyon scrub	<0.5
Mountain meadow	6.3	Acacia	<0.5
Oak	4.4	Desert willow	<0.5
Cottonwood-willow	4.2	Mexican elder	<0.5
Mixed scrub	3.0		
Cattail	2.1	Flood scoured*	7.4
Sycamore	1.2	Unlabelled**	5.4

* *Vegetated according to satellite data, but scoured by winter flooding before classification with videography.*

** *Not classified due to lack of videography coverage.*

General land ownership and land use maps for Arizona are also presented in this report. As directed by the legislation, the land ownership map displays federal, state, private and tribal lands. Although the legislation did not specify land uses to be mapped, AGFD attempted to locate data sources for mapping the land use activities listed in the Waters - Riparian Protection Program law (Section 6, chapter 298, Laws 1992). In some cases, limitations on data availability restricted our ability to map land uses. In other instances, such as for recreational activities, it was difficult to delineate specific geographic areas where an activity was taking place. That is, some activities can realistically occur almost anywhere.

Accompanying each land use map is a brief description of what is depicted. Data sources, methods of verification, and limitations on use of the maps are discussed. Summary statistics calculated from land use and land ownership databases are presented.

Land use maps presented in this report include:

(1) Commercial Grazing Activities
(2) Commercial Wood Harvesting Activities
(3) Urban, Industrial and Agricultural Lands
(4) Public Recreation
(5) Current and Historical Mining Locations
(6) Active Mining Locations
(7) Sand and Gravel Mine Locations
(8) Mineral Potential

The purpose of compiling land ownership and land use data was to identify activities occurring in and adjacent to riparian areas across the state. Several examples are presented in this report to illustrate the application of these data to evaluate land use influences on a riparian area.

Factors that affect landform, and vegetative and wildlife diversity are discussed in the report. These factors consequently influence the diversity of functions occurring within a riparian area and are the key to functional assessment of riparian areas. Because of the Arizona Game and Fish Commission's legislated authority and the Department's mission, our efforts this past year were focused on evaluating methods to assess biological life support functions and wildlife values provided by riparian habitats for vertebrate wildlife (fishes, amphibians, reptiles, birds and mammals).

An approach that was specifically developed for assessment of riparian wildlife habitats in Arizona, and that can be evaluated rapidly in the field was conceived by Anderson and Ohmart (1984) for the Bureau of Reclamation (USBR). Ohmart and Anderson subsequently reviewed alternate methodologies for AGFD and attempted to further develop their own technique to provide a single index value that would allow comparison among riparian habitat types. The methodology they developed was specific to riparian forest and riparian scrub habitats.

The utility of a simple index of wildlife value for riparian areas is multifold. It could be used to provide a range of potential wildlife values based on identified vegetative community type (Brown, Lowe and Pase series level). Remotely sensed data combined with ground-truthing can provide additional information to decision-makers. AGFD will continue to evaluate the utility of a simple index of wildlife value. Anderson and Ohmart's report to AGFD is still being finalized and must undergo final internal review.

The AGFD was instructed to incorporate a hierarchical designation system based on relative functions and values into the development of a classification system for riparian areas (Chapter 298, Laws 1992). Based on direction from the legislation, the approach to a riparian designation system must take into account an assessment of functionality. The overall functional condition of a riparian area should be the focal point of a designation system.

There have been few attempts at formulating a method to rapidly assess the functionality of riparian areas. Previously, national approaches created for application to wetlands were applied

to arid and semi-arid riparian areas with limited success. Two recent federal reports describing approaches to assessing functions of riparian and wetland areas are of particular interest. They are BLM's "Process for Assessing Proper Functioning Condition" and COE's "A Hydrogeomorphic Classification for Wetlands" (Brinson 1992). A brief discussion of each is presented. Components of these two approaches serve as the basis for the proposed hierarchical designation system.

The development of a hierarchical designation system based on riparian functions and values should take into account a number of items.

1) New information on riparian functions is almost constantly being presented as research continues on this subject. Therefore, the approach should be flexible enough to allow for the incorporation of new information.

2) According to the legislation, the approach must incorporate functions and values of these resource areas. Use of indicators and rapid assessment methods has been discussed.

3) Because there is so much federal land in the state, the approach should be compatible with federal activities, or should be able to incorporate the data and information collected by federal agencies into the approach. At this time, data collection techniques appear to be inconsistent and incompatible.

4) Completion of the three project areas under this legislation (AGFD, ADWR, ADEQ) adds a great deal of information to our knowledge base. Riparian vegetation, land ownership and land use maps are contained in a digitized format. GIS maps and databases provide us with a powerful tool to apply to riparian assessment.

5) Recent controversial proposals included in the Clean Water Act reauthorization have attempted to classify or rank wetlands according to their functions and values, and then regulate these categories differently. The primary question is whether all wetlands should be treated the same or not. If all wetlands have some functions and values, do some have more than others, and consequently should those with lesser values be accorded less stringent regulatory protection? This controversy raises issues directly applicable to riparian area protection strategy development for Arizona.

6) The designation system chosen should address a number of other considerations.

   (a) A consistent geographic unit of evaluation should be identified.
   (b) The evaluation system should have a systems perspective and should be able to take into account the effect of upstream and downstream activities of an assessment area.
   (c) It should be capable of dealing with potential functions since systems are often degraded.
   (d) Temporal variability of the system needs to be considered because the system is dynamic.

7) Several federal agencies are in the process of formulating functional assessment methods for application to riparian areas. These methods have been devised by interdisciplinary teams of scientists and land managers and are currently undergoing public review. However, these approaches represent the best available methods for assessing functionality within riparian and wetland systems at this time.

8) Information needs should be balanced with the development of action strategies. "Enough information needs to be amassed to allow for sound policy choices, but collecting too much information can stall action. It's important to remember that decisions can be made and actions taken before all the needed information has been gathered. Gathering information can take a lot of time and resources, delaying strategy development for years. To the extent possible, a state should draw on existing data and the professional judgement of people familiar with the state's wetlands. As gaps in data are identified, objectives can be set for collecting and analyzing any missing data and information" (World Wildlife Fund 1992).

Based on these considerations, AGFD proposes a preliminary outline as a first step in the development of a hierarchical designation system for riparian assessment based on functions and values. The preliminary approach is outlined in the document and illustrated by a flowchart.

Step 1. Assess the functional condition of a given unit of riparian area (stream and terrestrial land area).

Step 2. Categorize areas based on their general functional condition (BLM approach).

Step 3. Each of these categories has implications as to protection and management actions.

Step 4. Within each category, assess whether high, medium or low values exist.

Step 5. Prioritize areas for protection or management action based on assessment of values and functional category.

The completion of this report does not signal the end of AGFD's work on inventorying and assessing riparian areas in Arizona. In fact, in the next year, AGFD staff will be working on bridging information gaps that will help us achieve an implementable hierarchical designation system. The following is a list of action items that are either in process or are proposed for next year:

1) AGFD will continue to refine the perennial database and map riparian areas in Arizona, including areas associated with intermittent waters. AGFD will continue to assess the full capability of the remote sensing technology and accompanying databases and videotapes.

2) To assist with our understanding of riparian functions, AGFD applied for and was awarded a grant from the EPA under the Clean Water Act, 104(b)(3) Wetlands Grant Fund. The grant will allow us to develop a functional assessment methodology and a methodology to determine status and trends of riparian areas statewide.

The final section of this report identifies existing options for protecting riparian areas in the state. While the listing of regulatory and nonregulatory riparian programs in Arizona appears extensive, it is important to recognize that there are no regulatory programs (at any level of government) specifically developed or implemented for the protection of riparian areas. Existing programs have only limited applicability to the protection of important riparian area functions by focusing only on the management and planning of water, soil and/or landscape--typically within a small geographic area. Furthermore, even though most of the listed programs have been in place for some time, it is widely recognized that some greater degree of riparian area protection is needed to preserve and maintain the health and integrity of our existing riparian resources in Arizona.

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Field Biologists

Mark Brennan, Field Team Leader
Jeff Sorenson, Field Team Leader
Vir McCoy
Gary Benoit

Laurel Schulze, Field Team Leader
Mary Franks
Vince Fitzpatrick
Jennifer Hodge

Riparian Vegetation Mapping

O. Eugene Maughan, Unit Leader
Arizona Cooperative Fish and Wildlife Research Unit
210 Biological Sciences East
University of Arizona
Tucson, Arizona

Lee A. Graham, Ph.D., Assistant Professor
Wildlife and Fisheries Sciences
School of Renewable Natural Resources and Advanced Resource Technology
University of Arizona
Tucson, Arizona

Riparian Habitat Evaluation Model

Robert Ohmart, Ph.D.
Professor of Research
Center for Environmental Studies
Arizona State University
Tempe, Arizona

Bertin Anderson, Ph.D.
President
Revegetation & Wildlife Management Center
201 S. Palm
Blythe, California

ARIZONA RIPARIAN INVENTORY AND MAPPING PROJECT

Project Overview

This report is submitted to the Governor, the President of the Senate, the Speaker of the House of Representatives and the Riparian Area Advisory Committee in response to the requirements of the Waters - Riparian Protection Program signed into law in 1992, amending ARS 45-101. The act directs the Arizona Game and Fish Department (AGFD) to conduct investigations relating to Arizona's riparian areas and to report on its findings by December 1, 1993. Specifically, it mandates the following:

(1) development of a system for classifying riparian areas including physical and ecological criteria to be used to develop riparian designations consistent with the definition prescribed in this statute. A hierarchical designation system is to be developed according to relative functions and values;

(2) identification, classification and mapping of riparian areas in the state, giving priority to those riparian areas associated with perennial waters;

(3) identification and mapping of land ownership of identified riparian areas according to the general categories of Indian, federal, state and private lands and mapping of current land uses of those areas, and;

(4) identification of existing options for protecting riparian areas in each ownership category that may be available under existing state and federal laws (Section 5, Chapter 298, Laws 1992).

The format for this report reflects, to some degree, the sequence of steps taken to satisfy the requirements of the legislation, as opposed to the sequence of tasks listed above. This sequence is primarily because the methods chosen to identify, describe and map riparian areas influenced the decisions regarding classification and designation systems. The mapping method combines remote sensing techniques and a Geographic Information System (GIS) to create a computerized framework for data storage, display and analysis of spatial data. This method represents an innovative and experimental approach in statewide ecological mapping of riparian areas.

Because of its exploratory nature, decisions regarding the general approach to mapping needed to be made early in the process to allow time for development of the methods and to ensure that the mapping was completed in the given timeframe. Several issues inherent to those decisions had to be evaluated early in the planning stages. First, the success of a remote sensing technique hinged on whether ecologically important units of riparian vegetation were discernible from an aerial view. Second, the question had to be addressed as to whether there was a way to accurately delineate and classify these units once they were identified. Assuming both of these issues could be accomplished, the choice of a classification system was somewhat limited to systems based on features and characteristics that could be determined from these remote sensing techniques.

Our ability to evaluate and analyze data associated with riparian areas is enhanced by the flexibility of a GIS format. GIS allows us to make spatial calculations and to visually analyze spatial interrelationships. Integration of other GIS databases containing natural resource and wildlife data expands our analytical abilities. The full potential of the system has not entirely been explored in this first year of data collection.

Discussion of a hierarchical designation system based on functions and values takes into account the future potential of this system. By combining or "overlaying" GIS databases containing data on hydrology, water quality, vegetation, land use, land ownership, etc., our ability to categorize riparian areas is enhanced as is our ability to identify landscape level processes that affect riparian vegetation.

It should be noted that the definition of riparian area provided in the legislation is inclusive of riparian vegetation occurring "within or adjacent to natural perennial or intermittent stream channel(s) or within or adjacent to a lake, pond or marsh bed maintained primarily by natural water sources." In this first year of the riparian inventory and mapping project, AGFD focused efforts on riparian vegetation associated with perennial streams. Perennial waters associated with lakes, ponds and marshes or cienegas were, for the most part, excluded from this first stage of mapping. Some marshes or cienegas that occur adjacent to a perennial stream have been mapped. However, completion of mapping riparian vegetation associated with intermittent waters, marshes and other types of wetlands is important for comprehensive management of these precious resources.

This report is divided into six sections. The first section presents the classification system applied to riparian vegetation mapping and discusses the reasons for choosing that particular classification system. The next section contains the general approach to the identification, classification and mapping of riparian areas as well as the method for compiling a perennial waters map of Arizona. A general description of the mapping methodology is provided with emphasis on (1) the use of satellite imagery to delineate the extent of the riparian zone and to establish boundaries for vegetation classes, and (2) the use of aerial videography to identify and classify vegetation. Since this process was experimental, the Department devised a ground-truthing method to evaluate accuracy of maps. Results of this verification process are presented along with a discussion of limitations on the application of these maps.

Although it was impossible to present all the riparian vegetation maps in this report, examples of maps are included at two different scales. A statewide map shows areas of riparian vegetation mapped during the past year. Portions of riparian vegetation maps from Cave Creek in the Chiricahua Mountains, the San Pedro River and the Colorado River are depicted at a large scale to show the degree of mapping detail. Summary statistics calculated from the statewide databases are also presented.

Land use and land ownership maps with associated statistics are presented in the third section. A brief description of each map, along with data sources, and a summary of pertinent data and assumptions are provided. These maps were digitized into a GIS and can be printed at various sizes and scales.

The fourth section contains an overview of riparian functions and values with emphasis on wildlife and fish habitats. Indicators or measurements necessary to evaluate functionality and quality of a riparian area are discussed. A method to rapidly assess the relative values of riparian areas for wildlife is presented. The method is based on description of vegetation species composition, foliage density and vertical height diversity. The method was tested on low elevation riparian areas and needs further evaluation before it can be applied statewide.

Section five outlines a preliminary approach to a hierarchical designation system based on functions and values. This approach is based on methods currently being evaluated for application by the federal government. The application and analysis of GIS databases compiled by state and federal agencies has a great deal of utility in this arena. The riparian vegetation classification system and wildlife habitat evaluation methodology are two components that expand our ability to evaluate the functionality of a riparian area.

The final section lists existing options used for riparian area protection in Arizona under existing state and federal laws. Included under riparian protection mechanisms are regulatory and nonregulatory programs that have some degree of applicability in protecting resources that support and sustain riparian areas. A discussion is offered on how this information might be used to improve riparian area protection is offered.

Section I

Classification System

All classifications have as their objective the orderly arrangement of objects into groups or sets on the basis of similarities or relationships (Daubenmire 1968, Platts 1980). For purposes of this study, the term "classification" describes systems that are almost purely descriptive and that do not impose a value based on ranking or position in the classification system. In the case of riparian areas, classification groupings might be based on any number of characteristics, such as vegetation type, stream channel geometry, hydrology or elevation. Or, the groups might be comprised of areas that function in a similar manner. The many attributes on which one can group or classify riparian areas is a reflection of their complexity. The complexity of these areas makes the task of classification a challenging endeavor.

State and federal agencies have developed numerous riparian and wetland classification systems for a variety of purposes (Gebhardt et al. 1990, World Wildlife Fund 1992). Some systems deal solely with wetlands such as bogs, fens, marshes and swamps (Windell et al. 1986, National Wetlands Working Group 1987), while others take into account the special features of both riparian and wetland ecosystems (Brown et al. 1979, Cowardin et al. 1979, Youngblood et al. 1985, Hann and Jensen 1987, Kovalchik 1987, S. Swanson et al. 1988, Hansen et al. 1990). Some are regional in scope and have limited applicability, while others attempt to classify areas on a national level. The stated objectives of these systems are fairly similar, but the individual categories of measurement are quite varied. Most systems categorize at least on the basis of stream/wetland attributes and vegetation or biotic community type. However, in some cases, categories are based on highly detailed criteria, taking into account features such as soil type, stream channel morphology, species composition, substrate, climate, vegetation structure and seral stage. (See glossary and page 94 for description of seral stage.)

Our choice of classification system was based on the desire to identify geographic areas that represent ecological units having similar properties. An ecological unit contains species that share a common evolutionary history; there is a shared flora and fauna between areas of the same name. In addition, our charge was to identify, classify and map riparian areas which are defined by "the presence of deep-rooted plant species that depend on having roots in the water table or its capillary zone" (ARS 45-101.6). Another factor considered was the need for uniform identification of the different types of riparian areas, thus providing a means to more accurately assess distribution and relative amounts. This method should result in a categorization of riparian areas that provides a management tool for land and resource professionals. Finally, this project required the selection of a classification system that could be easily applied to the mapping methodology.

The classification system applied to this project was devised by Brown, Lowe and Pase (1979). This system provides an ecological basis for the location of plant and animal communities in the American Southwest and arranges them within a hierarchical structure. A systematic hierarchy has the great advantage of having data ordered from the general to the specific, so that it can

be used at different levels of organization - national, regional or local. The hierarchy is open-ended, in that it provides for expansion at all levels as more information is known about an area. Table 1 summarizes the categories and units of classification used in the Brown, Lowe and Pase hierarchical vegetation classification system.

The Brown, Lowe and Pase classification system is based on natural groupings of biotic communities that occur across the landscape. Biotic communities represent complex aggregations of plants and animals that are the result of responses to integrated physical and biological factors, more or less regional in scope. These factors include common evolutionary history, climate, and moisture available to plants (Brown et al. 1979). In this system, biotic communities are primarily delineated by the composition and form of vegetation.

Vegetation tends to be naturally grouped in different combinations forming communities. In other words, the plant species are not scattered at random, but are distributed in a pattern over the landscape. The concept of a community presumes a degree of biologic homogeneity in structure and species composition that is associated within a defined area (Daubenmire 1968). Similar vegetative communities tend to appear wherever equivalent environmental conditions occur. Since vegetation is more readily identified, inventoried and mapped than the animal component of a community, vegetation communities provide a convenient unit of classification. Although animal constituents are an important factor in the determination and classification of biotic communities, it is the vegetative form, structure and components that provide the readily observable and, therefore, measurable manifestation of these natural communities (Brown et al. 1979).

Any large unit of vegetation is a mosaic of plant communities creating a corresponding mosaic of habitats for wildlife. Vegetation serves as a valuable criterion of degrees of similarity and difference among habitats. One obvious advantage of classifying and mapping natural vegetation is to enable wildlife, forest and range managers to efficiently stratify and sample populations in any given land area (Leopold 1933). Statistically valid surveys then can be used to measure and predict an area's wildlife density, timber potential or range capability (Brown et al. 1979).

Under this system, the hierarchy is organized into a digital, numerical array that makes the system computer-compatible. Thus the classification system has been applied as the basis of several habitat and wildlife databases in the Southwest, such as RUNWILD (Patton 1978) and the AGFD Native Fish Database. It has been incorporated into the Arizona Land Resources Inventory System (ALRIS) at the Arizona State Land Department (ASLD) and has been used extensively as a means of describing and identifying habitat types in AGFD wildlife studies.

The hierarchical sequencing of this classification system permits mapping at any scale and maintains the needed flexibility for mapping complex communities where more intensive systems are impractical or needlessly time consuming (Brown et al. 1979). This flexibility is especially pertinent when attempting to conduct a statewide classification and mapping of riparian areas. The inventory covers thousands of stream miles across the state thus requiring a small-scale approach. By applying a small scale, we are able to evaluate the entire state at once to analyze extent of riparian areas as compared to upland areas, for instance. However, the utility of

differentiating riparian vegetative communities on small-scale ecological maps is limited because these ecosystems tend to cover small areas relative to other upland communities. In fact, on a small-scale map of the state, riparian areas are almost indiscernible.

The flexibility provided by the Brown, Lowe and Pase system coupled with the use of remote sensing techniques allowed us to classify riparian areas at a large-scale while maintaining the capability to produce maps at a local, regional or statewide level. For the most part, riparian vegetation was classified to the series level (also called community type). In some cases, riparian areas were classified according to the vegetation associations occurring there. These classes are represented by the fifth and sixth levels in the Brown, Lowe and Pase system (See Table 1 and Figure 1).

Vegetation communities within riparian areas do not often occur as distinct, easily discernible units. Various classifications of riparian vegetation tend to intergrade over a considerable area, forming broad transitional zones called ecotones. At the outer extent of the riparian zone, vegetation transitions into upland communities; sometimes gradually, sometimes abruptly. In some vegetation communities, such as mesquite or sacaton grass communities, the same plant will characterize both the riparian and the upland community, growing more vigorously in the riparian area where soil moisture is more readily available. It is important to understand this natural phenomenon when viewing maps of riparian vegetation because lines drawn to delineate vegetation communities may mislead one into thinking these are distinct and separate units on the ground.

Table 1. Brown, Lowe and Pase Hierarchical Classification System (1979)

	Where:
DIGIT PRECEDING COMMA	1,000 = Biogeographic Realm
FIRST LEVEL	1,100 = Vegetation
SECOND LEVEL	1,110 = Formation type
THIRD LEVEL	1,111 = Climatic (Thermal) Zone
FOURTH LEVEL	1,111.1 = Regional Formation (Biome)
FIFTH LEVEL	1,111.11 = Series (Community of generic dominants)
SIXTH LEVEL	1,111.111 = Association(Community of specific dominants)
SEVENTH LEVEL	1,111.1111 = Composition - structure - phase

Digit preceding the comma: This identifies the world's biogeographic realm. Since all of our classification will take place in Continental North America, the biogeographic realm will be identified as Neartic and will be designated with a "1."

First Level: The first digit after the comma refers to vegetation. All existing and potential natural vegetation is classified as belonging to uplands (1,100) or wetlands (1,200). In this system, wetlands include those periodically, seasonally or continually submerged ecosystems populated by species and/or life forms different from the immediately adjacent (upland) climax vegetation, and which are dependent on conditions more mesic than provided by the immediate precipitation. Riparian ecosystems are treated as wetlands under this classification.

Second Level: The second digit after the comma refers to one of the following recognized ecological formations, or formation-types. On continents, these are referred to as formations, which are vegetative responses (functions) to integrated environmental factors most importantly plant-available moisture. Wetland formations are divided into the following categories:

1,210	Wet Tundra	Temperatures are so low that available moisture is unavailable during most of the year. Area is characterized by an absence of trees with establishment of low herbaceous plant structure in a hydric matrix.
1,220	Swamp-Forest /Riparian-Forest	Overstory of trees potentially over 10 meters (31 ft) in height, and frequently characterized by closed and/or multilayered canopies.
1,230	Swamp-scrub /Riparian-scrub	Dominated by short trees and/or woody shrubs, generally under 10 meters (31 ft) in height and often presenting a closed physiognomy.
1,240	Marshland	Principal plant components are herbaceous emergents which normally have their basal portions annually, periodically, or continually submerged.
1,250	Strandland	Beach and river channel communities subject to infrequent but periodic submersion, wind driven waves and/or spray. Plants are separated by significant areas devoid of perennial vegetation.
1,260	Submergent Aquatic	Comprised of plants that are mostly submerged or are lacking emergent structures.
1,270	Non-vegetated	Essentially without vegetation or sparingly populated by simple organisms (e.g. playas, sinks, etc.)

Table 1 (cont'd.)

Third Level: The third digit beyond the comma refers to one of four world climatic zones in which minimum temperature remains a major evolutionary control of and within the zonation and the formation-type. All four of these broad climatic zones are found in the Southwest. They are:

1,211-1,261	Arctic-Boreal	Lengthy periods of freezing temperatures, short growing season (60-150 days), occasionally interrupted by nights of below freezing temperatures.
1,222-1,262	Cold Temperate	Freezing temperatures of short duration although of frequent occurrence during winter months. Potential growing season generally 100-200 days and confined to spring and summer when freezing temperatures are infrequent or absent.
1,223-1,263	Warm Temperate	Freezing temperatures of short duration but generally occurring every year during winter months. Potential growing season over 200 days with an average of less than 125-150 days being subject to temperatures lower than 0 degrees C or to chilling fogs.
1.224-1,264	Tropical-Subtropical	Infrequent or no 24-hour periods of freezing temperatures, chilling fogs or wind.

Fourth Level: The fourth digit beyond the comma refers to a subcontinental unit that is a major biotic community (biome). Biotic communities are natural communities characterized by a distinctive vegetation physiognomy within a formation.

Examples of Biotic Communities:

1,223.2	Interior Southwestern Riparian Deciduous Forest and Woodland
1,224.5	Sonoran Riparian and Oasis Forests
1,244.7	Sonoran Interior Marshland
1,244.8	Sonoran Maritime Marshland

Fifth Level: The fifth digit beyond the comma refers to the principal plant-animal communities within the biomes distinguished primarily on taxa that are distinctive climax plant dominants. These are referred to as "Series" or "vegetation types" and are composed of one or more biotic associations characterized by shared climax dominants within the same formation, zone, and biome.

Examples of Series Level:

1,223.21	Cottonwood-willow Series
1,223.22	Mixed Broadleaf Deciduous Series
1,244.71	Cattail Series
1,244.81	Saltgrass Series

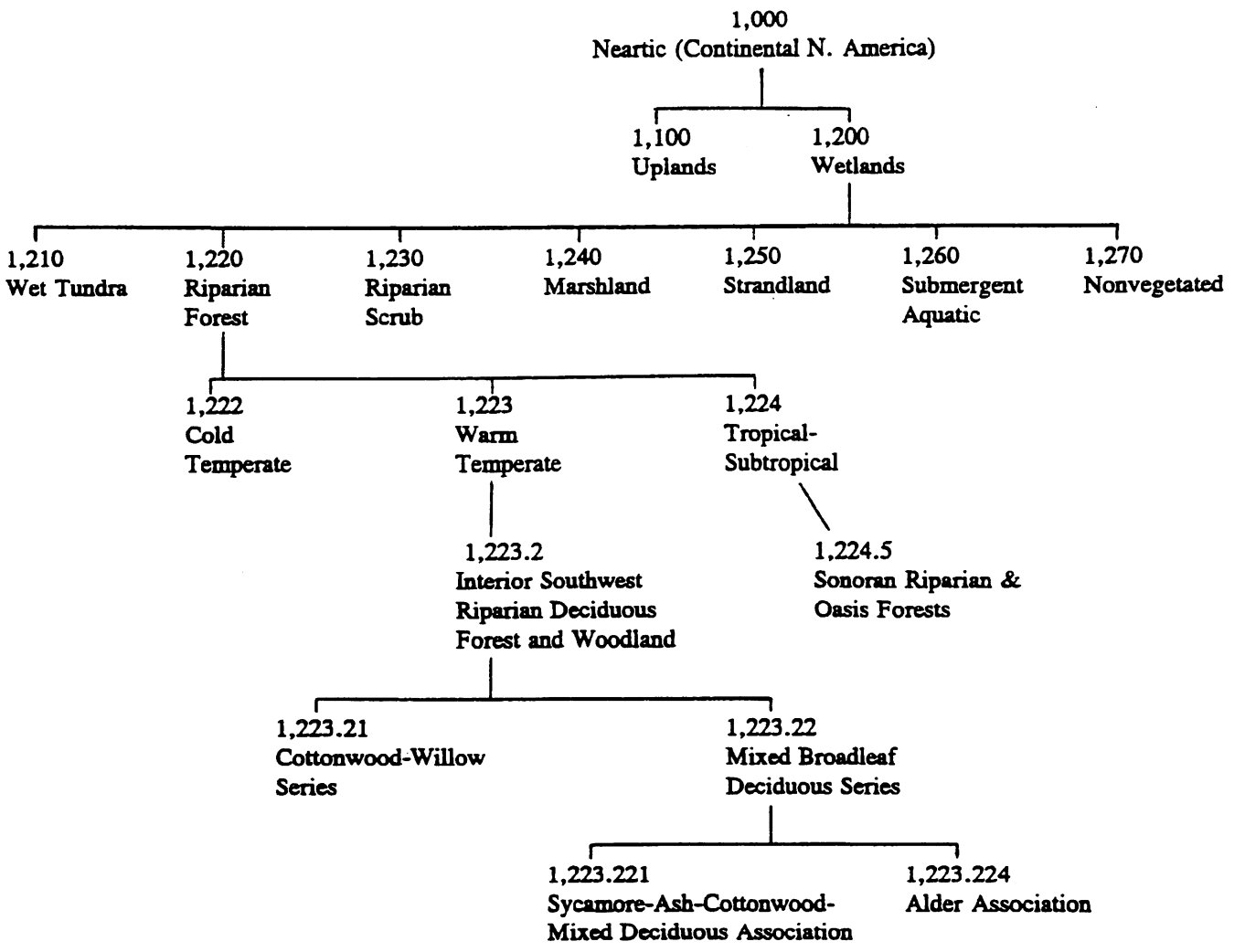
Sixth Level: The sixth digit beyond the comma refers to distinctive plant associations based on the occurrence of particular dominant species more or less local or regional in distribution and generally equivalent to habitat-types as outlined by Daubenmire (1968), Layser (1974), Pfister et al (1977) and others.

Examples of Association Level:

1,223.221	*Platanus wrightii-Alnus oblongifolia-Populus fremontii*-Mixed Deciduous Association (Sycamore-Alder-Cottonwood-Mixed Deciduous)
1,223.224	*Alnus oblongifolia* Association (Arizona Ash)
1,244.711	*Typha domingensis* Association

Seventh Level: The seventh digit beyond the comma accommodates detailed measurement and assessment of quantitative structure, composition, density and other attributes for dominants, understories, and other associated species. This level and additional ones in the system provide the flexibility required for encompassing data for ecological parameters measured in intensive studies on limited areas.

Figure 1. Flowchart of Brown, Lowe and Pase Hierarchical Classification System (1979). The example shown is for Interior Southwest riparian deciduous forest, mixed broadleaf series, sycamore-ash-cottonwood-mixed broadleaf deciduous association, and alder association.



Section II

Riparian Mapping Methodology

A. Introduction

The primary objective for this mapping methodology was to quantify the extent, distribution and representation of major riparian vegetation communities in the state. The methodology also needed to accommodate the Brown, Lowe and Pase (1979) vegetation classification system, as described in the previous section. The methodology chosen was determined to be the best technology available to map riparian areas on a statewide basis given the time requirements of this project.

AGFD contracted with Dr. Lee Graham through the Arizona Cooperative Fish and Wildlife Research Unit at the University of Arizona to formulate the methodology to identify and map riparian areas. Graham was successful in mapping statewide vegetation under the Arizona GAP Analysis Project by applying an innovative remote sensing technique combining satellite imagery and aerial videography (Graham in prep.). Graham modified this approach for mapping riparian areas across the state. Because riparian vegetation tends to occur in narrow linear corridors, the mapping methodology needed to be adapted to a much larger scale than was used on the GAP Analysis project. The vegetation mapping was conducted at the University of Arizona Advanced Resource Technology Laboratory (UA-ART).

It is important for the map user to understand what is being represented on the riparian vegetation maps. The maps were created using two major sources of imagery - Landsat Thematic Mapper (TM) digital satellite data and Multiple Resolution Aerial Videography (MRAV). The satellite imagery was used as the base map for this study and for determining the extent of riparian vegetation along stream corridors. The system that records MRAV was devised by Graham as a cost-effective means of acquiring geographically referenced, high resolution data. Aerial videography flights were initiated in October 1992 and continued periodically throughout the year ending in September 1993. Application of Landsat TM data and MRAV is described in more detail in sections C and D.

The resulting maps show the extent of riparian vegetation along perennial stream corridors in Arizona. Identification of the lateral extent of the riparian zone was accomplished through the manipulation of satellite data. Within the riparian zone, natural groupings of vegetation were identified, again by using the satellite imagery. The videography was used to provide finer resolution imagery suitable for determining the type of vegetation within those groupings. These groupings represented vegetation communities and were then classified according to dominant vegetation types using the Brown, Lowe and Pase system.

The identification, classification and mapping of riparian vegetation is being completed in a phased approach. In this first year, priority was given to mapping riparian areas associated with perennial waters. Several areas appearing on the perennial waters map were not mapped this past year because of flight restrictions. These areas include the Colorado River and its

tributaries which occur within or adjacent to Grand Canyon National Park. In addition, several lakes and wetlands were not mapped because of time constraints. AGFD will begin to map riparian areas associated with intermittent waters in the state once maps of perennial waters have been completed.

AGFD devised a method to assess the accuracy of the riparian vegetation maps through ground verification. Stream corridors in the southeastern portion of the state were investigated during this first year of the project. Results of that effort are presented. However, AGFD is continuing to verify maps across the state. Modifications will be made to the riparian maps as errors are found. This process will continue until all maps are found to be at least 80% accurate.

Riparian vegetation maps are the result of a broadly applied remote sensing process. However, precision of data can often be a problem. Therefore, data should always be field verified. That means the site represented on a map should be visited to ensure the information is correctly represented. The maps are a representation of the general location and type of riparian vegetation that existed in an area at the time the satellite images were created. The process was not intended to create maps that delineate each tree and shrub in the riparian corridor. In fact, any attempt to create statewide maps on this scale would be futile. Riparian vegetation is subject to many disturbances, primarily flood events. By the time one portion of the state is completed, other riparian areas in the state may have been severely altered. Therefore, it is important to realize that these maps are best used (1) for collecting general data on the amount of riparian vegetation existing at a given time in the state, (2) for determining the general location and percentage of various riparian vegetation community types, and (3) for change analysis studies (comparing general trends or changes between years). The suitability of these maps for regulation can only be evalulated at a later date.

The extensive flooding that occurred this past year drove home the point that riparian areas are, indeed, dynamic systems. Any attempt at mapping riparian areas is limited by the fact that it simply represents a "point in time" condition. The representation may cease to exist before the map is even complete. In other words, riparian vegetation identified from the satellite imagery may no longer exist in the same form or condition due to the massive flood events of 1993. Such flood events have occurred periodically over recorded history. The method of dealing with this type of problem on this project is discussed later in this section.

B. Determination of Perennial Waters

Before the identification, classification and mapping process could begin, perennial stream segments in the state had to be identified and a GIS database representing these stream segments had to be created. The identification of perennial stream segments was a complex process for a number of reasons. First, there is no comprehensive and definitive streamflow map for the state (i.e., a map that shows which streams are considered perennial, intermittent or ephemeral). Streamflow determinations are typically made from data collected at U.S. Geological Survey (USGS) stream gages. However, there are only about 250 stream gaging stations in the state. Secondly, the complex hydrology of arid and semi-arid stream systems results in a great deal of disparity in streamflow determinations. A third factor that added to the complexity of this task was the historical disturbances to Arizona's stream systems (Minckley and Brown 1982). In some cases, streams that were historically perennial have been altered by increased pumping of groundwater from alluvial and regional aquifers, diversions of surface water, modifications of streamflow by upstream dams, and watershed land use practices that alter water flow patterns or water retention capacity of the floodplain (Arizona Department of Water Resources 1993).

There were two previous efforts conducted by AGFD to identify perennial streams in Arizona. The objective of these efforts was to provide a working tool for fisheries and wildlife biologists for use in categorizing and cataloging data on fisheries resources and wildlife habitats. The first study (Brown et al. 1981) was a joint effort with the USGS. Results were published as a statewide map in 1977 and updated in 1978 and 1981. These maps displayed perennial streams and important wetlands at a scale of 1:1,000,000. Perennial streams were differentiated on the maps according to the following characteristics:

(1) streamflow is regulated or unregulated;
(2) base flow is mainly or entirely municipal, industrial or agricultural wastewater, and;
(3) flow was perennial prior to diversion, impoundment or decline of groundwater levels.

Wetlands were differentiated by whether they had a regulated or unregulated water supply, and whether they were mainly or entirely supplied by wastewater. Within each category, wetlands were differentiated into two size categories, less than 500 acres or greater than 500 acres. Some former wetlands were also identified.

The second effort (Silvey et al. 1984) was conducted in cooperation with the U.S. Forest Service (USFS), Rocky Mountain Forest and Range Experiment Station. The purpose was to create a listing of all naturally occurring perennial waters in Arizona. This listing was coded so that the streams could be easily referenced in a computer database. The approach was based on evaluation of each drainage system in the state. Perennial stream segments were identified using a variety of data gleaned from such sources as scientific publications and reports, fish collection data, and field experience. Ground-truthing was conducted over a period of years in the late 1970s (a drier period than the current decade). Stream segment locations were referenced using the latitude and longitude readings from USGS topographic maps for the upstream point of the

segment followed by the number of miles in the stream segment. The resulting list was reviewed and revised by fisheries biologists and others over a period of six years. Today, this system serves as the basis of the AGFD Native Fish Database. The current list contains approximately 545 stream segments and assigns a hierarchical code number to each segment. Although this list serves as an excellent source of information on perennial waters in Arizona, the stream segments were not georeferenced to a computer based map. Therefore, each stream segment listed must be located manually on a map.

Results of these efforts serve as reliable sources of information on perennial waters in Arizona. However, we were not able to directly convert these data into a digital form. We were unable to digitize directly from the Brown et al. (1981) map because it was printed at a scale of 1:1,000,000, and digitizing from this scale could result in large inaccuracies. The Silvey et al. (1984) database could not be converted to GIS without a great deal of data collection, because it did not contain latitude and longitude for both the beginning and ending points of the stream segments.

Because a georeferenced database was required to create the base map of perennial streams, the information in the USGS Digital Line Graph (DLG) database was analyzed. This database represents all line map information that appears on USGS topographic maps (USGS 1991). As part of this database, USGS digitized hydrographic features represented on 1:100,000 scale maps. In the arid and semi-arid areas of the western United States, all stream channels, lakes, reservoirs, ponds, springs, industrial impoundments, playas, marshes, stocktanks, reservoirs and "dry-wash" or ephemeral channels have been mapped (USGS 1971).

According to USGS mapping principles, natural or manmade water features (streams, ponds, etc.) are classified by the periodicity of surface water. In other words, the feature is coded as to whether it is perennial, intermittent or ephemeral according to the USGS definition of these terms (Table 2). However, the perennial code is only applied when the streamflow can be reliably and accurately determined to be perennial. A water feature not definitely known to be perennial is classified as intermittent (USGS 1971).

None of the water-related features that are represented in the USGS DLGs for Arizona have been identified as perennial. Apparently there was enough uncertainty about the periodicity of flow on hydrographic features in Arizona that the perennial coding was never applied. However, because this database contains comprehensive, statewide hydrologic information in a GIS format, the decision was made to use the USGS DLGs as a basis for a perennial waters map. Perennial stream segments were then identified through a process of elimination using the previously mentioned sources and best available knowledge as guides.

The process of identifying perennial waters began by creating a subset of the USGS DLGs roughly representing the Brown et al. (1981) map. This subset served as an evaluation tool to which modifications would be made throughout the process. The subset was evaluated by a variety of reviewers and against a variety of sources.

Table 2. USGS Streamflow Definitions
Perennial waters are those "containing water throughout the year (except for infrequent periods of severe drought)."
Intermittent waters are those "containing water only part of the year."
Ephemeral waters are those containing water only as a direct result of local storms.
Source: USGS 1971

The most difficult part of this process was communicating to reviewers the criteria for determination of perennial waters. The arid Southwest has many unique hydrologic features that make the determination of perennial waters open to a variety of interpretations. For instance, many streams and rivers have perennial reaches or segments that are interspersed among intermittent stretches. Depending on the hydrology and geology of a stream corridor, this phenomenon is sometimes referred to as an interrupted stream (Meinzer 1923). Under these circumstances, perennial segments sometimes surface at different locations in the stream, depending on the local influences (substrate, geology, etc.). This type of situation increases the difficulty of geographically locating perennial waters for mapping purposes. Another question encountered was whether to include perennial stream segments that were historically perennial but are now dominated by effluent. These areas are included on the map, but have been differentiated with unique identifiers in the database. On the map, they are indicated by a black dashed line. Some examples of this type of situation are found along portions of the Santa Cruz River and the Salt River.

To address these ambiguities, a set of streamflow definitions was drafted with the hope that this would provide reviewers with some standard for determination of streamflow. The definitions were reviewed by Arizona Department of Water Resources (ADWR), Arizona Department of Environmental Quality (ADEQ) and AGFD staff, and were modified accordingly. The resulting definitions appear in Table 3. Reviewers were instructed to review the existing map and make changes, as necessary. AGFD made an arbitrary decision that perennial stream segments had to be at least one-half mile in length to be included on the map. With this in mind, reviewers were asked to:

(1) delete stream segments that were not perennial;
(2) identify and add perennial stream segments not appearing on the map;
(3) denote effluent-dominated, perennial stream segments, and;
(4) denote perennial stream segments whose flows are regulated by dam structures.

Table 3. AGFD Streamflow Definitions

Perennial Stream	A stream or part of a stream with surface flow throughout the year, drying only during periods of drought.
Intermittent Stream	A stream or part of a stream that flows only at certain times of the year when it receives water from springs, snowmelt, surface run-off or other sources (Meinzer 1923).
Ephemeral Stream	A stream or part of a stream that flows only in direct response to precipitation. It receives no water from springs and no long-continued supply from melting snow or other surface source (Meinzer 1923).
Wetland	Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands include swamps, marshes, bogs, cienegas, tinajas and similar areas (ADEQ).
Cienega	Most often applied to a mid-elevation marshland community (1,000 - 2,000 m) in Semidesert Grassland and more seldom in Madrean Evergreen Woodland, associated with perennial springs and headwater streams. Cienegas are perpetuated by permanent, scarcely-fluctuating sources of water, and are controlled by permanently saturated, highly organic reducing soils (Hendrickson and Minckley 1984).

Maps of the DLG subset were initially sent to AGFD Regional Offices and to the Hydrology and Engineering Divisions at ADWR for review and comment. The changes received were then checked with other sources for verification before any corrections were made to the database. USFS and Bureau of Land Management (BLM) personnel were consulted in specific areas, as were private sector hydrologists, academicians, and various state agency personnel. Information contained in the Arizona State Parks Rivers Assessment database was utilized and, in some cases, sources named in the database were contacted for verification. For some stream segments, we received conflicting information. When this occurred, we checked as many sources as possible within our timeframe before making a decision about the flow type.

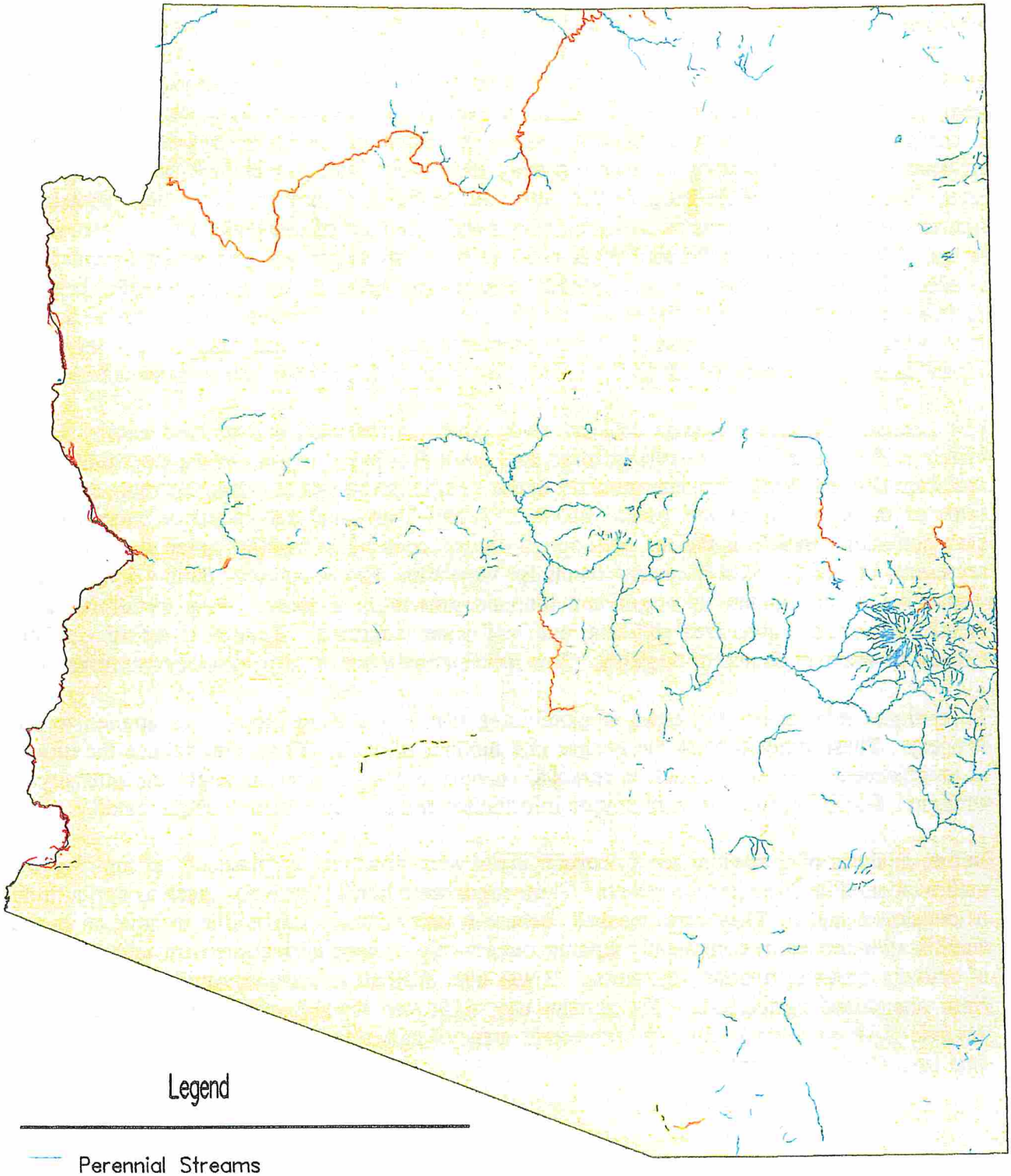
The resulting map was compared again to the Brown et al. (1981) map. This map was used as our basis for mapping riparian vegetation associated with perennial waters. Over the course of the year, this map was compared to the hand-drawn maps created during the compilation of data that appears in Silvey et al. (1984). Stream segments that appear only on the digitized map are

not assumed to be in error unless an additional reliable source can be found to concur. This criterion is due to the fact that Silvey's work may have missed some streams (B. Silvey pers. comm.). There may be a margin of error in assuming that all streams appearing on Silvey's map are indeed perennial. In some instances during a series of wet years, intermittent streams may actually support fish populations but not be considered perennial by our definition. In addition, because our minimum mapping unit for stream segments is one-half mile, some areas may be too small to be represented on the current map.

The legislative definition of a riparian area excluded "artificially created stockponds, man-made storage reservoirs constructed primarily for conservation or regulatory storage, municipal and industrial ponds or man-made water transportation, distribution, off-stream storage and collection system." Every effort was made to exclude these areas from the map. However, our method of differentiating between natural and artificial ponds using remote sensing techniques alone is not highly accurate. Use of aerial videography, when available, increased our ability to determine the nature of the pond. To determine whether a man-made reservoir should be excluded, the sources that identified the purpose for which the reservoir was constructed had to be consulted. In cases where we were able to verify that a reservoir was constructed for purposes listed as exclusions, the reservoir was removed from the map.

The resulting map (Figure 2) represents our best attempt to identify perennial waters in Arizona. Perennial stream segments are identified according to three criteria. Those stream segments that are somehow regulated by a dam structure are identified in red. Stream segments whose base flow is mainly or entirely municipal, industrial or agricultural wastewater are identified by a black dashed line. All other stream segments are identified in blue. Because the map is based primarily on reviewers' knowledge and not on quantitative stream gage data, caution should be exercised in the application of the map beyond this study.

Statewide Riparian Inventory & Mapping Project
Perennial Waters



Legend

- Perennial Streams
- Perennial Stream – Flow Regulated
- Base flow mainly or entirely municipal, industrial, or agricultural wastewater

ARIZONA GAME & FISH HERITAGE FUND

Figure 2.

C. Satellite Imagery - Method of Analysis

One of the most critical parts of mapping riparian areas was correctly representing the extent of the riparian area and the various vegetation types that occur within that area. This task was accomplished through the analysis of satellite imagery. The satellite imagery used in this project was obtained from the Earth Observation Company, Landsat satellites 4 and 5, Thematic Mapper (TM) data. Satellite images are collected in scenes, which are areas depicting a specific geographic extent. Approximately 19 scenes are needed to cover the entire state. Each scene is comprised of rows and columns which make up picture elements, or "pixels." Each pixel represents a square cell covering approximately 984 square yards and is 31.4 yards along each side. The Landsat satellite imagery that was used as the base map for this project represents riparian vegetation as it existed in April, May and September of 1991 and 1992. The reason images from multiple months and years were used is that scenes are sometimes obscured by clouds. Graham attempted to use satellite information taken in the spring months because riparian vegetation was more distinct from adjacent vegetation before the summer rains. Scenes from April and May of 1991 and 1992 were used to avoid cloud covered images. In a few cases where cloud cover obscured all spring scenes for an area, September scenes were applied.

The Landsat TM sensor system collects seven bands of reflected and emitted energy in the visible, reflective-infrared, middle-infrared, and thermal-infrared regions of the electromagnetic spectrum (Jensen 1986). To determine the extent of riparian vegetation along a stream corridor, three of the seven bands are used. Bands 3, 4 and 5 are analyzed based on their spectral characteristics. Band 3 is the red chlorophyll absorption band of healthy, green vegetation. It represents one of the most important bands for vegetation discrimination. Band 4 is especially responsive to the amount of vegetation biomass present in a scene. It is useful for crop identification and emphasizes soil-crop and land-water contrasts. Band 5 is sensitive to the amount of water in plants, or turgidity. This information is useful in plant vigor investigations.

To evaluate reflectance, a process of combining bands, via band ratios, was applied to the imagery. These ratios modify the images in a number of ways. First, they reduce the effects of environmental conditions such as seasonal changes in the illumination angle and intensity of sunlight. Secondly, they provide unique information not available from a single band.

Before analysis of a satellite scene, certain areas were removed or "masked" to improve the quality of satellite classification results. These areas were human use areas, such as agricultural or developed lands. They were masked because it was virtually impossible to have an image classification procedure consistently separate out actively growing agriculture from adjacent areas of actively growing riparian vegetation. It was also difficult to separate sand and gravel bars from abandoned agriculture. The human use mask was developed by Graham during the Arizona GAP Analysis Project and represents areas of agriculture, urban, industrial and mixed land uses (Graham in prep.).

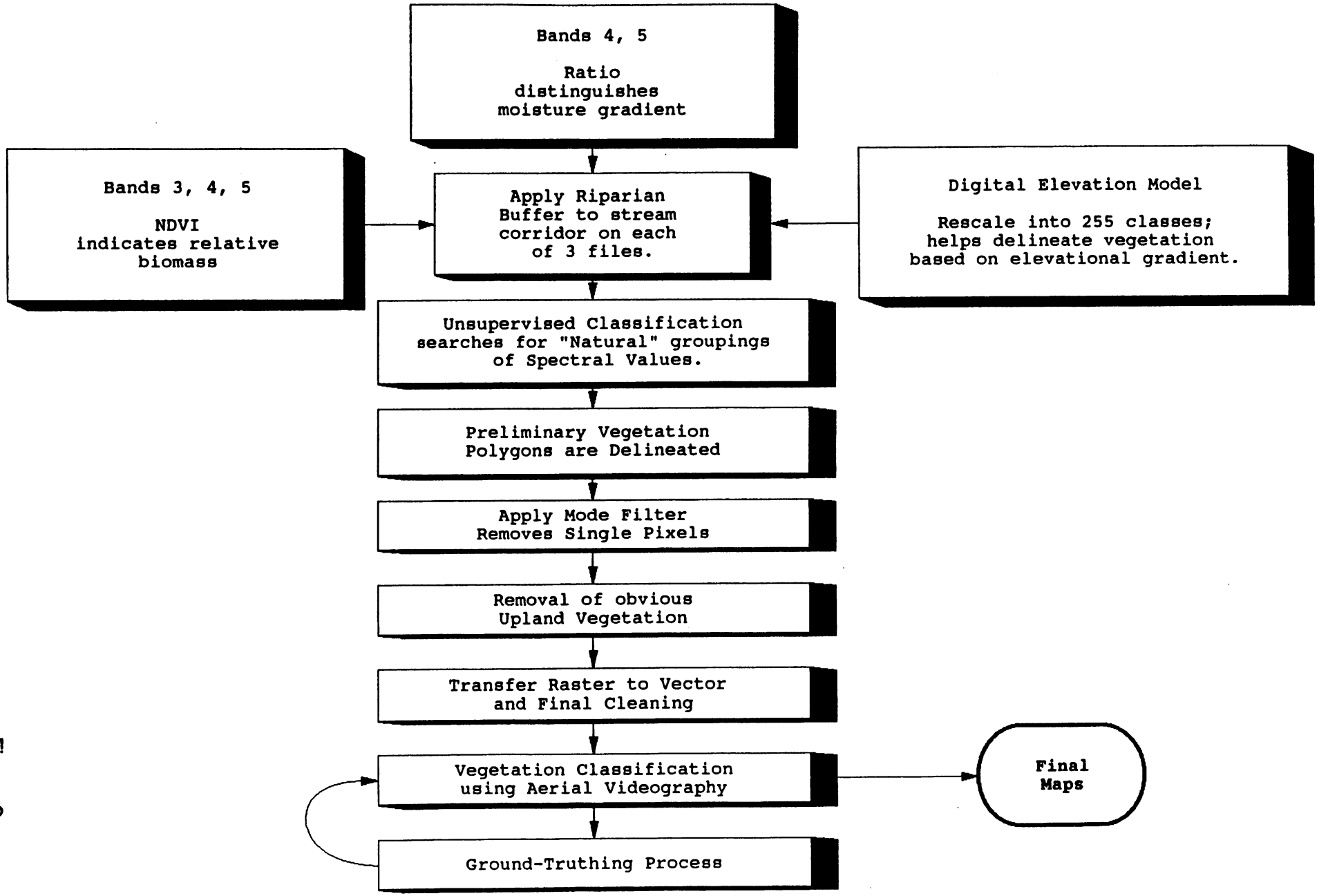

Bands 4, 5
Ratio distinguishes moisture gradient
Bands 3, 4, 5
NDVI indicates relative biomass
Apply Riparian Buffer to stream corridor on each of 3 files.
Digital Elevation Model
Rescale into 255 classes; helps delineate vegetation based on elevational gradient.
Unsupervised Classification searches for "Natural" groupings of Spectral Values.
Preliminary Vegetation Polygons are Delineated
Apply Mode Filter Removes Single Pixels
Removal of obvious Upland Vegetation
Transfer Raster to Vector and Final Cleaning
Vegetation Classification using Aerial Videography
Final Maps
Ground-Truthing Process

Figure 3.

The process used to identify the extent of riparian vegetation and to differentiate the types of vegetation is represented in the flowchart in Figure 3. The process was applied to each satellite scene using two different band ratios and elevation data. Examples of images that result from each stage of the process are shown in Figure 4. The first ratio created a normalized difference vegetation index (NDVI), the output of which indicated relative vegetation biomass. The second ratio between bands 4 and 5 distinguished moisture gradients within the scene. The third step applied elevation ranges for the geographic area represented within the scene. The data set used is referred to as a Digital Elevation Model. The elevation data assisted in segmenting the data into regions that were physically and spectrally more homogeneous. It indirectly distinguished topographic changes in the landscape by accounting for illumination effects and stratified a satellite scene into ecological zones (Scott et al. 1993). These three processing steps resulted in three separate computer files.

The next step of the analysis required use of the digital perennial waters map. The map was overlaid on the satellite image contained in each file. Using Arc/Info software, a buffer was created around the stream bed to include all potential riparian vegetation. Buffering is a process that calculates an equal area around a given location. Buffer distance was determined by the application of Arc/Info software. Because the satellite image displays a bright red color where high amounts of vegetation biomass were present, the buffer distance was determined at the furthest red area from the stream bed. The resulting corridor of vegetation was extracted from the satellite scene to be further refined.

Once the riparian corridors were extracted, the three files were combined and analyzed together. An image classification procedure was conducted using cluster analysis. This procedure is referred to as unsupervised classification. It involves clustering of individual units, or "pixels," into classes based on measured reflectance values. More simply, it grouped together those areas that show similarities on the basis of biomass, moisture gradient, topography and elevation.

The result of this image classification is pictured in Figure 4(i). Polygons (contoured areas) outlined on this map represent areas of similar vegetation as identified by cluster analysis. However, at this point, the map was still in a preliminary stage and had to undergo continued refinement. First, areas of upland vegetation that were inadvertently included in the buffering process were identified and removed. Next, a mode filter was applied, which removed or integrated areas that fell below the minimum mapping unit (MMU). The MMU was 0.4 acre (0.4 acre = 2 pixels). However, it increased to 4 acres (4 acres = 20 pixels) in large river corridors (San Pedro, Verde, Colorado, Santa Cruz, Gila and Virgin rivers).

Two units of scale have been presented in this section: pixel size and MMU. Pixel size represents the resolution of satellite imagery. MMU refers to the size of the smallest area depicted on a map. By establishing a MMU of 2 pixels (0.4 acres) for the majority of areas and applying a mode filter during the mapping process, a 2 pixel area becomes the smallest area depicted on the maps. For the large river corridors listed, the MMU is 20 pixels (4 acres).

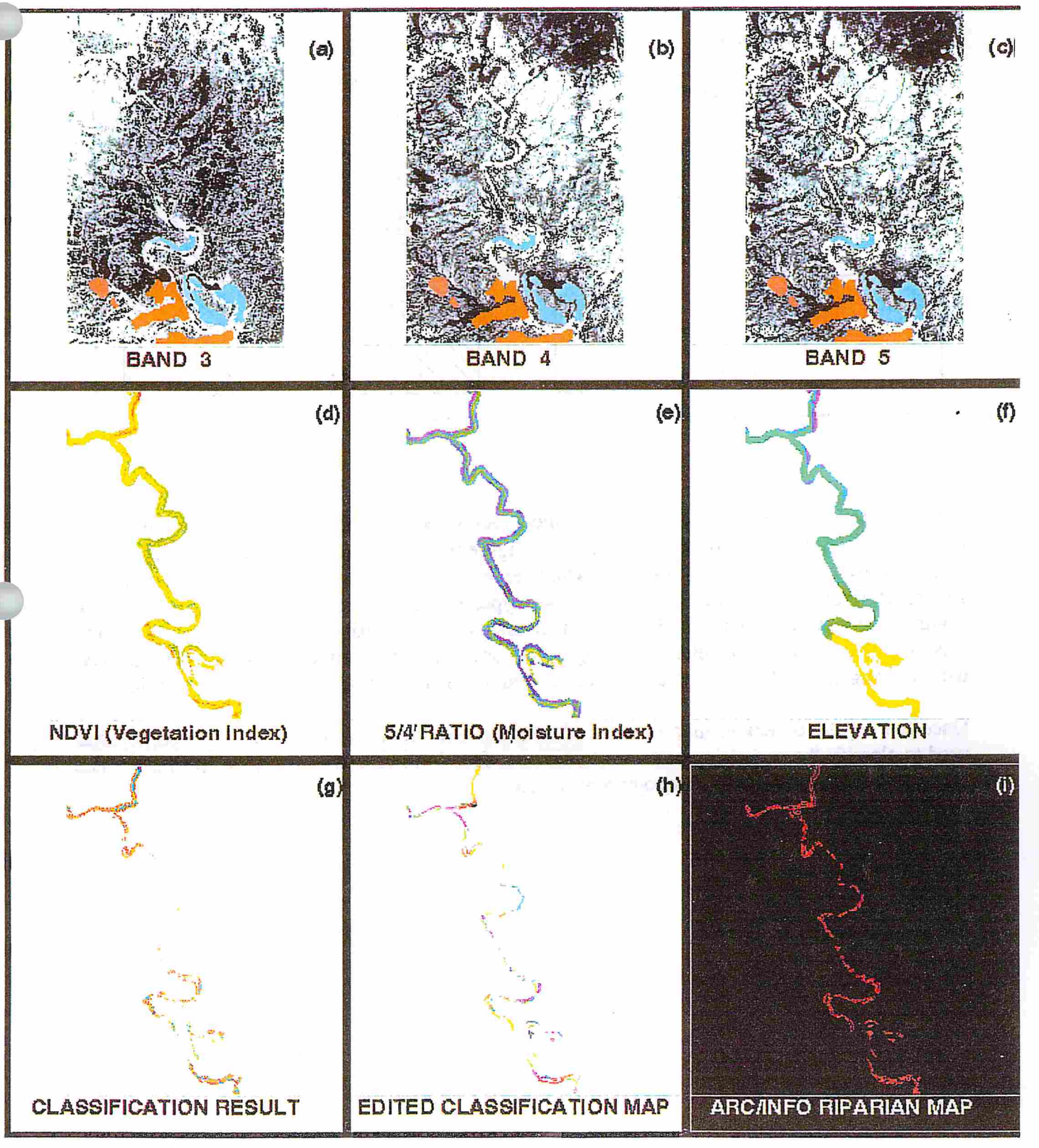
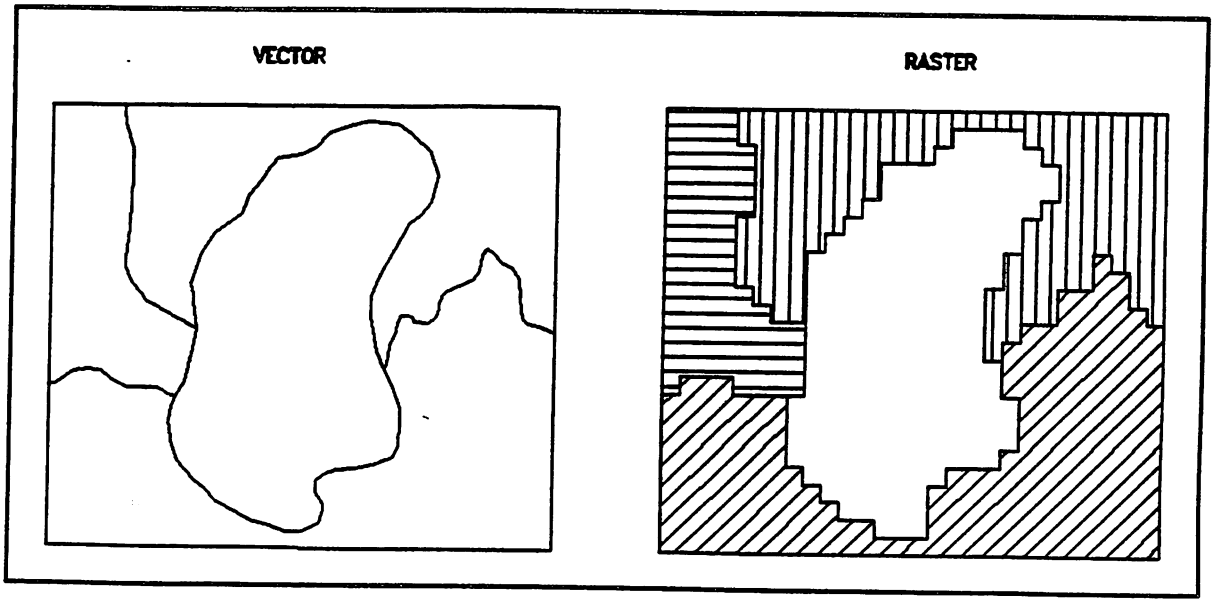

(a)
BAND 3
(b)
BAND 4
(c)
BAND 5
(d)
NDVI (Vegetation Index)
(e)
5/4' RATIO (Moisture Index)
(f)
ELEVATION
(g)
CLASSIFICATION RESULT
(h)
EDITED CLASSIFICATION MAP
(i)
ARC/INFO RIPARIAN MAP

Figure 4.

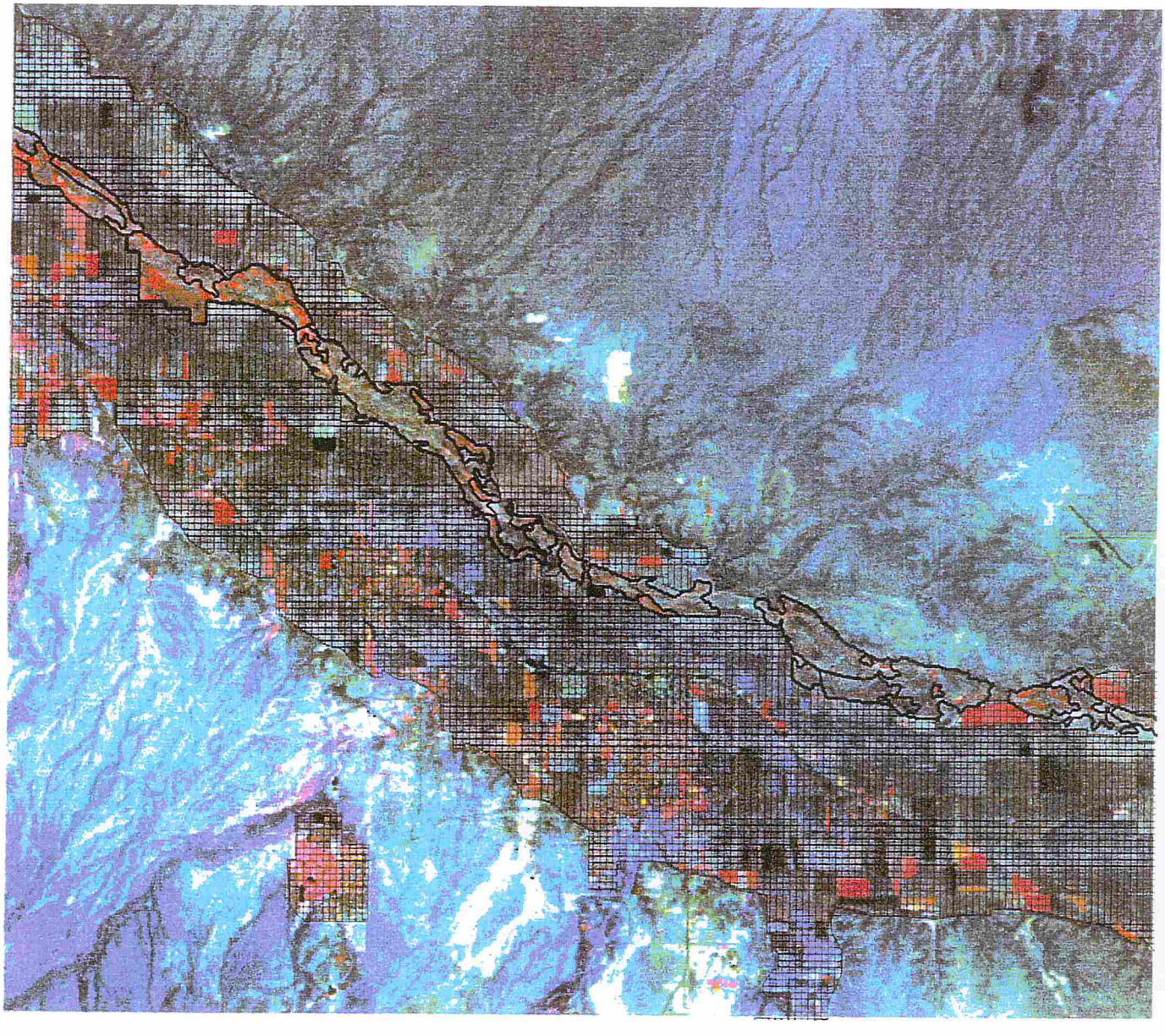
Figure 5. Representation of vector and raster data.



Polygons delineated by this process were then vectorized, a process that changes the square raster format into smooth-lined vector format (Figure 5). The map was manually checked and outliers were rejected. The finished product represents the extent of riparian vegetation in a stream corridor and differentiates the various types of vegetation found there. Figure 6 and Figure 7 represent sections of the Gila River and San Pedro River, respectively, after these processes have been completed. The vegetation polygons are outlined in black. The hatched pattern designates the extent of the agricultural and urban areas near the riparian corridor.

Once the vegetation extent map was completed from satellite imagery, aerial videography was used to classify the vegetation community that was found to occur within a given polygon. The application and use of aerial videography follows.

Example of Satellite Imagery along Gila River with Vegetation Polygons and Masking Layer



Land use mask applied to satellite imagery during image classification.

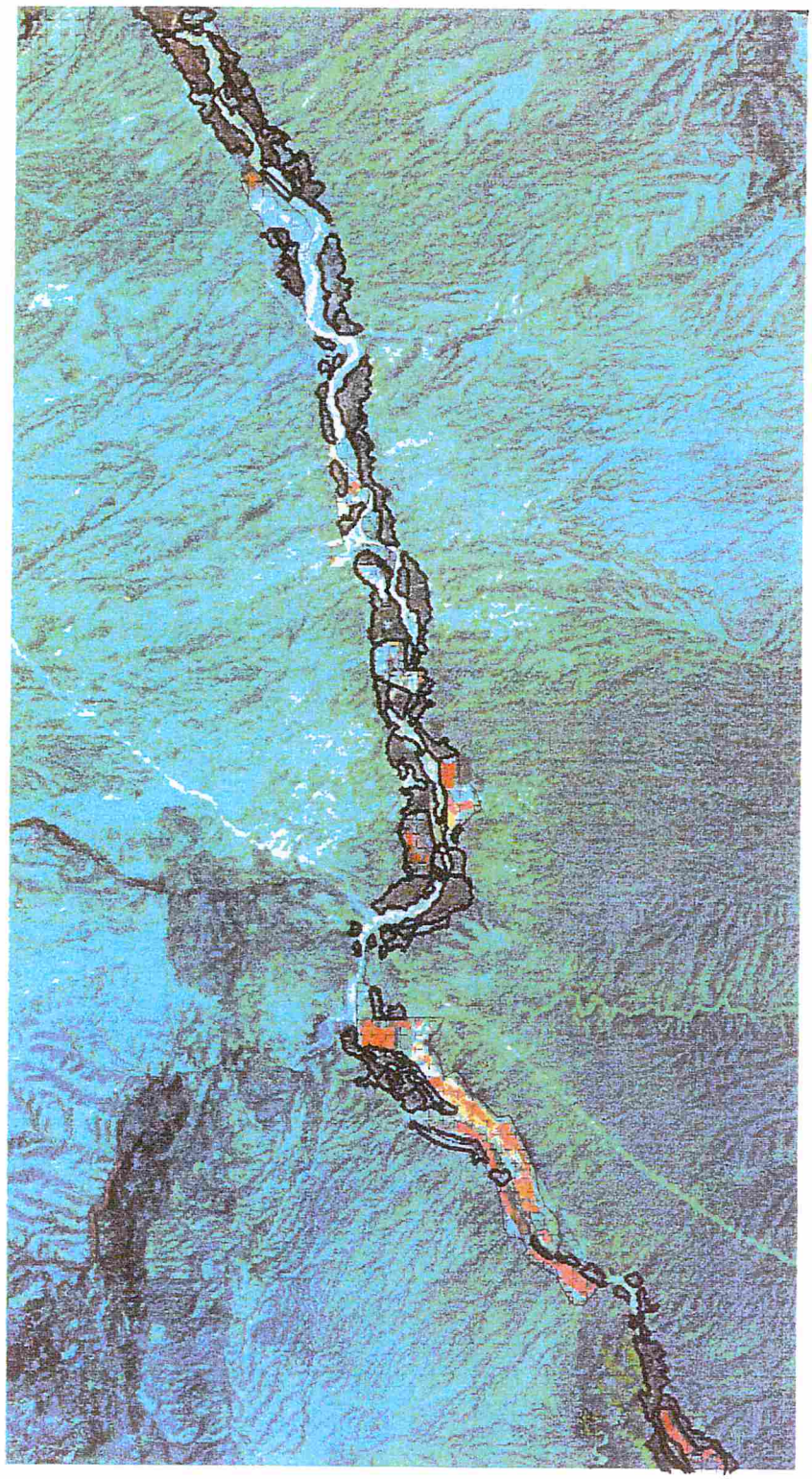
Vegetation polygons resulting from the imagery classification.

N

Vegetation data generated at UofA ART Lab.

Figure 6.

Example of Satellite Imagery along San Pedro River with Vegetation Polygons and Masking Layer



N

Land use mask applied to satellite imagery during image classification.

Vegetation polygons resulting from the imagery classification.

Vegetation data generated at UofA ART Lab.

Figure 7.

D. Vegetation Classification Using Aerial Videography

Multiple resolution aerial videography was obtained by flying pre-determined streams, lakes or wetlands in an airplane equipped with two professional grade 3-CCD Super VHS (S-VHS) video cameras. Areas to be flown were determined using the perennial waters map. These cameras produced true color S-VHS videotapes. One camera was set to record a wide-angle image, while the second camera was equipped with a remote controlled zoom lens that was used to record mid- to full 15X zoom subsamples. Aerial videography was recorded at a height of approximately 2000 feet above land surface. A zoom lens frame of video imagery represented a ground width of about 76.5 -109 yards. A wide-angle frame represented a ground width of about one-half mile.

The system integrated a global positioning system (GPS) that projected a time-code onto each video frame. GPS is a system of satellites that accurately determines coordinates of any ground location. The time-code corresponded to GPS positional data that was simultaneously logged to a file on a microcomputer. The GPS interface provided a number of important capabilities: (1) it assisted the pilot and camera operator in maintaining the proper course along a stream channel; (2) it identified the ground location at which the video recording was made; (3) GPS information allowed the wide-angle and zoom videotapes of an area to be synchronized for viewing purposes; (4) it allowed us to more accurately match a position on the satellite image to the video image.

Aerial videography served a dual purpose. Although wide-angle and zoomed video images were viewed simultaneously, they had different applications. The wide-angle view provided a broad perspective of the actual riparian vegetation occurring in a riparian area. This perspective allowed the interpreter to refine the mapping accuracy by comparing the size and extent of vegetation polygons on the satellite map with the actual vegetation communities, as seen on the video picture (Figure 8). Polygons representing vegetation communities were modified, added, merged or deleted as necessary to more accurately represent the actual vegetation as assessed by the interpreter.

Zoomed videography displayed a detailed picture of the vegetation, to an extent where individual plants could be differentiated. The person viewing the video (the interpreter) used the zoomed image to identify the type of vegetation occurring within a polygon. The interpreter then integrated the information from both views to assign a classification code to the polygon.

Because aerial views of vegetation often look quite different than at ground level, the interpreter had to initially discern the various plants that appeared on the video by working through a training process. This training process involved checking the identity of plants at specific locations on the ground. As the interpreter viewed the zoomed videos along a stream corridor, locations of specific plants, trees or clumps of similar looking vegetation were noted and GPS time codes for that particular video frame were recorded. These specific plants then were located and identified on the ground by biologists. In time, the interpreter built a reference log of information that contained plant species that had been ground-truthed and referenced to specific video frames (Figures 9 and 10). This reference library allowed the interpreter to

recognize a plant or vegetation type by learning its aerial "signature," i.e., its unique color, texture, shape and size.

As previously discussed, the hierarchical classification system chosen for this mapping project was devised by Brown, Lowe and Pase. Because of the high resolution provided by the zoomed videography, classification was accomplished at the fifth level (see Table 1). This level of classification identifies distinctive vegetation series or communities, and is based on the determination of dominant plant species more or less local or regional in distribution (Brown et al. 1979). In some cases, classification was taken to the sixth level, or vegetation association level.

The protocol for identifying plant associations from the MRAV is as follows. The dominant plant species was identified as the species whose canopy cover was equal to or greater than 50% of the polygon area. A co-dominant situation was identified when two species covered approximately equal portions of the polygon area. The classification was further refined through evaluation of additional species found to be common in the polygon. These were termed associate species - species that were found throughout the area, but not in sufficient abundance to be noted as dominants. An associate species was named in the classification if it covered at least one-half as much area as the dominant species. An additional associate species was named in the classification if it covered at least half as much area as the first associate species.

During this process, the interpreter also assigned a code to each polygon representing the percent canopy coverage of vegetation. One of the following four categories was assigned to each polygon:

a = 1 - 25%	c = 51 - 75%
b = 26 - 50%	d = 76 - 100%

Percentages refer to the amount of canopy cover for total vegetation in the polygon.

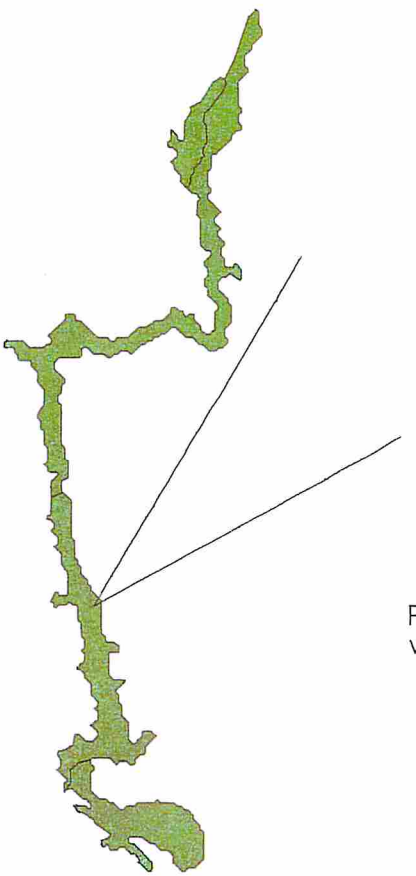


Figure 8. Sample of wide angle aerial videography of riparian vegetation along the Big Sandy River in Arizona.

Figure 9. Example of midzoom aerial videography for rectangular area on wide angle photo.

Figure 10. Example of zoom aerial videography for rectangular area on midzoom photo. The vegetation types represented include arroweed and tamarisk.

E. Map and Classification Accuracy

Field verification and ground-truthing efforts have been devised to assess the effectiveness of this remote sensing technique for mapping riparian areas. The method is briefly described here along with some of the results. A detailed reporting of methodology and results is in a separate technical document (AGFD in press).

Field verification is a process whereby biologists randomly select classified vegetation polygons in a stream corridor or watershed and verify the vegetation classification and polygon boundaries using ground-truthing techniques. Polygons are first stratified by vegetation classification type and polygon size. For each selected polygon, data were collected in a manner derived from field procedures developed by the Colorado Plateau Vegetation Advisory Committee (1992). In general, this method uses a technique based on "species prominence values," a rating that combines estimated dominance, biomass and frequency of occurrence. A prominence value is assigned to each species observed at the site on a scale of 1 through 5. Multiple sites are sampled within each polygon. The arithmetic mean and species frequency is calculated for each species group recorded in the polygon. This results in a set of values which assist in the determination of vegetation class. Additional vegetation data are also collected in the field such as height, size class frequency and distribution. General environmental and habitat conditions on the site are recorded as well as information on groundcover and adjacent vegetation types.

During the early development of sampling protocol, accuracy and data standards were established. Maps correctly classifying vegetation at least 80% of the time were deemed acceptable. We chose this level of accuracy because the overall accuracy of remote sensing derived data (satellite imagery) is generally considered to be no greater than 85% (Jensen 1986). It was also determined that a sample of 20 percent of all classified polygons would be taken. A conservative estimate of map accuracy is provided by sampling only 15.8% of the total polygons, i.e., the estimate is within 5% of the true value 90% of the time. However, the higher sampling rate was chosen because it allowed for a buffer should some polygons be unavailable or otherwise unsuitable for sampling.

To ensure consistency in ground-truthing effort, selected polygons were sampled using 0.5 acre plots (roughly equal in size to the minimum mapping unit). One plot was used for every 2.5 acres of polygon size, with an upper limit of ten for any single polygon. This maximum was established because of time limitations and was based on the fact that 71 percent of mapped polygons were 25 acres or less in size (Figure 11). Therefore, most polygons were sampled at a rate proportional to their size and only some at a rate lower than desired. Since biologists examined the entire polygon before choosing where to place representative plots, they were able to visually detect and note on video prints any inconsistencies in species composition of large polygons.

To date, the field verification process has been conducted on perennial waterways in southeastern Arizona. Area boundaries (inclusive) were the Gila River on the north (inclusive), New Mexico on the east, Mexico on the south, and the Santa Cruz River on the west (inclusive). These

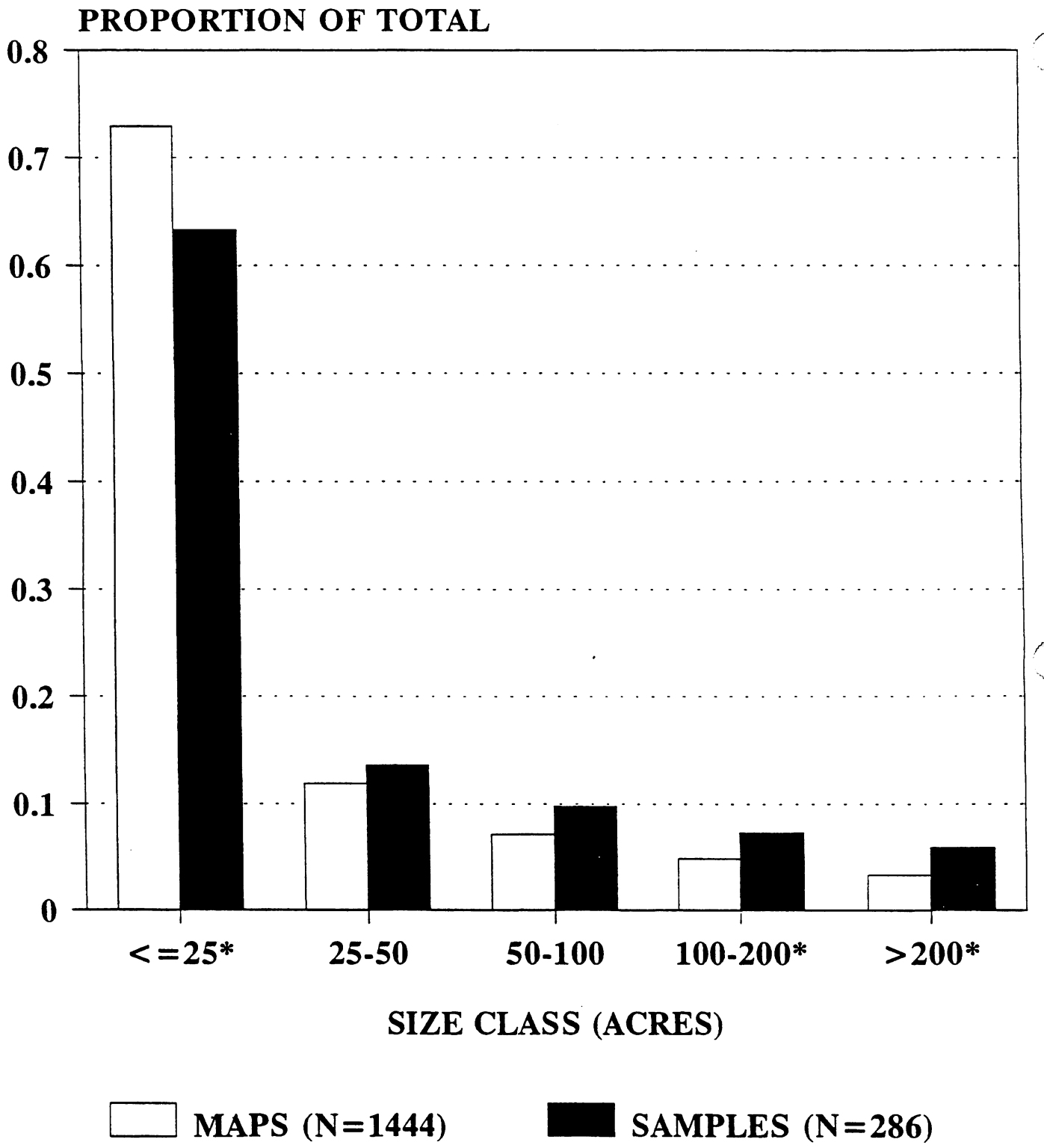


Figure 11. Comparison between map and sample polygon sizes. Asterisks mark size classes that have significantly different proportions (confidence level=90 percent).

waterways were the first areas to be mapped and classified by UA-ART. The verification area contained 1,444 riparian vegetation polygons (59,615 acres). Of these, 286 polygons (17,079 acres) were selected for verification. It was determined that 1,651 plots should be sampled.

AGFD biologists were given lists showing only an identification number, acreage and the required number of plots. In this way, their verification data could not be biased by prior knowledge of vegetation classification. After transferring some information from GIS to field maps, biologists were also aware of polygon shape and location. With this limited knowledge, biologists were then sent afield and were asked to accurately and consistently evaluate vegetation they found on site. Data were recorded on standardized report forms. Biologists also recorded on maps any boundary discrepancies they encountered while assessing polygons.

One of the most important aspects of the field verification process was to give feedback to the aerial video interpreter to help in finding and correcting classification errors during the mapping process. As errors were identified, information was provided to UA-ART for use in correcting maps. In this way, errors were minimized in later phases. Not only were specific polygons changed, but maps were re-evaluated and the corrections applied throughout. This step was critical to increasing the overall accuracy of the vegetation maps.

Data from comparison of field verifications to first draft maps is summarized in Table 4. The number of polygons in which errors or changes effected only a portion of the polygon area are shown in parentheses and are accounted for in acreage and plot values. Partial polygons are in addition to the number of whole polygons listed. Acreage and plot number has been adjusted up or down to account for portions of polygons impacted by various problems. A polygon is correctly classified when field data indicates that it is within the same vegetation community type as its map classification.

Initially, only about a third of the sampled polygons were found to be correctly classified. Initial accuracies ranged from 64% correct in some narrow mountain riparian areas to about 35% correct in large, low elevation rivers. It is important to realize that accuracy estimates calculated from the initial field sampling do not represent the end results of the mapping effort. Our goal was to attain at least 80% accuracy. Therefore, the next step was to re-evaluate mapping accuracy after field verification data were reported to the video interpreter and changes were made to maps. Once changes were made, the accuracy would increase. To measure this increase, a new sample set was selected from the San Pedro River and biologists applied the verification process on revised maps.

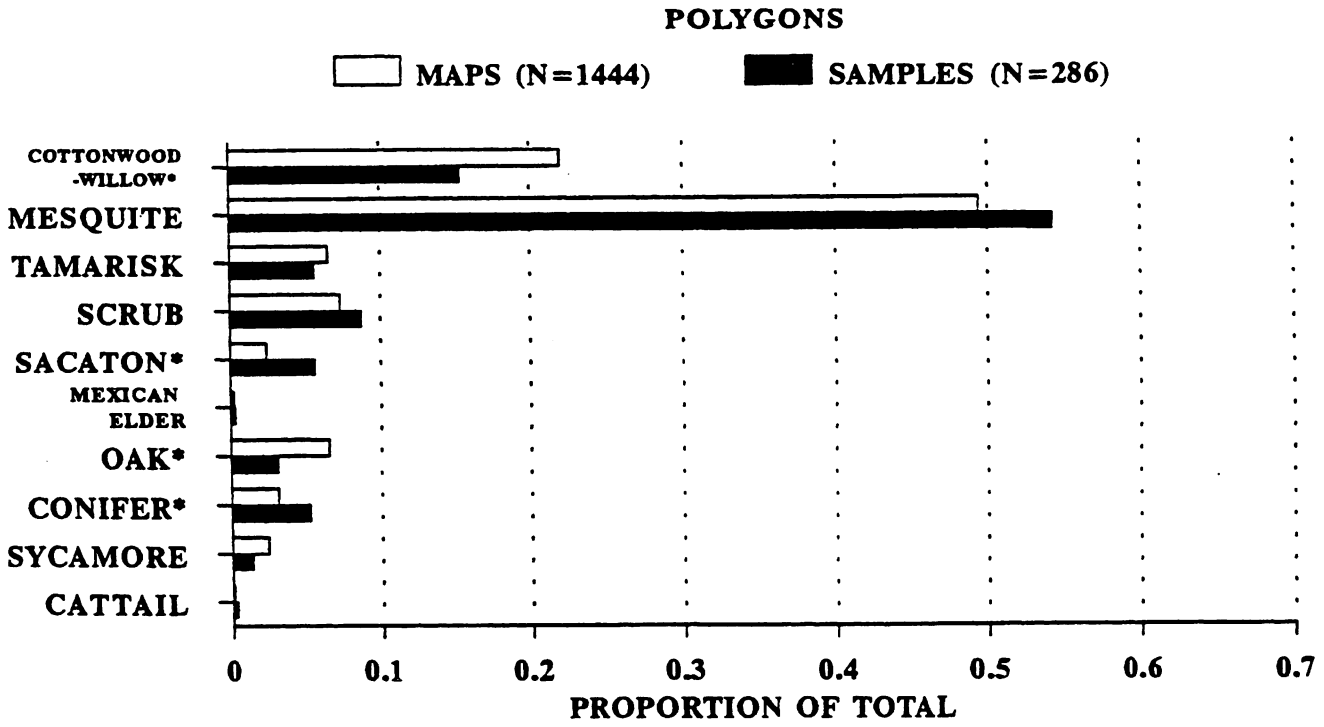
Our revised sample set on the San Pedro River showed an increase in accuracy by approximately 20 percent (Table 5). This change came primarily from a decrease in the misclassification of upland vegetation as riparian communities. Classification and boundary changes based on new field data will be incorporated into further map revisions and should substantially improve overall accuracy.

Table 4. Summary of sample results from initial ground-truthing. The number of polygons in which errors or changes affected only a portion of the polygon area are shown in parentheses and are accounted for in acreage and plot values. Partial polygons are in addition to the number of whole polygons listed.

	Number of polygons	Number of acres	Number of plots
Selected for sample	286	17,079.6	1,651
Unavailable	17 (22)	1,009.6	134
Missed	5 (4)	969.9	30
Total Sampled	**264 (26)**	**15,100.0**	**1,487**
Non-riparian (upland)	48 (36) 18.2%	4,812.2 31.9%	391 26.3%
Incorrect classification	127 (37) 48.1%	5,412.7 35.8%	599 40.3%
Correct classification	89 (22) 33.7%	4,875.1 32.3%	497 33.4%

Several types of errors were recognized in this process. As the verification process continues to be applied across the state, modifications are being made to reduce as many of these errors as possible. A summary of errors followed by proposed solutions is presented below.

Despite efforts to stratify samples by vegetation class, some vegetation classes were sampled more often (or less often) than desired (Figure 12). Data sets were received sporadically at AGFD as maps were completed at the UA-ART. Therefore, the number of riparian corridors, the variety of plant classifications, and the number of polygons and acreage differed within each set of data processed for random selection. Because of this, some small sized and/or infrequent vegetation classes often were not selected. They simply did not cover enough acreage within a data set to require sampling. However, when combined across all maps their "importance" increases (i.e. they were actually sampled less often than required). The fact that some small polygons were not chosen as often as they should have been is also supported by Figure 11. Polygons less than or equal to 25 acres were under represented in the combined sample, while all other size classes were either proportionally or over represented. This error can readily be minimized by using larger sets of polygons for sample selection.



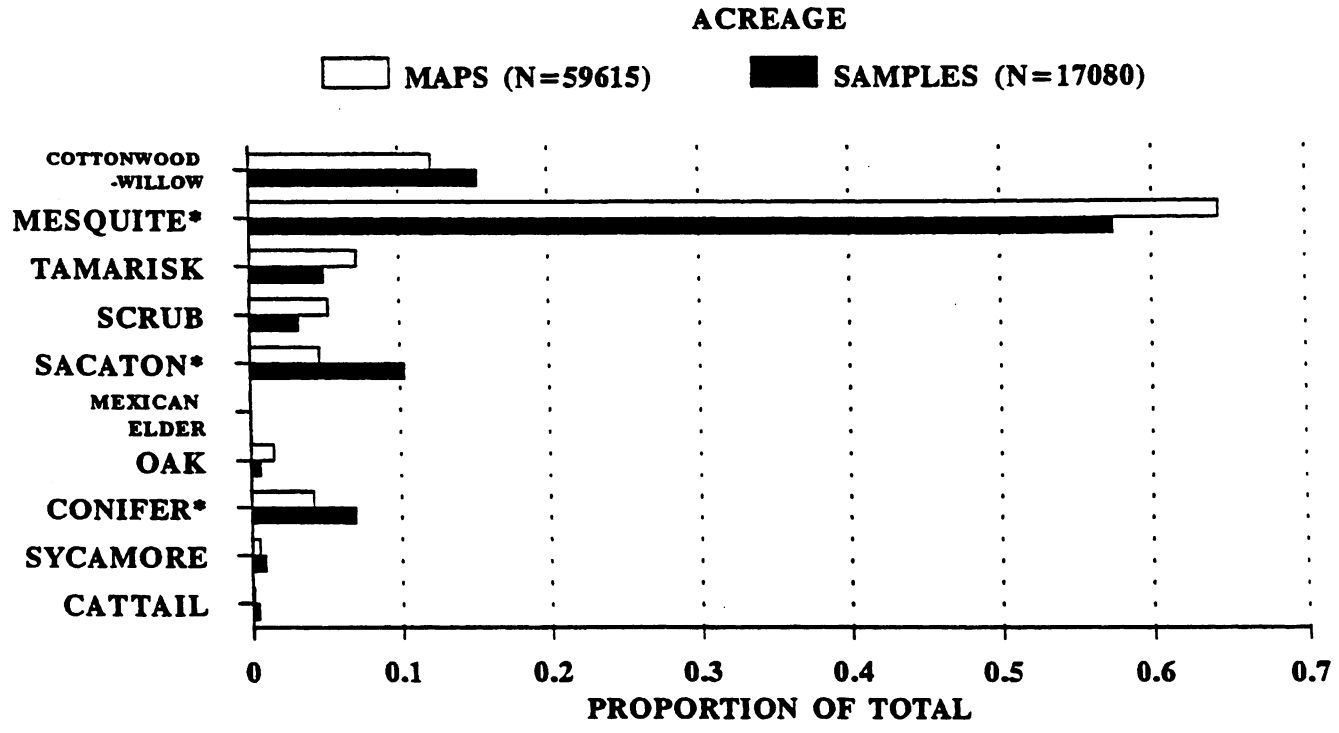


Figure 12. Comparison by plant community for map and sample polygon number and acreage. Asterisks mark pairs that have significantly different proportions (confidence level = 90 percent).

Table 5. Comparison of initial and subsequent verification of the San Pedro River. The number of polygons in which errors or changes effected only a portion of the polygon area are shown in parentheses and are accounted for in acreage and plot values. Partial polygons are in addition to the number of whole polygons listed.

	Number of polygons		Number of acres	
	Old	New	Old	New
Selected for sample	94	85	9,021.9	8,232.6
Unavailable	3(5)	2(4)	302.1	213.5
Missed	2	2(4)	902.6	181.1
Total Sampled	**89(5)**	**81(6)**	**7,817.2**	**7,838.1**
Non-riparian (upland)	26(13) 29.2%	12(11) 14.8%	4,135.4 52.9%	2,459.8 31.4%
Incorrect classification	32(11) 36.0%	25(10) 30.9%	1,767.9 22.6%	1,712.7 21.8%
Correct classification	31(6) 34.8%	44(20) 54.3%	1,913.8 24.5%	3,665.5 46.8%

A small amount of discrepancy resulted because the required sample size was rounded to the nearest whole number. In some cases, this increased the number of samples taken (i.e. they were sampled slightly more often than required).

From the outset, problems that might affect map accuracy were documented. Some polygons were not available for sampling because they had been scoured by floodwater and were devoid of vegetation. Others were underwater due to high reservoir levels. In a few cases, landowners chose to deny access. Biologists overlooked or missed a small number of polygons in the field. These factors resulted in a reduction in the number of polygons available for sampling to 264 (a minimum of 228 was needed).

The impact of flood events on riparian vegetation in 1993 was extensive. Much of the aerial videography was taken after the majority of floods occurred, with the exception of streams and rivers in southeastern Arizona. The satellite imagery, however, represented pre-flood vegetation. Because the videography is needed to identify vegetation community type, we were unable to identify areas scoured of vegetation during the floods. These areas are still considered as riparian areas but are identified as "flood scoured" on the maps. In most cases, field

biologists found extensive regeneration of riparian species at these sites during ground-truthing.

Some classification errors were due to the incorrect identification of the extent of the riparian area. Nearly 32% of the acreage was classified as riparian vegetation when in fact it was upland vegetation, agricultural lands, or adjacent to rural dwellings. This type of error was more prevalent on maps for larger rivers, such as the San Pedro, than on maps for smaller drainages and was essentially non-existent for narrow mountain riparian areas. Most misclassifications of this type were in mesquite communities that transition from the riparian zone into the adjacent upland. Although plant stature and density differ between the two zones, the boundary was not always delineated on maps properly. Boundaries can be corrected through application of ground-truthing methods that include recording the coordinates of upland/riparian edges. Topographic maps may also help by showing contour lines that may approximate the boundary.

By randomly selecting polygons only from areas that have been identified as riparian, we made the assumption that the area mapped as upland or non-riparian was accurate. The process did not account for the amount of riparian vegetation that may be misclassified as non-riparian. In addition, the agricultural mask applied to areas adjacent to the riparian corridor early in the process may have actually obscured some riparian vegetation. This situation was especially true for areas where large acreages of agricultural lands occurred in the floodplain. Underestimation of the riparian zone was found to occur on the Santa Cruz River and the Verde River at Camp Verde. Aerial videography and modification to the ground-truthing process are being used to identify and correct this problem.

Some polygons likely will always be misclassified because many understory species are not visible from above, but they may have enough prominence to influence classification by field biologists. For example, several evergreen oaks often form a mid-level canopy underneath an upper canopy of pine. The video interpreter sees the pine, but not the oak.

Other misclassifications occurred because some species were indistinguishable from others when viewed on video. Two common errors were to confuse ash and walnut with cottonwood and to confuse mesquite with tamarisk. Adding to these difficulties was the fact that often these plants occurred close together or in mixes. The result was polygons assigned to the wrong series.

Both of these errors can be reduced by producing videography at different times of the year. Appearance changes through the year as plants grow new foliage, flower, gain autumn color and shed foliage. The sequence of change varies among plant species. Videography can be timed to take advantage of a time period when two usually similar appearing species look different. For instance, tamarisk blooms when mesquite does not and has a white or pink tint from its flowers.

Some improvement in classification would be expected if a more comprehensive photo reference log is provided to the video interpreter. A wide variety of situations should be illustrated so that species are recognizable whenever observed. Situations should include seasonal changes for a species, a species combined with a variety of other species, and a species at different densities. A reference log needs to evolve as new plants and situations are encountered.

Although great effort was made to ensure accurate positioning of biologists in the field, some error should be attributed to the ground-truthing process itself. The primary source of this error was improper location of polygons on the ground. This source of error is likely to be greater for small polygons than for large ones. Small polygons are more difficult to locate to begin with and often are a different density of the same vegetation as the surrounding area. Currently biologists have to rely on topographic maps, their own navigational skills and wide angle photos to locate points on the ground. The use of GPS in conjunction with a base station should more accurately confirm where biologists collected information. A base station allows differential correction of coordinates so that true location can be more accurately determined.

AGFD will continue to apply this process to the riparian vegetation maps and make modifications accordingly until all maps across the state are at 80% accuracy. Maps of the San Pedro River and Santa Cruz River have also been reviewed by staff at ADWR and the Center for Environmental Studies at Arizona State University. This has greatly assisted AGFD staff in identifying and correcting errors. This has also helped to sensitize us to other types of errors that might not be readily apparent from the field verification process. AGFD will continue to work with land managers and researchers across the state to verify the accuracy of these maps.

F. Presentation of Maps and Summary of Findings

Products of this riparian inventory include numerous GIS databases and aerial videotapes. Examples of some of these products are presented in this section, along with a summary of findings. These examples are intended to give the reader an idea of (1) the types of maps that can be produced, and (2) the types of data contained within these GIS databases.

Figure 13 is a representation of the total amount of riparian vegetation associated with perennial waters mapped during this first year of inventory. The inventory covered 4,628.95 miles of streams and mapped 266,786.39 acres of riparian vegetation. Portions of the Colorado River and its tributaries that are within Grand Canyon National Park have not yet been inventoried because of flight restrictions. This portion represents an additional 393.52 miles of regulated river. Table 6 shows the total number of perennial stream miles identified and stream miles divided into regulated, unregulated and effluent-dominated categories, while Table 7 divides them by landownership category (federal, state, private, tribal) and land management category (BLM, USFS, AGFD, etc).

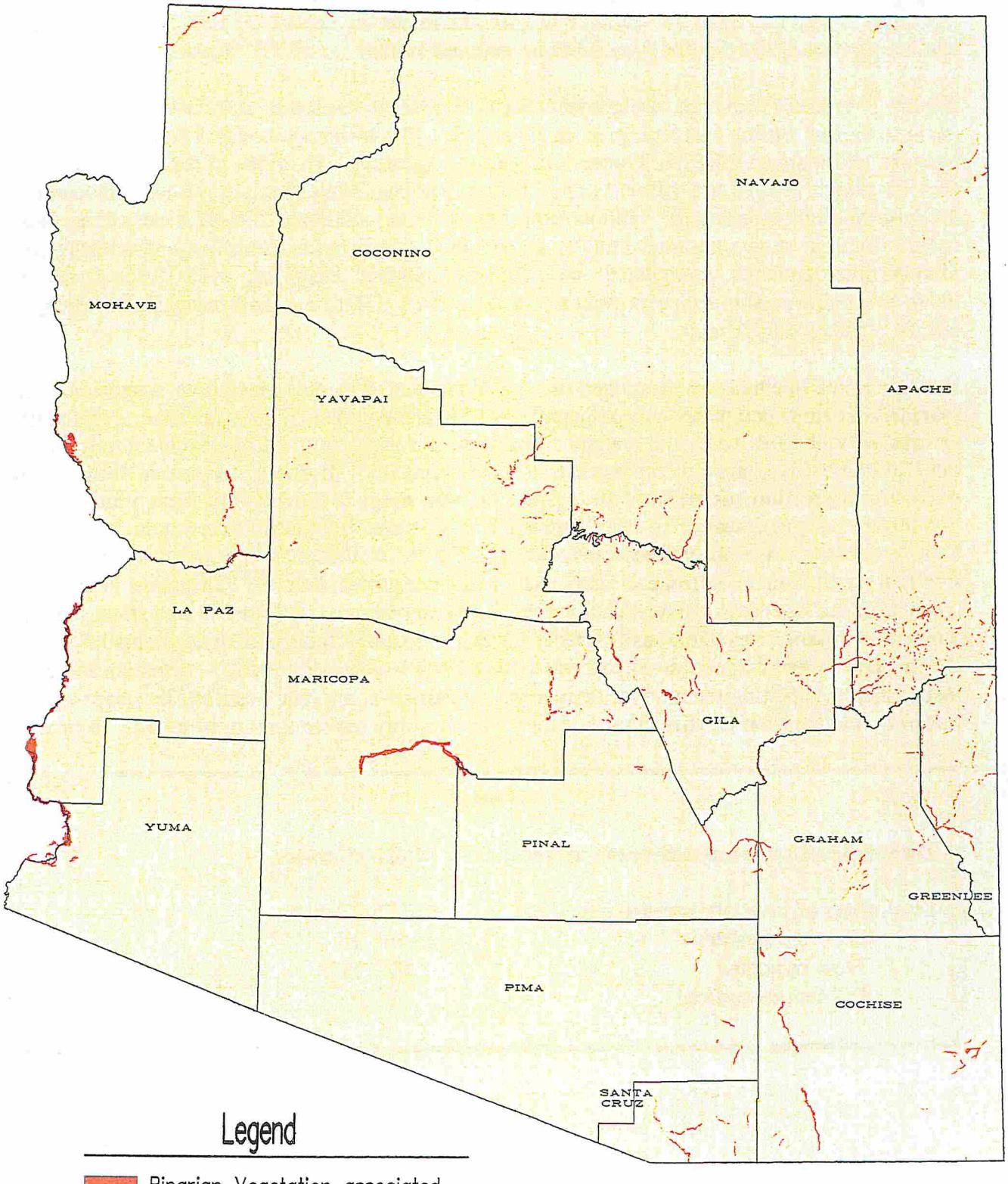
Based on the methods as described in this document, riparian vegetation associated with perennial streams comprises approximately 0.4% of the total land area of the state. Vegetation associated with most lakes and wetlands (marshes, cienegas) and with the excluded portions of the Colorado River are not represented in these numbers. **It should be noted that not all riparian vegetation, as defined by legislation was mapped during this first phase of the inventory.** A great deal of riparian vegetation is supported by intermittent waters in Arizona, but, these areas have not yet been inventoried. Figure 14 illustrates the fact that much of the riparian vegetation in Arizona is associated with intermittent waters. The maps represent a portion of the San Pedro River that alternates between perennial and intermittent flow, and the amount of riparian vegetation associated with each segment. (Intermittent segments of the San Pedro River were mapped to correspond with ADWR's case study area.) Although there are many factors affecting the amount of riparian vegetation at any one location, the maps help to illustrate the fact that the first phase of this inventory only covers a portion of the resource.

Table 6

Total miles of perennial streams inventoried	**4,628.95 miles**
Total miles of perennial streams identified	5,022.47 miles
Flow unregulated	3,961.26
Flow regulated	972.95
Effluent dominated	88.26

Riparian Vegetation

Associated with Perennial Waters in Arizona



Legend

Riparian Vegetation associated with Perennial Waters.

ARIZONA GAME & FISH HERITAGE FUND

Vegetation data generated at UofA ART Lab.

Figure 13.

Table 7.. Miles of perennial waters by land ownership category*

	Miles	Percent of Total Mapped
Total Federal	2,510.79	49.99
National Forests	1,573.50	31.33
National Parks	611.90	12.18
BLM	289.07	5.76
Wildlife Refuges	28.26	0.56
Military	8.06	0.16
Total State & Municipal	254.58	5.07
State trust/state sovereign	156.06	3.11
State & municipal parks	82.40	1.64
AGFD lands	16.12	0.32
Total Private	856.67	17.06
Total Tribal	1,408.80	28.05

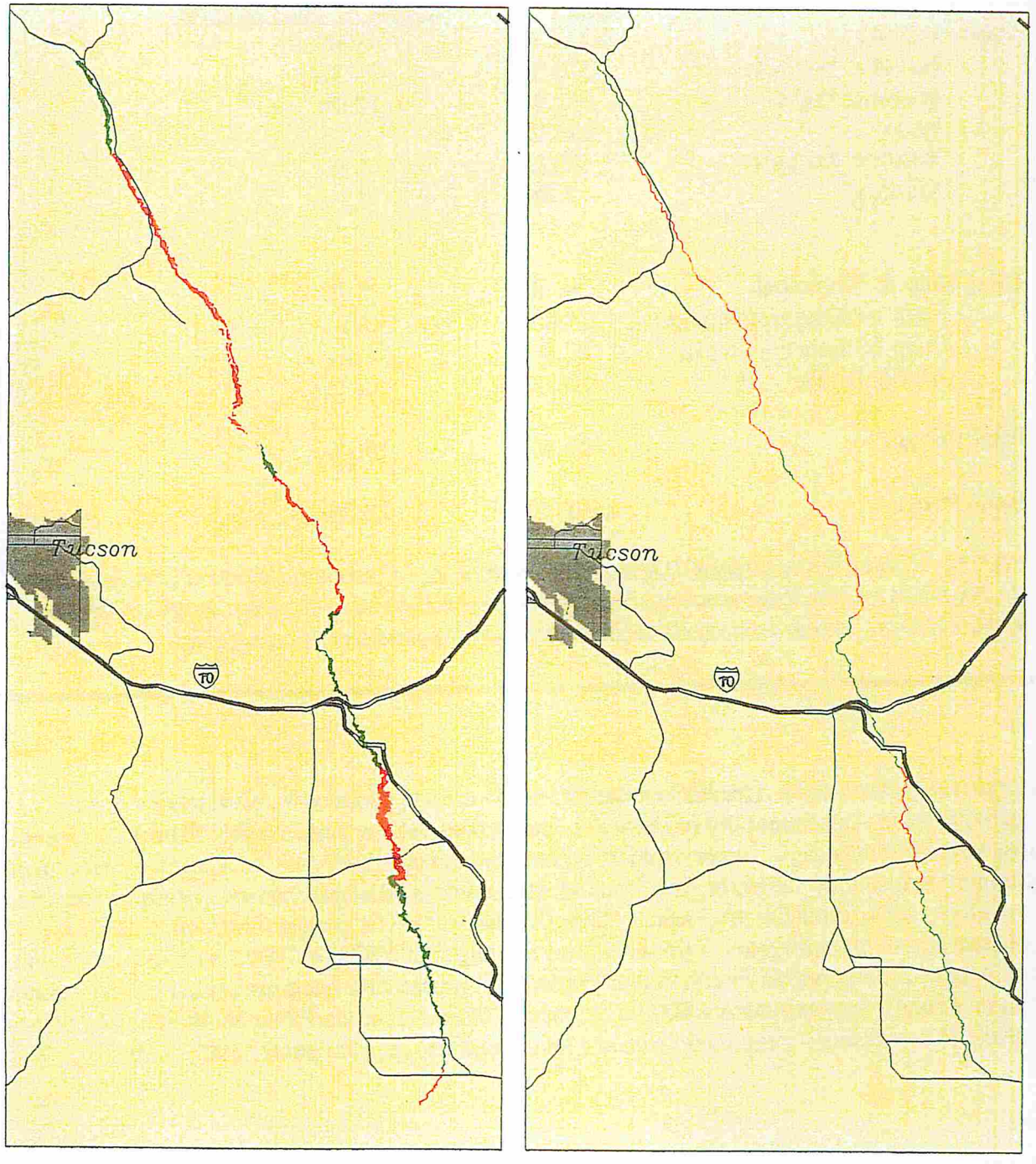
**NOTE: These figures exceed 100% of the total miles of perennial streams because there are instances where landownership is different on each bank of a given length of stream. In those cases, stream mileage is included in both landownership categories.*

As previously discussed, riparian vegetation maps can be produced at a variety of scales. At a statewide scale it is impossible to show the detail contained on these maps. Therefore, several maps were produced at a larger scale to give a better indication of the mapping resolution. Riparian areas at three different locations are presented to illustrate various riparian vegetation community types found in the state. Cave Creek in the Chiricahua Mountains (Figure 15) represents a mountain stream, with elevation ranging from 7600 to 4700 feet above sea level. A segment of the upper San Pedro River (Figure 16) represents a large unregulated river system at an elevation of approximately 4000 ft. A portion of the Colorado River south of Lake Havasu (Figure 17) represents a regulated river at low elevations, approximately 500 ft. msl.

San Pedro River Vegetation Comparison

Vegetation

Water Course



Vegetation associated with perennial streams = 12,238 acres.

Vegetation associated with intermittent streams = 19,159 acres.

Perennial Segments = 66 Miles.

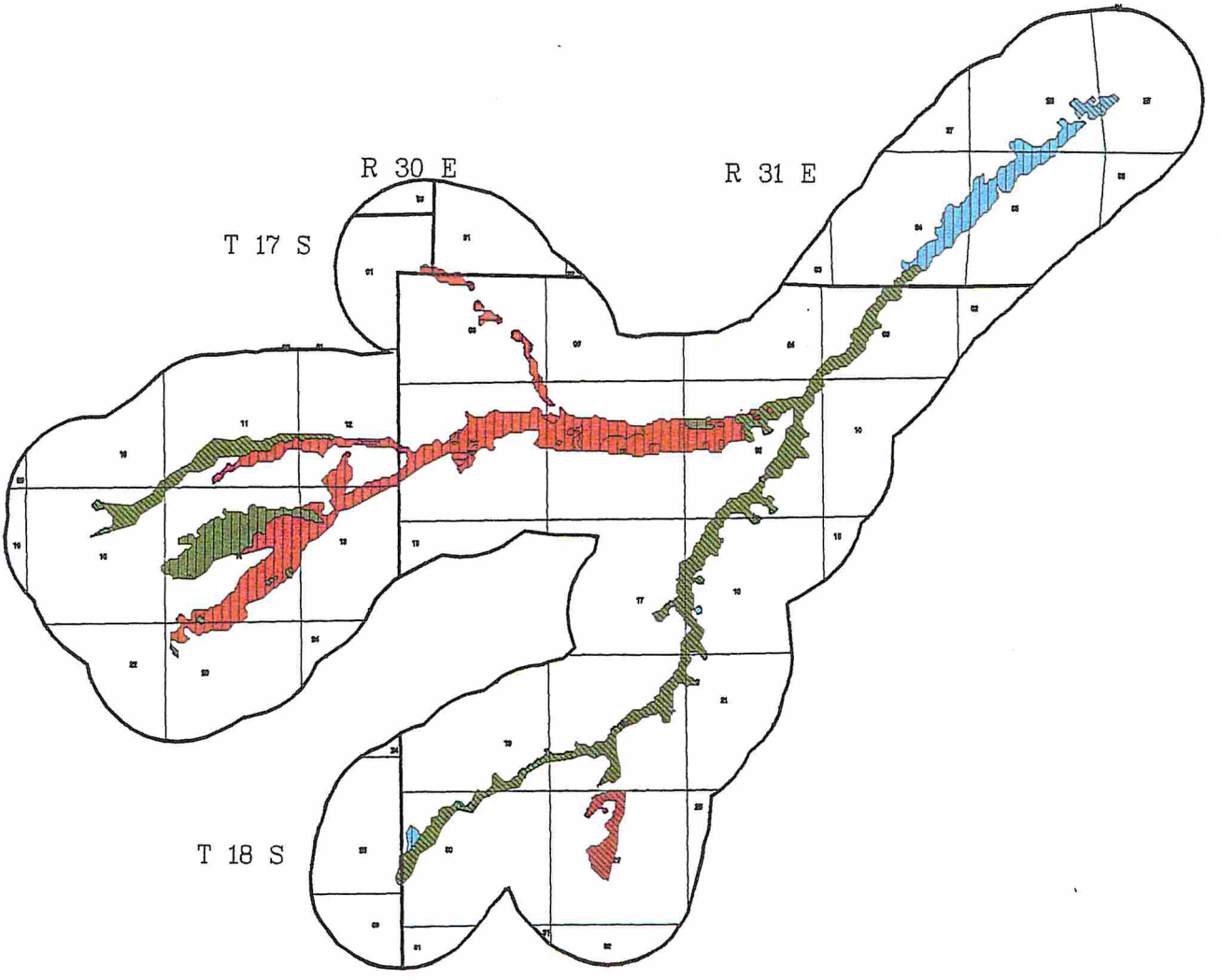
Intermittent Segments = 80 Miles.

N

Figure 14.

Vegetation data generated at UofA ART Lab.

Cave Creek
Riparian Vegetation



Legend

- Oak Communities
- Coniferous Forest Communities
- Sycamore Communities
- 1 – 25 percent canopy cover.
- 26 – 50 percent canopy cover.
- 51 – 75 percent canopy cover.
- 76 – 100 percent canopy cover.

N

Scale in Miles

0 1 2

Vegetation data generated at UofA ART Lab.

Figure 15.

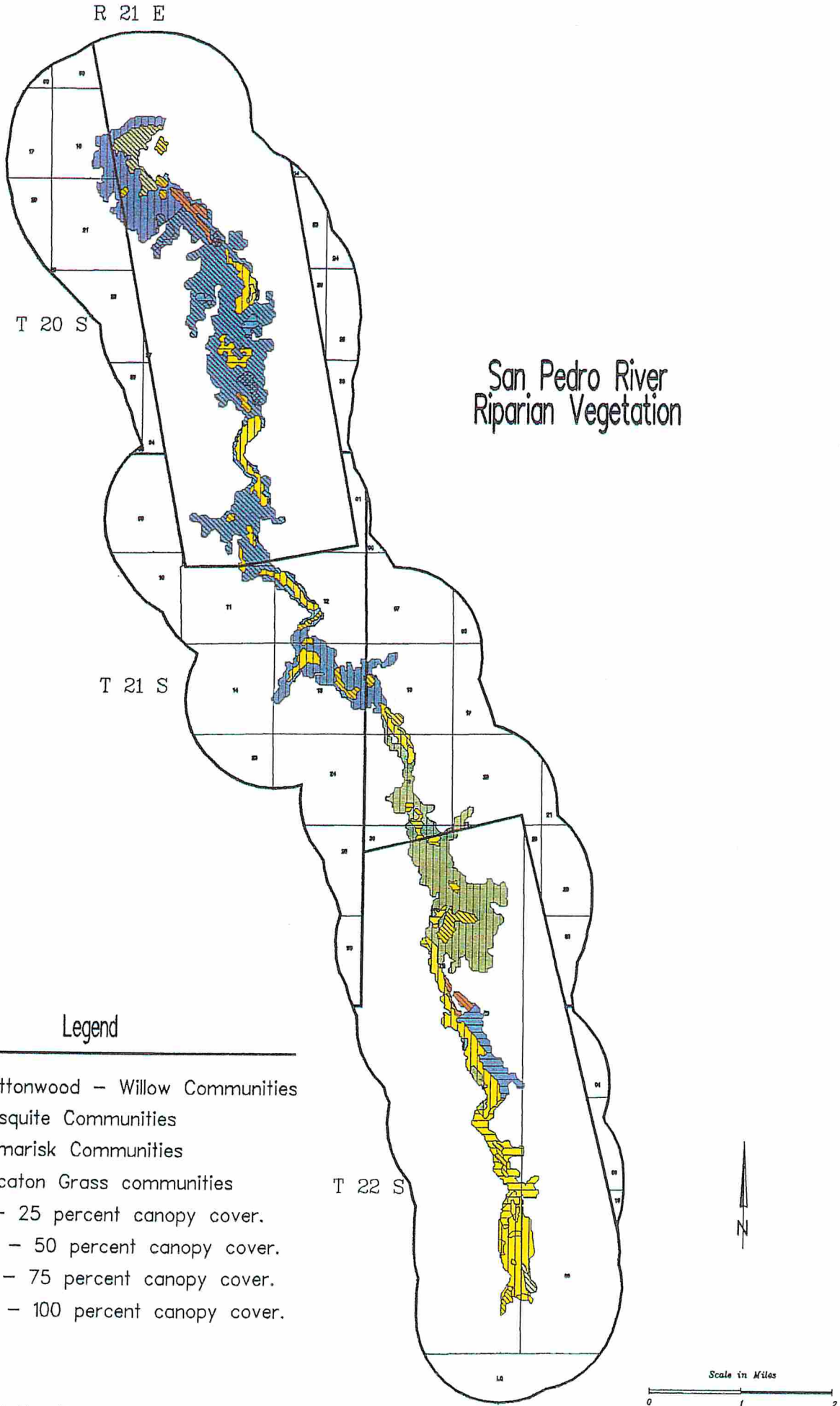

R 21 E
T 20 S
T 21 S
T 22 S
San Pedro River
Riparian Vegetation
Legend
Cottonwood – Willow Communities
Mesquite Communities
Tamarisk Communities
Sacaton Grass communities
1 – 25 percent canopy cover.
26 – 50 percent canopy cover.
51 – 75 percent canopy cover.
76 – 100 percent canopy cover.
N
Scale in Miles
0
1
2
Vegetation data generated at UofA ART Lab.

Figure 16.

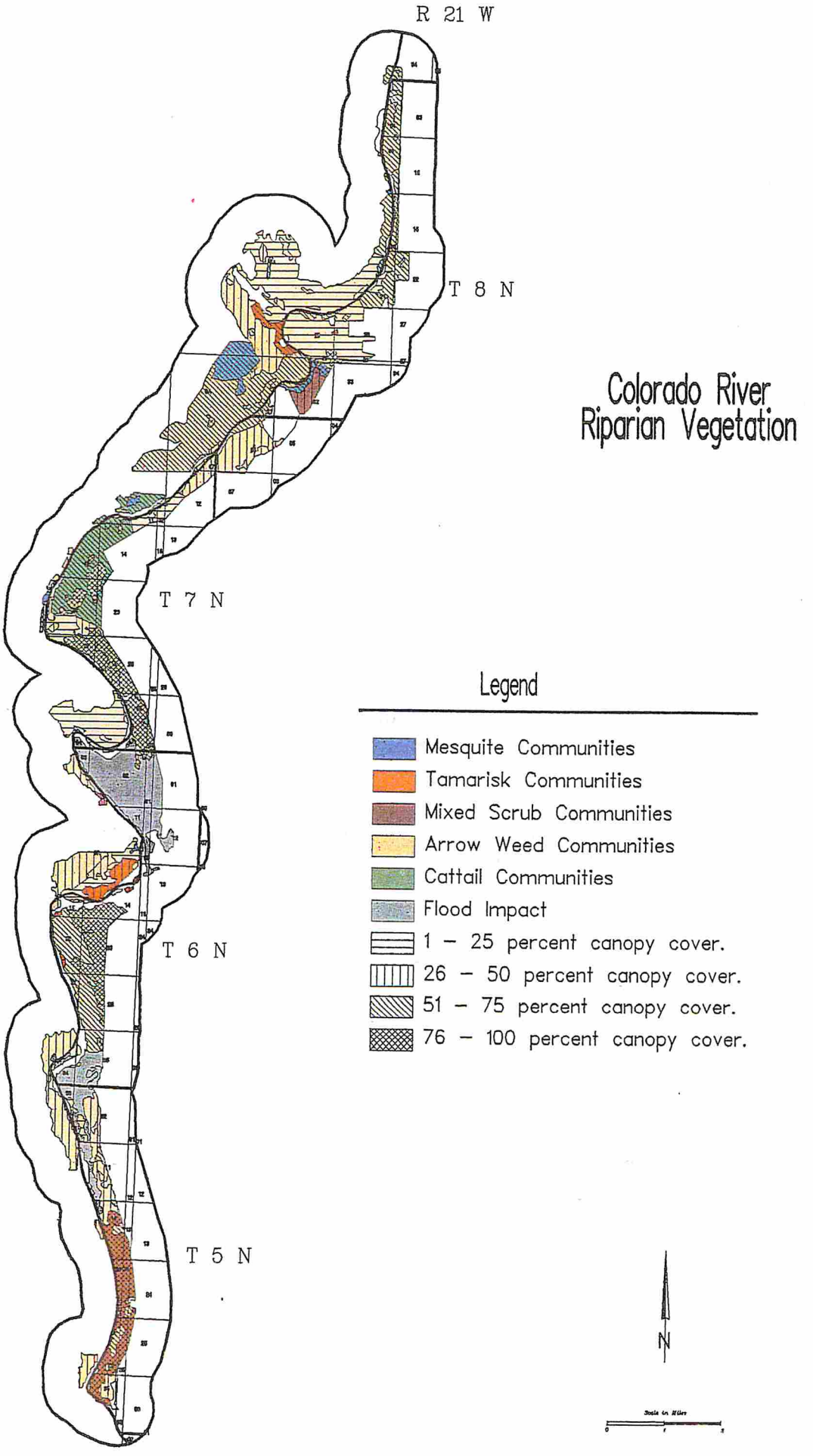

R 21 W
T 8 N
T 7 N
T 6 N
T 5 N
Colorado River
Riparian Vegetation
Legend
Mesquite Communities
Tamarisk Communities
Mixed Scrub Communities
Arrow Weed Communities
Cattail Communities
Flood Impact
1 – 25 percent canopy cover.
26 – 50 percent canopy cover.
51 – 75 percent canopy cover.
76 – 100 percent canopy cover.
N
Vegetation data generated at UofA ART Lab.

Figure 17.

Table 8. Relative amounts of riparian vegetation communities associated with perennial waters in Arizona.

Total acres of riparian vegetation associated with perennial waters as inventoried by AGFD in 1992-1993: 266,786.39 acres

Vegetation Community	Percent	Vegetation Community	Percent
Tamarisk	20.3	Russian olive	<1.0
Mesquite	17.5	Reed	<1.0
Arrowweed	14.8	Sacaton grass	<1.0
Conifer	11.2	Mixed canyon scrub	<0.5
Mountain meadow	6.3	Acacia	<0.5
Oak	4.4	Desert willow	<0.5
Cottonwood-willow	4.2	Mexican elder	<0.5
Mixed scrub	3.0		
Cattail	2.1	Flood scoured*	7.4
Sycamore	1.2	Unlabelled**	5.4

* *Vegetated according to satellite data, but scoured by winter flooding before classification with videography.*

** *Not classified due to lack of videography coverage.*

This inventory revealed seventeen (17) riparian vegetation community types (series level), and approximately 85 vegetation associations in Arizona. Accuracy on vegetation data is still being verified and should be completed by June 1994. Conversion of vegetation classes to the Brown, Lowe and Pase (1979) system is currently underway. Table 8 shows riparian vegetation community types as a percentage of the total amount of riparian vegetation mapped during this phase of the inventory. Although the inventory is not complete, these percentages begin to give a picture of the relative amounts of the various riparian vegetation community types found in Arizona. More detailed data on vegetation classifications will be available from AGFD when all components have been verified.

Section III

Land Use and Land Ownership Maps

A. Introduction

General land ownership and land use maps for Arizona are presented in this section. As directed by the legislation, the land ownership map displays federal, state, private and tribal lands. Although the legislation did not specify land uses to be mapped, AGFD attempted to locate data sources for mapping the land use activities listed in the Waters - Riparian Protection Program law (Section 6, chapter 298, Laws 1992). In some cases, limitations on data availability restricted our ability to map land uses. In other instances, such as for recreational activities, it was difficult to delineate specific geographic areas where an activity was taking place That is, some activities can realistically occur almost anywhere.

Maps presented in this section are:

(1) Arizona Land Ownership
(2) Commercial Grazing Activities
(3) Commercial Wood Harvesting Activities
(4) Urban, Industrial and Agricultural Lands
(5) Public Recreation
(6) Current and Historical Mining Locations
(7) Active Mining Locations
(8) Sand and Gravel Mine Locations
(9) Mineral Potential

Accompanying each map is a brief description of what is depicted. Data sources, methods of verification, and limitations on use of the maps are discussed. If additional data or maps are expected to be completed in the near future, that information is also provided.

Specific land uses occurring on private and tribal lands could not be identified because no comprehensive data sets exist for these areas. Even though activities on these lands are not represented on maps, many of the land use activities presented here can potentially occur on them. Potential activities include recreational activities, development, agriculture, grazing, and timber or fuelwood cutting.

These maps display areas where various land use activities occur statewide. We felt it was important to map the entire state so that land use activities within the watershed could be analyzed in conjunction with those within the riparian area proper. At the end of this section, we address how the information can be analyzed within each riparian corridor. A series of maps are presented as examples of how GIS can assist in the analysis of land use impacts on riparian corridors.

B. Arizona Land Ownership

The land ownership map presented in Figure 18 displays land ownership according to the following categories. Federally owned lands are differentiated by the land management agency responsible for the management of an area. These federal land managers include the BLM, USFS, military bases, national parks and monuments and national wildlife refuges. State owned lands include state trust lands and state sovereign lands managed by the ASLD, state wildlife areas managed by the AGFD, state park lands operated by the Arizona State Parks Board (ASPB), miscellaneous state owned lands and some municipal parks. All lands owned by Native American tribes are represented on this map under the category "tribal lands". The "private lands" category groups all lands under private ownership. Individual owners are not identified or delineated in this database.

Land ownership statistics were computed from the various land ownership databases and compiled at AGFD. Land acreages attributed to each ownership and management category are listed below:

	Acres		Acres
Federal	30,386,374	**State**	9,590,923
BLM	12,130,966	ASLD	9,388,373
USFS	11,238,805	State/Municipal Parks	178,087
National Parks	2,517,464	AGFD	24,463
Military	2,796,646	**Private**	13,448,643
Wildlife Refuges	1,702,493	**Tribal Lands**	19,685,226
		TOTAL ALL	73,111,166

Data Source:	1991-1992 "Land" Database contained in the Arizona Land Resource Information System (ALRIS) at the ASLD.
Verification Method:	Verification occurs at ALRIS on an annual basis. No additional verification was undertaken by AGFD.
Data Limitations:	Recent changes in land status may not be represented on this map. All federal land was last updated in 1991 except for USFS and Bureau of Indian Affairs lands which were updated in 1992. Arizona state lands were updated in 1991.

Arizona Land Ownership

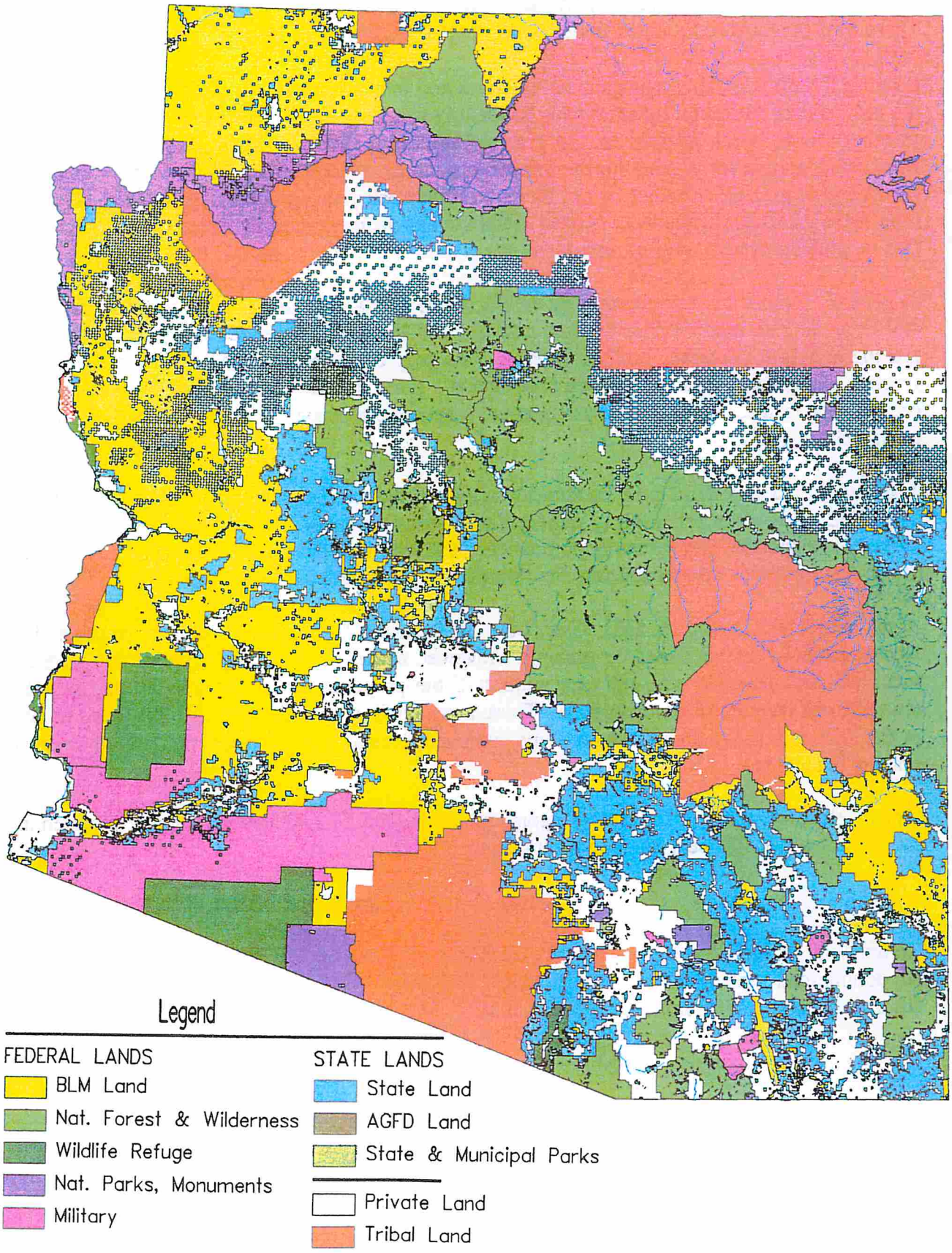


Figure 18.

C. Commercial Grazing Activities

The map presented in Figure 19 displays public lands by current livestock grazing status. No comprehensive source of geographic data was found to exist for private and tribal lands. Therefore, they are represented under a category of "no data" on this map.

Because livestock grazing management practices and intensities vary so greatly, we approached the task of data collection by attempting to identify areas where livestock grazing is prohibited. In other words, areas mapped as "no grazing" are lands that have been specifically removed from consideration for grazing for the foreseeable future. Grazed areas are those lands available for livestock grazing, whether or not there was livestock grazing occurring on the land at the time these data were compiled. Grazed lands are not differentiated by livestock type, stocking rate or grazing system used on that land.

In general, livestock grazing occurs on USFS, BLM and ASLD lands. National Park Service, ASPB, U.S. Fish and Wildlife Service refuges, and U.S. military bases reported no livestock grazing activities occurring on their lands. With only a few exceptions, AGFD lands are not grazed. All grazing information was collected at a point in time and may vary from what may occur in the future. Public lands management practices are especially subject to change to meet management goals.

Although USFS and BLM have established allotment boundaries, they are not in digital form. Therefore, they were not used to delineate areas on this map. Past experience at digitizing allotment boundaries has shown large boundary discrepancies between land management areas. These discrepancies made digitizing the boundaries impossible for this report.

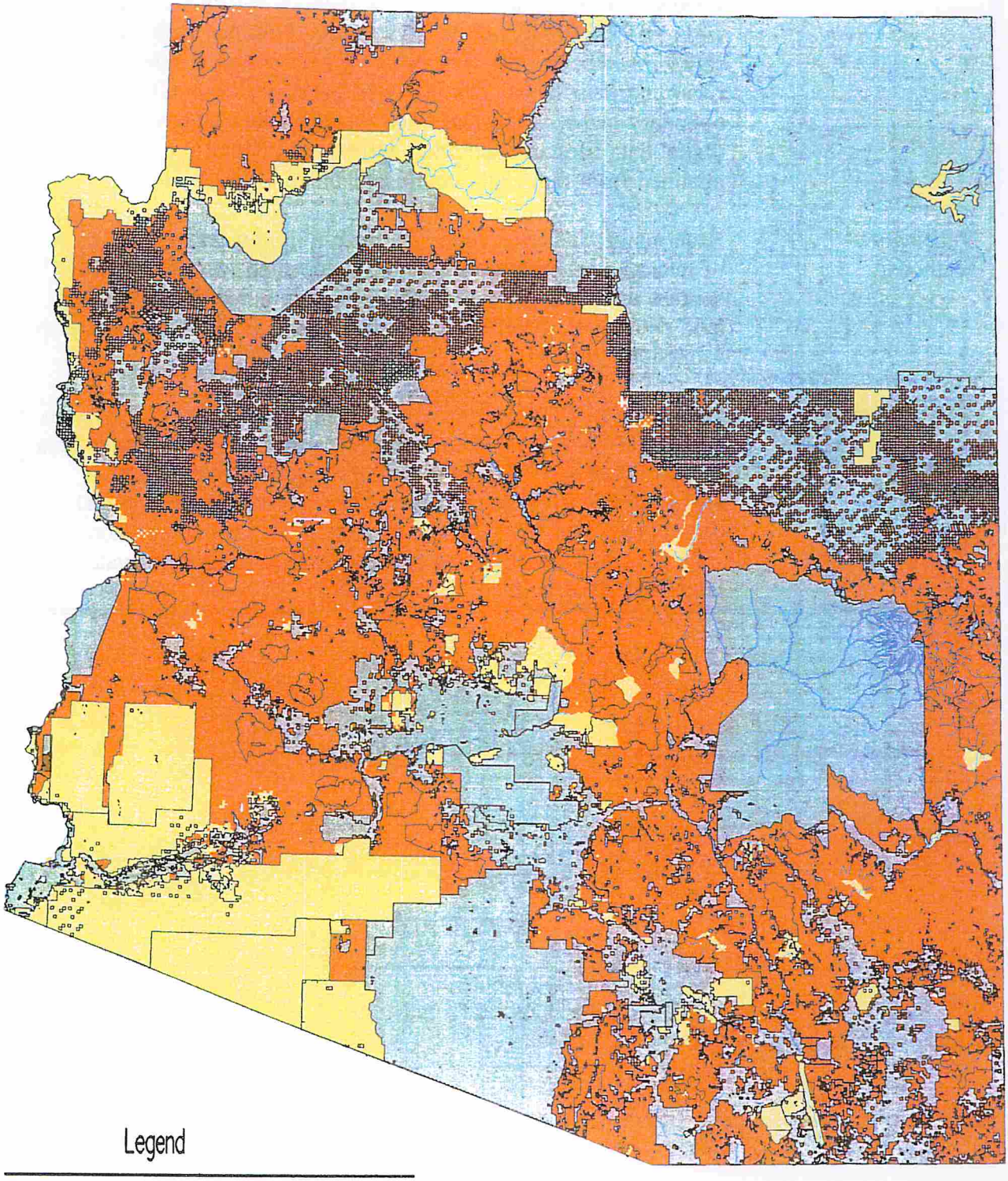
A few small areas along the Gila River were coded to the "no grazing" category because they have historically not been used for grazing. However, according to agency representatives, these areas will be opened to grazing upon request if the proposed activity meets the management objectives of the administering agency. These areas could potentially add 118,208 acres of land to the "commercial grazing" category and remove the same amount from the "no commercial grazing" category.

Listed below are acreages for each category represented on the map and the number of perennial stream miles that intersect lands in each category.

	Acres	Perennial Stream Miles
Commercial grazing	31,021,328	1,729
No commercial grazing	9,051,411	1,082
No data (private and tribal)	33,038,427	2,211

Data Source:	Grazing activities were investigated according to general land management or ownership categories, as discussed under the Land Ownership Map. Primary sources of information came from ASLD, USFS, and BLM. AGFD, National Park Service (NPS), ASPB, and the U.S. Military also provided information regarding their lands. The map was generated from allotment boundary maps, USFS and BLM management plans, ASLD digital data files and additional written and verbal information obtained from range and land-use planners in each agency.
Verification Methods:	Each major land ownership was broken up into areas of management responsibility. Data collected from the above sources were mapped and verified through personal contact with land managers. After verifying with agencies involved, data were refined and updated.
Data Limitations:	Due to the minimum mapping unit, graphic display overestimates ASLD grazed areas in some locations. In other areas, recent land status changes result in an overall under-estimation of ASLD grazed lands. However, grazing statistics are based on actual data as compiled by ASLD as of June 1993. No comprehensive source of geographic data was found for activities on private lands and tribal lands.

Commercial Grazing Activities



Legend

- Commercial Grazing
- No Commercial Grazing Occuring
- No Data (Private and Tribal Lands)
- Perennial Streams

Figure 19.

D. Commercial Wood Harvesting Activities

The map presented in Figure 20 displays areas that are open to timber or fuelwood harvesting on public lands. Again, no comprehensive geographic data exists for activities on private and tribal lands.

The identification of timber and fuelwood harvesting areas was based on the potential for the activity to occur at a given location. That is, any area which may potentially host this activity was classified as a harvesting area. Some areas included in the "open to harvest" category are not currently active but are scheduled for future harvesting.

Much of the area shown as "no harvest" is actually unsuitable for timber harvesting (i.e., desert scrublands). Due to the minimum mapping unit, some of the areas delineated as open to harvesting have small inclusions of unsuitable area. These unsuitable areas are primarily a factor of slope and are fairly minor in extent. Some unreported fuelwood harvesting may be occurring on lands identified as "no harvest" areas.

Timber harvesting occurs primarily on USFS lands. Although, the ASLD has no land specifically closed to timber harvesting, they have only issued permits for timber harvesting on a few tracts of land near Flagstaff. Since there were no additional records of harvesting activities in the ASLD database, all other ASLD lands are shown as "no harvest."

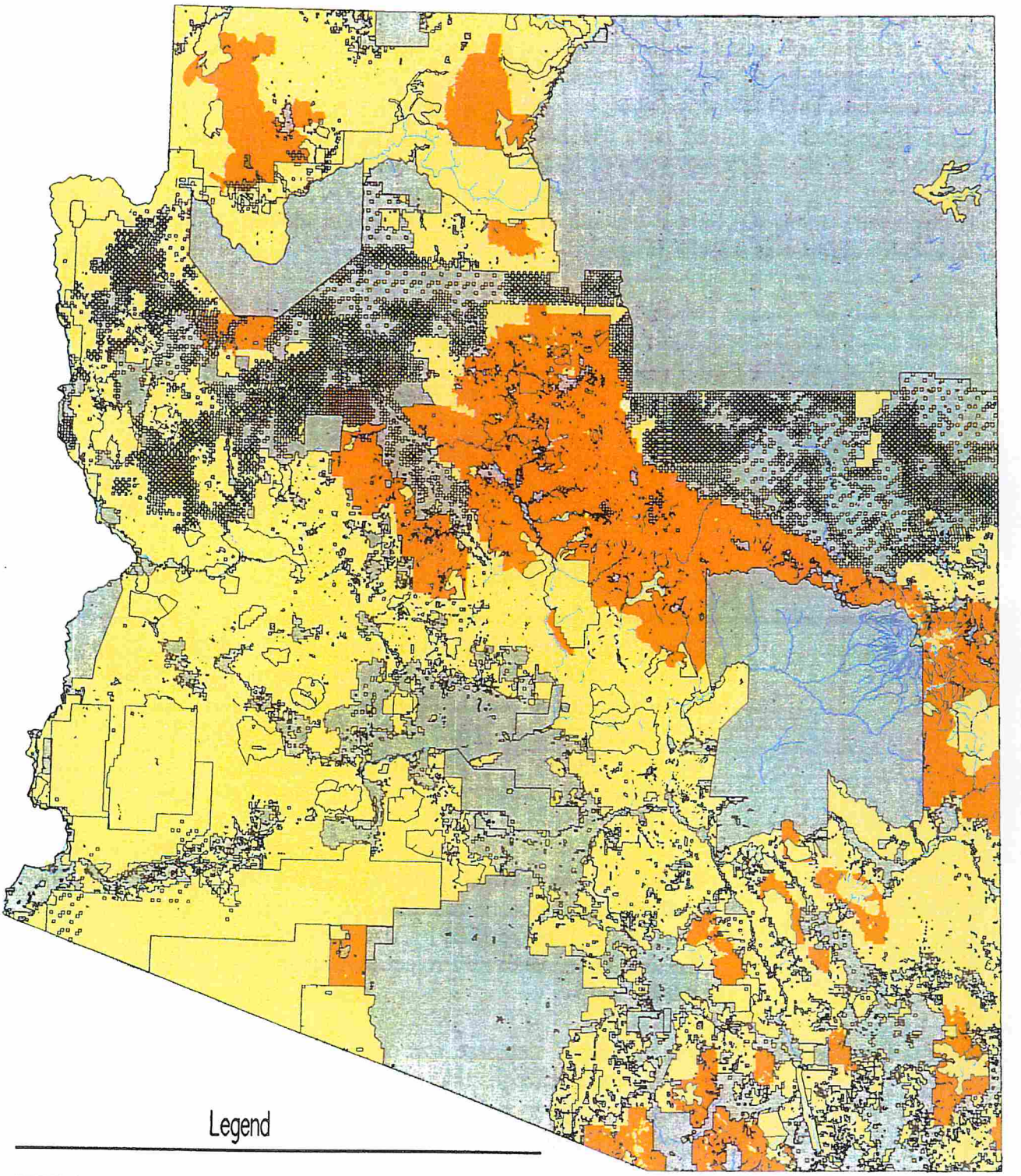
All areas are subject to changes in agency management goals. All areas mapped have restrictions and limitations addressing harvest methods and allowable cut. Refinements such as these are not represented on this map or in an associated database. Riparian areas are not exempt from harvest, but normally riparian corridors are delineated as zones requiring harvest prescriptions different from those of adjacent uplands. Typically, these are more restrictive and harvests are used as "enhancement" of riparian areas. Land management agencies also have the prerogative to cut timber in areas currently closed to timber harvesting for emergency management purposes, such as disease control, and fire management. National forests have detailed forest stand information. Please refer to the agency management plans for more detail.

Listed below are acreages for each category represented on the map and the number of perennial stream miles that intersect lands in each category.

	Acres	Perennial Stream Miles
Open to commercial wood harvesting	8,056,906	901
Commercial wood harvesting not occurring	32,015,477	1,919
No data (private and tribal lands)	33,038,783	2,211

Data Source:	Timber harvesting activities were investigated according to general land management or ownership categories, as discussed under the Land Ownership Map. Primary sources of information came from ASLD, USFS, and BLM. AGFD, NPS, ASPB, and the U.S. Military also provided information regarding their lands. Data was collected using BLM and USFS management plans, timber allotment boundaries, written and verbal information.
Verification Methods:	Each category of land ownership was divided into areas of management responsibility. Data collected from the above sources were mapped and verified through personal contact with land managers. After verifying with agencies involved, data was refined and updated.
Data Limitations:	Due to the minimum mapping unit, some unsuitable lands are included within harvested areas. There is no representation of activities on private and tribal lands.

Commercial Wood Harvesting Activities



Legend

- Lands Open to Commercial Wood Harvesting
- Commercial Wood Harvesting Not Occurring
- No Data (Private and Tribal Lands)
- Perennial Streams

Figure 20.

E. Urban, Industrial and Agricultural Lands

The map presented in Figure 21 displays urban, industrial, agricultural and mixed land uses. The mixed land use category is applied to areas where a combination of the other three land uses occur in such close proximity that individual uses are difficult to distinguish. The urban lands category represents all populated areas in the state as identified by 1990 census data. This includes cities, small towns, villages, etc., and represents 2,728,273 acres. Urban areas overlap areas represented as mixed land use because the data sets are contained in two separate databases. Of the 1,099,185 acres of mixed land use, 648,722 acres overlap with urban areas on the map. Where there is no overlap between urban and mixed categories, the mixed category is displayed. Industrial, mixed use and agricultural lands were identified and delineated from false color composite satellite imagery.

Listed below are acreage for each category represented on the map and the number of perennial stream miles that intersect lands in each category.

	Acres	Perennial Stream Miles
Urban	2,728,273	297
Agricultural	1,568,855	63
Mixed Use	1,099,185	88
Industrial	118,593	9

Data Source:	Urban lands were compiled from the ASLD (ALRIS) "Azplaces" database. This database consists of census designated place boundaries for the state. The data were extracted from 1990 U.S. Census Bureau Tiger files. All other categories were derived from the UA-ART "AzGap" database. This database was generated using false color composite satellite imagery from 1991 and 1992.
Verification Method:	"Azplaces" was verified at the ASLD (ALRIS) through normal quality control procedures following the creation of the database. "AzGap" will be verified by UA-ART upon completion of the Arizona GAP Analysis Project (expected completion date, June 1994).
Data Limitations:	The "Azplace" database was created from 1990 data, so it does not represent changes that may have occurred since then. The "Azgap" database has a similar limitation in that it was created from 1991-1992 satellite imagery. Satellite imagery resolution is 31.4 yds. x 31.4 yds., thus limiting the accuracy of data at smaller resolutions.

Urban, Industrial, and Agricultural Lands

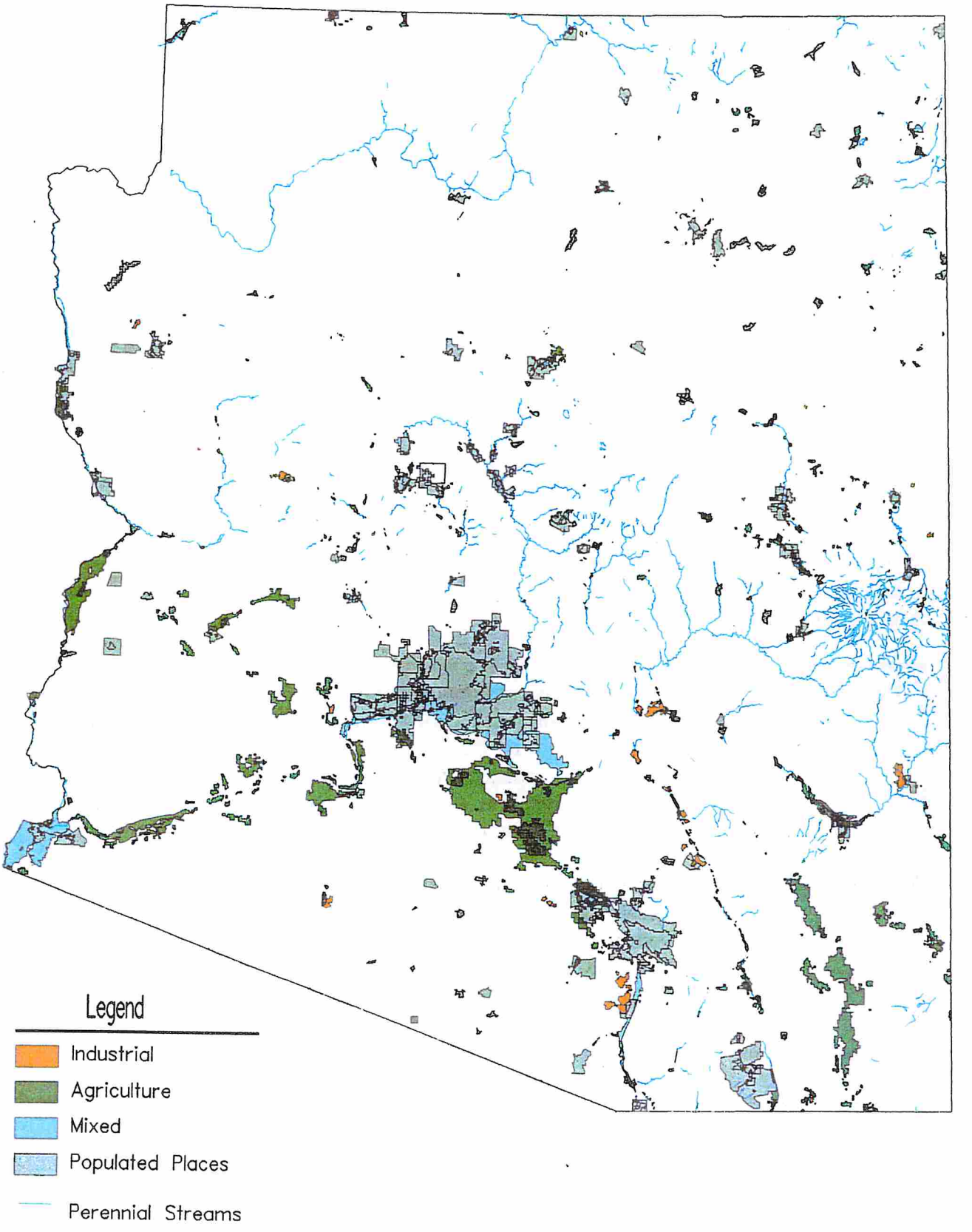


Figure 21.

F. Public Recreation

Recreational activities, such as hiking, birdwatching, hunting, fishing, camping, ATV riding, and horseback riding, tend to be dispersed over broad geographic areas. Because they are not associated with specific locations, they do not adapt well to mapping. In addition, there is no comprehensive source of locational data on this topic, especially activities occurring on private lands.

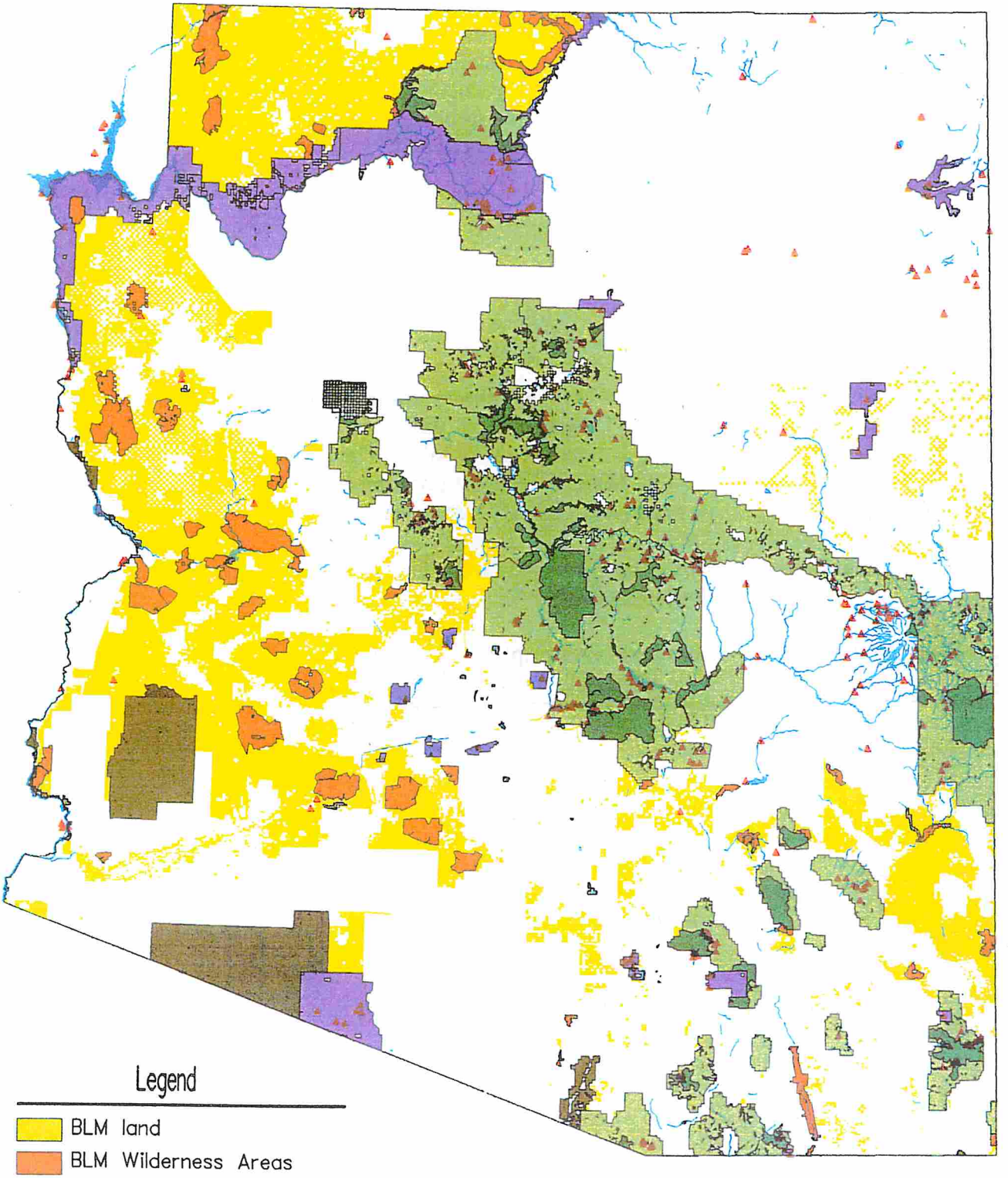
Therefore, the map presented in Figure 22 represents recreational areas in the state that the general public can access and that can be geographically referenced. These include developed campgrounds and picnic sites on public and tribal lands, state and municipal parks, wildlife refuges, wilderness areas, national parks, national forests and BLM lands. Recreational lakes are also shown.

Lands under the management of ASLD are available for various land use activities but are accessible by permit only. State lands are not openly accessible for recreational activities so they are not represented on this map. However, we acknowledge that these lands are regularly used for hunting and fishing. Properly licensed hunters and anglers lawfully taking wildlife on state lands are considered permittees.

The information is presented on the map in two ways. First, developed recreation sites, such as public campgrounds and picnic areas, are indicated by point locations. A point location does not show the actual physical boundaries of an area and is simply indicated by a single point. A total of 352 point locations of recreational sites are represented on the map. All other categories (parks, refuges, wilderness areas, national forests, and lakes) are represented by actual geographic boundaries.

Data Source:	National parks, monuments, historical sites, and state parks were extracted from the ALRIS "Land" database. State parks not represented in the "Land" database were digitized from ASPB maps into a separate database by AGFD staff. Point locations were digitized from the 1992 Western Geographic "Topographical Recreational Map of Arizona."
Verification Method:	State parks missing from the ALRIS "Land" database were located and verified with the assistance of ASPB staff. Point locations of recreational sites were verified against USFS 1:62,500 scale maps and USGS 7.5 minute quadrangle maps to insure locational accuracy by AGFD staff.
Data Limitations:	This map represents only a portion of the locations where recreational activity occurs in the state.

Public Recreation



Legend

- BLM land
- BLM Wilderness Areas
- Federal Refuge Wilderness
- National Forest
- National Forest Wilderness
- National Parks, Monuments, Historic Sites, & Wilderness
- State & Municipal Parks
- Lakes
- Campsite Locations
- Perennial Streams

Figure 22.

G. Current and Historical Mining Locations

Figure 23 displays current and historical mining sites in Arizona. These sites represent locations of mines, prospects, quarries, processing mills and plants. As of August 1993, 10,341 mining sites were recorded in Arizona. Current and historical status have not been differentiated on this map because the accuracy of this information was found to be variable in the source data. The accompanying database contains the following information for each location: primary mine name; mineral extracted; and status of the mine (producer, past producer, current producer).

Data Source:	"AzMILS" database from the Arizona Department of Mines and Mineral Resources (ADMMR). The database acronym stands for Arizona Mineral Industry Location System. The database file was converted from Dbase to an Arc/Info format at AGFD.
Verification Method:	This database is updated and verified by the ADMMR on a continuous basis.
Data Limitations:	Accuracy of descriptive data may vary and should be verified with ADMMR.

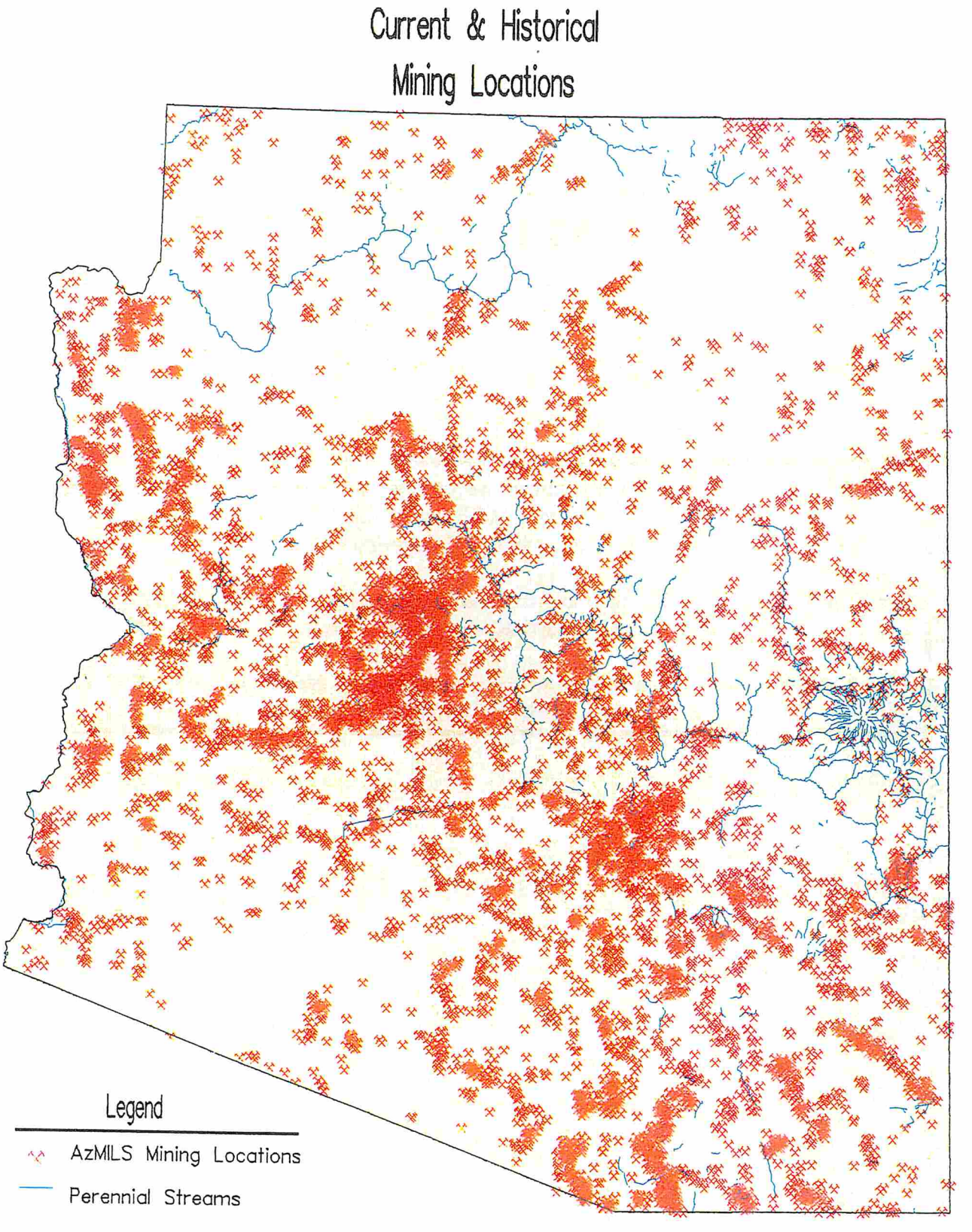

Current & Historical
Mining Locations
Legend
AzMILS Mining Locations
Perennial Streams

Figure 23.

H. Active Mining Locations

The map presented in Figure 24 displays point locations for all metal and nonmetal mines and processing plants that were active in Arizona as of November 1992. A total of 103 mining locations is recorded on the map. Active mine data were compiled from current records by the ADMMR. The ADMMR database lists the primary name used for the mine and the owner. The "Directory of Active Mines in Arizona," a publication prepared by ADMMR, contains detailed information on these mines such as the type of minerals extracted, amount extracted, and the type of mining process used at the site.

Data Source:	ADMMR, current records in the "Directory of Active Mines in Arizona 1993." AGFD staff digitized the data from a 1:1,000,000 scale hard copy map.
Verification Method:	The map and database were verified by the ADMMR. The database is updated on an annual basis.
Data Limitations:	A new map will be available after November 1993 at which time this map will be out of date.

Active Mining Locations

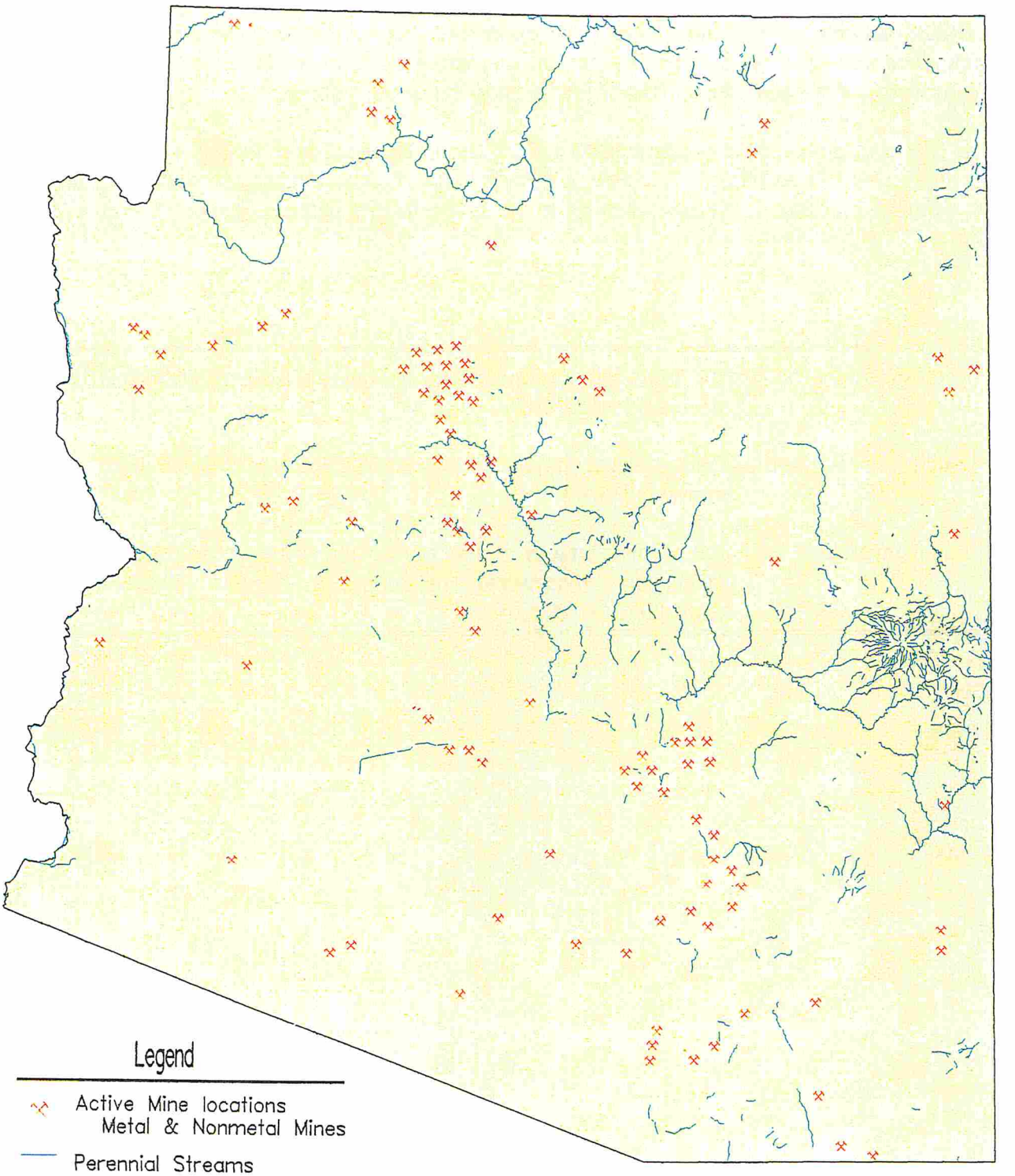


Figure 24.

I. Sand and Gravel Mine Locations

The map presented in Figure 25 is a subset of mine locations from the AzMILS at ADMMR. The mine locations shown on this map represent all mines coded as sand and gravel in the AzMILS database as of August 1993. A total of 582 mining locations are represented on the map. The map does not differentiate current and historical status of the sites depicted because the accuracy of this data was found to be variable in the data source.

The sand and gravel mining locations shown are not to be considered inclusive of all locations for this activity in the state. In 1994, ADMMR plans to have a database of active sand and gravel mine locations in Arizona, similar to the Active Mines database shown in Figure 24.

Data Source:	Sand and gravel mining sites were extracted from the "AzMILS" database at ADMMR.
Verification Method:	This database is updated and verified by the ADMMR on a continuous basis.
Data Limitations:	Due to inaccuracies in the "status" field, current and historical sites cannot be accurately differentiated. The map represents data as of August 1993.

Sand & Gravel Mine Locations

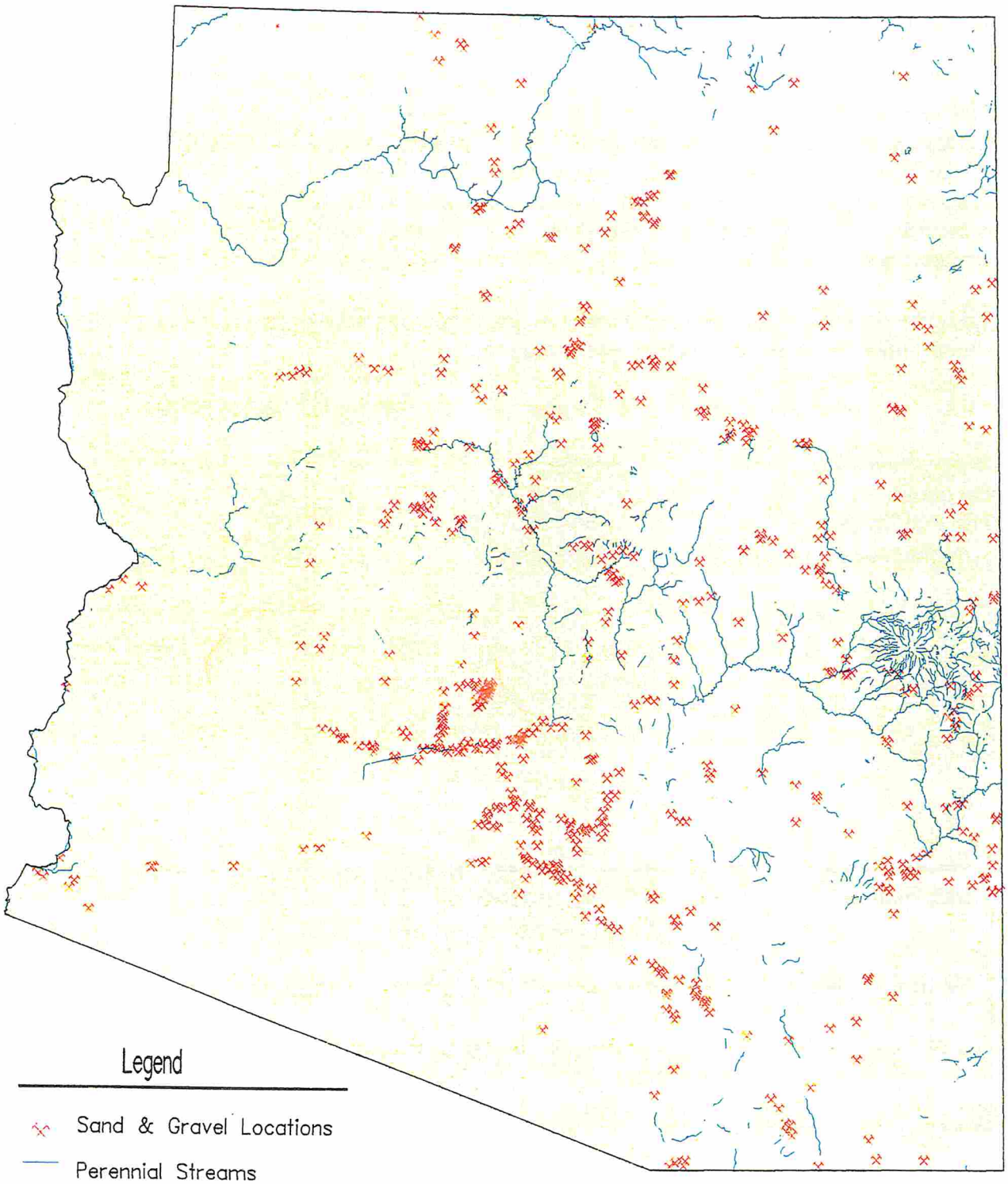


Figure 25.

J. Mineral Potential

The map presented in Figure 26 identifies potential areas for mineral discovery and development for both metallic and nonmetallic resources across the state. This data indicate areas favorable for future discovery and development of mineral deposits for land use planning considerations.

The determination of "highly favorable" or "favorable" status for the discovery of mineral deposits is based on data from past production of mineral districts, ADMMR file data, polling of the mineral exploration industry and compilation of exploration targets. Past production represents additional areas of past metallic mineral production. Low potential areas are estimated to have relatively less potential for metallic-nonmetallic mineral deposits based on available data as of October 1984.

Listed below are acreage for each category represented on the map and the number of perennial stream miles that intersect lands in each category.

	Acres	Perennial Stream Miles
Highly Favorable	2,625,757	173
Favorable	14,775,563	868
Past Production	445,777	9
Low Potential	55,086,045	3,972

Data Source:	The data were compiled by ADMMR in 1984 and digitized from a 1:500,000 scale blueprint by AGFD staff.
Verification Method:	The map was verified in 1984 by the ADMMR.
Data Limitations:	The database does not include areas for potential uranium development.

Mineral Potential

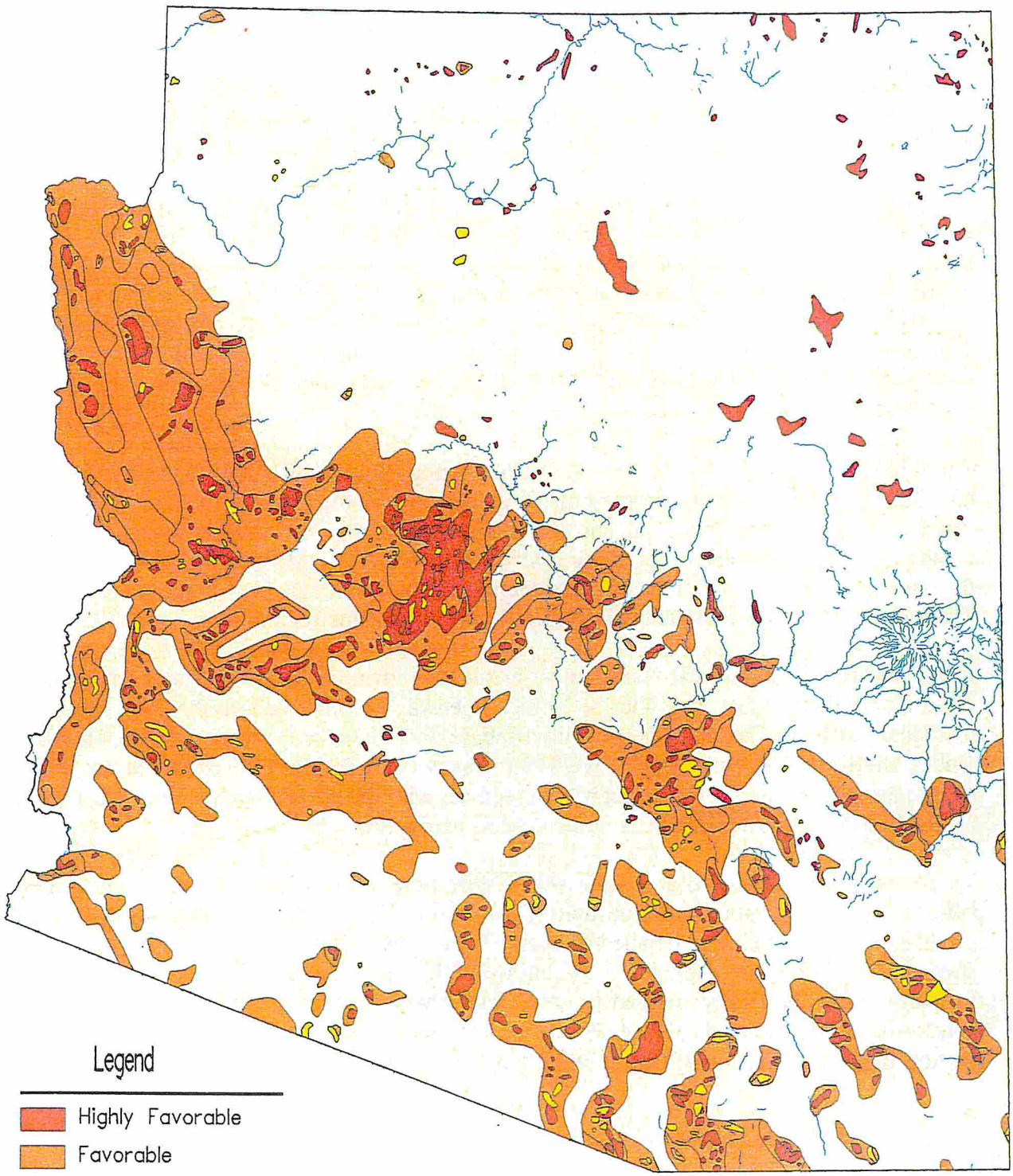


Figure 26.

K. Examples of Map Applications

The purpose of compiling land ownership and land use data was to identify activities occurring in and adjacent to riparian areas across the state. Several examples are presented in this section to illustrate the application of these data to evaluate land use influences on a riparian area (Figures 27 and 28). A portion of the Verde River was selected and the various GIS land use and land ownership maps were overlaid on the riparian vegetation map. This section of the Verde River was chosen because all the mapped land use activities occur to some extent within this region and could, therefore, be illustrated.

The first map (Figure 27a) shows riparian vegetation and land ownership along the Verde River from Clarkdale to Camp Verde. Private lands predominate along the river except for some State Parks lands and minor amounts of USFS lands. In the second map (Figure 27b), urban, industrial, agricultural and mixed land use patterns are identified within the corridor. Most of this area is identified as mixed land use because of the patchwork of residential/industrial development and agricultural fields. The majority of the agricultural fields in this region are included in the mixed land use area. Two of the five agricultural fields shown are within the State Park boundaries.

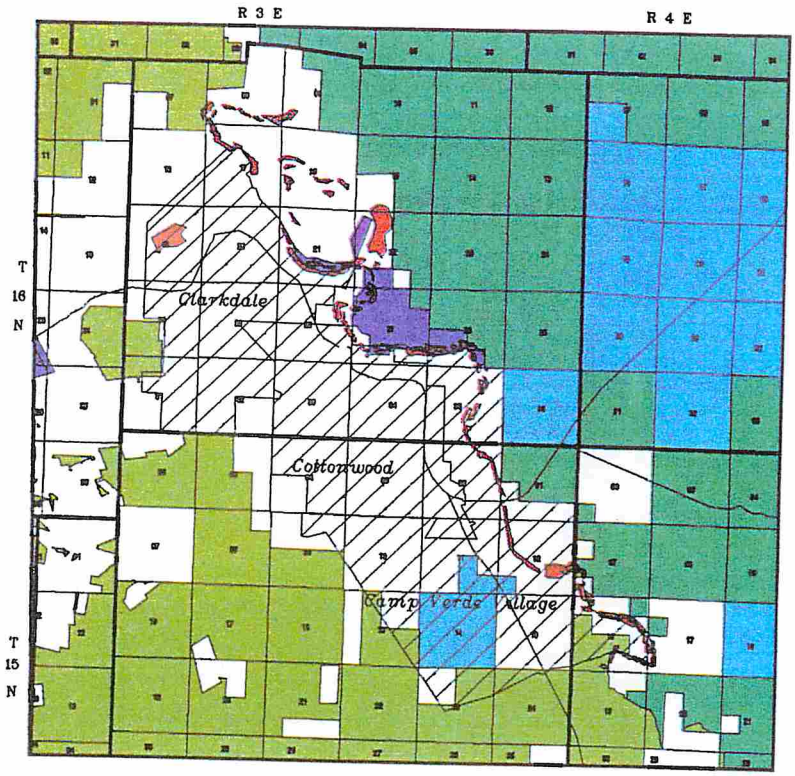
The first map in Figure 28a is a compilation of grazing, timber and mining activities in the same corridor. Mine locations are represented by point data and are not delineated by geographic extent. However, the industrial and mine tailings category on the previous page indicates geographic extent of some of the mining activities in the area. Most of the wood harvesting in this area is for fuelwood cutting, because the vegetation is not suitable for commercial logging. The lack of data for private lands is especially notable in this region.

Parks, recreation and special management areas are shown on the second map in Figure 28b. Dead Horse Ranch State Park and the Verde Greenway are indicated on the map. Some small municipal parks are not included in this database and, therefore, are not shown on the map. Under wildlife management areas, we added Tavasci Marsh, portions of which are currently being managed by the AGFD through an agreement with the private landowner. We also added a Research Natural Area which is under special management by the USFS.

These maps were produced at a scale which shows the various land uses and land ownership patterns affecting a rather large portion of the Verde River. Maps of finer resolution can be produced to conduct a more detailed evaluation of an area. However, when working with these statewide databases, data limitations as outlined in this section must be taken into consideration. In many cases, the databases used to create these maps are constantly being updated. When conducting a regional or local level evaluation, one should refer to the data sources listed in this section to get the most up-to-date information.

Examples of Riparian Vegetation with Land Use Overlays along a portion of the Verde River

Land Ownership & Population Centers

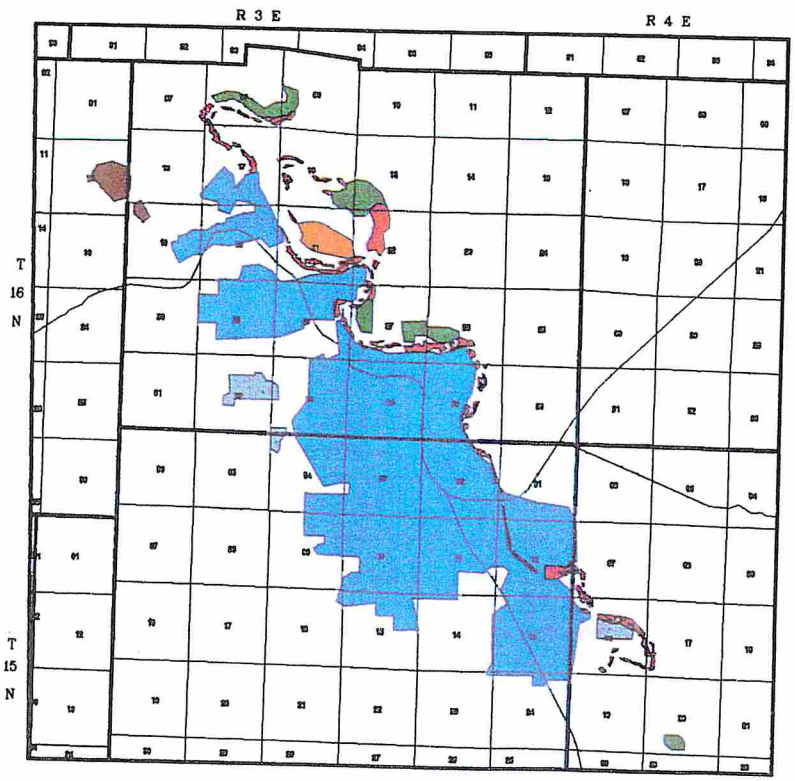


Legend

- Private Lands
- State Trust
- Prescott National Forest
- Coconino National Forest
- Tuzigoot National Monument
- State Parks
- Yavapai Indian Reservation
- Riparian Vegetation
- Urban Development
- Roads

Figure 27a.

Urban, Industrial, & Agricultural Lands



Legend

- Agriculture
- Urban Development
- Industrial
- Mine Tailings
- Mixed Land Use
- Riparian Vegetation
- Roads

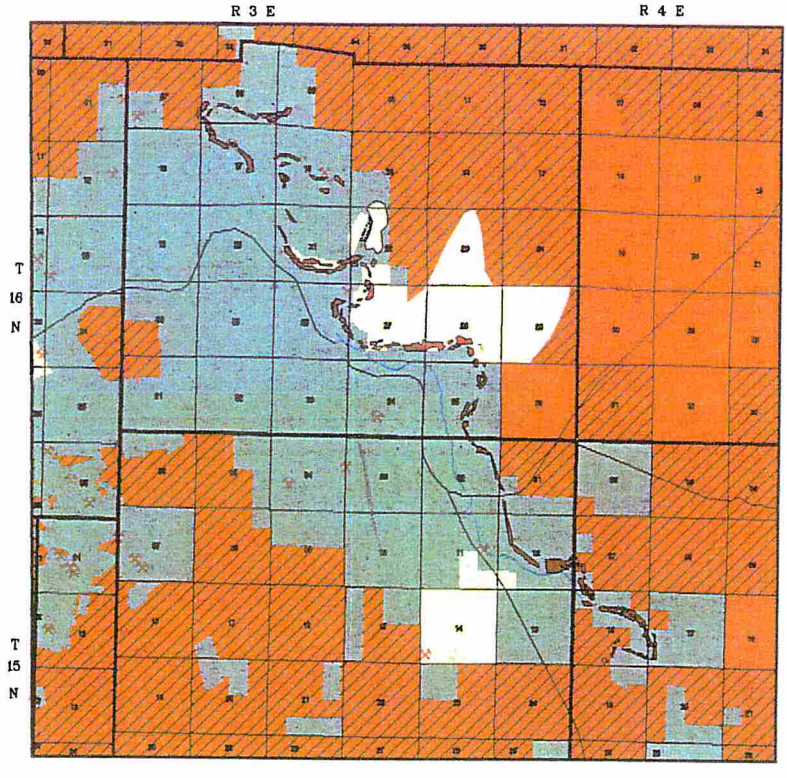
N

Vegetation data generated at UofA ART Lab.

Figure 27b.

Examples of Riparian Vegetation with Land Use Overlays along a portion of the Verde River

Grazing, Timber, & Mining Activities

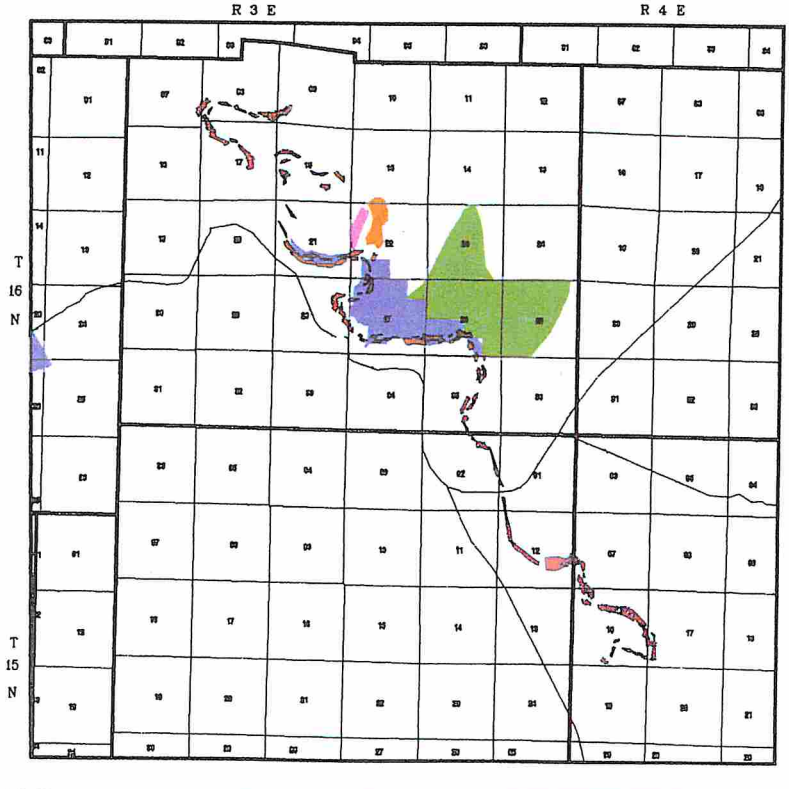


Legend

- Grazing
- No Grazing
- No Data–Private & Tribal Lands
- Lands Open to Wood Harvesting
- Riparian Vegetation
- Roads
- Diversion Ditch
- Current & Historic Mines

Figure 28a.

Parks, Recreation & Special Management Areas



Legend

- Wildlife Management Areas
- State Parks
- Tuzigoot National Monument
- USFS Research Natural Area
- Riparian Vegetation
- Roads

N

Figure 28b.

Vegetation data generated at UofA ART Lab.

Section IV

Riparian Areas and Wildlife Habitats

A. The Riparian Ecosystem

Although riparian areas cover only a small percentage of the landscape, they are among the most biologically productive of all lands. A basic knowledge of riparian ecosystems and the functions that occur within these systems is essential to understanding their biological importance.

An ecosystem can be defined as a discrete geographic unit of the landscape consisting of various biotic and abiotic components which are related through interchanges of chemical nutrients and energy (Collier et al. 1973, Bailey 1982). More simply, an ecosystem consists of a community of organisms together with its physical habitat. The boundaries of ecosystems are open and permeable to allow for the transfer of energy and materials to or from other ecosystems.

Riparian areas are found at the interface between terrestrial (upland) and aquatic ecosystems and, therefore, interact with both. Because of their transitional location within the landscape, riparian areas are especially complex. This transitional zone, or ecotone, is influenced by changes in upland activities as well as by changes occurring in the stream channel, lake or marsh bed. The biotic and abiotic components of the riparian system are inextricably linked to groundwater, surface water and hydrologic processes in the aquatic environment and to changes in vegetative cover, rates of erosion and surface water run-off in upland ecosystems.

Riparian systems can also be viewed as being connected linearly, forming corridors along the network of water courses within a watershed. These water courses provide a means of transferring energy, nutrients, genetic material and abiotic components along the system. The associated riparian area provides natural travel corridors for wildlife movement and a linear patchwork of wildlife habitats that, in desert areas, is dramatically different than the adjacent upland vegetation (Figure 29). These travel ways keep areas from becoming reproductively isolated.

The linear connectedness and the ecotonal nature of riparian areas illustrate the principle that changes in one part of the system may directly influence other parts of the system. In other words, a stand of riparian vegetation is influenced by surface and ground water, flood events, nutrient availability, the actions of invertebrates and wildlife, adjacent land uses and numerous other components. Because one aspect cannot and should not be viewed in isolation of other components, riparian areas should be examined within the context of the entire watershed.

Riparian areas are intimately tied to the watercourse along which they are located. As dynamic features of the landscape, they are constantly adjusting in response to geologic and hydrologic forces (Brown et al. 1978). Disturbances of both upland and fluvial origin, such as flood and

Figure 29. Cienega Creek in Pima County, Arizona supports a corridor of riparian vegetation that winds through semi-desert grasslands.

debris flows, affect riparian areas. Some of the hydrologic forces influencing riparian ecosystems are:

1) periodicity and duration of flow (surface and groundwater),
2) depth and fluctuation of the water table,
3) interaction of regional and local groundwater flow systems,
4) rate of surface flow,
5) chemical composition of inflows (both surface and groundwater) and
6) temperature of the water and surrounding environment (Cooper et al. 1990).

Geologic influences include:

1) depth of valley alluvium and degree of channel cutting,
2) width of valley floor,
3) valley and stream channel gradients,
4) channel sediments and floodplain soils and
5) interaction of regional water table with local aquifers and the topographic surface (Cooper et al. 1990).

Geomorphic events include debris flows, sediment transport, scouring, sediment deposition, channel migration and erosion.

Understanding disturbance is critical to understanding riparian ecosystems primarily because ecologically diverse areas are maintained by these natural disturbances (Naiman 1992). Because the biotic community found in riparian ecosystems has had to adapt to constantly changing conditions, a high degree of ecological diversity results (Kalliola et al. 1992). The high degree of diversity in riparian areas is particularly evident in the vegetative communities found there. Numerous studies of vascular plants in riparian areas show unusually high levels of biodiversity (Nilsson 1986, Salo et al. 1986, Kalliola and Puhakka 1988, Nilsson et al. 1989, Raedeke 1989, Tabacchi et al. 1990, Gregory et al. 1991, Kalliola et al. 1992, Nilsson 1992, Decamps and Tabacchi 1993, Naiman et al. 1993, Stromberg 1993a). One explanation for this apparent diversity is that riparian vegetation occupies one of the most dynamic areas of the landscape. Distribution and composition of riparian vegetative communities reflect:

1) the intensity and frequency of floods;
2) variations in climate as streams flow from high to low altitudes or across biomes;
3) disturbances imposed on the riparian corridor by upland environments (debris flows, erosion), and;
4) small-scale variations in topography and soils as a result of lateral migration of river channels (Naiman et al. 1993).

Collectively, these forces create a mosaic of plant communities and provide a variety of habitats in which a diversity of species are able to co-exist. Plant species richness and diversity tend to greatly influence terrestrial and aquatic wildlife.

Factors influencing the composition, size and function of riparian areas are also found to change with elevation. The Brown, Lowe and Pase (1979) classification system described in Section I, can be used to classify riparian plant communities according to where they are located on a valley longitudinal profile. For instance, in the upper reaches of a valley, channel gradients tend to be steep and stream energy is high. Very little sediment deposition occurs so floodplains and riparian ecosystem development is minimal, usually occurring in narrow bands along the stream corridor. The vegetation is dominated by scrub willows with conifers and aspen invading from the adjacent uplands (Neff et al. 1979). At high elevations where valley gradients level off, wet meadows are often formed. Some of these wet meadows are spring-fed and occur at the base of mountains. They tend to be too wet for major tree encroachment and are dominated by a mix of grasses, sedges and an assortment of forbs (Subirge no date).

The mid-portion of the stream is characterized by the development of a narrow but distinct floodplain. Within this zone, the floodplain tends to constantly adjust to changes in channel aggradation and degradation processes (Cooper et al. 1990). These areas may be vegetated by either mixed broadleaf deciduous communities or cottonwood-willow communities (Neff et al. 1979). Cave Creek and Turkey Creek in the Chiricahua Mountains are examples of this zone.

At lower elevations, the stream gradient levels out and sediment depositional processes dominate. It is within this area where the floodplain reaches its maximum development. Large streams or rivers that occur lower in the watershed are characterized by larger and more diverse vegetative

communities that develop in response to wide, geomorphically complex floodplains. These broad floodplains are formed by hydrologic and geomorphic processes that result in seasonal flooding, lateral channel migration, sediment deposition or aggradation, and formation of backwaters and marshes (Naiman 1992). They tend to be dominated by cottonwood-willow communities and mesquite bosques. In disturbed systems, cottonwood-willow may be replaced by salt cedar. In Arizona, the San Pedro River and the lower Verde River provide excellent examples of this type of riparian corridor.

We begin to see, then, that ecological linkages between the terrestrial and aquatic ecosystems occurring in riparian areas take place within the context of the fluvial and geomorphic processes that occur there. Modification of landforms by the actions of these processes may occur slowly over long periods of time or may occur as large-scale, episodic events. Their spatial scale may range from a localized shift in a stream channel to a basin-wide flood event. The result of these events is the mosaic of landforms that characterize riparian areas such as stream channels, floodplains, channel bars, terraces and alluvial fans. In fact, the shape and area of each of these features is directly influenced by its location within the drainage network, the amount of streamflow and local geology and geomorphology (E. Swanson et al. 1988).

Component processes of riparian ecosystems take on a pattern of interdependency with geomorphic and hydrologic factors influencing development of riparian vegetation, and riparian vegetation influencing the animal community, hydrologic and geomorphic factors. The following statements illustrate these relationships. Disturbances and processes within the ecosystem determine the spatial pattern and successional development of riparian vegetation. In the presence of sufficient water, riparian area development increases as the width and depth of valley alluvium increases (Cooper et al. 1990). Valley floor landforms and associated riparian vegetation form an array of physical habitats within the active channels and floodplains. The streamside plant communities that occupy these habitats determine the abundance and quality of nutritional resources for aquatic ecosystems (Gregory et al. 1991). Riparian vegetation, in turn, influences the evolution of geomorphic surfaces. Networks of roots from grasses and woody vegetation that cover the banks of streams and lakes increase resistance to erosion. Aboveground stems of streamside vegetation increase channel roughness during overbank flow and may decrease the erosive action of floods and actually cause deposition of sediment. This interrelatedness between riparian vegetative communities, and fluvial and geomorphic processes characterizes the riparian ecosystem. The complexity of relationships that exists between riparian areas and adjacent streams and uplands makes it mandatory that any assessment of riparian areas be based on an ecosystem approach, evaluating the total functional condition of the system as opposed to a singular component.

The ADWR report mandated by this legislation (ADWR 1993) addresses the relationships between riparian vegetation and hydrology including the effects of changes in water availability and streamflow on riparian vegetation. It is our intent to present information in this section that supports the ADWR report, but that focuses more heavily on relationships between riparian areas and wildlife.

B. Functions and Values of Riparian Areas

Factors that affect landform, and vegetative and wildlife diversity consequently influence the diversity of functions occurring within a riparian area (Naiman et al. 1993). These factors are the key to functional assessment of riparian areas. The term "functions" refers to biological, chemical, or physical processes that occur in riparian areas and wetlands as a result of the geomorphic, topographic, physiographic and hydrologic position in the landscape (Jakle 1991). Functions are part of the self-sustaining properties of the ecosystem. They operate within a riparian area whether or not they are viewed as important to society (Adamus et al. 1991). Some functions may also have a corresponding societal value. However, "value" denotes the social significance of an attribute. This dichotomy is the origin of the commonly used phrase "functions and values."

Some examples of riparian values include importance to wildlife, recreation, scenic and aesthetic qualities, water quality, commercial/agricultural activity, waterborne commerce and urban development. Because values are determined by society, this factor is subject to change over time as societal views of resource values change. Therefore, it is important to separate out the evaluation of function and the determination of value. Functional assessment should be firmly grounded in the natural and physical sciences. Indicators of value should be developed by the appropriate discipline (i.e., economic indicators are quite different from biological indicators.).

Some functions of riparian areas are very well understood while others may be virtually unknown. Much of the discussion about functions of riparian areas has been inferred from research on wetlands or more mesic riparian ecosystems. The Wetland Evaluation Technique (WET) developed by the U.S. Army Corps of Engineers (COE) is an example (Adamus et al. 1991). The technique is a rapid approach to wetland evaluation based on information about correlative predictors of wetland functions. Predictors, or indicators, are based on extensive review of wetlands research. Because this technique was created for nationwide application, it did not take into account regional variations in wetlands and riparian areas.

Riparian areas in the arid and semi-arid Southwest sometimes "behave" differently than riparian areas in the eastern, midwestern and coastal areas. In actuality, these "behavioral differences" are the result of the system's response to a unique set of climatic, ecologic, hydrologic and geomorphic factors influencing the ecosystem. Consequently, scientists and land managers have had to exercise caution in applying studies conducted on wetlands or riparian areas that developed under one set of conditions to areas that developed under a different set of conditions.

One of the most complete evaluations of existing data on riparian functions in western ecosystems was conducted by Cooper et al. (1990) for the U.S. Environmental Protection Agency (EPA). The study first assessed the extent of scientific literature that exists on the subject of riparian area functions in the Intermountain West. This exercise was followed by a discussion of the functions and values associated with wetlands, as listed in WET (Adamus et al. 1991) and an evaluation of their applicability to western riparian areas. In addition, the study discusses whether there are sufficient scientific data to suggest that riparian areas perform a

particular function and how to evaluate that function.

Cooper et al. (1990) attributed the following broad classes of functions to riparian areas:

1) sediment stabilization;
2) water quality functions;
3) production export;
4) flood flow alteration;
5) groundwater recharge/discharge, and;
6) terrestrial wildlife and aquatic diversity/abundance.

Both Cooper et al. (1990) and Adamus et al. (1991) provide detailed discussions regarding these functions. For purposes of this report, a brief description of each function is presented below. This is by no means a comprehensive summary of riparian and wetland functions. For additional discussions on riparian and wetland functions and values, the reader is encouraged to review Brown and Lowe (1978), Jahn (1978), Knight and Bortorff (1984), Soil Conservation Service (1987), DeBano and Schmidt (1989), Chaney et al. (1990), Williams (1990), Brinson (1992), Pitt (1992), and Finch and Ruggiero (1993).

1. Sediment Stabilization

Sediment stabilization includes consideration of two processes. The first is the removal of sediment from the water column and the second is the prevention of sediment from entering the water column. Sediment removal is accomplished through bed load or suspended sediment deposition within the channel or through overbank flooding. The type and density of riparian vegetation, both on the bank and in the channel, increases channel roughness which decreases the velocity of water, slowing erosion and enhancing deposition of sediments. Other factors affecting channel roughness are bed material, channel geometry, obstructions and degree of meandering.

Sediment contributions to a stream are typically from bank erosion and surface runoff. Riparian areas may modify water quality impacts from other stream reaches or upland areas by assisting the processes of sediment deposition, removal and filtration. Riparian vegetation plays an important role in preventing sediment deposition into the stream channel by stabilizing stream banks and stream beds. Trees and shrubs are excellent protectors of bank soil because their roots penetrate deeply and often provide a physical barrier between the stream and soil. Rushes, sedges and reed grass are especially effective in stabilizing submerged soil while reducing the erosive impact of waves and stream current (Seibert 1968).

Buffer strips of riparian vegetation serve to trap sediments from upland erosion reducing the amount that enters the stream. The width necessary for effective filtering (buffer zone) depends on characteristics of both the erosional area and the buffer area. In the riparian area, type and distribution of ground cover, slope and resistance of the buffer zone to deterioration are factors important to buffer zone effectiveness.

2. Water Quality Functions

Water quality functions include retention and removal of sediments and toxins as well as retention and transformation (cycling) of nutrients. Some wetlands and riparian areas accomplish these functions on either a net annual basis or during the growing season by:

1) physically or chemically trapping and retaining inorganic sediments;
2) physically or chemically trapping and retaining chemical substances generally toxic to aquatic life;
3) retaining or transforming inorganic phosphorus into an organic form;
4) retaining or transforming nitrogen into an organic form or transforming (removing) nitrogen into a gaseous form (Cooper et al. 1990).

Removal of metals from the water column requires processes such as ion exchange and adsorption to sediments and dissolved organic matter, precipitation as oxides, pH changes, and plant and microbial uptake (Cooper and Emerick 1987, Cooper et al. 1990).

Large quantities of nitrogen in the water column can result in degraded water quality through promotion of algal blooms and enhancement of populations of undesirable species (Sather and Smith 1984). The primary mechanism for removal is nitrification or denitrification by bacteria. Nitrogen compounds are effectively removed by saturated, low gradient wetlands where nutrients come into contact with reduced, fine-textured or organic soils (Cooper et al. 1990). It is not known whether well-drained, sandy alluvial soils along streams and rivers support this function. However, according to Skinner et al. (1984), soils near stream edges, even along high gradient streams, are usually wetter, with more abundant organic matter and little dissolved oxygen, and may be important sites for the regulation of nutrient inputs into surface waters. Thus, while the main portions of riparian forests and floodplains do not perform nitrogen removal functions, smaller portions of these ecosystems may.

3. Production Export

Production export pertains to the flushing of organic plant material from wetland and riparian lands into streams. The plant material is a food source for aquatic organisms. According to Cooper et al. (1990), very few studies address key questions on the value of riparian vegetation for food chain support. Research points to the importance of debris dams and other retention devices such as boulders, branches and roots in retaining litter in the streams where it can be processed to support large populations of aquatic insects. Beavers can also play an important role in retaining sediment and organic matter, thereby reducing the amount of nutrients going downstream.

4. Flood Flow Alteration

Flood flow alteration refers to the storage of water on or in the floodplain and or alteration of its velocity. The primary result of flood flow alteration is a reduction in downstream flood

peaks and decreased frequency of downstream overbank flooding. This process can also result in an improvement in water quality as sediments are deposited outside the stream channel where they can be stabilized. Cooper et al. (1990) state that there are only a few reports on observed effects of riparian lands on flood flows. However, they present a number of methods to calculate flood flows at gaged and ungaged sites using various models and techniques. Characteristics or measurements used to calculate or estimate flood flows include stream type, source of flood (e.g., snowmelt, thunderstorm, etc.), drainage area, mean basin elevation, average annual precipitation, basin slope, bankfull width and land use.

5. Groundwater Discharge/Recharge

Groundwater discharge occurs when there is a net movement of groundwater to the surface. Groundwater will discharge into a riparian area when the regional or local water table is higher than the surrounding water table (Cooper et al. 1990). When this discharge occurs in a riparian area or wetland, the alluvial soils have the ability to store the water. It is then slowly released to surface systems (streams or marshes) at low water periods. The overall effect on low flows will depend on the amount of surface storage area available in the soils or alluvium.

Groundwater recharge is the net movement of surface water into groundwater. The groundwater may be at a considerable depth, such as a regional aquifer. In the arid and semi-arid Southwest, recharge to the alluvium tends to occur during high flow events. In mountainous areas, snowmelt is an important factor in providing a large and consistent supply of water for streamflow and recharge into alluvial aquifers.

6. Terrestrial Wildlife and Aquatic Habitat

Distinctions between wildlife functions and wildlife values are often clouded by incorrect use of terms in the literature. Wildlife may perform or support certain processes within the context of the ecosystem. This is a function. However, riparian areas may be valued for providing high quality wildlife or fisheries habitats. For this discussion, we group wildlife and fisheries diversity and abundance with riparian functions because of the precedent set by Adamus et al. (1991) and Cooper et al. (1990). This choice is due to the fact that development of indicators of wildlife diversity and abundance are based in the natural and physical sciences, as are other functional indicators, and are formulated in a similar manner.

Wetland and riparian areas are very productive ecosystems and provide important habitat for many wildlife species in Arizona (Brown et al. 1979, Ohmart and Anderson 1982, Anderson and Ohmart 1984). That productivity and importance is at least partly a reflection of the availability of water and rich alluvial soils. The combination of water and soils sets the stage for development of potentially diverse and structurally complex vegetative communities. Structural diversity (different layers of vegetation, different ages of plants, and ground litter) in the plant community provides a wide diversity of habitats for wildlife (Kupchella and Hyland 1986).

Riparian areas provide many critical life support functions for wildlife. They may provide

habitat components dealing with defense, escape cover, food or prey, feeding substrate, nest or birthing substrate, reproduction, resting substrate, and temperature regulation (Jones 1986). Different wildlife species require different situations to meet their specific habitat needs. Because of vegetative diversity and close proximity to water, riparian areas typically provide a wide variety of habitat components. Riparian areas, therefore, typically meet the needs of more wildlife species than the adjacent upland areas.

Some species of wildlife are tied to riparian areas throughout their lives (obligates), while others only depend on them during certain periods of their lives (facultative). Ohmart and Anderson (1986) report that more than 60 percent of vertebrates in the arid Southwest are obligate users of riparian areas. Another 10 to 20 percent are facultative users.

Obviously, fish require water, but they are dependent upon riparian areas for more than just water. Shade, escape and hiding cover, and food items (insects and organic debris) may be products of the surrounding riparian plant community (Meehan et al. 1977, Wesche et al. 1985). Indeed, the capability of streams to produce or support fish often is correlated with condition of riparian vegetation (Cuplin 1986). Riparian vegetation is an important food source for stream organisms (Mahoney and Erman 1984). Macroinvertebrates that consume aquatic vegetation and detritus provide fish with most of their food (Cuplin 1986). Leaf fall provides much of the detritus found in streams.

Amphibians are dependent on water for reproduction, but other life support functions may be provided by either water or the surrounding riparian area (Jones 1986). In the Sonoran Desert, about 80 percent of amphibian species are obligate or facultative users of riparian areas (Ohmart and Anderson 1982). Some reptiles are also tied to riparian areas during their life cycles (Jones and Glinski 1985, Jones et al. 1985). Of these, only two turtle species, one lizard species, and three snake species are considered riparian obligates (Ohmart and Anderson 1982). Reduction of naturally-occurring water and modification of habitats has been shown to affect composition of reptile and amphibian species in riparian areas (Jones 1988).

A number of studies have shown that riparian areas support very high densities of breeding birds, including neotropical migrants (Carothers et al. 1974, Anderson and Ohmart 1984, Johnson and Jones 1977, Hehnke and Stone 1978). The bald eagle, common black-hawk, gray hawk and zone-tailed hawk are four raptor species in Arizona that are dependent on riparian areas for nesting and foraging (Ohmart and Anderson 1982, Kochert 1986).

For some mammals, the presence of running water is more important than the associated plant community. Species dependent on perennial water include river otter, beaver, muskrat and water shrew. Associated with riparian areas but less dependent on water are some bats, ringtail cat, raccoon, Arizona gray squirrel and Apache fox squirrel (Minckley and Brown 1982, Hoffmeister 1986). Beaver dams create conditions that increase growth and vigor of woody riparian species that, in turn, provide important habitat for breeding birds and other animals (Stromberg 1993a).

Not all riparian areas provide habitat for all wildlife. First, because they differ in plant species composition, in maturity, and in degree of disturbance, riparian areas differ in what habitat components they may provide. Second, animal species differ in what habitat components they require. Because of this, riparian areas are not equal wildlife habitats. It is difficult to assign ranking to riparian areas because habitat value varies according to which animal guild or species is selected for evaluation. The same riparian area may be excellent habitat for a particular species, but totally unsuitable for another species. Since riparian areas are mosaics of diverse plant communities, they provide some habitat components for most wildlife species most of the time. Following are examples of how riparian areas differ in providing wildlife habitat.

Cottonwood-willow riparian communities are generally recognized as being important habitat for nesting birds and neotropical migrants (Carothers et al. 1974, Ohmart and Anderson 1982, Anderson and Ohmart 1984). Tree species diversity in Sonoran cottonwood-willow riparian communities is low, but age class and structural diversity is high. And often these communities support an understory assemblage of plants that is more diverse than other riparian types (Stromberg 1993a). Reduction in the diversity of size and age classes adversely affects the abundance and diversity of birds and mammals that require a particular strata within the canopy (Ohmart and Anderson 1986). Some animals (e.g. yellow-billed cuckoo and blue-throated hummingbird) are almost entirely restricted to cottonwood-willow communities (Neff et al. 1979).

Mesquite bosques typically have three vegetational strata that include a tree canopy, a shrub and vine stratum, and an herbaceous understory (Stromberg 1993b). High diversity of plant species and high density of foliage at many heights contribute to an abundance and diversity of the avian community associated with bosques (Ohmart and Anderson 1986). Bosques have high productivity that is partly expressed by the production of abundant flowers and fruits. Flowers support a great number of insects that provide food over a long period of time for birds, bats and other animals. Fruits provide abundant and highly nutritious food for mammals such as javelina, coyote and cattle. Most mammals use a variety of habitats, but the range of at least one species (mesquite mouse) is restricted to mesquite bosques (Stromberg 1993b).

Interior mixed broadleaf communities typically occur at elevations above the previous two riparian communities. They consist of a wide variety of broadleaf trees such as walnut, ash, sycamore, and alder interspersed in varying degrees with oaks and conifers from adjacent mountains (Minckley and Brown 1982). Intensive wildlife studies are generally lacking for this riparian community, but numerous wildlife species are totally or primarily dependent on it (Neff et al. 1979). For example, the Arizona gray squirrel and Apache fox squirrel are largely confined to mixed broadleaf forests (Minckley and Brown 1982).

Wildlife relationships with riparian scrub communities are also poorly investigated, but there appears to be considerable interaction with animal populations from adjacent upland areas (Neff et al. 1979). For instance, thickets in low elevation riparian areas often support high densities of upland game species such as desert cottontail and Gambel's quail (Minckley and Brown 1982). Tamarisk (saltcedar) may dominate some riparian scrub communities and generally

provides poor habitat for most wildlife species because there is low plant diversity, low canopy height, and low structural complexity (Rosenberg et al. 1991). Willow thickets at high elevations, on the other hand, may support a diverse bird community during part of the year (Carothers 1968).

C. Development of Indicators - A Methodology for Rapid Assessment of Riparian Area Wildlife Values

According to Cooper et al. (1990), to determine whether an area is supporting a particular function, the function (1) can be directly measured, (2) can be deduced from site specific data, or (3) inferred from the system's membership in a particular category. For example, nesting habitat for a neotropical migratory bird species may be implied if (a) a nesting pair of birds was observed, (b) suitable characteristics for a nesting site as well as abundant food supplies were observed, or (c) the area was categorized as a cottonwood-willow gallery forest, known to be preferred as nesting sites for this species. Obviously, the potential for error increases with the type of generalization applied.

Direct measurement of many of functions described in the previous section can be a time-consuming and expensive endeavor. Therefore, functions are often deduced from the characteristics of a site or inferred from scientific measurements made on a similar area. The broader levels of analysis (types 2 and 3, above) may require evaluation of more features or characteristics than the straight-forward measurement. Yet, this broader type of approach can be very effective in differentiating and identifying functional processes and attributes.

Assessment of functions at a broad level often involves the establishment of indicators. Indicators are features or characteristics which have a known or hypothetical correlation with an item or event of interest. Indicators are not intended to replace general knowledge about characteristics of an area, but rather to provide shortcuts to predicting whether a process is occurring or whether it has the potential to occur. Establishment of a reliable indicator requires verification through research and testing (direct measurements). Once a correlation is established between a functional process and its effect on the system, and the process is well understood, then indicators of a functional process can be identified.

Riparian evaluation procedures used by the EPA, COE, USFS and the BLM all depend on the application of indicators to varying degrees. In addition, these approaches each acknowledge the utility of the three levels of assessment ranging from general to specific, as listed above. In fact, USFS and BLM approaches structure their data collection and evaluation to reflect these levels. Data collection proceeds from the more general to the more specific, with evaluation occurring at whatever level of specificity is required for a particular application. The decision to pursue a general level evaluation over a specific level is typically driven by the purpose or objectives of the evaluation. That is, the type of evaluation applied will depend on the scale of the endeavor (statewide, regional, local), the necessary precision or accuracy, the time frame

allotted for the analysis and the data collection and financial resources available. For instance, intensive, site-specific field data would need to be collected to answer specific questions such as species habitat requirements or species food preferences. The purpose of a general level inventory might be to locate, quantify and broadly classify riparian ecological sites (Myers 1989).

The broadest level of evaluation begins with the assembly and interpretation of existing maps and data. Features and characteristics of an area can be derived from topographic maps, vegetation data, water quality data, remotely sensed data, historical accounts, databases or field accounts. Inferences can be made from features observed in the field, such as high water marks, nesting sites, species occurrences or valley shape. Data collection and evaluations occurring at this level are useful for identification, categorization and general classification of areas based on general features or characteristics. Once areas are grouped into categories reflecting similarities, inferences can be made about areas where very little detailed data have been collected. General level inventories are also used to identify priorities for more intensive inventories based on resource values and site characteristics.

Because of the Arizona Game and Fish Commission's legislated authority and the Department's mission, our efforts this past year were focused on evaluating methods to assess biological life support functions and wildlife values provided by riparian habitats for vertebrate wildlife (fishes, amphibians, reptiles, birds and mammals).

AGFD sought a method that could be employed to rapidly assess the relative values of riparian areas

- without intensive commitment of personnel,
- that could be carried out with only a moderate amount of training,
- that was not overly subjective in its application, and
- that could correlate with mapping activities being undertaken by the Department.

A number of methods or techniques of assessing wildlife functions and values of wetland or riparian areas have been developed. Many of these techniques require complex, extensive, site-specific measurements or are not specific to Arizona (Table 9). Selection or development of a wildlife function/value methodology is one important contributor to development of an overall, hierarchical designation system.

An approach that was specifically developed for Arizona, and that can be evaluated rapidly in the field was conceived by Anderson and Ohmart (1984) for the Bureau of Reclamation (USBR). Ohmart and Anderson subsequently reviewed alternate methodologies for AGFD and attempted to further develop their own technique to provide a single index value that would allow comparison among riparian habitat types. The methodology they developed was specific to riparian forest and riparian scrub habitats. Their work in development of this technique is summarized in three reports to the AGFD:

The development of an Arizona habitat evaluation model with wildlife values (Anderson and Ohmart 1993),

Functions and values of riparian habitats to Arizona wildlife (Ohmart and Zisner 1993), and

Literature review of functions and values of riparian habitat to wildlife in Arizona (Ohmart and Zisner 1993).

All three reports will be available for inspection through the Habitat Branch of the Arizona Game and Fish Department.

The method described is based on description of vegetation and vegetation structure. Key features of the assessment method include vegetation species composition, foliage density, and vertical height diversity (i.e., the percentage of existing foliage occupying each of three vertical layers) (Figure 30).

The field inventory methods are described in Anderson and Ohmart (1984). In that report, they separated riparian structural types into 6 discernable categories (I-VI). For purposes of creating a wildlife habitat index, those structural types were collapsed into three categories.

As Ohmart and Anderson proposed to further develop an index of wildlife value provided by riparian areas based upon vegetation attributes as determiners of wildlife function, their challenge was to express that value as a simple index. We required that the index value be applicable to classification methods selected by the Department for our riparian mapping and that the classification system developed by Brown, Lowe, and Pase (1979) would be incorporated as a predictor variable in their index model.

Because they proposed to develop an index rather than select an existing methodology, it was essential that the index could be generated in a very short time-frame. To that end, Anderson and Ohmart's (1993) existing data on wildlife utilization specific to riparian habitats was readily available and relatively complete. Their survey data for their Colorado River studies included avian as well as some reptile and small mammal utilization. Data available from other sites was generally restricted to avian utilization, but they argued that general associations between wildlife value and value to birds could be drawn from their Colorado River data and applied to bird survey data collected elsewhere.

Table 9. Description and Comparison of Various Riparian Habitat Evaluation Models reviewed by Ohmart and Zisner (1993).

NAME OF METHOD AUTHORSHIP	BASIS OF METHOD	INTENSITY OF EFFORT	TARGET HABITAT	AREA OF USE
HABITAT EVALUATION SYSTEM Corps of Engineers (1980)	index of wildlife species richness	HIGH, requires site specific field measurements	wetland and riparian areas, based upon plant communities including wooded swamps and bottomland hardwoods	Lower Mississippi River Valley, would require modification and field verification for Arizona
WILDLIFE HABITAT APPRAISAL PROCEDURE Frye (1984)	index of wildlife species diversity	LOW, designed for rapid assessment	wetland and riparian areas, based upon soils, vegetative structure and diversity and scarcity of plant community type	Texas, would require some modification and field verification for Arizona
STREAM CORRIDOR INVENTORY AND EVALUATION SYSTEM Garcia *et al.* (1984)	index of wildlife value of stream corridors, wildlife species richness and density	HIGH, requires significant site specific data collection, some may be derived from remote sensing, best applied by interdisciplinary team	riparian habitats, flexible method designed specifically for riparian inventory	
HABITAT SUITABILITY INDEX (HSI) FOR WILDLIFE SPECIES RICHNESS IN SHELTERBELTS Schroeder (1986)	index of wildlife species richness	MODERATE, requires measurements of vegetation structure, plant diversity and shelterbelt size	Shelterbelts including woody riparian habitats	Minnesota shelterbelts, would require modification and field verification in Arizona.
WILDLIFE WETLAND EVALUATION MODEL Golet (1976)	index of wildlife diversity and productivity in wetlands	HIGH, requires some specific field measurements of water regime and water chemistry	wetlands	Northeastern US
WILDLIFE SPECIES RICHNESS IN WETLANDS Adamus (1983)	index of year-round wildlife species richness	MODERATE, requires some specific field measurement, other features can be derived from maps and remote sensing	wetlands, only designed to compare wetlands of the same type	48 contiguous Untied States

NAME OF METHOD AUTHORSHIP	BASIS OF METHOD	INTENSITY OF EFFORT	TARGET HABITAT	AREA OF USE
HABITAT EVALUATION INDEX Graber and Graber (1976)	comparison of plant community conditions	LOW, limited fieldwork, requires mapping and classifying the state and determination of average condition	All plant communities, meant to compare areas against a standard of average condition	Illinois, would require significant mapping and classification across Arizona before could be used
ARIZONA GUILD LAYERS OF HABITAT MODELS Short (1984)	index of habitat suitability for guilds of animals	MODERATE, wildlife species indicators must be guilded, requires field measurement of eight habitat layers based on vegetation height and density	desert and riparian habitats	Southwestern US, deals mostly with Sonoran Desert habitats.
INDICATOR SPECIES IN COLORADO Hoover and Willis (1984)	index of wildlife species richness	MODERATE, requires measurement of habitat variables for specific indicator species	forested habitats (17 communities) with specific indicator wildlife species	forest communities of Colorado

Table 9 (cont'd.)

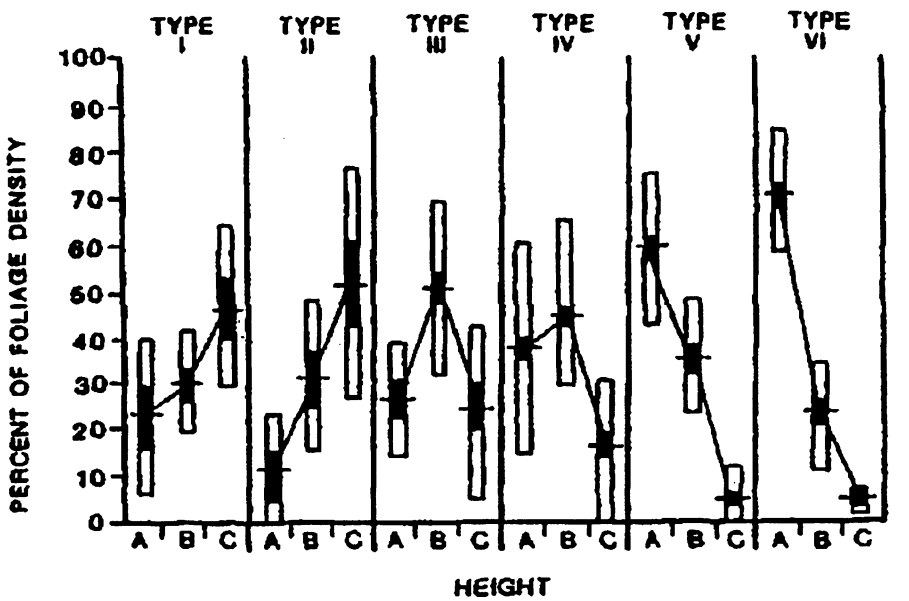


Figure 30. Structural classes of vegetation (A) lower (0-2 ft above ground level), (B) middle (2-15 ft), and (C) upper layers (above 15 ft) of riparian forest (Anderson and Ohmart 1986).

To document this they used principle components, correlation, and regression analyses to determine:

- If survey data for birds from their data sets could be explained by plant community type,
- If a relationship existed between overall wildlife value (i.e., birds, mammals, and reptiles) and value of community types to birds, and
- If a relationship existed between overall wildlife value (i.e., birds, mammals, and reptiles) and value of community types to mammals.

Anderson and Ohmart (1993) concluded from analyses of their Colorado River data that these relationships all existed and were significant.

To derive their index of wildlife value associated with riparian areas, Ohmart and Anderson constructed a regression model that placed a dimensionless index of value upon categories of riparian community types (Anderson and Ohmart 1993). They used existing wildlife data from their work on the Colorado River (Anderson and Ohmart 1984) and data sets from the Gila

River (Hunter 1988) and the Tonto National Forest (Higgins and Ohmart 1981) to derive an indicator of value to wildlife (based heavily upon cavity-nesting birds). The goal of their efforts was to associate existing wildlife data with rank-quantified riparian plant community types (based on structural composition).

Ohmart and Anderson recognized that elevation, latitude, and longitude were also potential determiners of wildlife value. Data assembled for riparian areas represented elevational (Tonto National Forest), latitudinal (Gila River), and longitudinal (Colorado River) gradients across Arizona.

There are several assumptions and limitations implicit in the development of the index proposed by Anderson and Ohmart (1993).

1) The index is developed for terrestrial wildlife, and thus is limited to riparian forest and scrub communities. No data for fishes or aquatic wildlife were included, and value of riparian areas to their associated aquatic components is only inferred rather than explicitly evaluated.

2) It is assumed that value to birds and mammals is correlated with value to all forms of wildlife. Anderson and Ohmart's (1993) data represent rather complete, long-term survey of birds and other wildlife in riparian areas. However, the data sets in areas other than the Colorado River do not represent complete surveys for mammals, amphibians, and reptiles. If the value of riparian areas to birds can be determined, then Anderson and Ohmart assume that value to all terrestrial wildlife can be computed based upon their analyses of Colorado River data. In fact, Anderson and Ohmart's analyses are based heavily upon their data recording cavity nesting bird utilization of riparian habitat.

3) It is assumed that the specific index of wildlife value can be applied uniformly at elevations below 3,500 feet msl because data used to develop the index all came from riparian areas at or below this elevation. While the approach to developing an index value may be applicable in higher elevation areas, it requires the collection of data in riparian areas found within that elevation range. Until then, there is less confidence in using the index at higher elevations than were tested, and thus the model requires field testing at elevations above 3,500 ft.

4) The indexed wildlife value represents value to wildlife across all seasons and across years. Riparian areas which are valuable to wildlife seasonally may be under valued to some extent.

5) Anderson and Ohmart assumed that riparian plant community types can be rank-quantified. An important factor in determining wildlife value is the relative value of plant species composition in the riparian area. The quantification is a ranking based upon wildlife densities associated with plant community types observed by

the authors in previous studies.

6) The model does not account for acknowledged high value habitats of wetlands or cienegas. These areas do not fit into the structural types proposed by Anderson and Ohmart.

Anderson and Ohmart (1993) report a multiple regression model that provides an index value for wildlife that allows comparison among riparian forest/shrub community types. For ease of use, they proposed a look-up table with values evaluated for specific community types (Brown, Lowe and Pase series level), altitudes, and regions of the state. A brief excerpt from their look-up table is presented in Table 10. Index values in the table range from approximately +3 (highest value) to approximately -3 (lower value). Anderson and Ohmart are careful to caution that lower values or 0 values of the index do not reflect an absence of value to wildlife, but simply lesser value when compared to riparian forest/scrub habitats of highest value. The data necessary to generate an index value are quantified vegetation type (Brown, Lowe and Pase series level), vegetation structure type, altitude, and longitude and latitude. Vegetation structure types (Type 1 and 2 = 2, Type 3 and 4 = 4, and Type 5 and 6 = 6) are illustrated in Figure 30. Altitude, longitude, and latitude were used as categories.

The utility of a simple index of wildlife value for riparian areas is multifold. It could be used to provide a range of potential wildlife values based on identified vegetative community type (Brown, Lowe and Pase series level). Remotely sensed data combined with ground-truthing can provide additional information to decision-makers. AGFD will continue to evaluate the utility of a simple index of wildlife value. Anderson and Ohmart's report to AGFD is still being finalized and must undergo final internal review.

Table 10. Example look-up table for wildlife value index generated by Anderson and Ohmart (1993). Values are dimensionless and provide comparison among Vegetation Structure types by altitude and area of the state. Wildlife values range from -3 to +3.

			LONGITUDE/LATITUDE ZONE (from Fig. 2)					
VEGETATION TYPE	STRUCTURAL TYPE	ALTITUDE (FT)	1	2	3	4	5	6
Populus- Salix and mixes (Series 1)	2	0-600	3.0	2.9	3.0	3.0	3.2	3.2
	4	0-600	2.6	2.5	2.7	2.7	2.9	2.9
	6	0-600	2.4	2.3	2.5	2.5	2.7	2.7

Section V

Development of A Hierarchical Designation System

A. Introduction

AGFD was instructed to incorporate a hierarchical designation system based on relative functions and values into the development of a classification system for riparian areas (Chapter 298, Laws 1992). The development of such a system has long been discussed and debated by scientists and land managers across the nation. In the past, formulation of a designation system was limited primarily by a lack of comprehensive data and information on riparian functions and values. This was complicated by the fact that many different methods of collecting and analyzing data have been applied by scientists and land managers. These data collection efforts have been driven by a variety of designation and classification systems devised to meet a wide variety of objectives.

Because of the land base managed by federal agencies in Arizona, a state designation system should not be formulated without evaluation and consideration of approaches taken by federal land management agencies. The BLM has responsibility for more than 12 million acres of public lands in Arizona. About 289 perennial stream miles occur on those BLM managed lands. National forest lands cover more than 11 million acres and include almost 1,600 perennial stream miles, many of which are headwaters of stream systems in the state. National parks, wildlife refuges and military bases add another 7 million acres to lands and over 600 perennial stream miles under management of federal agencies within the state. In contrast, private and state lands combined comprise only about 23 million acres and 1,100 perennial stream miles. The amount and type of data that will be generated by federal efforts, as well as the type of management practices applied on these lands will have critical implications to state-level efforts.

The USFS, BLM, EPA and COE have all been struggling with the formulation of a riparian evaluation system that is applicable to arid and semi-arid regions of the U.S. The Southwestern Region of the USFS developed the "Riparian Area Survey and Evaluation System" (RASES) (USDA 1989) and the Intermountain Region developed the "Integrated Riparian Evaluation Guide" (USDA 1992) as a means to evaluate the need for adjustment in land management practices to improve conditions in riparian areas under their jurisdiction. In Arizona, RASES has been modified by at least three National Forests, resulting in further fragmentation in approaches.

The Bureau of Land Management devised the Ecological Site Inventory (ESI) approach to meet its goals for the inventory and management of riparian and wetland resources (see Batson et al. 1987, Myers 1989, Leonard et al. 1992, Gebhardt et al. 1990, Prichard et al. 1993). It is important to note that the BLM procedures have been incorporated into the Standards and Guidelines section of the Rangeland Reform Act '94 (USDI 1993). The "Riparian-Wetland

Initiative for the 1990s" (USDI 1991) established national goals and objectives for managing riparian and wetland resources on public lands. One of the primary goals of the initiative is "to restore and maintain riparian-wetland areas so that 75 percent or more are in proper functioning condition by 1997" (USDI 1993).

In addition to these, there are many other approaches being applied at federal, state and local levels across the nation. However, to date, no system has been devised that is universally acceptable to all entities involved in the assessment and evaluation of wetlands and riparian areas in the arid and semi-arid Southwest. Even as this report was being written, information was being received about new developments in evaluation procedures.

Although the federal agencies have fairly recently begun to apply their evaluation procedures to riparian areas and wetlands within their jurisdiction, there is a growing body of knowledge and data on riparian resources on a number of streams across the state. The lack of consistency in approach, the fact that these efforts are not yet complete and the lack of a centralized repository for this information makes it more difficult, but not impossible, to extrapolate this data to riparian resources on a statewide basis.

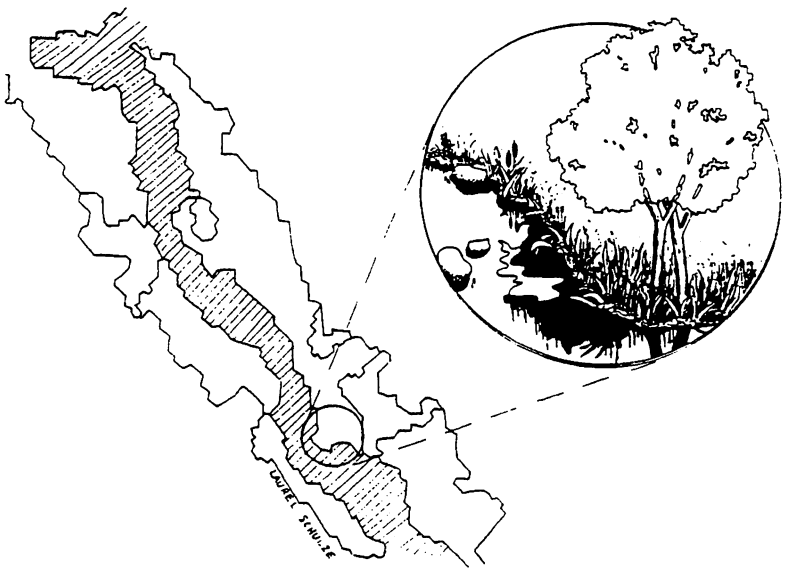
B. GIS - An Evaluation Tool

As discussed earlier in this report, compiling natural resource data into a GIS expands our ability to evaluate these areas because it has the capacity to display geographically-based data at a variety of scales. We can view the entire state or we can zoom in on a specific area. In addition, a database can be linked to a geographical location allowing the incorporation of detailed data on a particular site. In fact, the current technology even allows us to overlay a photographic image of a location while viewing the corresponding computerized map on a computer screen.

The potential to reference site specific data to a map location expands our ability to compile and analyze information. More importantly, we can expand this database to incorporate information on sites collected by other agencies or researchers, as long as the data are compatible and can be georeferenced. (Care must be exercised in the incorporation of data to ensure that the date of data collection is referenced.) In addition, the database can be expanded to include new fields for data that can be derived from existing maps or GIS databases or for data that become available in the future. For instance, orientation, stream order and valley confinement can be derived from topographic maps and added to the database. One very important data set that is not available at this time, but that could be added in the future is soils information. Soils data have been digitized for a few areas, but specific data are not yet available on a statewide basis.

GIS gives us a powerful evaluation tool that allows us to combine various levels of data, from general to more specific. However, precision of data can often be a problem, therefore, data

should **always** be field verified. That means the site represented on a map should be visited to ensure that information is correctly represented.



During the riparian map verification process, field biologists collected general site information while ground-truthing riparian vegetation. This information included a list of all woody species present categorized by size class, frequency of size class, and height. In addition, they listed adjacent land uses, special habitat features, adjacent upland vegetation and land uses evident at the site. Presence of seedlings and saplings of native riparian woody vegetation was noted as was the presence of emergent aquatic plants. General habitat condition was rated based on bank stability, bank vegetative stability, streamside cover and pool/riffle factors. Field biologists gathered general stream information including channel substrate and presence of special features such as organic debris, beaver dams, backwater marshes and man-made structures. When entered into a database, these data can be referenced to the map site at which it was collected. Because field biologists will be checking 20% of the total acreage of riparian vegetation mapped, this will give us an excellent information source on a number of characteristics of riparian areas. Details on the type and method of data collection are being compiled in a technical document (AGFD in press).

C. Assessment of Functionality - Two Approaches

Based on direction from the legislation, the approach to a riparian designation system must take into account an assessment of functionality. This aspect of riparian evaluation systems has been greatly neglected. However, two recent federal reports describe approaches to assessing functions of riparian and wetland areas. They are BLM's "Process for Assessing Proper Functioning Condition" and COE's "A Hydrogeomorphic Classification for Wetlands" (Brinson 1992). A brief discussion of each is presented here.

The BLM approach is based on an assessment of the riparian areas's capability and potential. Capability is defined as "the highest ecological status a riparian-wetland area can attain given political, social or economical constraints." Potential is "the highest ecological status an area

can attain given no political, social or economical constraints, often referred to as potential natural community (PNC)" (Prichard et al. 1993). The approach is based on data and information collected during the Ecological Site Inventory process and is used to analyze whether a riparian area is properly functioning based on the following definition:

"Riparian-wetland areas are functioning properly when adequate vegetation, landform, or large woody debris is present to:

1) dissipate stream energy associated with high waterflows, thereby reducing erosion and improving water quality;
2) filter sediment, capture bedload, and aid floodplain development;
3) improve floodwater retention and groundwater recharge;
4) develop root masses that stabilize streambanks against cutting action;
5) develop diverse ponding and channel characteristics to provide a habitat and the water depth, duration and temperature necessary for fish production, waterfowl breeding, and other uses, and;
6) support greater biodiversity" (Prichard et al. 1993).

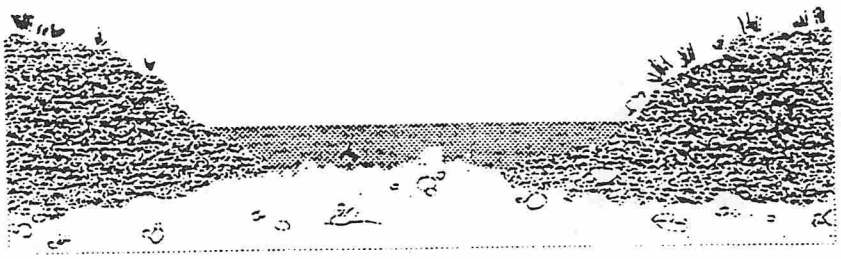
The next step in the assessment is to analyze the attributes and processes occurring in the riparian-wetland area according to five general categories: (1) hydrogeomorphic factors, (2) vegetation factors, (3) erosion/deposition factors, (4) soil factors and (5) water quality characteristics. The results of this procedure will allow the land manager to determine which one of the following functional categories is represented at that site:

1) The area is properly functioning.
2) The area is functional-at-risk. Trend is also reported in this category (recovery versus continued degradation) and is a key consideration in interpreting the data.
3) The area is nonfunctional, most of the riparian values have already been lost.
4) Condition unknown.

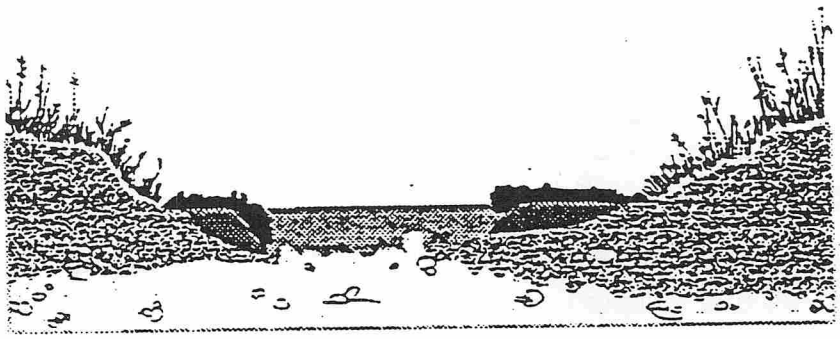
The functional categories have direct management implications. Areas identified as functional-at-risk with a downward trend tend to be the highest management priorities for BLM. In these cases, a change in management practices may reverse the decline, especially when the system has not been so degraded as to lose its resiliency, i.e., its natural ability to recover from disturbance. Functional-at-risk areas exhibiting an upward trend of recovery are often a priority for monitoring to ensure that the recovery continues. Areas determined to be properly functioning are evaluated to determine whether they are meeting site specific objectives. This involves evaluation of riparian vegetation seral stage. Seral pertains to a succession of plant communities in a given habitat leading to a particular climax association (Figure 31). Prichard et al. (1993) explain that, if the objective is to maximize wildlife diversity in the area, the site will be managed so that vegetation advances to late seral stage. If the intent is to maximize vegetation for grazing, the intent is to maintain the system in proper functioning condition, but to limit the development of vegetation to early seral stages (Prichard et al. 1993).

Figure 31. Seral stages of riparian vegetation along a stream channel (Prichard et al. 1993).

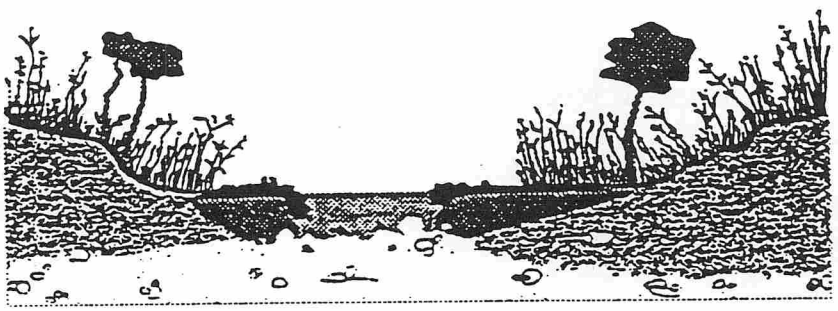
A
Bare Ground



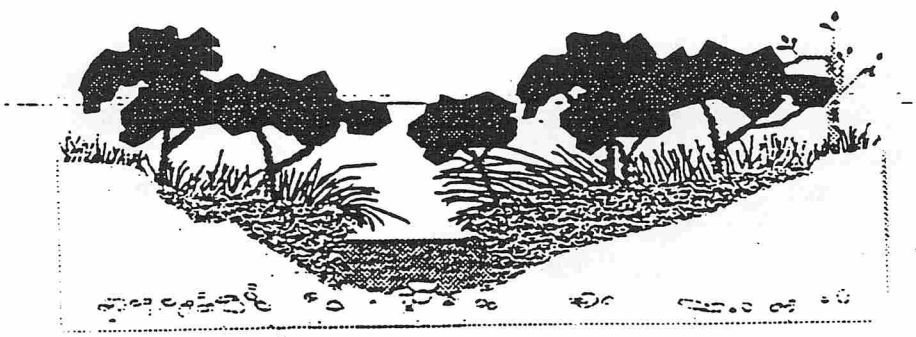
B
Early Seral



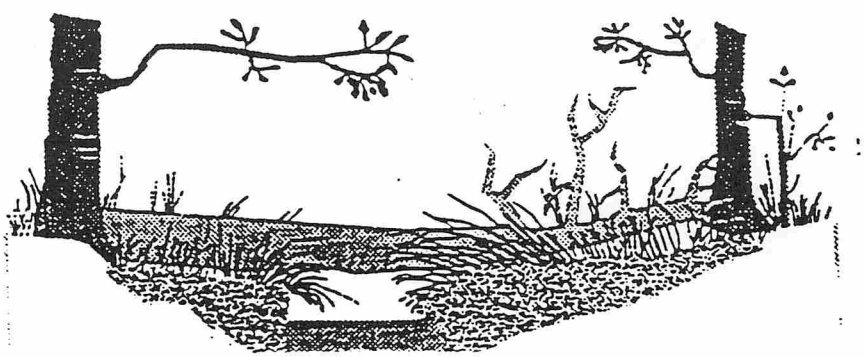
C
Mid-Seral



D
Late Seral



E
PNC or PPC



A totally different approach, termed the hydrogeomorphic approach, is currently being developed by the COE (Brinson 1992). A draft of the report is available for review but further modifications may be made to this document. For our purposes, it is assumed that the general approach outlined in the draft report is the direction that will ultimately be proposed for classification and evaluation of riparian and wetland areas.

The hydrogeomorphic system is basically a means of developing an assessment methodology. Brinson (1992) proposes an approach that categorizes wetlands and riverine systems based on similarity in functional properties. To do this, a more simplified concept of wetlands and riparian areas must be applied. This requires a broad-scale evaluation of these areas recognizing that, while each area may be unique, there are characteristics by which streams and wetlands can be grouped. Brinson states that these characteristics should include consideration of geomorphic setting, water source and its transport and hydrodynamics. There are no pre-set categories under this approach because, as it is applied in various physiographic regions, different categories of wetlands and riparian areas will emerge.

Categorization of wetlands and riparian areas into functional groups requires the use of indicators and other surrogates of ecosystem function. Indicators help in determining the type of wetland or riparian area and in evaluating the ecological significance of the area. Slobodkin et al. (1980) suggest that the development of a species list for an ecosystem is the most useful approach to answering questions about function. That is, the habitat and life cycle requirements of a species can provide useful insight and information about the environmental conditions at that site.

The first step in this approach is to establish the functional attributes for a given category. This is accomplished by establishing a system of reference areas and then providing a detailed analysis of those areas. Reference areas are sites where "indicators have been tested, measured and related to corresponding ecosystem functions" (Brinson 1992). These are areas where research efforts should be focused to facilitate the development of better indicators or to discover unknown functions. Reference areas represent benchmarks against which other wetlands are to be compared.

The detailed analysis of these areas is termed "profile development." Profile development is a description of the reference site presented in a narrative form. In this way, any and all information and data collected at a site can be incorporated into the profile, ranging from a site visit to a detailed study. Profiles are intended to be the goal or endpoint of this approach. The intention is for a particular region of the country to develop an array of profiles to describe the various categories of wetlands and riparian areas occurring within the region. The development of this information base should begin to reveal dominant hydrologic processes and their relationships to ecological factors within the ecosystem. This information is then used to define the categories of wetland and riparian types.

The resulting categories would be identified with a unique list of functions and associated indicators. All efforts should be made to include types of wetlands or riparian areas that presently occur within a region or occurred there at one time. Once identified, these areas need

to be protected and monitored to facilitate our understanding of these systems and to provide a "type specimen" of this type of ecosystem. Other wetlands or riparian areas within the same category can then be compared to these representative areas for purposes such as assessment, training and mitigation.

This approach incorporates the following factors.

1) It provides a management assessment procedure.
2) It provides standards to evaluate wetland and riparian area construction and restoration projects.
3) It is useful for training scientists who will be working on permit review, assessment of functions, construction of new wetlands and restoration of degraded ones.
4) The structure of the approach can be modified as new data become available and the systems become better understood.
5) It can be adapted to a variety of physiographic and geographic regions.

The process of establishing reference areas must take into consideration that the functional potential of most rivers in Arizona has been greatly reduced and that even the best reference sites may be functioning below their potential. Regardless, it is imperative to identify reference sites for the various riparian vegetation and geomorphic stream types in the state and manage them so as to enhance their natural biological potential by excluding factors that could potentially decrease this potential. This is the only way one can begin to discriminate between degraded versus healthy ecological condition and to truly assess the impacts of various land and water use activities through comparison with a non-degraded control site.

D. Recommended Approach

In summary, the development of a hierarchical designation system based on riparian functions and values should take into account a number of items.

1) New information on riparian functions is almost constantly being presented as research continues on this subject. Therefore, the approach should be flexible enough to allow for the incorporation of new information.

2) According to the legislation, the approach must incorporate functions and values of these resource areas. Use of indicators and rapid assessment methods has been discussed.

3) Because there is so much federal land in the state, the approach should be compatible with federal activities, or should be able to incorporate the data and information collected by federal agencies into the approach. Federal agencies have begun to collect a variety of data and information about riparian and wetlands across the state. Some regions have been inventoried more intensively than others, but, in general, there is a growing body

of information about Arizona's riparian resources. However, at this time, data collection techniques appear to be inconsistent and incompatible.

4) Completion of the three project areas under this legislation (AGFD, ADWR, ADEQ) adds a great deal of information to our knowledge base. Riparian vegetation, land ownership and land use maps are contained in a digitized format. Additional data can be calculated from topographic maps and GIS covers to add to this information source. Upon completion of ground-truthing, general data on 20% of riparian vegetation across the state will be input into a database and geographically referenced to the maps. This provides us with a powerful tool to apply to riparian assessment.

5) Recent controversial proposals included in the Clean Water Act reauthorization have attempted to classify or rank wetlands according to their functions and values, and then regulate these categories differently. The primary question is whether all wetlands should be treated the same or not. If all wetlands have some functions and values, do some have more than others, and consequently should those with lesser values be accorded less stringent regulatory protection? This controversy raises issues directly applicable to riparian area protection strategy development for Arizona.

   Advocates of ranking contend that not all wetlands are of equal ecological or social value and therefore are not deserving of equal protection. Regulatory approaches are currently being challenged on the basis of uncertainty and a perceived unfairness in regulating wetlands with little apparent public value. Opponents of ranking point out that it is impossible to place values on individual wetlands, much less compare or evaluate different wetlands locally or regionally. To develop a system of ranking would require years and tremendous expense, not to mention the administrative burden on resource agencies. Further, because rankings are overly simplistic and scientifically invalid, legal challenges would be a likely outcome. Because wetland restoration efforts have generally not been successful, eliminating the "low-value" wetlands from protection will inevitably result in net loss of wetland resources.

6) The designation system chosen should address a number of other considerations.

   (a) A consistent geographic unit of evaluation should be discussed. Some approaches use an ecological unit which roughly equates to a stream reach and is based on similarities in hydrology, geomorphology and vegetation. Others are based on management objectives.
   (b) The evaluation system should have a systems perspective and should be able to take into account the effect of upstream and downstream activities of an assessment area.
   (c) It should be capable of dealing with potential functions since systems are often degraded.
   (d) Temporal variability of the system needs to be considered because the system is dynamic.

7) One of the most important items for consideration is that several federal agencies are in the process of formulating functional assessment methods for application to riparian areas. These methods have been devised by interdisciplinary teams of scientists and land managers and are currently undergoing public review. We cannot and should not ignore this work, nor can we speculate on their final form and content after public review and comment. However, these approaches represent the best available methods for assessing functionality within riparian and wetland systems at this time.

8) Information needs should be balanced with the development of action strategies. "Enough information needs to be amassed to allow for sound policy choices, but collecting too much information can stall action. It's important to remember that decisions can be made and actions taken before all the needed information has been gathered. Gathering information can take a lot of time and resources, delaying strategy development for years. To the extent possible, a state should draw on existing data and the professional judgement of people familiar with the state's wetlands. As gaps in data are identified, objectives can be set for collecting and analyzing any missing data and information" (World Wildlife Fund 1992).

Based on these considerations, AGFD proposes a preliminary outline as a first step in the development of a hierarchical designation system for riparian assessment based on functions and values. The preliminary approach is outlined below and illustrated by the flowchart in Figure 32.

Step 1. Assess the functional condition of a given unit of riparian area (stream and terrestrial land area).

(a) Functional assessment should be based on hydrologic, geomorphic, vegetative and biotic features of a riparian ecosystem.

(b) The assessment should be based on the application of reference areas, profile development and formation of general riparian categories as proposed by Brinson (1992).

(c) Other data sources should be brought into consideration to complete determinations of functional condition. An interdisciplinary, interagency team should be brought together to discuss data and information about various riparian areas within their jurisdiction to facilitate the choice of reference areas, profile development and categories. Team discussions may also facilitate determinations of functional condition of a riparian area based on previous data collection and research efforts.

(d) Determinations of functional condition should take into account the capability and potential of the areas. Definitions of these terms were presented previously in this report (see Prichard et al. 1993.)

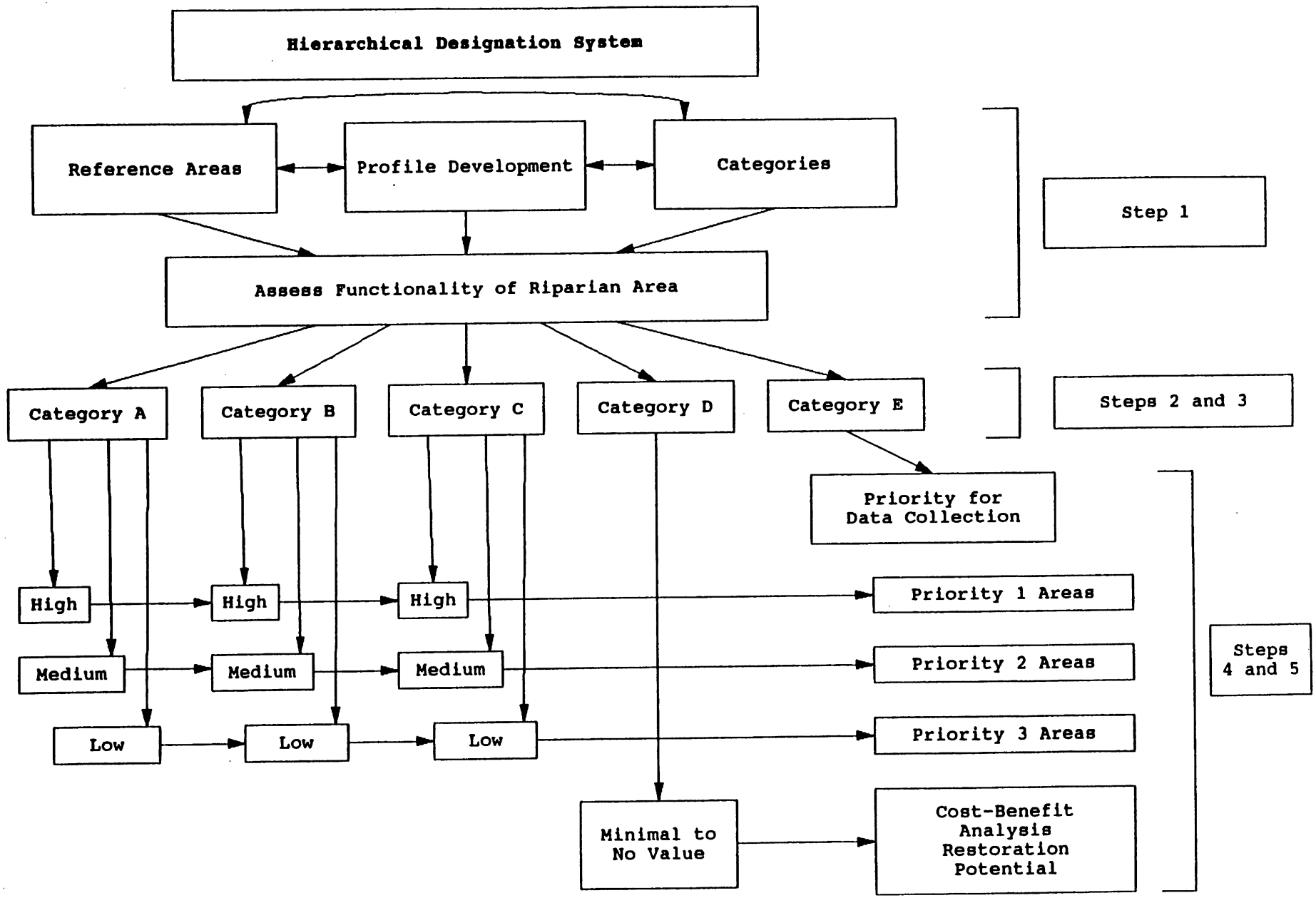


Figure 32. Flowchart of steps in the preliminary hierarchical designation system.

Step 2. Categorize areas based on their general functional condition (BLM approach).

CATEGORY A: The area is determined to be properly functioning.

CATEGORY B: The area is functional-at-risk, trending toward recovery.

CATEGORY C: The area is functional-at-risk, trending toward further degradation.

CATEGORY D: The area is nonfunctional, most of the riparian values have already been lost.

CATEGORY E: Condition unknown.

Step 3. Each of these categories has implications as to protection and management actions, as follows.

CATEGORY A: Actions may include monitoring of condition and quality to ensure the area does not degrade, or protection as a reference area. These represent our highest quality areas, but they may already be degraded from their potential.

CATEGORY B: Actions may include support of management practices that are contributing to the positive trend toward recovery. Identify and minimize effects of negative influences on system.

CATEGORY C: Actions may include modifying or eliminating those activities that are contributing to degradation.

CATEGORY D: Actions may include a cost-benefit evaluation to assess whether restoration is feasible or desirable. These represent our most degraded systems.

CATEGORY E: Additional data or information is needed on these areas to properly assess their condition. These areas may become priorities for further study.

Step 4. Within each category, assess whether high, medium or low values exist.

(a) The types of values to be assessed must be determined. Typically, areas are evaluated on the basis of wildlife and aquatic habitat, recreational value, and aesthetic value. However, there are other commercial and economic values. Assessment methods for values should be devised by proper experts in each

area.

(b) AGFD has dealt with determining value for wildlife habitat in this report and will continue to refine a rapid assessment methodology for that component. Additional information available for use in determining valuable wildlife habitat includes:

(1) locational data on critical habitat and sensitive species contained in the AGFD Heritage Data Management System, and;
(2) location of areas of high biodiversity from the GAP Analysis Project (Graham in prep.) to be completed in June 1994.

It should be noted that sensitive species data are based on intensive survey data and may not be comprehensive for the state, because not all areas of the state have been equally surveyed for all species.

(c) Possible data sources for determination of recreational and aesthetic values include the Arizona Rivers Assessment Database (ASPB) and various Arizona-based documents related to proposals under the Wild and Scenic Rivers Act.

Step 5. Prioritize areas for protection or management action based on assessment of values and functional category.

(a) Priority ranking should be based on the number of high values given to an area, not on a numerical average. This will produce a range of priority rankings, the number of which will depend on the number of values assessed. For instance, if wildlife, recreation and aesthetic quality are assessed, priority rankings may range from 3 high quality determinations to 3 low quality determinations with a number of combinations in between.

(b) Since priority rankings will occur within each functional category, determinations must be made as to which category takes priority. In other words, do areas that are fully functional with high value rankings take priority over areas that are degrading but possess high value rankings? There has been much discussion among scientists and land managers regarding this very issue. Some propose that functional-at-risk areas should get first priority so that trends of degradation can be reversed before the area becomes totally nonfunctional. Others state that fully functional areas should be given priority because so few of them are protected or monitored and they represent the best examples of functional systems. Still others believe that risks to the system should be evaluated and priority should be given to those areas with highest values that are most at risk of degradation or destruction.

E. The Next Step

The completion of this report does not signal the completion of AGFD's work on inventorying and assessing riparian areas in Arizona. In fact, in the next year, AGFD staff will be working toward bridging information gaps that will help us achieve an implementable hierarchical designation system. The following is a list of action items that are either in process or are proposed for next year:

1) AGFD will continue to refine the perennial database and map riparian areas in Arizona, including areas associated with intermittent waters. The map verification process will continue until map accuracy reaches at least 80%.

2) Although a great deal of information necessary to achieve the goal of a designation system is currently available, it must be compiled and assessed. AGFD will continue to assess the full capability of the remote sensing technology and accompanying databases and videotapes.

3) To assist with our understanding of riparian functions, AGFD applied for and was awarded a grant from the EPA under the Clean Water Act, 104(b)(3) Wetlands Grant Fund. The grant will allow us to develop a functional assessment methodology and a methodology to determine status and trends of riparian areas statewide.

4) An interdisciplinary, interagency team should be brought together to:

   (a) identify possible reference areas and to exchange data and information about status of riparian areas;

   (b) develop minimum data collection needs for referencing riparian data to GIS.

   AGFD proposes that this action item be a component of investigations occurring in conjunction with wetlands grant activities listed in item 3.

Section VI

Existing Options for Riparian Protection

A. Introduction

The legislation under which this report is prepared requires that AGFD identify "existing options for protecting riparian areas in each ownership category that may be available under existing state and federal laws." The following listings (inventory) of state and federal riparian and wetland protection programs and mechanisms includes those currently being used in Arizona as well as potential programs. Potential programs are those existing national programs that have not been, but potentially could be, applied in Arizona. Protection mechanisms are grouped into the following categories: regulation; policy and guidelines; acquisition; planning; restoration, creation and management; incentives and disincentives; technical assistance, education and outreach; and research. Also indicated are the land ownership category (federal, state, tribal, and private) that each of the protection mechanisms apply to either directly or indirectly. These lists were developed based on previously compiled listings from a variety of local and national reports as well as recent input AGFD gathered from participating state and federal agencies serving on the Riparian Areas Advisory Committee.

This section does not attempt to assess existing programs as to their particular effectiveness nor does it describe each of the programs. Additional information sources are noted under item E of this section: Synopsis of Wetland/Riparian Protection Program Reports. These reports include information on each of the listed protection options, who administers them, and how and where they may be used for wetland/riparian protection. Further, some of the reports include evaluations of the effectiveness of specific programs and propose strategies for improving their effectiveness in protecting riparian areas.

B. Listing of State and Federal Riparian Protection Mechanisms in Arizona

STATE MECHANISMS APPLIED IN ARIZONA
By Category and By Landownership
(F=federal, S=state, I=Tribal, P=private)

F	S	I	P	
				Regulation
				ARS Title 49 - Water Quality Control
X	X		X	Water Quality Standards for Waters of the State
X	X		X	CWA Section 401 Water Quality Certification
X	X		X	CWA Section 402 Point Source Discharge (NPDES)
X	X		X	CWA Section 208 and 319 - Nonpoint source pollution impacts
X	X		X	ADEQ Aquifer Protection Program
X	X		X	ARS 17-237 - Pollution of Waters
	X		X	State Flood Control Statutes: ARS 45-1401 through 1501
	X		X	ARS 48-3601 through 3628 - County Flood Control Districts: Flood Control Planning and Management
X	X		X	ARS 37-1101 through 1156 - Ownership of Streambeds
X	X		X	ARS 9-21-303 - Unique Waters
X	X		X	ARS 9-21 - Water Pollution Control
X	X		X	ADEQ Point and Nonpoint Source Programs
				ARS Title 45 - Water Rights:
X	X		X	Adjudication of surface water
X	X		X	Sever and transfer
X	X		X	Instream flow rights
X	X		X	Groundwater Management Act
				Policy and Guidelines
	X			Executive Order No. 89-16: Streams and Riparian Resources
	X			Executive Order No. 91-6: Protection of Riparian Areas
X	X		X	ADEQ Best Management Practices for grazing; and for sand and gravel operations - DRAFT
X	X		X	AZ Water Quality Control Council Policy for Construction and Related Activities in Water (1977)
				Acquisition
X	X	X	X	AGFD and ASPB Heritage Fund and Natural Area Programs
X	X		X	Waterfowl Conservation Fund (AZ Duck Stamp)

F	S	I	P	
				Planning
	X			Report of the Governor's Riparian Task Force 1990
X	X		X	Verde River greenway/corridor plans
X	X		X	Santa Cruz River greenway/corridor plans-initial study phase
	X			ASLD Riparian Ecosystem Strategic Plan 1989
X	X		X	State Comprehensive Outdoor Recreation Plan (SCORP) 1989
X	X		X	ASPB Arizona Wetlands Priority Plan 1988
X	X		X	ASPB Arizona Rivers Assessment - DRAFT
	X			ADOT Wetlands Preservation Policy
	X			AGFD Policies for: Riparian Habitat, Verde River, Wildlife Compensation Policies
				Restoration, Creation, and Management
X	X		X	ADEQ Water quality programs - Unique waters, Antidegradation standards, Nonpoint Source Management Zones
X	X		X	AGFD Game, Nongame, Fish and Endangered Species Fund
X	X	X	X	AGFD and ASPB Heritage Fund and Natural Areas Programs
X	X		X	State Lake Improvement Fund (SLIF)
X	X		X	Waterfowl Conservation Fund (AZ Duck Stamp)
		X		Wastewater treatment projects
				Potential-
X	X		X	AZ Navigable Stream Adjudication Commission Riparian Trust Fund
X	X	X	X	CAP Environmental Trust Fund*
				Incentives and Disincentives - none identified
				Technical Assistance, Education, and Outreach
X	X	X	X	Environmental Education Act
X	X	X	X	Interagency Committee on Environmental Education
X	X	X	X	AGFD and ASPB Heritage Fund
X	X	X	X	AGFD Project Wild, Aquatic Project Wild
X	X	X		ASPB Arizona Rivers Assessment and Natural Areas inventory
X	X	X	X	ASPB Verde River and Santa Cruz River corridor studies
X	X	X	X	AGFD Heritage Data Management System
X	X	X		Natural Resource Conservation Districts

F	S	I	P	
				Research
X	X	X	X	State universities
X	X	X	X	Scientific and policy research programs
X	X		X	AGFD Game, Nongame, Fish and Endangered Species Fund

* The Governor's Central Arizona Project Advisory Committee Final Report and Recommendations (October 1993) included a proposal for an Environmental Trust Fund to be administered by ADWR for the maintenance, enhancement and restoration of aquatic, wetland and riparian habitats.

FEDERAL MECHANISMS APPLIED IN ARIZONA
By Category and By Landownership
(F=federal, S=state, I=Tribes, P=private)

F	S	I	P	
				Regulation
				Clean Water Act (CWA):
X	X	X	X	Section 404
				Regional and General Conditions
				General Permits
				Advanced Identification
				Guidelines (Mitigation/Monitoring, Mitigation Banking)
X	X	X	X	Section 401 (Water Quality Certification)
X	X	X	X	Section 402 (National Pollutant Discharge Elimination System)
X	X	X	X	Section 301 and 303 (State Water Quality Standards)
X	X	X	X	Rivers and Harbors Act - Section 10 (Colorado River only)
X	X	X	X	Endangered Species Act
X	X		X	Federal Power Act:
				Federal Energy Regulatory Commission (FERC)
				Electric Consumers Protection Act
X		X		Federal Reserve Water Rights
X	X	X	X	Fish and Wildlife Coordination Act (FWCA)
X	X	X	X	National Environmental Protection Act (NEPA)
X	X	X	X	National Flood Insurance Program
X				Water Resources Development Act
X	X		X	Wild and Scenic Rivers Act
X	X		X	Wilderness Act
				Acquisition
X	X			Emergency Wetlands Resources Act
X	X			Federal Aid in Sport Fish and Wildlife Restoration Acts
X	X			Land and Water Conservation Fund (LWCF) Act
				Potential-
X	X	X	X	North American Wetlands Conservation Act
	X	X	X	Watershed Protection and Flood Prevention Act

F	S	I	P	
				Planning
X	X			Emergency Wetlands Resources Act - National Wetlands Priority Conservation Plan
X	X	X	X	Endangered Species Act
X	X	X	X	EPA Wetlands Program State Development Grants
X	X			Land and Water Conservation Fund (LWCF) Act
				State Comprehensive Outdoor Recreation Plans (SCORP)
				State Wetland Priority Plans
		X		National Flood Insurance Program
X				BLM San Pedro National Riparian Conservation Area
X	X	X	X	Verde River Advanced Identification - Section 404
X				Wetland/riparian management policies for BLM, USFS, SCS, and USBR
				Restoration, Creation, and Management
	X			BIA Fish, Wildlife and Recreation Program
X				Executive Order 11988: Floodplain Management
X				Executive Order 11990: Protection of Wetlands
X	X	X		Federal Aid in Sport Fish and Wildlife Restoration Acts
X				Federal Land Policy and Management Act
X	X		X	Flood Control Act
X				Multiple Use Sustained Yield Act
X				National Forest Management Act
X				National Wildlife Refuge System Act
X	X		X	North American Waterfowl Management Plan
X				Organic Administrative Act
		X		Private Lands Assistance and Restoration Program
X				Public Rangelands Improvement Act
X	X	X		Resource Conservation and Development Program:
				Natural Resource Conservation District programs
X	X		X	Soil Conservation Service guidelines
		X		Wastewater Treatment Projects
X				Water Resources Development Act
X	X		X	Wild and Scenic Rivers Act
				Potential-
X				North American Waterfowl Management Plan
				Food Security Act (Farm Bill):
		X		Conservation Reserve Program
		X		Wetlands Reserve Program
X	X	X	X	North American Wetlands Conservation Act
		X		Stewardship Incentive Program
	X		X	Watershed Protection and Flood Prevention Act

F	S	I	P	
				Incentives and Disincentives
		X		National Flood Insurance Program
		X		Internal Revenue Code
X	X		X	Soil Conservation Service programs
				Potential-
				Food Security Act (Farm Bill):
		X		Swampbuster
		X		Agricultural Conservation Program
				Technical Assistance, Education, and Outreach
X	X	X		Emergency Wetlands Resources Act
				National Wetlands Inventory (NWI)
	X	X		EPA Wetlands Program State Development Grants
X	X	X	X	EPA technical assistance programs: Wetlands Protection Hotline
X	X		X	Wild and Scenic Rivers Act
X	X		X	Various Agency Programs by BLM, NPS, USFS, USFWS, USBR, COE, SCS, and USDA

C. Discussion

These relatively long lists of riparian protection mechanisms give the deceptive impression that sufficient protection is already in place for Arizona's diminishing riparian resources. Doppelt et al. (1993) state that "all levels of government have failed to stem the degradation of America's riverine systems and the extinction of riverine-riparian biodiversity. ...[T]here are no national policies that mandate coordinated federal, state, and private management and conservation of whole riverine systems. ...[N]o policies effectively integrate riverine protection and restoration with local economic benefits and community revitalization." While this latter perspective applies to the nation, a recent report by the Riparian Habitat Task Force (1990) substantiated the fact that there are no specific statutory mandates to protect riparian ecosystems in Arizona. What we do have is a mixed assortment of agency programs that are very restrictive in scope and effectiveness and at best offer limited or indirect levels of protection.

Existing riparian protective mechanisms are generally a component of a broader natural resource program with few mechanisms being riverine-riparian specific. Protective mechanisms tend to focus on reducing, and not necessarily eliminating, the negative effects of projects and activities on riparian areas. Many of Arizona's existing riparian protection mechanisms address only one or a few of the functional aspects of riparian areas such as:

- flood control
- water quantity
- water quality
- wildlife habitat
- biological diversity
- groundwater recharge
- erosion control
- bank stabilization
- recreation

Further, other programs apply only to specific land ownership categories, management agencies, discrete stream segments or are merely planning or policy guidelines that afford no real protection.

The Statewide Wetlands Strategies guidebook (World Wildlife Fund 1992) suggests that conducting an inventory of current programs, such as presented in this report, is a fundamental step in developing a statewide protection strategy and should lead to the following:

1) Identifying and establishing contact with groups whose programs affect riparian areas.
2) Discovering successful programs that may serve as models.
3) Identifying areas where cooperative efforts are possible.
4) Identifying weaknesses of programs or inconsistencies and gaps among them.
5) Locating sources of technical information and other useful resources.

After this information is gathered, the next logical step is to make existing programs more effective. Improving the effectiveness and efficiency of existing programs is an essential and important first step leading towards increased protection of riparian areas in Arizona. These improvements include intra- and interagency programmatic changes.

Intra-agency problems with existing riparian protection mechanisms include a lack of funding and personnel resources, technical support, authority, monitoring and evaluation capability, enforcement, consistency, predictability and timeliness. Furthermore, programs and guidelines for federal, state and local entities often conflict, are redundant, and are uncoordinated. These conflicts result in delays, case by case reconciliation, or worse, inaction. Some protection programs are cumbersome in that they are adopted haphazardly and incoherently, or have significant limitations that include large gaps in protection.

Interagency improvements of existing programs will require a high degree of cooperation and coordination with various agencies and groups--likely encountering many institutional barriers, policy and program conflicts, and limited or constrained resources. Making existing programs work better will require consideration of the following approaches.

Comprehensive approach requires: 1) coordination, integration and collaboration of various programs to achieve an overall goal for riparian area protection, 2) full utilization of the entire range of available mechanisms, 3) broaden scope of protection to include watershed or ecosystem, and 4) expansion of agency authority over riparian areas.

Flexible approach provides for: 1) a combination of programs and approaches as necessary and appropriate for an area, and 2) refining and coordinating programs by expanding successful programs and eliminating redundancy and inconsistencies in others.

Regional focus calls for the development of site specific, customized solutions while accounting for a variety of conflicting and competing local interests.

Doppelt et al. (1993) suggests that while improving existing policies is important, this will still not provide the strategies and policies needed to initiate an era of comprehensive watershed restoration leading to long-term maintenance and health of riparian ecosystems. There simply are no existing protection mechanisms that effectively protect all critical functions of riparian areas.

As a case in point, the Clean Water Act Section 404 program, while recognized as the nation's primary mechanism for protecting and improving water quality, is generally applied only to the low flow channel (ordinary high water) of streams in Arizona and delineated wetlands (which do not include riparian areas). Even within these applicable areas, many activities damaging to riparian areas are exempted from Section 404 regulatory authority or allowed to occur when prescribed terms and conditions are followed. Further, the large majority of Arizona's riparian areas lie outside Section 404 jurisdictional areas and therefore are not included within its limited regulatory protection.

The reader should note that there are also a few existing local and private mechanisms that afford some degree of riparian area protection within Arizona. Pima County has a Floodplain and Erosion Hazard Management Ordinance, a Comprehensive Plan including open space, and a Trail System Master Plan. A Tucson ordinance limits developments within areas of listed

washes. The City of Scottsdale has an Environmentally Sensitive Lands and a Native Plants Ordinance. Nonprofit conservation organizations such as the Nature Conservancy, Sierra Club, American Rivers, Arizona Riparian Council, Trout Unlimited, Arizona Wildlife Federation and others have acquired riparian areas, obtained instream flow water rights, provided technical and educational information, and/or provided funds for protection, restoration and management.

D. Summary of Findings

While this listing of regulatory and nonregulatory riparian programs in Arizona appears extensive, it is important to recognize that there are no regulatory programs at any level of government) specifically developed or implemented for the protection of riparian areas. Existing programs have only limited applicability to the protection of important riparian area functions by focusing only on the management and planning of water, soil and/or landscape--typically within a small geographic area. Furthermore, even though most of the listed programs have been in place for some time, it is widely recognized that some greater degree of riparian area protection is needed to preserve and maintain the health and integrity of our existing, yet declining, riparian resources in Arizona.

E. Synopsis of Wetland/Riparian Protection Program Reports

Arizona State Parks, Statewide Planning Section. 1988. Arizona wetlands priority plan - an addendum to the 1983 SCORP.

A plan developed to comply with the Emergency Wetlands Resources Act of 1986 and to be compatible with Statewide Comprehensive Outdoor Recreation Plans (SCORP) and the National Wetlands Priority Conservation Plan. This Arizona planning document includes: a description and an assessment of federal, state, local and private program effectiveness in protecting wetlands; a discussion of wetland resources; priorities for wetlands protection; state and local alternatives for wetlands protection;

Commission on Arizona Environment. 1991. Final report on agency authorities and programs relating to riparian resources. Prepared for the Arizona Governor's Riparian Habitat Task Force by the Arizona Department of Environmental Quality. (January)

A supporting document based on an instate survey of 10 state, 2 county and 11 federal agencies and Indian communities conducted for the Arizona Governor's Riparian Habitat Task Force. The report provides narrative summaries of agency and tribal statutory authorities, policies, programs and activities, and identifies problems associated with riparian management in Arizona.

Doppelt, B., M. Scurlock, C. Frissel, and J. Karr. 1993. Entering the watershed: a new approach to save America's river ecosystems. The Pacific Rivers Council. Island Press.

This newly released book is the product of a project to develop new federal river protection and restoration policy alternatives and represents one of the first national publications dealing strictly with riparian ecosystem protection strategies. The book assesses the capability of the nation's riverine conservation approaches and policies to address impacts to, and depletion of, riverine-riparian biodiversity. The authors conclude that existing riverine protection laws and policies are inadequate and have failed. A comprehensive new approach is proposed that includes: a strategic national community- and ecosystem-based watershed restoration initiative. The appendices include an extensive assessment and description of the nation's existing federal, state and local riverine policies and programs on federal, state and private lands.

Environmental Protection Agency. 1992. The private landowner's wetlands assistance guide: voluntary options for wetlands stewardship in Maryland.

A description of existing voluntary options and programs for private landowners who are interested in conservation with information about Federal, State, and private/nonprofit assistance programs which are available. The guide may be viewed as a way to help private landowners conserve and manage wetlands and other natural resources while attempting to simultaneously meet their economic needs and goals. Assistance includes technical information, financial incentives, and education and outreach opportunities.

Governor's Riparian Habitat Task Force. 1990. Final report and recommendations of the Governor's Riparian Habitat Task Force.

A multi-agency collaborative report with recommendations on establishing a comprehensive program of riparian resources management and preservation in Arizona. Recommendations include: approval of a state riparian policy, adoption of an Executive Order for the protection of riparian areas, implementation of priority management strategies, and coordination with federal and local agencies, tribal councils, and private organizations.

Governor's Riparian Habitat Task Force. 1990. Draft briefing paper: riparian management--implementation tools.

This paper explores programs, rules and policies currently available to implement six riparian area protection and enhancement Task Force policy statements. These policy statements represent the basis for a moderately comprehensive, yet practicable riparian protection program for Arizona. Information is provided on short and long term implementation and associated funding for: a statewide riparian inventory and classification, creation of a Watershed Enhancement Board, development of a State Riparian Area Protection Law, pursuing special protective designations for key riparian areas, enhancing local floodplain management planning, and legislation for a State Environmental Policy Act.

Kusler, J. A., C. Ray, M. Klein, and S. Weaver. In Draft (1993). State wetland regulation: status of programs and emerging trends. The Association of State Wetland Managers.

A report summarizing state or cooperative state/local wetland regulatory programs for all 50 states. Also indicated are trends and possible future directions for state programs based upon experience to date. The report includes summaries of wetland programs in each state as submitted by respondents, an evaluation of common and key components of state wetland regulatory statutes, emerging issues, and special projects, programs and nonregulatory initiatives.

National Audubon Society. 1992. Saving wetlands: a citizens' guide for action in California. Western Regional Office.

This manual is designed to guide individuals who are beginning their first action to protect wetlands, and to serve as a reference resource for long-time wetlands advocates. Included are chapters on: action strategies; wetland functions and values; federal, state and local levels of government regulatory and protective programs; loopholes and gaps in existing protection programs; and development of protection programs by the private sector. This manual is a supporting document for the Save Our Wetlands Campaign by the National Audubon Society.

Rich, J., and V. Coltman. 1991. Summary and recommendations: Clean Water Act Section 404 Discharge of Dredged and Fill Materials and Section 401 Water Quality Certification Programs in Arizona. Prepared for Arizona Department of Environmental Quality. (August 30, 1991)

An evaluation report on whether ADEQ's role in wetlands and riparian area protection could be strengthened and improved through Clean Water Act Section 401 certification and 404 permitting programs. Included are summaries and evaluations of Section 401 and 404 programs in Arizona and recommended procedural and regulatory protection improvements to make these programs more effective in protecting riparian areas.

Steiner, F., S. Pieart, and E. Cook. 1991. The interrelationship between Federal and State wetlands and riparian protection programs. Arizona State University Herberger Center. Prepared for Arizona Department of Environmental Quality. (July 26, 1991)

The report summarizes the results of a nationwide survey of state wetland and riparian protection programs. Regulatory and nonregulatory programs were queried and summarized by state. Federal Clean Water Act, Section 404 programs were also surveyed.

Want, W. 1990. Law of wetland regulation. Clark Boardman, Co., New York.

A treatise of wetlands law and regulation describing and analyzing protection regulations, case law, judicial decisions and agency regulations. The treatise includes practical advice on how to proceed through the regulatory process. Comprehensive and understandable, the treatise is a one-stop shoppers' source collection of all federal wetlands law.

World Wildlife Fund. 1992. Components of a California wetlands strategy - lessons from other states. Prepared for the California Resources Agency.

The report provides information about how other states have addressed the wetlands conservation issues now facing California. Sections include description of state wetland programs, state assumption of the Section 404 program, incentive programs, state acquisition and restoration programs, local and regional wetlands planning, state program general permits, Section 401 certification, and state and local wetlands regulatory programs. The information will be used to assist in the development of a statewide comprehensive wetlands protection strategy.

World Wildlife Fund. 1992. Statewide wetlands strategies: a guide to protecting and managing the resource. Island Press.

A management and planning guidebook on developing comprehensive, statewide wetland strategies. Sections include: creating a statewide wetlands strategy and selecting an overall goal; organizing a strategy development process; federal, state, local and private programs for wetland protection and management; and wetland data sources and collection methods.

List of Abbreviations

ADEQ	Arizona Department of Environmental Quality
ADMMR	Arizona Department of Mines and Mineral Resources
ADOT	Arizona Department of Transportation
ADWR	Arizona Department of Water Resources
AGFD	Arizona Game and Fish Department
ALRIS	Arizona Land Resources Inventory System
ARS	Arizona Revised Statues
ASLD	Arizona State Land Department
ASPB	Arizona State Parks Board
ATV	All Terrain Vehicle
AzMILS	Arizona Mineral Industry Location System
BLM	Bureau of Land Management
CAP	Central Arizona Project
COE	United States Army Corps of Engineers
CWA	Clean Water Act
DLG	Digital Line Graph
EPA	Environmental Protection Agency
ESI	Ecological Site Inventory
FERC	Federal Energy Regulatory Commission
FWCA	Fish and Wildlife Coordination Act
GIS	Geographical Information System
GPS	Global Positioning System
LWCF	Land and Water Conservation Fund
MMU	Minimum Mapping Unit
MRAV	Multiple Resolution Aerial Videography
NDVI	Normalized Difference Vegetation Index
NEPA	National Environmental Protection Act
NPS	National Park Service
NWI	National Wetlands Inventory
PNC	Potential Natural Community

RASES	Riparian Area Survey and Evaluation System
SCORP	State Comprehensive Outdoor Recreation Plan
SCS	Soil Conservation Service
SLIF	State Lake Improvement Fund
S-VHS	Super Video Home System
TM	Thematic Mapper
UA-ART	University of Arizona-Advanced Resource Technology Laboratory
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WET	Wetland Evaluation Technique
WWF	World Wildlife Fund

Glossary of Terms

Abiotic: Not pertaining to life; non-biological.

Aggradation: The process wherein a stream deposits its excess load to its channel (Cole 1983).

Alluvium: Any stream deposited sedimentary material (McKnight 1990).

Aquifer: A permeable subsurface rock layer that can store, transmit, and supply water (McKnight 1990).

Bed load: The part of a stream load that is rolling and sliding along because it is too heavy to be carried by suspension (Cole 1983).

Brightness value: Remote sensing systems record the amount of reflected or emitted energy exiting from the earth's surface. These data are stored as digital values on computer compatible tapes for digital image processing purposes. The greater the brightness of the scene (or return from the scene), the higher the digital value. Hence the values stored on the computer compatible tapes are often referred to as brightness values (Jensen 1986).

Biotic: Of or pertaining to life; biological (Steen 1971).

Classification: The process of assigning individual pixels of a multispectral image to discrete categories (Jensen 1986).

Clustering: The statistical analysis of a set of pixels to detect their inherent tendency to form clusters in multidimensional measurement space (Jensen 1986).

Degradation: Erosion of a stream channel; the opposite of aggradation (Cole 1983).

Denitrification: Reduction of nitrates to free nitrogen (McKnight 1990).

Digital data: Data displayed, recorded, or stored in binary notation (Jensen 1986).

Digitization: The process of converting material from a continuous into a discrete format (Jensen 1986).

Ecosystem: A natural unit of living and nonliving components which interact to form a stable system in which a cyclic interchange of materials takes place between living and nonliving units (Steen 1971).

Ecotone: A transition zone (Steen 1971).

Electromagnetic spectrum: The ordered array of electromagnetic radiation extending from short cosmic waves into radio waves (Jensen 1986).

Episodic: Events occurring on an irregular basis and without clear relationship to other events.

Fluvial: Pertaining to running water, including both overland and stream flow (McKnight 1990).

Ground truth: Term used in a remote sensing investigations to imply that the data collected in the field are without error (Jensen 1986).

Geographic Information System: A data base management system used to store, retrieve, manipulate, analyze and display spatial information (Jensen 1986).

Geomorphic: Of or pertaining to the figure of the earth or the forms of its surface (Cooperrider et al. 1986).

Guild: A group of species having similar ecological resource requirements and foraging strategies and therefore having similar roles in the community (Cooperrider et al. 1986).

Hydrologic: Relating to the science dealing with the properties, distribution, and circulation of water on the surface of the land, in the soil and underlying rocks, and in the atmosphere (Cooperrider et al. 1986).

Image: The representation of one object by something else. Usually, the recorded representation of a scene by optical, electro-optical, optical mechanical, or electronic means (Jensen 1986).

Landsat: Unmanned, polar orbiting, U. S. earth resources satellite (Jensen 1986).

Maximum likelihood rule: A statistical decision criterion to assist in the classification of overlapping signatures; pixels are assigned to the class in which they have the highest probability of being a member (Jensen 1986).

Mesic: Characterized by moderately moist conditions; neither too moist nor too dry (Steen 1971).

Multispectral: Refers to remote sensing in two or more spectral bands, such as visible and near-infrared regions of the spectrum (Jensen 1986).

Nitrification: The process of oxidizing ammonia to nitrite, and nitrite to nitrate (Cole 1983).

Physiographic: Pertaining to a description of the features and phenomena of nature (Neufeldt and Guralnik 1986).

Pixel: A picture element having both spatial and spectral properties. The spatial variable defines the apparent size of the resolution cell (i.e., the area on the ground represented by the data values), and the spectral variable defines the intensity of the spectral response for that cell in a particular band (Jensen 1986).

Raster: A cell data structure composed of rows and columns, with the value of each cell representing a feature value. Groups of cells are used to represent each feature (Environmental Systems Research Institute 1991).

Reduced soils: Soils in which one or more electrons are gained or soils having an addition of hydrogen atoms or a loss of oxygen atoms (Steen 1971).

Reflectance: The ratio of the radiant energy reflected by a body to that incident on it (Jensen 1986).

Remote sensing: The measurement or acquisition of information of some property of an object or phenomenon by a recording device that is not in physical contact with the object or phenomenon under study (Jensen 1986).

Satellite: An object in orbit around a celestial body (Jensen 1986).

Sensor: Any device that gathers energy, electromagnetic radiation or other, converts it into a signal, and presents it in a form suitable for obtaining information about the environment (Jensen 1986).

Seral: Pertaining to a succession of plant communities in a given habitat leading to a particular climax association ; a stage in a community succession (Cooperrider et al. 1986).

Signature analysis techniques: Techniques that use the variation in the spectral reflectance or emittance of objects as a method of identifying the objects (Jensen 1986).

Spectral band: An interval in the electromagnetic spectrum defined by two wavelengths or frequencies (Jensen 1986).

Spectral reflectance: The reflectance of electromagnetic energy at specified wavelength intervals (Jensen 1986).

Spectral response: The response of a material as a function of wavelength to incident electromagnetic energy, particularly in terms of the measurable energy reflected form and emitted by the material (Jensen 1986).

Spectral signature: Term referring to the spectral characteristic of an object in a scene, which infers that each object reflects radiation in a unique and identifiable manner (Jensen 1986).

Suspended sediment: The very fine particles of clay and silt that are in suspension and move along with the flow of water without touching the stream bed (McKnight 1990).

Thermal cover: Features that reduce the amount of energy expended by an animal to adapt to extreme changes in temperature and wind.

Topographic: Pertaining to a representation of surface features of a region on maps and charts (Guralnik 1984).

Vascular plant: Any plant possessing a system of vessels (xylem and phloem) to conduct water and food (Steen 1971).

Vector: A coordinate-based data structure commonly used to represent map features. Each linear feature is represented as a list of ordered x,y coordinates. Attributes are associated with the feature (as opposed to a raster data structure, which associates attributes with a grid cell) (Environmental Systems Research Institute 1991).

Wavelength: Wavelength = velocity/frequency. In general, the mean distance between maxima (or minima) of a roughly periodic pattern. specifically, the least distance between particles moving in the same phase of oscillation in a wave disturbance. Optical and infrared wavelengths are measured in nanometers, micrometers, and angstroms (Jensen 1986).

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APPENDIX C

REMOTE SENSING MAPPING OF ARIZONA

INTERMITTENT STREAM RIPARIAN AREAS

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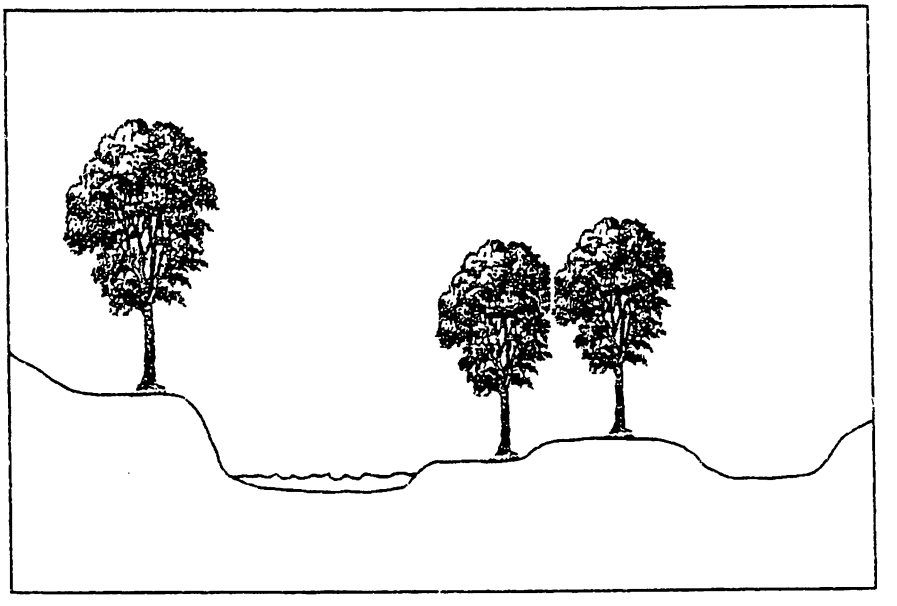
Charles R. Wahl, Nongame Biologist
Susan R. Boe, Research GIS Analyst
Jennifer A. Wennerlund, Research GIS Analyst
Richard A. Winstead, Nongame Biologist
Linda J. Allison, Nongame Statistician
Dennis M. Kubly, Nongame Program Support Supervisor



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Nongame and Endangered Wildlife Program
Program Chief: Terry B. Johnson
Arizona Game and Fish Department
2221 West Greenway Road
Phoenix, AZ 85023-4399

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ARIZONA DEPARTMENT OF WATER RESOURCES
WATER PROTECTION FUND
500 NORTH 3RD STREET
PHOENIX, AZ 85004

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The Arizona Game and Fish Department complies with all provisions of the Americans with Disabilities Act. This document is available in alternative format by contacting Mary Turner, Nongame Branch, Arizona Game and Fish Department, 2221 West Greenway Road, Phoenix, Arizona 85023-4399 -- (602) 789-3501.

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EXECUTIVE SUMMARY

This last phase of the Statewide Riparian Inventory and Mapping (SRIM) project concentrated on the remote sensing mapping of riparian areas along intermittent streams in Arizona. The effort followed on the heels of earlier work by the Arizona Game and Fish Department (AGFD) directed at remote sensing mapping of riparian areas associated with perennial streams (Valencia et al. 1993, Winstead 1997)). In both efforts, we attempted to differentiate riparian areas that met the legislated definition provided in ARS 45-101, as amended, that is, areas along waterways populated by plants whose existence is dependent upon deep roots implanted in the water table or its capillary zone. As identified by Winstead (1997), our working definition more closely approximated that of Lowe (1961) who defined a riparian plant association as one occurring in or adjacent to drainages and/or their floodplains and further characterized by species and/or life-forms different from that of the immediately surrounding nonriparian climax.

Valencia et al. (1993) used the approach advocated by Graham and Wissler (1992), a combination of Landsat Thematic Mapper (TM) satellite imagery and aerial videography, in an attempt to determine the extent of riparian boundaries along streams and to classify the vegetation in these areas. As reported by Winstead (1997), the first of these objectives was attained, but the latter could not be accomplished satisfactorily. Polygons of riparian vegetation along perennial streams were not adequately classified (≥80% accuracy) even though the 17 classes reported by Valencia et al. (1993) were combined into 10 classes.

Preliminary investigations of remote sensing techniques in a portion of the Tonto Creek Basin suggested that riparian vegetation along intermittent streams could be separated from upland vegetation with TM satellite data in part, but not all, of that area. The area in which TM data appeared to work successfully corresponded to several Brown and Lowe (1980) low to intermediate elevation vegetation classes that were termed collectively the "high contrast area." Riparian vegetation in the remaining high elevation classes, termed the "low contrast area," was assessed using multiple resolution aerial videography. No attempt was made to classify vegetation beyond riparian or upland within either of the areas.

The true identity of vegetation along intermittent streams was determined by field crews who were sent primarily to randomly selected sites thought to be dominated by riparian vegetation based on an interpreters evaluation of the satellite imagery. Sites were located by field crews from topographic maps and by using Geographic Positioning System navigation equipment receiving signals from orbiting satellites. Before testing accuracy of the remote sensing, we first evaluated consistency of field crews in assigning dominant plants as either riparian or upland. We found that the field crews were consistent at least 85% of the time in this determination, and for nine species of dominant plants they were 100% consistent.

TM satellite image analysis did not live up to our expectations for differentiating obligate to facultative riparian vegetation from upland vegetation in the high contrast area. The method produced an overall accuracy for the high contrast area of only 58.8%, and dominant plants were

not consistently classified as riparian or upland. Both user and producer accuracies exceeded our desired ≥80% in only two of seven Brown and Lowe (1980) vegetation classes. For both measures, riparian areas in most desertscrub biotic communities were differentiated from upland better than in grasslands.

Several reasons can be identified for our accuracy problem. First, initial designations of riparian and upland areas had to be made by applying density slicing to TM band ratios for the entire high contrast area, rather than restricting our sampling universe to just the intermittent streams and adjacent vegetation. This approach was necessitated by the lack of a base digitized intermittent hydrology map, which could not be produced in time to initiate this phase of the project. A second problem was the small size and linear nature of riparian areas relative to the pixel area and minimum mapping unit size for TM satellite image data. Many riparian areas are sufficiently narrow that the minimum mapping unit of two 30 m diameter pixels will not fall exclusively in streamside vegetation, but rather will exhibit hybrid reflectance from a combination of riparian and upland vegetation. A third problem was the interval of time between acquisition of the satellite imagery, which occurred in mid-1993, and the measurement of vegetation characteristics in the field, which occurred in 1995-1996. Intervening floods and vegetation growth may have contributed to differences in class identification between remote sensing and field crews.

A digital database of intermittent streams in Arizona eventually was created in a Geographic Information System (GIS) by using the U.S. Geological Survey (USGS) topographic digital line graph as a map base and adding assessments based on interviews with knowledgeable individuals from a wide variety of state and federal land management agencies. The database identifies approximately 10,000 km of intermittent streams in Arizona, an amount 25% greater than that previously identified for perennial streams in the state. About 54% of the intermittent stream reaches lie in the higher elevation low contrast zone, with the remaining 46% in the lower elevation high contrast zone.

Our aerial videography analysis was conducted to determine whether we could differentiate four classes of vegetation based on density of the riparian vegetation relative to the adjoining upland and whether the streamside vegetation was classed as obligate to facultative riparian or non-riparian. The four vegetation classes were as follows: (1) nearly bare substrate, i.e. cover <25%; (2) obligate to facultative riparian vegetation with canopy cover greater than the adjoining upland vegetation; (3) non-riparian streamside vegetation with canopy cover greater than adjacent upland; and (4) non-riparian streamside vegetation with canopy cover less than the adjacent upland.

The first test of accuracy using aerial videography was to determine whether we could distinguish reaches of intermittent streams with plant cover <25% (class 1) and ≥25% (classes 2-4). Eighteen of 19 evaluated reaches were judged correctly for an accuracy of 95%. Using the same data set, we next determined whether class 2, obligate and facultative riparian vegetation with canopy cover greater than the adjacent upland vegetation, could be distinguished from class 3, non-riparian dominated vegetation having the same canopy characteristic. The overall accuracy of this determination was only 55.6%, well less than our desired minimum of 80%.

Our next test was to determine whether class 2 could be differentiated from class 4, where the latter differed from the former in both species composition and relative cover. This comparison yielded an accuracy of 100% for our test sample. Next, we combined classes 1 and 4, and tested them against the combination of 2 and 3. This test asked whether areas having particularly low vegetative cover combined with areas of upland vegetation with relatively low plant cover could be separated from areas having either obligate to facultative riparian vegetation or upland vegetation, both with canopy cover greater than the adjacent upland. The result of this test was an accuracy of 100%. Therefore, we merged vegetation categories to differentiate two classes of streamside vegetation: (1) streamside vegetation more dense and more green than the adjoining upland; and (2) streamside vegetation not more dense and more green than the adjoining upland vegetation.

Of 5230 km filmed by aerial videography in the low contrast zone, 3442 km (34%) had streamside vegetation more dense and/or more green than the adjoining upland. When measured as the frequency of reaches classified with the same identity, the results were somewhat different; 48% of all reaches had vegetation judged more dense and/or more green than adjacent upland. Therefore, reaches containing heavier streamside vegetation were shorter and, possibly, more fragmented than those appearing no different from uplands.

Our success in mapping and classifying riparian vegetation through use of remote sensing was limited largely by technologies that are rapidly improving. For example, the 30 m pixel size limitation of Landsat TM satellite imagery has now been improved to a much finer 5 m scale. Since most of our riparian areas in Arizona are narrow bands of vegetation that lie along linear streamcourses, this is a major improvement for future use of remote sensing to define and classify these landscape features. With respect to work that could profitably be done with existing information generated during the SRIM project, including the earlier work of Valencia et al. (1993) and Winstead (1997), we provide the following recommendations.

1. Relational databases created to store, retrieve, and analyze ground truthing data for this project need to be integrated and attributed in a GIS to improve the utility of these databases. A metadata document needs to be created and provided along with any export of these data.

2. Data contained in ground truthing and digital databases have many potential applications, and they should be distributed to AGFD Regional offices and to other entities who wish them for their use. A work unit should be assigned to be responsible for communicating any updates of these databases to all recipients.

3. Given our inability to meet or exceed our minimum accuracy standard, we do not advocate that high contrast area intermittent stream riparian maps be produced without additional work. If an attempt is to be made to produce these maps, they should be adjusted through use of a buffer algorithm that disallows the designation of riparian more than a set distance from an intermittent streamcourse. This adjustment can be made now that an intermittent

streamcourse GIS cover exists. We recognize that the accuracy of such maps would not be known precisely, but they would represent our best available information for these intermittent stream riparian areas.

4. A classification system for Arizona riparian areas should be completed using ground truthing data from the perennial and intermittent stream investigations. The riparian classification system should not be strictly taxonomically based, but should include elements of structure that have been proven important to wildlife diversity. The classification system should be related to wildlife functions and values.

5. Develop a Riparian Vulnerability Index similar to the Aquifer Vulnerability Index developed by Environmental Protection Agency and Arizona Department of Environmental Quality to identify riparian areas in need of protection, restoration, or remedial action.

6. Integrate data held in the AGFD Heritage Data Management System into the GIS of hydrologic and riparian areas in Arizona to serve as a foundation for developing a management model for wildlife that depend on this important ecotone between terrestrial and aquatic systems.

REMOTE SENSING MAPPING OF ARIZONA INTERMITTENT STREAM RIPARIAN AREAS

Charles R. Wahl, Susan R. Boe, Jennifer A. Wennerlund,
Richard A. Winstead, Linda J. Allison, and Dennis M. Kubly

INTRODUCTION

Riparian areas lie within the floodplains of drainageways and are further characterized by vegetation different in species or life forms than that of the adjoining uplands (Lowe 1961, Szaro 1989). They are broadly recognized as important three-dimensional zones of direct interaction between juxtaposed terrestrial and aquatic ecosystems (Gregory et al. 1991). In the arid Southwest, green ribbons of riparian vegetation are particularly valuable for their functions in recreation, shade and shelter, scenic relief, wildlife habitat, flood attenuation, and maintenance of water quality (Szaro 1989). Riparian areas provide habitat for a wide array of wildlife species, particularly relative to their limited areal extent, and they comprise one of the most valuable and threatened habitats in Arizona (Szaro 1989) and the arid West (Kusler 1985).

Riparian areas have sharp environmental gradients that result in a diverse mosaic of habitats and functions in the larger landscape; thus, they are extremely valuable to the surrounding natural communities (Naiman et al. 1993). Because of greater available moisture, riparian plant communities typically have greater species diversity and structural complexity than the adjacent upland communities. Plant species adapted to saturated, or frequently wetted, soils add to the diversity of riparian areas when compared with the adjacent upland. Many studies have shown that there is a positive relationship between vertebrate and invertebrate species diversity and abundance and the complexity of vegetation structure of riparian areas (e.g. Carothers et al. 1974, Carothers and Johnson 1975, Anderson and Ohmart 1984, Knopf 1985, Nelson and Andersen 1994).

Concern for riparian areas in Arizona resulted in creation of the Waters-Riparian Protection Program (WRPP), amending Arizona Revised Statute (ARS) 45-101 (ARS 1992). This program included a mandate from the Arizona legislature to inventory and map riparian areas throughout the state. Perennial streams were given first priority for reporting; however, legislators were clear in their interest in the extent and condition of all natural intermittent and perennial riparian areas. ARS 45-101, as amended, excluded ephemeral streamcourses (washes), human-made impoundments, and water distribution, transportation, or storage systems from the definition of riparian areas.

Riparian areas are defined in the amended ARS 45-101 as "characterized by the presence of deep-rooted plant species that depend on having roots in the water table or its capillary zone." Lowe (1961) and others have recognized that riparian vegetation includes species and/or lifeforms that differ from the immediately surrounding upland vegetation. The broadest definition of riparian includes all vegetation adjacent to a stream (Arizona Riparian Council 1994). Kusler (1985) identified distinctive characteristics of all riparian areas: (1) located near water bodies (e.g.

streams, lakes, ponds); (2) populated by vegetation dependent on relatively high soil moisture content; (3) subject to periodic flooding; (4) contain alluvial or other characteristic soils; (5) serve special water-related functions (e.g. erosion control); and (6) have special management needs. Szaro (1989, 1990) classified riparian vegetation in Arizona and New Mexico into 28 community types based on analysis of vegetation data from 152 sample sites. Brown et al. (1979) provided many examples of riparian associations in Arizona in their digitized classification system for the biotic communities of North America.

For the purposes of conservation planning, Arizona Game and Fish Department (AGFD), Arizona Department of Environmental Quality (ADEQ), and Arizona Department of Water Resources were directed through WRPP to gather information on riparian areas and threats to these areas. AGFD mapped perennial stream riparian areas for most of Arizona except lands under the jurisdiction of Native American tribes, utilized Brown et al. (1979) as the basis for a riparian vegetation classification system, began the development of methods for assessing riparian area wildlife functions and values, and recommended an approach to development of an hierarchical designation system based on those functions and values (Valencia et al. 1993). AGFD used Landsat Thematic Mapper (TM) digital satellite data and multiple resolution aerial videography (Graham and Wissler 1992, Graham 1993) coupled with a GIS to map and classify perennial stream riparian vegetation (Valencia et al. 1993, Winstead 1997). They were able to remove areas of agricultural, urban, industrial, and mixed land uses from the GIS riparian cover by using GAP covers (Arizona GAP Project, in progress) to mask out areas of human use. This procedure was followed by a buffering process, which restricted areas not closely aligned with streamcourses on a digital perennial waters map. Corridors of riparian vegetation were then extracted from the remaining satellite scene.

Accuracy assessment of the statewide mapping and classification of perennial streams remained incomplete when reported by Valencia et al. (1993). Wennerlund et al. (1995) later estimated that accuracy of the Graham (1993) and Graham and Wissler (1992) method of vegetation classification was only 30% prior to modifications based on ground truthing data collected by AGFD field crews. Winstead (1997) later used field crew data unavailable at the time of publication of the Valencia et al. (1993) report and extrapolated their findings to the complete set of perennial riparian polygons. Winstead (1997) reported that 87% of riparian polygon boundaries in the data set available to him could be correctly delimited and separated from the adjacent uplands. He could not determine the statewide accuracy of the perennial stream riparian area mapping, however, because there was no opportunity to conduct a verification exercise with field samples from an untested area.

Adjustments to polygon boundaries made since Valencia et al. (1993) reported their findings reduced the estimate of statewide perennial riparian area from about 267,000 acres to 166,000 acres (Winstead 1997). Although AGFD did not map all perennial waters in the state, the latter figure is considerably less than the 279,000 acres (113,000 ha) of riparian area in Arizona estimated by Babcock (1968).

Based on results from the work of Graham and Wissler (1992), Valencia et al. (1993) included conifer, oak, mixed scrub, and mixed canyon scrub among 17 riparian communities (series level of Brown et al. 1979), although these dominants often are regarded as representing upland communities. They were included because the combination of satellite imagery and aerial videography was unable to consistently distinguish between obligate riparian plants, as described by ARS 45-101, as amended, and adjacent upland plants. Winstead (1997) reduced from 17 to 10 the number of vegetation communities reported by Valencia et al. (1993) to be riparian (Table 1). He emphasized that, in addition to species differences, contrasts in plant life-forms (shape, size, and density) are important features distinguishing riparian plants from their upland counterparts. Major changes in classification by Winstead (1997) included the combination of conifer-oak and tamarisk-arrowweed, and the elevational subdivision of cottonwood-willow (above and below 3200 ft) and conifer-oak (above and below 5000 ft). Despite this lumping of classes, Winstead was unable to improve the accuracy of vegetation classification above 45% for the analyzed samples.

Table 1. Riparian categories used by AGFD researchers in classification of perennial stream vegetation in Arizona as determined by remote sensing.

Winstead (1997)	Valencia et al. (1993)
Cottonwood-Willow	Cottonwood-Willow[1], Sacaton Grass (with Cottonwood)
Mesquite	Mesquite, Sacaton Grass[2], Mexican Elder, Desert Willow, Acacia
Tamarisk	Tamarisk, Arrowweed
Strand	Mixed Scrub
Wet Meadow	Mountain Meadow[3]
Russian Olive	Russian Olive
Conifer-Oak	Conifer[4], Oak[4]
Marsh	Cattail, Reed
Mountain Shrub	Mountain Meadow[5]
Mixed Broadleaf (Cottonwood-Willow[6], Sycamore, Oak and Conifer[7], Ash, Walnut, Maple, Mulberry, Hackberry, Alder)	Mixed Broadleaf

[1] Less than 3200 ft elevation; [2] Associations with mesquite and mixed scrub; [3] Without shrubs; [4] Greater than 5000 ft elevation; [5] With shrubs; [6] Greater than 3200 ft elevation; [7] Less than 5000 ft elevation

This report covers the application of remote sensing methods to mapping of intermittent stream riparian areas in Arizona by the AGFD. We provide an extensive evaluation of these methods and implications for our earlier studies of perennial riparian areas reported by Valencia et al. (1993) and Winstead (1997).

METHODS

INTERMITTENT STREAM HYDROLOGY

Valencia et al. (1993) discussed their approach to compilation of information on Arizona perennial streams and development of a digital database. A similar process was used to designate intermittent streams using the USGS topographic digital line graph (DLG) as a map base. Intermittent stream hydrology information was compiled from a variety of sources. District, regional, and state offices of state and federal land management agencies were queried for information on stream hydrology. Maps corresponding to the agency jurisdiction were sent to state and federal land management agency staff (AGFD, Bureau of Land Management [BLM], National Park Service, and U.S. Forest Service [USFS]) with a cover letter explaining the intended use of the information requested. Agency staff were asked to color code stream segments on the maps corresponding to perennial, interrupted perennial, or intermittent hydrology. Definitions of perennial, interrupted perennial, and intermittent (Meinzer 1923) were given in the letter. The office with the most direct knowledge of local conditions was contacted, e.g. Ranger District offices of USFS and Resource Area offices of BLM. AGFD riparian project staff also visited agency staff in person to discuss hydrology definitions and answer questions about the requested information.

Marked maps were compared to the perennial stream hydrology map produced by Valencia et al. (1993). Where two or more sources disagreed on stream segment hydrology, a follow-up call was made to resolve the difference. If differences could not be resolved, the segment identity was coded as "in dispute."

Intermittent stream segments from the source maps were attributed as perennial, interrupted perennial, intermittent, or in dispute and placed in a Geographic Information System (GIS) cover using the DLG as a base. Line segments representing stream hydrology were checked for continuity and accuracy within the GIS. Removal of the perennial, interrupted perennial, and all uncoded reaches resulted in an intermittent hydrology base cover. All isolated intermittent stream segments less than 0.8 km in length were then deleted, because they were too short for a project of this scale and resolution.

SELECTION OF IMAGE PROCESSING METHODS

Several remote sensing techniques are available and appropriate for distinguishing riparian and upland vegetation (Price and Ridd 1983, Turner and Gardner 1991, Bobbe et al. 1993, Wilkie and Finn 1996). Budget and time constraints led to the decision that satellite image interpretation was the most suitable method for this statewide project (Wennerlund et al. 1995). Landsat TM satellite image interpretation was the only technique not rejected outright, although our previous experience with TM on perennial streams caused doubt about whether we could resolve images as narrow as intermittent stream riparian corridors.

Using TM data and the Imagine® modeler, four different image processing methods were used to determine whether riparian and upland vegetation could be differentiated (Wennerlund et al. 1995): (1) a buffered unsupervised classification using the Normalized Difference Vegetation Index (Valencia et al. 1993); (2) an unsupervised classification using buffered TM satellite data (bands 3, 4, and 5); (3) a supervised classification using raw TM satellite data (bands 3, 4, and 5); and (4) an index derived from the ratio of band 4/band 3 followed by density slicing (Haralick 1973, Jensen 1986, Campbell 1987, Turner and Gardner 1991).

The efficacy of each image processing method was evaluated by examining locations in a test area during a two day visit in late summer 1995, and by reference to the National Wetlands Inventory database. A partial TM scene (TM Path 36 Row 36 imaged June 20, 1993) covering an area of 5000 km^2 was used as the test area. The area (Fig. 1) included perennial and intermittent streams within the Salt River watershed from its confluence with the Verde River north and east to Tonto Basin. It was selected because it contained desert (Arizona Upland Sonoran Desertscrub), middle elevation (Semidesert Grassland and Interior Chaparral), and high elevation (Great Basin Conifer Woodland and Petran Montane Conifer Woodland) vegetation.

Two conclusions were drawn from this evaluation: (1) the most effective differentiation of riparian and upland vegetation was obtained from an index based on the band 4/band 3 ratio (method 4 above); and (2) TM data were not sufficient for distinguishing all riparian and upland vegetation communities along intermittent streams. We refer to those communities where TM data and image processing were judged inadequate as "low contrast" and those where TM was adequate as "high contrast." Low contrast communities in our test area were at medium to high elevations, while high contrast areas were at low elevations. Further inspection revealed that divisions between low and high contrast communities separated along community lines identified by Brown and Lowe (1980). Therefore, TM satellite data and image processing were applied only to those intermittent streams passing through Brown and Lowe biotic communities in the low elevation, high contrast areas (Table 2, Fig. 2). Aerial videography, which was used by Valencia et al. (1993), was chosen for evaluation of the low contrast zone.

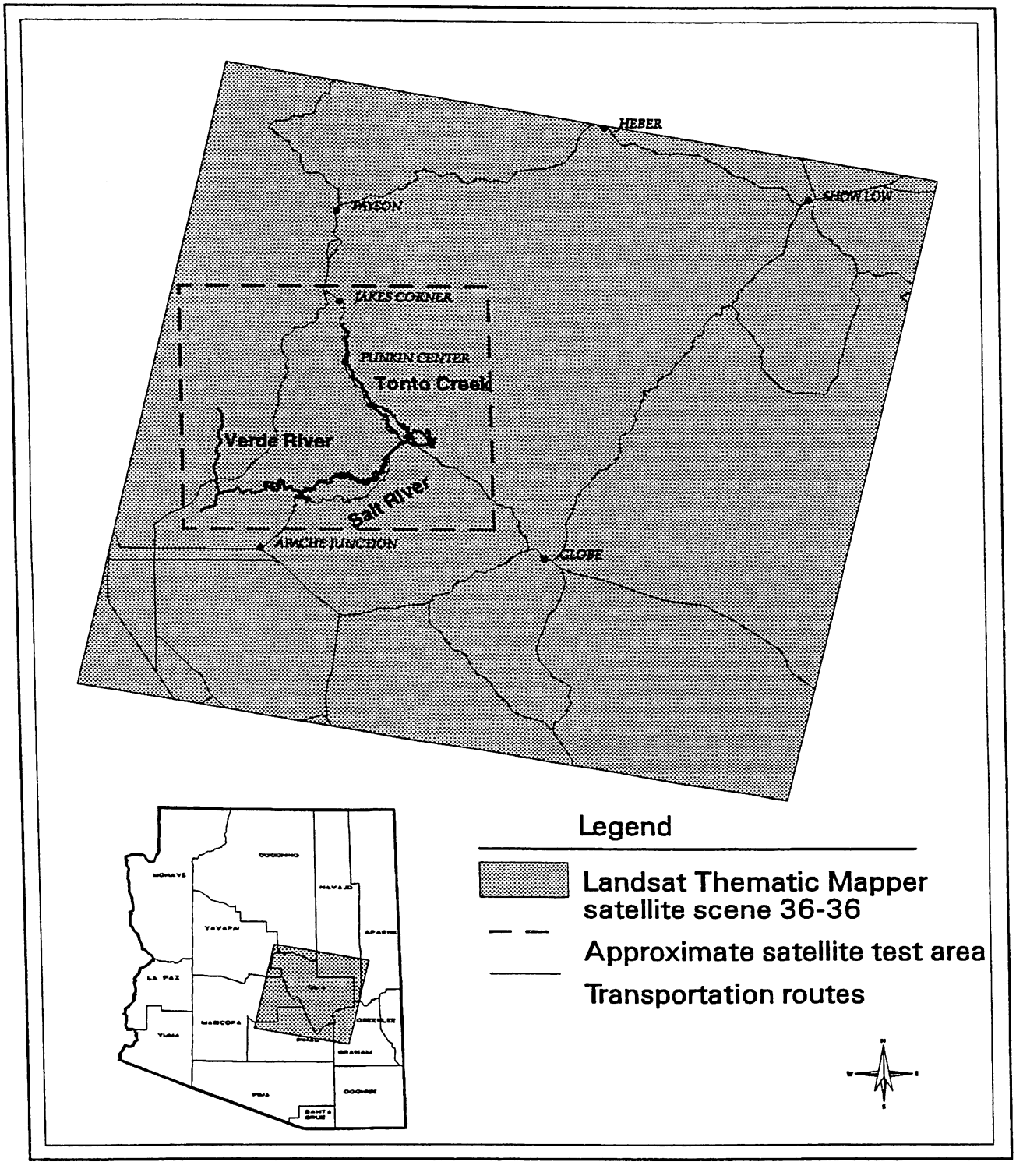

Figure 1. Area of the Tonto Basin used to develop and test remote sensing techniques for intermittent stream mapping.

Table 2. Vegetation communities in low and high contrast classes for the Arizona intermittent stream vegetation mapping project, 1995-96. Communities after Brown and Lowe (1980).

HIGH CONTRAST	LOW CONTRAST
Chihuahuan Desertscrub	Interior Chaparral
Mohave Desertscrub	Madrean Evergreen Woodland
Great Basin Desertscrub	Great Basin Conifer Woodland
Arizona Upland Sonoran Desertscrub	Petran Montane Conifer Forest
Lower Colorado Sonoran Desertscrub	Petran Subalpine Conifer Forest
Plains and Great Basin Grassland	Subalpine Grassland
Semidesert Grassland	

HIGH CONTRAST ZONE MAPPING

Image Processing

A major challenge to completion of intermittent stream mapping was lack of a digital hydrology base prior to initiation. Waiting until completion of that base was not possible, because of time constraints in completing the project. Because the satellite imagery was available that had been collected during perennial mapping in 1993 (Fig. 2) and the aerial videography was not, it was decided to initiate high contrast area image processing. Use of the 1993 satellite imagery created the additional problem of temporal differences between remote sensing and field crew measurements caused by intervening floods and revegetation, but this problem could not be avoided. By the time the high contrast zone mapping was complete, the intermittent hydrology base also was available for use in developing the sampling regimen for aerial videography and the low contrast zone field crew ground truthing.

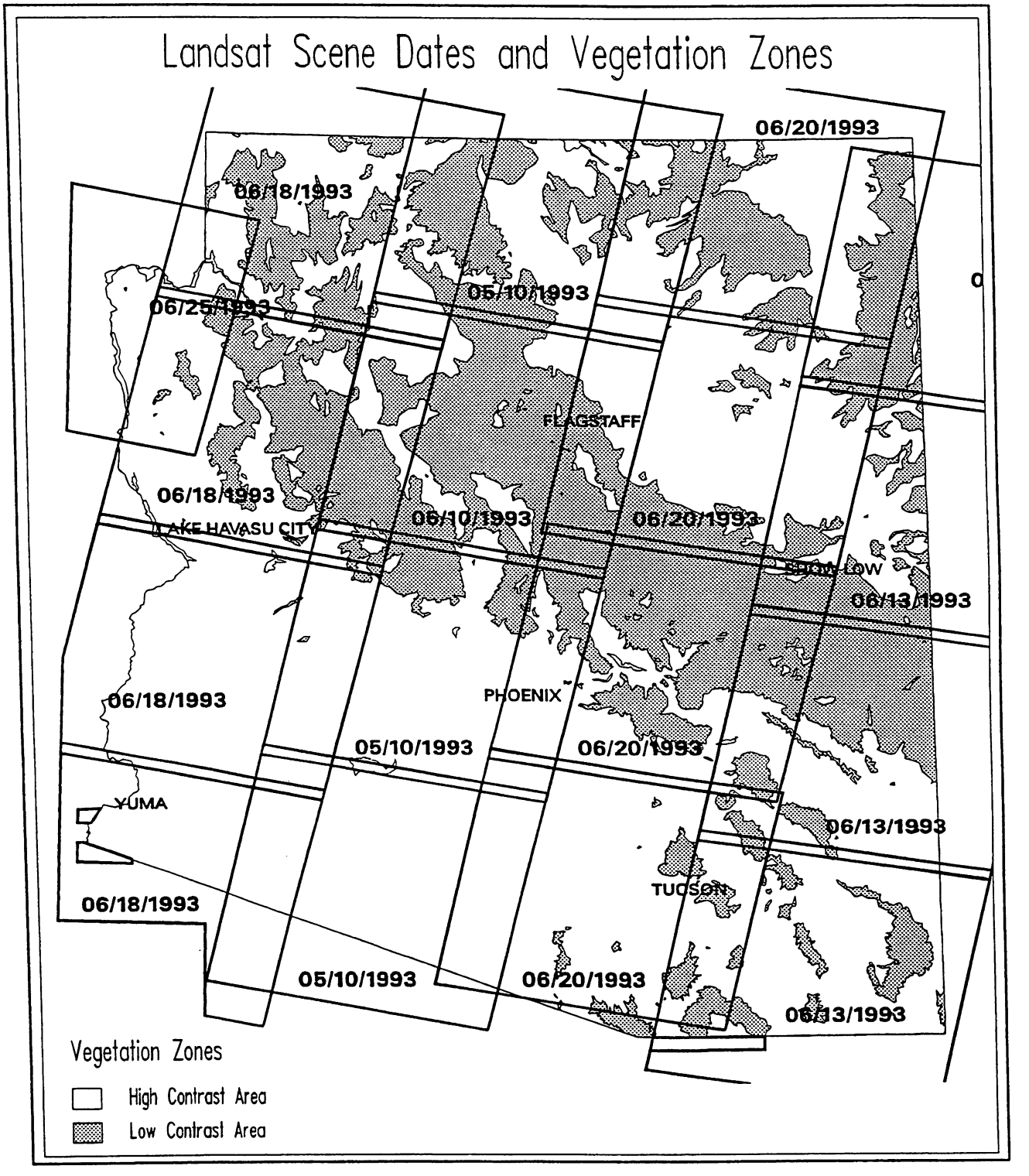

Figure 2. Landsat TM satellite imagery scenes with dates of acquisition and division of low contrast and high contrast vegetation areas.

The method of TM satellite imagery enhancement for the high contrast zone was selected to help remove shadow effects from the imagery, since initial digital values contain mixed information from surface reflectance and shadowing. A band ratio decreases the effect of reflectance caused by topographic variables (Campbell 1987). Thus, an image interpreter can examine spectral properties of surfaces without unduly confusing the effects of mixed topographic brightness and material reflectance. Separating the two is necessary if thematic information is to be derived from the image (Campbell 1987). Band ratios also can be used for discriminating between soils and vegetation (Satterwhite 1984).

Density slicing is the conversion of the continuous gray tone of the band ratio image into a series of discrete intervals, each corresponding to a range of band ratio values (Jensen 1986). We assigned unique colors to individual band ratio ranges to designate what the interpreter thought was vegetation associated with stream channels.

Landsat scenes were merged into six working areas (files), each for a different geographical area (Fig. 3). The biotic communities of Arizona (Brown and Lowe 1980) digital database developed by AGFD was used in ARC/INFO® to create a vegetation mask attributed with two values (1 = high contrast; 2 = low contrast). The mask was used to remove low contrast portions in each of the six working areas from further analysis. The Imagine® modeler was used to perform the band 4/band 3 ratio analysis on the six working areas to identify reflectance values thought to represent vegetation associated with stream channels. Output of the model was a single band image with values ranging from 0 to 255.

The resulting image was displayed as a pseudocolor image in Imagine®. Using a table that displayed the digital (density slicing) values, the image interpreter identified the range of ratio values that was thought to identify riparian vegetation. Value ranges were determined by visually comparing Landsat 3-band color composite photographic prints (1:250,000 scale) to hydrologic (linear and dendritic) patterns on the projected image. This interpretation was necessary because an intermittent stream digital hydrology cover was not yet available to use as a base for the mapping. Comparisons with previous vegetation mapping efforts and interpreter knowledge also were used to determine the range of density slicing values used to code presumptive riparian areas. Once the ranges were selected for each of the six separate working images, they were recoded to contain two values (1 = presumptive upland, 2 = presumptive riparian vegetation.

Working images were further processed to remove areas of "spectral confusion." The GAP agriculture/urban land cover layer (Arizona GAP Project, in progress) was modified to identify boundary inaccuracies in the biotic communities digital layer, highly reflective agricultural fields and temporal changes in vegetation patterns. Areas where spectral confusion occurred were delimited from Landsat 3-band color composite photographic prints. Often this spectral confusion occurred at the boundary between the high and low contrast areas. The resulting cover was used

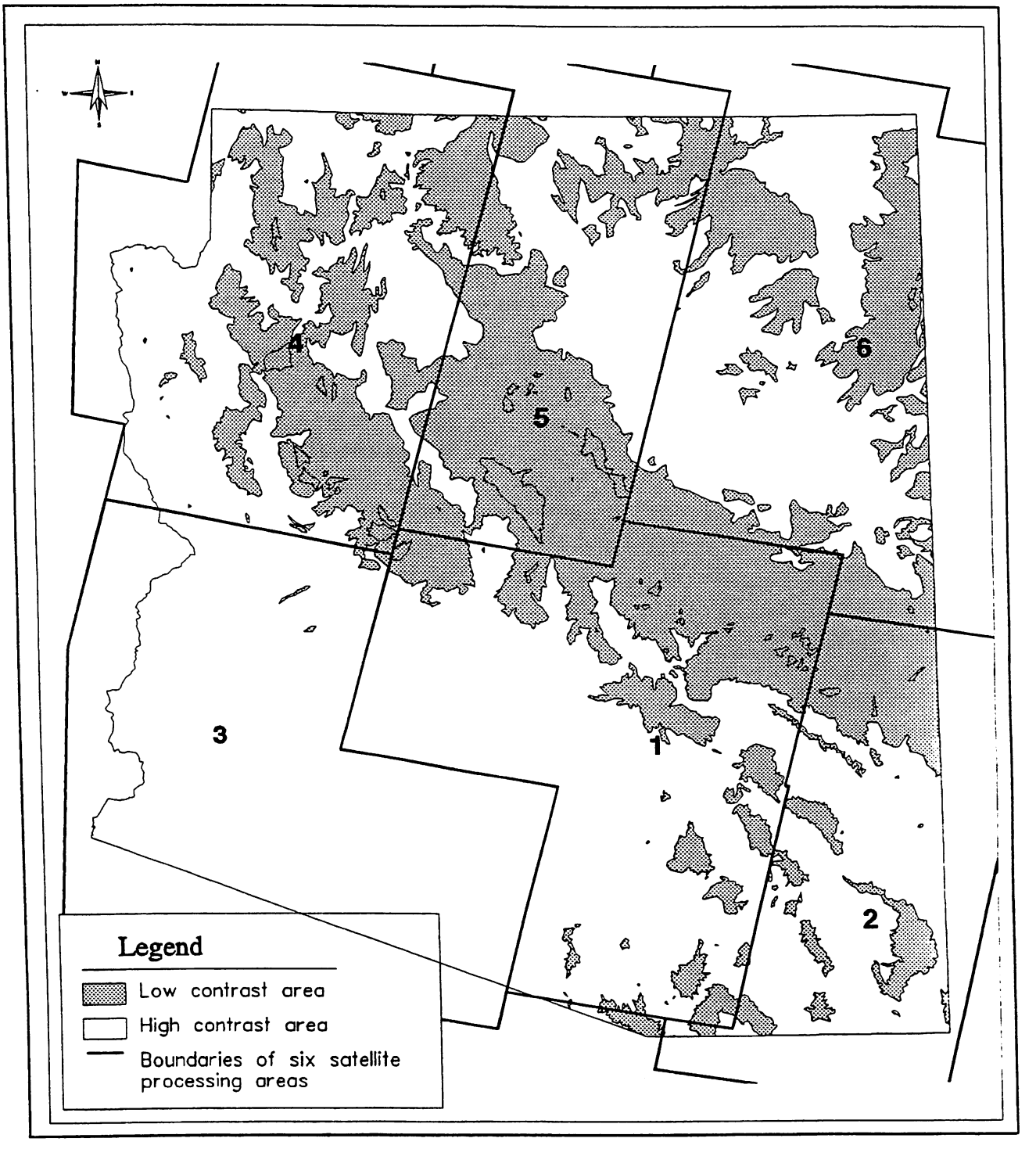

Figure 3. Six geographic working areas merged from the Landsat TM satellite scenes, with high contrast and low contrast boundaries.

as a mask on the recoded satellite image. When all six satellite areas were masked, the images were mosaiked into one database to form the classified statewide image.

Field Verification

Accuracy of the satellite-generated classification was evaluated at 782 randomly sampled field plots. These plots were classified as riparian or upland by field crews based on the identities of predominant vegetation, and the results were used to assess map accuracy. Sample site coordinates were chosen from the putative riparian vegetation satellite GIS cover using a random point generating algorithm in Imagine®. We concentrated our limited time and resources on examining the accuracy of classification for riparian vegetation, since that was of much more importance than the upland vegetation. In most cases, sample sites were limited to public lands where permission for access was readily gained.

Field observers attempted to reach the precise sample site coordinates by using topographic maps, triangulation, and Global Positioning System (GPS) receivers, but field plot coordinates were not known exactly until the GPS location file was processed. Wherever possible, a GPS rover file (computerized) with at least 180 positions was recorded at the plot. After returning from the field, the GPS location file was differentially corrected and averaged using PFINDER® software (Trimble Navigation Limited 1992) to obtain an accurate location for the field plot. Thus, accuracy assessment evaluated the classification of field plots actually observed.

To compensate for position and resolution errors in the satellite image (Campbell 1987, Jensen 1986, ERDAS 1991, Verbyla 1995), field crews were instructed to make all vegetation plot observations away from distinct transitions in vegetation composition (edges). Crews attempted to locate sample observation plots within relatively homogeneous stands of vegetation at least 50 m from any edges. Where the "target" riparian coordinate resulted in an ecotonal location having heterogeneous vegetation, the crew made a note on the field form indicating the nature of the site.

Each sample plot covered a circular area having a 30 m diameter. The following vegetation variables were used for ground truthing:

1. Total canopy cover of all perennial species (0-25%; 26-50%; 51-75%; and 76-100%.
2. Predominant perennial species (up to three) based on canopy cover.
3. Relative cover of each predominant species as a percentage of the 30 m diameter plot.

The GPS file (rover file) name was recorded on the field data form for later differential correction and determination of spatial coordinates. The crew then identified each site as riparian or upland, based on composition of predominant vegetation. Sites classified as riparian contained predominant plant species considered to be obligate riparian or wetland indicators (Dick-Peddie

and Hubbard 1977, Minckley and Brown 1982, Dick-Peddie et al. 1987, Reed 1988, see Appendices A and B, this paper).

Field Crew and Remote Sensing Consistency

A necessary precursor to testing the accuracy of TM satellite imagery interpretation was to determine how consistent field crews were in using specific plants to identify high contrast plots as riparian or upland. Crews were expected to be consistent and their determinations were taken as "truth," but no specific criteria were provided for which vegetation constituted "riparian" other than the limited language provided by the legislature in ARS 45-101, as amended. Therefore, before testing accuracy of remote-sensing, we first evaluated whether crew classifications were consistent in assigning dominant species as riparian or upland. To evaluate this, we examined the most prevalent plants on each plot. Eighty-two plant species served as dominants for 681 plots tested; an additional 66 plots were bare or covered only by annuals (grasses and forbs), and six plots were dominated by unidentified shrubs. Only 28 of the 84 dominant plants were dominants on at least five plots. We evaluated consistency of field crew classifications using these 28 plants. If 80% of the classifications were consistently either riparian or upland, the crew was judged consistent with regard to that species.

Accuracy Assessment Data Analysis

The vegetation, observers, substrate, and other variables on the field form, including the GPS rover file name, were entered into SPSS® (Norušis 1993) files. The GIS file containing the satellite image classifications was then merged with the SPSS® file for all rover file names. Thus, each set of vegetation observations from the field had an associated satellite image classification based on the location coordinates. We converted to dBASE® (.dbf) database files for storage and retrieval (Appendix A), but used these files as input to SPSS® to examine differences between TM and crew classifications. This was done by generating an error matrix, according to the conventions of remote sensing accuracy assessment (Congalton 1991, Verbyla 1995).

Our accuracy assessment method may underestimate accuracy, because it assumes an exact spatial match of TM pixels and field crew plots, i.e. it is unforgiving of positional errors in the Landsat imagery and GPS coordinates. For our particular data set, this method also is conservative because the narrow width of many intermittent stream riparian corridors results in a mixed pixel effect and drops below the level of resolution recommended for Landsat TM (approximately 1:100,000 scale; Welch et al. 1984, W. Krausmann, USFS, pers. comm.). As a lower limit, it is recommended that linear features, such as riparian corridors, should be at least 2-3 pixels (60-90 m) across to be detected consistently (W. Krausmann, USFS, pers. comm.). Because many perennial stream riparian corridors in Arizona are narrower than this limit (Winstead 1997), some intermittent riparian corridors may not have been detected by this inventory. This problem would have been reduced if the digital intermittent stream hydrology base cover had been available.

Field crews were instructed to locate 15 m-radius plots in the center of homogeneous parcels having radii of at least 65 m, so our assessment relaxes the site-specific assumptions that otherwise make error matrices so conservative. We also relaxed the requirement for a one-to-one match by running a non-site-specific assessment (optimistic *sensu* Verbyla 1995). Using this method, a TM-classified pixel was considered in agreement with the field-identified riparian plot if the field coordinates for this plot fell inside a pixel coded as streamside vegetation (as for the conservative assessment), or was within 30 m (1 pixel) from a pixel classified as riparian vegetation (this makes the assessment "non-site-specific"). The same logic was applied when field coordinates for plots identified as upland fell inside a pixel coded as upland or was within 30 m of a pixel coded as upland.

The non-site-specific accuracy assessment depends on the reliability of classifying adjacent pixels. We evaluated the suitability of the non-site-specific assessment by using an independent source of information to classify pixels. We used USGS 7.5 minute topographic maps to provide information on local drainage patterns for a random sample of 61 plots, 25% of the 245 cases where non-site-specific assessment reversed a conservative assessment. For each plot, we identified the coordinates on both the GIS image and on the topographic map. To be accepted as a correctly classified riparian observation, the plotted GIS location had to be: (1) within 100 m of a USGS stream symbol and at the same elevation; (2) within 30 m of the field sample plot boundary; and (3) associated with a linear or dendritic pattern similar to that of the streamcourse shown on the USGS topographic map.

To further compare crew classification and satellite classification, we looked for significant differences in the predominant species composition. Classes analyzed (from the 2X2 error matrix) were:

1. Upland vegetation classed riparian in the satellite image (commission errors).
2. Riparian vegetation classed upland in the satellite image (omission errors).
3. Riparian vegetation classed riparian vegetation in the satellite image.

Each of the above classes was compared using the entire data set and within Brown and Lowe (1980) biotic community strata.

Low Contrast Zone Mapping

Remote Sensing

Aerial videography was used to obtain remote sensing data on riparian vegetation along low contrast area intermittent streams contained in the intermittent hydrology database. Flights were made in a Cessna 206 equipped with a GPS receiver, video camera (VHS format), Horita® digital encoder, and a computer for storing information from the GPS (modified from Graham and Wissler 1992, Graham 1993). To reduce the effects of canyon shading, they usually were

conducted in the morning after the sun had risen to a favorable angle. Occasional zooming of the video camera lens was used for a series of test flights in an attempt to identify stand species composition.

A video interpreter differentially corrected the flight GPS files, transferred the output to the GIS system, and observed the video tapes using a video player. The flight GPS file contained a time code recorded on the audio channel of the video tape. The video interpreter watched the video tape and recorded the starting and ending time code for each stream reach assigned to the following cover classes:

(1) nearly bare substrate, i.e. cover <25%;
(2) obligate riparian vegetation with canopy cover greater than the adjoining upland;
(3) non-riparian vegetation with canopy cover greater than adjacent upland;
(4) non-riparian vegetation with canopy cover less than the adjacent upland

We tested our ability to classify streamside vegetation into the above four cover classes by comparing a video interpreter's classification of visible spectrum aerial videography (Bobbe et al. 1993) with corollary field crew observations (Valencia et al. 1993). We were especially interested in determining if stands of riparian vegetation meeting the definition provided in ARS 45-101, as amended, could be distinguished from stands of upland vegetation growing along the stream channel.

Four intermittent streams in the low contrast zone--Pumphouse Wash, Wildcat Canyon, Salome Creek, and Workman Creek--(Fig. 4) were chosen for initial interpretation. Once interpreted, randomly drawn stream reaches from each of the four cover classes were sampled in three reach length classes: 200 to 500 m; 500 to 1500 m; and >1500 m.

Field Evaluation: Aerial Video Classification

To determine field sample plot placement within the video interpreted reaches, each one was divided into consecutively numbered 15 m lengths. Random numbers, each corresponding to a 15 m length, were drawn to determine which 10 plots (10X15 m) would be sampled in each reach. Plots were oriented with the long axis (15 m) parallel to the stream axis. One long edge of the plot was placed nearest the thalweg, the deepest part of the channel. Thus, areas closest to the channel were within the plot. If the active channel was so wide that the plot contained no vegetation, the plot was offset. Plots were alternated on either side of the stream.

Each plot was divided into two vertical strata, shrubs (<3 m tall) and trees (>3 m tall). For each plant in the shrub plot the observer recorded species identification and maximum canopy dimensions (length and width) to the nearest decimeter. Mat forming species or species with multiple stems (e.g. *Rosa* spp.) were measured as a clump, and several 1X1 m subplots used to estimate the average number of stems per unit area.

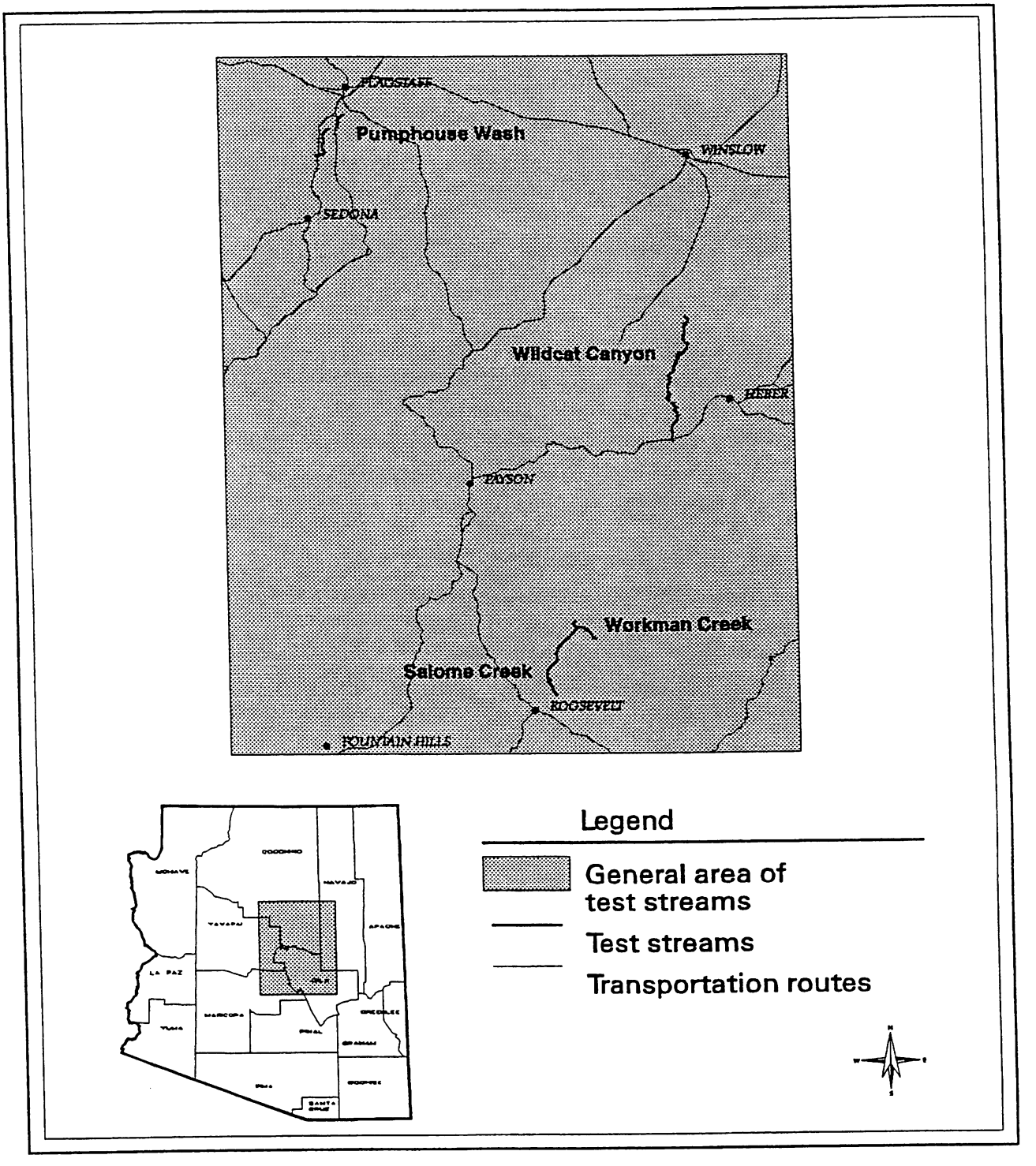

Figure 4. Map of four intermittent test streams used to test aerial videography in the low contrast zone.

In the tree plot (>3 m) the observer recorded species, stem by size class, maximum canopy dimension to the nearest 0.5 m, and height to the nearest 1.0 m of the canopy within the plot for each plant. Only the portion of canopy within the plot was measured for trees with stems located outside the plot. Where possible a GPS receiver was used to record a rover file, which was later corrected to determine the exact location of the sample plot. Satellite geometry and steep canyons sometimes prevented an accurate GPS location. Several accurate GPS locations were known for each reach, however, so it was possible to measure from the known locations to other sample plots using USGS topographic maps.

Data Analysis

For each plot we calculated total cover, relative cover by species, and a riparian plot score. For all species in the plot the canopy area was calculated as the area of a circle of diameter d, where d equals the average of the two canopy measurements length (L) and (W) ($d = (L+ W)/2$) rounded to the nearest 0.5 m. Relative cover is the sum of canopy area for a given species divided by the sum of canopy area for all species in the plot. Total cover was the sum of canopy area for all species, expressed as a percentage of the plot area (150 m^2).

Plot riparian scores were derived from a species-specific riparian ranking and an importance value for the species in a plot (relative cover). Each species was ranked 1-5 along a wet-dry scale (1 = obligate wetland to 5 = upland), based on the frequency of occurrence of that species in wet or dry soils (see Dick-Peddie et al. 1987). We used Reed (1988) as our main standard to rank each species (Appendix B, C) and supplemented that work with information from Dick-Peddie and Hubbard (1977), Dick-Peddie et al. (1987), and Szaro (1989). Species not listed in these references were ranked 5 (upland), unless contraindicated by other references.

For each species in a plot, a riparian score was calculated by multiplying the species' riparian rank by its relative cover. Summing the species riparian scores for each plot provided the plot's riparian score. Plot scores were interpreted as ≤4 = riparian and >4 = upland. By using a score of 4 as the break between riparian and upland, we included in the riparian class many species commonly considered facultative riparian plants (e.g. mesquite, *Prosopis velutina*).

For each stream reach, plot scores and plot total cover were evaluated for both tree plots and shrub plots. If 80% of the plot scores in the reach matched the video classification and had total cover >25%, the classification and ground observations were judged a match. If ≥20% of plot scores were not matches with the video classification, the reach was considered incorrectly classified. Reaches in class 1 (canopy cover <25%) were judged solely on canopy cover, without regard to plot score (riparian or upland), because the class was based on canopy cover alone (<25%).

RESULTS

INTERMITTENT STREAM BASE HYDROLOGY

Based on information from our intermittent hydrology database, there are approximately 10,000 km of intermittent streams in Arizona (Fig. 5, Table 3). This amount is about 25% more than the 8,100 km (5,020 mi) of perennial streams identified by Valencia et al. (1993). Our estimate is probably somewhat conservative, because all streams may not be included and stream reaches considered in dispute were excluded. About 54% of the intermittent streams distance occurs in the higher elevation streams of the low contrast zone, leaving 46% in the high contrast zone. Considerably lesser lengths of intermittent streams are found in the Mohave Desertscrub, Petran Subalpine Conifer Forest, and Subalpine Grassland biotic communities than in the remaining Brown and Lowe (1980) classes.

SATELLITE IMAGE CLASSIFICATION ACCURACY

Field Crew and Remote Sensing Accuracy

The field crew was very consistent in their assignment of riparian and upland identities based on the dominant plant species. Details not evident from Table 4 are that the crew was consistent at least 85% of the time, and for nine species they were 100% consistent. In contrast, remote sensing was not consistent or accurate. This impression is compounded when we ask whether remote sensing was classifying plots with at least better accuracy than random. To test this, we ask if the 95% confidence interval for these accuracies overlaps 50%. If so, this accuracy is no different from tossing a fair coin to label a plot upland or riparian. With a single exception, classification of these plants can not confidently be said to differ from random. The single exception is velvet mesquite, which was classified as riparian 64.1% of the time. The natural history of this species, particularly its ability to use relatively deep groundwater, provides an understanding of the capability of this plant to live in streamside corridors and at considerable distance from streams. This ability also is reflected in the Reed (1988) facultative upland riparian rating for the species and the fact that the field crew classified it as riparian 68.6% of the time.

Another point can be made by considering Table 4. Eight species were consistently ranked either upland (*Larrea tridentata*, *Gutierrezia sarothrae*, *Cirsium* spp., *Acacia greggii*, *Chrysothamnus nauseosus*) or riparian (*Opuntia* spp., *Pinus ponderosa, Cercocarpus betuloides*) by TM. Although the plants classified as upland by TM are in agreement with field crew classifications, it is instructive that the three classified as riparian by TM were considered upland by the field crew and not included by Dick-Peddie and Hubbard (1977), Dick-Peddie et al. (1987), or Reed (1988) in their lists of riparian and wetland plants.

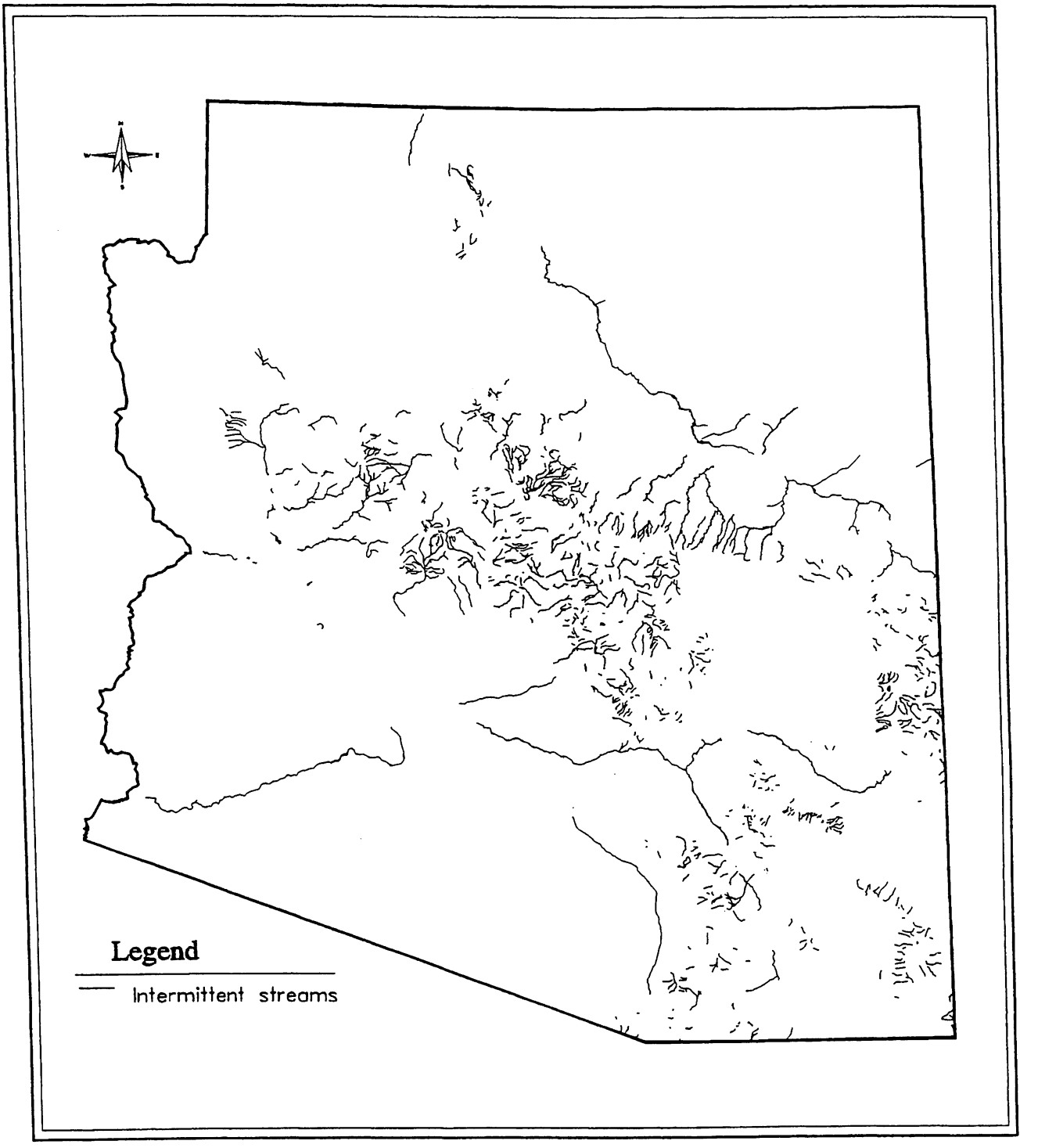

Figure 5. Map of known intermittent streams and stream reaches in Arizona.

Table 3. Total length of intermittent stream reaches within Brown and Lowe (1980) biotic communities as estimated from AGFD GIS digital hydrology database.

Upland Biome	Stream Length (km)	Zone Fraction (%)	State Fraction (%)
Arizona Upland Sonoran Desertscrub	1,520	33	15
Lower Colorado Sonoran Desertscrub	574	12	6
Mohave Desertscrub	8	<1	<1
Chihuahuan Desertscrub	137	3	1
Semidesert Grassland	1,036	22	10
Plains and Great Basin Grassland	693	15	7
Great Basin Desertscrub	695	15	7
High Contrast Zone Total	*4,663*	*100*	*46*
Great Basin Conifer Woodland	1,838	33	18
Interior Chaparral	1,602	29	16
Madrean Evergreen Woodland	707	13	7
Petran Montane Conifer Forest	1,350	24	13
Petran Subalpine Conifer Forest	63	1	<1
Subalpine Grassland	12	<1	<1
Low Contrast Zone Total	*5,574*	*100*	*54*
State Total	**10,237**		**100**

Conservative Accuracy Assessment

We assessed our confidence in the Landsat TM-based classification of riparian and upland ground types by comparing these assignments with those from field sample verifications. Plots that were identified as riparian by TM were over-sampled deliberately relative to their proportion in the GIS cover, because it is our ability to correctly identify riparian plots that is most important to this study. Plots identified as upland are in the sample set only because GPS error caused the field crew to sample them in lieu of desired riparian plots.

Three measures of accuracy--overall accuracy, user accuracy and producer accuracy--can be assessed by comparisons of TM and field crew designations in an error matrix (Congalton 1991,

Table 4. Consistency of crew and of TM in classifying plots as riparian or upland based on dominant plant species. Scores for consistent, i.e. ≥80% correct, are (1) upland; (2) riparian; and (3) not consistent.

Dominant Plant		Consistency		
Common Name	Taxonomic Name	Remote	Crew	No. of Plots
Velvet mesquite	*Prosopis velutina*	3	3	158
Juniper	*Juniperus* spp.	3	1	86
Shrub live oak	*Quercus turbinella*	3	1	53
Creosote bush	*Larrea tridentata*	1	1	46
Salt cedar	*Tamarix pentandra*	3	2	46
Toothleafed sagebrush	*Artemisia tridentata*	3	1	30
Oak	*Quercus* spp.	3	1	26
Fremont cottonwood	*Populus fremontii*	3	2	22
Four-wing saltbush	*Atriplex canescens*	3	1	19
Rabbitbrush	*Chrysothamnus nauseosus*	1	1	19
Broom snakeweed	*Gutierrezia sarothrae*	1	1	15
Arizona sycamore	*Platanus wrightii*	3	2	13
Greasewood	*Sarcobatus vermiculatus*	3	1	10
Velvet ash	*Fraxinus velutina*	3	2	10
Colorado pinyon	*Pinus edulis*	3	1	9
Sage	*Artemisia* spp.	3	1	8
Willow	*Salix* spp.	3	3	8
Net leaf hackberry	*Celtis reticulata*	3	2	7
Wolfberry	*Lycium* spp.	3	1	7
Cholla, Prickly pear	*Opuntia* spp.	2	1	7
Burro brush	*Hymenoclea monogyra*	3	2	6
Thistle	*Cirsium* spp.	1	1	6
Ponderosa pine	*Pinus ponderosa*	2	1	6
Catclaw	*Acacia greggii*	1	1	6
Alligator juniper	*Juniperus deppeana*	3	3	5
Birch-leaf mountain mahogany	*Cercocarpus betuloides*	2	1	5

Verbyla 1995). Dividing agreement scores by column totals would normally be a measure of producer accuracy. In our case, this division determines what percentage of sites identified as riparian by the ground crew were correctly identified by the remote sensing interpretation. We emphasize that our accuracy estimates must be carefully interpreted. Column accuracies will be

biased by the disproportionately large number of riparian plots sampled. We report these estimates with the caution that the reported producer accuracies may be biased due to the practical decision to over-sample riparian sites.

Agreement scores divided by row totals provide user accuracies, which denote the probability that a TM-based pixel on a computer screen has the same identity as that area on the ground. The sampling program used in this study maximized our ability to estimate riparian user accuracy. The estimate can be used only with reservation, however, because there is a definite bias toward underestimating the accuracy of the remote sensing data. This follows because the surveyed upland sites are not a random sample of pixels identified by TM interpretation as upland. Instead, they are sites that fell so close to riparian-identified sites only GPS or satellite positional errors left the ground crew in these sites, instead of the sought after riparian sites.

Overall accuracy of both riparian and upland class designations, which is not a good measure due to stratified sampling, was 58.8% (460/782; Table 5). Producer accuracy was higher (67.2%) for riparian designations than for upland designations (54.7%), whereas user accuracy was 42.3% for riparian and 77.1% for upland agreements. For the riparian plots, which are of most interest, this means that 67.2% of plots in that category were correctly classified, but that only 42.3% of the plots called riparian actually belonged in that category. In all cases, accuracies did not meet the ≥80% level set by Valencia et al. (1993) and desired for this study.

Table 5. User and producer accuracies, with 95% confidence limits, for Landsat TM-based designations of riparian and upland vegetation plots in the high contrast zone.

		Ground Crew			User Accuracy (%) (95% C. L.)
		Riparian	Upland	Total	
Satellite	Riparian	174	237	411	42.3 (37.5, 47.1)
	Upland	85	286	371	77.1 (72.8, 81.4)
	Total	259	523	782	
Producer accuracy (%) (95% C. L.)		67.2 (61.5, 72.9)	54.7 (50.4, 59.0)		

Further division of the 782 data points among the Brown and Lowe (1980) biotic communities allows inspection of whether there might be vegetation-based differences in user or producer accuracies. User accuracies for riparian vegetation ranged widely, from 100% in the Chihuahuan Desertscrub stratum to only 11% in Plains and Great Basin Grassland. With the exception of Great Basin Desertscrub, the scrub communities had considerably higher user accuracies than the

grassland communities. Of the seven Brown and Lowe communities, only Lower Colorado River Sonoran Desertscrub and Chihuahuan Desertscrub had user accuracies ≥80%. Producer accuracies exhibited less variation across biotic communities, from a high of 93% for Mohave Desertscrub to a low of 54% for Plains and Great Basin Grassland (Table 6). In the same manner as for user accuracies, desertscrub communities exhibited higher producer accuracies than did the grassland communities, and only two biotic communities, Lower Colorado River Sonoran Desertscrub and Mohave Desertscrub, had scores of ≥80%.

Table 6. User and producer accuracies, with 95% confidence limits, for Landsat TM-based riparian classification among Brown and Lowe (1980) biotic communities in the high contrast zone.

B&L Community (% Area of State)	User Accuracy (%) (95% C.L.)	Producer Accuracy (%) (95% C.L.)
Chihuahuan Desertscrub (1.7%)	100 (80.9, 100.0)	63 (43.1, 81.9)
Lower Colorado River Sonoran Desertscrub (16.0%)	88 (64.8, 97.7)	88 (64.8, 97.7)
Arizona Upland Division Sonoran Desertscrub (14.4%)	74 (64.3,84.3)	76 (66.6,86.2)
Mohave Desertscrub (4.8%)	64 (43.5, 83.7)	93 (69.8, 99.7)
Semidesert Grassland (9.6%)	46 (36.0, 55.2)	58 (47.3, 68.7)
Great Basin Desertscrub (7.8%)	33 (18.6, 46.6)	61 (41.0, 80.8)
Plains and Great Basin Grassland (13.5%)	11 (5.7, 16.1)	54 (35.1, 72.1)

Non-site-specific Accuracy Assessment

There may be other problems associated with satellite and GPS position error that affected our accuracy estimates. For this reason, we relaxed the assumption of absolute convergence in our remote sensing and field locations by performing a non-site-specific accuracy assessment (Table 7). Our results suggest a marked improvement in accuracy for all comparisons. It is not surprising that the producer accuracy assessment for the upland area increased more than that for the riparian classification. Because 99.15% percent of all pixels statewide were judged to be upland and riparian zones have linear shape, the riparian pixels are usually adjoined by many upland pixels. Thus, it is easier to bring the map and ground truthing into agreement for the upland classification. It should also be stated that this is an *overestimate* of the accuracy assessment, even at this coarser level of analysis, because this method precludes increase in number of disagreements; neighboring pixels were used to bring the target pixel into agreement with the truthing crew. An alternative that would have tested the likelihood that coarser analysis is less accurate would use a majority rule to independently classify these nine-pixel blocks, a procedure that would also cause some new discordance with the truthing classification and might convert all riparian pixels to upland! So this table provides a liberal estimate of user accuracy using this remote sensing method.

Table 7. Map accuracy with neighboring pixels used to adjust fine-scale classification disagreements.

		Ground Crew			User Accuracy
		Riparian	Upland	Total	
Satellite	Riparian	405	84	489	82.8%
	Upland	57	464	521	89.1%
	Total	462	548	1010	
Producer Accuracy		87.7%	84.7%		

Next, a test was done to check whether use of the non-site-specific approach could be justified. The non-site-specific assessment caused 245 discords to be converted to agreements. A random sample of 61 of these pixels (25%) was plotted on topographic maps. Of these 61 sites, 34 had originally been classified as riparian by remote sensing and were identified as upland by the field crew. Only nine of these 34 reversals were found to be supported by topography and proximity to streamcourses. This means that on average only 26% (confidence interval: 10-39%) of the 84 reversals bringing remote sensing into agreement with truthing could be justified.

The adjusted non-site-specific accuracies (Table 8) were not very different from that for the site-specific error matrix (Table 5), and neither set of accuracies was high enough (≥80%) to warrant use of this method without further refinement. In summary, this remote-sensing method was not accurate enough for identifying riparian corridors and separating them from adjoining uplands, and our accuracy was not improved markedly by using a less-demanding, non-site-specific assessment. to warrant use of this method without further refinement.

Table 8. Map accuracy with topographic features used to evaluate non-site-specific, neighboring-pixel correction.

		Ground Crew			User Accuracy
		Riparian	Upland	Total	
Satellite	Riparian	329-354	182-229		59.0-66.0%
	Upland	108-133	319-366		70.5-77.2%
	Total	462	548	1010	
Producer Accuracy		71.2-76.6%	58.2-66.8%		

AERIAL VIDEOGRAPHY

Accuracy Assessment

The first test of accuracy using aerial videography was to determine whether we could distinguish reaches of intermittent streams with plant cover <25% (class 1) and ≥25% (classes 2-4). Only 19 reaches could be evaluated from the four test streams. Several reaches in Wildcat Canyon had to be excluded, because video flight dates were earlier than average leaf-out dates for dominant riparian vegetation in that region and elevation range (R. Hevly, NAU Herbarium, pers. comm.). Eighteen of the 19 evaluated reaches were judged correctly for an accuracy of 95% (Table 9).

Table 9. Accuracy assessment for low contrast aerial videography comparing class 1 and classes 2-4 combined. Overall accuracy for this matrix is 94.7%.

		Video Classification	
		< 25%	> 25%
Field Crew Classification	< 25%	5	1
	> 25%	0	13

Using the same data set, we next determined whether class 2, obligate and facultative riparian vegetation with canopy cover greater than the adjacent upland vegetation, could be distinguished from upland dominated vegetation having the same canopy characteristic. The overall accuracy of this determination was only 55.6% (Table 10).

Table 10. Accuracy determination for low contrast aerial videography class 2 vs class 3. Overall accuracy is 55.6%.

		Video Classification	
		Class 2	Class 3
Field Crew Classification	Class 2	4	4
	Class 3	0	1

Our next test was to determine whether class 2 could be differentiated from class 4, where the latter differed from the former in both species composition and relative cover. This comparison yielded an accuracy of 100% for our test sample (Table 11).

Table 11. Accuracy determination for low contrast aerial videography class 2 vs class 4.

		Video Classification	
		Class 2	Class 4
Field Crew Classification	Class 2	4	0
	Class 4	0	4

Next, we combined classes 1 and 4, and tested them against the combination of 2 and 3. This test asked whether areas having particularly low vegetative cover combined with areas of upland vegetation with relatively low plant cover could be separated from areas of either obligate to facultative riparian vegetation and upland vegetation, both with canopy cover greater than the adjacent upland. The result of this test also was perfect agreement (Table 12), leaving us with two sets that could be judged against each other and include all four of our original categories. Therefore, we conducted our subsequent interpretation of aerial videography with these two combined classes.

Aerial Video Vegetation Classification

Approximately 5600 km of intermittent streamcourses were filmed in the low contrast zone for the aerial video classification. Within that set 370 km were not available for classification, because

Table 12. Accuracy determination for low contrast aerial videography classes 1 and 4 vs classes 2 and 3.

		Video Classification	
		Classes 1,4	Classes 2,3
Field Crew Classification	Classes 1,4	10	0
	Classes 2,3	0	9

aircraft movements took the streamcourse off camera. Of the remaining 5230 km, only 34% (3442 km) had streamside vegetation more dense and/or more green than the adjoining upland. When measured as the frequency of reaches classified with the same identity, the results were somewhat different. There were 48% of all reaches that had vegetation judged more dense and/or more green than adjacent upland. Therefore, reaches containing heavier streamside vegetation apparently were shorter and, possibly more fragmented, than those appearing no different from uplands.

PRODUCTS OF THIS EFFORT

Valencia et al. (1993) and Winstead (1997) previously identified products that are available as a result of the SRIM effort at AGFD. Our efforts to map intermittent streams have resulted in additional work products, including maps of potential riparian vegetation along intermittent streams and databases containing information from both remote sensing and field crew efforts. Fig. 6 is an example of a map identifying potential riparian areas near Camp Verde, Arizona, in Semidesert Grassland and Interior Chaparral biotic communities. We use the term "potential riparian vegetation" because of our difficulties in adhering to the strict legislative definition of this vegetation and the problems in attaining our desired accuracy for classification. Areas identified as riparian, but apparently not associated with streamcourses, are apparent in the figure.

File structures for data gathered by field crews are provided in Appendix A. There are individual files for the low contrast and high contrast zones, but they can be linked by rover file values (GPS coordinates). Ancillary information identifying plant species found in these zones and their designations in the continuum from obligate riparian to upland is provided in Appendix B and Appendix C.

AGFD contracted with Arizona State University to assess relationships between riparian vegetation community species composition and hydrogeomorphic variables as part of the SRIM effort. Results of this work are contained in a report by Wasklewicz (1996).

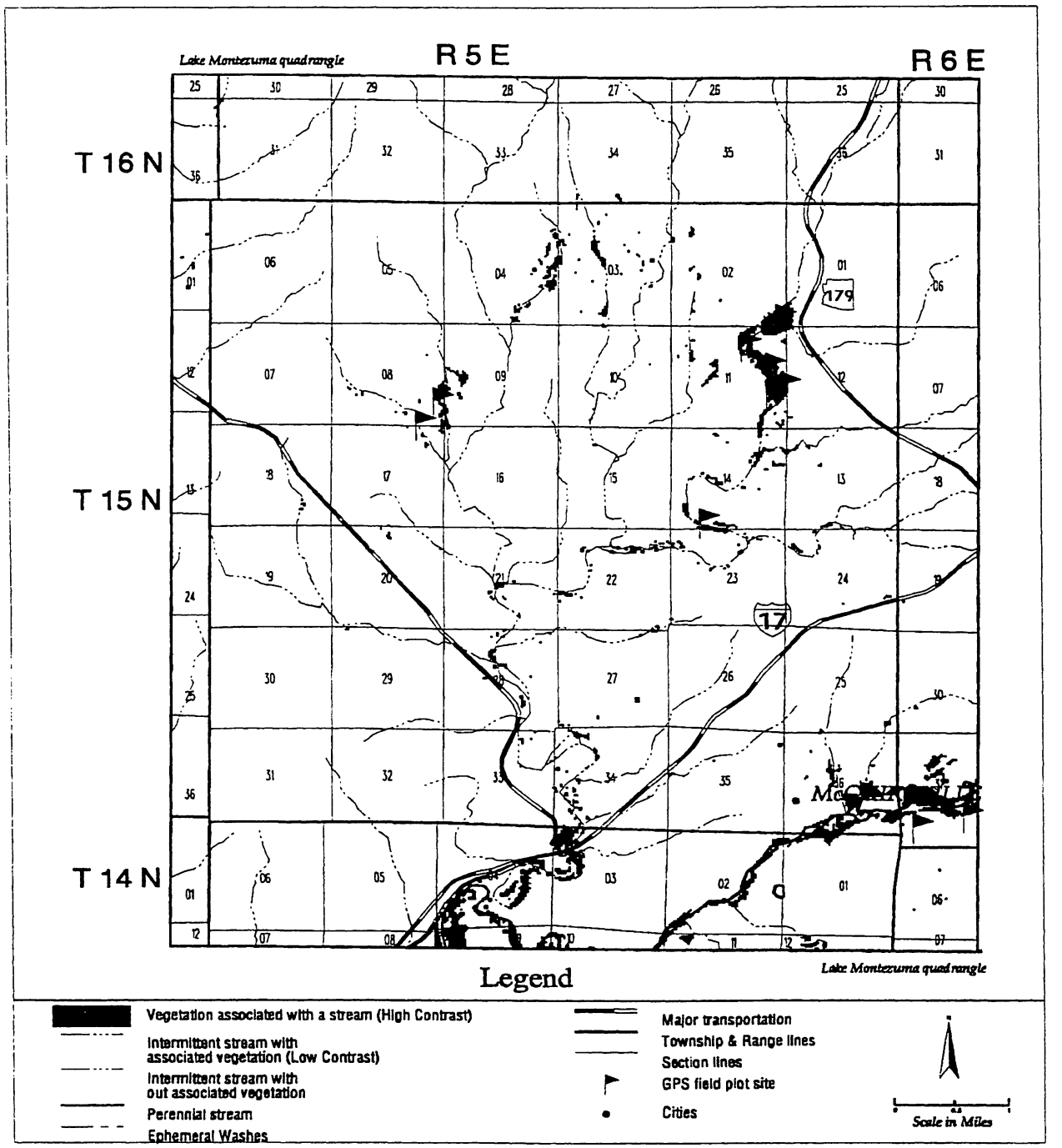

Figure 6. Riparian areas along intermittent and perennial streams near Camp Verde, Arizona.

DISCUSSION

The primary charge of AGFD in legislated directives from the 1992 Waters-Riparian Protection Program was to identify, classify, and map riparian areas that are defined by "the presence of deep-rooted plant species that depend on having roots in the water table or its capillary zone" (ARS 45-101.6). AGFD set a desired 80% accuracy for classification of riparian vegetation at the association level of Brown et al. (1979). At the time of production of the perennial streams report (Valencia et al. 1993), it had become apparent that inherent limitations of the chosen inventory and mapping method would make that objective difficult to obtain without widespread and intense ground truthing efforts coupled with expert review of maps. Valencia et al. (1993) discussed difficulties with the remote sensing method and identified several sources of error, including: (1) removal of riparian vegetation by floods in 1993, which occurred between the time satellite imagery was taken and aerial videography was flown; (2) inability of existing GIS masks to accurately remove agricultural lands; (3) misidentification of the boundary of riparian areas, particularly their separation from upland vegetation, agricultural lands, or lands adjacent to rural dwellings; (4) improper locations of polygons on the ground by field crews prior to consistent use of GPS units; and (5) inability of the video interpreter to distinguish some species of vegetation, particularly when they occurred in mixed stands. Winstead (1997) provided two accuracy estimates in his update of the Valencia et al. (1993) effort. He reported an accuracy of 87.4% (1461 of 1671 polygons) for distinguishing riparian vegetation from upland communities along perennial streams after adjustments in riparian boundaries and changes in the class of some polygons.

Our overall accuracy for differentiating riparian from upland vegetation in high contrast zone intermittent streams was 58.8%, considerably less than that of Winstead. There are several reasons why these values are not directly comparable, however, including: (1) although TM satellite data were used for both perennial and high contrast intermittent streams, different spectral bands were used, and the former study used aerial videography in conjunction with TM; (2) scale of measurement for the perennial phase was for plots from 0.5 acres to >1000 acres, whereas a pixel-to-pixel (30 m diameter) comparison was used for the intermittent portion; (3) determinations for perennial streams were made from an existing digitized hydrology base that allowed exclusion of much upland, whereas no comparable base was available for high contrast zone intermittent streams; (4) field measurements of perennial streams were made in close temporal proximity to acquisition of satellite imagery, whereas comparable intermittent stream field measurements were made up to three years later; (5) perennial streams and their associated riparian areas generally were wider than intermittent streams, and perennial stream vegetation may have been more dense and produced stronger reflectance than that along intermittent streams; and (6) our accuracy estimates were based on single visits to field sites and not on an iterative process of repeated field sampling in some geographical areas.

Large differences occurred in producer and user accuracies among Brown and Lowe (1980) vegetation classes in the high contrast zone. With one exception (Great Basin Desertscrub), the

two grassland classes had lower accuracies than did the desertscrub classes. We suspect that these differences are a result of differences in spectral contrast that can be attributed to the vegetation complexes in these areas. At first glance it would appear that differences between large woody riparian vegetation and that of uplands would be greater in grasslands than in desertscrub. In reality, however, historical densities of large woody riparian species in the grasslands have been diminished by land use practices and, thus, expected contrasts may not be realized.

Our difficulties in using Landsat TM imagery to identify and classify riparian areas beg the question of what comparable studies have been completed using this technology. Hewitt (1990) provided one of the first summaries of Landsat TM data as applied to the inventory of riparian habitats along the Yakima River of central Washington. He used bands 2, 4, and 7, in contrast to our use of band 3/band 4 ratios, and supplemented satellite data with aerial photographs and ground transect measurements. Hewitt was able to differentiate three classes--water, riparian vegetation, and nonriparian vegetation--at an accuracy of 81%, a level above our minimum standard; however, the Yakima River is considerably larger than intermittent streams in Arizona.

Hewitt (1990) made several recommendations to improve map classification accuracy. First, he recommended acquiring satellite imagery from winter or spring when water is high and will provide a reference from which to locate riparian habitat, and another image from summer when vegetation is in full leaf and chlorophyll reflectance is at a maximum. Second, he recommended employing a buffer algorithm that masks out all pixels greater than some predetermined distance from the water class.

In our study, TM satellite imagery was acquired through a funding agreement with several other agencies and there were insufficient resources to purchase a second set of scenes. Without a spring series of satellite scenes showing streams at high water, it was necessary to depend upon the higher chlorophyll reflectance of riparian areas during summer to separate them from upland areas. It is questionable, however, whether a spring series of satellite scenes actually would have revealed a water class in our smaller, intermittent desert streams.

Several studies have used Landsat TM data to delineate wetlands (e.g. Hodgson et al. 1988, Pickus 1990) other than riparian areas. These studies generally were able to attain classification accuracies exceeding 80%, although the authors identified limitations in assessing small wetlands (<2 acres), some classes of vegetation, and open water. Problems with small wetlands may well have a corollary in our linear to dendritic riparian corridors.

Other combinations of remote sensing technology have been used previously for evaluations of riparian areas, and a review of their successes and failures is instructive. Balogh and Becker (1986) used simultaneous infrared aerial photography (1:12,000) and multispectral scanner data in an attempt to determine vegetation community composition and structure types along the Lower Colorado River in Arizona. The investigators did not quantitatively check their map product for accuracy, but they indicated that the "accuracy of the map should compare favorably with other

projects of similar mapping schemes, photo scale and interpreter skill." They did identify several problems, including inability to differentiate two species of mesquite, difficulty in differentiating boundaries in areas of heterogeneous plant densities, and difficulty in classifying and typing different marsh associations.

Mouat and Lancaster (1996) successfully used Landsat Multispectral Scanner (MSS) images in conjunction with black and white aerial photographs to measure temporal change in vegetation composition in the Upper San Pedro River watershed, southeastern Arizona. Vegetation classes varied from the Brown et al. (1979) formation level through series classes to a mixed grass-mixed scrub association, with riparian contained in a single category. Discernment of obligate riparian from facultative riparian vegetation was not an objective of the study.

Aerial videography typically is looked upon as a source of ancillary data for other remote sensing, such as satellite imagery or aerial photography, and not as the sole source of remote sensing data (Bobbe et al. 1993). Wu (1989) used VHS-format aerial videography for multisensor mapping of coastal wetlands in Louisiana. U.S. Fish and Wildlife Service has been using aerial video to aid in the assessment of wetland and riparian areas in the Midwest (Driscoll 1990). Along the Colorado River in Grand Canyon, Arizona, aerial videography from a helicopter has been used to assess changes in the number of backwaters (McGuinn-Robbins 1994) and to measure temporal changes in riparian extent (Pucherelli 1986).

Our test set of low contrast zone reaches showed perfect agreement in differentiation of two vegetative streamside classes using aerial videography; however, we were unable to confirm this accuracy independently on a larger and more inclusive cross-section of low contrast streams. Our results suggest that riparian areas along measured low contrast zone streams are frequently interrupted by reaches having vegetative cover no more dense than the adjoining upland. We suspect this finding implies fragmentation of riparian areas along low contrast streams, but this suspicion should be investigated by additional field measurements at a scale appropriate to address this question.

RECOMMENDATIONS

With respect to work that could profitably be done with existing information generated during the SRIM project, including the earlier work of Valencia et al. (1993) and Winstead (1997), we provide the following recommendations.

1. Relational databases created to store, retrieve, and analyze ground truthing data for this project need to be integrated and attributed in a GIS to improve the utility of these databases. A metadata document needs to be created and provided along with any export of these data.

2. Data contained in ground truthing and digital databases have many potential applications, and they should be distributed to AGFD Regional offices and to other entities who wish them for their use. A work unit should be assigned to be responsible for communicating any updates of these databases to all recipients.

3. Maps produced of high contrast zone intermittent riparian areas should be adjusted through use of a buffer algorithm that disallows the designation riparian more than a set distance from an intermittent streamcourse.

4. A classification system for Arizona riparian areas should be completed using ground truthing data from the perennial and intermittent stream investigations. The riparian classification system should not be strictly taxonomically based, but should include elements of structure that have been proven important to wildlife diversity. The classification system should be related to wildlife functions and values.

5. Develop a Riparian Vulnerability Index similar to the Aquifer Vulnerability Index developed by Environmental Protection Agency and ADEQ to identify riparian areas in need of protection, restoration, or remedial action.

6. Integrate data held in the AGFD Heritage Data Management System into the GIS of riparian areas in Arizona to serve as a foundation for developing a management model for wildlife that depend on this important ecotone between terrestrial and aquatic systems.

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APPENDIXES

Appendix A. Database file structures for high contrast and low contrast zone intermittent stream riparian mapping in Arizona.

File name: HICONFT2.DBF, created 13 Feb 1997 17:21:55; file size: 20 variables and 782 cases; file type: dBASE Windows File; n of cases: 782; total number of defined variable elements: 22; file contains case data from high contrast zone.

Variable Name	Description	Format	Value(s)	Label(s)
RVRFILE	Rover File No.	C (8)		
COVER	Canopy Cover Class, Estimated by Crew	N (1)	1 2 3 4	0-25% 26-50% 51-75% 76-100%
RELCVR1	Relative Cover, Species 1	N (4.2)		
RELCVR2	Relative Cover, Species 2	N (4.2)		
RELCVR3	Relative Cover, Species 3	N (4.2)		
LAYERS	No. Distinct Canopy Layers, up to 3	N (1)		
HGTCLS	Height Class	N (1)	1 2 3 4	0-3 M 3.1-5 M 5.1-7 M >7 M
SUBSTRT	Substrate Class	C (8)	cly slt snd gvl cbl rck h20	clay silt sand gravel cobble bedrock water

Appendix A. Continued.

Variable Name	Description	Format	Value(s)	Label(s)
OBSVRS	Field Crew Members	C (6)	am b cm e f h r z	Amy Mazurczyk Mark Brennan Chris Mehling Heidi Erickson Mary Franks Jennifer Hodge Natalie Robb Wade Zarlingo
NOTES		C (20)		
UTMX	UTMx GPS Coordinates	C (7)		
UTMY	UTMy GPS Coordinates	C (7)		
ELEV	Elevation in Meters	N (4)		
GISCLS	Remote Sensing Class	N (1)	1 2	Upland Riparian
BLPCLS	Brown, Lowe & Pase Class	N (6.2)	142.10 143.10 152.10 153.10 153.20 154.11 154.12	Plains and Great Basin Grassland Semidesert Grassland Great Basin Desertscrub Mohave Desertscrub Chihuahuan Desertscrub Lower Colorado R. Son. Desertscrub AZ Upland Sonoran Desertscrub
CREWCLS	Field Crew Class	N (1)	1 2	Upland Riparian

Appendix A. Continued.

Variable Name	Description	Format	Value(s)	Label(s)
HITMISS	Remote/Crew Agreement	N (8)	1 2 3 4	Crew/Remote Upland Crew Upland/Remote Riparian Crew Riparian/ Remote Upland Crew/Remote Riparian
SPECIES1	Most Common Plant	C (8)		
SPECIES2	Second Most Common Plant	C (8)		
SPECIES3	Third Most Common Plant	C (8)		

File LOWCON.DBF, created 05 Mar 97; 23 variables and 31,685 cases; file type: dBASE Data File; total number of defined variable elements: 309; file contains case data from low contrast zone. Variable types: C = character; N = numeric; D = date (dd·mmm·yy).

Variable Name	Description	Format	Value(s)	Label(s)
GPS_AREA	Rover File of Nearest Geolocated Plot	C (9)		
UTMX	Universal Transverse Mercator X Coordinate	N (13.3)		
UTMY	Universal Transverse Mercator Y Coordinate	N (13.3)		
BLP	Brown, Lowe & Pase (BLP) Biotic Community	N (6.2)		

Appendix A. Continued.

Variable Name	Description	Format	Value(s)	Label(s)
CONTRAST	Zone of BLP Community	C (1)	H L	High Contrast Zone Low Contrast Zone
TOPO	USGS Topographic Quadrangle Map	C (20)		
STREAM	Name of Stream	C (30)		
SEGNO	Stream Reach	C (8)		
ROVER	Rover File When Measured	C (9)		
PLOTNO	Plot Number	N (8)		
CANOPY	Canopy Cover Relative to Adjacent Upland	N (1)	1 2 3	> Upland = Upland < Upland
PLTTYP	Vegetation Stratum	N (1)	1 2	< 3 M > 3 M
AREA	Canopy Area Calculated at Data Entry (m^2)	N (3.2)		
MAX_L	Maximum Length of Canopy (m)	N (3.1)		
MAX_W	Maximum Width of Canopy (m)	N (3.1)		
HEIGHT	Species Height for Plants >3 M Tall	N (4.1)		
STMCLS	Stem Size Class for Plants >3 M Tall	N (1)		

Variable Name	Description	Format	Value(s)	Label(s)
ENTRY	Entry Number from Original Data Sheets	N (9)		
SPECIES	Plant Species Abbreviation	C (7)		
DBSOURCE	Source Files for Original Data			
DATE	Date of Collection	D (9)		
ELEV	Elevation in Meters	N (4)		

Appendix B. Species codes, scientific names, and common names for plants found in riparian areas along intermittent streams in Arizona. Plant names from Kearney and Peebles (1960), Vines (1960), Hitchcock and Cronquist (1973), Lehr (1978), and Brown (1982).

Code	Family	Scientific Name	Common Name
ACACON	Leguminosae	*Acacia constricta*	Whitethorn
ACAGRE	Leguminosae	*Acacia greggii*	Catclaw
ACEGRA	Aceraceae	*Acer grandidentatum*	Bigtooth maple
ACENEG	Aceraceae	*Acer negundo*	Box elder
AGASPP	Agavaceae	*Agave* spp.	Century plant
AGRSMI	Graminae	*Agropyron smithii*	Western wheatgrass
AGRSTR	Rosaceae	*Agrimonia striata*	Agrimony
ALHCAM	Leguminosae	*Alhagi camelorum*	Camelthorn
ALNOBL	Betulaceae	*Alnus oblongifolia*	Arizona alder
ALNTEN	Betulaceae	*Alnus tenuifolia*	Thin-leaf alder
AMEUTA	Rosaceae	*Amelanchier utahensis*	Utah serviceberry
AMOFRU	Leguminosae	*Amorpha fruticosa*	Bastard indigo
ANITHU	Acanthaceae	*Anisacanthus thurberi*	Desert honeysuckle
APIPED	Polypodiaceae	*Adiantum pedatum*	Common maidenhair fern
ARCPAT	Ericaceae	*Arctostaphylos patula*	Green-leaf manzanita
ARCPRI	Ericaceae	*Arctostaphylos pringlei*	Pringle manzanita
ARCPUN	Ericaceae	*Arctostaphylos pungens*	Mexican manzanita
ARCSPP	Ericaceae	*Arctostaphylos* spp.	Manzanita
ARTSPP	Compositae	*Artemisia* spp.	Sage
ARTTRI	Compositae	*Artemisia tridentata*	Big sagebrush
ATRCAN	Chenopodiaceae	*Atriplex canescens*	Four-wing saltbush
ATRSPP	Chenopodiaceae	*Atriplex* spp.	Saltbush
BACSAL	Compositae	*Baccharis salicifolia*	Seep willow
BACSAR	Compositae	*Baccharis sarathroides*	Desert broom
BACSPP	Compositae	*Baccharis* spp.	Groundsel tree
BERFRE	Berberidaceae	*Berberis fremontii*	Desert barberry
BERREP	Berberidaceae	*Berberis repens*	Creeping barberry
BERSPP	Berberidaceae	*Berberis* spp.	Barberry
BLETRI	Graminae	*Blepharoneuron tricholepis*	Pine dropseed
BOUCUR	Graminae	*Bouteloua curtipendula*	Sideoats grama
BOUGLA	Graminae	*Bouteloua glandulosa*	Grama grass
BOUGRA	Graminae	*Bouteloua gracilis*	Blue grama
BOUSPP	Gramineae	*Bouteloua* spp.	Grama
BRICAL	Compositae	*Brickellia californica*	Pachaba
BRISPP	Compositae	*Brickellia* spp.	Bricklebush
CARSPP	Cyperaceae	*Carex* spp.	Sedge

Appendix B. Continued.

Code	Family	Scientific Name	Common Name
CEAFEN	Rhamnaceae	*Ceanothus fendleri*	Buck brush
CEAGRE	Rhamnaceae	*Ceanothus greggii*	Desert ceanothus
CEAINT	Rhamnaceae	*Ceanothus integerrimus*	Deer brush
CEASPP	Rhamnaceae	*Ceanothus* spp.	
CELPAL	Ulmaceae	*Celtis pallida*	Desert hackberry
CELRET	Ulmaceae	*Celtis reticulata*	Net-leaf hackberry
CELSPP	Ulmaceae	*Celtis* spp.	Hackberry
CEPOCC	Rubiaceae	*Cephalanthus occidentalis*	Common button bush
CERBET	Rosaceae	*Cercocarpus betuloides*	Birch-leaf mountain mahogany
CERFLO	Leguminosae	*Cercidium floridum*	Blue paloverde
CERMIC	Leguminosae	*Cercidium microphyllum*	Foothill paloverde
CERMON	Rosaceae	*Cercocarpus montanus*	Alder-leaf mountain mahogany
CERSPP	Rosaceae	*Cercocarpus* spp.	Mountain mahogany
CHAMIL	Rosaceae	*Chamaebatiaria millefolium*	Fernbush
CHILIN	Bignoniaceae	*Chilopsis linearis*	Desert willow
CHRNAU	Compositae	*Chrysothamnus nauseosus*	Rubber rabbitbrush
CHRSPP	Compositae	*Chrysothamnus* spp.	Rabbitbrush
CIRSPP	Compositae	*Cirsium* spp.	Thistle
CLELIG	Ranunculaceae	*Clematis ligusticifolia*	Western virgin's bower
CLESPP	Ranunculaceae	*Clematis* spp.	Virgin's bower
CONSPP	Rhamnaceae	*Condalia* spp.	
CORSTO	Cornaceae	*Cornus stolonifera*	Red osier dogwood
COWMEX	Rosaceae	*Cowania mexicana*	Quinine bush
CUPARI	Cupressaceae	*Cupressus arizonica*	Arizona cypress
CUPSPP	Cupressaceae	*Cupressus* spp.	Cypress
CYNDAC	Graminae	*Cynodon dactylon*	Bermuda grass
DASWHE	Agavaceae	*Dasylirion wheeleri*	Sotol
DATMET	Solanaceae	*Datura meteloides*	Sacred datura
DODVIS	Sapindaceae	*Dodonaea viscosa*	Hopbush
ECHSPP	Cactaceae	*Echinocereus* spp.	Hedgehog cactus
ELAANG	Elaeagnaceae	*Elaeagnus angustifolia*	Russian olive
ELEOVA	Cyperaceae	*Eleocharis ovata*	Spike rush
EMECMB			Emergents combined
EPIADE	Onagraceae	*Epilobium andenocaulon*	Willow weed
EQUSPP	Equisetaceae	*Equisetum* spp.	Horsetail
ERASPP	Graminae	*Eragrostis* spp.	Lovegrass

Appendix B. Continued.

Code	Family	Scientific Name	Common Name
ERIANG	Hydrophllaceae	*Eriodictyon angustifolium*	Narrow-leaved yerba santa
EURLAN	Chenopodiaceae	*Eurotia lanata*	Winter fat
EXOTIC			Unidentified exotic
FALPAR	Rosaceae	*Fallugia paradoxa*	Apache plume
FERNSP		Fern spp.	Unidentified fern
FORNEO	Oleaceae	*Forestiera neomexicana*	Desert olive
FRAANO	Oleaceae	*Fraxinus anomala*	Single-leaf ash
FRASPP	Oleaceae	*Fraxinus* spp.	Ash
FRAVEL	Oleaceae	*Fraxinus velutina*	Velvet ash
GARFLA	Garryaceae	*Garrya flavescens*	Silktassel bush
GARWRI	Garryaceae	*Garrya wrightii*	Wright silktassel
GRSCMB			Grasses combined
GUTSAR	Compositae	*Gutierrezia sarothrae*	Broom snakeweed
HAPSPP	Compositae	*Haplopappus* spp.	
HAPTEN	Compositae	*Haplopappus tenuisectus*	Burroweed
HOLDUM	Rosaceae	*Holidiscus dumosus*	Mountain spray
HYMMON	Compositae	*Hymenoclea monogyra*	Burro brush
HYPEMO	Labiatae	*Hyptis emoryi*	Desert lavender
IRIMIS	Iridaceae	*Iris missouriensis*	Rocky Mountain iris
JUGMAJ	Juglandaceae	*Juglans major*	Arizona walnut
JUNCOM	Cupressaceae	*Juniperus communis*	Common juniper
JUNCSP	Juncaceae	*Juncus* spp.	Rush
JUNDEP	Cupressaceae	*Juniperus deppeana*	Alligator juniper
JUNMON	Cupressaceae	*Juniperus monosperma*	One-seed juniper
JUNOST	Cupressaceae	*Juniperus osteosperma*	Utah juniper
JUNSCO	Cupressaceae	*Juniperus scopulorum*	Rocky Mountain juniper
JUNSPP	Cupressaceae	*Juniperus* spp.	Juniper
KOESPI	Koeberliniaceae	*Koeberlinia spinosa*	Allthorn
LARTRI	Zygophyllaceae	*Larrea tridentata*	Creosote bush
LONARI	Caprifoliaceae	*Lonicera arizonica*	Arizona honeysuckle
LYCPAL	Solanaceae	*Lycium pallidum*	Rabbit thorn
LYCSPP	Solanaceae	*Lycium* spp.	Wolfberry
MALSPP	Rosaceae	*Malus* spp.	Apple
MALVSP	Malvaceae	*Malva* spp.	Mallow
MENSPP	Labiatae	*Mentha* spp.	Mint
MIMBIU	Leguminosae	*Mimosa biuncifera*	Wait-a-minute

Appendix B. Continued.

Code	Family	Scientific Name	Common Name
MORMIC	Moraceae	*Morus microphylla*	Texas mulberry
MORSPP	Celastraceae	*Mortonia* spp.	
MUHRIG	Graminae	*Muhlenbergia rigens*	Deergrass
MUHSPP	Graminae	*Muhlenbergia* spp.	Muhly
MUHWRI	Graminae	*Muhlenbergia wrightii*	Spike muhly
NOLMIC	Agavaceae	*Nolina microcarpa*	Beargrass
OENSPP	Onagraceae	*Oenothera* spp.	Evening primrose
OLNTES	Leguminosae	*Olneya tesota*	Ironwood
OPULEP	Cactaceae	*Opuntia leptocaulis*	Desert Christmas cactus
OPUPHA	Cactaceae	*Opuntia phaeacantha*	Engelmann prickly pear
OPUSPP	Cactaceae	*Opuntia* spp.	
PARINS	Vitaceae	*Parthenocissus inserta*	Thicket creeper
PICSPP	Pinaceae	*Picea* spp.	Spruce
PINEDU	Pinaceae	*Pinus edulis*	Colorado pinyon
PINENG	Pinaceae	*Pinus engelmannii*	Apache pine
PINFLE	Pinaceae	*Pinus flexilis*	Limber pine
PINLEI	Pinaceae	*Pinus leiophylla*	Chihuahua pine
PINMON	Pinaceae	*Pinus monophylla*	Single-leaf pinyon
PINPON	Pinaceae	*Pinus ponderosa*	Ponderosa pine
PINSTR	Pinaceae	*Pinus strobiformis*	Southwestern white pine
PLAWRI	Platanaceae	*Platanus wrightii*	Arizona sycamore
POASPP	Gramineae	*Poa* spp.	Bluegrass
POLAMP		*Polygonum amphibium*	Water smartweed
POPACU	Salicaceae	*Populus acuminata*	Lance-leaved cottonwood
POPANG	Salicaceae	*Populus angustifolia*	Narrow-leaf cottonwood
POPFRE	Salicaceae	*Populus fremontii*	Fremont cottonwood
POPTRE	Salicaceae	*Populus tremuloides*	Quaking aspen
PROGLA	Leguminosae	*Prosopis glandulosa*	Honey mesquite
PROSPP	Leguminosae	*Prosopis* spp.	Mesquite
PROVEL	Leguminosae	*Prosopis velutina*	Velvet mesquite
PRUEMA	Rosaceae	*Prunus emarginata*	Bitter cherry
PRUSPP	Rosaceae	*Prunus* spp.	
PRUVIR	Rosaceae	*Prunus virginiana*	Common chokecherry
PSEMEN	Pinaceae	*Pseudotsuga menziesii*	Douglas-fir
PTEANG	Rutaceae	*Ptelea angustifolia*	Narrow-leaf hoptree
PTETRI	Rutaceae	*Ptelea trifoliata*	Hoptree

Appendix B. Continued.

Code	Family	Scientific Name	Common Name
QUEARI	Fagaceae	*Quercus arizonica*	Arizona white oak
QUEDUN	Fagaceae	*Quercus dunnii*	Palmer oak
QUEEMO	Fagaceae	*Quercus emoryi*	Emory oak
QUEGAM	Fagaceae	*Quercus gambelii*	Gambel oak
QUEGRI	Fagaceae	*Quercus grisea*	Gray oak
QUEHYP	Fagaceae	*Quercus hypoleucoides*	Silver-leaf oak
QUESPP	Fagaceae	*Quercus* spp.	Oak
QUETUR	Fagaceae	*Quercus turbinella*	Shrub live oak
RHACAL	Rhamnaceae	*Rhamnus californica*	California buckthorn
RHACRO	Rhamnaceae	*Rhamnus crocea*	Red berry buckthorn
RHUGLA	Anacardiaceae	*Rhus glabra*	Smooth sumac
RHUMIC	Anacardiaceae	*Rhus microphylla*	Desert sumac
RHUOVA	Anacardiaceae	*Rhus ovata*	Sugar sumac
RHURAD	Anacardiaceae	*Rhus radicans*	Poison ivy
RHUSPP	Anacardiaceae	*Rhus* spp.	Sumac
RHUTRI	Anacardiaceae	*Rhus trilobata*	Squaw bush
RIBAUR	Saxifragaceae	*Ribes aureum*	Golden current
RIBINE	Saxifragaceae	*Ribes inerme*	Whitestem gooseberry
RIBMON	Saxifragaceae	*Ribes montigenum*	Gooseberry currant
RIBSPP	Saxifragaceae	*Ribes* spp.	Currant
ROBNEO	Leguminosae	*Robinia neomexicana*	New Mexico locust
RORNAS	Cruciferae	*Rorippa nasturtium-aquaticum*	Watercress
ROSFEN	Rosaceae	*Rosa fendleri*	Fendler rose
ROSSPP	Rosaceae	*Rosa* spp.	Rose
RUBNEO	Rosaceae	*Rubus neomexicanus*	New Mexico raspberry
RUBPAR	Rosaceae	*Rubus parvifloris*	Western thimbleberry
RUBSPP	Rosaceae	*Rubus* spp.	Blackberry
SALAMY	Salicaceae	*Salix amygdaloides*	Peach-leaf willow
SALEXI	Salicaceae	*Salix exigua*	Coyote willow
SALGOO	Salicaceae	*Salix gooddingii*	Goodding willow
SALIRR	Salicaceae	*Salix irrorata*	Bluestem willow
SALLA1	Salicaceae	*Salix lasiandra*	Pacific willow
SALLA2	Salicaceae	*Salix lasiolepis*	Arroyo willow
SALLAE	Salicaceae	*Salix laevigata*	Red willow
SALSPP	Salicaceae	*Salix* spp.	Willow

Appendix B. Continued.

Code	Family	Scientific Name	Common Name
SALTAX	Salicaceae	*Salix taxifolia*	Yew-leaf willow
SALIBE	Chenopodiaceae	*Salsola iberica*	Russian thistle
SAMMEX	Caprifoliaceae	*Sambucus mexicana*	Mexican elder
SAPSAP	Sapindaceae	*Sapindus saponaria*	Western soapberry
SARVER	Chenopodiaceae	*Sarcobatus vermiculatus*	Greasewood
SCISPP	Cyperaceae	*Scirpus* spp.	Bulrush
SENSPA	Compositae	*Senecio spartiodes*	Broom groundsel
SENSPP	Compositae	*Senecio* spp.	Groundsel
SIMCHI	Buxaceae	*Simmondsia chinensis*	Jojoba
SITHYS	Graminae	*Sitanion hystrix*	Squirreltail
SOLSPP	Solanaceae	*Solanum* spp.	Nightshade
SORDUM	Rosaceae	*Sorbus dumosa*	Mountain ash
SPHAMB	Malvaceae	*Sphaeralcea ambigua*	Desert mallow
SYMORE	Caprifoliaceae	*Symphoricarpos oreophilus*	Mountain snowberry
SYMROT	Caprifoliaceae	*Symphoricarpos rotundifolius*	Round-leaf snowberry
SYMSPP	Caprifoliaceae	*Symphoricarpos* spp.	Snowberry
TAMPEN	Tamaricaceae	*Tamarix pentandra*	Salt cedar
TESSER	Compositae	*Tessaria sericea*	Arrow weed
TYPLAT	Gramineae	*Typha latifolia*	Broad-leaved cattail
UNKSPP		Unknown spp.	Unidentified species
VALSPP	Valerianaceae	*Valerian* spp.	Valerian
VERAME	Scrophulariaceae	*Veronica americana*	American brooklime
VERSPP	Scrophulariaceae	*Veronica* spp.	Speedwell
VERTHA	Scrophulariaceae	*Verbascum thapsus*	Common mullein
VITARI	Vitaceae	*Vitus arizonica*	Canyon grape
YUCSPP	Agavaceae	*Yucca* spp.	Yucca
ZIZOBT	Rhamnaceae	*Zizyphus obtusifolia*	Graythorn

Appendix C. Scientific names, common names, and wetland ratings for vegetation found along intermittent streams in areas of 11 Brown and Lowe (1980) biotic communities divided into high contrast and low contrast zones. Grasses excluded largely because of insufficient taxonomic determinations to species level.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Acacia constricta	Whitethorn								X						X		
Acacia greggii	Catclaw	X	X			X		X		X		X		X		X	X
Acer grandidentatum	Bigtooth maple	X	X			X	X			X							
Acer negundo	Box elder	X	X	2	FACW-	X	X	X		X							
Agave spp.	Century plant							X	X	X		X					
Agrimonia striata	Agrimony				FAC-		X										
Alhagi camelorum	Camelthorn		X										X				
Alnus oblongifolia	Arizona alder	X	X	2	FACW+	X		X	X	X		X					
Alnus tenuifolia	Thin-leaf alder	X	X			X	X	X		X							
Amelanchier utahensis	Utah serviceberry					X	X										
Amorpha fruticosa	Bastard indigo	X		2	FACW+	X	X	X	X	X							X
Anisacanthus thurberi	Desert honeysuckle					X		X									
Arctostaphylos patula	Green-leaf manzanita							X		X							
Arctostaphylos pringlei	Pringle manzanita							X		X							
Arctostaphylos pungens	Mexican manzanita					X	X	X		X							
Arctostaphylos spp.	Manzanita							X	X	X							
Artemisia spp.	Sage			5		X		X		X	X		X				
Artemisia tridentata	Big sagebrush					X					X						
Atriplex canescens	Four-wing saltbush												X	X	X	X	
Atriplex spp.	Saltbush		X					X									
Baccharis salicifolia	Seep willow		X			X	X	X	X	X	X	X	X	X	X		X
Baccharis sarathroides	Desert broom	X	X		FAC-	X				X		X			X		X
Baccharis spp.	Groundsel tree								X	X			X				X

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Berberis fremontii	Desert barberry					X		X		X	X						
Berberis repens	Creeping barberry					X		X		X							
Berberis spp.	Barberry					X		X	X	X		X					X
Brickellia californica	Pachaba	X		4	FACU+	X		X									
Brickellia spp.	Bricklebush			4		X		X	X	X	X				X		X
Carex spp.	Sedge	X	X			X	X	X		X					X		
Ceanothus fendleri	Buck brush					X	X	X	X	X							
Ceanothus greggii	Desert ceanothus					X	X	X		X							
Ceanothus integerrimus	Deer brush						X	X	X	X							
Ceanothus spp.								X	X	X							
Celtis pallida	Desert hackberry		X			X											X
Celtis reticulata	Net-leaf hackberry	X	X	3	FACU	X		X	X	X		X			X		X
Celtis spp.	Hackberry											X					
Cephalanthus occidentalis	Common buttonbush		X		OBL					X							
Cercidium floridum	Blue paloverde		X														X
Cercidium microphyllum	Foothill paloverde					X								X			X
Cercocarpus betuloides	Birch-leaf mountain mahogany					X		X	X	X		X		X			
Cercocarpus montanus	Alder-leaf mountain mahogany					X	X	X	X	X							

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Cercocarpus spp.	Mountain mahogany							X		X							
Chamaebatiaria millefolium	Fernbush							X									
Chilopsis linearis	Desert willow	X	X			X			X	X	X	X			X		X
Chrysothamnus nauseosus	Rubber rabbitbrush	X					X	X	X	X	X	X			X		X
Chrysothamnus spp.	Rabbitbrush							X		X							
Cirsium spp.	Thistle					X											X
Clematis ligusticifolia	Western virgin's bower				FAC	X		X									
Clematis spp.	Virgin's bower							X	X	X							
Condalia spp.												X					
Cornus stolonifera	Red osier dogwood	X	X		FACW	X	X	X									
Cowania mexicana	Quinine bush					X		X									
Cupressus arizonica	Arizona cypress		X			X		X		X							X
Cupressus spp.	Cypress						X	X	X	X							
Dasylirion wheeleri	Sotol					X		X	X	X							
Datura meteloides	Sacred datura			5		X	X										
Dodonaea viscosa	Hopbush					X						X					X
Echinocereus spp.	Hedgehog cactus							X		X							
Elaeagnus angustifolia	Russian olive	X	X		FACW-						X						
Eleocharis ovata	Spike rush								X								
Equisetum spp.	Horsetail	X	X			X				X							

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Eriodictyon angustifolium	Narrow-leaved yerba santa									X							
Eurotia lanata	Winter fat							X									
Fallugia paradoxa	Apache plume	X				X		X	X	X	X						
Forestiera neomexicana	Desert olive	X		4	FACU	X	X	X		X			X				
Fraxinus anomala	Single-leaf ash									X							
Fraxinus spp.	Ash	X					X	X	X	X							
Fraxinus velutina	Velvet ash	X	X	3	FAC+	X	X	X	X	X	X	X			X		X
Garrya flavescens	Silktassel bush					X		X		X							
Garrya wrightii	Wright silktassel			4		X	X	X	X	X							
Gutierrezia sarothrae	Broom snakeweed					X	X	X	X	X		X			X		
Haplopappus spp.									X	X							
Haplopappus tenuisectus	Burroweed														X		
Holidiscus dumosus	Mountain spray								X								
Hymenoclea monogyra	Burro brush	X	X			X		X	X	X		X	X	X	X		X
Hyptis emoryi	Desert lavender								X								
Iris missouriensis	Rocky Mountain iris				FACW-	X	X	X									
Juglans major	Arizona walnut	X	X	2	FACW-	X	X	X	X	X	X						X
Juncus spp.	Rush	X	X			X				X							
Juniperus communis	Common juniper					X				X							
Juniperus deppeana	Alligator juniper		X	5		X	X	X	X	X	X	X					
Juniperus monosperma	One-seed juniper			5		X		X	X	X							

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Juniperus osteosperma	Utah juniper			5		X		X	X	X		X					
Juniperus scopulorum	Rocky Mountain juniper			5		X	X	X									
Juniperus spp.	Juniper						X	X	X	X	X	X					X
Koeberlinia spinosa	Allthorn							X									
Larrea tridentata	Creosote bush														X	X	X
Lonicera arizonica	Arizona honeysuckle							X		X							
Lycium pallidum	Rabbit thorn							X									
Lycium spp.	Wolfberry							X	X			X		X			X
Malva spp.	Mallow								X								
Mentha spp.	Mint					X	X			X							
Mimosa biuncifera	Wait-a-minute					X		X	X	X		X			X		
Mortonia spp.								X	X	X							
Morus microphylla	Texas mulberry	X	X	3	FACU	X				X							
Nolina microcarpa	Beargrass					X				X							
Oenothera spp.	Evening primrose					X				X							
Olneya tesota	Ironwood		X			X											X
Opuntia leptocaulis	Desert Christmas cactus							X									
Opuntia phaeacantha	Engelmann prickly pear						X	X	X	X							
Opuntia spp.							X	X	X	X							X
Parthenocissus inserta	Thicket creeper		X		FACW-	X	X	X		X							

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Picea spp.	Spruce						X	X									
Pinus edulis	Colorado pinyon			5		X	X	X	X	X	X						
Pinus engelmannii	Apache pine					X	X		X								
Pinus flexilis	Limber pine					X	X		X								
Pinus leiophylla	Chihuahua pine					X	X		X	X							
Pinus monophylla	Singleleaf pinyon							X		X							
Pinus ponderosa	Ponderosa pine		X		FACU	X	X	X		X	X						
Pinus strobiformis	Southwestern white pine						X										
Platanus wrightii	Arizona sycamore	X	X	2	FACW-	X		X	X	X	X	X					X
Polygonum amphibium	Water smartweed			4			X										
Populus acuminata	Lance-leaved cottonwood	X		2	FACW			X									
Populus angustifolia	Narrow-leaf cottonwood	X	X	2	FACW	X	X	X		X							
Populus fremontii	Fremont cottonwood	X	X	2	FACW	X	X	X	X	X	X	X	X	X	X		X
Populus tremuloides	Quaking aspen	X	X		FACU	X	X			X							
Prosopis glandulosa	Honey mesquite	X	X	4	FACU				X						X		
Prosopis spp.	Mesquite							X	X	X							X
Prosopis velutina	Velvet mesquite		X		FACU	X		X	X	X		X		X	X	X	X
Prunus emarginata	Bitter cherry		X				X	X	X								
Prunus spp.			X				X	X	X	X		X					

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Prunus virginiana	Common chokecherry	X			FAC					X							
Pseudotsuga menziesii	Douglas-fir					X	X	X	X								
Ptelea angustifolia	Narrow-leaf hoptree	X		4	FACU*	X		X									
Ptelea trifoliata	Hoptree				FACU*			X									
Quercus arizonica	Arizona white oak		X	5		X	X	X	X	X		X					
Quercus dunnii	Palmer oak									X							
Quercus emoryi	Emory oak		X	5		X	X	X	X	X							
Quercus gambelii	Gambel oak		X	5		X	X	X	X	X							
Quercus grisea	Gray oak					X	X		X	X							
Quercus hypoleucoides	Silver-leaf oak					X	X	X	X								
Quercus spp.	Oak							X	X	X	X	X					
Quercus turbinella	Shrub live oak					X		X	X	X		X		X			X
Rhamnus californica	California buckthorn					X	X	X		X							
Rhamnus crocea	Red berry buckthorn					X		X		X							
Rhus glabra	Smooth sumac		X			X	X	X									
Rhus microphylla	Desert sumac	X				X			X						X		
Rhus ovata	Sugar sumac					X				X							
Rhus radicans	Poison ivy		X		FACW	X	X	X	X	X							
Rhus spp.	Sumac								X								
Rhus trilobata	Squaw bush			4	NI[4]	X	X	X	X	X	X	X					

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Ribes aureum	Golden current				FACW				X		X						
Ribes inerme	Whitestem gooseberry				FACW-		X	X	X								
Ribes montigenum	Gooseberry currant					X	X										
Ribes spp.	Currant		X			X		X		X							
Robinia neomexicana	New Mexico locust		X			X	X	X	X	X							
Rorippa nasturtium-aquaticum	Watercress			1	OBL	X	X	X									
Rosa fendleri	Fendler rose				FACU		X	X	X								
Rosa spp.	Rose					X	X	X									
Rubus neomexicanus	New Mexico raspberry					X	X	X	X								
Rubus parvifloris	Western thimbleberry				NI[5]	X			X								
Rubus spp.	Blackberry		X					X		X							
Salix amygdaloides	Peach-leaf willow		X		FACW	X								X			
Salix exigua	Coyote willow		X	1	OBL	X	X	X	X	X	X		X				
Salix gooddingii	Goodding willow	X	X	1	OBL	X	X	X	X	X		X		X			X
Salix irrorata	Bluestem willow		X	2	FACW+	X	X										
Salix laevigata	Red willow				FACW+		X		X	X							
Salix lasiandra	Pacific willow				FACW+	X	X	X		X							
Salix lasiolepis	Arroyo willow		X		FACW	X	X	X	X	X							

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Salix spp.	Willow	X	X				X	X		X		X		X	X		X
Salix taxifolia	Yew-leaf willow				FACW-						X						
Salsola iberica	Russian thistle		X	4	FACU	X							X		X		
Sambucus mexicana	Mexican elder		X		FAC							X					X
Sapindus saponaria	Western soapberry	X	X			X				X		X					X
Sarcobatus vermiculatus	Greasewood	X			FACU+								X				
Scirpus spp.	Bulrush	X	X			X	X	X					X				
Senecio spartiodes	Broom groundsel						X										
Senecio spp.	Groundsel					X	X	X									
Simmondsia chinensis	Jojoba																X
Solanum spp.	Nightshade		X			X		X									
Sorbus dumosa	Mountain ash								X								
Sphaeralcea ambigua	Desert mallow						X	X									
Symphoricarpos oreophilus	Mountain snowberry						X										
Symphoricarpos rotundifolius	Round-leaf snowberry						X			X							
Symphoricarpos spp.	Snowberry					X	X	X		X							
Tamarix pentandra	Salt cedar		X		NI[6]	X		X	X	X	X		X	X	X	X	X
Tessaria sericea	Arrow weed	X	X		FACW-									X		X	
Typha latifolia	Broad-leaved cattail	X	X		OBL					X							
Verbascum thapsus	Common mullein			5		X	X										

Appendix C. Continued.

Scientific Name	Common Name	Wetland Ratings[1]					Low Contrast Zone[2]				High Contrast Zone[3]						
		1	2	3	4	5	122.3	122.4	123.3	133.3	142.1	143.1	152.1	153.1	153.2	154.11	154.12
Veronica americana	American brooklime				OBL	X			X								
Veronica spp.	Speedwell									X							
Vitus arizonica	Canyon grape		X	3	FAC	X	X	X	X	X							
Yucca spp.	Yucca						X	X	X	X							
Zizyphus obtusifolia	Graythorn		X			X				X		X			X	X	X
Number of Taxa (Total=184)							78	112	79	108	23	34	13	15	23	7	36

[1] Group 1 plants are listed as "major obligate riparian plants found in New Mexico" (Dick-Peddie and Hubbard 1977). Group 2 plants are listed as species occurring in wetland biotic communities (Brown 1982). Group 3 plants are found along the Gila and San Francisco rivers, New Mexico (Dick-Peddie et al. 1987). Frequency of occurrence index numbers range from 1 (obligate) to 5 (upland). Group 4 are wetland indicator ratings for the Southwest (Reed 1988). Categories are OBL (obligate wetland), FACW (facultative wetland), FAC (facultative), and FACU (facultative upland). Positive (+) and negative (-) signs indicate higher and lower frequency in wetlands, respectively. NI (no indicator) denotes species with insufficient information to determine indicator status. An asterisk (*) identifies tentative assignment based on limited knowledge. Group 5 plants were found within riparian forest and scrubland communities in Arizona and New Mexico (Szaro 1989).

[2] Vegetation classes (Brown and Lowe 1980) within the low contrast area as defined by this study. Classes where species were observed by AGFD biologists are marked. No data were collected from class 111.5.

[3] Vegetation classes (Brown and Lowe 1980) within the high contrast area as defined by this study. Classes where species were observed by AGFD biologists are marked. No data were collected from classes 121.3 and 141.4.

[4] Rated NI for the Southwest, but has a tentative national rating of FAC (Reed 1988).

[5] Rated NI for the Southwest, but has a national rating of FACU,FAC+ (Reed 1988).

[6] Rated NI for the Southwest, but has a national rating of FACW (Reed 1988).

APPENDIX D

R18-11-113. Effluent Dependent Waters

A. The Director shall use rulemaking to classify a surface water as an effluent dependent water.

B. The Director may adopt, by rule, site-specific water quality standards for an effluent dependent water.

C. Any person may submit a petition for rule adoption requesting that the Director classify a surface water as an effluent dependent water. The petition for rule adoption shall include:

- 1. A map and a description of the surface water.
- 2. Information that demonstrates that the surface water consists primarily of discharges of treated wastewater.

D. The following surface waters are classified as effluent dependent waters:

- 1. In the Colorado River Main Stem Basin:
  - a. Bright Angel Wash from South Rim Grand Canyon WWTP outfall to confluence with Coconino Wash.
  - b. Cataract Creek from Williams WWTP outfall to 1 kilometer downstream from the outfall.
  - c. Holy Moses Wash from Kingman WWTP outfall to 3 kilometers downstream from the outfall.
  - d. Transept Canyon from North Rim Grand Canyon WWTP outfall to 1 kilometer downstream.
- 2. In the Little Colorado River Basin:
  - a. Dry Lake.
  - b. Lake Humphreys.
  - c. Lower Walnut Canyon Lake.
  - d. Ned Lake.
  - e. Pintail Lake.
  - f. Telephone Lake.
  - g. Rio de Flag from City of Flagstaff WWTP outfall to confluence with San Francisco Wash.
  - h. Whale Lake.
- 3. In the Middle Gila River Basin:
  - a. Unnamed wash from the Town of Prescott Valley WWTP outfall to the confluence with the Agua Fria River, and the Agua Fria River below the confluence with the unnamed wash receiving treated wastewater from the Prescott Valley WWTP to State Route 169.
  - b. Agua Fria River from El Mirage WWTP outfall to 2 kilometers downstream from the outfall.
  - c. Gila River from Florence WWTP outfall to Felix Road.
  - d. Gila River from confluence with the Salt River to Gillespie Dam.
  - e. Queen Creek from Superior Mining Division discharge outfall to confluence with Potts Canyon.
  - f. Unnamed wash from Gila Bend WWTP outfall to confluence with Gila River.
  - g. Unnamed wash from Luke AFB WWTP outfall to the confluence with Agua Fria River.
  - h. Unnamed wash from Queen Valley WWTP outfall to confluence with Queen Creek.
- 4. In the Rios de Mexico Basin:
  - a. Mule Gulch, from Bisbee WWTP outfall to confluence with Whitewater Draw.
  - b. Unnamed wash from Bisbee-Douglas International Airport WWTP outfall to Whitewater Draw.
- 5. In the Salt River Basin:
  - a. Unnamed wash from Globe WWTP outfall to confluence with Pinal Creek and from confluence of unnamed wash and Pinal Creek to Radium.
  - b. Salt River from 23rd Avenue WWTP outfall to confluence with the Gila River.
- 6. In the San Pedro River Basin:
  - a. Unnamed wash from Mt. Lemmon WWTP outfall to 0.25 kilometers downstream.
  - b. Walnut Gulch from Tombstone WWTP outfall to confluence with Tombstone Gulch.
- 7. In the Santa Cruz River Basin:
  - a. Santa Cruz River from Nogales International WWTP outfall to Tubac Bridge.

- b. Santa Cruz River from Roger Road WWTP outfall to Baumgartner Road crossing.
- c. Unnamed wash from Oracle WWTP outfall to 5 kilometers downstream.
- d. Sonoita Creek from Town of Patagonia WWTP outfall to 750 feet downstream.

- 8. In the Upper Gila River Basin:
  - a. Bennett Wash from Arizona Department of Corrections-Safford WWTP outfall to Gila River.
  - b. Unnamed wash from Arizona Department of Corrections-Globe WWTP outfall to the boundary of the San Carlos Indian Reservation.
- 9. In the Verde River Basin:
  - a. American Gulch from Northern Gila County Sanitary District WWTP outfall to the East Verde River.
  - b. Bitter Creek from Jerome WWTP outfall to 2.5 kilometers downstream from the outfall.
  - c. Jacks Canyon Wash from Big Park WWTP outfall to confluence with Dry Beaver Creek.

E. The NPDES permit issuing authority shall use the water quality standards that apply to an effluent dependent water to derive discharge limitations for a point source discharge from a wastewater treatment plant to an ephemeral water which changes that ephemeral water into an effluent dependent water.

Historical Note

Adopted effective February 18, 1992 (Supp. 92-1). Amended effective December 18, 1992 (Supp. 92-4). Amended effective April 24, 1996 (Supp. 96-2).

APPENDIX E

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EXPERIMENTAL STUDIES IN STREAM–AQUIFER INTERACTION ALONG THE ARKANSAS RIVER IN CENTRAL KANSAS — FIELD TESTING AND ANALYSIS

MARIOS SOPHOCLEOUS, M.A. TOWNSEND, L.D. VOGLER, T.J. McCLAIN, E.T. MARKS and G.R. COBLE

Kansas Geological Survey, University of Kansas, Lawrence, KS 66046-2598 (U.S.A.)

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ABSTRACT

Sophocleous, M., Townsend, M.A., Vogler, L.D., McClain, T.J., Marks, E.T. and Coble, G.R., 1988. Experimental studies in stream–aquifer interaction along the Arkansas River in Central Kansas — Field testing and analysis. J. Hydrol., 98: 249–273.

During the last several years, streamflows of a number of Kansas streams have been reduced as a result of groundwater declines. In order to better understand and quantify stream–aquifer interrelationships, an eight-day comprehensive stream–aquifer pumping test, followed by recovery monitoring, was conducted along the Arkansas River near Great Bend, Kansas. In addition to water level monitoring in numerous observation wells, streamflow data, streambed hydraulic gradients, neutron probe-based water content of dewatered sediments, water chemistry and other data were collected. The alluvial aquifer is shown to be highly transmissive ($T = 1803\,m^2\,d^{-1}$) with the pumping stress ($9538\,m^3\,d^{-1}$) having a radius of influence larger than 1.77 km, impacting both the aquifer levels and the streamflow in the nearby Arkansas River. Drawdown and recharge boundary effects were observed in all observation wells, including those on the opposite side of the river. The alluvial aquifer did not exhibit a water table behavior and responded as a leaky confined aquifer. A semiconfining clay layer less than 3 m thick and an additional recharge source from a nearby stream-alluvial system were the probable causes of the observed phenomena. Actual streamflow depletion is shown to be appreciably less than the computed depletion based on analytical solutions.

INTRODUCTION

During the last several years, streamflows of several western and central Kansas streams have been reduced as a result of groundwater declines. Fish and wildlife resources in and along the Arkansas River and other streams in western and south–central Kansas have been significantly impacted due to losses in baseflows (Water Research Needs Conference, Wichita, Kansas, Nov. 11, 1984). The implementation by the Kansas Legislature of the minimum desirable streamflow standards for some streams has resulted in the need to examine the interrelationship of streamflow and groundwater in the river alluvium and associated aquifers, which may contribute to the water available for baseflows in these streams. "Stream–Aquifer Interaction" was identified in

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the highest priority category of research needs in the "Kansas Water Authority Annual Research Report (1986)".

The Kansas Geological Survey (KGS), in response to this problem, proposed a multiphased research endeavor. The first phase of this research, which lasted for approximately one year, involved a comprehensive stream–aquifer pumping test in order to demonstrate and quantify the extent and nature of the stream-flow–groundwater flow interaction and the fundamental hydrologic principles governing water movement at the stream–aquifer boundary. The results of this study phase are reported here.

STREAM-AQUIFER PUMP TEST DESIGN

A site near Great Bend in Barton County, Kansas (T19S, R13W., sect. 36) was selected for the stream–aquifer pumping test (Fig. 1).

A 0.5 m diameter pumping well, approximately 64 m from the south bank of the Arkansas River, was constructed in April 1986, specifically for this test. Twenty-five observation wells were installed, including eight small-diameter

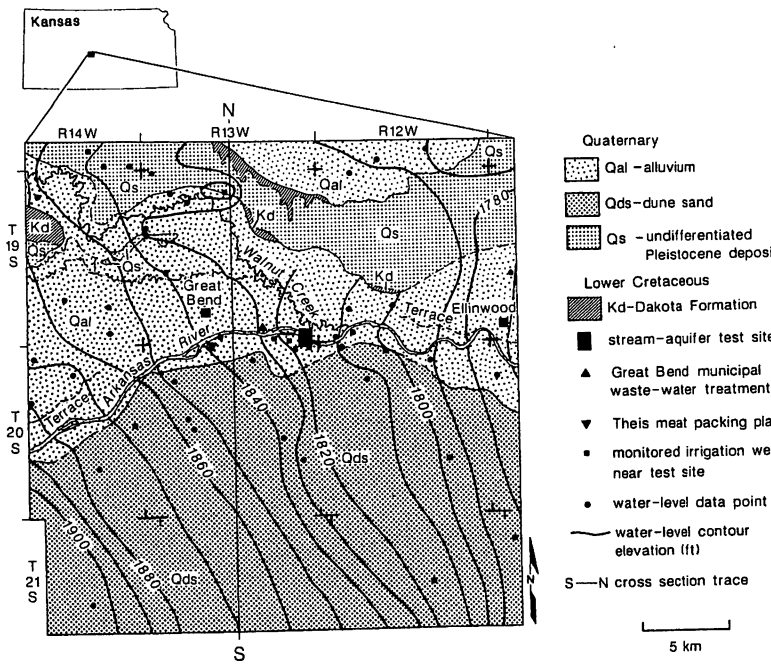

Fig. 1. Location, general geology (adapted from Latta, 1950) and December 1986 water level contours of the stream–aquifer test site and vicinity. To convert contours in ft to m multiply by 0.3.

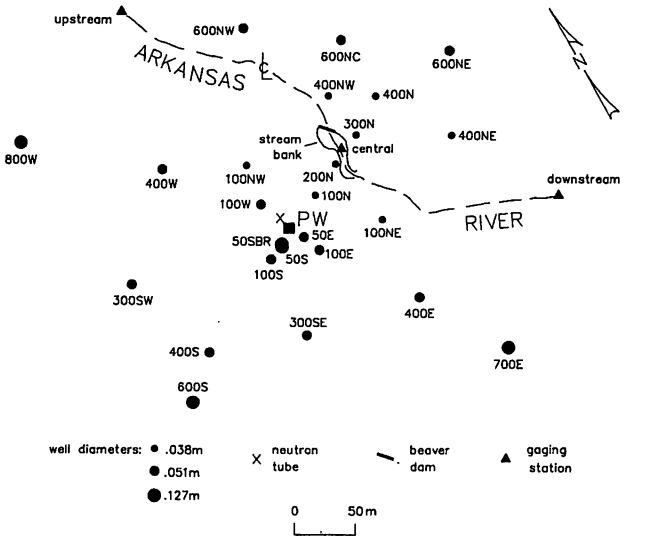

Fig. 2. Observation well layout at the stream–aquifer test site.

well points, located along lines approximately parallel and perpendicular to the Arkansas River, as well as in other positions. Figure 2 depicts to scale the well layout at the site.

A flood-protection earth dike existed between the pumping well and the Arkansas River. All wells on the distant side of the dike are called north wells, while all wells on the pump well side of the dike are called south wells.

A 13.4 m deep neutron probe access tube made from a galvanized steel pipe, tightly sealed at the bottom, was installed approximately 7.6 m from the pumping well (Fig. 2). Five 0.019 m diameter minipiezometers, constructed by KGS, with a 0.127 m long screen were inserted in the stream bottom at depths ranging from 0.6 to 1.8 m. Seven seepage meters, constructed similar to those of Lee (1977), including a novel KGS-designed recording seepage meter, were installed in the streambed to a 0.2 m depth. A weather station consisting of a meteorograph recording air temperature, relative humidity, and barometric pressure, and a mechanical weather station unit recording air temperature, wind speed and direction, and rainfall (through a tipping-bucket rain gage) was also installed at the site.

Three stream-gaging stations designated as upstream, center, and downstream, separated by a distance of approximately 240 m (Fig. 2), were selected for monitoring during the test. Each station was equipped with a staff gage. In addition, four nearby irrigation wells (Fig. 1) were selected for monitoring during the test.

TEST LOGISTICS

Because of the large number of observation wells at the site, the manpower requirements were high. To economize on field personnel, three Stevens water level recorders were installed at the most distant 0.127 m diameter wells from the pumping well (800W, 700E, 600S in Fig. 2), expecting that the most distant wells would show smaller water level declines. The recorded water levels at the site prior to pumping were stable. Three pressure transducers connected to data logging units were also installed: one in the pumping well, one in the 50S well screened in the consolidated aquifer underlying the alluvial aquifer, and one (which failed to function) in the 50E well. In order to further economize on personnel, the 0.05 m 400S, 400E, and 400W wells (Fig. 2) were converted to recording wells during recovery by specifically constructing 0.025 m PVC float tubes and specially adjusting the type-F Stevens recorders so that the recording drum was speeded up to a complete traverse in 6 h instead of the shortest factory preset time of 12 h. Several state and local agencies, in addition to KGS staff and students, offered to help in this test to ease the manpower requirements. To further reduce manpower requirements, the pump test, initially scheduled for a two-week duration was reduced to eight continuous pumping days. A fully equipped trailer was used as headquarters at the pump-test site.

The pumping started at 13:02 Central Standard Time (CST) on April 21, 1986, and was maintained at approximately 9538 $m^3 d^{-1}$ until 13:01 Daylight Savings Time (DST) on April 29, 1986. A McCrometer flow meter was installed on the pumping-well discharge pipe to continuously monitor the pumping rate. The pumped water was diverted back to the river downstream from the pumping well through a 0.23 m irrigation pipe approximately 305 m long.

GEOLOGY AND INITIAL CONDITIONS

The surficial geology of the area is that of a typical river-alluvium environment consisting of generally coarse granitic sands and gravels intermingled with relatively thin clays. The surface is partially covered by dune sand forming relatively low mounds. The generalized geology of the region near the pump-test site is shown by the north–south cross section in Fig. 3 adapted from Latta (1950). Figure 1 also depicts the water level pattern in the area. A general west–east flow direction along the river alluvium is present.

Bedrock consisting of fine-to-medium yellowish sandstone with very thin yellowish clay streaks was encountered at approximately 29.3 m below land surface. At the 35 m depth interval of the bedrock observation well (50SBR), a very hard white quartzose sandstone was encountered which the rotary drill was unable to penetrate. It is inferred that the formation below the alluvium is a sandstone bed in the Kiowa Formation (Latta, 1950), although a Dakota Sandstone interpretation is not excluded because an iron-stained sandstone cobble typical of the Dakota Formation was removed from the bottom of the pumping well borehole.

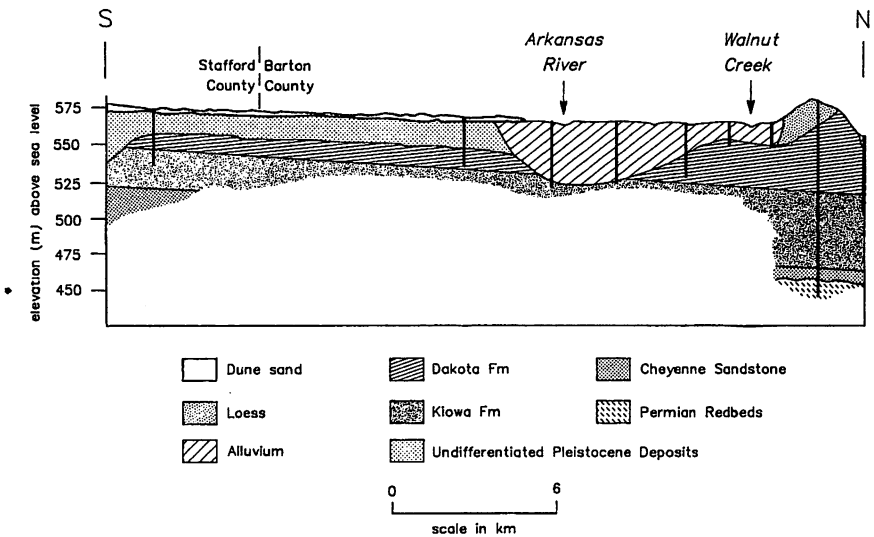

Fig. 3. North–south geologic cross section near the stream-aquifer test site indicated in Fig. 1 (adapted from Latta, 1950).

The pump-test site geology, based on drillers' logs and gamma-ray logs, is shown by the fence diagram of Fig. 4. A clay layer of varying thickness and depth, but of approximately continuous extent, is evident around the 9–12 m depth interval. This clay layer is closer to the surface in the pumping well vicinity. Another thinner and more discontinuous clay layer is evident above the main clay layer. These clay layers have significant implications for interpreting the results of the stream–aquifer pumping test as will be seen further on. Generally, a coarsening of the sand and gravel sediments is observed with depth, especially below the clay layer.

The static water-level configuration at the stream–aquifer site (Fig. 5) showed an elongated "bulge" approximately parallel to the Arkansas River. This indicates a local groundwater divide with a flow component towards the river and another one southwestward away from the river at the test site. The regional groundwater gradient is generally from west to east, and along the river course (Fig. 1). Water level surveys conducted after the test period (May 1, 1986 and December 1986), showed the same groundwater level pattern, indicating that the earlier-mentioned clay layer, most likely creates a "perched-type" water level condition in that area.

COMPLICATING CONDITIONS DURING THE TEST

While the drawdown test was underway, the nearby irrigation wells (Fig. 1), with the exception of the SE irrigation well, started pumping at different times,

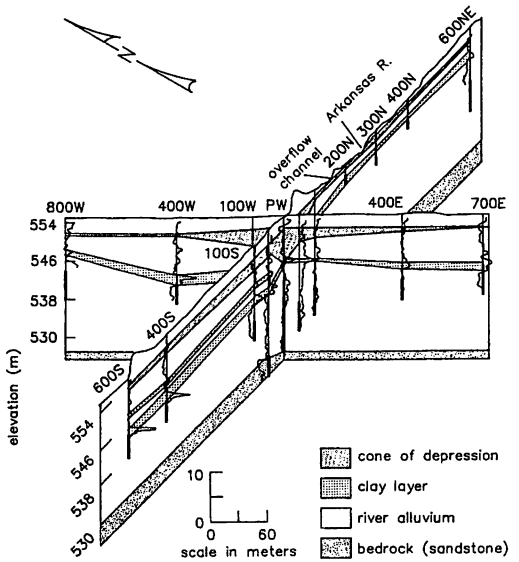

Fig. 4. Fence diagram of the stream–aquifer test site showing major lithologic units based on gamma ray logs and drillers logs. Cone of depression just before pump shut down is also shown. Thickened portions of vertical lines (observation wells) indicate screen intervals.

stopped for a short-time interval, and resumed pumping again (Sophocleous et al., 1987). All these irrigation wells stopped pumping when a rainstorm started. This 51 mm rainstorm which occurred in the early morning hours of April 27, created high stream stage on April 27 and 28. No significant barometric

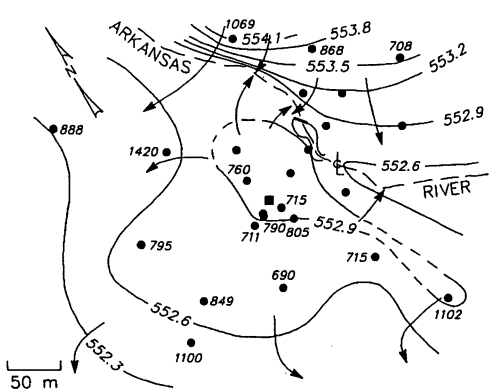

Fig. 5. Static water-level configuration at the stream–aquifer test site. Groundwater specific conductance values from wells taken after the completion of test (July, 1986) are also shown.

pressure changes were observed during the test period (Sophocleous et al., 1987). In addition to these complications, the pumping rate was difficult to maintain at a constant level during certain time intervals, especially during the first minute, during the 10–21 min time interval and around the 2740–2750 min period.

STREAM RESPONSE TO PUMPING

As shown in Fig. 2, three river sections were being monitored during the test period using pygmy water-current meters. A beaver dam was present immediately upstream of the central gaging station (Fig. 2). A stream level recorder was used to record stream stage inside a perforated drum emplaced on the streambed near the central stream-gaging section. The municipal waste-water treatment plant for the city of Great Bend is located approximately 2.4 km west of the pump test site (Fig. 1). The treatment plant released a daily average effluent of 9245 $m^3 d^{-1}$ to the Arkansas River during the test period. The daily discharge from that plant was fairly constant (Sophocleous et al., 1987). However, the hourly discharges fluctuated widely, although in a fairly constant manner, as shown in Fig. 6. This effluent variability is significant because it affected the hourly streamflow discharge and stage of the Arkansas River.

A record of stream stage during the test period is shown in Fig. 7. A stream-stage-decline pattern is evident once the pumping phase started (time 0). This decline was temporarily interrupted by the rain storm around the 8100 min mark. The stream-stage decline stopped only after the pumping stopped, after approximately 11,500 min. Figure 7 also shows the effect of effluent releases to the stream on the pattern of stream hydrographs, indicating that these fluctuations are not the result of evapotranspiration processes. If that were the case, one would expect high stage (and flows) during the night and early morning hours which is contrary to what is observed. Figure 8 shows the same declining pattern with regard to streamflows. Streamflows declined from approximately 11.88 $m^3 min^{-1}$ at the start of the test to approximately 3.06 $m^3 min^{-1}$ by the fifth day of pumping just before the rainstorm occurred. The decline stopped right after the pump was turned off at 11,459 minutes (Fig. 8). Figure 9 shows streamflow differences between the downstream and central gaging stations. It

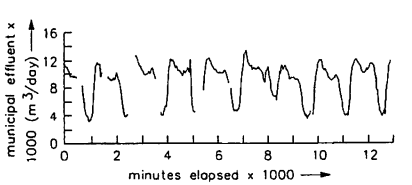

Fig. 6. Continuous effluent release curve to the Arkansas River from the Great Bend municipal waste-water treatment plant during the test period.

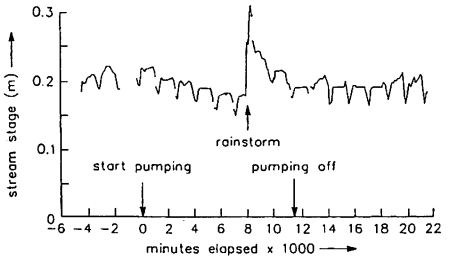

Fig. 7. Arkansas River stage hydrograph during the test.

is evident that throughout the duration of the test the 213 m stream reach was losing water (with the exception of the rainstorm period) and that only after the pump was shut off did the reach return to its natural "gaining" condition. Excluding the flooding event of April 27, 1986, the average streamflow (seepage) loss across this 213 m stream reach during the pump test period was $0.78\,m^3\,min^{-1}$ while the streamflow gain after the pumping was stopped was $0.36\,m^3\,min^{-1}$ across the same reach. This latter value most probably represents the natural streamflow gain over that reach.

Five minipiezometers were installed in the streambed near the central gaging station at depths of 0.6, 0.9, 1.2, 1.5 and 1.8 m. The stream was very shallow (~0.18 m deep), with an average width of 5.5 m at the test site. The streambed consisted of gravel and coarse sand, with no significant silt layer evident. A reference horizontal line was marked on the minipiezometer standpipes, and all measured minipiezometer water levels were referenced to that datum for consistency because the sand and gravel streambed was constantly changing due to sediment transport and streambed scouring. A plot of water levels from the minipiezometer nest (Fig. 10) indicates that prior to the pumping test, upwards gradients from the alluvial sediments to the streambed were in existence making the stream in that vicinity a gaining one. As soon as the pump was turned on, these gradients were reversed and became downward gradients from the streambed to the underlying sediments, making the stream

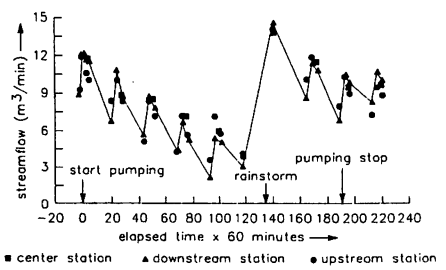

Fig. 8. Arkansas River streamflow hydrograph during the test.

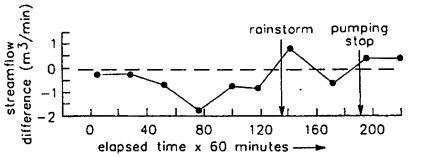

Fig. 9. Streamflow difference hydrograph between the downstream and central gaging stations on the Arkansas River during the test.

in the same vicinity a losing one (induced infiltration). This situation continued until the pumping well was shut off, immediately after which the minipiezometer gradients were again reversed to their natural condition. Streamflow fluctuations and the high stream stage resulting from the rainstorm are reflected in the minipiezometer response (Fig. 10). Analysis of water chemistry data also supports the stream–aquifer interaction as will be further discussed in the water-chemistry analysis section.

Analysis of the seepage meter data indicated that due to the highly permeable nature of the streambed and the shallow depth of insertion (0.2 m), the seepage meters were probably unable to hermetically isolate the streambed area covered by them, resulting in a high degree of correlation between stream stage and flow through the seepage meters.

AQUIFER AND OVERLYING SEDIMENT RESPONSE TO PUMPING — SOME FUNDAMENTAL QUESTIONS

A typical drawdown-recovery response from a well with a recorder on it is shown in Fig. 11 for the 600S observation well. A sharp initial drawdown as well as a sharp initial recovery are evident from the hydrograph. Also, the effects of the on and off pumping of nearby irrigation wells are evident in the hydrograph. The fact that the rate of drawdown was sharply reduced after the first few minutes of pumping is indicative of a recharge and/or leakage effect. Figure 12a depicts the drawdown versus time on a semilog graph for the 100S

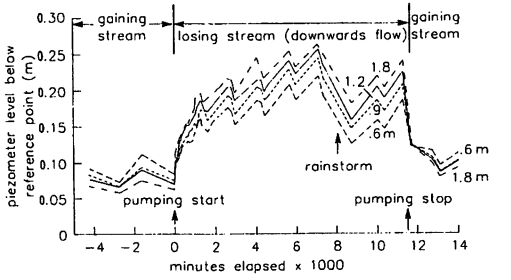

Fig. 10. Water level hydrographs from minipiezometer nest in streambed sediments during the test.

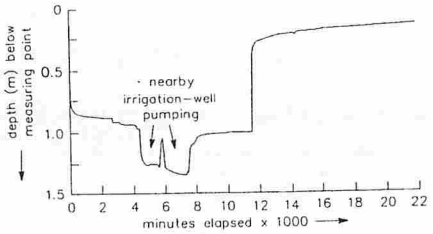

Fig. 11. Drawdown-recovery well hydrograph for the 600 S observation well.

observation well which was chosen as a typical one. The effects of pump adjustments during the 10–20 min interval, as well as the effects of nearby irrigation wells pumping are clearly evident. Also, the flattening of the drawdown curve, especially evident after the 10 min mark, is indicative of recharge and/or leakage effects which, however, have not completely stabilized the cone of depression. The water level (Figs. 11 and 12) is still continuously declining, albeit at a very slow rate due to the recharge/leakage effects. A log–log plot of the same 100S well hydrograph (Fig. 12b) is nearly flat, with the above-mentioned irrigation-well interference effects and pump adjustment effects subdued. The log–log recovery response (Fig. 12c), like the arithmetic recovery response (Fig. 11), shows a steep initial slope which flattens considerably after the first couple of minutes.

Figures 11 and 12 indicate that we are dealing with a very transmissive aquifer because of the extremely rapid recovery, the extremely rapid transmission of the pumping stress to the most distant wells, and the rapid flattening of the drawdown curve, indicating ready transmission of recharging water to the cone of depression.

Figure 13 shows the resulting cone of depression on the southern side of the

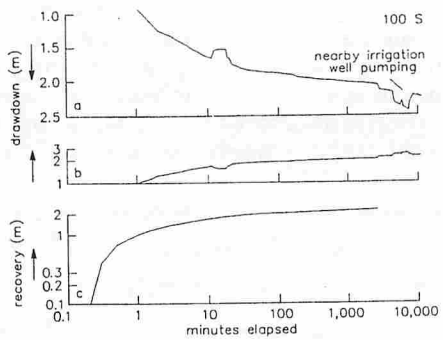

Fig. 12. Semilog graph of drawdown hydrograph (a), and log–log graphs of drawdown (b) and recovery (c) hydrographs for the 100 S observation well.

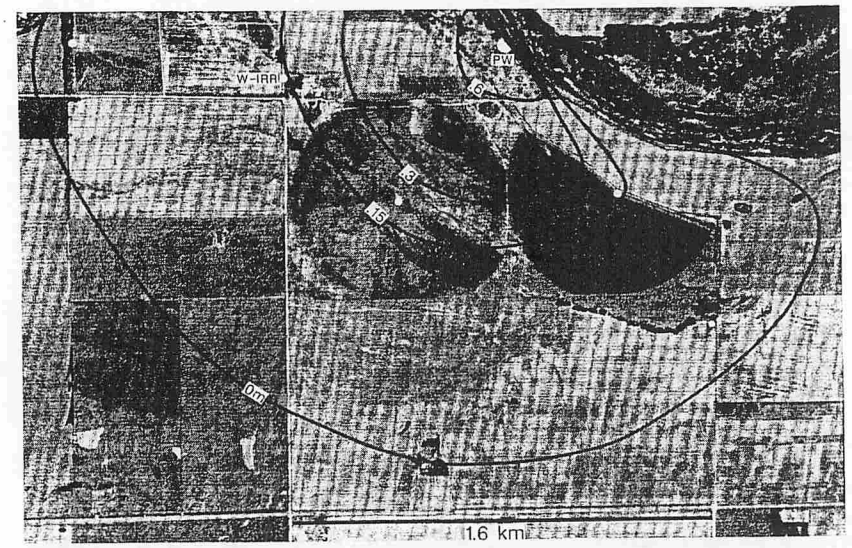

Fig. 13. Cone of depression on the southwestern side of the Arkansas River on the morning of April 29, 1986. PW indicates the pumping well and W-IRR the west irrigation well.

river on the morning (9:00 a.m.) of April 29, 1986, three hours before pump shut down. Note the steep gradients towards the stream, indicating a recharge source from the stream. Also, note the large area of influence of the pumping well, despite the presence of the stream, with a radius of influence of at least 1.77 km. This corroborates the earlier inference that we are dealing with a very transmissive aquifer.

Figure 14 shows a detailed plot of the cone of depression at the test site during the same time as that of Fig. 13. A quasi-elliptical shape of the cone of depression with the long axis approximately parallel to the stream is evident. Again, steeper gradients are developed northeast of the pumping well in the direction towards the river indicating the river is a source of recharge.

A steep cone of depression in the immediate vicinity of the pumping well can be recognized (Fig. 14), with a drawdown of more than 7.5 m at the pumping well, which reduces to less than 2.7 m approximately 15 m away. Such a steep cone of depression is indicative of low storativity.

Figure 14 indicates that drawdown is observed on the opposite side of the river from the pumping well despite the highly permeable nature of the streambed, indicating that the stream was not acting as a constant head boundary. The observed drawdowns were relatively small close to the river, but they increased as one moved farther away from the river (Fig. 14) to the distant stream side from the pumping well. A fundamental question to be asked, then,

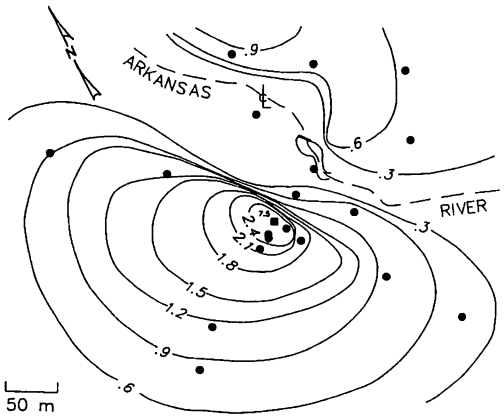

Fig. 14. Cone of depression at the test site at the same time as that of Fig. 13.

is: *why is drawdown observed on the other side of the river*? This question will be dealt with later.

A typical response of the observation wells on the opposite, northeastern side of the river is exemplified by the semilog plot of drawdown for the 600NW observation well (Fig. 15). Two facts from such well response are of significance. First, the effects of the pumping irrigation wells are felt on all wells on the distant side of the river, reinforcing the previous observations of a highly transmissive aquifer. Second, the drawdown response of the north wells can be seen in the semilog plots, as exemplified by the 600NW well, as a flattening of slope indicating a recharge source. Another fundamental question to be asked is: *why is a recharge source evident on the north wells*? The obvious recharge source is the Arkansas River, and the pumping well on the southeastern side of the river is creating a sink towards which all water is directed, including water from the recharge source and water from the north-side wells. This question will also be dealt with later.

From the responses of the observation wells (Figs. 12 and 15), one can easily deduce that the aquifer response to the pumping well is not typical of water-

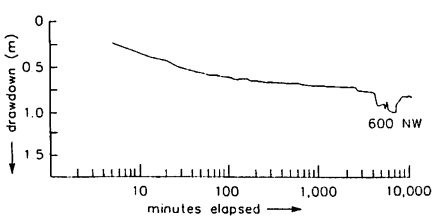

Fig. 15. Semilogarithmic plot of drawdown hydrograph for the 600 NW observation well.

table or unconfined aquifers, of which alluvial aquifers, such as the Arkansas River alluvial aquifer, are characteristic. No sigmoid drawdown curves with delayed drainage effects are observed, and no indications of large storativities typical of unconfined aquifers are observed. One may, therefore, pose another fundamental set of questions: *Why did the aquifer not exhibit a water table behavior, and why was "delayed" drainage response not observed*?

In order to answer the above questions, the response of the overlying sediments and dewatered aquifer sediments will be examined to answer the last set of questions first.

Prior to and during the pumping and recovery phases, the water content of the overlying and dewatered aquifer sediments and the porosity of the aquifer were determined using a neutron probe. The neutron probe was operated continuously during the test, with detailed readings taken in the vicinity of the static water table and of the expected dewatered aquifer sediments. Figure 16 shows a neutron-based water content/porosity (if the sediments are water-saturated) profile just before the pump test started and just before the pump was shut down for the recovery phase of the test. It is evident from that figure that despite an estimated drop in the water table of approximately 2.74 m at the neutron access-tube locality (7.6 m from the PW), the decrease in water content (dewatering) in the drawdown zone was minimal, with most of the dewatering occurring within 0.15 to 0.3 m of the static water table (Fig. 16). Some dewatering of the zone immediately above the water table (capillary fringe zone?) was also observed (Fig. 16). The water content of the alluvial sediments was also monitored during recovery. Despite full water table recovery, sediment water-content recovery was not complete by the end of the recovery period, probably due to the high water-level recovery speed and the slow diffusion of entrapped air bubbles from the dewatered zone.

To highlight these observations, a set of moisture–time patterns at different depths is plotted in Figure 17. It is evident from the figure that sediment water content started decreasing right after pumping started in the vicinity of the

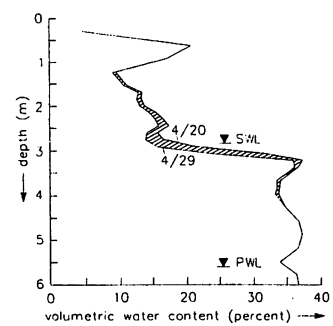

Fig. 16. Volumetric water content vs. depth profiles of sediments near the pumping well immediately before pumping and at the maximum drawdown.

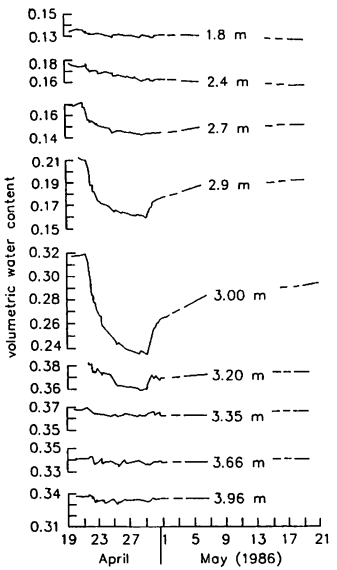

Fig. 17. Sediment water content vs. time patterns for various depths during the drawdown and recovery phases of the test.

static water level, with the maximum dewatering observed at the 3 m depth, where the static water level was located. Below the 3.35 m depth, negligible amounts of dewatering were observed. The sediment water content started recovering right after the pump was shut off, with the moisture recovery not completed even three weeks after complete water level recovery (Fig. 17).

The reason for no appreciable deep drainage in the vadose zone is due to the existence of a clay layer at a depth of approximately 9–12 m (Fig. 4) which was not penetrated by the cone of depression. The clay layer acted as a "leaky" seal effectively preventing dewatering of the sediments above it over the time scale of the test. Had the test continued for several weeks (or months), it is possible that delayed drainage effects would have been observed, especially after the cone of depression penetrated deeper than the level of the clay layer. The clay layer acted as an effective confining layer over the aquifer, causing it to behave as a confined, albeit leaky, aquifer and not as a water table aquifer.

As a consequence of the semiconfining clay layer overlying the main aquifer and of the observation well responses to pumping, a leaky confined aquifer-analysis methodology was employed to analyze drawdown/recovery data. It should be noted that little difference exists between unconfined-aquifer response, nonleaky confined aquifer response with a recharge source (image well), and leaky confined aquifer response over certain time intervals. All above-mentioned analysis methodologies (Lohman, 1972) were employed on the

observed data. However, the Hantush–Jacob (1955) leaky confined-aquifer methodology with no water-storage effects from the semipervious confining bed gave the best match to the observed data and the most consistent results. The Hantush (1960) modified theory of confined aquifers did not match most of the observed data.

All aquifer-analysis methodologies employed in this study resulted in two groups of transmissivities. One group of wells consistently resulted in high transmissivities of the order of 4967 $m^2 d^{-1}$. This group of wells includes predominantly the north wells, especially the 600N group (600NE, 600NC, and 600NW), the 400N, and the 700E wells (Fig. 2). It seems that an extremely high transmissive zone exists northeast and southeast of the pumping well crossing the Arkansas River. Most other wells resulted in a geometric mean transmissivity (T) of 1803 $m^2 d^{-1}$, a mean storativity (S) of 5.6×10^{-4}, and a mean leakance of $3 \times 10^{-2} d^{-1}$ (Sophocleous et al., 1987).

A distance–drawdown analysis of the data (Sophocleous et al., 1987), from the wells approximately parallel to the river, did not result in a straight line which could be drawn with confidence. The resulting patterns, however, resembled the expected theoretical profiles for a stream–aquifer system (Kazmann, 1948; Rorabaugh, 1956) as shown in Fig. 18, indicating that recharge did occur from the river source. The river line curve in Fig. 18 may not actually represent the main aquifer because the relatively shallow 100N and 200N well points did not penetrate the main aquifer (Fig. 4).

To answer the first-posed question as to why drawdown was observed on the north side of the river, one should examine the geology and screen-interval locations of the pumping and observation wells. It can be seen from Fig. 4 that the semiconfining clay layer becomes shallower closer to the Arkansas River. When installing well point 200N in the immediate vicinity of the river, a clay

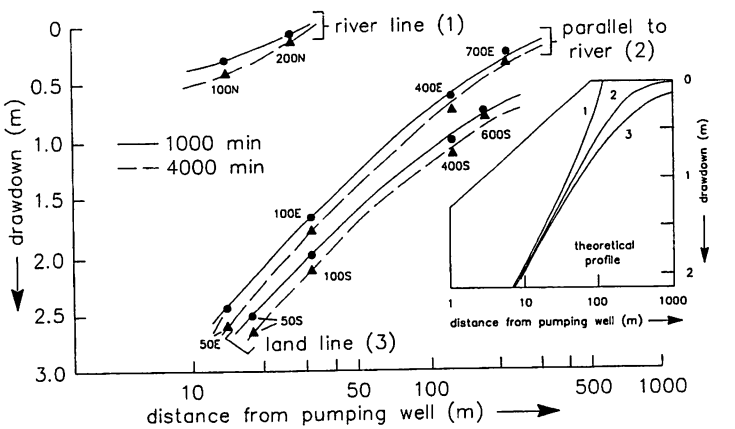

Fig. 18. Semilogarithmic distance vs. drawdown plot for various lines of wells approximately parallel (*2*) or perpendicular (*1* and *3*) to the Arkansas River. Theoretical distance–drawdown diagram adapted from Rorabaugh (1956).

layer was encountered at approximately 3 m from the surface. The clay layer also is present at varying depths on the distant side of the river. It should also be noted that all 0.05 and 0.127 m observation wells, as well as the pumping well, are screened below the semiconfining clay layer (Fig. 4). The combination of the semiconfining layer and the screen locations could explain why the north wells responded to the distant irrigation-well pumping, as exemplified in Figure 15. In other words, only the semiconfined lower aquifer, which extends beneath the Arkansas River and beyond, is the stressed and monitored entity. The fact that the 100NW, the 100N, and the 200N well points did not penetrate the clay layer (Fig. 4) resulted in minimal drawdowns in these wells and in barely noticeable effects of the distant irrigation-well pumping (Fig. 19); nearby well points, however, which either penetrated or did not encounter the clay layer exhibited larger drawdowns and showed the effects of distant pumping (Fig. 20). Thus, the semiconfining clay layer acted as a partial seal, creating a "perched-type water table" condition. This explains why near the stream, with the source of water and resulting induced infiltration, drawdowns were minimal; while further away from the stream and the pumping well, larger drawdowns were observed. These observations also possibly explain why the Hantush–Jacob leaky confined-aquifer analysis is applicable: negligible drawdown was observed on the water table aquifer above the confined aquifer, and also negligible storage effects were expected from the confining layer because of its small thickness (generally less than 3 m thick) and its partial continuity.

It is interesting to note that only two observation wells did not exhibit a significant recharge effect. Both of these (Fig. 19, wells 100NW and 100N) were well points completed within the clay layer that acted as a partial "barrier boundary" and negated the "recharge boundary" effect.

Given the above explanation of observed drawdowns on the distant side of the river, it would be expected that the induced infiltration through the river bed and the leakage through the semiconfining clay layer would be diverted towards the pumping well and, therefore, continued drawdown would be

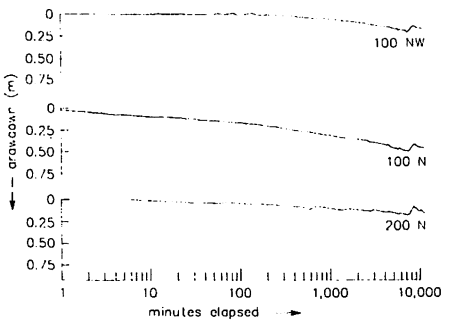

Fig. 19. Semilogarithmic drawdown hydrographs for the 100 NW, 100 N and 200 N observation wells.

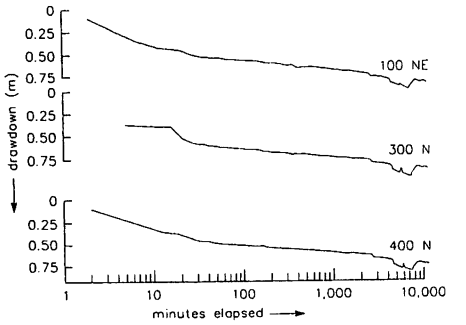

Fig. 20. Semilogarithmic drawdown hydrographs for the 100 E, 300 NE and 400 N observation wells.

expected in the north wells on the distant side of the river. However, the north wells show a flattening of the semilogarithmic time–drawdown curve (Figs. 15 and 20) indicating a source of recharge. Although this could be interpreted as a leakage effect, a more likely explanation is a combination of both leakage and a recharge source from Walnut Creek, some 945 m north and northeast of the pumped well (Fig. 1).

Figure 21 represents the water-level elevations after 8 h of continuous pumping (21:00 h, April 21, 1986). Two important features can be seen: (1) A more highly transmissive path from the northeast, consistent with the high-transmissivity layer encountered in the 600N group of wells, the 400N, and 700E wells, indicating a water transport from the northeast and pointing towards the Walnut Creek alluvium as a source of water. The distance to Walnut Creek from the pumped well is well within the zone of influence of the

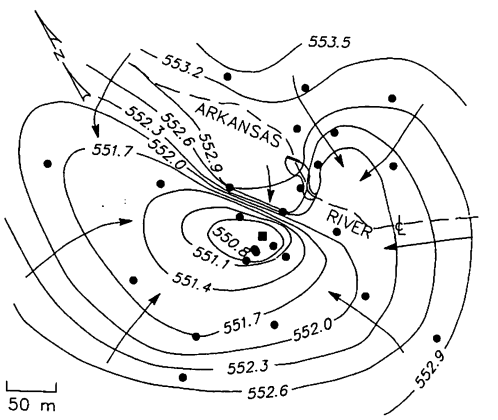

Fig. 21. Water-level elevation contours at the test site after 8 h of continuous pumping.

pumping well, especially if one considers the appreciable impact of pumping by the west irrigation well (W-IRR in Fig. 13), on the 600N group of wells more than 1.6 km away. Water chemistry data discussed in the water chemistry section, further support the Walnut Creek source of recharge. (2) The steep hydraulic gradients along the line of 100N and 100NW wells, indicate that the clay layer is acting as a partial barrier to flow from the northeast, thus emphasizing the highly transmissive paths to the northeast and southeast.

DISTANCE-TO-SOURCE ANALYSIS

Rorabaugh (1956) developed a number of equations for calculating the distance a to the line source given that drawdowns, s, at any two observation wells (OW) at known distances, r, from the pumped well (PW), and of different configurations relative to the line source, are known. These equations are based on the following assumptions: homogeneous, nonleaky confined aquifer of infinite extent, in which pumping has continued long enough to establish equilibrium or steady-flow conditions. Also, barometric pressure and river elevation remain constant, and the temperature of the river water and water in the aquifer are equal and remain constant. Rorabaugh's equations shown in Table 1, column a, are rearranged for iterative (trial-and-error) calculations in column b.

If various pairs of wells are used and values of a are consistent, the assumed conditions are verified. However, if the assumed conditions are valid and values of a differ, the transmissivity may not be uniform. Other graphical and analytical methods exist for determining values of a (Kazmann, 1946, 1948; Heath and Trainer, 1981; Hantush, 1959, 1965). Although probably none of these was applicable to the data from this test (all above-mentioned methods were attemped), Kazmann's method (1948) relying exclusively on the river line of wells, was employed because of its simplicity (Fig. 18) resulting in a distance to the line source, $a = 33.5$ m, subject to the reservations expressed previously in the paragraph related to distance-drawdown analysis.

Iterative application of the formulas in column (b) of Table 1 for selected pairs of wells using drawdown values near the end of the test (where near steady-state conditions may be acceptable) resulted in the distance values to the line source shown in Table 2.

The variability in calculated a values shown in Table 2 indicates that the already-mentioned assumptions on which these formulas are based are not entirely validated. However, the differences in calculated a are not extreme, with a resulting average or effective $a \simeq 155$ m, possibly indicating the existence of not only the Arkansas River source, but also of an additional source of water at some farther distance away (Walnut Creek). The calculated distance to source based on the "river line" (100N and 200N well points), using either the Rorabaugh ($a = 83$ m) or Kazmann ($a = 33.5$ m) methods, are of the correct order of magnitude, with the actual distance to the Arkansas River (64 m) being the approximate average of these two estimates.

TABLE 1

Rorabaugh's (1956) equations for calculating the distance a to a line source

	a	b
Pair of OW on line perpendicular to river on river side of PW	$\frac{s_1}{s_2} = \frac{\log \frac{2a - r_1}{r_1}}{\log \frac{2a - r_2}{r_2}}$	$a_j = \frac{1}{2}(2a_i - r_2)^k \left(\frac{r_1}{r_2^k}\right) + \frac{r_1}{2}$
Pair of OW on line perpendicular to river on land line (side of PW away from river)	$\frac{s_1}{s_2} = \frac{\log \frac{2a + r_1}{r_1}}{\log \frac{2a + r_2}{r_2}}$	$a_j = \frac{1}{2}(2a_i + r_2)^k \left(\frac{r_1}{r_2^k}\right) - \frac{r_1}{2}$
Pair of OW on line through PW parallel to river	$\frac{s_1}{s_2} = \frac{\log \frac{\sqrt{(4a^2 + r_1^2)}}{r_1}}{\log \frac{\sqrt{(4a^2 + r_2^2}}{r_2}}$	$a_j = \sqrt{\left[\frac{1}{4}(4a_i^2 + r_2^2)^k \left(\frac{r_1}{r_2^k}\right)^2 - \frac{r_1}{4}\right]}$

$k = s_1/s_2$ (drawdown ratio); assume a_i and obtain a_j; solution obtained when $a_j = a_i$ in an error tolerance. PW = pumped well, OW = observation well.

Knowing the effective distance to the line source a, the aquifer transmissivity (T) can be computed on the basis of drawdown at each observation well (Rorabaugh, 1956). Also, knowing a and T, the aquifer storativity can be determined through a trial-and-error procedure (Walton, 1964). All these relationships are based on the assumptions stated at the beginning of this section.

In order to check the plausibility of the derived hydrogeologic constants, the above-mentioned equations for T and S estimation, based on knowing a and s, were applied to the field data under the assumption that all leakage is lumped into induced infiltration from a line source. The results agreed satisfactorily with the estimated values (Sophocleous et al., 1987).

INDUCED INFILTRATION AND *sdf* ANALYSIS

A number of analytical streamflow depletion models are being increasingly used for purposes of water rights administration in several western states. However, there have been no adequate field studies of the hydrologic properties of stream-bottom sediments, and of the effects of pumping on aquifer hydrodynamics very close to streams to assess the limitations of simplifying assumptions in analytical equations or to verify the predictive capabilities of numerical models.

The vertical conductivity of the streambed sediments was determined using an infiltrometer (Sophocleous et al., 1987) at two places near the central stream-gaging station (Fig. 2). The resulting streambed hydraulic conductivity ranged from 7.2×10^{-5} to 9.6×10^{-5} m s^{-1}.

Theis (1941) developed an equation to estimate streamflow depletion caused

TABLE 2

Distance to line source values calculated from Rorabaugh's (1956) equations

Well pair	Calculated a (m)
400W–800W	146
100W–400W	241
50E–100E	116
100E–400E	177
50S–100S	154
100S–400S	171
100N–200N	83

by pumping wells at different distances from the stream. The equation is based on the assumption that the aquifer is under nonleaky confined conditions, is homogeneous and isotropic, and extends to infinity away from the stream. The equation also assumes that the stream completely penetrates the aquifer and is straight and infinite in extent. Glover (1952), Glover and Balmer (1954), and Glover (1974) built upon Theis' (1941) solution so that the length of the stream stretch from which various percentages of the well flow are derived can be easily calculated.

Values for streamflow depletion at the pump test site caused by pumping were computed from the Glover equation (1952; see also Maasland and Bittinger, 1963) shown in eqn. (1) below:

$$\frac{q_{\Delta L}}{Q} = \frac{1}{2\pi}\int_0^{\alpha}\frac{e^{-k_1(1+\alpha^2)}}{(1+\alpha^2)}\,d\alpha \qquad (1)$$

where $k_1 = a^2/[4(T/S)^2t]$, and $\alpha = \Delta L/a$; a is the perpendicular distance from the pumping well to the stream, $q_{\Delta L}$ is the flow of the well drawn from the stream reach length ΔL whose origin is the intersection of the distance a with the stream bank; Q is the well discharge (pumpage), S is storativity, T is transmissivity, and t is the time since the pumping stress commenced. Equation (1) was compared to the measured values to determine the validity of the equation in predicting streamflow depletion (Fig. 22). For the computations, the actual distance to the stream was used, i.e. $a = 64\,\mathrm{m}$; $T/S = 3.219 \times 10^7\,\mathrm{m^2\,d^{-1}}$ and $\alpha = \Delta L/a = 3.33$. Comparison of these values indicates that the depletion of

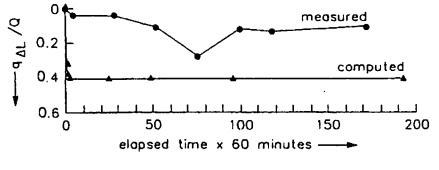

Fig. 22. Comparison of measured and computed streamflow depletion for the Arkansas River reach length, ΔL, between the central and downstream gaging stations based on Glover's (1952) equation.

flow between the central and downstream gaging sites was appreciably less than the computed depletion. The partially penetrating nature of the stream and the fact that most of the water moving from the stream toward the well had to move vertically downward through the less-permeable clay layer which was semiconfining the main aquifer are the apparent reasons for the observed discrepancies.

Jenkins (1970) presented dimensionless tables and curves for computing streamflow depletion caused by pumping a well. The equation used by Jenkins to compute the streamflow-depletion rate is:

$$\frac{q}{Q} = \operatorname{erfc}\sqrt{\left[\frac{sdf}{4t}\right]} \qquad (2)$$

where the stream-depletion factor (sdf) is defined as $(a^2S)/T$, q is the stream depletion caused by the discharging well pumping at a rate of flow Q, and erfc is the complementary error function.

Employing Jenkins' curve relating q/Q to t/sdf and using our pump test analysis values with $sdf = 1.27 \times 10^{-3}\,\mathrm{d}$ (employing the actual distance to the stream), or with $sdf = 7.5 \times 10^{-3}\,\mathrm{d}$ (using the computed effective $a = 155\,\mathrm{m}$), results in the streamflow-depletion rate as a function of time depicted in Fig. 23. This figure shows that within a very short time since pumping started (in the order of very few minutes), a substantial proportion of pumpage (more than 80%) was being supplied by the stream.

Glover's (1974) stream–aquifer analysis allows one to estimate the reach of the river, centered on the perpendicular distance to the stream from the pumping well, which supplies various percentages of the flow of the pumping well, provided steady-state conditions are achieved. Under these conditions, the flow from the linear reach $-x$ to $+x$ is given by:

$$\int_{-x}^{+x} f\,dx = \frac{2Q}{\pi}\arctan(x/a) \qquad (3)$$

where f is the flow from the stream per unit length of the streambank. Thus, for

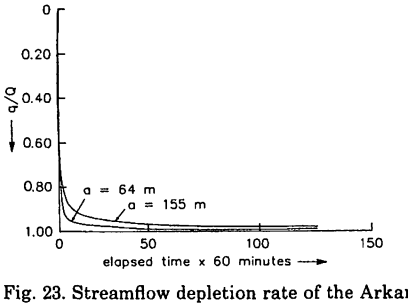

Fig. 23. Streamflow depletion rate of the Arkansas River at the test site based on Jenkins' (1970) equation.

example, one half of the flow of the well will come from a linear reach of the river $2a$ long centered on the well, and over 70% of the well flow will be supplied by a similar reach $4a$ long. Consequently, more than 90% of the well flow will be supplied by a linear river reach $13a$ long centered on the well. Using the actual distance to the Arkansas River (a = 64 m), this translates to an 832 m long linear reach. Using this river length as the effective stream source supplying the pumping well and assuming that the average measured streamflow loss between the central and downstream gaging stations ($0.78\,m^3\,min^{-1}/213$ m reach) is representative of the induced infiltration over the estimated entire effectively contributing river length 832 m, the equation results in a total induced infiltration amount of $3.05\,m^3\,min^{-1}$. (It should be noted that this is probably an overestimated amount because the measured river reach is closest to the pumping well.) Given that the amount of pumpage was $9538\,m^3\,d^{-1}$ or $6.62\,m^3\,min^{-1}$, the ratio of streamflow depletion to the quantity of water pumped is $q/Q \simeq 46\%$, which is considerably less than the percentages derived from the *sdf* analysis (Fig. 23). Also if the measured average groundwater contribution to streamflow (baseflow rate) over the stream reach between the central and downstream gaging stations ($0.36\,m^3\,min^{-1}/213$ m) is extended over the estimated effectively contributing river length of 832 m, then this stream baseflow would amount to $1.41\,m^3\,min^{-1}$, which is close to half the amount of induced infiltration.

WATER CHEMISTRY ANALYSIS

Selected water samples for chemical analysis were collected prior to, during, and after the eight-day pumping test. The most marked changes in chemistry were noted in the pumping well (Sophocleous et al., 1987): Ca, Mg, Na, SO_4, Cl and NO_3 increased over time, as did the water specific conductance (Fig. 24), suggesting that mixing of poorer quality waters has caused the water-quality decline in the pumping well. An inverse trend with the stream discharge is evident in Fig. 24.

Two possible sources for poorer quality water exist: the Arkansas River and the bedrock aquifer immediately underlying the alluvial aquifer. Both types of waters have conductivities greater than $1400\,\mu S\,cm^{-1}$. The bedrock water can probably be eliminated because of its very low concentrations of nitrate ($0.1\,mg\,l^{-1}$; Sophocleous et al., 1987). The Arkansas River water has sufficient amounts of sulfate, chloride, nitrate, and other chemical constituents to account for the resultant increase of these constituents in the pumping well (Sophocleous et al., 1987). By the end of the test, there was an approximate 25% increase in calcium (from 67 to $85\,mg\,l^{-1}$), magnesium (from 12 to $15\,mg\,l^{-1}$), sodium (from 83 to $100\,mg\,l^{-1}$), and chloride (from 80 to $101\,mg\,l^{-1}$) concentrations; a 73% increase in sulfate (from 62 to $107\,mg\,l^{-1}$); and a 178% increase in nitrate (from 1.8 to $5.0\,mg\,l^{-1}$) in the pumping well, indicating an Arkansas River water source. The other constituents did not change noticeably.

In the 600N group of wells, conductivity increased the closer the well was to

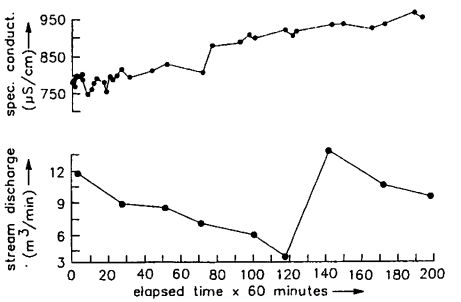

Fig. 24. Relationship between specific conductance of groundwater from pumping well and stream discharge at the central gaging station.

the river. The chemistry of 600NE and 600NC wells differed from the chemistry of the 600NW well. After the end of the test, the 600NE well had a specific conductivity of $708\,\mu S\,cm^{-1}$, the 600NC well had $868\,\mu S\,cm^{-1}$, and the 600NW well had $1069\,\mu S\,cm^{-1}$. These values may indicate an influx of fresher water from the northeast, such as from the direction of Walnut Creek and associated alluvium (Figs. 5 and 21).

In addition to the inferred groundwater flow paths, Fig. 5 also shows the measured groundwater electrical conductivities taken in July, 1986, well after the completion of the stream–aquifer test and after reequilibration of the aquifer system. The area around the pumping well is characterized by generally fresher groundwater and higher water-table elevations than the rest of the area west and southwest of the Arkansas River. The occurrence of higher conductivity water away from the area around the pumping well in July, 1986 helps support the idea of a perched-type water table in the vicinity of the pumping well. A perched-type water table would prevent or slow down recharge due to rainfall and runoff from reaching the lower aquifer.

CONCLUSIONS AND RECOMMENDATIONS

The results of this test indicate that the Arkansas River alluvial aquifer is a prolific aquifer with very high transmissivity. As a result, it readily responds to imposed stresses such as the well pumping. The pumping stress ($\sim 9500\,m^3d^{-1}$) during this test affected an area with a radius greater than 1.7 km, demonstrating that irrigation pumping in that aquifer has a significant area of influence and impact on both groundwater levels and streamflows in nearby streams. Drawdown and recharge boundary effects were observed in all observation wells completed within the aquifer, including the ones on the opposite side of the Arkansas River. The alluvial aquifer did not exhibit a water table behavior, and "delayed" drainage response was not observed due to a semiconfining clay layer less than 3 m thick and an additional recharge source from the nearby Walnut Creek alluvial system. Actual streamflow depletion

due to groundwater pumping was appreciably less than the computed depletion based on analytical solutions.

Pumping tests are the most reliable way of obtaining aquifer properties for use in developing groundwater supplies, in predictive numerical simulations and management of water resources. However, they are expensive tests because of both the required equipment and manpower.

In testing alluvial aquifers near streams, a minimum of several weeks pumping should be carried out to allow the aquifer to fully respond and adjust to the imposed stress, if meaningful results on storativities, transmissivities, leakances, and boundary effects are expected. In this case, the aquifer storativity could not be determined using the neutron probe because the time scale of the test was not long enough to allow dewatering of the upper aquifer unit through the underlying clay layer. Had the drawdown extended below the clay layer, which could possibly happen through a longer duration pumping stress, the derived aquifer storativity of the aquifer might have been different.

Also, in conducting stream–aquifer tests, the first seconds and few minutes are essential to data analysis and interpretation. Data interpretation would have been much easier in this case if we had measurements during the first seconds after pumping started so that a better curve matching could be obtained.

A better system needs to be developed for maintaining constant and stable pumping rate than the one employed in this test, which involved a hard-to-manipulate throttle without any fine-tuning capability.

To complete this test, a three-dimensional numerical simulation of the stream–aquifer system at the pumping test site may be needed. Through this type of simulation, all fundamental questions posed and answered in this report could be validated and reinforced. Work in this direction is being considered.

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STREAMFLOW DEPLETION: MODELING OF REDUCED BASEFLOW AND INDUCED STREAM INFILTRATION FROM SEASONALLY PUMPED WELLS[1]

Xunhong Chen and Yanfeng Yin[2]

ABSTRACT: Numerical modeling techniques are used to analyze streamflow depletion for stream-aquifer systems with baseflow. The analyses calculated two flow components generated by a pumping well located at a given distance from a river that is hydraulically connected to an unconfined aquifer. The two components are induced stream infiltration and reduced baseflow; both contribute to total streamflow depletion. Simulation results suggest that the induced infiltration, the volume of water discharged from the stream to the aquifer, has a shorter term impact on streamflow, while the reduced baseflow curves show a longer term effect. The peak impacts of the two hydrologic processes on streamflow occur separately. The separate analysis helps in understanding the hydrologic interactions between stream and aquifer. Practically, it provides useful information about contaminant transport from stream to aquifer when water quality is a concern, and for areas where water quantity is an issue, the separate analysis offers additional information to the development of water resource management plan.
(KEY TERMS: modeling; streamflow depletion; reduced baseflow; stream infiltration; anisotropic aquifer; baseflow.)

INTRODUCTION

When a pumping well is located near a stream hydraulically connected to an unconfined aquifer, it diverts ground water flow, which under natural conditions would have discharged into the stream as baseflow. As a result, the baseflow to the stream is reduced. As pumping continues, a reverse hydraulic gradient around the stream is ultimately formed and the stream begins to discharge water to the aquifer. This induced stream infiltration further reduces streamflow (Hantush, 1964). The reduced baseflow and the induced stream infiltration lead to total streamflow depletion.

A number of studies have focused on the analysis of total streamflow depletion because, for water resources issues, it is not always necessary to differentiate between reduced baseflow and induced infiltration (Conrad and Beljin, 1996). Examples of analytical solutions include Theis (1941), Glover and Balmer (1954), Hantush (1965), and Hunt (1999), which calculated the total streamflow depletion for simplified stream-aquifer systems where there is no baseflow. Under this circumstance, the total streamflow depletion is equal to the induced infiltration. For more complex stream-aquifer systems, numerical models have been used to calculate the total streamflow depletion (Sophocleous *et al.,* 1995; Chen and Yin, 1999a).

For water quality issues, a separate analysis of induced infiltration from reduced baseflow is important. For example, if the stream water is contaminated, the induced infiltration provides information about the contaminant transport from the stream to the aquifer. Wilson (1993) developed an analytical solution to calculate the induced infiltration for simple stream-aquifer systems. This solution helps in understanding the movement of stream water to the aquifer. However, the assumptions of a fully penetrating stream (stream incising through the entire thickness of the surrounding aquifer), steady state conditions, and isotropic aquifers limits the application to field conditions. Conrad and Beljin (1996) showed some significant departures between the results of the analytical solution and a numerical model for cases where there are violations to the assumptions. As pointed out by Wilson (1993), the assumption of a steady state flow condition is seldom

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[2]Conservation and Survey Division, University of Nebraska-Lincoln, 113 Nebraska Hall, Lincoln, Nebraska 68588-0517 (E-Mail/Chen: xchen2@unl.edu)

true in the field. He suggested additional analyses of induced infiltration under transient conditions.

Although the induced infiltration has been analyzed for water quality issues by Wilson (1993) and Conrad and Beljin (1996), reduced baseflow has not been fully evaluated. In matters of water resources rights, knowledge of reduced baseflow is critical. Chen and Yin (1999b) have demonstrated that irrigation wells located at a certain distance from a gaining stream will not reverse hydraulic gradient below the stream and thus do not induce stream infiltration. However, the pumping depletes streamflow entirely from the reduced baseflow. A close examination of the processes of induced infiltration and reduced baseflow is a very important step in the study of stream-aquifer interactions.

The objective of this study is to demonstrate that a separate analysis of induced infiltration and reduced baseflow will be beneficial to the study of hydraulic connectivity between streams and aquifers. The role of the two flow components in the total streamflow depletion will be evaluated. We will focus on seasonal pumping wells, that is, irrigation wells. Irrigation seasons in many U. S. Midwestern states typically last from June to August. The study will consider two pumping seasons. The induced infiltration and reduced baseflow will be calculated for the pumping and nonpumping periods so that their temporal variations can be analyzed. Aquifer systems in many river valleys, particularly in the High Plains region (Nebraska, Kansas, etc.), are unconfined, where rivers usually partially penetrate the aquifers. A partially penetrating river generates a vertical flow component near the interface of river and aquifer. To account for such complex flow systems, a three-dimensional numerical model will be designed for this study.

BASEFLOW AND STREAM INFILTRATION

In a stream-aquifer system, the stream may receive discharge from ground water when the hydraulic head in the aquifer is higher than the stream stage. Streamflow originating from ground water discharge is referred to as baseflow. Typically, baseflow is not subject to wide fluctuations due to seasonal changes, and it is indicative of aquifer characteristics within a basin (Todd, 1980). Figure 1a is a schematic diagram showing a stream-aquifer system where the stream gains water from the aquifer through baseflow.

For baseflow streams, the amount of ground water discharge is directly proportional to the hydraulic gradient toward the stream and to the hydraulic conductivity of stream channel sediment and surrounding aquifers. For a fully penetrating stream, ground water flow to the stream is dominantly horizontal and the horizontal hydraulic conductivity (K_h) plays an important role. For a stream-aquifer system where the stream partially penetrates the aquifer, three-dimensional conditions exist in the vicinity of the streambed (Conrad and Beljin, 1996). Under this circumstance, the vertical hydraulic conductivity (K_v) has a significant role in controlling the ground water discharge rate. A pumping well near a stream can intercept baseflow and thus reduce the ground water discharge rate to the stream (Figure 1b).

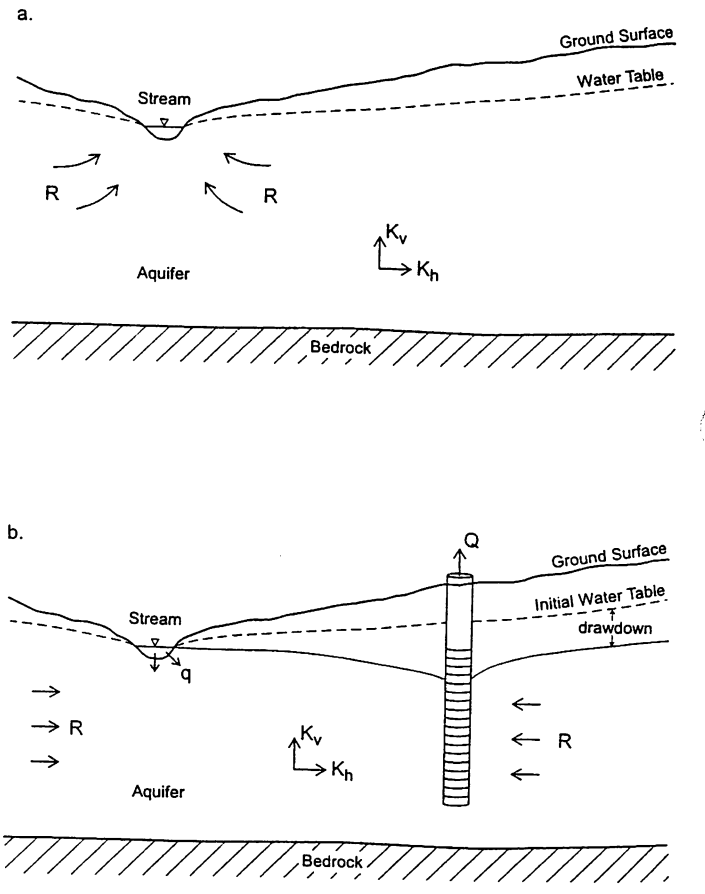

Figure 1. Schematic Drawing Showing (a) the Hydraulic Relationship Between an Aquifer and a Stream, Where Baseflow (R) Discharges to the Stream; and (b) a Pumping Well Intercepts Baseflow and Induces Stream Infiltration (q). K_v and K_h are vertical and horizontal hydraulic conductivity of the aquifer.

Two processes can cause a gaining stream to temporarily recharge the aquifer. First, when stream stages (elevation of water level in the stream) are higher (for example during flooding) than the water

table in the aquifer, the stream discharges water to the aquifer. Second, after a continuation of pumping, a reverse gradient established below a segment of the stream leads to streambed infiltration (Figure 1b). The stream infiltration rate may be different in various parts of the channel segment.

METHODS AND MODEL DESIGN

Recent studies on stream-aquifer interactions (Sophocleous *et al.*, 1995; Chen and Yin, 1999a) have shown that the widely used ground water flow model MODFLOW (McDonald and Harbaugh, 1988) has the capabilities for the analysis of total streamflow depletion. MODFLOW is a modular three-dimensional finite difference ground water flow model developed by the U. S. Geological Survey. Conrad and Beljin (1996) applied MODFLOW to calculate the induced infiltration for steady state conditions. MODFLOW has advantages over analytical solutions because it takes into account the vertical flow component in the vicinity of streambed. Although the model has the capability of analyzing the hydraulic relationships between stream and aquifers, its application to the analysis of the relationship between the reduced baseflow and induced infiltration under transient conditions has not been reported.

In this study, the river package in MODFLOW is utilized to simulate the flow between stream and aquifer under transient conditions. Consideration of transient conditions is necessary because irrigation wells extract ground water seasonally and steady-state ground water conditions are rarely achieved around pumping wells. Even if an irrigation well generates a local steady state condition, it will not last in the nonirrigation period. During each simulation, a water budget zone was designated around a stream. The model calculates the cumulative volume of water exchange between the aquifer and stream.

For each time step, the model records the stream leakage and ground water discharge. The induced infiltration D_r is calculated using

$$D_r = (q_0 - q)/Q \quad (1)$$

where q_0 is the stream leakage before the beginning of well pumping; q is the stream leakage if the well pumped; and Q is the pumping rate of a well.

The reduced baseflow D_b is calculated similarly using

$$D_b = (R_0 - R)/Q \quad (2)$$

where R_0 is the baseflow if the well is not pumped; R is the baseflow if the well is pumped; and Q is the pumping rate of the well. Both D_r and D_b are time dependent. Curves of D_r and D_b vs. time can be plotted to show the depletion processes.

The stream-aquifer model was built using MODFLOW. The dimension of the model domain is 25,756 m in length (the x-direction), 26,158 m in breadth (the y-direction), and 19 m in thickness (the z direction). Figure 2 shows the plan view and cross section of the domain. The west and east boundaries are set to be impermeable and the south and north boundaries are designated to be constant head boundaries. The domain was sufficiently large so that a pumping well near its center will not be impacted by the assigned boundary conditions.

A stream traverses from west to east boundaries in the middle of the domain. It is 30.5 m wide and 0.9 m deep. The stream stage is lower than the water table in the aquifer. Therefore, the stream gains water from the aquifer.

The model simulated the stream-aquifer interaction for a two-year period. For each year, a 90-day pumping period of constant rate was applied. The pumping period was followed by a 275-day nonpumping period. The next pumping season begins on the 366th day. The pumping well has a 9.1 m (30 ft) screen located in the lower part of the aquifer. The pumping rate is 2,727 m^3/d (500 gpm). The induced infiltration and reduced baseflow were calculated for the two-year period.

The horizontal hydraulic conductivity (K_h) is 82.3 m/d (270 ft/d), and the values of 0.82, 8.2, and 82.3 m/d for vertical hydraulic conductivity (K_v) were used for separate simulations. The storage coefficient was 10^{-6} and the specific yield was 0.1. No recharge is applied to the model to replenish the water storage. Table 1 summarizes the parameter values of aquifer, stream, and well used in the simulations. Chen (1998) reported the horizontal hydraulic conductivity for an alluvial aquifer in the Platte River valley ranges from 85 to 120 m/d, and the K_h values reported by Ayers *et al.* (1998) for the alluvial aquifer at another location are from about 40 to 220 m/d. The ratio of K_h/K_v is from 15 to more than 100.

RESULTS: INDUCED INFILTRATION AND REDUCED BASEFLOW

The degree of streamflow depletion depends on the strength of hydraulic connectivity between stream and aquifer. The parameters affecting the streamflow depletion may include stream penetration and low

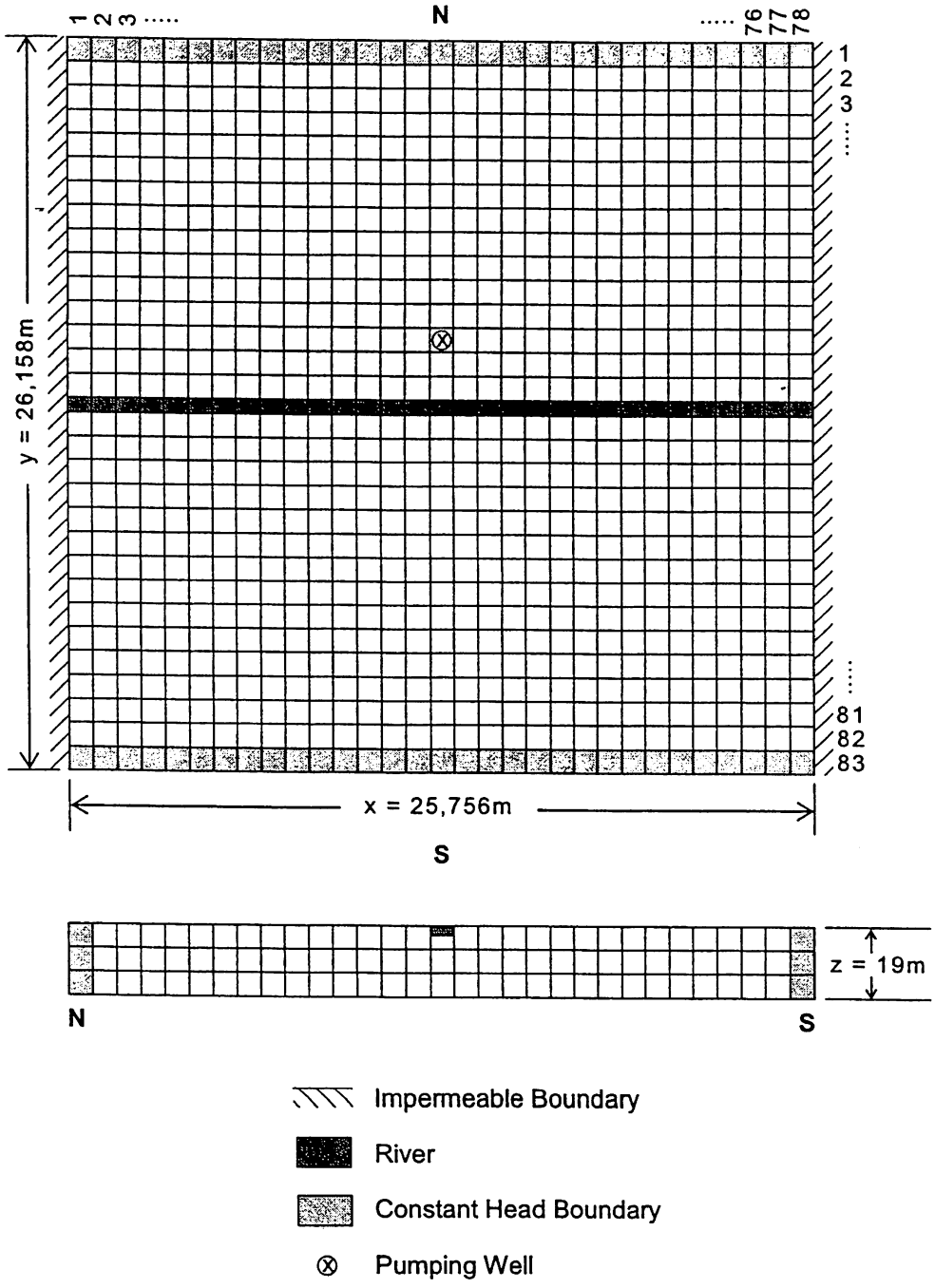

Figure 2. Layout of a Three-Dimensional Numerical Model of a Stream-Aquifer System. The model has three layers. Grid spacing is not scaled.

permeability layers, aquifer anisotropy, well locations, recharge, etc. (Sophocleous *et al.*, 1995; Wilson, 1993; Conrad and Beljin, 1996; Chen and Yin, 1999a). In this study, we analyzed the effects of stream stage, aquifer anisotropy, and the well-stream distance on the streamflow depletion.

Effects of Stream Stage

Variations in stream water levels or ground water tables will change the hydraulic head difference (Δh) between the stream and aquifer. For a gaining stream, it will affect the baseflow rate. Three

TABLE 1. Parameter Values of the Stream, Aquifer, and Pumping Well Used for the Simulations of Stream-Aquifer Interactions.

Aquifer	Well	Stream
K_h = 82.3 m/d	Q = 2,727 m^3/d	Width = 30.5 m
Three Kz Values Used	Pumping Duration = 90 days for each year	Water Depth = 0.9 m
K_v = 0.82, 8.2, and 82.3 m/d	Well Screen = 9.1 m (30 ft), located in the	No low-permeability stream bed
Specific Yield S_y = 0.1	lower part of the aquifer	r_{wr} (distance between the well and river)
Storage Coefficient S = 10^{-6}		varies from 152 to 1524 m)
Aquifer Thickness = 19 m		

scenarios were simulated: Δh = 0.15, 0.3 and 0.6 m, respectively. The aquifer is anisotropic with K_h = 82.3 m/d and K_v = 8.2 m/d. The well, 152 m (500 ft) from the stream, pumped at a rate of 2,727 m^3/d (see Table 1 for the other parameter values).

Figures 3a and 3b show the variations of reduced baseflow and stream infiltration with time. As indicated by Figure 3a, a larger hydraulic head difference (Δh) results in a stronger reduced baseflow. A small variation in Δh, for example, Δh values = 0.15 vs. 0.3 m, can result in a 10 percent difference in the reduced baseflow. Note that for each scenario the reduced baseflow in the first year is larger than that for the second year although the pumping rate for both seasons is the same. This is because the first pumping season results in the decline of the ground water table in the aquifer. Before the beginning of the second pumping season, the ground water level is not fully recovered, as indicated by the reduced baseflow curve. At the end of the first year (the 365th day), reduced baseflow continues (about 1 percent, Figure 3a). For the first pumping period, the reduced baseflow peak for each scenario occurs eight to 15 days after the pumping has begun, while the peak of reduced baseflow occurs one to seven days after the pumping stops for the second year. During the nonpumping period, streamflow is continuously impacted because of the continuation of the reduced baseflow. However, the magnitude of the reduced baseflow is much smaller and is the same for the three cases of varied Δh. As indicated by Figure 3a, the reduced baseflow is relatively large in the first several days after pumping has begun. This is mainly because the pumped well is only 152 m (500 ft) from the river.

Figure 3b shows the stream infiltration induced by the pumping well. For a larger Δh, the induced stream infiltration is small, which is in contrast to the reduced baseflow. Stream infiltration does not occur until the hydraulic gradient is reversed between the stream and the aquifer. As shown in Figure 3b, the infiltration for the case Δh = 0.6 m occurs eight days after pumping has begun. Infiltration increases rapidly and reaches its peak at the end of each pumping season. In contrast to the reduced baseflow, the curves of stream infiltration show a very rapid decrease after pumping stops, the induced infiltration does not last long in the nonpumping period. For example, infiltration disappears three, seven, and 10 days after cessation of the first pumping period. Note that the infiltration is higher in the second year. That is because the aquifer has less water available for supplying the pumping well and more water must come from the river to balance the pumped water.

Figure 3c shows the summation of the stream leakage and the reduced baseflow, which is considered the total streamflow depletion caused by the pumping well. Although the reduced baseflow and induced infiltration vary for each scenario, the total streamflow depletion is the same. Note that the total depletion is slightly higher in the second year. This is because the initial condition in the aquifer did not recover before the beginning of the second pumping season. More water must come from the river to sustain the constant pumping in the aquifer. This indicates that overextraction of ground water year after year leads to streams more vulnerable to depletion.

Anisotropic Aquifer

The values of vertical hydraulic conductivity (K_v) are generally smaller than that of the horizontal hydraulic conductivity (K_h) in nonfractured porous media. Freeze and Cherry (1979) explained that layered heterogeneity leads to regional anisotropy. K_h values can be one to two orders of magnitude larger than those of K_v. For example, the ratio of K_h to K_v for an alluvial aquifer in the Republican River valley, Nebraska, ranges from 10 to 30 (Chen *et al.*, 1999) and the ratio for an alluvial aquifer in the Platte River valley varies from 15 to more than 100 (Chen 1998). Examples of anisotropic hydraulic conductivity

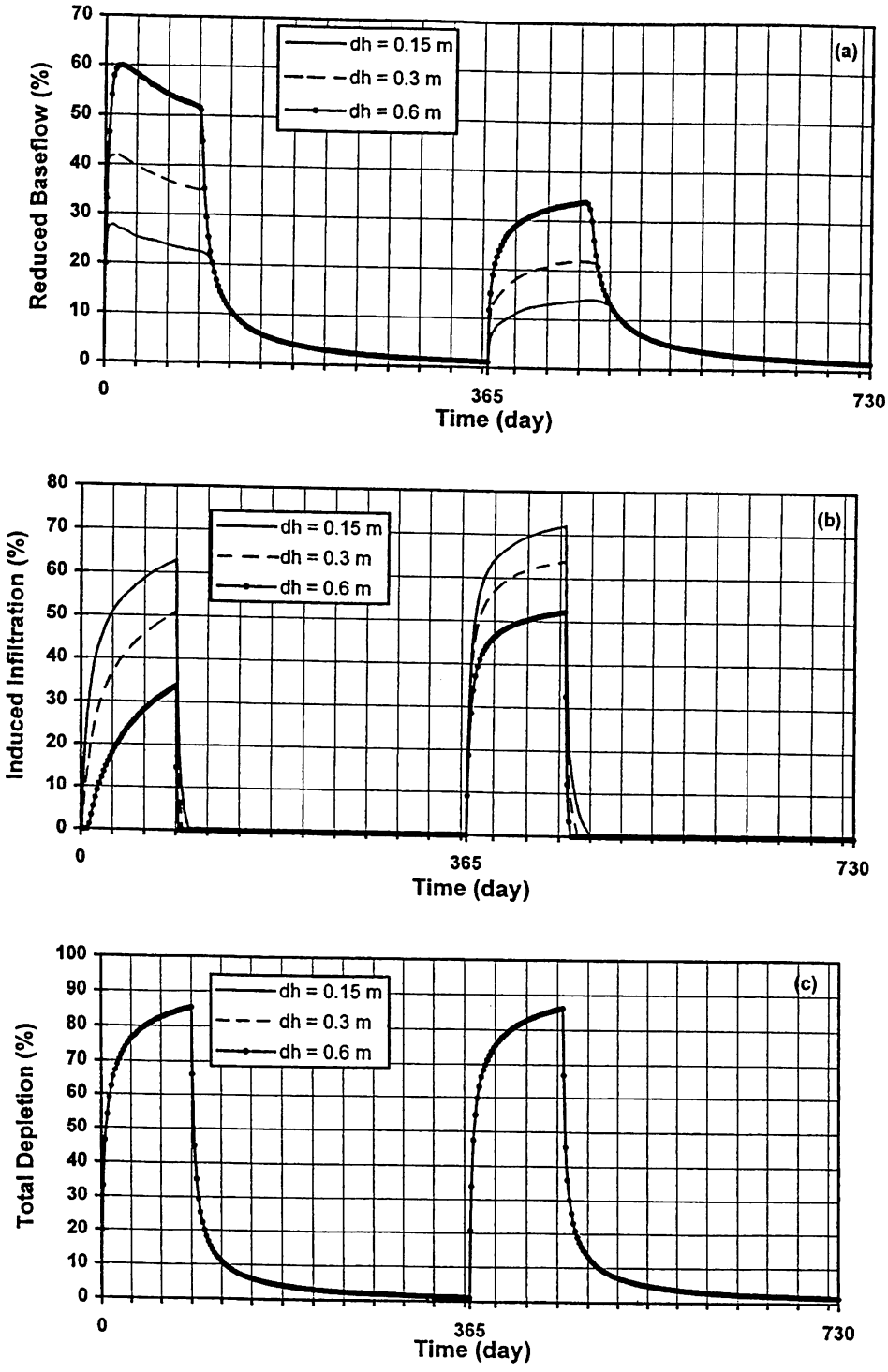

Figure 3. Graph Showing the (a) Reduced Baseflow, (b) Induced Infiltration, and (c) Total Streamflow Depletion for Three Stream Aquifer Systems Where the Difference of the Hydraulic Head Between the Stream and Aquifer is 0.15, 0.3, and 0.6 m, respectively. Each interval along the time-axis represents 30 days. Note that the total depletions for the three cases are so close to each other that their trends presented in Figure 3c cannot be distinguished.

in other areas include pumping tests at Vekol Valley, Arizona, where the ratio of K_h to K_v ranges from 9 to 63 (Marie and Hollett, 1996). The estimated K_h/K_v ratio for an aquifer system on the Susquehanna River, New York, varies from 125 to 250 (Yager, 1993).

Streams in river valleys often partially penetrate the adjoining alluvial aquifers. For example, both the Platte and the Republican rivers in Nebraska are often less than 1 m in water depth while the aquifer can be as thick as 30 m. A partially penetrating river leads to a strong vertical flow between river channel and aquifer. The vertical hydraulic conductivity (K_v) thus plays a role in streamflow depletion.

Simulations were conducted to compare the streamflow depletion in isotropic (K_h/K_v = 1) and anisotropic aquifers (K_h/K_v = 10, and 100) with K_h = 82.3 m/d. The hydraulic head difference between the aquifer and the stream (Δh) is 0.15 m. Figures 4a and 4b show the reduced baseflow and induced infiltration, and Figure 4c shows the total streamflow depletion. Generally, when the K_h value is constant, a smaller K_v value results in a larger reduced baseflow but a smaller stream infiltration. The total streamflow depletion is smaller for a stronger anisotropic aquifer. The difference of total streamflow depletion can be as much as 20 percent between K_h/K_v = 10 and 100. As shown by Figure 4a, a strong anisotropic aquifer will need a longer time to return to the initial aquifer conditions. For example, the reduced baseflow for K_h/K_v = 100 remains 2.5 percent of the pumping rate at the beginning of the next pumping season. Stream infiltration stops within about one month of the cessation of pumping. A larger K_v implies a higher connectedness between stream and aquifer for a partially penetrating stream.

Well-Stream Distance

The well stream distance (r_{wr}) for the previous simulation examples is 152 m. Streamflow depletion was calculated for three additional distances between pumping well and stream: r_{wr} = 305, 710, and 1524 m (1,000, 2,000, and 5,000 ft, respectively). The aquifer is anisotropic with K_h = 82.3 m/d and K_v = 8.2 m/d, Δh = 0.15 m, and the pumping well was pumped at a constant rate of 2,727 m^3/d (500 gpm) for a 90-day period of each year.

Figure 5a shows the reduced baseflow for the three cases. For r_{wr} = 305 and 710 m, reduced baseflow occurs immediately after pumping begins; for r_{wr} = 1524 m, the reduced baseflow did not occur until four days after pumping began. The reduced baseflow increases rapidly after pumping. In the first pumping period, the reduced baseflow peaks at 18, 70, and 110 days after pumping for the three cases (Figure 5a). Reduced baseflow continues in the nonpumping period. As shown in Figure 5a, the reduced baseflow is greater for a larger r_{wr} during the nonpumping. Note that at the end of the first year (or just before the beginning of the second pumping period) the reduced baseflow remains 1.9, 3.2 and 5.6 percent, with the highest for the longest well stream distance. The peak reduced baseflow for the three r_{wr} occurs after the 15 to 40 days following the end of the pumping.

In contrast to reduced baseflow, induced stream infiltration does not occur immediately with pumping. This is particularly apparent for the first year. For example, the stream does not discharge water to the aquifer until six days after pumping began for r_{wr} = 305 m. The delay period is longer for a well located farther from the river. For example, stream infiltration for r_{wr} = 1,525 m does not occur until 78 days after pumping begins. The infiltration peak occurs at the end of the pumping period for r_{wr} = 305 m, but the peak occurs 13 days after pumping stops for r_{wr} = 1,525 m. The infiltration will continue for a certain period after pumping stops. For a larger r_{wr}, it takes a longer time to completely stop the induced infiltration. The time when the infiltration stops indicates the end of the reverse hydraulic gradient below the stream channel. As shown in Figure 5b, the induced infiltration for r_{wr} = 1,525 m is significantly smaller than those for the other two well stream distances.

The total depletion is smaller for a larger distance to the river during each pumping period. The depletion continues during the nonpumping period. However, during the nonpumping period, the total depletion is larger for a pumping well located farther from the river.

DISCUSSIONS

As pointed out by Wilson (1993), there are two issues associated with induced stream infiltration. Where water rights are concerned, it is one of streamflow depletion. Where water quality is the issue, it is the actual source of water contaminating the aquifer. While streamflow has been studied for decades, the water quality problem has not. The above examples have shown the benefits of the separate analysis to both water quantity and quality issues occurring in river valleys.

The volume of water discharged from stream to aquifer can be easily calculated from the time infiltration curves. The product of pumping rate and the area delineated by the time infiltration curve is the total

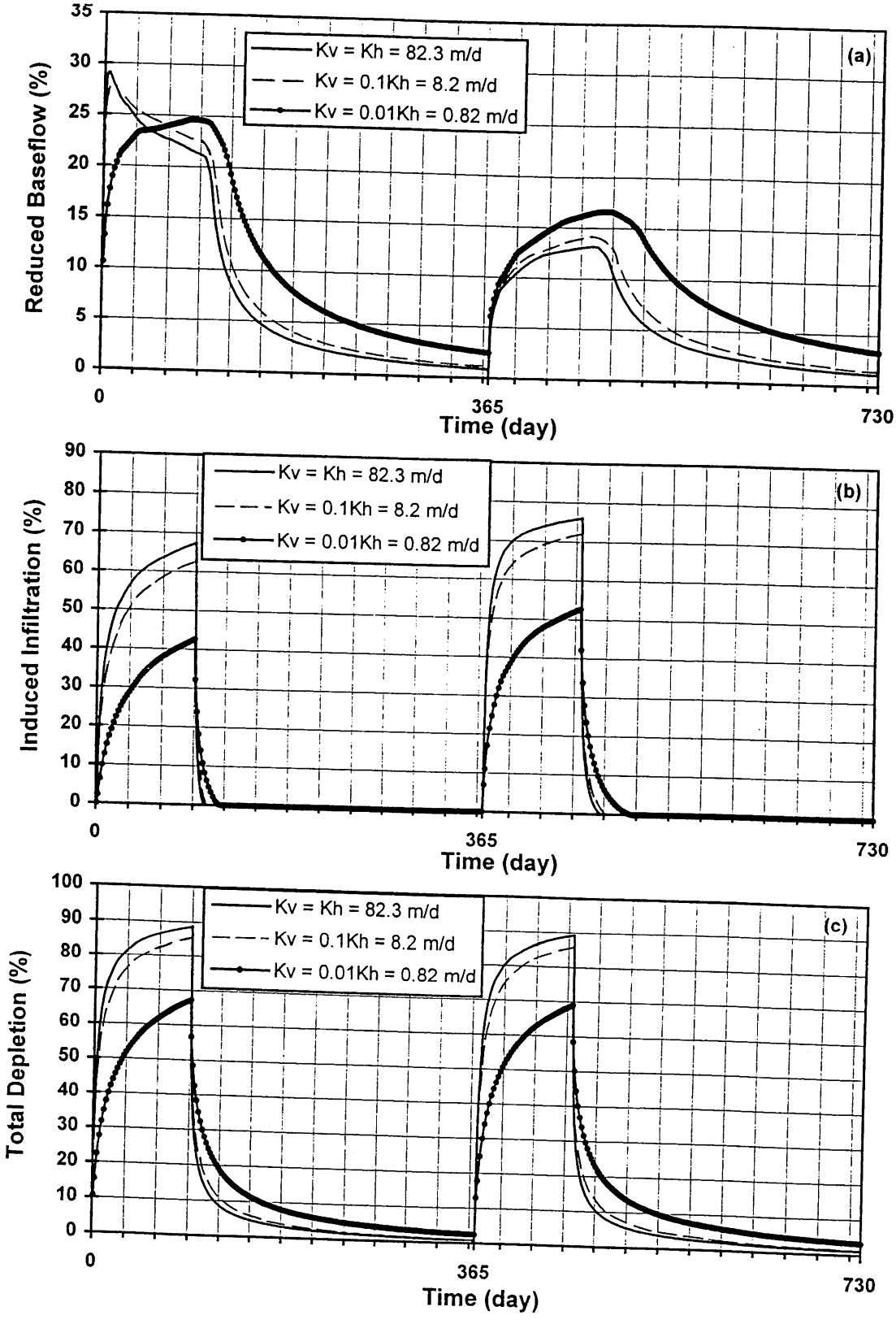

Figure 4. Graph Showing the (a) Reduced Baseflow, (b) Induced Infiltration, and (c) Total Streamflow Depletion for Three Aquifers Where K_h = 82.3 m/d, and K_h/K_v = 1, 10, and 100, respectively. Each interval along the time-axis represents 30 days.

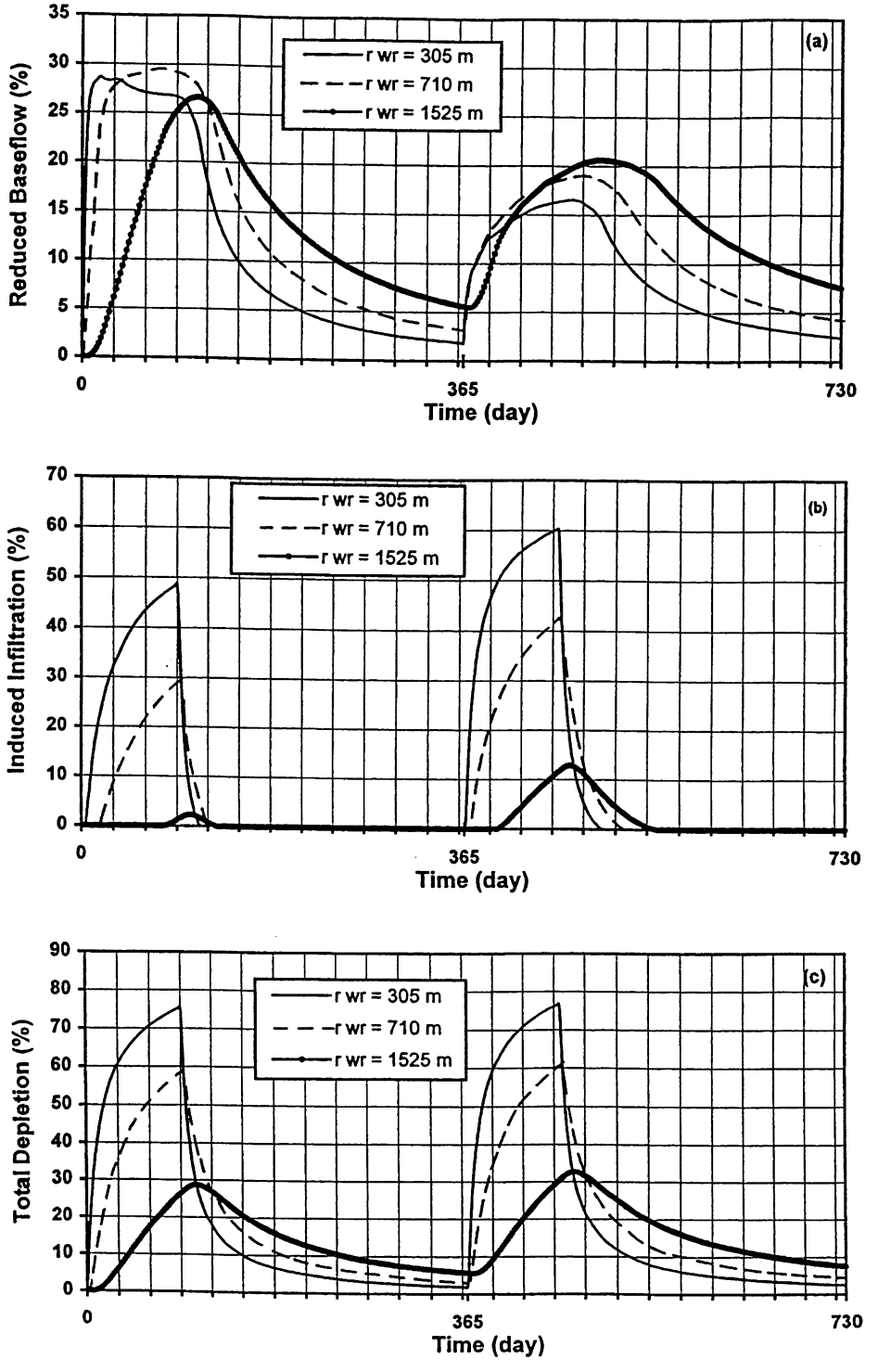

Figure 5. Graph Showing the (a) Reduced Baseflow, (b) Induced Infiltration, and (c) Total Streamflow Depletion for Three Pumping Wells Located 305, 710, and 1,525 m From the Stream. Each interval along the time-axis represents 30 days.

volume of stream water discharged into the aquifer. If the river water is contaminated, the amount of contaminant moved to the aquifer can be estimated. The volume can also be calculated separately for pumping and post pumping periods. One can also determine the period of stream infiltration from the transient induced infiltration curve. According to the simulation results, stream infiltration may remain strong for some cases even after pumping stops.

The simulation examples have demonstrated that the processes of induced infiltration and reduced baseflow resulting from irrigation wells are highly variable with time, and so is the total streamflow depletion. The level of depletion varies not only in the pumping period but also in the nonpumping period. It is clear that consideration of transient condition is appropriate for the analysis of streamflow depletion in ground water irrigation areas. In contrast, when a steady state condition is used, as by Wilson (1993) and Conrad and Beljin (1996), only one value can be obtained for one scenario to show induced infiltration. That is not sufficient to evaluate the process of depletion.

The hydraulic head difference (Δh) between the aquifer and river is one of the factors controlling induced infiltration. Although as shown by Figure 3c, the total streamflow depletion is the same for varied Δh, the reduced baseflow and induced infiltration can be very different for the same pumping well. This is because the Δh regulates the stream receiving water from the aquifer. For a stream-aquifer system where there is no head difference, reduced baseflow will be zero, and the total streamflow depletion is equal to the induced stream infiltration. For a dry year or later in a pumping season, when the stream stage is lower, the river gains more water from the aquifer.

After pumping stops, the aquifer will recover. Two factors control the recovery process. One is the water sources to replenish the aquifer, which may include recharge from precipitation and lateral ground water flow; the other is time. In aquifer systems where the initial hydraulic condition is not fully recovered before the second irrigation season, the aquifer will have less water than that of the previous year, so more water will come from the stream to supply the constant pumping of the well. If the condition repeats itself year after year, the stream will become more vulnerable to depletion, and each of the following pumping seasons will induce more stream water to the aquifer. Because the pumping well will induce a stronger stream infiltration in the next pumping season, for areas where stream contamination is also a concern, the water quality in the aquifer only becomes worse in the following years.

If a stream is gaining water from the aquifer, it is not necessary for the well to reverse gradients below the stream and induce infiltration. It depletes streamflow simply by capturing some of the baseflow discharge before it reaches the stream (Wilson, 1993). This impact may not occur until many days after pumping begins but does not stop until many days after the cessation of pumping. The location of a pumping well far from the river can induce small-magnitude and short-term stream infiltration. On the other hand, the reduced baseflow has a longer term impact and the greatest reduction will occur many days after the pumping stops.

There are several other parameters affecting the connectivity between stream and aquifer. For example, existence of a lower permeability bed in a stream channel will reduce the total streamflow depletion, as indicated by Sophocleous *et al.* (1995) and Chen and Yin (1999a). When the stream penetration in the aquifer increases, the stream and aquifer have a stronger connectivity, and the role of K_v in controlling the streamflow depletion decreases. In these simulations, recharge was not applied in the model domain. Recharge will reduce the magnitude of drawdown in the pumping season and enhance the recovery rate of the water table in the nonpumping period. As a result, recharge will reduce the streamflow depletion. Because the emphasis of the paper is to demonstrate the benefits from the separate analysis of induced infiltration and reduced baseflow in seasonally pumped areas, the effects of a number of other parameters on streamflow depletion were not analyzed for this study.

CONCLUSIONS

Separate calculation of the two processes of streamflow depletion offers a better understanding of stream-aquifer interaction and provides practical information for management of ground water resource and for water quality concerns. For water resources issues, the results show that the reduced baseflow has a longer term impact on streamflow and that its impact can continue into the next pumping season. This information is important for long-term water resources management. For water quality determinations, the calculation provided the amount of water discharged to the aquifers.

Both induced infiltration and reduced baseflow vary highly with time. That variation is observed in pumping and nonpumping periods. It is apparent that transient conditions must be considered in seasonally pumped areas.

When the river stages or ground water tables vary, the total depletion is the same for a pumping well, but the ratio of the induced infiltration to reduced baseflow is different. If there is a desire to have a smaller amount of stream water discharged to the aquifer, the stream stage may be lowered.

The vertical hydraulic conductivity has an important impact on the calculation of induced infiltration and reduced baseflow. Careful investigation of aquifer anisotropy will help determine the hydraulic connectivity between stream and aquifer.

When the water level in the aquifer does not fully return to the original conditions before the beginning of the next pumping season, total streamflow depletion increases slightly in the next pumping season. The induced infiltration, however, can be much larger.

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Drawdown and Stream Depletion Produced by Pumping in the Vicinity of a Partially Penetrating Stream

by James J. Butler Jr.[1,3], Vitaly A. Zlotnik[2], and Ming-Shu Tsou[1]

Abstract

Commonly used analytical approaches for estimation of pumping-induced drawdown and stream depletion are based on a series of idealistic assumptions about the stream-aquifer system. A new solution has been developed for estimation of drawdown and stream depletion under conditions that are more representative of those in natural systems (finite width stream of shallow penetration adjoining an aquifer of limited lateral extent). This solution shows that the conventional assumption of a fully penetrating stream will lead to a significant overestimation of stream depletion (> 100%) in many practical applications. The degree of overestimation will depend on the value of the stream leakance parameter and the distance from the pumping well to the stream. Although leakance will increase with stream width, a very wide stream will not necessarily be well represented by a model of a fully penetrating stream. The impact of lateral boundaries depends upon the distance from the pumping well to the stream and the stream leakance parameter. In most cases, aquifer width must be on the order of hundreds of stream widths before the assumption of a laterally infinite aquifer is appropriate for stream-depletion calculations. An important assumption underlying this solution is that stream-channel penetration is negligible relative to aquifer thickness. However, an approximate extension to the case of nonnegligible penetration provides reasonable results for the range of relative penetrations found in most natural systems (up to 85%). Since this solution allows consideration of a much wider range of conditions than existing analytical approaches, it could prove to be a valuable new tool for water management design and water rights adjudication purposes.

Introduction

Stream-aquifer interactions are an important component of the hydrologic budgets of many watersheds and have significant socioeconomic and political ramifications (Bouwer and Maddock 1997). In watersheds undergoing ground water development, pumping-induced water transfers (stream depletion) often comprise a sizable proportion of the stream-aquifer interactions. Many of the approaches currently used to quantify these transfers are based on analytical models of idealized configurations that often bear little resemblance to natural systems. In this article, a transient analytical model that is based on a more realistic representation of the stream-aquifer system is proposed. This model can be used for estimation of the drawdown and stream depletion produced by a pumping well in the vicinity of a finite-width stream of shallow penetration. Although an analytical approach cannot represent stream-aquifer interactions to the same degree of detail as a numerical model, it can provide a useful screening tool for consideration of the influence of various factors and to obtain estimates commensurate with the level of commonly available data.

Over the last 60 years, several analytical models have been developed to assess the influence of nearby streams on ground water development. Theis (1941) was the first to propose a transient model for evaluation of the impact of a stream on pumping activities. This approach, later generalized by Glover and Balmer (1954), is based on a series of idealistic assumptions that include a fully penetrating stream and a perfect hydraulic connection between the stream and adjoining aquifer (Figure 1a). The Jenkins (1968) implementation of this approach has become a standard tool for water management design and water rights adjudication. Hantush (1965) extended this model to consider an imperfect hydraulic connection between the aquifer and the stream (Figure 1b), but this extension has seen relatively little use in practice.

Unfortunately, the idealized configurations of Figure 1 bear little resemblance to many natural systems. For example, streams in the Great Plains region of the United States commonly only partially penetrate the adjoining aquifer. In many cases, the depth of penetration is a few tens of percent or less of the aquifer thickness (Larkin and Sharp 1992). Although not widely known outside the former Soviet Union, a steady-state model of stream-aquifer interactions has been developed that incorporates a simplified representation of a partially penetrating stream (Grigoryev 1957; Bochever 1966). This model, which has been extensively used in the former Soviet Union (Bochever et al. 1969, 1978; Mironenko et al. 1994), is based on the assumptions that the depth of penetration is very small relative to aquifer thickness and that the stream and aquifer are separated by a thin zone of relatively low hydraulic conductivity. Recently, Zlotnik et al. (1999) have developed a tran-

[1]Kansas Geological Survey, 1930 Constant Ave., Campus West, University of Kansas, Lawrence, KS 66047

[2]Department of Geosciences, University of Nebraska-Lincoln, Lincoln, NE 68588

[3]Corresponding author: (785) 864-2116; jbutler@kgs.ukans.edu

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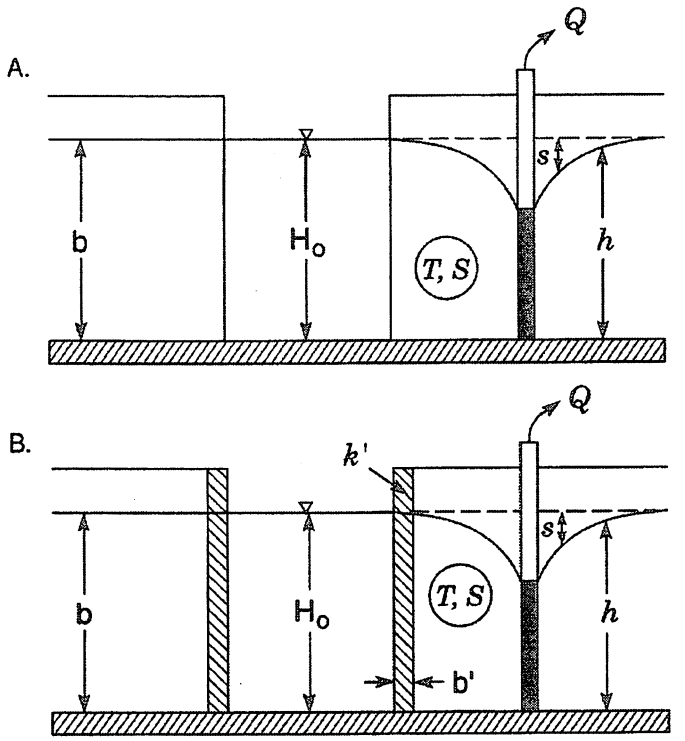

Figure 1. Cross-sectional views of hypothetical stream-aquifer systems (notation explained in text): (a) fully penetrating stream model of Theis (1941), Glover and Balmer (1954), and Jenkins (1968); (b) fully penetrating stream with low-conductivity streambed model of Hantush (1965).

sient analytical solution for estimation of stream depletion in systems that can be represented by the Grigoryev-Bochever model. Concurrent with that work, Hunt (1999) has proposed a solution for drawdown and stream depletion in an infinitely thin stream variant of this model. In both cases, the authors employ various simplifying assumptions that reduce the general applicability of their solutions.

In this paper, the steady-state Grigoryev-Bochever model is used as the starting point for the development of a general analytical solution for transient drawdown and stream depletion in the stream-aquifer system depicted in Figure 2. The solution will be used to assess the influence of a low-permeability streambed, stream width, lateral boundaries, and stream-channel penetration on drawdown and stream depletion. The degree of error introduced by the fully penetrating stream models of Figure 1 will be emphasized throughout the presentation. The article will conclude with a discussion of the most significant limitations of the solution and the implications of this work for water resources management in interconnected stream-aquifer systems.

Problem Statement

The problem of interest here is that of the drawdown (as a function of x, y, and t) and stream depletion (as a function of t) produced by pumping from a fully penetrating well in the configuration of Figure 2. Flow properties are assumed uniform within each zone, and vertical flow within the aquifer is neglected (Dupuit assumptions). The stream and aquifer are separated by a thin zone of relatively low hydraulic conductivity, which is represented mathematically as an incompressible aquitard (Hantush and Jacob 1955). Portions of the aquifer underneath the stream are confined, but can be confined or unconfined elsewhere.

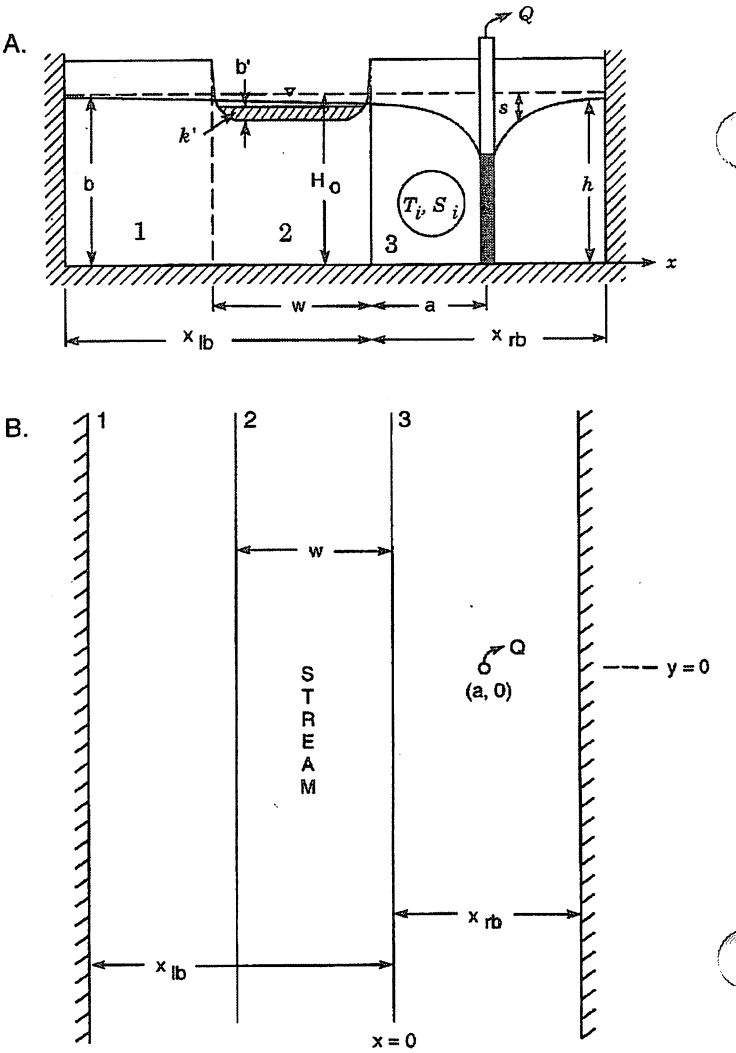

Figure 2. Cross-sectional (a) and areal (b) views of stream-aquifer configuration examined in this paper (notation explained in text; stream depletion in this configuration consists of vertical leakage across the low-permeability streambed).

Governing Equations:

$$\frac{\partial^2 s_1}{\partial x^2} + \frac{\partial^2 s_1}{\partial y^2} = \frac{S_1}{T_1}\frac{\partial s_1}{\partial t}, \; -x_{lb} \le x \le -w, \quad -\infty < y < \infty, t > 0 \qquad (1)$$

$$\frac{\partial^2 s_2}{\partial x^2} + \frac{\partial^2 s_2}{\partial y^2} - \frac{k'}{b'T_2}s_2 = \frac{S_2}{T_2}\frac{\partial s_2}{\partial t}, \; -w \le x \le 0, \quad -\infty < y < \infty, t > 0 \qquad (2)$$

$$\frac{\partial^2 s_3}{\partial x^2} + \frac{\partial^2 s_3}{\partial y^2} + \frac{Q}{T_3}\delta(x-a)\,\delta(y) = \frac{S_3}{T_3}\frac{\partial S_3}{\partial t}, \; 0 \le x \le x_{rb}, \quad -\infty < y < \infty, t > 0 \qquad (3)$$

Initial Conditions:

$$s_i(x, y, 0) = 0, \; -x_{lb} \le x \le x_{rb}, \; -\infty < y < \infty, \; i = 1,3 \qquad (4)$$

- **Boundary Conditions:**

$$\frac{\partial s_1}{\partial x}(-x_{lb}, y, t) = \frac{\partial s_3}{\partial x}(x_{rb}, y, t) = 0, -\infty < y < \infty, t > 0 \tag{5}$$

$$s_i(x, \pm\infty, t) = 0, -x_{lb} \le x \le x_{rb}, t > 0 \tag{6}$$

$$s_1(-w, y, t) = s_2(-w, y, t), -\infty < y < \infty, t > 0 \tag{7}$$

$$\frac{\partial s_1}{\partial x}(-w, y, t) = \frac{T_2}{T_1}\frac{\partial s_2}{\partial x}(-w, y, t), -\infty < y < \infty, t > 0 \tag{8}$$

$$s_2(0, y, t) = s_3(0, y, t), -\infty < y < \infty, t > 0 \tag{9}$$

$$\frac{\partial s_2}{\partial x}(0, y, t) = \frac{T_3}{T_2}\frac{\partial s_3}{\partial x}(0, y, t), -\infty < y < \infty, t > 0 \tag{10}$$

where i is zone number (i = 1,2,3); $s_i(x,y,t)$ is drawdown in zone i; T_i is transmissivity of zone i; S_i is specific yield or storativity of zone i; k′ is hydraulic conductivity of streambed; b′ is streambed thickness; Q is pumping rate from well located at (a,0); x_{lb}, x_{rb} are distance from right boundary of stream to left and right lateral boundary of the aquifer, respectively; and w is stream width.

Stream depletion is defined as the total flow across the incompressible streambed

$$\Delta q(t) = \frac{k'}{b'}\int_{-\infty}^{\infty}\int_{-w}^{0} s_2\, dxdy, t > 0 \tag{11}$$

where Δq is the pumping-induced leakage from the stream (Figure 2 and caption).

Table 1
Definition of Dimensionless Parameters

Parameter	Notation	Expression
Drawdown	Φ_i	s_iT_3/Q
Stream depletion	ΔQ	$\Delta q/Q$
Time	τ	$(T_3t)/(w^2S_3)$
Stream leakance	B	$(k'w^2)/(b'T_2)$
Direction perpendicular to stream	ξ	x/w
Direction parallel to stream	η	y/w
Distance between pumping well and stream	α	a/w
Distance to the left aquifer boundary	X_{LB}	x_{lb}/w
Distance to the right aquifer boundary	X_{RB}	x_{rb}/w

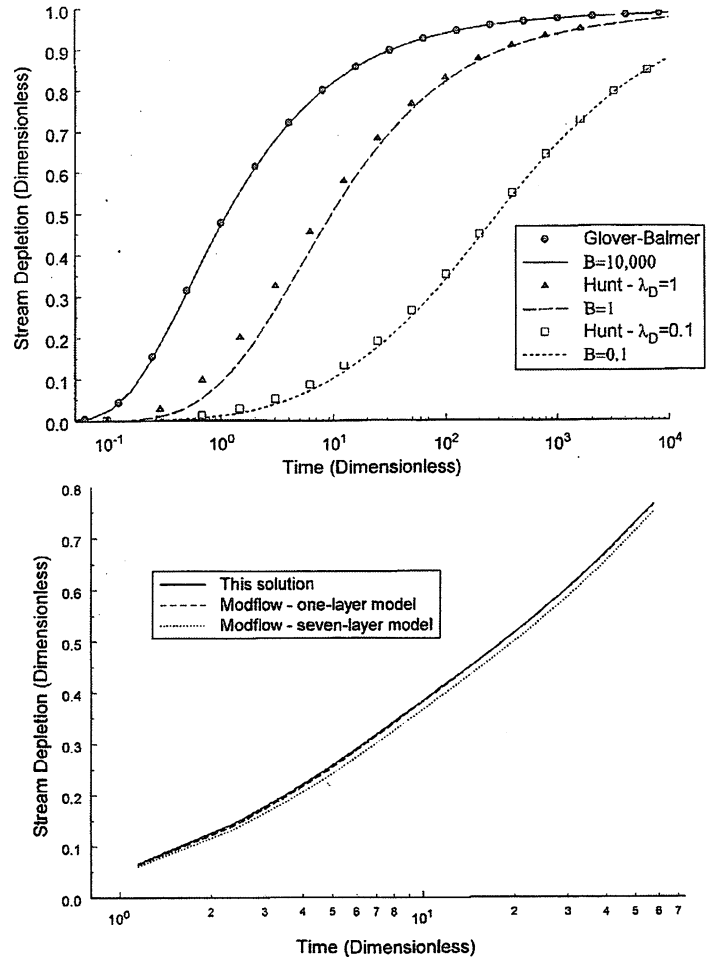

Figure 3. (a) Dimensionless stream depletion (Δq/Q) versus time (T_3t/w^2S_3) plot of the analytical models of Glover and Balmer (1954) and Hunt (1999, $\lambda_D = [k'wa]/[b'T]$), and the new solution ($B = [k'w^2]/[b'T_2]$) for an aquifer of infinite lateral extent ($\alpha = a/w = 1$); (b) Dimensionless stream depletion versus time plot of the new solution and single- and seven-layer MODFLOW models for an aquifer of limited lateral extent ($\alpha = 1.1$, $B = 0.58$, $X_{LB} = x_{lb}/w = 8.9$, $X_{RB} = x_{rb}/w = 7.9$; see Table 2 for grid details).

The mathematical model defined by Equations 1 through 10 was solved using an approach analogous to that of Butler and Liu (1991). Since the solution is a straightforward application of conventional methods, the details are not provided here (Butler and Tsou 2000). Stream depletion was calculated using the approach of Hunt (1999) with the transform-space analog of Equation 11. Transform-space expressions for both drawdown and stream depletion are given in the Appendix, and the numerical inversion of these expressions is implemented in Butler and Tsou (1999).

The drawdown and stream depletion computed using this solution have been compared to results from existing analytical and numerical models. The dimensionless parameters of Table 1 are used to illustrate the results of these comparisons (see Butler and Tsou [2000] for derivation of dimensionless parameters). The new solution will reduce to existing analytical approaches for special cases as shown by the example comparison given in Figure 3a, where normalized stream depletion is plotted versus dimensionless time for a laterally infinite aquifer (solutions of Glover and Balmer [1954] and Hunt [1999] shown for reference). In these conditions, the Glover and Balmer solution is reproduced using a large value for stream leakance (B). Since the Hunt solution is based on the assumption of an infinitely

Table 2

Grid Details and Parameter Values for MODFLOW Model

Size of model. 69 columns (x), 85 rows (y), and either one or seven layers (z).

Spacing in x direction. From x = 0 m to right boundary, spacing is as follows (all distances in meters, number of columns at a particular spacing given in parentheses): $\Delta x = 1.0$ m (23), $\Delta x = 1.5$ m (1), $\Delta x = 2.3$ m (1), $\Delta x = 3.4$ m (1), $\Delta x = 5.1$ m (1), $\Delta x = 7.6$ m (1), $\Delta x = 11.4$ m (1), and $\Delta x = 17.1$ m (1). Note that distance from x = 0 m to left boundary includes stream so nine additional cells ($\Delta x = 1.0$ m) are required.

Spacing in y direction. From center of grid (cell that includes y = 0 m) to top boundary, spacing is as follows (number of rows at a particular spacing given in parentheses): $\Delta y = 1.0$ m (6), $\Delta y = 1.5$ m (4), $\Delta y = 3.0$ m (3), $\Delta y = 5.0$ m (5), $\Delta y = 10.0$ m (5), $\Delta y = 20.0$ m (5), $\Delta y = 40.0$ m (3), $\Delta y = 80.0$ m (3), $\Delta y = 160$ m (3), $\Delta y = 320$ m (3), and $\Delta y = 640$ m (3).

Equal spacing in z direction ($\Delta z = 7.0$ m for one-layer model; $\Delta z = 1.0$ m for seven-layer model).

Model parameters used in simulations are as follows:

Hydraulic conductivity (uniform) = 20 m/day;

Specific storage (uniform) = 4.3×10^{-4} m^{-1};

Stream width = 9 m; streambed thickness = 0.5 m;

Hydraulic conductivity of streambed = 0.5 m/d (Figure 3B) and 0.1 m/d (Figure 10);

Pumping rate = 210 m^3/day.

Boundary conditions. No-flow boundaries are defined on all sides of grid (x,y,z). Boundaries in y direction are sufficiently far from the pumping well that they have no impact on the simulation results.

thin stream, the stream leakage is concentrated at x = 0. Figure 3a shows that this assumption can lead to an overestimation of stream depletion when B is large and the pumping well is relatively close to the stream ($B > 0.1$ for $\alpha = 1$). However, additional work has shown that the Hunt solution is in excellent agreement with the new model for the case of a laterally infinite aquifer when the pumping well is a normalized distance of five or more from the stream ($\alpha \geq 5$). Note that although the Hunt leakance parameter, λ, was not originally defined in terms of physical quantities, Butler and Tsou (2000) show that for a uniform aquifer ($T_i = T$, i =1,2,3) the dimensionless form of the parameter can be written as

$$\lambda_d = (k'wa)/(b'T) = B\alpha \qquad (12)$$

Figure 3b displays the stream depletion computed for a bounded aquifer using the new solution and two MODFLOW (Harbaugh and McDonald 1996) simulations (Table 2). Both the analytical solution and the single-layer MODFLOW simulation neglect the vertical component of flow by using vertically averaged heads to calculate the stream depletion. In the seven-layer simulation, heads vary in the vertical direction and stream depletion is introduced into the top layer. The small difference between the single- and seven-layer results is a consequence of the neglect of vertical flow in the single-layer model. When the hydraulic conductivity of the streambed is small relative to that of the aquifer, the neglect of vertical flow should not be of practical significance except when the aquifer is thick and the pumping well is close to the stream.

These comparisons demonstrate that the new solution provides a reasonable representation of stream-aquifer interactions under a wide range of conditions. Therefore, for the remainder of the paper, this solution is used to assess the impact of a variety of factors on drawdown and stream depletion in stream-aquifer systems. As with the comparisons of this section, dimensionless parameters will be used to increase the generality of the presentation.

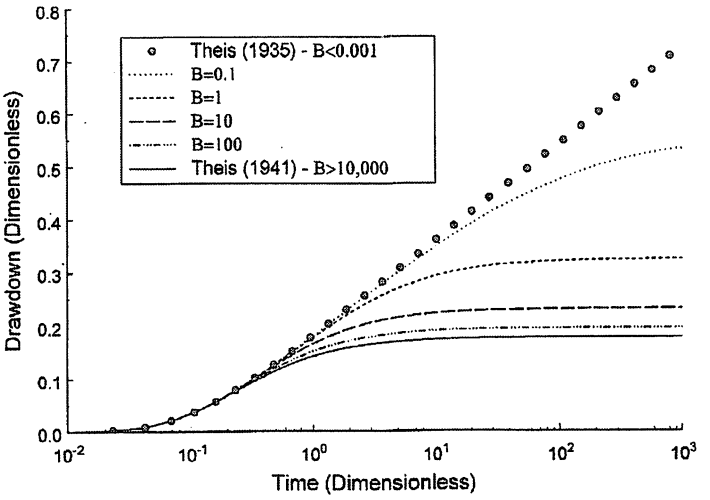

Figure 4. Dimensionless drawdown (s_3T_3/Q) versus time plot of the analytical models of Theis (1935, 1941) and the new solution for an aquifer of infinite lateral extent ($\alpha = 1$, $\xi = x/w = 0.5$, $\eta = y/w = 0.0$).

Dependence on Streambed Properties

A low-permeability zone in the portion of the aquifer immediately adjacent to the stream appears to be a common feature of many systems. Larkin and Sharp (1992) and Conrad and Beljin (1996) provide estimates of streambed properties that show a dramatic contrast between the permeability of the streambed and that of the aquifer in many cases. The impact of a low-permeability streambed can be readily assessed with this solution by changing the stream leakance parameter (B). If all other dimensionless parameters are kept constant, changes in B equate to changes in the k′/b′ratio. Figure 4 is a plot of drawdown at an observation well midway between the stream and the pumping well. In this case, a seven order of magnitude variation in B spans the range of conditions expected in natural systems. For $B < 0.001$, the drawdown is equal to that of the infinite-aquifer model of Theis (1935), i.e., the contribution of the stream is negligible. On the other extreme, $B > 10{,}000$, the drawdown converges on the fully penetrating stream model of Theis (1941). Figure 5 is a pair of contour plots that graphically display the influence of streambed properties on the areal distribution of drawdown. The propagation of drawdown beneath a partially penetrating stream, such as illustrated in Figure 5a, is commonly observed in the field (Sophocleous et al. 1988). These results, in keeping with findings of earlier investigations, clearly show that the stream leakance parameter (B) is an important control on behavior in stream-aquifer systems. Field investigations should therefore be focused on acquiring data about the quantities comprising this parameter.

The conclusions from the drawdown analysis are further substantiated by consideration of stream depletion. Figure 6a is a stream depletion plot for the conditions of Figure 4. Although increases in B lead to convergence on the Glover and Balmer model, this convergence occurs at extremely large B values for pumping wells close to the stream. As the distance between the stream and the pumping well increases, the influence of streambed properties decreases and the Glover and Balmer model becomes a more reasonable representation of system behavior (Figures 6b and 6c).

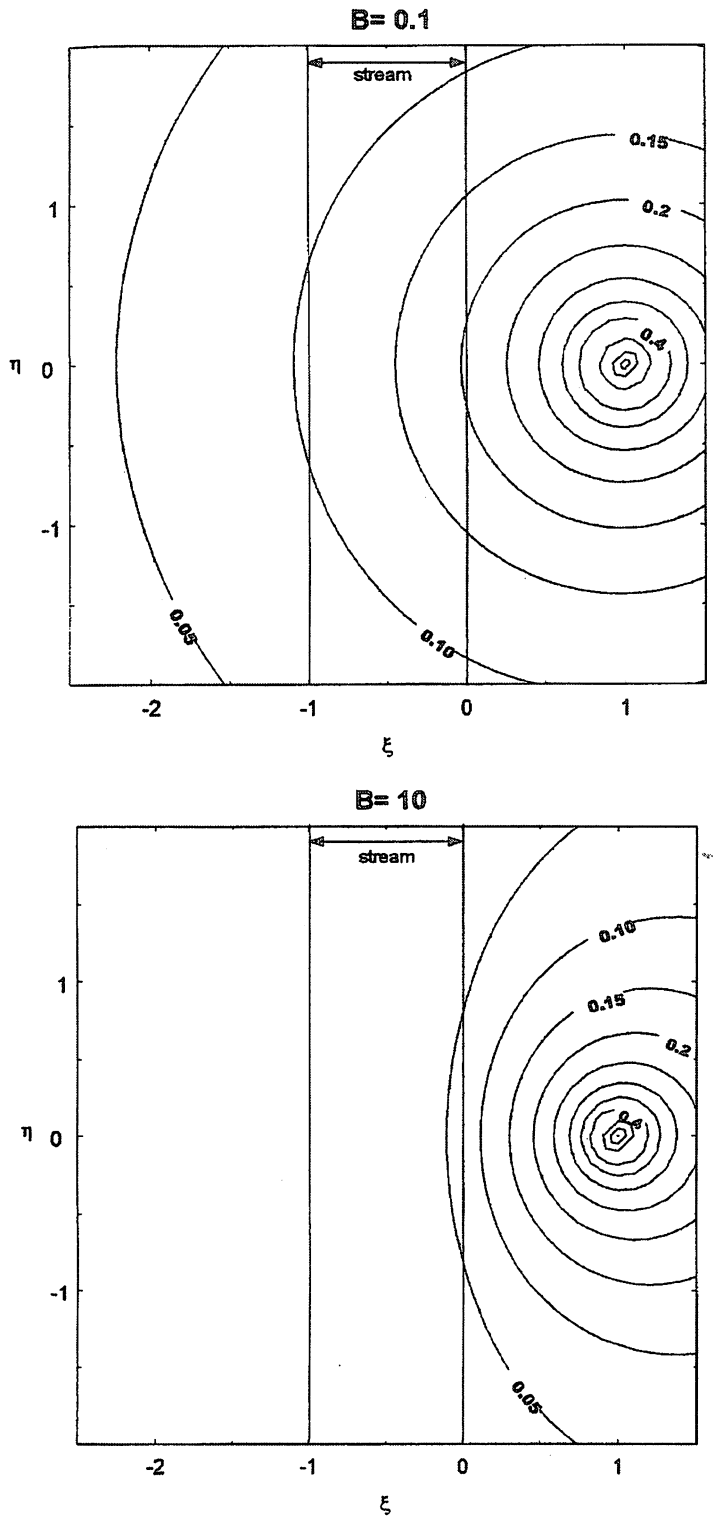

Figure 5. Contour plots of dimensionless drawdown (s_1T_3/Q) for a laterally infinite aquifer ($\tau = T_3t/w^2S_3 = 5$, $\alpha = 1$): (a) B = 0.1; (b) B =10.0. Contour interval of 0.05 used for drawdown below 0.4 while contour interval of 0.1 used for drawdown above 0.4.

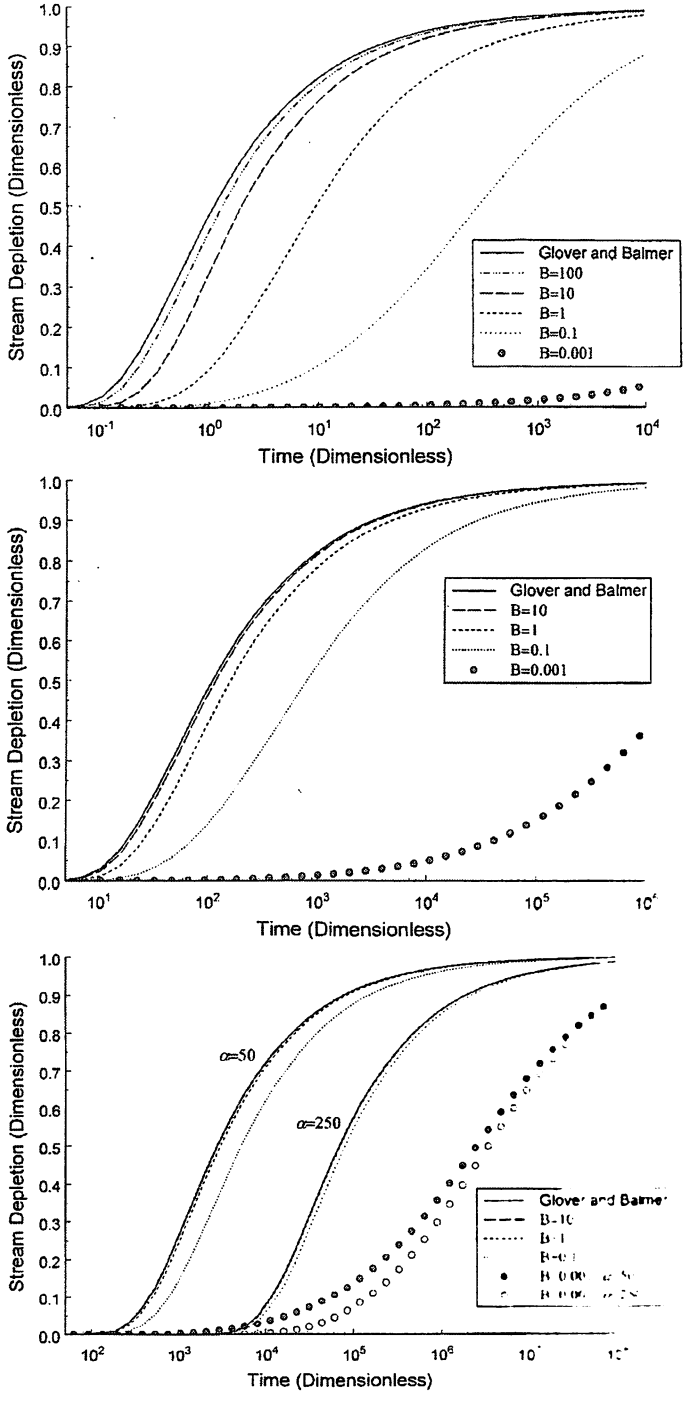

Figure 6. Dimensionless stream depletion versus time plots of the analytical model of Glover and Balmer (1954) and the new solution for an aquifer of infinite lateral extent: (a) α = 1; (b) α = 10; (c) α = 50 and 250.

Figures 6a to 6c demonstrate that the Glover and Balmer model may introduce considerable error into stream depletion estimates when the pumping well is relatively close to the stream (α < 20 to 30). In order to assess the magnitude of this error for conditions commonly faced in the field, B estimates based on physically plausible parameter values must be considered. Reasonable values of hydraulic conductivity and aquifer thickness for an unconsolidated sand and gravel aquifer are 50 m/day and 15 m, respectively. Reported values for k′ and b′ (Conrad and Behm 1996) indicate that 0.1 to 1 m/day and 0.1 m, respectively, would be plausible values for these quantities. Using these values and a stream width of 10 to 20 m to represent conditions in streams of a moderate size, a range of 0.1 to 5.0 is obtained for B. Figures 6a to 6c show that sizable error (can exceed 1000%) may be introduced when the Glover and Balmer model is used in these conditions. Only when the pumping well is at a relatively large distance from the stream (α > 200 to 250) can the k′/b′ ratio be neglected (Figure 6c).

It is important to note that the practical significance of the error introduced by the Glover and Balmer model for a stream of shal-

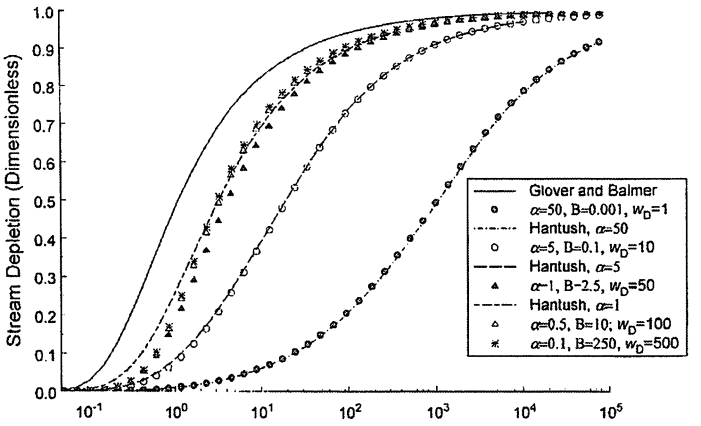

Figure 7. Dimensionless stream depletion versus modified time (T_3t/a^2S_3) plot illustrating the dependence of the new solution on stream width for a laterally infinite aquifer (α and B vary only with stream width; $w_D = w/w_{\alpha=50}$; analytical models of Glover and Balmer [1954] and Hantush [1965] shown for reference).

low penetration will depend on the time (duration of pumping) at which the stream-depletion curve for a certain B converges on that for the Glover and Balmer model. Assuming an unconfined aquifer (specific yield = 0.10) and the parameter values of the preceding paragraph, the B = 1 and B = 0.1 curves of Figure 6b (α = 10) will converge (within 20%) on the stream-depletion curve for the Glover and Balmer model after 3.5 and 150 days of pumping, respectively. Clearly, this error can be of considerable practical significance.

The discussion of this section demonstrates that the conclusions drawn from consideration of drawdown and stream depletion are quite similar. Thus, for the sake of succinctness, the analysis and discussion will focus on stream depletion for the remainder of the paper.

Dependence on Stream Width

Stream width (w) is not considered in existing analytical approaches for estimation of stream depletion (Jenkins 1968; Hunt 1999). However, for streams of shallow penetration, width can be a factor of some importance (Bochever 1966). Figure 7 is a stream-depletion plot in which w is varied by a factor of 500 but all other quantities are kept constant. The distance between the pumping well and the stream does not vary, but α and B change with increases in w (α decreases while B increases). The Glover-Balmer and Hantush models are shown for reference. Note that a modified dimensionless time parameter using distance to the pumping well as the normalizing length (T_3t/a^2S_3) is employed to illustrate the dependence on stream width.

The lack of convergence on the Glover-Balmer solution with increases in w can be explained by considering the definition of stream depletion (Equation 11) and the differences in the hydrogeologic settings (Figures 1a and 2). The Glover-Balmer model assumes a constant-head boundary at the stream edge, so, unless the k′/b′ ratio is large, the stream-depletion curves for the new solution will always be offset from the Glover-Balmer model. This offset is a result of the additional time required for the drawdown cone to propagate beneath a large enough area of the streambed to produce the same leakage. With further increases in stream width, the curves for the new solution will converge because the incremental change in stream depletion gradually decreases due to drawdown diminishing with distance from the pumping well. Eventually, w

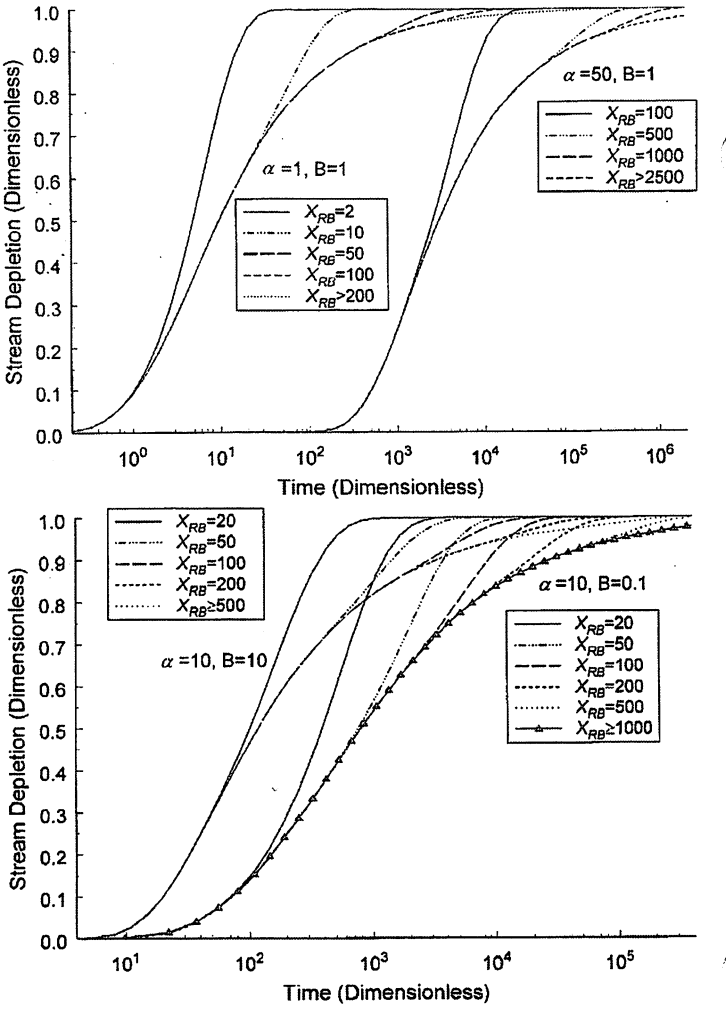

Figure 8. Dimensionless stream depletion versus time plots illustrating the dependence on aquifer width (stream located at valley center): (a) α = 1 and 50, B = 1; (b) α = 10, B = 0.1 and 10.

becomes so large and the drawdown underneath the far side of the stream so small that stream depletion essentially does not change with further increases in width. Thus, an extremely wide stream will not necessarily be well represented by the Glover-Balmer model.

Hunt (1999) describes the correspondence between the Hantush stream leakance parameter and his λ parameter. Butler and Tsou (2000) use this correspondence to derive conditions (aquifer thickness = 0.5w) for which the Hantush solution is an approximation of the solution proposed here. As shown in Figure 7, this approximation is quite reasonable when the pumping well is a normalized distance of five or more from the stream (α ≥ 5) in a laterally infinite aquifer.

Dependence on Lateral Boundaries

The discussion of the preceding sections focused on aquifers that can be conceptualized as laterally infinite units. In many situations, however, the aquifer is of relatively limited lateral extent (Rosenshein 1988; Larkin and Sharp 1992). Figures 8a and 8b display the dependence of stream depletion on aquifer width for a stream in the middle of an alluvial valley. The width above which the aquifer can be considered as laterally infinite will depend on the normalized distance from the pumping well to the stream (α) and, to a lesser extent, the stream leakance parameter (B). In all cases, as α increases, the width above which the laterally infinite assumption is reasonable increases (Figure 8a). Conversely, as B increases,

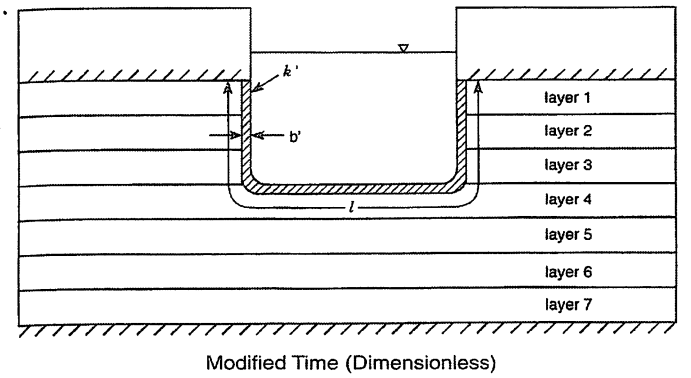

Figure 9. Cross-sectional view of partially penetrating stream configuration investigated with seven-layer MODFLOW model (see Table 2 for model details, notation defined in text).

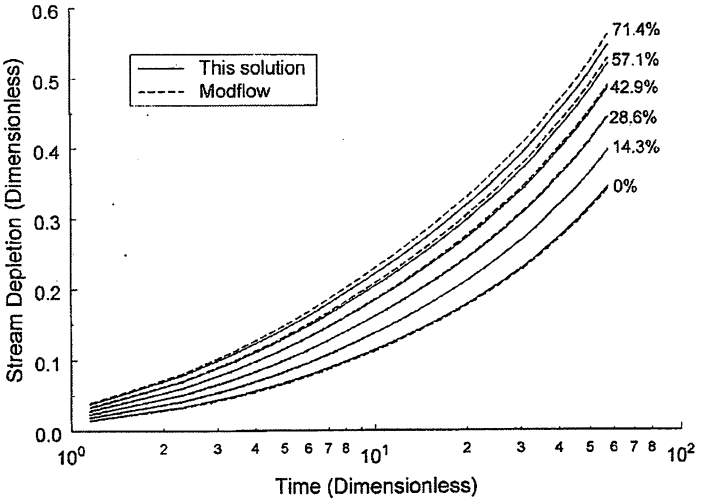

Figure 10. Dimensionless stream depletion versus time plot comparing the extended analytical solution to the seven-layer MODFLOW model (α = 1.1; B = 0.12 for case of 0% penetration) percent penetration ranging from 0 (stream above first layer of MODFLOW model of Figure 9) to 71.4 (stream above sixth layer of MODFLOW model).

the width above which the laterally infinite assumption is reasonable decreases (Figure 8b). For most conditions, aquifer width must be on the order of hundreds of stream widths before the assumption of a laterally infinite aquifer is appropriate. Given the results shown in Figures 8a and 8b and the fact that the stream channel may often be located near one side of the valley, the impact of lateral boundaries on stream depletion calculations will often be of considerable practical significance.

Dependence on Degree of Penetration

This new analytical model is based on the assumption that the depth of penetration is small relative to aquifer thickness (Figure 2). In many situations, however, the degree of penetration is not negligible. Since a significant degree of penetration will lead to an increase in the perimeter of the streambed relative to the negligible-penetration case, an approximate extension of the model to a significant degree of penetration can be obtained through a redefinition of B:

$$B^* = \frac{Bl}{w} = \frac{k' \, wl}{b' \, T_2} \tag{13}$$

where (l) is the length along the intersection between the aquifer and the streambed (henceforth, the wetted perimeter). A seven-layer MODFLOW model (Figure 9 and Table 2) was used to assess the viability of this approximate extension of the analytical model. The results presented in Figure 10 demonstrate that the approximations used in the extended model do not translate into errors of practical significance for the range of penetrations expected in most natural systems. If errors of practical significance are defined as deviations greater than 20% of the actual stream depletion, this approximate model is valid for relative penetrations as large as 85%. As shown in Figure 10, estimates of stream depletion are dependent on the degree of penetration when the pumping well is close to the stream. This dependence, however, will decrease for pumping wells located at greater distances from the stream.

The results shown in Figure 10 were for B = 0.12 and α = 1.1. Closer agreement between the numerical and analytical results will be obtained as B decreases and/or α increases. Although the extended analytical model becomes more approximate with increases in B and/or decreases in α, further simulations have demonstrated that this model will be a reasonable approximation at α = 1.1 for B values as large as 11.6 and relative penetrations from 10% to 50%. For B > 10, the Glover and Balmer solution is a reasonable approximation for all ranges of penetrations at larger α values ($\alpha \geq 10$, Figures 6b and 6c).

The results of the numerical assessment indicate that this approximate extension should enable reasonable stream-depletion estimates to be obtained for the range of stream-channel penetrations found in most natural systems. Although these conclusions are based on results for a confined aquifer, they should also be appropriate for unconfined systems except when pumping causes a significant decrease in the wetted perimeter (l).

Model Limitations

The findings of this study must be considered within the light of the major assumptions that are invoked in the analytical model. Assumptions of note include: (1) vertical flow is negligible; (2) the aquifer is isotropic; (3) aquifer heads remain above the stream bottom; (4) the stream level is unaffected by pumping; and (5) the pumping well is fully screened across the aquifer. In the following paragraphs, the ramifications of each of these assumptions will be briefly considered.

A fundamental assumption of this model is that the vertical component of flow can be neglected (Dupuit approximations). Figure 3b shows that neglect of vertical flow does introduce error into stream-depletion estimates. This error can be of practical significance (> 20%) when B is large (> 1) and α is small (< 1). However, neglect of the vertical component of flow should rarely introduce errors of practical significance outside of these conditions. A nonnegligible degree of stream-channel penetration will further diminish the impact of vertical flow.

An anisotropy in aquifer hydraulic conductivity ($K_h \neq K_v$, where K_h and K_v are horizontal and vertical hydraulic conductivity, respectively) can magnify the error introduced by neglect of vertical flow. Several studies (Sophocleous et al. 1995; Chen and Yin 1999) have shown that anisotropy can be an important control on stream-aquifer interactions. Although not emphasized in this previous work, the impact of anisotropy is a function of the distance from the pumping well to the stream. Additional simulations per-

formed with the seven-layer MODFLOW model found that a moderate degree of anisotropy ($K_h/K_v = 10$) can be neglected when $\alpha > 15$. For a high degree of anisotropy ($K_h/K_v = 100$), the impact can be neglected when $\alpha > 75$. If $B < 1$ and/or the degree of stream-channel penetration is nonnegligible, the distances at which anisotropy can be ignored will be much less. Thus, unless anisotropy is large or the aquifer is thick and the pumping well is close to the stream, neglect of anisotropy should not introduce errors of practical significance.

As Rushton (1999), among others, has pointed out, leakage across the streambed will not increase once aquifer heads fall below the bottom of the stream. In that situation, all of the existing analytical approaches will overpredict stream depletion and can produce errors of practical significance. A numerical model should therefore be used when heads have been drawn beneath a significant portion of the streambed.

The viability of the assumption that stream levels are unaffected by pumping depends on the ratio of the pumping rate to stream discharge. When this ratio is large, stream levels may decrease with time leading to decreases in stream depletion. The analytical model can be used to identify the time at which stream depletion becomes a significant fraction of stream discharge, but it should not be used beyond that point.

The validity of the assumption of a fully penetrating pumping well is a function of the distance from the pumping well to both the stream and the observation well, and the degree of anisotropy. If the distance to both the stream and the observation well is greater than $2b(K_h/K_v)^{1/2}$, where b is aquifer thickness, the error introduced by a partially penetrating pumping well will be negligible (Hantush 1964).

Conclusions

A new analytical solution has been developed for estimation of the drawdown and stream depletion produced by pumping in the vicinity of a stream. The solution is based on a model of the stream-aquifer system that is more realistic than that employed in commonly used analytical methods for estimation of pumping-induced water transfers. This new solution was used to assess the influence of a variety of factors on drawdown and stream-depletion calculations, and to demonstrate the magnitude of the error introduced by commonly used analytical methods. The major findings of this study are described in the following paragraphs.

The assumption of a large stream leakance, which underlies the commonly used fully penetrating stream model of Glover and Balmer (1954), can lead to a significant overestimation of stream depletion (100% to 1000%) in many practical applications. The degree of overestimation depends on the value of the stream leakance parameter (B) and the normalized distance from the pumping well to the stream (α). For pumping wells at large distances from the stream ($\alpha > 250$), this overestimation is usually not of practical significance. Although leakage will increase with stream width, a very wide stream will not necessarily be well represented by the Glover and Balmer model.

The assumption of a laterally infinite aquifer is often adopted for stream-depletion calculations (Glover and Balmer 1954; Hunt 1999). Many natural systems, however, are of quite limited lateral extent. Thus, the impact of lateral boundaries on stream-depletion calculations will frequently be of practical importance. The significance of that impact depends on the distance from the pumping well to the stream and the magnitude of the stream leakage. For most cases, aquifer width must be on the order of hundreds of stream widths before the laterally infinite assumption is appropriate.

This new solution is based on the assumption that stream-channel penetration is negligible relative to aquifer thickness. When applied to conditions of nonnegligible penetration, the solution can introduce considerable error into stream-depletion estimates. However, by including the wetted streambed perimeter in a redefinition of the stream-leakance parameter, an extension of the solution can be obtained that is a reasonable approximation for relative penetrations up to and exceeding 85%. Although the approximation must be used with caution when stream leakance is large ($B > 1$) and the pumping well is close to the stream ($\alpha < 1$), this extension is applicable for a wide range of conditions expected in natural systems.

The findings of this paper demonstrate that this new solution is quite useful for rapid assessment of pumping-induced water transfers in a wide range of stream-aquifer settings. Regulatory agencies throughout the world currently quantify such transfers using analytical models of idealized stream-aquifer configurations that often bear little resemblance to natural systems. Since this solution greatly extends the range of conditions that can be considered with analytical methods, it could prove to be a valuable new tool for water management design and water rights adjudication purposes.

Code and Reference Availability

An executable file for this model and example input and result files can be downloaded from the KGS Stream-Aquifer Interactions Web site (www.kgs.ukans.edu/StreamAq). The Fortran code is available from the KGS Publication and Sales Office for a nominal charge [request Computer Program Series #99-1 (Butler and Tsou 1999)]. Since the Zlotnik et al. (1999) and Butler and Tsou (2000) references are not widely available, downloadable copies of these documents can also be found on the KGS Stream-Aquifer Interactions Web site.

Acknowledgment

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Appendix

In this section, the transform-space form of the solution to the mathematical model defined by Equations 1 through 11 is presented. A complete derivation using dimensionless parameters is given in Butler and Tsou (2000).

A solution for drawdown can be obtained from Equations 1 through 10 using integral transforms (Robinson 1968). Except for the addition of lateral boundaries and the stream leakance term, the approach is equivalent to that of Butler and Liu (1991). A Laplace transform in time followed by an exponential Fourier transform in the y direction produces Fourier-Laplace space analogs to Equations 1 through 3. The solution to these equations in Fourier-Laplace space can be written as

$$\bar{\bar{s}}_1(x, \omega, p) = k_1\left[e^{2\lambda_1 x_{lb} + \lambda_1 x} + e^{-\lambda_1 x}\right] \quad \text{(A1)}$$

$$\bar{\bar{s}}_2(x, \omega, p) = k_1\left[a_1 e^{\lambda_2 x} + b_1 e^{-\lambda_2 x}\right] \quad \text{(A2)}$$

$$\bar{\bar{s}}_3(x, \omega, p) = k_1\left[c_1 e^{\lambda_3 x} + d_1 e^{-\lambda_3 x}\right],\ 0 \le x < a \quad \text{(A3a)}$$

$$\bar{\bar{s}}_3(x, \omega, p) = \left(\frac{k_1 f_1}{g_1}\right)\left[e^{\lambda_3 x} + e^{2\lambda_3 x_{rb} - \lambda_3 x}\right],\ a < x \le x_{rb} \quad \text{(A3b)}$$

where $\bar{\bar{s}}_i$ is the Fourier-Laplace transform of s_i; p is the Laplace transform variable; ω is the Fourier transform variable; $\lambda_1 = (\omega^2 + P_1 p)^{1/2}$; $\lambda_2 = (\omega^2 + L + P_2 p)^{1/2}$; $\lambda_3 = (\omega^2 + P_3 p)^{1/2}$; $P_i = S_i/T_i$; $L = k'/(b'T_2)$; $a_1 = \frac{1}{2}\left(e^{2\lambda_1 x_{lb} - \lambda_1 w + \lambda_2 w} + e^{(\lambda_1 + \lambda_2)w}\right) + \frac{\lambda_1}{2\gamma_1\lambda_2}\left(e^{2\lambda_1 x_{lb} - \lambda_1 w + \lambda_2 w} - e^{(\lambda_1 + \lambda_2)w}\right)$; $b_1 = \frac{1}{2}\left(e^{2\lambda_1 x_{lb} - \lambda_1 w - \lambda_2)w} + e^{(\lambda_1 - \lambda_2)w}\right) - \frac{\lambda_1}{2\gamma_1\lambda_2}\left(e^{2\lambda_1 x_{lb} - \lambda_1 w - \lambda_2 w} - e^{(\lambda_1 - \lambda_2)w}\right)$; $c_1 = \frac{1}{2}[a_1 + b_1] + \frac{\lambda_2}{2\gamma_2\lambda_3}[a_1 - b_1]$; $d_1 = \frac{1}{2}[a_1 + b_1] - \frac{\lambda_2}{2\gamma_2\lambda_3}[a_1 - b_1]$; $e_1 = -Q/(T_3\lambda_3 p\sqrt{2\pi})$; $f_1 = c_1 e^{\lambda_3 a} + d_1 e^{\lambda_3 a}$; $g_1 = e^{\lambda_3 a} + e^{2\lambda_3 x_{rb} - \lambda_3 a}$; $h_1 = c_1 e^{\lambda_3 a} - d_1 e^{-\lambda_3 a}$; $j_1 = e^{\lambda_3 a} - e^{2\lambda_3 x_{rb} - \lambda_3 a}$; $k_1 = e_1 g_1/[f_1 j_1 - h_1 g_1]$; $\gamma_1 = T_2/T_1$; and $\gamma_2 = T_3/T_2$.

A numerical scheme based on that of Butler and Liu (1991) is used to invert the Fourier-Laplace space expressions into real space. This scheme, which is implemented in Butler and Tsou (1999), uses Romberg integration (Carnahan et al. 1969) and the Stehfest (1970) algorithm to evaluate the Fourier and Laplace inversion integrals, respectively.

The solution for stream depletion is found using an approach similar to that of Hunt (1999) to obtain a Laplace-space expression for stream depletion in a laterally bounded aquifer:

$$\overline{\Delta q}(p) = \frac{k_1}{\lambda_2^*}\left[a_1\left(1 - e^{-\lambda_2^* w}\right) - b_1\left(1 - e^{\lambda_2^* w}\right)\right] \quad \text{(A4)}$$

where $\overline{\Delta q}$ is the Laplace transform of Δq and $\lambda_2^* = (L + P_2 p)^{1/2}$ This expression is numerically inverted using the Stehfest algorithm (Butler and Tsou 1999).

Readers' Forum

University of Wisconsin Professor Named Editor of *Ground Water*

Dr. Mary P. Anderson, chair of the Department of Geology and Geophysics at the University of Wisconsin-Madison, has been appointed editor-in-chief of *Ground Water.* Anderson will succeed Dr. Warren W. Wood, a research hydrologist with the U.S. Geological Survey in Reston, Virginia. Anderson assumes her editorial responsibilities January 1, 2002.

Anderson serves on the National Research Council's Committee on Hydrologic Science and the Geological Society of America Council. She is past president of the American Geophysical Union's Hydrology Section and has served on editorial boards for seven publications, including *Ground Water.*

Anderson is affiliated with the Geological Engineering Program in Madison, with appointments in the Institute for Environmental Studies and the Water Resources Management Program. Author of more than 90 articles, she is co-author of *Applied Groundwater Modeling: Simulation of Flow and Advective Transport,* a textbook offered in three languages. Anderson earned a Ph.D. in hydrology from Stanford University.

Corrections

"Drawdown and Stream Depletion Produced by Pumping in the Vicinity of a Partially Penetrating Stream" by James J. Butler Jr., Vitaly A. Zlotnik, and Ming-Shou Tsou, September–October 2001, v. 39, no. 5: 651–659.

Three minor errors were introduced into this paper. The corrections are as follows:

In Equation 3:

$$\frac{S_3}{T_3}\frac{\partial S_3}{\partial t} \text{ should be } \frac{S_3}{T_3}\frac{\partial s_3}{\partial t}$$

The x axis label "Modified Time (Dimensionless)" should be on Figure 7 instead of Figure 9.

In the Appendix, definition of notation Equation A3b, the b_1 expression

$$e^{2\lambda_1 x_{1b} - \lambda_1 w - \lambda_2)w} \text{ should be } e^{2\lambda_1 x_{1b} - \lambda_1 w - \lambda_2 w}$$

and the f_1 expression $d_1 e^{\lambda_3 a}$ should be $d_1 e^{-\lambda_3 a}$.

Ground Water regrets any inconvenience these errors may have caused.

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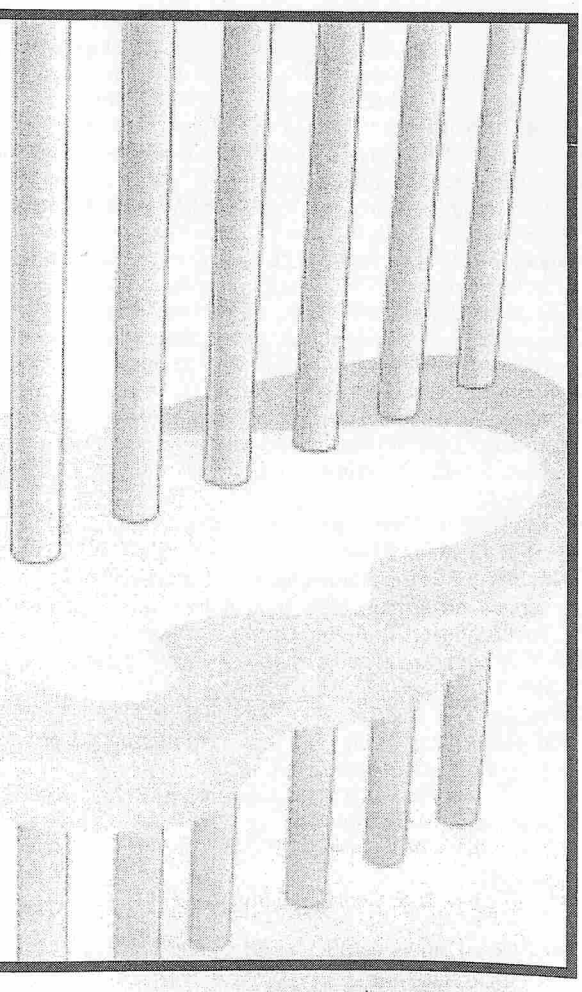

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APPENDIX F

WATER RESOURCES RESEARCH, VOL. 34, NO. 1, PAGES 33–46, JANUARY 1998

Hydraulic characterization of aquifers, reservoir rocks, and soils: A history of ideas

T. N. Narasimhan

Department of Materials Science and Mineral Engineering, Department of Environmental Science Policy and Management, Earth Sciences Division, Ernest Orlando Lawrence Berkeley National Laboratory University of California at Berkeley

Abstract. Estimation of the hydraulic properties of aquifers, petroleum reservoir rocks, and soil systems is a fundamental task in many branches of Earth sciences and engineering. The transient diffusion equation proposed by Fourier early in the 19th century for heat conduction in solids constitutes the basis for inverting hydraulic test data collected in the field to estimate the two basic parameters of interest, namely, hydraulic conductivity and hydraulic capacitance. Combining developments in fluid mechanics, heat conduction, and potential theory, the civil engineers of the 19th century, such as Darcy, Dupuit, and Forchheimer, solved many useful problems of steady state seepage of water. Interest soon shifted towards the understanding of the transient flow process. The turn of the century saw Buckingham establish the role of capillary potential in governing moisture movement in partially water-saturated soils. The 1920s saw remarkable developments in several branches of the Earth sciences; Terzaghi's analysis of deformation of water-saturated earth materials, the invention of the tensiometer by Willard Gardner, Meinzer's work on the compressibility of elastic aquifers, and the study of the mechanics of oil and gas reservoirs by Muskat and others. In the 1930s these led to a systematic analysis of pressure transients from aquifers and petroleum reservoirs through the work of Theis and Hurst. The response of a subsurface flow system to a hydraulic perturbation is governed by its geometric attributes as well as its material properties. In inverting field data to estimate hydraulic parameters, one makes the fundamental assumption that the flow geometry is known a priori. This approach has generally served us well in matters relating to resource development primarily concerned with forecasting fluid pressure declines. Over the past two decades, Earth scientists have become increasingly concerned with environmental contamination problems. The resolution of these problems requires that hydraulic characterization be carried out at a much finer spatial scale, for which adequate information on geometric detail is not forthcoming. Traditional methods of interpretation of field data have relied heavily on analytic solutions to specific, highly idealized initial-value problems. The availability of efficient numerical models and versatile spreadsheets of personal computers offer promising opportunities to relax many unavoidable assumptions of analytical solutions and interpret field data much more generally and with fewer assumptions. Currently, a lot of interest is being devoted to the characterization of permeability. However, all groundwater systems are transient on appropriate timescales. The dynamics of groundwater systems cannot be understood without paying attention to capacitance. Much valuable insights about the dynamic attributes of groundwater systems could be gained by long-term passive monitoring of responses of groundwater systems to barometric changes, Earth tides, and ocean tides.

> Many of the important details of history and interaction in science are often forgotten; we know about such-and-such an idea, that somebody had it at some point, but we don't know just how it happened, who said what to whom, and so on. Those things can be terribly important in the real development of science. So let me tell you something about the history of the maser and the laser.
>
> *C. H. Townes* [1994, p. 53]

1. Introduction

In order to solve practical problems of interest in the fields of groundwater seepage, hydrogeology, agricultural engineering, petroleum engineering, environmental engineering, soil physics, and geophysics, it is necessary to have reliable estimates of hydraulic parameters such as permeability, hydraulic capacitance, and porosity. Since the early work of Darcy, Dupuit, Forchheimer, and others in Europe during the second half of the 19th century, a substantial body of literature has accumulated in diverse fields of Earth sciences and engineering pertaining to methods for estimating hydraulic characteristics by inverting data collected from experiments conducted on field installations. For a student of the Earth sciences it is of considerable interest not only to gain an understanding of how the ideas relating to hydraulic characterization have evolved historically but also to decipher the fundamental notions which unite all these methods.

It is reasonable to state that all the hydraulic characteriza-

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tion methods in use today have two themes in common: an empirical equation of motion, familiarly known as Darcy's law, which gives formal identity to the notion of permeability, and the equation of transient heat conduction, originally proposed by Fourier in 1807, which has established itself as the working model for diffusion-type processes in physical sciences. The equation of motion is imbedded in the diffusion equation.

Intrinsic to the transient diffusion equation (stemming from Fourier's equation of transient heat conduction) are the parameters hydraulic conductivity and hydraulic capacitance. In turn, hydraulic capacitance includes, among other properties, the porosity of the porous medium. The terms "storativity" and "specific storage" are often used in groundwater hydrology to denote hydraulic capacitance and specific hydraulic capacity of water-saturated geologic materials. For purposes of generality, we shall prefer, in this work, the term "hydraulic capacitance." This term includes storativity as a special case. Hydraulic capacitance represents the quantity of water released from storage because of a unit change in pressure due to a combination of three independent processes: pore volume change, change in water saturation, and expansion of water. The transient diffusion equation provides the foundation for hydraulic characterization. Ultimately, all the hydraulic characterization methods consist of fitting the field data to the transient diffusion equation and finding the best combination of parameters that agree with the field data. Thus hydraulic characterization methods are "inverse" methods concerned with the estimation of parameters compatible with the diffusion model.

In the inversion venture outlined above, Earth scientists and engineers have historically relied on the use of "analytic solutions" (also referred to as "closed-form solutions"). A variety of ingenious techniques (type-curve matching, early-time and late-time approximations) have been devised to back the parameters out from the field data. Taking advantage of developments in digital computers, researchers have, over the past two decades, been successfully experimenting with numerical models to estimate hydraulic parameters by way of "calibration" exercises. With the improvements in the reliability of solutions generated by numerical models and the increased availability of powerful "spreadsheets" on the personal computer, there are indications that numerical models will soon become preferred tools of inversion of field data to estimate hydraulic parameters. Numerical models are especially attractive because they can help minimize many assumptions that enter into the idealizations that are essential for obtaining closed-form solutions.

At present, as the personal computer drastically changes our approach to analyzing field data from hydraulic tests, it is worth our while to summarize our current knowledge of hydraulic characterization in a systematized manner and to assess where we stand. So motivated, the present work is an attempt to take an integrated view of concepts, ideas, and methods developed in agricultural engineering, soil physics, hydrogeology, petroleum engineering, civil engineering, geophysics, and related fields. This is a substantial task, considering the vast amount of literature that has accumulated on this topic over many decades, not to speak of the many differences that exist among these fields in articulating questions and describing ideas. Under the circumstances the goal of the present study, of generating an overall synthesized understanding of the field based primarily on literature from the United States, is a modest one. Even in this regard no claim is made that the literature compiled is comprehensive or complete. The hope is that the literature surveyed is adequate enough to capture the essential elements of the major ideas and concepts of relevance. *Hall* [1954] presented a well-reasoned review of literature on the topic of seepage towards wells. His survey is especially comprehensive in regard to the 19th century European literature. Hall's paper has been a valuable source of information in regard to the European literature discussed in the present work.

This work primarily focuses on field methods rather than laboratory methods. The hydraulic response of a subsurface flow system is governed by its geometric attributes, its forcing functions, and its material properties. In inverting field data to estimate hydraulic parameters, it is traditional to assume that the geometric attributes of the flow system and the forcing functions are known and the hydraulic parameters are the unknowns to be estimated. This work is restricted to those methods in which geometric details (symmetry, layering) are assumed known a priori. Over the past two decades an increasing body of literature has accumulated on the application of stochastic methods and probability concepts to the hydraulic characterization of pervasive heterogeneities (especially hydraulic conductivity variations within a homogeneous medium) in subsurface flow systems. These methods are outside the scope of the present work.

The history of science is such that ideas are born and methods are fabricated in response to pure curiosity or practical needs. Sometimes new ideas are born by accident or by inspiration. Integration of ideas to identify underlying unity among diversity comes later. Individual disciplines in the Earth sciences have generally been focused on problems of special interest to their needs. For example, until recently, soil physicists have devoted much of their attention to the process of infiltration into soils and the movement of water in the root zone. Thus, although the various Earth disciplines have a common thread of unity in terms of physical processes governing hydraulic characterization, these disciplines have traditionally maintained distinct identities, with limited flow of ideas among themselves. A consequence is that when one attempts an integration of ideas reaching beyond disciplinary boundaries, as in the present work, the portrayal of the individual disciplines cannot be very even. This is an unavoidable human limitation.

In the following the evolution of ideas is presented in a chronological fashion. As a prelude to the details that are to be presented, Figure 1 shows the important developments since 1807, and Figure 2 shows the important publications pertaining to the developments shown in Figure 1.

2. Darcy in Context

Darcy's law has come to play such a central role in the study of flow of fluids in the Earth's subsurface that Darcy's work gives the appearance of the start of a new era. However, Darcy came upon the scene at a time when mathematical physics was blossoming in France in the wake of the Newtonian revolution. Thus it is instructive to place Darcy's work in a historical context.

Our conceptual model for understanding the occurrence and movement of fluids in geological materials is based on treating fluid flow as a process mathematically analogous to heat conduction in solids. As a consequence, the working mathematical model for the transient flow of fluids in geologic materials is the partial differential equation of heat conduction, originally proposed by Fourier (Theorie de la propagation de la Chaleur

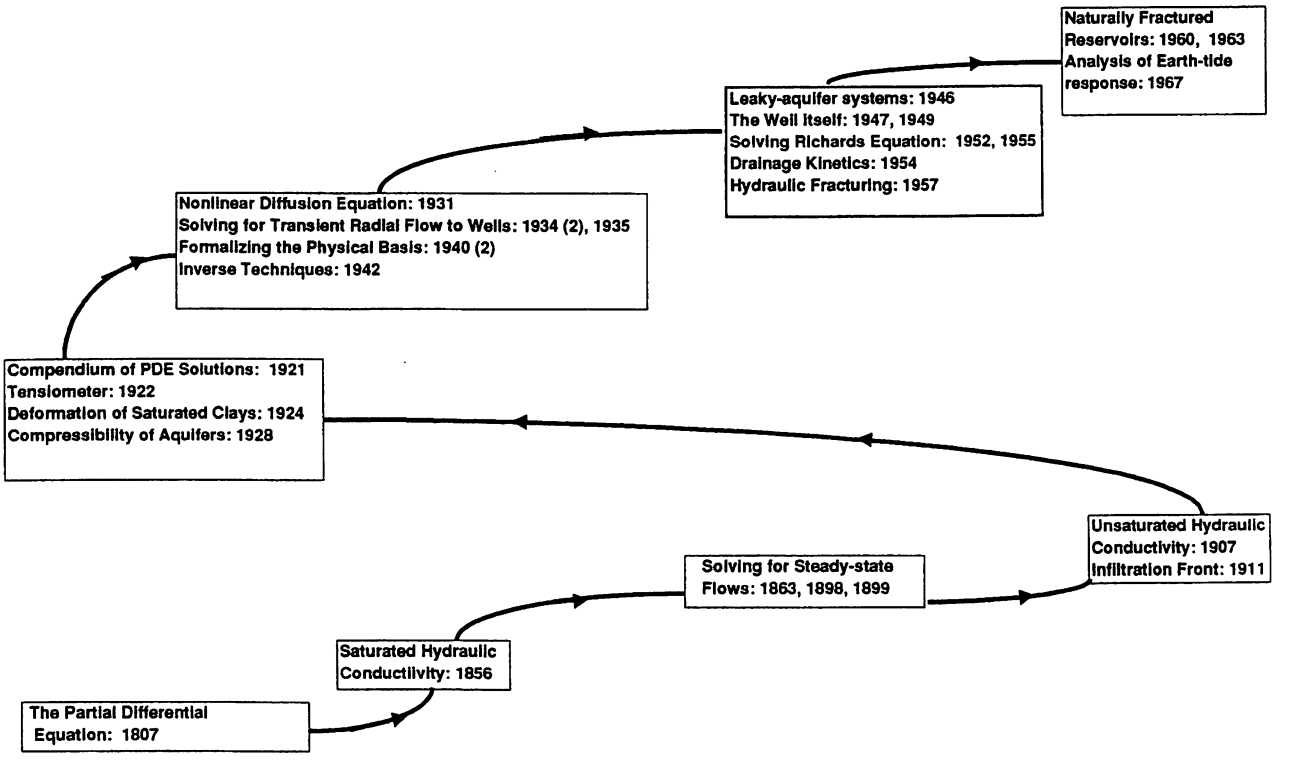

Figure 1. Chronology of important developments.

dans les solides, manuscript submitted to the Institute de France, 1807). As it happened [*Grattan-Guinness*, 1972], Fourier's 1807 work was never formally published. After much additional work to answer criticisms of the reviewers (Laplace, Lagrange, Monge, and Lacroix), Fourier's classic *Theorie Analytique de la Chaleur* was published in 1822. Intrinsic to Fourier's model are the parameters conductivity and capacitance. The development of these two concepts in the study of heat are

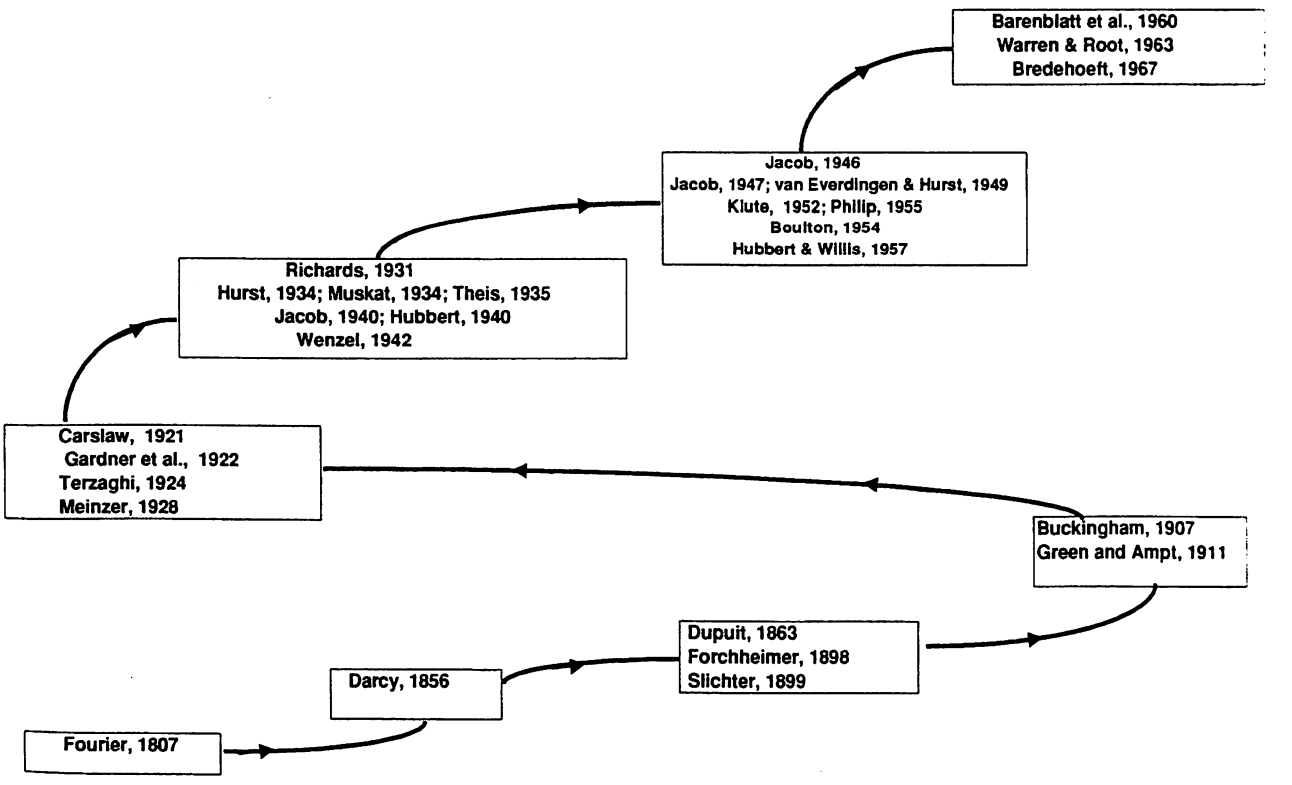

Figure 2. Chronology of important papers.

of fundamental scientific importance, and it is pertinent to start with a brief look at their history.

The construction of reliable thermometers for the precise measurement of heat was critical to the development the science of heat during the second half of the 18th century. Although the mercury thermometer was first constructed in France by Boulliau in 1659, accurate thermometers with well-defined scales became available only by the middle of the 18th century through Fahrenheit in 1724 and Celsius in 1742 [*Cajori*, 1898]. With the availability of these instruments, Joseph Black, a pioneer of modern quantitative chemistry at Edinburgh, discovered latent heat and specific heat, devised an ice calorimeter, and measured these quantities around 1760. However, he did not publish his work. The first published measurement of the specific heat of solids is attributed to a collaborative memoir by Lavoisier and Laplace ("Memoire sur la Chaleur") presented to the Royal French Academy in 1783. Thus the origin and definition of the concept of heat capacity is well documented. Fourier, in his 1807 manuscript on the propagation of heat, introduces the conductivity parameter (he calls it "specific internal conducibility") in precise mathematical terms. Since heat flux is difficult to measure without a calorimeter, it is reasonable to suspect that the measurement of thermal conductivity became established after the successful use of the calorimeter by Lavoisier and Laplace in 1780.

Other noteworthy developments were taking place in the sciences during the 18th century and the first half of the 19th century. In his most important work, *Hydrodynamica*, published in 1738, Daniel Bernoulli of Switzerland identified the three components that make up the mechanical energy of a moving fluid; potential energy due to gravity, elastic energy due to fluid pressure, and kinetic energy. Working with direct current, *Ohm* [1827] experimentally determined the inverse relationship between electric current and voltage drop along an electric conductor, the constant of proportionality being the electrical resistance of the conducting body. This electrical resistance was found to be a function of the material of the conductor as well as its shape and size. *Poiseuille* [1842], a medical doctor interested in the mechanisms of blood flow through human and animal veins, studied the mechanisms governing the flow of liquids through fine capillary tubes. These meticulous experiments were carried out on horizontal capillary tubes, and fluxes as low as 0.1 cm^3 over several hours were measured. Through these experiments Poiseuille established that the volumetric flux of liquid was directly proportional to the pressure drop over the tube and the area of cross section and inversely proportional to the length of the tube, the constant of proportionality being represented by K. According to *Herschel* [1940], the commonly used expression for Poiseuille's law involving the fourth power of capillary radius was not proposed by Poiseuille himself. Rather, the function was derived by several workers, including James Clerk Maxwell, by integrating Newton's equation for viscosity as applied to a cylindrical tube. In Germany *Hagen* [1839] had experimentally obtained similar results.

It is easy to see from the foregoing that by the time Darcy ventured into conducting his experimental studies on sand filters for water supply to Dijon [*Darcy*, 1856], a well-defined framework was already in place for the design of the experiment and the interpretation of the results, thanks to the contributions of Fourier, Ohm, and Poiseuille. One could reasonably assume that Darcy was aware of these developments and made use of them in his work. Darcy's work was unique in that it dealt with a natural material rather than an engineered material, such as a capillary tube, and that he accounted for gravity. Here again one could reasonably assume that Bernoulli's work in the field of hydraulics had influenced Darcy in including gravity in the definition of fluid potential.

It is pertinent here to take note of the difference between the mathematical forms of Darcy's law and Ohm's law. In Ohm's law one considers the resistance of the conducting body as a whole. Resistance, as it appears in Ohm's law, is an integral, evaluated over the body as a whole. Darcy's law, on the other hand, has a form exactly the same as Fourier's law for conductive heat flux and involves spatial derivative of potential. Whereas Darcy's law casts experimental observations in a form that is compatible with the differential equation, Ohm's law, it appears, is inherently well suited for integral equations and flow nets.

3. Second Half of the 19th Century

Immediately following Darcy's insightful contribution, analogy to heat conduction was actively pursued by engineers in Austria, France, and Germany to solve practical problems of groundwater seepage that were of interest to civil engineers during the second half of the 19th century. Although Fourier's general equation addressed the transient heat conduction process, these civil engineers restricted themselves to steady state flow systems. Whereas the transient process involves two parameters (conductance and capacitance), the steady state problem involves only the conductivity parameter.

The following discussion of the development of ideas in Europe during the 19th century is based on work by *Hall* [1954], who reviewed the European literature in considerable detail.

Jules-Juvenal Dupuit, a contemporary of Darcy, was a theoretically oriented civil engineer who dealt with problems of open channel flow as well as seepage through soils. The chapter on seepage in his book on open-channel flow [*Dupuit*, 1863] later proved to be a standard reference on the subject. It is interesting that Dupuit, starting from the hydraulic principles of open-channel flow, derived an expression for movement of water through soils that proved to be equivalent to Darcy's empirical law. By integrating the equation of motion over a radial domain, Dupuit derived solutions for steady flow in a confined aquifer (artesian well) and in an unconfined aquifer (gravity well). He idealized the well to be at the center of a circular island so as to satisfy the mathematical needs of a credible boundary condition. The assumption of horizontal flow he made in the case of a gravity well in an unconfined aquifer, while yet accounting for the variation in the saturated thickness of the aquifer, is used even now and is referred to as the Dupuit assumption. In addition to analyzing well hydraulics, Dupuit also studied the role of wells in regional groundwater systems such as artesian basins. Another important figure of this period was Joseph Boussinesq, who, in investigating the role of friction in laminar flow of fluids (liquids and gases), derived the expression for the flow of water in an idealized parallel-plate fracture, now referred to as the cubic law [*Boussinesq*, 1868].

In Germany, Adolf Thiem and, later, his son, Gunther Thiem, carried out pioneering work on groundwater seepage, especially in the study of the flow of water to wells. They are also credited with the collection of extensive observational information on the subject. Although he later became aware of

the contributions of Dupuit and Darcy, Adolph Thiem independently derived the expressions for the steady radial flow of water in confined and unconfined aquifers. In the field of groundwater hydrology, Gunther Thiem [*Thiem*, 1906] is widely known for the equation describing the steady radial flow of water in a confined aquifer, although that solution was derived earlier by Dupuit. Gunther Thiem distinguished himself by systematizing and documenting the application of field methods rather than by creating new methods himself.

At this juncture it is appropriate to briefly digress and discuss terminologies. The word "groundwater" ("grundwasser" in German) appears in the literature by the early 1880s in the work of Adolph Thiem. The engineers of the late 19th century distinguished between "gravity wells" and "artesian wells." The former term referred to wells in a phreatic aquifer whose upper boundary is a free surface or the water table over which the pressure is atmospheric. The latter term referred to what is currently recognized as a confined aquifer. Although the possibility of a seepage face above the water level in a gravity well was recognized, the term "seepage face" had not yet been coined. Aquifers were commonly referred to as "groundwater streams" [*Hall*, 1954].

Perhaps the most well known researcher of this era was Phillipp Forchheimer of Austria, whose distinguished career spanned nearly a half century and influenced the work of many who followed him. He was among the earliest to recognize the concepts of isopotential lines and streamlines with regard to groundwater seepage and extended these concepts systematically to generate flow nets as a means of quantitatively analyzing steady flow fields, including flow of water to wells under varying geometric conditions. Forchheimer formally wrote down the Laplace equation [*Forchheimer*, 1898] to describe the steady flow of groundwater and went on to use mathematical techniques such as conformal mapping to solve problems. It appears [*Hall*, 1954] that he was influenced by the work on conformal mapping of *Holzmüller* [1882] for the solution of heat conduction problems. In addition to formally explaining the results of earlier workers such as Dupuit and Thiem, Forchheimer presented new results for single wells as well as groups of wells and sloping aquifers.

In the United States *Slichter* [1899] pioneered the study of groundwater systems by mathematically analyzing the steady flow of water through geologic media. In particular, he investigated mutual interference between artesian wells and the perturbation of the regional steady state groundwater flow field by a producing water well. Slichter was unaware of Forchheimer's work and formulated the Laplace equation independently. He obtained solutions using the conformal mapping method. It appears that Slichter too, like Forchheimer, was influenced by the work of Holzmüller. Another important contribution of Slichter was that he investigated the physical significance of hydraulic conductivity, which was merely treated as an empirical coefficient by Darcy. By studying the geometric properties of various spherical packs, Slichter identified the geometric component and the viscous drag components of hydraulic conductivity.

4. The Turn of the 20th Century

In retrospect it is easy to see that our understanding of the flow of fluids through porous media during the 19th century was largely due to the contributions of researchers from France. The turn of the century saw the center of activity in relation to the study of water movement in earth materials gradually shift from Europe to North America.

Edgar Buckingham, a leading physicist of the time, was a member of the Physical Laboratory of the Bureau of Soils, U.S. Department of Agriculture (USDA), during the first decade of this century. His insightful studies on the movement of moisture in soils resulted in two fundamental contributions, published as bulletins of the USDA. In the first, devoted to aeration in soils, he formulated [*Buckingham*, 1904] the parabolic equation to describe the movement of gases in unsaturated soils and evaluated the time lag and damping associated with the migration of air driven into and out of the soil because of changes in barometric pressure. Recognizing the fact that earlier workers such as Dupuit, Forchheimer, and Slichter addressed the steady state problems, Buckingham appears to be the first worker to address the transient migration of fluids in the Earth's subsurface. Buckingham's second bulletin, published in 1907, proved to be far reaching in impact [*Buckingham*, 1907]. Studying the movement of moisture in unsaturated soils theoretically and experimentally, he defined capillary potential and proposed an equation similar in form to Darcy's law to describe the movement of moisture in unsaturated soils. A special feature this formulation was that hydraulic conductivity was treated as a function of capillary potential rather than simply being a constant, as in Darcy's law. The full scope of Buckingham's contribution would become possible later with the invention of the tensiometer. It is remarkable that Buckingham, who was probably not aware of Darcy's work [*Sposito*, 1987], gave a theoretical basis for Darcy's empirical law and extended the law to the unsaturated zone. Because Darcy's law is now used widely for both the saturated zone and the unsaturated zone, some would argue that Darcy's law should be properly called the "Darcy-Buckingham law." Buckingham's work is central to the fields of soil physics and multiphase flow analysis still in use today. *Buckingham* [1914] is also widely known for his seminal contribution on dimensional analysis. Most of the methods used to invert field data to obtain hydraulic parameters on the basis of analytic solutions routinely use dimensionless groups to minimize the number of variables that need to be handled. The rationale for defining these dimensionless groups stems from the "pi theorem" proposed by Buckingham in 1914.

The early 20th century saw the simultaneous recognition of the importance of time in many Earth science disciplines: soil science, soil mechanics, groundwater hydrology, and petroleum engineering [*Narasimhan*, 1986, 1988]. Researchers in these fields recognized that almost all subsurface fluid flow systems are dynamic in nature. In the field of soil physics *Green and Ampt* [1911] proposed a simple approximation to quantify the vertical infiltration of water into an unsaturated soil. The Green and Ampt idealization assumes that as water infiltrates into a soil, a sharp, piston-like zone of saturation advances with time. This approximation is still used in interpreting field data from infiltrometer tests to estimate in situ hydraulic conductivity of soils.

5. The Remarkable Era: 1920–1940

In the evolution of ideas pertaining to the flow of fluids in geological media, the period 1920–1940 must rank as truly remarkable. Conceptual as well as mathematical contributions of fundamental importance relating to the dynamic behavior of fluid flow systems were made simultaneously in the fields of

soil physics, petroleum engineering, groundwater hydrology, and civil engineering. Through a combination of laboratory studies, field observations, and mathematical analysis, the foundations were laid during this period for the systematic study of the dynamics of subsurface flow system.

Willard Gardner was among the earliest [*Gardner and Widtsoe*, 1921] to attempt to quantify nonsteady moisture movement in unsaturated soils in terms of a transient diffusion equation analogous to Fourier's transient heat conduction equation. It is now known that his failure to achieve satisfactory agreement between experiment and theory was due to the fact that he did not account for the dependence of hydraulic conductivity on capillary potential, suggested a decade earlier by Buckingham. In other words, he tried to fit experimental data to a linear partial differential equation, when in fact a nonlinear parabolic equation should have been used.

The early 1920s saw the publication of the classic book *Introduction to the Mathematical Theory of Conduction of Heat in Solids* [*Carslaw*, 1921]. This book and its revision [*Carslaw and Jaeger*, 1947] constituted a remarkably well-organized compendium of a variety of closed-form solutions to problems in steady state and transient heat conduction. The availability of these solutions and the methods used to derive these solutions have proved to be of great benefit to Earth scientists and engineers over the past 75 years in solving a host of fluid flow problems of the Earth's subsurface.

The 1920s saw the publication of two major contributions in the Earth sciences focusing attention on physical processes. *Terzaghi* [1924] experimentally studied the deformation of water-saturated clays and established the relationships among external stresses, pore-fluid pressure, and deformation. In the process, he introduced the important notion of effective stress. Some would consider Terzaghi's paper to have founded the discipline of soil mechanics. Terzaghi proceeded to write down and solve the equation for transient movement of water in a one-dimensional clay column by analogy with the heat conduction equation. In his paper, Terzaghi was meticulous in establishing the one-to-one correspondence between the attributes of the heat-conduction system and the porous-medium flow system. Probably he was the first to point out that the compressibility of a clay is conceptually analogous to specific heat of a solid.

A second major contribution of the 1920s was the paper by *Meinzer* [1928], whom many would consider to be the founder of the discipline of groundwater hydrology in the United States. Meinzer's distinctly descriptive paper was a careful synthesis of observations by many geologists of the U.S. Geological Survey (USGS) of the early 20th century who had studied the decline in water pressures in artesian aquifers such as the Dakota sandstone in North Dakota because of overdraft. These observations, based on water budget calculations, led to the inference that the declines in water pressures were correlated with a decrease in porosity and an increase in water volume, which together accounted for the mass of water mined from the aquifer. Considering the fact that the strains so caused in the porous medium and in the water are extremely small (less than one part in a million), it was remarkably perceptive of Meinzer and his coworkers to have drawn their inferences on the basis of rough estimates of water balance. *Meinzer* [1937], in fact, had made rough estimates that as a result of the decrease in porosity, the land in the North Dakota artesian basin should have subsided by 4–5 inches (10.2–12.7 cm), and this was viewed with skepticism by contemporary geologists and engineers. In essence, Meinzer had described the physics of hydraulic capacitance in saturated geologic materials, which would be described as "storage coefficient" by Theis a decade later.

Contemporaneously with Terzaghi's new leadership in the field of soil mechanics, important developments were also taking place in the analysis of seepage through soils. *Forchheimer* [1930] published his book *Hydraulik*, and *Dachler* [1936] published his book on groundwater flow, which contained a host of steady seepage problems, including flow to wells. For the first time a successful attempt was made by *Weber* [1928] to analyze the nonsteady flow of water to a gravity well (that is, nonsteady flow to a fully penetrating well in an unconfined aquifer). The approach taken by Weber to analyze this problem is worth some discussion because it differs significantly from the more rigorous mathematical approach of later workers such as Muskat, Hurst, and Theis, who solved a parabolic partial differential equation.

Weber considered a well in which the water level is maintained at a constant (constant drawdown test). As pumping progresses, the radius of the cone of depression (also referred to as the radius of influence) increases with time. As a first step in the analysis of this problem, Weber derived an approximate expression for the radius of influence, assuming that water is released from storage by physical drainage of the volume of the aquifer through which the water table moves and that the volume of water so drained per unit volume is the "effective porosity" (the modern notion of specific yield). Mass balance requires that the volume of water so drained is equal to the cumulative production at the well. Once the effective radius is estimated, drawdown as a function of distance from the well is estimated from the steady state solution of radial flow to a gravity well. About a decade later, similar results were obtained by *Steinbrenner* [1937] in Austria.

By the late 1920s the tensiometer had become well developed, thanks to the efforts of Willard Gardner and his coworkers [*Gardner et al.*, 1922]. This work, an abstract, is reportedly the first published reference to the tensiometer (W. Gardner, personal communication, 1991), an instrument that has played a vital role in the evolution of modern soil physics. Because of the tensiometer, routine measurements of moisture content and its relation to capillary pressure had become possible [*Richards*, 1928]. Combining *Buckingham*'s [1907] work on the equation of water motion in unsaturated soils with the newly available soil moisture retention curves, *Richards* [1931] formally wrote down, for the first time, the nonlinear partial differential equation describing transient flow of water in unsaturated soils. The slope of the moisture content versus capillary pressure curve came to be the hydraulic capacitance and was referred to as "moisture capacity." Because of the difficulties of obtaining closed-form solutions to nonlinear differential equations, Richards equation remained unsolved for nearly two decades. It would be the early 1950s before *Childs and Collis-George* [1950] showed that the severity of nonlinearity of the parabolic equation could be lessened by using volumetric moisture content as the dependent variable, rather than capillary potential. Following this suggestion, *Klute* [1952], *Philip* [1955], and others began obtaining solutions for Richards' equation under highly simplified conditions using numerical methods.

In the field of petroleum reservoir engineering, the 1930s was an eventful decade. The need for applying rigorous methods of mathematical physics to understanding the dynamics of

oil and gas reservoirs had been recognized. The decade started with careful theoretical and experimental study of steady state flow systems as a prelude to the study of transient systems which followed immediately thereafter. *Muskat and Botset* [1931] experimentally studied the steady flow of gases in geologic materials and verified that the mass flux of gas was proportional to the drop in the square of the pressure along the flow path. This dependence on the drop in the square of pressure for gases had been theoretically derived by *Boussinesq* [1868]. They then went on to formulate the nonlinear parabolic equation for transient gas flow in a reservoir and solved the special case of steady radial flow in a circular reservoir with a well at the center and a constant pressure outer boundary. *Wyckoff et al.* [1932], with the help of physical models, experimentally studied the radial flow of water in a sand body with a free surface (an unconfined aquifer) and verified the assumptions of Dupuit. They also extensively discussed the importance of the seepage face, the capillary fringe, and water movement in the unsaturated zone above the water table.

The notion of estimating reservoir permeability from transient field tests was initiated by *Moore et al.* [1933]. They articulated a need for estimating, from field tests, important properties of reservoir rocks so that the drainage of oil reservoirs could be studied. This little-known work is very significant for many reasons. Although detailed mathematical derivations were not presented, the authors formally laid down the parabolic equation involving a slightly compressible fluid, presented solutions for a well of finite radius producing at constant pressure from a finite cylindrical reservoir, calculated drawdown and buildup, and demonstrated how the solution can be made use of to estimate reservoir permeability. Furthermore, the authors presented their results in terms of the two important dimensionless groups, dimensionless time and dimensionless drawdown. These dimensionless groups have since become part of the petroleum engineering and groundwater hydraulics literature. At about the same time, *Muskat* [1934] presented a detailed analysis of transient flow of compressible fluids in oil and gas reservoirs. He derived solutions for wells of finite radius as well as of vanishingly small radius in a circular reservoir with prescribed potential boundary or with prescribed flow rate at the well. He then went on to establish the veracity of his model with pressure decline data from an oil field in east Texas. *Hurst* [1934] formulated the parabolic equation in radial coordinates for slightly compressible fluids (liquids) and obtained solutions for production at constant pressure and at constant discharge from a well of finite radius, pumping a cylindrical reservoir of finite radius. Both Hurst and Muskat considered hydraulic capacitance arising purely from fluid expansion and neglected changes in porosity. Shortly afterward, *Muskat* [1937] published his definitive work on the flow of homogeneous fluids through porous media in which he elucidated the fundamental problems of modern petroleum reservoir engineering and the mathematical methods for solving them.

In the field of groundwater hydrology, *Theis* [1935] set up and obtained a solution to the parabolic equation similar to that of *Hurst* [1934] and *Muskat* [1934] but considered a laterally infinite aquifer with a well of vanishingly small radius (line-source well) producing at a constant rate. He verified the credibility of his model by applying it to field data from an unconfined aquifer. Theis used the term "storage coefficient" to denote the hydraulic capacitance parameter in the parabolic equation, a term which still enjoys common usage. Although he was quite cognizant of the analogy between heat capacity and hydraulic capacitance [*Freeze*, 1985], Theis did not explicitly discuss the physical meaning to storage coefficient in his paper. It appears that Theis took a fairly limited view of storage coefficient, restricted to the particular boundary value problem he was interested in, namely, a laterally infinite aquifer of finite thickness, in which water flows horizontally. Thus *Theis* [1940] explains storage coefficient as the volume of water released from a vertical prism of the aquifer of unit cross-sectional area in response to a unit change in hydraulic head. Moreover, *Theis* [1940] identified the role of compressibility in regard to storage coefficient in an artesian aquifer but did not recognize expansion of water. This restricted view of storage coefficient came to enjoy popular usage among groundwater hydrologists in the USGS in subsequent decades.

Theis' work has proved to be a milestone not only in groundwater hydrology but in the Earth sciences in general. In addition to constituting the basic and simplest technique used widely for interpreting data from transient aquifer tests, the Theis' model is also frequently used as the standard against which the transient behavior of more complex aquifers is studied for comparison. One of the factors contributing to the popularity of Theis' work appears to be the fact that hydrologists of the USGS actively developed workable techniques for practically applying the Theis' solution to interpret field data from aquifer tests. They widely communicated their results through USGS publications, which are readily available to field geologists. In addition, these contributions provided a large-scale regional perspective of hydraulic characterization in terms of Earth processes in general. In contrast, contributions in the fields of civil engineering, petroleum engineering, and soil physics took a limited local view of the characterization venture. A landmark publication in this regard was USGS Water Supply Paper 887, by *Wenzel* [1942], which elaborately described the various methods for interpreting pumping test data.

It is worth noting here that *Moore et al.* [1933], *Muskat* [1934], and *Hurst* [1934] were all concerned with laterally limited reservoirs, whereas groundwater hydrologists such as *Theis* [1935] were concerned, in general, with laterally infinite systems. Also, petroleum engineers concentrated on developing techniques for analyzing data from the production well, whereas groundwater hydrologists devoted attention to pumped-well analysis as well as analysis of interference test data (that is, data from passive, observation wells which respond to the removal of water at the pumped well). More than one reason can be attributed to these differences in the styles of design and analysis of hydraulic tests between petroleum engineers and groundwater hydrologists. According to W. E. Brigham (personal communication, 1996) petroleum engineers generally had to work with active well fields, in which many wells were producing fluids at the same time. Under such conditions, planes of no-flow boundaries developed between producing wells, leading to the dynamic isolation of each well. Groundwater hydrologists, on the other hand, did not often deal with well fields. Moreover, the occurrence of oil is very commonly associated with dissolved natural gas and, as the pressure drops during production, gas tends to come out of solution. A consequence is that the apparent compressibility of such oil may be orders of magnitude higher than gas-free oil, leading to a great increase in the effective hydraulic capacitance. In turn, increased hydraulic capacitance contributes to a relatively small radius of influence around a production well,

and hence there is reduced need for interference analysis. Another possible explanation for the differences in styles between petroleum engineering and groundwater hydrology is that petroleum reservoirs often constitute closed systems, while groundwater systems are in general open in nature.

Upon reflection, it is evident that the notion of capacitance is essential for describing the transient flow process. In the work of *Gardner and Widtsoe* [1921], hydraulic capacitance was restricted purely to the rate of change of saturation with capillary pressure, referred to as moisture capacity in the soil physics literature. In Terzaghi's work, hydraulic capacitance was restricted solely to the compressibility of a relatively soft porous material for which one could reasonably neglect the compressibility of water. Meinzer's work combined porous medium compression and fluid expansion in giving form to hydraulic capacitance. *Hurst* [1934] and *Musket* [1934] restricted hydraulic capacitance solely to expansion of the fluid [*Narasimhan*, 1986, 1988]. In general, in a saturated-unsaturated deformable porous medium hydraulic capacitance includes all the three components, namely, pore-volume change, change in water saturation, and expansion of water [*Narasimhan and Witherspoon*, 1977].

At present, it is almost invariably assumed by hydrogeologists that the Theis method is applicable to confined aquifers in which water release from storage is due to the elastic properties of the porous medium and of water. However, it must be noted that in his classic paper, *Theis* [1935] applied his method to an unconfined aquifer and stated that "the equation applies rigidly only to water bodies . . . and [is] applicable only to unconfined water bodies—in which the water in the volume of sediments through which the water table has fallen is discharged instantaneously with the fall of the water table" (p. 521). However, it had been recognized by previous workers that the drainage of water in an unconfined aquifer is an extremely complex physical process. Therefore, as noted by *Hall* [1954], the instantaneous drainage assumption of Theis is a shortcoming of the Theis method as applied to unconfined aquifers.

Arthur Casagrande is a respected name in the field of soil mechanics. Although he did not publish many papers on the theory of flow to wells, *Hall* [1954] notes that commencing from 1934, Casagrande introduced his students at Harvard University to novel ideas in regard to seepage theory, including the flow of water to wells. As part of his lectures, Casagrande had demonstrated that for large values of time, the drawdown predicted by Weber's method and that predicted by Theis' method are essentially the same.

In the field of civil engineering a little known but major discovery, made in the early 1930s, was to influence the attention of Earth scientists and engineers for the next half a century. *Rappleye* [1933], of the U.S. Coast and Geodedic Survey, carefully documented substantial "areal subsidence" of land in the Santa Clara Valley of California based on rerunning of first-order leveling surveys during 1931–1932. He reported that between 1920 and 1933 a benchmark in San Jose had subsided by 4.1 feet (1.25 m) and that as much as 0.5 feet (0.15 m) of that subsidence had occurred during 1932–1933. Although heavy groundwater pumpage was suspected to be the cause of the subsidence [*Tibbetts*, 1933], it was left to *Meinzer* [1937] to advance a rational physical mechanism correlating groundwater pumpage and observed land subsidence. Meinzer not only recognized the applicability of his North Dakota observations [*Meinzer*, 1928] to the San Jose subsidence, but he also conjectured that the substantial magnitude of subsidence observed was probably due to a preponderance of soft, fine-grained sediments in the Santa Clara basin. As we shall see later, Meinzer's conjecture was confirmed subsequently by meticulous field observations by Poland and coworkers in the Santa Clara Valley and the San Joaquin Valley of California.

6. The War Years: Formalizing the Foundations

The decade of the 1940s was quite eventful in the study of transient groundwater systems. *Hubbert* [1940] published "The Theory of Ground-Water Motion," a paper that still remains definitive. In this paper Hubbert elaborated the physical meaning of a fluid potential, formally defined permeability on the basis of balance between impelling forces and resistive forces, derived a tangent law for the refraction of flow lines, and went on to establish the foundations for the study of regional groundwater systems and petroleum reservoirs.

We saw earlier that *Theis* [1940] took a restricted view of storage coefficient limited to horizontal flow in an elastic aquifer. However, *Jacob* [1940] took a much more fundamental view of storage coefficient in the sense of hydraulic capacitance and derived an expression combining the deformability of the porous medium (its bulk modulus) and the compressibility of water. He thus gave formal identity to the processes heuristically recognized by *Meinzer* [1928, 1937]. Jacob also went on in this classic paper to derive an expression for the change in water pressures in aquifers subjected to external stress changes, such as those caused by passing trains, and to barometric pressure changes and defined the parameter "tidal efficiency." Jacob's theoretical work paved the way for interpreting hydraulic parameters of aquifers by analyzing these responses. Jacob went on to make two other major contributions during the 1940s.

7. Post–World War: Building the Superstructure

By the early 1940s the physical and mathematical foundations for transient movement of fluids in subsurface geological systems involving porous medium deformation, desaturation, and fluid expansion had been clearly formalized. The succeeding half a century, extending to the present, has seen the application of these basic ideas and tools to field conditions involving a wide variety of flow geometry, initial conditions, and forcing functions.

Jacob [1946] extended Theis' method to heterogeneous media when he published a paper on radial flow to a leaky aquifer, which opened up a fertile area of research relating to multiple-aquifer systems in groundwater hydrology and petroleum engineering. It is not quite clear whether Jacob was influenced by the land subsidence research of the 1930s. It is now well established that the study of leaky aquifer systems and the study of land subsidence in sedimentary basins go hand in hand. Also, motivated by a desire to account for the role of the well itself, *Jacob* [1947] devoted attention to hydraulic efficiency of the well, as water dynamically flows from the aquifer into the well. He defined the notion of effective well radius and the well-loss function. In accounting for well losses, Jacob accounted for nonlaminar flow conditions arising because of high flow velocities in the vicinity of well screen. Such flows are some times referred to as "non-Darcy" flows. In the field of petroleum engineering, *van Everdingen and Hurst* [1949] used the Laplace transformation to quantify the effects of well bore

storage on pressure transients around a pumping well and also accounted for skin effects arising from formation damage in the immediate vicinity of the well.

These developments in the fields of hydrogeology and petroleum engineering occurred primarily because the researchers mentioned above were interested in aquifers and reservoirs with fairly large areal extent lying at depths of a few hundred meters or more. In such formations the region of pressure perturbation around the well often extended to several hundred meters or more. However, in the fields of soil physics and civil engineering, transient flow problems of interest were of a smaller spatial scale. Soil scientists and agronomists were primarily interested in the plant root zone of the soil above the water table, which seldom exceeds a few meters from the land surface. Civil engineers and geotechnical engineers on the other hand were interested in seepage and ground settlement problems extending from a few meters to perhaps a few tens of meters. The nature of problems tackled by these researchers was such that they needed to estimate hydraulic parameters rather quickly and inexpensively. Soil physicists dealing with soils in the vadose zone not only were confronted with significant spatial variability on the scale of their observation but also had to contend with a very difficult-to-solve highly nonlinear diffusion process. The term "vadose zone" denotes the region between the water table and the land surface within which water and air coexist in the pore spaces. It is also referred to as the "zone of aeration" or the "unsaturated zone." Out of practical necessity, judicious compromise between mathematical rigor and practical need gave rise to greatly simplified models, resulting in field techniques based on infiltrometers, constant-head permeameters, auger-hole tests, and variable-head permeameters.

The auger-hole methods and piezometer methods were pioneered by Kirkham and coworkers [*Kirkham*, 1946; *Luthin and Kirkham*, 1949; *van Bavel and Kirkham*, 1948]. These methods improved the estimation of the hydraulic conductivity of the saturated soil below the water table and are still being used. Essentially, these are field adaptations of the variable-head permeameter. Although the experiment itself involves a nonsteady flow process, the interpretation logic neglects the role of hydraulic capacitance. The time-dependent falling water level is treated as a function, among other factors, of the hydraulic conductivity of the soil and a shape factor dependent on the flow geometry. Because the flow geometry involved combinations of radial, hemispherical, and vertical components of flow, a great deal of effort was spent by Kirkham and others to calculate shape factors for a variety of field conditions. Thus, calculating the shape factors using available mathematical techniques constituted an important part of developing these techniques.

As in the case of soil science, the variable-head permeameter was found to be adequately inexpensive and rapid to satisfy the hydraulic characterization needs in the field of civil engineering. Special efforts were made to systematize and standardize these methods. A widely used work in this regard was that of *Hvorslev* [1951], published under the auspices of the U.S. Army Corps of Engineers. In providing a set of shape factors for a number of field situations, Hvorslev drew upon earlier work of Dachler and others.

Richards, who formulated the nonlinear partial differential equation for flow in unsaturated soils was known for his many innovative experiments. *Richards et al.* [1956] demonstrated a method by which the hydraulic conductivity function could be estimated in the field by measuring the depth profile of gauge pressure head as well as moisture content as a function of time during redistribution of soil moisture immediately following an infiltration event. In this experiment soil moisture distribution was measured rather laboriously by a gravimetric method. A powerful and useful development of the early 1950s in the field of soil physics was the use of neutron scattering to quantitatively estimate soil moisture [e.g., *Gardner and Kirkham*, 1952]. Soon this developed into a workable field neutron probe, which continues to play an important role in the measurement of soil moisture profile in the field for research and engineering purposes. During the 1960s the field method of Richards and his coworkers was improved by other researchers by taking advantage of the neutron probe.

Another important work in soil science during the 1950s was that of *Gardner* [1957]. Because of the nonlinearity of Richards' equation, it was evident that inversion of field data on unsaturated hydraulic conductivity would not be possible unless some simple relationship between hydraulic conductivity and gauge pressure head could be assumed. On the basis of available data, *Gardner* [1957] found that over a limited range of gauge pressure, one could reasonably assume an exponential relationship between hydraulic conductivity and gauge pressure head. Gardner then went on to point out that an exponential relation helps to obtain closed-form solution for the one-dimensional problem. This work of Gardner and the work of *Philip* [1955] continue to influence present day research relating to hydraulic characterization of unsaturated soils in the field.

A significant contribution of the 1950s was the work of N. S. Boulton, a civil engineer from England. As was noted earlier, *Theis* [1935] illustrated the credibility of the transient groundwater flow equation by applying it to data gathered from an unconfined aquifer. Nevertheless, as Theis himself recognized, his method hinged on the assumption that water drains instantly from the zone through which the water table declines. However, it was recognized by many that the drainage of water from the unsaturated material above the water table, governed by the theory of capillary potential, was a time-dependent, noninstantaneous process. This time-dependent drainage is mathematically analogous to chemical disequilibrium processes such as precipitation or adsorption. Therefore it is reasonable to refer to the noninstantaneous drainage of water from the vadose zone as "kinetically controlled drainage." Some researchers felt the need to mathematically account for this noninstantaneous process. *Boulton* [1954] initiated investigation of the transient flow of water to a well in an unconfined aquifer. Instead of venturing to rigorously solve the highly complex flow process above the water table as embodied in Richards' equation, Boulton simplified the effect of the unsaturated zone by introducing the approximation of delayed yield in conjunction with the notion of specific yield. As an approximation, he assumed that drainage from the unsaturated zone was an exponential function of time. The resulting governing equation was solved for potentials within the saturated domain, while yet approximately accounting for contribution from the unsaturated zone by means of a time-dependent source term. With minor modifications and extensions, Boulton's model still continues to be used by groundwater hydrologists as the basis for estimating parameters of an unconfined aquifer.

Another important contribution of the 1950s was the work by *Skempton* [1954]. A soil mechanician, Skempton investi-

gated the relations between external stress changes (including shear) and the changes in pore fluid pressure in water saturated soils. Skempton proposed pore pressure coefficients A and B, which are related in principle to the concept of tidal efficiency proposed earlier by Jacob but which account for multidimensional deformation and pertain to the effects of mean principal stress (coefficient B) and the effects of shear stress (coefficient A). The basis for estimating the hydraulic parameters of an aquifer from passive response of wells to barometric tides, Earth tides, and ocean tides is contained in the contributions of *Jacob* [1940] and *Skempton* [1954].

Soon after the publication of *Theis'* [1935] work, groundwater hydrologists developed several approaches to interpret drawdown data as well as data on water level recovery after cessation of pumping. Although groundwater hydrologists were routinely using Theis' recovery method for over a decade, it was not until the 1950s that petroleum engineers developed methods to systematically analyze pressure buildup (or pressure recovery) data. Research in this direction was pioneered by *Horner* [1951] and *Miller et al.* [1950]. Incidentally, it appears that modern pressure transient analysis in petroleum engineering commenced after the second world war, during the 1950s.

By now, the field of groundwater hydrology had become well enough established, and a definitive textbook on groundwater hydrology was published by *Todd* [1959]. This book devoted considerable attention to groundwater hydraulics and presented a comprehensive literature on the topic. Roger de Wiest brought to the western world some of the developments in the erstwhile Soviet Union by translating *Theory of Groundwater Movement* [*Polubarinova-Kochina*, 1952].

The 1960s witnessed many and varied developments of significance to hydraulic characterization. A group of USGS groundwater hydrologists, led by Hilton Cooper, elegantly extended the Theis approach to solve many well-defined initial value problems that have since enabled hydraulic characterization under test conditions that are more general than those of *Theis* [1935]. Among these contributions one should take special notice of the interpretation of data from slug tests [*Cooper et al.*, 1967], analysis of pressure transient data from an anisotropic aquifer [*Papadopulos*, 1965], transient flow of water to a well of large diameter [*Papadopulos and Cooper*, 1967], and response of a well to seismic waves [*Cooper et al.*, 1965]. The work on seismic response showed how a well could, under certain conditions, amplify a seismic signal. Following this work, *Bredehoeft* [1967] analyzed the response of aquifers to Earth tides, giving consideration to multidimensional strains experienced by an aquifer and proposing a method for estimating the storage coefficient (hydraulic capacitance) of an aquifer. This work continues to be widely used to interpret passive response of aquifers to Earth tides.

The 1960s briefly witnessed an interest in the use of electrical analog models to analyze the transient behavior of groundwater systems, including the flow of water to wells. Although the use of electrical network models was know in other branches of science, *Skibitzke* [1963] recognized the possibility of using resistor network models to simulate the transient behavior of wells in aquifers, with electrical resistance being analogous to hydraulic resistance and electrical capacitance being analogous to hydraulic capacitance. This idea was soon pursued by researchers in USGS. *Papadopulos* [1965] used such a model to verify his analytical solution for the flow of water in an anisotropic aquifer, while *Bredehoeft et al.* [1966] used an harmonic oscillator circuit in conjunction with resistors and capacitors to simulate inertial effects of water column movements in a finite diameter well subject to periodic loading. The interest in electrical analog models soon waned with the rapid development in digital computer technology during the late 1960s.

The study of leaky aquifers, pioneered by Jacob a decade earlier, was continued with vigor by Hantush and Jacob through the 1960s. Because they were primarily concerned with groundwater as a resource, Hantush and Jacob focused attention on analysis of drawdown data from the aquifer itself and did not venture into obtaining solutions for changes in potential within the aquitards which constituted the source of leakage. *Hantush* [1964] provided a comprehensive summary of developments related to leaky aquifers as well as other aquifer configurations in the paper "Hydraulics of Wells."

The leaky aquifer problem attracted the attention of petroleum engineers from two different perspectives. On the one hand, engineers were aware of leakage of oil into reservoir rocks from leaky caprocks. On the other hand, they were also interested in the role of leaky caprocks in the context of artificial storage of natural gas in deep aquifers. In the latter case it was critical that the "integrity" of the caprock and its ability to keep the gas trapped in the aquifer be known. This necessitated a knowledge of the pressure changes in the aquitard itself rather than just the aquifer. Accordingly, *Neuman and Witherspoon* [1969] extended the leaky aquifer model of Jacob and Hantush to hydraulically characterize the aquifer as well as the aquitard.

Immediately following the discovery of land subsidence in the Santa Clara Valley [*Rappleye*, 1933; *Meinzer*, 1937] Joseph Poland of the USGS started a systematic study of land subsidence in different parts of California. Over the next four decades Poland and coworkers collected a wealth of data confirming *Meinzer*'s [1937] conjecture about the importance of fine-grained sediments in contributing to large subsidence magnitudes. Their work also established the applicability of Terzaghi's one-dimensional consolidation theory to large-scale geologic systems. *Poland and Davis* [1969] documented these observations in a classic paper. Note that from a process point of view, land subsidence is a manifestation of the hydraulic capacitance parameter.

During the 1960s the movement of oil in fractured reservoirs attracted the attention of petroleum engineers for two different reasons: the depletion of naturally fractured reservoirs and the pressure response of reservoirs stimulated by hydraulic fracturing. The analysis of flow in naturally fractured reservoirs received significant impetus from the work in the former Soviet Union of *Barenblatt et al.* [1960], who proposed a model for the dynamic, macroscopic interactions between a pervasive high-diffusivity continuum (fracture network) embedded in which are islands of low-diffusivity continua (porous rock matrix). The work of Barenblatt et al. was extended formally to the study of petroleum reservoirs with idealized fracture networks by *Warren and Root* [1963]. The conceptual basis provided by Warren and Root is still widely used in the fields of petroleum engineering and hydrogeology. The frequently referred to phrases "double-porosity systems," "dual-porosity systems," and "multiple-interacting continua" derive their existence from the work of Barenblatt et al. and of Warren and Root.

By the 1960s stimulation of low-permeability reservoirs by hydraulic fracturing had become commonplace in petroleum production engineering. Through an elegant analysis of the mechanics of hydraulic fracturing in an elastic rock, *Hubbert*

and Willis [1957] showed that massive hydraulic fractures tend to manifest themselves as planar vertical fractures or horizontal fractures depending on ambient tectonic stress conditions. It became immediately clear that such high-permeability planar fractures will profoundly perturb the radial flow field around the production well. *Prats* [1961] was among the earliest workers to investigate the effects of discrete vertical fractures on the steady flow of oil into a well. Soon the analysis was extended to transient flow conditions by *Scott* [1963] and *Russell and Truitt* [1964].

In the field of geophysics the technique of hydraulic fracturing, originally developed for petroleum reservoir stimulation, was perceived as a means of estimating in situ rock stresses through "min-frac" experiments. Drawing upon the theoretical foundations of Hubbert and Willis and of *Kiehle* [1964], *Haimson and Fairhurst* [1969] and others pioneered work in this direction.

A significant research direction of the 1960s was the development of numerical models. The era of the digital computer had dawned, and computer development was advancing with incredible rapidity. The digital computer provided the possibility of solving transient fluid flow problems in complex geological systems which are far beyond the reach of closed-form solutions. The finite element method [*Clough*, 1960], which was initially designed for solving structural engineering problems, was soon adapted to solve steady state and transient problems of groundwater flow [*Javandel and Witherspoon*, 1968]. In the field of petroleum engineering *Fayers and Sheldon* [1962] illustrated the use of a digital computer to solve fluid flow problems in three dimensions using the classical finite difference approximations. In the field of civil engineering *Tyson and Weber* [1964] presented an integral form of the finite difference method which could efficiently handle groundwater systems with complex geometry. One of the important upshots of the development of the numerical model was the effort to hydraulically characterize the field system on the basis of observed water levels in numerous wells. Hydraulic characterization is achieved by a process of trial and error adjustment of hydraulic parameters in a numerical model to best match the field data. This approach to hydraulic characterization is popularly referred to as the "inverse method." Inverse methods, stemming from this approach, continue to engage the attention of researchers today.

8. The 1970s: A Shift in Emphasis

The 1970s witnessed a shift in research emphasis among Earth scientists from issues based on resource development to issues related to environmental degradation. Research on topics introduced in the previous decades was continued, but new issues pertaining to chemical contamination began to be introduced. The delayed drainage concept of Boulton (in relation to unconfined aquifers) was questioned by *Neuman* [1972], who invoked vertical anisotropy instead of delayed drainage to account for the pressure transient behavior of unconfined aquifers. In keeping with emerging interest in environmental issues, strong research interests continued in improving methods for characterization of shallow groundwater systems and the vadose zone, in particular, slug tests, permeameters, and infiltrometers. In the field of petroleum engineering, considerable interest continued on the characterization of naturally fractured reservoirs. In order to better understand hydraulic properties of the vadose zone, *Weeks* [1978] devised a field method for evaluating pneumatic conductivity and diffusivity of the vadose zone based on transmission of barometric pressure changes from the land surface to the water table. Note that this possibility was inherent in the early work of *Buckingham* [1904].

During the 1980s groundwater contamination arising from leaky gasoline tanks of gas stations and contamination arising from the uncontrolled disposal of industrial hydrocarbons such as lubricants, transformer oils, and cleaning fluids came into unexpectedly sharp focus. Also, as a potentially serious health hazard, attention was given to the entry of radon gas into human dwellings in regions of the United States underlain by granitic rocks. In late 1987 the Congress of the United States decided that unsaturated zone disposal of high-level radioactive wastes at Yucca Mountain in Nevada would be the preferred geologic disposal alternative and that detailed site characterization studies should be carried out there before licensing. As a result, there has been a great impetus among researchers to develop techniques for characterizing the hydraulic properties as well as the pneumatic properties of the vadose zone.

Until the 1980s hydraulic characterization of soils by agricultural engineers was by and large limited to measuring the saturated hydraulic conductivity below the water table using auger hole tests, piezometer tests, and permeameter tests pioneered by Kirkham and others. The 1980s saw notable effort among soil physicists to apply already established theoretical results to devise instruments and methods to estimate hydraulic characteristics of unsaturated soils in the field. The theoretical basis for these efforts was already implicit in the studies of *Childs and Collis-George* [1950], *Philip* [1955, 1956], *Gardner* [1957], and others. The Guelph permeameter [*Reynolds and Elrick*, 1985] was a constant-head permeameter designed for small unlined boreholes a few meters deep and designed to estimate saturated hydraulic conductivity as well as the matric flux potential. The latter is an integral of the unsaturated hydraulic conductivity, between the limits of ambient pressure head in the vicinity of the borehole and zero pressure head. The 1980s also saw the development of disc tension permeameters [*Clothier and White*, 1981; *White and Perroux*, 1987; *Perroux and White*, 1988]. Designed for measuring the vertical hydraulic conductivity of the soil at the land surface, this instrument was especially designed to apply a constant moisture tension boundary condition at the land surface to enable infiltration at a water potential less than atmospheric. The disc permeameters were used in infiltration experiments carried out on the basis of the theoretical analysis of infiltration from circular ponds and under prescribed moisture suctions imposed at the disc at the land surface and measuring the infiltration rates. In essence, these are constant-head permeameters, except that a constant moisture suction is imposed. Interpretation of data is incumbent on several idealizations; for example, it is often assumed that hydraulic conductivity is exponentially related to moisture suction. In addition to saturated hydraulic conductivity, the disc permeameters enabled the estimation of sorptivity. In systems involving one-dimensional infiltration, sorptivity is a measure of the quantity of moisture absorbed by a one-dimensional column as a function of the square root of time.

The 1980s also saw active research designed to understand the role of water in influencing natural earthquakes. To aid in the interpretation of these field experiments, researchers extended *Bredehoeft*'s [1967] work to interpret the response of aquifers to barometric tides, Earth tides, ambient changes in tectonic stresses, and earthquakes.

The past 25 years have witnessed significant changes in the motivation for hydraulic characterization as well as the approaches used for the purpose. Interest in resource development has been accompanied by an increasing interest in mitigating and preventing the contamination of natural resources. There has been a growing desire to identify geological formations of very low hydraulic conductivity in which toxic wastes can be safely disposed. As a consequence, topics such as leaky aquifers and unconfined aquifers have gradually receded from researchers' focus of attention. Interest has been steadily growing in characterizing flow processes in the vadose zone, which mediates between the wastes deposited at the land surface and the water table at depth. Methods are being developed to quantify the movement of air, gases, and vapor through the vadose in addition to moisture movement. The dynamic coupling between gases in the vadose zone and atmospheric pressure changes is proving to be of considerable practical interest. To gain an understanding of local flow fields which control dispersion of contaminants, sensitive flowmeters are used by some researchers to get a profile of flow velocities with depth in boreholes and wells.

Major multimillion dollar hydraulic characterization ventures have been supported by the U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Environmental Protection Agency (EPA), and others to hydraulically characterize heterogeneities in simple aquifers, in fractured rock systems, and in unsaturated media. Current emphasis is on characterizing the details of heterogeneity at different scales because such detailed information is necessary for quantifying the migration of contaminant plumes. As attempts are made to physically describe the heterogeneities in greater and greater detail, it is being realized that the traditional methods based on the differential equation are inadequate. For example, attempts to characterize fractured rock systems through interference tests and tracer tests have shown that on the scale of observation carried out, these systems can hardly be treated as homogeneous media.

9. Concluding Remarks

Presently, hydrogeologic systems are studied by researchers with interests varying widely, from the shallow soils in which plant roots thrive to the oceanic crust beneath the deep oceans in which hydrothermal fluids circulate. The motivation for these studies vary from engineering design to pure curiosity. To study these systems, field instruments of great sophistication (e.g., pressure transducers, sensitive flowmeters) of unprecedented precision have been fabricated. Automatic data loggers enable us to acquire data at frequencies of less than a second. Powerful desktop computers enable us to collect, store, retrieve, and rapidly manipulate enormous amounts of data. Yet it is reasonable to state that our ability to interpret data lags behind our ability to collect them. It is not uncommon to collect data at great expense and interpret the same with extremely simplified models, doing little justice to the system complexities, for no reason other than that no other methods of analysis are available. Or vast amounts of data may be gathered and simply stored because necessary resources and time are not available for interpretation.

The traditional basis of our data interpretation, the partial differential equation, is a statement of physical processes of cause and effect which are related through the model parameters. As we continue to use this model for hydraulically characterizing subsurface flow systems, we are confronted with, on the one hand, questions pertaining to the intrinsic worth of the cause-effect model itself and, on the other hand, questions relating to the information that is fed to the model for purposes of analysis. In the present work we have restricted ourselves to data inversion from hydraulic tests on systems with explicitly defined heterogeneities (e.g., leaky aquifers, double porosity systems). Each material component has been assumed to be homogeneous on the scale of observation. We do not concern ourselves with pervasive heterogeneities within a homogeneous medium, information on whose geometric attributes are not known in sufficient detail.

Because the concepts of homogeneity, geometry, and continuity are essential for properly posing a problem with the differential equation, one has to set up one separate differential equation for each of the components in a heterogeneous system and couple them together at the interfaces between the components. Thus, for each component of the heterogeneous system, we must have an appropriate macroscopic scale in which the component can be considered homogeneous so that macroscopically defined parameters have physical meaning. In the case of hydraulic tests (be it a disc tension permeameter on the soil surface or an interference test between wells separated by kilometers) the scale is dictated by the scale of the experiment and the geometric details of the system are taken to be known at that scale based on geological, geophysical, and other information. Therefore one of the intrinsic limitation of our methodology is that field data cannot be inverted to estimate parameters on a smaller scale for which geometric details are lacking. Even when geometric details of the flow system are known on the scale of the field test, nonuniqueness of the estimated set of parameters is often to be expected because the number of parameters to be estimated may exceed the number of observation sites at which observations have been made. Finally, devices such as boreholes and wells, which enable the measurement to be made, themselves disturb the natural system and fundamentally influence the measurement that is being made. In order that the intrinsic hydraulic properties of the formation are evaluated, the masking influence of the influence of the device on the measurement must be carefully removed.

Looking purely from the viewpoint of science, it may appear as though what stands between us and satisfactory characterization is adequate data. Often we are limited by resource availability for data gathering, be it a research venture or engineering venture. Even in those situations where sufficient resources are available, one must consider whether the wells or boreholes themselves may compromise the integrity of the site. Constrained by these practical concerns, we need to recognize that the Earth's subsurface is difficult to access. Consequently, our methods of hydraulic characterization are only capable of yielding estimates, and we function on the reasonable premise that the estimates become more reasonable with better information and fewer assumptions in the interpretation process.

Insofar as interpretation of data from field hydraulic tests is concerned, we can hope to improve over our traditional approach of fitting the data to analytic solutions. As we have noted, the flow system has to be considerably idealized before particular solutions can be obtained for the partial differential equation. Numerical models have certainly arrived at a point at which the configuration of a field test can be given full consideration in a numerical model, thereby minimizing the assumptions that otherwise go into an analytic solution. With the availability sophisticated graphics softwares, numerical models have the potential of helping us design complex field experi-

ments, the data from which can be inverted in a credible fashion. Also, if modern tomographic methods that are being developed in the field of geophysics are successful, we may in fact have access to hitherto unavailable geometric detail which can be very valuable in data inversion.

Currently, the issue of heterogeneity pertaining to hydraulic conductivity is particularly in focus among many researchers. This interest has arisen because of the nature of certain field problems engaging the attention of these researchers (e.g., efficient application of irrigated water to the roots of cultivated crops, the prediction of the behavior of contaminant plumes, and the secondary recovery of oil by water flooding). It is worth noting here that hydraulic conductivity is only one of the two parameters of fundamental importance in dynamic subsurface flow systems. Hydraulic capacitance is an equally important parameter. Indeed, we cannot conceptualize the transient groundwater flow system without introducing hydraulic capacitance. The timescale of response of a groundwater body is dictated by its diffusivity, which is hydraulic conductivity divided by specific hydraulic capacity. By excessively focusing attention on hydraulic conductivity, one may overlook transient phenomena that are of great intellectual and practical interest.

Passive monitoring of the response groundwater systems to changes in barometric pressures, earth tides, ocean tides and changes in tectonic stresses can yield information of great value about the hydraulic capacitance as well as the hydraulic conductivity of the system. With the availability of electronic data loggers, passive monitoring can be used to great advantage in gathering information which is distinct from and complementary to information gathered from conventional hydraulic tests. Much remains to be done to systematize the interpretation of these data. It is even likely that long-term passive monitoring may yield information on the gradual change in system properties over long periods of time.

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T. N. Narasimhan, Department of Materials Science and Mineral Engineering, University of California, 467 Evans Hall, Berkeley, CA 94526. (e-mail: tnnarasimhan@lbl.gov)

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Determination of Hydraulic Characteristics and Yield of Aquifers Underlying Vekol Valley, Arizona, Using Several Classical and Current Methods

By JAMES R. MARIE and KENNETH J. HOLLETT

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.59	square kilometer
acre-foot (ft)	0.001233	cubic hectometer
million gallons (Mgal)	3785.0	cubic meter
gallon per minute (gal/min)	0.06309	liter per second
gallons per day (gal/d)	0.003785	cubic meters per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute per foot [(gal/min)/ft]	0.207	liter per second per meter
foot squared per day (ft^2/d)	0.0929	meter squared per day

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Determination of Hydraulic Characteristics and Yield of Aquifers Underlying Vekol Valley, Arizona, Using Several Classical and Current Methods

By James R. Marie *and* Kenneth J. Hollett

Abstract

Extensive hydrologic investigations were conducted in south-central Arizona during the late 1970's and early 1980's pursuant to the Ak-Chin Indian Community Water Rights Settlement Act, Public Law 95-328. The Act directed the Secretary of the Interior to deliver a permanent water supply of 85,000 acre-feet annually to the Ak-Chin Indian Reservation no later than 25 years from the date of the enactment—July 28, 1978. The Act further directed that if sufficient ground water was available beneath Federal Lands near the Reservation to meet the emergency needs of the Community, a well field and pipeline would be constructed to deliver 30,000 acre-feet of water annually. Initial studies by the U.S. Geological Survey indicated that the emergency supply could be obtained from several large tracts of nearby Federal land. The Secretary selected Vekol Valley as the area to be developed and directed that the well field and pipeline be built.

The investigation to obtain the required information to construct the well field and pipeline in Vekol Valley began during 1981 and was conducted in two phases. The first phase was limited to the north part of the valley, which is closer to the Reservation, to determine if the total amount of water required could be produced from that area. The investigation included an extensive well-drilling program. Nineteen boreholes, including two continuous-core holes, ranging in depth from about 200 to 3,000 feet were drilled at 10 sites. Most of the holes were drilled through the entire aquifer system and into the underlying bedrock. Three of the holes were completed as 18-inch production wells, fourteen as smaller-diameter water-level observation wells, and two as heat-flow monitoring wells. Tests were conducted on all wells, including one 23-day aquifer test. A ground-water recharge experiment was conducted in conjunction with this aquifer test.

Analysis of test information for the upper, unconfined aquifer gave hydraulic property values for transmissivity of about 13,500 feet squared per day, specific yield of about 0.12, and a ratio for vertical to horizontal hydraulic conductivity of about 1:12. For the most conductive zone in the lower, confined aquifer, the analysis gave a transmissivity of about 2,000 feet squared per day and a storage coefficient of about 4×10^{-4}. Analysis of data obtained during the recharge experiment produced infiltration rates for an ephemeral channel that ranged from about 0.64 to 1.09 cubic feet per second per 1,000 feet of channel length. Vertical hydraulic conductivity values calculated for the underlying material using these steady, channel-infiltration rates ranged from about 2.9 to 7.1 feet per day. The value calculated from the aquifer test data was about 2.2 feet per day. Time required for water to move vertically through the underlying 330-feet thick unsaturated zone to the water table was about 4 days. The results obtained from all these tests were used in a ground-water flow model to evaluate various well-field designs and pumping scenarios. A description of the model and the results of the

evaluations were published in an earlier, companion report by Hollett and Marie, 1987. During the evaluation, it was determined that the entire emergency water supply of 30,000 acre-feet could not be obtained from the northern part of Vekol Valley; consequently, the investigation was expanded to include the southern part.

The investigation of south Vekol Valley also included an extensive well-drilling program. Twenty-one holes ranging in depth from about 200 to 2,000 feet were drilled at 14 sites. Six continuous-core holes were drilled, two through the entire aquifer system and into the underlying bedrock. Most of the other holes also were drilled through the entire aquifer system. Thirteen wells, including four large-diameter production wells and nine water-level observation wells, were installed. These wells ranged from 2 to 26 inches in diameter and from about 200 to 2,000 feet deep. Two vertical extensometers were installed to measure anticipated compaction of the aquifer system that would be caused during the planned 30-year pumping period. Tests were conducted on all wells installed, including two aquifer tests, one for about 9 days of pumping and the other for 21 days. All available wells were used to monitor water-level changes during the aquifer tests. Analyses of the tests show that the aquifer system underlying south Vekol Valley has a transmissivity of about 9,000 feet squared per day and a storage coefficient of about 3×10^{-4}. The test results exhibit characteristics of a leaky, confined aquifer system with a ratio of vertical to horizontal hydraulic conductivity of about 1:60. The 21-day test created locally unconfined conditions in the aquifer system, and a specific yield of about 0.12 was estimated. Pumping from the proposed well field also will cause the conversion from confined to unconfined conditions. On the basis of the results of investigations of Vekol Valley, it was concluded that the 30,000 acre-feet of water required annually to meet the emergency needs of the Ak-Chin Indian Community could be obtained from the aquifer system underlying the valley.

INTRODUCTION

The Ak-Chin Indian Community Water Rights Settlement Act, Public Law 95-328, enacted by the Congress of the United States on July 28, 1978, directed the Secretary of the Interior to deliver a permanent water supply of 85,000 acre-ft/yr of water to the Ak-Chin Indian Reservation no later than 25 years from the date of the enactment. The Settlement Act further directed the Secretary of the Interior to determine if sufficient ground water was available beneath Federal Lands near the Reservation to meet the interim, emergency needs of the community—about 30,000 acre-ft/yr—until the permanent supply could be provided. The Settlement Act also stated that if sufficient quantities of ground water were available that a well field and pipeline would be constructed to deliver the emergency supply.

Initial work to determine if the interim, emergency supply could be obtained near the Ak-Chin Community was started in late 1978 and the resulting studies by Wilson (1979) and Matlock (1981) indicated that the emergency supply could be obtained. On the basis of these studies and other information, the Secretary of the Interior selected Vekol Valley as the area to be developed and directed that the well field and pipeline capable of delivering the emergency supply be constructed. The tests described in this report were conducted in Vekol Valley, Arizona, by the U.S. Geological Survey in cooperation with the U.S. Bureau of Indian Affairs and the Ak-Chin Indian Community to fulfill part of the requirements of the Ak-Chin Indian Community Water Rights Settlement Act.

Purpose and Scope

To fulfill the Secretary of Interior's directive, work was begun during 1981 to design and construct the well field and pipeline to develop and deliver the emergency water supply. To determine whether sufficient water could be developed to satisfy the entire emergency supply from the aquifer systems underlying Vekol Valley, a series of carefully designed and planned aquifer and well tests were conducted in the valley. These tests were used to determine, as accurately as possible, the hydraulic characteristics of the units that comprise the two aquifer systems underlying the valley. These tests and their results are documented in this report.

The objectives of the initial phase of this investigation were to: (1) determine the geologic and hydraulic characteristics of the aquifer systems underlying Vekol Valley to determine whether the emergency supply could be developed in the valley, (2) develop and test preliminary well designs that would efficiently produce the maximum quantity of water consistent with the hydraulic characteristics of the aquifer system, (3) provide the information necessary and then actually construct a ground-water flow model that would be used to show the effects of various alternative well-field designs, and (4) complete the preliminary design of the well field and pipeline that could produce and deliver the amount of water required to satisfy the emergency needs of the Ak-Chin Community.

This investigation of Vekol Valley was conducted in two phases. The first phase was limited to the northern part of the valley, which is closer to the Ak-Chin Reservation, to determine whether the aquifer system underlying this area could be developed to supply the emergency water needs of the Community. When it was determined that the entire, emergency supply could not be developed from the northern part of Vekol Valley, the study was expanded to include the southern part of the valley.

The results obtained from test drilling and aquifer tests, combined with information gained from a concurrent recharge experiment, also described in this report, provided the basic hydraulic information essential to defining the extent of the aquifer systems underlying Vekol Valley and their capability to supply the water required to meet the stipulations of the Ak-Chin Indian Community Water Rights Settlement Act. The results described in this report were also used in a companion study and report describing the ground-water flow simulations of the aquifer-system response to the planned pumping in the northern part of Vekol Valley (Hollett and Marie, 1987).

Study Area

Vekol Valley is in south-central Arizona about 40 mi south of Phoenix and 30 mi east of Gila Bend (fig. 1). The north-trending valley is about 25 mi long and extends from the Cimarron Mountains on the south to the Booth Hills on the north. The valley is bounded on the east by the Table Top and Vekol Mountains and on the west by the Maricopa and Sand Tank Mountains. The mountains average about 2,500 ft in altitude and have isolated peaks that exceed 4,000 ft. Vekol Wash, an ephemeral stream, flows from south to north through the valley.

Vekol Valley is divided into two distinct areas by a low, east-west ridge that extends partly across the middle of the valley. South of the ridge, the valley is a broad, flat, almost circular basin about 12 mi in diameter. This southern part lies at an altitude of about 2,000 ft and slopes gently to the north at less than 10 ft/mi. The center of the basin generally is covered with low grass. The side slopes are covered by sparse desert vegetation. North of the ridge, the valley is only about 5 mi wide, and the valley floor has a steeper slope to the north of about 35 ft/mi. Desert vegetation, although sparse, is much more abundant in the northern part of the valley. About one third of the southern part of the valley is part of the Tohono O'Odham (previously named Papago) Indian Reservation. Most of the remaining land in the valley is Federally owned.

The climate of the valley is semiarid with precipitation about equally divided between local, summer thunderstorms and regional winter storms. The annual precipitation averages about 7 in. The potential evaporation rate is about 10 times that amount. Runoff occurs mainly as sheetflow and floods of short duration.

Geologic Framework

Vekol Valley is a north-south trending structural trough bounded by block-faulted mountains and partially filled with sediment that was eroded from the mountain blocks (fig. 2). The valley is divided into two distinct areas by a low, east-west-trending ridge that lies across the middle of the valley. This low ridge is the surface expression of several smaller uplifted structural blocks comprised of early Proterozoic metamorphic rocks that crop out near the center of the valley (fig. 1). On the basis of geologic mapping, core and drill-hole information, and geophysical information, several significant differences exist between the northern and southern parts of the valley.

North of the ridge, the structural trough is composed of many relatively small blocks that form a stair-step surface that deepens from north to south (figs. 3 and 4). Near the northern end of the valley, several of the blocks are exposed at the surface along

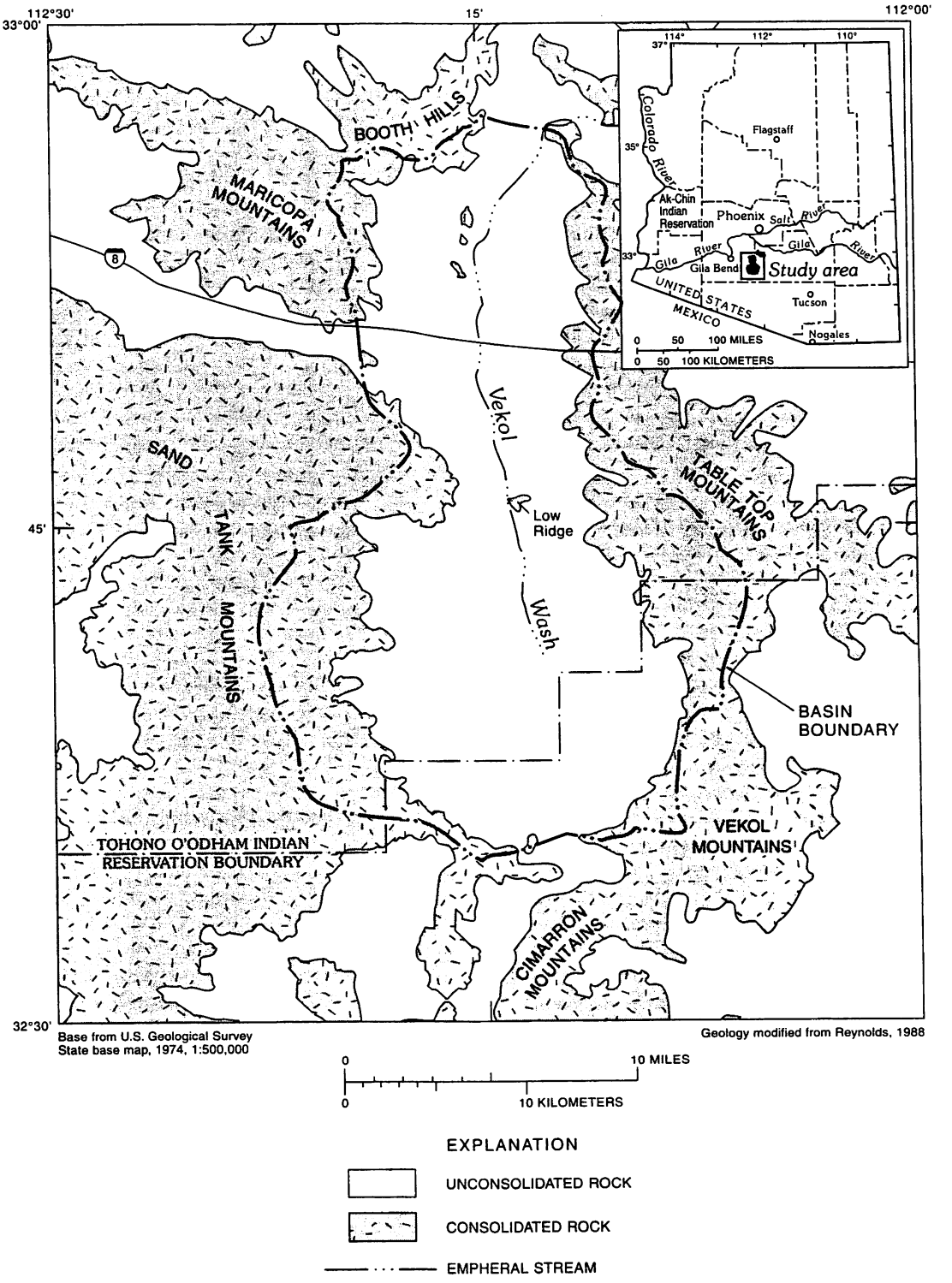


Figure 1. Location of Vekol Valley, south-central Arizona.

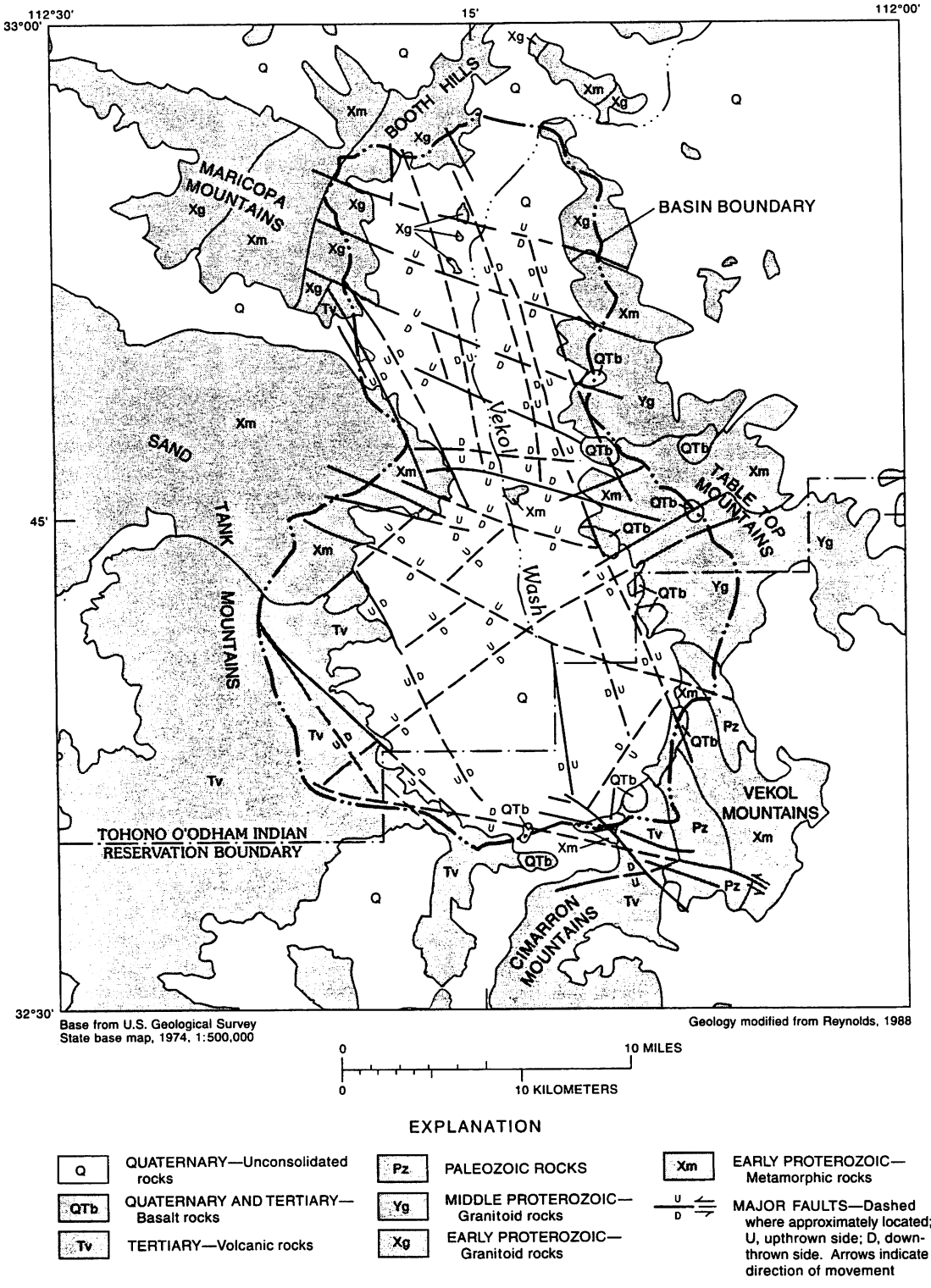


Figure 2. Generalized geology of Vekol Valley.

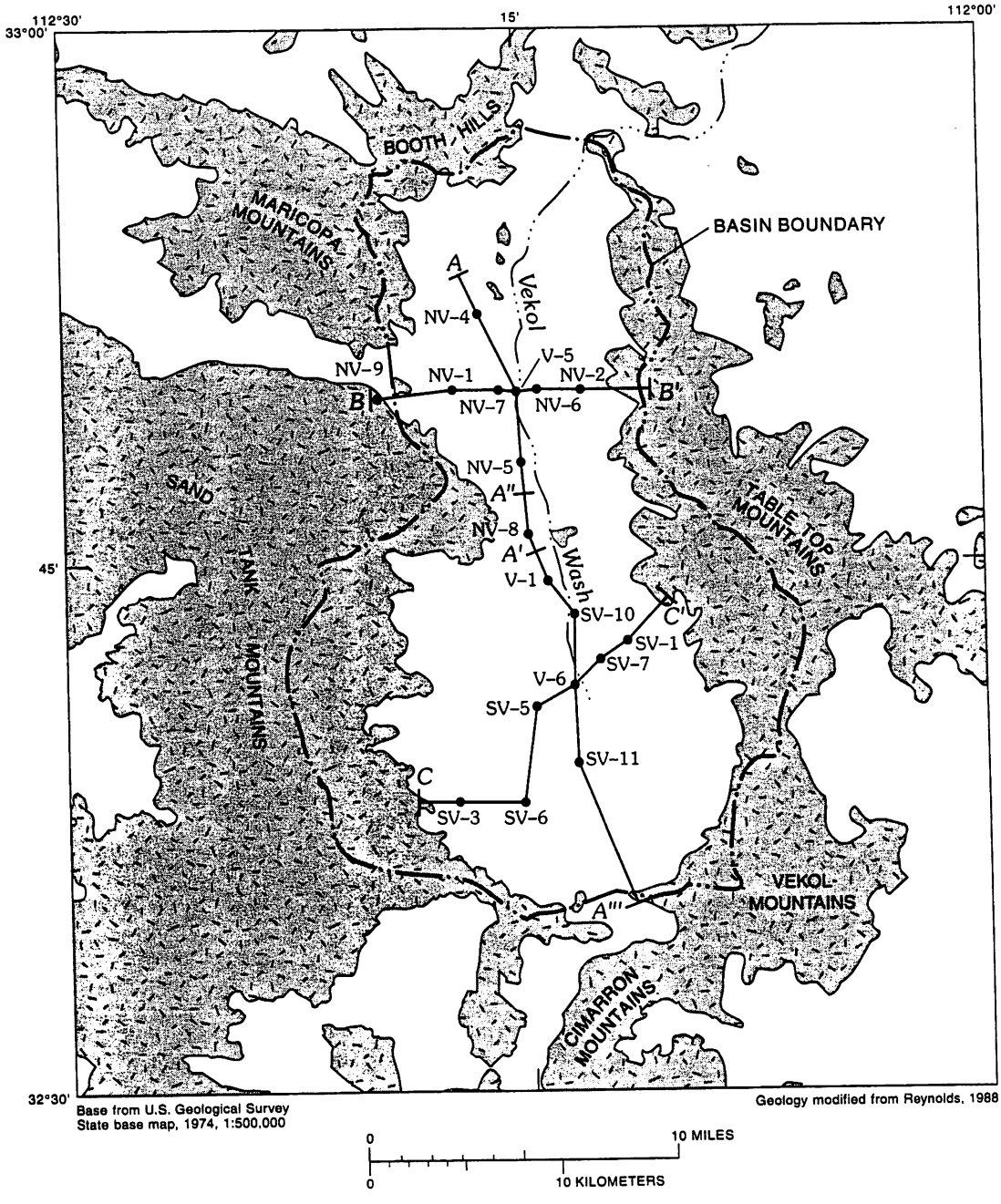


Figure 3. Location of wells or well sites and traces of hydrogeologic sections in Vekol Valley.

the center of the valley. However, immediately north of the low ridge, the tops of the down-faulted blocks lie at a depth of about 3,000 ft. South of the low ridge, the trough is almost circular and appears to be composed of fewer, but larger blocks that are progressively deeper from the edge of the trough toward its center. The tops of the deeper blocks were not encountered during drilling in the southern part of the valley. On the basis of these drill-hole data, however, it is inferred that the depth to the tops of these blocks exceeds 2,000 ft. Interpretation of geophysical data (Davis, 1984) indicate that the depth to the tops of the blocks that underlie the south-central part of the valley is at least 3,000 ft.

North of the low ridge, the basin-fill deposits (figs. 4*A* and 4*B*) are composed of a thick sequence of unconsolidated sand and gravel that grades to a well-cemented conglomerate with depth (Hollett and Marie, 1987). A sequence of volcanic rocks is intercalated with the conglomerate that overlies the older sedimentary, igneous, and metamorphic rocks. The total thickness of these sedimentary and intercalated volcanic rocks is about 3,000 ft in the area immediately north of the low ridge (fig. 4*A*). These younger rocks can be divided into four units (figs. 4*A* and 4*B*). Unit 1 is composed of unconsolidated sand and gravel that ranges in thickness from about 400 ft on the north to about 1,400 ft on the south. Unit 2 is a moderately to well-consolidated conglomerate that ranges in thickness from 0 to about 400 ft. Unit 3 is an unconsolidated to moderately consolidated silty sand, sand, and gravely sand with intercalated conglomerate that ranges in thickness from 0 to about 400 ft. Unit 4 is a thick sequence of conglomerate and intercalated volcanic rocks that ranges in thickness from 0 to about 1,800 ft. The wide range in thickness of some of these units is due to the faulting and subsequent, complex erosion and deposition that characterizes this area of the Basin and Range province.

South of the low ridge, the basin-fill deposits include a thick sequence of silt, sand, and gravel units (figs. 4*C* and 4*D*) deposited in a structurally controlled trough. These deposits also were divided into four units. Unit A is a thin, less than 200-foot thick, silty to sandy gravel. Unit B is a silt to sandy silt that ranges from a few feet thick around the perimeter of the basin to about 600 ft thick near its center. Unit C is a sequence of sand-and-gravel units that grades from unconsolidated to well cemented with depth similar to those units in the northern part of the valley. Unit C has a maximum thickness of about 1,200 ft. Unit D is a gravel and conglomerate that is about 1,000 ft thick in the central part of the valley. Unit D is not present in the northern and northwestern parts of the southern valley. Underlying Unit D in much of the southern valley and, at least in part contemporaneous with it, is a sequence of volcanic rocks that are as much as 900 ft thick. The volcanics, like the overlying conglomerate are not present in the northern part of the southern valley. In the northwestern part of the valley, however, the volcanic rocks are about 700 ft thick where the conglomerate is not present.

At several sites in the southern part of Vekol Valley, various rock units of Paleozoic age were encountered during drilling. Rocks of Paleozoic age were not found in the northern part of the valley.

AQUIFER SYSTEM UNDERLYING NORTH VEKOL VALLEY

The aquifer system underlying the northern part of Vekol Valley exists primarily in the thick sequence of sand-and-gravel units. The ground-water resource of the area is the water stored in these units. Compared to the amount of recoverable ground water in storage—about 350,000 acre-ft—the annual average amount of water that enters, moves through, and leaves the aquifer system is small—only about 1,200 acre-ft (Hollett and Marie, 1987, p. 20).

The sand, gravel, and conglomerate units grade from unconsolidated to well cemented with depth in the trough. The upper units contain two aquifers: (1) an upper, unconfined aquifer that ranges in thickness in the central 12-square-mile area of the valley from about 550 to 650 ft; and (2) the most productive zone in the lower, confined aquifer that ranges in thickness from about 50 to 300 ft. These aquifers are separated by a well-cemented conglomerate that ranges in thickness from about 210 to 300 ft.

Depth to ground water in the northern part of the valley ranges from about 270 to 430 ft. The direction of ground-water movement generally is from the mountains surrounding the valley on the east and west toward the center of the valley and then toward the north along the axis of the valley to the outflow area between the Booth Hills and the Table Top Mountains (fig. 5). Water level in the upper aquifer is a few feet higher than in the lower aquifer around the edge of the valley, showing downward movement of water

from the upper to the lower aquifer in these areas. Water levels are about the same in both aquifers in the central part of the valley. Water level in the lower aquifer is slightly higher than it is in the upper aquifer in the northern part of the valley, showing upward movement from the lower aquifer in the outflow area.

TEST HOLES AND WELLS INSTALLED IN NORTH VEKOL VALLEY

From 1978 to 1984, an extensive well-drilling program was undertaken in Vekol Valley. Nineteen holes that ranged in depth from about 200 to 3,000 ft

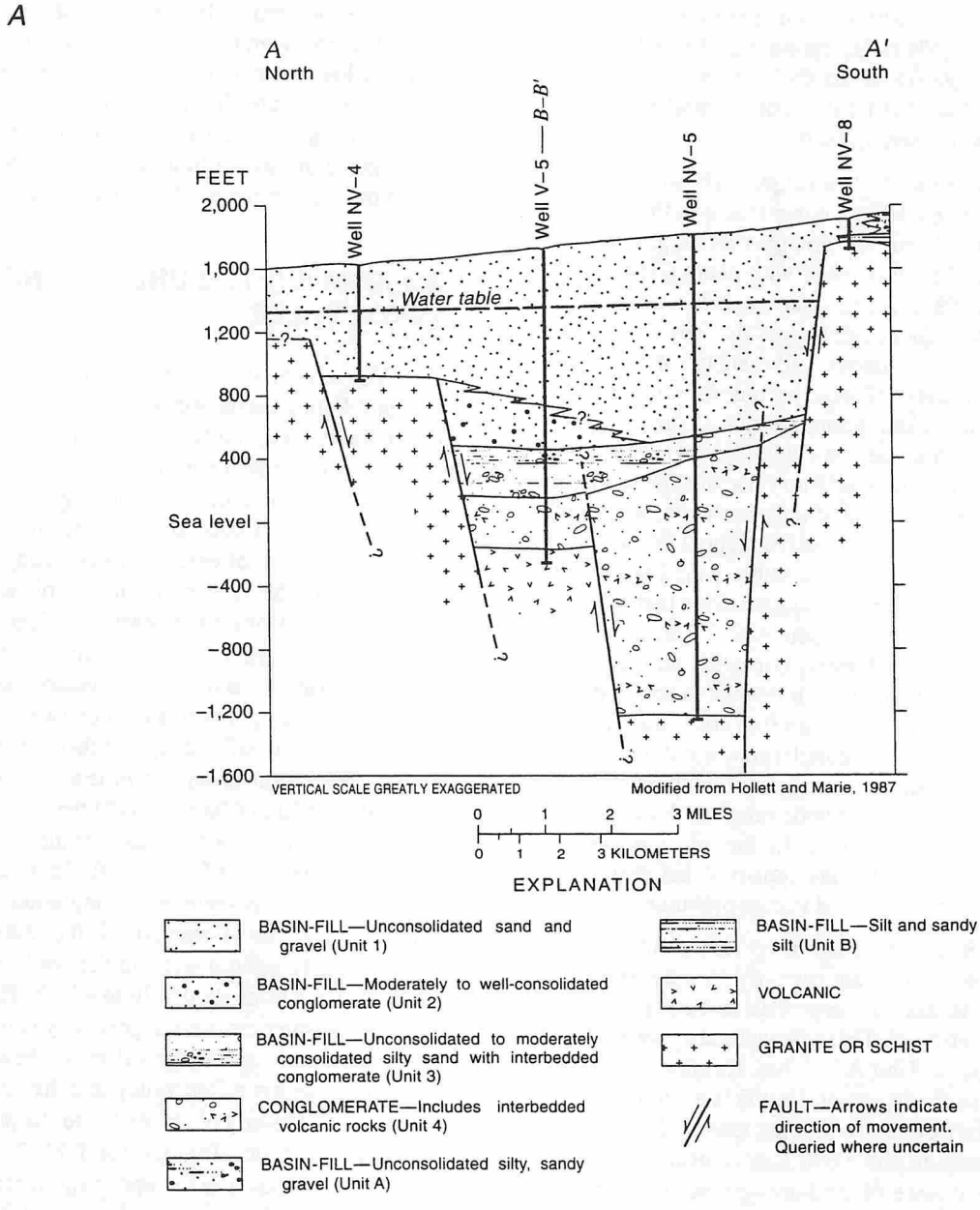


Figure 4. Hydrogeologic sections of Vekol Valley. *A*, Section *A–A'*; *B*, Section *B–B'*; *C*, Section *A"–A"'*; *D*, Section *C—C'*. (Traces of sections shown on fig. 3.)

were drilled at 10 sites in or near the northern part of the valley (fig. 6). The 19 holes included 2 core holes that were drilled through the entire aquifer system and into the crystalline basement rock—one to a depth of 1,553 ft, and the other to a depth of 2,000 ft. The core holes were drilled using continuous wireline coring tools and a combination of biodegradable polymer and bentonite mud. Core recovery from these holes was better than 90 percent. All holes for observation wells (table 1) were drilled using rotary methods and biodegradable polymer mud. All production wells (table 1) were drilled in stages using rotary methods and biodegradable polymer mud or using compressed air and foam for the initial stages and biodegradable polymer mud for the final stages.

Core hole NV–6c was completed as a water-level observation well and as a heat-flow monitoring tube. Core hole NV–7c was designed specifically as a heat-flow monitoring tube by cementing 1,981 ft of sealed, 1–3/4-inch-diameter pipe into the hole. Wells

B

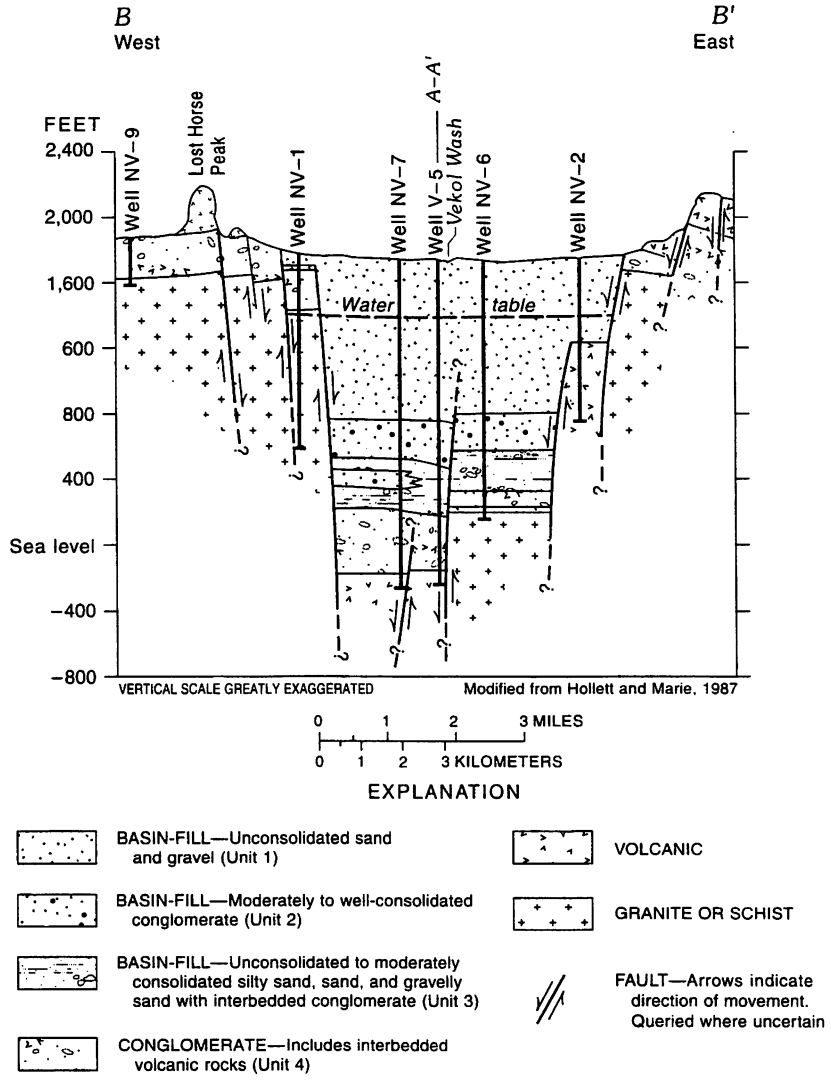


Figure 4. Continued

installed in the remaining 17 holes were fully developed and tested and included 4 production wells and 13 observation wells. Some of the wells are screened throughout the aquifer system, and some are screened only in specific aquifers. Most of the wells were finished using wire-wrapped, high-flow, stainless-steel screen and gravel packs. The wells ranged in diameter from 2 to 26 in. and in depth from about 200 to 2,000 ft. An aquifer test was conducted using well NV–6p as the pumping well. All other available wells (fig. 6) were used as water-level or heat-flow observation wells during this test. The well numbers

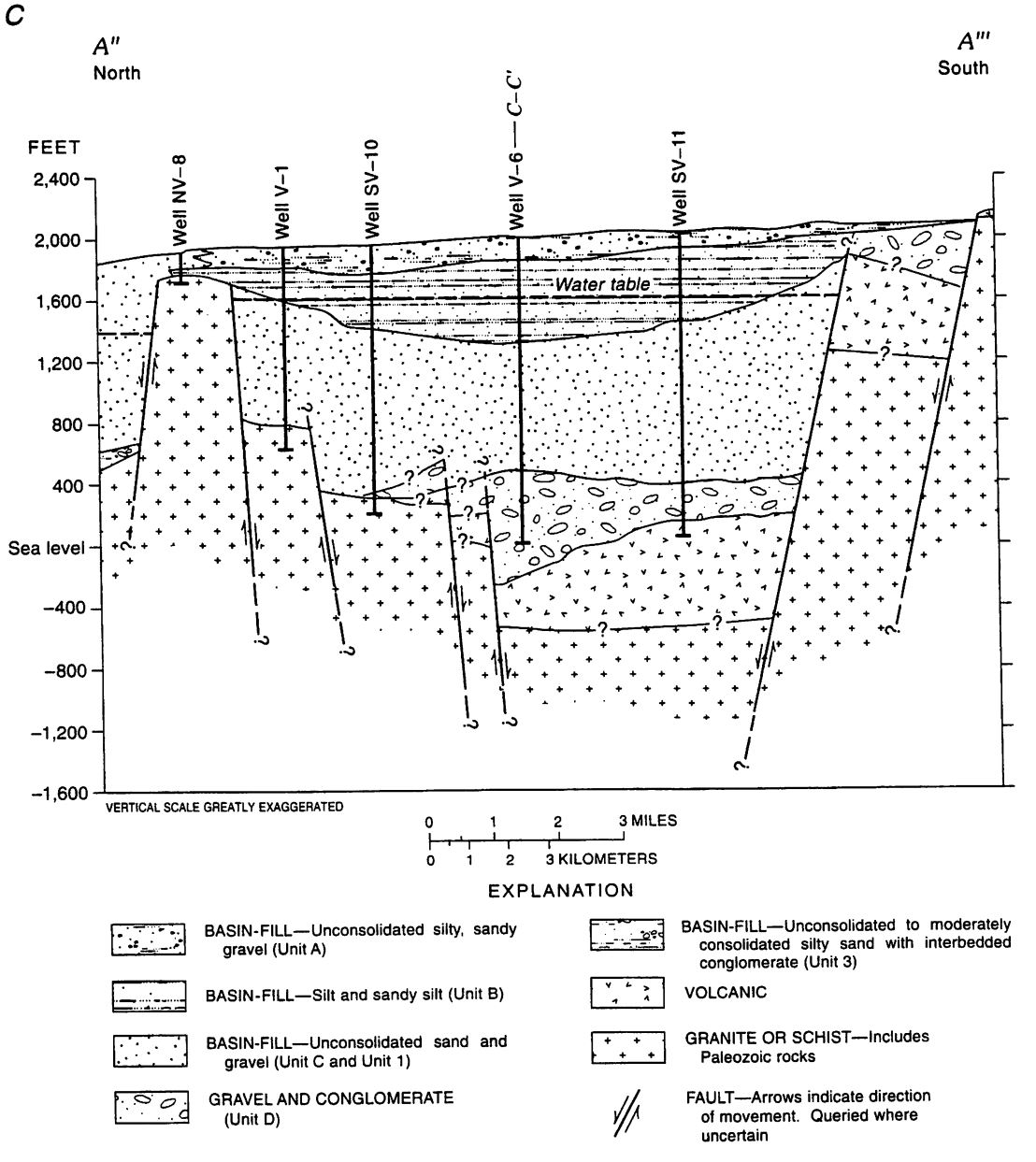


Figure 4. Hydrogeologic sections of Vekol Valley. *A*, Section *A–A'*; *B*, Section *B–B'*; *C*, Section *A"–A'''*; *D*, Section *C–C'*. (Traces of sections shown on fig. 3.)

and descriptions of the wells and the heat-flow tube are listed in table 1, locations of the 10 drill sites are shown on figure 6, and construction information for 11 selected wells is shown in the section entitled "Well-Construction Information" at the back of this report.

WELL DEVELOPMENT AND TESTS

All wells installed in the northern part of Vekol Valley were developed shortly after construction using a combination of jetting, surging, and pumping. Acceptance tests were then performed on all of the

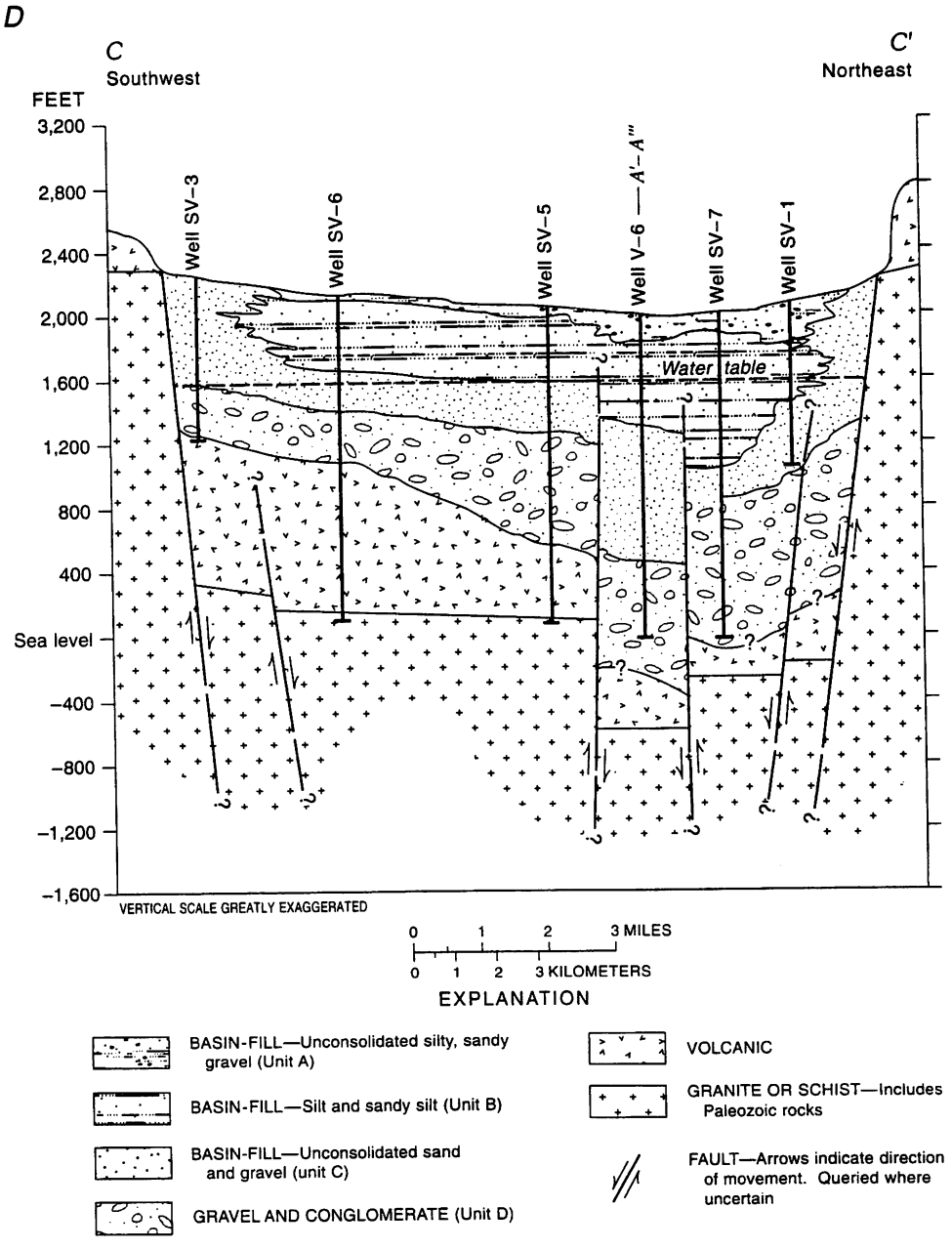


Figure 4. Continued

observation wells to ensure that each was open to the aquifer and would produce a specified, minimum quantity of clear water.

Additional tests consisting of a constant-discharge drawdown and recovery test or, in selected cases, a step-discharge drawdown and recovery test were then performed on all observation wells except NV–2. These tests were conducted to determine the specific capacity of each well, to estimate the efficiency of selected wells, and to estimate aquifer transmissivity. Well NV–2 was not tested because the aquifer underlying the site was too thin to provide useful information. All other observation wells, except NV–3, were tested using a submersible

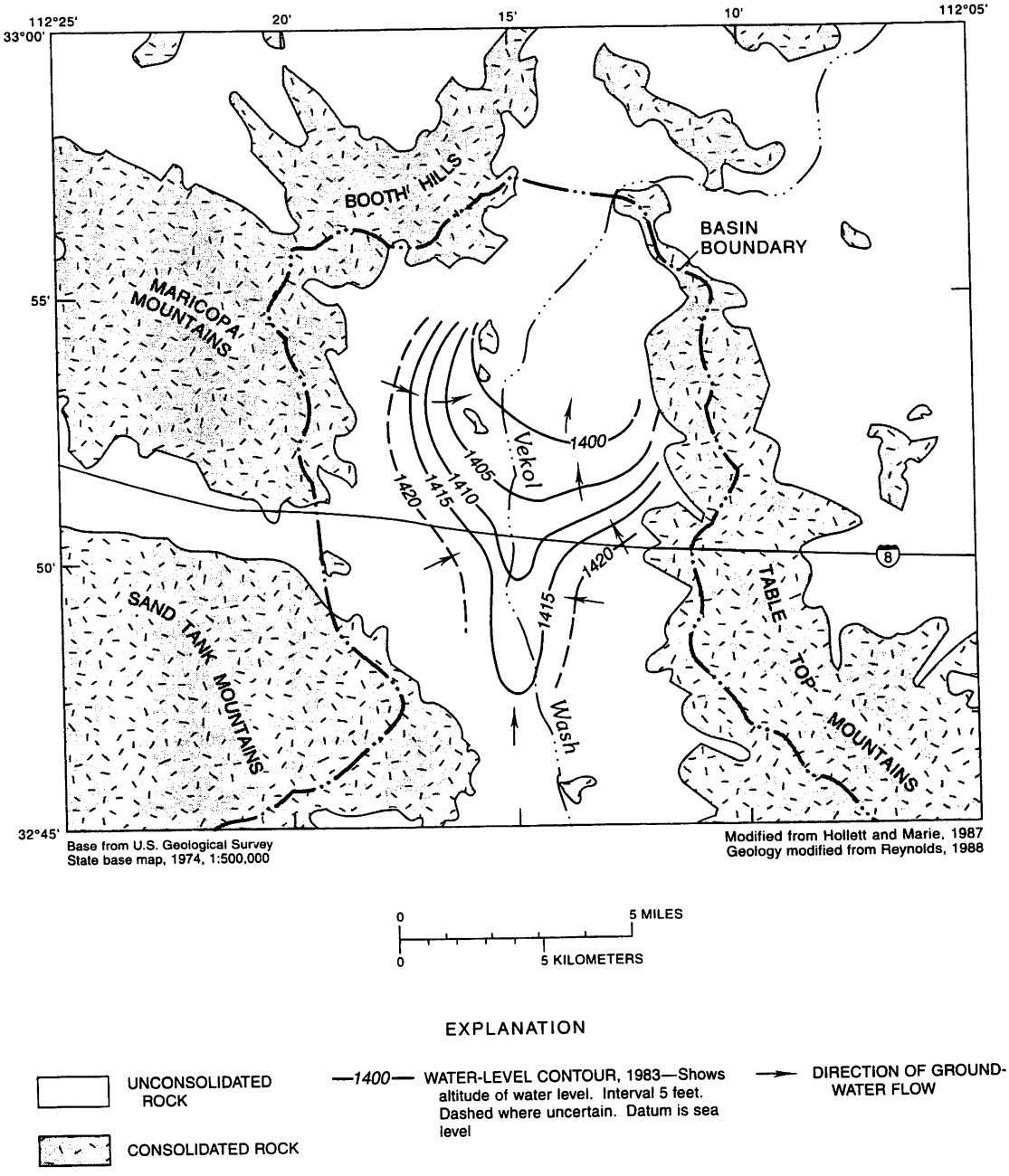


Figure 5. Configuration of the water table in north Vekol Valley, 1983.

pump rated at about 250 gal/min against a head of 600 ft. Well NV–3 was tested using a pump rated at 35 gal/min against a head of 500 ft. The actual pumping rates attained for these tests ranged from about 10 to 260 gal/min, and the tests ran from about 25 to 200 minutes depending on the depth to water, the diameter of the well, and the aquifer in which the well was completed. Water levels were measured during these tests using an electric sounder. Discharge rates were measured using an orifice plate or a calibrated orifice bucket.

The three large-diameter production wells (NV–5, NV–6p, and NV–7) were tested using a diesel-driven multistage turbine pump rated at 3,500 gal/min against a head of 600 ft. The tests of each of these wells consisted of a 4- or 5-step discharge drawdown test and a constant-discharge drawdown and recovery test. Discharge rates during

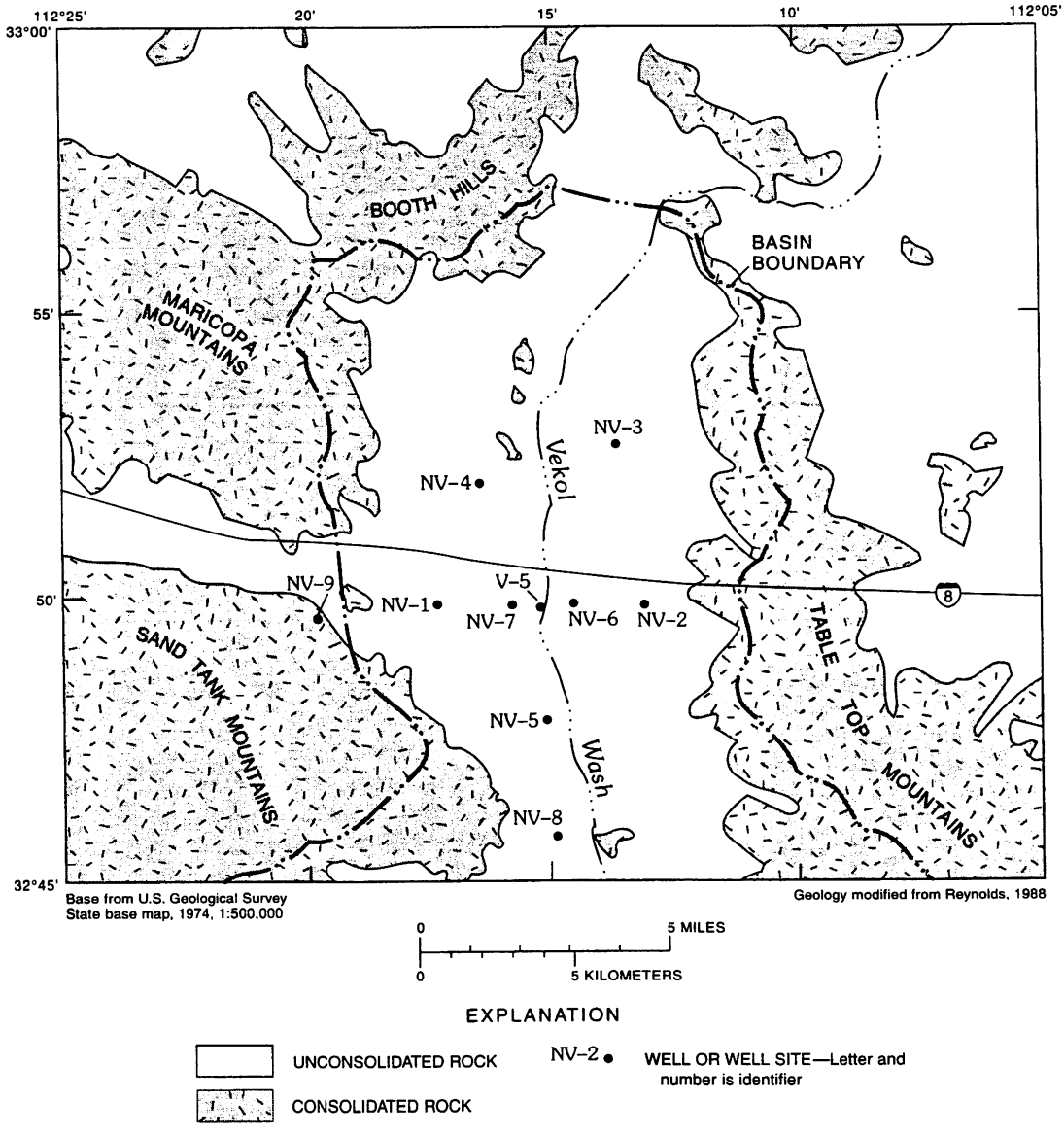


Figure 6. Location of selected wells and well sites in north Vekol Valley.

pumping were measured using a circular orifice weir and (or) a totalizing flowmeter. Water levels were measured in the pumping wells with an electric sounder. Water levels in all observation wells were measured with float- or pressure-sensor-activated recorders and (or) electric sounders.

AQUIFER TESTS IN NORTH VEKOL VALLEY

The first drawdown test conducted in north Vekol Valley was completed at site V–5 during 1979 (fig. 6). This test was conducted during the first phase of the USGS studies but was not completely analyzed until 1982 during the second phase of the work. The test at site V–5 consisted of pumping well V–5 at a rate of 2,000 gal/min for about 6 days with drawdown and recovery water levels being measured in the pumped well and in observation well V–4, which was 155.5 ft from the pumped well. A vertical-velocity log of flow in the well also was made earlier at well V–5 as it pumped 1,100 gal/min and after the drawdown had stabilized and was changing slowly. In 1982, the first aquifer test in north Vekol Valley was conducted at site NV–6 (fig. 6). The test design was based on the known geology, the estimated hydraulic properties, and the anticipated response of the aquifer system to the designed pumping rate. The test consisted of pumping from well NV–6p at a rate of 2,450 gal/min for about 23 days. Water levels were measured in the

Table 1. Test holes drilled and wells installed in north Vekol Valley

[Dashes indicate no data]

Well number	Location			Land-surface altitude, in feet above sea level	Depth, in feet below land surface	Screen, in feet below land surface		Water level above sea level	
	Township	Range	Section			From	To	Feet	Date
Production									
V–5	7S	1E	10	1,755	2,000	616	1,719	1,408.2	12-79
NV–5	7S	1E	22	1,830	2,000	466	1,782	1,408.5	9-82
NV–6p	7S	1E	10	1,756	1,534	392	1,510	1,411.4	10-82
NV–7	7S	1E	9	1,763	2,000	447	1,499	1,416.1	7-82
Observation									
V–4	7S	1E	10	1,755	1,994	478	1,874	1,409.2	11-79
NV–1	7S	1E	8	1,798	2,009	395	1,200	1,415.7	6-82
NV–2	7S	1E	12	1,797	1,067	396	1,057	1,416.8	7-82
NV–3	6S	1E	26	1,668	674	368	608	1,399.6	6-82
NV–4	6S	1E	32	1,695	592	445	455	1,407.9	10-82
NV–50b1	7S	1E	22	1,833	3,014	401	1,984	1,408.7	6-82
NV–6c	7S	1E	10	1,756	1,590	508	518	1,410.9	7-82
NV–6ob1	7S	1E	10	1,756	1,532	320	1,486	1,411.2	7-82
NV–6ob2	7S	1E	10	1,758	550	529	549	1,411.7	8-82
NV–6ob3	7S	1E	10	1,761	550	529	549	1,411.8	8-82
NV–6ob4	7S	1E	10	1,743	506	486	506	1,411.0	7-82
NV–6ob5	7S	1E	10	1,741	507	486	506	1,411.0	7-82
NV–7c-hft	7S	1E	9	1,762	2,000	([1])	([1])	---------	------
NV–8	8S	1E	3	1,935	200	159	179	([2])	------
NV–9	7S	1W	11	1,882	340	205	215	1,628.7	9-82

[1]None. [2]Dry.

pumped well and in 12 observation wells during both the drawdown and recovery periods.

Methods Used for Analyses

The aquifer-test data obtained from sites in north Vekol Valley were analyzed using the curve-matching technique by Boulton (1954, 1955, and 1963) and by Neuman (1972, 1973, 1974, and 1975). This technique is applicable to the analysis of the unconfined aquifer underlying the northern part of the valley.

Two separate approaches of this technique were used to determine transmissivity (T) and specific-yield (S_y) values. The first approach used the standard curve-matching procedure to calculate the T and S_y values at each observation well for that part of the drawdown (s) and time (t) plots after any partial-penetration effects had disappeared. The second approach then used these T and S_y values, along with several other calculated and measured values, to generate a site-specific type curve for the actual observation and pumped-well configurations to reanalyze for T and S_y using the complete s and t data plot. This method (Neuman, 1974) calculates the effects on water levels observed in any partially or fully penetrating observation well caused by a partially or fully penetrating pumped well. The computer code used to produce the type curves for each individual observation well was provided by S.P. Neuman. An improved computer code (Moench, 1993) also was used.

In addition, a technique, commonly referred to as a continuity test, was used to corroborate that previously calculated T and S_y values for all data sets were consistent and reasonable. The continuity test is a curve-matching technique using a plot of drawdown (s) and the ratio of time (t) to distance from the pumped well to the observation well squared (r^2) to calculate T and S_y or storage coefficient (S). The semi-logarithmic method of Cooper and Jacob (1946) also was used to obtain transmissivity values for each aquifer to corroborate those previously obtained values.

Partial-Penetration Effects

Some wells installed in Vekol Valley were, for various reasons, constructed so that the screen installed in the well is not open to the entire aquifer. When these partially penetrating wells are pumped, water moving through the aquifer converges as it moves toward the well screen. This convergence of flow causes vertical-flow components in the aquifer near the pumped well. If these vertical-flow components are large, analytical methods developed for fully penetrating wells may produce inaccurate values for the aquifer characteristics. The applicability of these solutions is complicated further and generally denigrated if the observation wells used to record water-level changes due to the pumping also are partially penetrating.

Techniques have been developed that allow adjustments to be made that account for the inaccuracies of these analytical methods. Hantush (1962, 1964) presented a technique that allowed adjustment to the Theis (confined) solution to account for the effects of partial penetration and vertical leakage that could be applied to determine properties of unconfined aquifers. Stallman (1965) published the results of electric-analog model studies for various partial penetrations of both pumped and observation wells. The principal results of Stallman's studies are presented as type curves on his figures 10 and 12. Neuman (1974) presented a technique that allows the effects of partially penetrating pumped and observation wells in an unconfined, anisotropic aquifer to be determined. Moench (1993) again improved the method. Although a complete discussion of these techniques is beyond the scope of this report, a brief description of their application to the tests conducted in Vekol Valley is presented below.

First, effects of partial penetration must be accounted for if:

$$\frac{r\sqrt{\frac{K_z}{K_r}}}{b} \leq 1.0\,, \qquad (1)$$

where

r = distance from pumped well to the observation well,
b = thickness of the aquifer,
K_z = vertical hydraulic conductivity, and
K_r = horizontal hydraulic conductivity.

However, for large values of time (t):

$$t > \frac{b^2 (S_y)}{2 (K_z/K_r) T}\,, \qquad (2)$$

where

S_y = specific yield, and
T = transmissivity.

The effects of partial penetration are constant in time.

The effects of a partially penetrating pumped well decrease with distance and with the ratio of K_z/K_r. At distances greater than:

$$r = \frac{b}{\sqrt{\frac{K_z}{K_r}}}, \tag{3}$$

and the effects disappear when:

$$t \geq \frac{10 S_y r^2}{T} \tag{4}$$

for a partially penetrating pumped well and a partially penetrating observation well(s).

For a partially penetrating pumped well and any fully penetrating observation wells, the effects disappear at distances greater than the distance defined by equation 3 at times greater than:

$$t = \frac{S_y r^2}{T}. \tag{5}$$

If the pumped well and the observation well(s) fully penetrate an anisotropic, unconfined aquifer, the solution of Neuman (1975) is applicable. That is, no adjustment for well penetration is required.

For a fully penetrating pumped well in an anisotropic, unconfined aquifer where the observation well(s) are partially penetrating, the duration of the effects may be determined by using the method developed by Stallman (1965). For any value of the partial-penetration depth coefficient (z) for either a pumped or an observation well and for each finite value (β) of:

$$\frac{r}{b}\sqrt{\frac{K_z}{K_r}}, \tag{6}$$

a value (x) is obtained for:

$$x = \frac{Tt}{r^2 S_y} \tag{7}$$

for the amount of partial penetration of the wells. Type curves may then be drawn to account for the effects of the particular partial penetration of pumped and observation wells.

Also, specific type curves may be drawn for each individual field situation of partially penetrating pumped and (or) observation well(s) using Neuman's (1974) or Moench's (1993) method and associated computer programs. Either of these programs calculates the partial-penetration adjustment required and includes this effect in the type curve produced for a specific aquifer-test configuration. Type curves generated using either method for a particular set of field conditions allow for values of transmissivity and specific yield to be calculated directly.

Tests at Site V–5

The first two tests conducted at site V–5 (fig. 6) included a tracer log and a flow-velocity (impeller type) log to determine the relative yield from each aquifer unit open to well V–5. These logs were made on November 28, 1979, as the well was pumped at a constant rate of about 1,100 gal/min and after the drawdown stabilized at about 111 ft. These logs support the interpretation of a heterogeneous aquifer system. Data from the logs (fig. 7 and table 2) include the distribution of discharge from each zone in the aquifer, in percent per foot at 1,100 gal/min; the total discharge for each aquifer zone, in percent; the discharge from each, in gallons per minute; and thickness of each zone, in feet. The discharge ranges from 0.019 to 0.632 percent/ft, which is a factor of about 33. About 80 percent of the water produced by the well was developed from about 30 percent (345 ft) of the total screened interval (1,104 ft) of the aquifer system.

During December 1979, the first drawdown test was conducted in north Vekol Valley. Well V–5 (fig. 6) was pumped at about 2,000 gal/min for almost 6 days. Well V–4, at a distance of 155.5 ft from the pumped well, was the only observation well. Wells V–5 and V–4 were screened only in the lower part of the unconfined aquifer; however, the wells fully penetrate the underlying confined aquifer.

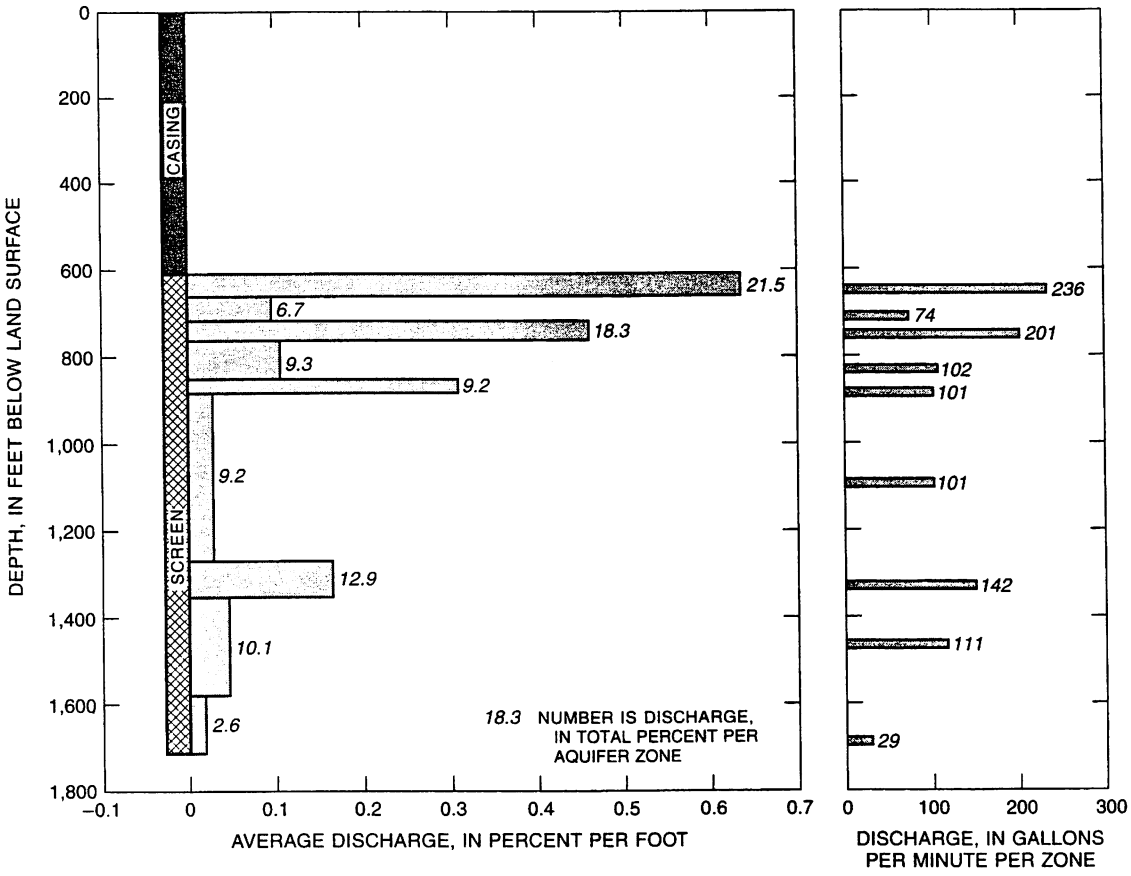


Figure 7. Discharge per aquifer zone in well V–5 while it was being pumped at 1,100 gallons per minute.

Table 2. Data obtained from velocity logs made in well V–5

Aquifer zone			Discharge		Apparent[1]	
Interval, in feet		Thickness, in feet	Percent	Gallons per minute	Transmissivity, in feet squared per day[2]	Hydraulic conductivity, in feet per day
From	To					
616	653	38	21.5	236	814	21.4
653	722	69	6.7	74	253	3.7
722	763	41	18.3	201	693	16.9
763	850	87	9.3	102	352	4.0
850	880	30	9.2	101	348	11.6
880	1,270	390	9.2	101	348	.9
1,270	1,350	80	12.9	142	488	6.1
1,350	1,580	230	10.1	111	382	1.7
1,580	1,719	175	2.6	29	98	.6
Total		1,140	99.8	1,097	3,776	

[1]The values are given to the number of significant figures shown for computational purposes only and do not imply an accuracy commensurate with the number of significant figures.

[2]Transmissivity determined from aquifer test was 3,800 ft^2/d.

Before analyzing the drawdown-test data, the assumption was made that the analysis of the early-time drawdown data, the only data that were available from this test, would give a usable value for the transmissivity of the part of the aquifer system actually yielding the water to the well during that part of the test. The plot of the observed drawdown with time in well V–4 (fig. 8) shows that the delayed gravity response began about 85 minutes after pumping began. This delayed response indicates, considering that about 270 ft of the unconfined aquifer was not open to the pumped well and about 135 ft not open to the observation well, that the unconfined aquifer has low resistance to vertical flow. No other boundary effects were observed during the 6-day drawdown test.

As stated above, Neuman's (1975) method was used for the time-drawdown analysis of this test. Well V–5 was pumped at a rate of about 2,000 gal/min for about 6 days. The match point for the "early-time" type-A curve on the log-log plot for well V–4 was shown in figure 8. The match point is

$$Wu_A = 1,$$
$$1/u_A = 10,$$
$$s = 8.0 \text{ feet},$$
$$t = 8.6 \text{ minutes, and}$$
$$\beta = 0.002;$$

where

$$\beta = \frac{r^2 K_z}{b^2 K_r}. \tag{8}$$

Solving for the properties of the apparent composite aquifer using Neuman's (1975) equations (6) and (8) gives:

$$T = \frac{Q}{4\pi s} Wu, \tag{9}$$

and

$$S = \frac{4Tu_A t}{r^2}; \tag{10}$$

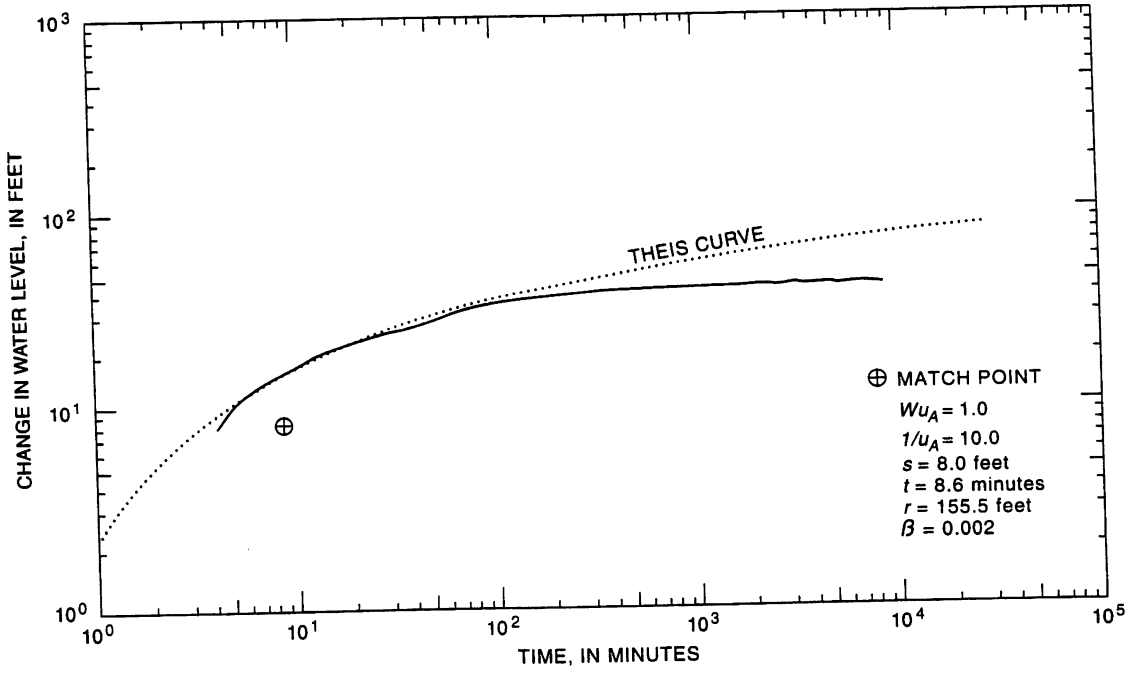


Figure 8. Drawdown data and type curve for well V–4 as well V–5 was being pumped at 2,000 gallons per minute.

therefore,

$$T = \frac{3.85x10^5}{4\pi(8)}(1) = 3,830 \text{ ft}^2/\text{d},$$

and

$$S = \frac{4(3,830)\,5.97x10^{-3}(0.1)}{155.5^2} = 3.8x10^{-4}.$$

These values for the composite aquifer are questionable for several reasons; but they are not unreasonable considering that only 345 ft of the total 1,104 ft of the aquifer system is screened or about 30 percent of the aquifer is contributing about 80 percent of water produced by the well. Also, as much as 65 percent of the water may be produced from the unconfined aquifer.

In order to obtain estimates of the transmissivity for each unit of the aquifer system, two assumptions were made. First, that the quantity of water produced from each unit of the aquifer is the same percentage of the total that was produced during the earlier test (fig. 7 and table 2). The yield of each unit is proportional to the average head change (drawdown) observed in the well. The drawdown measured in the well represents the average head change in the well bore opposite each aquifer unit. Then, using the transmissivity (3,830 ft²/d) calculated during "early time" or before the influence of the delayed gravity response, the transmissivity for each unit may be calculated from the percentage of flow from each unit. Figure 9 illustrates the results of these calculations. Using these results and the β value of 0.002 obtained from the drawdown test, the ratio of K_z:K_r was calculated to be 1:10. The effects of the delayed gravity response observed at about 85 minutes also suggests that a value in this range is not unreasonable. In spite of the many limitations inherent in these tests, the values obtained from this analysis were used as estimates to derive reasonable hydraulic properties for the complex aquifer system underlying north Vekol Valley and subsequently to design a more definitive test at site NV–6.

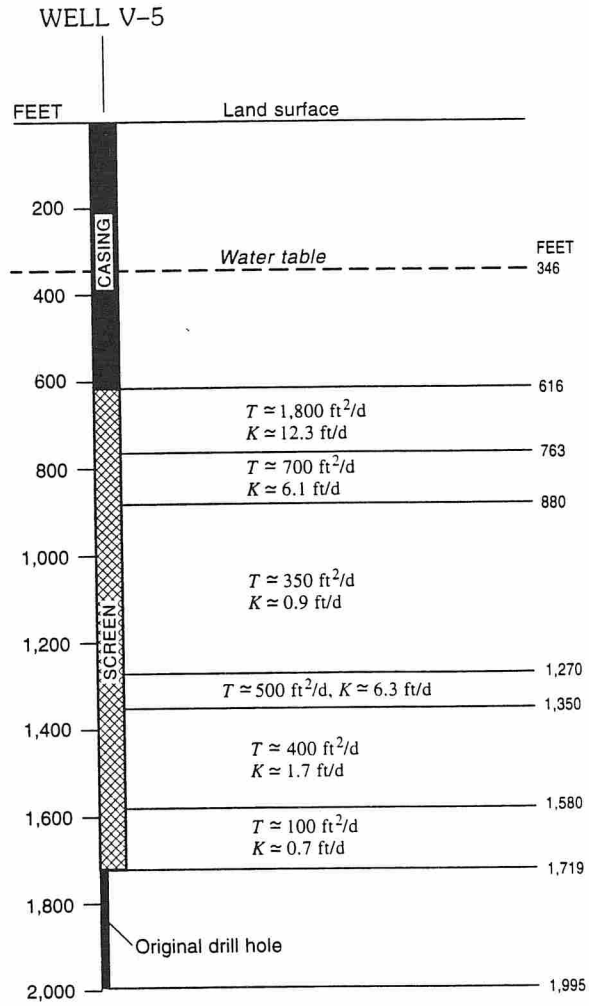


Figure 9. Estimated hydraulic characteristics for the aquifer system at well V–5.

Test at Site NV–6

The aquifer test conducted at site NV–6 during August and September 1982 was the first long-term aquifer test designed and completed in Vekol Valley. The test site is underlain by a sequence of sand, gravel, and conglomerate with a thickness of about 1,500 ft. The water table is at a depth of about 345 ft below land surface in the uppermost sand and gravel. On the basis of the geology, the aquifer-system geometry, and the hydraulic properties determined at site V–5, the hydraulic properties were estimated for the aquifer system and used to design the test at site NV–6. Figure 10 shows the geology and the aquifer-system geometry along a geologic section between wells V–5 and NV–6p. Figure 11 shows hydraulic properties calculated for the aquifer units at well V–5 and the corresponding estimated hydraulic properties

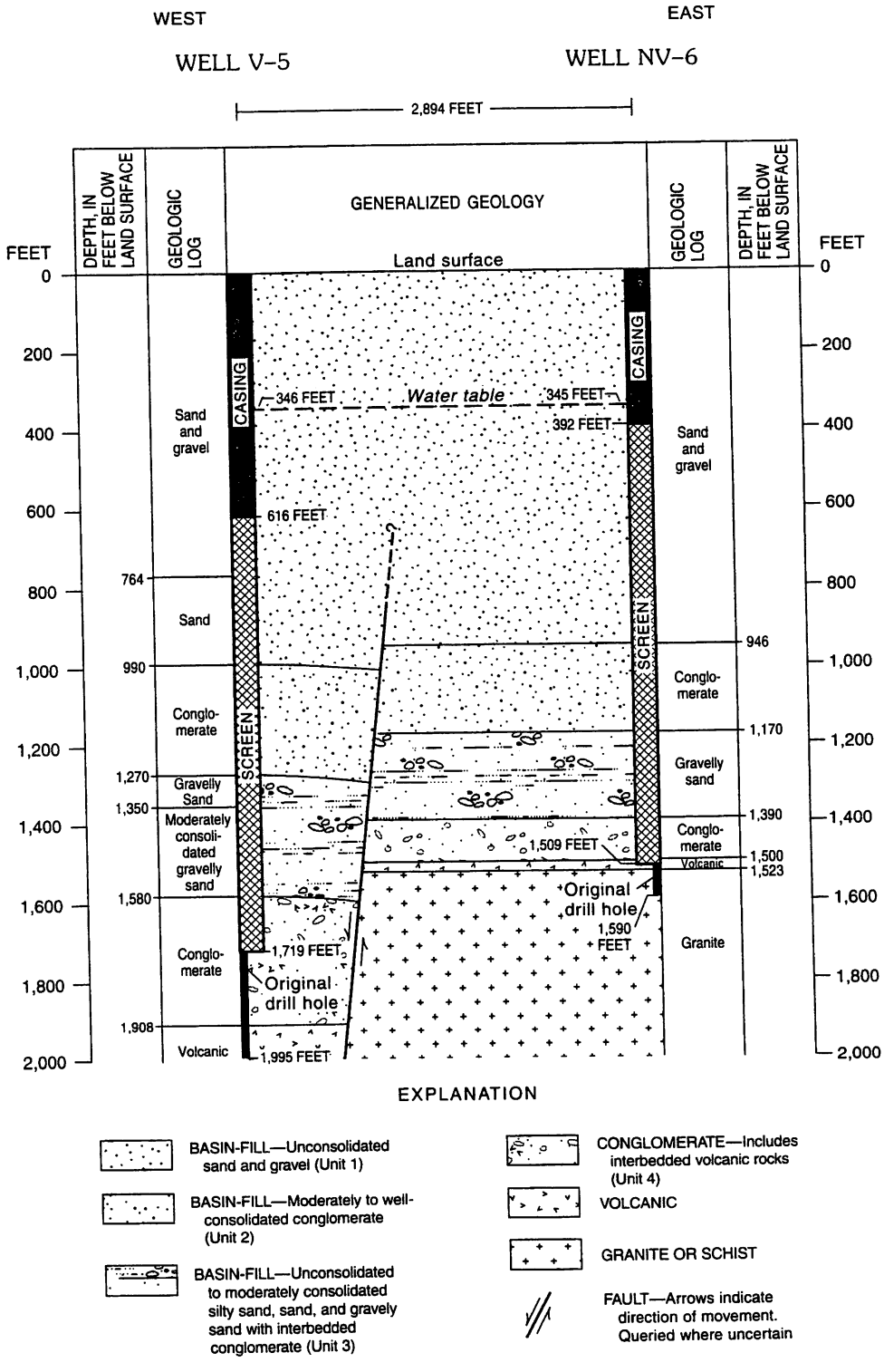


Figure 10. Geologic logs and generalized geologic section between wells V–5 and NV–6.

for the aquifer units at well NV–6p that were used to design the aquifer test at site NV–6. The aquifer test at site NV–6 was designed and conducted to: (1) determine the hydraulic properties of the unconfined part of the aquifer system, (2) corroborate the hydraulic properties of the confined part of the system that were determined from the tests conducted earlier at site V–5, and (3) conduct a recharge experiment. The recharge experiment was designed to (1) determine rates of recharge to the unconfined aquifer from water flowing in a natural ephemeral channel, (2) determine flow rates through the 330-foot-thick

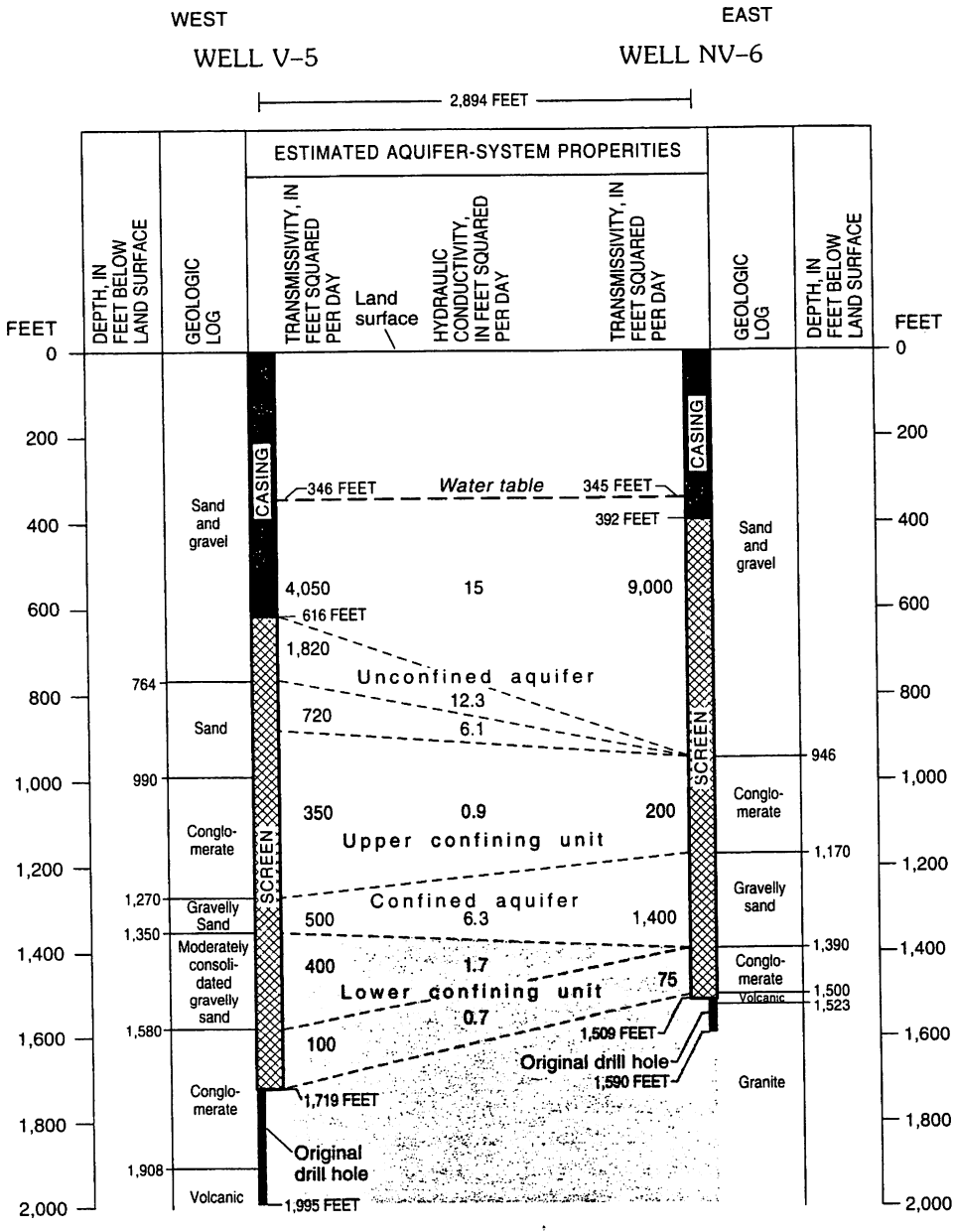


Figure 11. Geologic logs and estimated aquifer-system properties used to design the aquifer test at site NV–6. (See fig. 9 for changes in hydraulic characteritics.)

unsaturated zone at the experiment site, and (3) estimate the total amount and distribution of the water returning to the aquifer during the test. The locations of all observation wells and other installations used during the aquifer test are shown on figure 12.

The pumped well used for the aquifer test at site NV–6 was designed to produce 2,250 gal/min for 30 days. Actual measured discharge was 2,450 gal/min, which was maintained for 23 days. The water produced during the test was transported away from the site through a 10-inch pipeline for a distance of about 2,000 ft and discharged into a dry, ephemeral stream channel. Four weirs were installed in the channel from the outfall of the pipeline downstream for about 3,000 ft (fig. 12). Each weir was equipped with a continuous recorder. The pumping rate of the well (flow to the channel) was monitored using an in-line totalizing flowmeter and an automated, recording, circular orifice weir.

Twelve observation wells were used to monitor water-level changes and obtain other selected types of data. All observation wells were designed to provide data at specific depths, distances, and hydraulic conditions in relation to the pumped well to facilitate analysis of the aquifer test. These wells ranged in depth from about 500 to 2,000 ft (table 3). Their distance from the pumped well ranged from about 82 ft to 3.8 mi. Observation wells NV–5ob, NV–6ob1, and NV–7 fully penetrate the aquifer system. Wells NV–2ob and NV–3ob fully penetrate the upper, unconfined aquifer. Well V–5 partially penetrates the upper aquifer and fully penetrates the lower, confined aquifer. Wells NV–6c, NV–6ob2, NV–6ob3, NV–6ob4, and NV–6ob5 only partially penetrate the upper aquifer. Well NV–1ob was installed in one of the Basin and Range faults that forms the boundary of the valley. The heat-flow tube, NV–7c, which is about 100 ft from NV–7, fully penetrated the aquifer system; however, the tube was sealed and designed to provide only heat-flow data. Specific tests were conducted on all observation wells used during the aquifer test to assure adequacy as observation wells. Nine of the wells were equipped with recorders. The others were measured periodically using an electric sounder. Two recording barometers, two rain gages, and an evaporation pan equipped with a recorder also were installed. The discharge from well NV–6p was measured with an in-line flowmeter and a recording manometer. The discharge was adjusted as necessary to maintain a constant rate using a gate valve.

On August 3, 1982, a preliminary 20-minute test was run, and in this test, weirs 1 and 2 failed. All other equipment functioned properly. During the test, water moved downstream from weir 1 to weir 3. All of the weirs were reinforced with concrete for the aquifer test.

The aquifer test was started at 0832 hours, on August 9, 1982. The discharge of the pumped well stabilized at 2,450 gal/min in a few minutes. Data were collected until 0230 hours, August 10, when the engine driving the pump malfunctioned because of a fuel-flow problem. Recovery data were collected during this unscheduled shutdown. The problem with the pump was corrected, and the test resumed after 11 hours and 45 minutes at 1415 hours, August 10. The drawdown part of the test continued uninterrupted until the planned shutdown at 0830 hours, September 2, 1982, after about 23 days of pumping. During this time, the well yielded a consistent 2,450 gal/min. The recovery part of the test was continued for about 19 days.

The data collected from the aquifer test conducted at site NV–6 were analyzed using the curve-matching techniques described in the section of this report entitled "Methods Used for Analyses." The first step in the test analysis addressed the partial-penetration effects caused by well NV–6p. If the pumped well and the observation well(s) used during an aquifer test fully penetrate an anisotropic, water-table aquifer; the solution of Neuman (1972–75) is applicable, and no partial-penetration adjustment is required. For all other well penetrations, both for the pumped well and for all observation wells, adjustments must be made in order to solve for the aquifer properties.

The prepumping coefficient of penetration may be calculated using the equation:

$$Cp = \frac{b_b - Zt}{b_b - Wt}, \qquad (11)$$

where

b_b = bottom of aquifer,
Zt = top of well screen, and
Wt = water table.

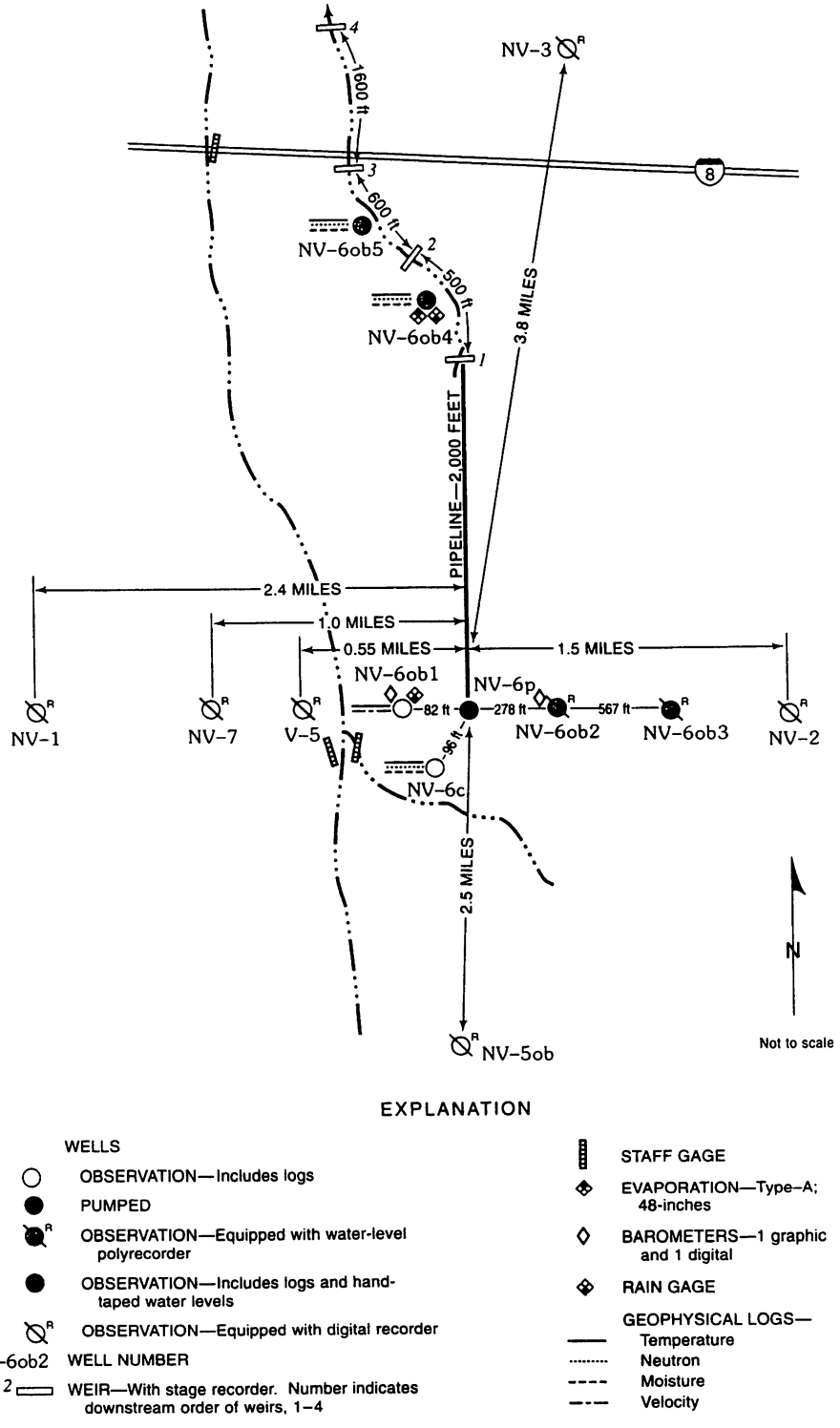


Figure 12. Location of wells and other equipment used for the aquifer test and recharge experiment conducted at site NV–6.

Table 3. Selected information from wells used during the aquifer test at site NV–6

Well number	Radius, in feet	Altitude, in feet above sea level	Depth to bottom of casing, in feet	Screened interval, in feet, below land surface		Method of water-level measurement
				From	To	
NV–6p	0.75	1,756	1,529	392	1,510	Air line/tape
NV–6c	96	1,756	1,395	508	518	Tape
NV–6ob1	82	1,756	1,496	320	1,486	Tape
NV–6ob2	278	1,758	550	529	549	Recorder
NV–6ob3	567	1,761	550	529	549	Recorder
NV–6ob4	1,943	1,743	506	486	506	Tape/logs
NV–6ob5	2,407	1,741	507	486	506	Tape/logs
V–5	2,894	1,755	1,729	616	1,719	Recorder
NV–1	12,670	1,798	1,212	395	1,200	Recorder
NV–2	7,920	1,797	1,057	396	1,057	Recorder
NV–3	20,060	1,668	648	368	608	Recorder
NV–5ob	13,200	1,833	1,994	401	1,984	Recorder
NV–7	5,197	1,763	1,519	447	1,499	Recorder

All values are in feet below datum. For well NV–6p:

$$b_b = 946 \text{ feet,}$$
$$Zt = 392 \text{ feet, and}$$
$$Wt = 345 \text{ feet.}$$

Using equation 11:

$$Cp = \frac{946 \text{ ft} - 392 \text{ ft}}{946 \text{ ft} - 345 \text{ ft}} = 0.92.$$

Because of this large coefficient of penetration (0.92), the assumption was made that the effects of partial penetration caused by the pumped well can be neglected for the first part of the analysis that uses the type-curve matching technique. However, the effects of partial penetration of the pumped well will be included in the second part of the analysis using Neuman's (1974) and Moench's (1993) computer programs to produce the site-specific type curves for each observation well. For the next step in the analysis, the data obtained from well NV–6ob1, the only fully-penetrating observation well, was analyzed.

Well NV–6ob1

Analysis of drawdown data from observation well NV–6ob1 (fig. 13), which fully penetrates the aquifer system, gives a transmissivity (using equation 9) for the "early part of the confined aquifer curve" of:

$$T = \frac{4.72x10^5}{4\pi(2)}(1) = 18,800 \text{ ft}^2/\text{d}.$$

For the "late unconfined part of the aquifer curve" using equation 9:

$$T = \frac{4.72x10^5}{4\pi(2.3)}(1) = 16,300 \text{ ft}^2/\text{d},$$

and using Neuman's (1975) equation 7:

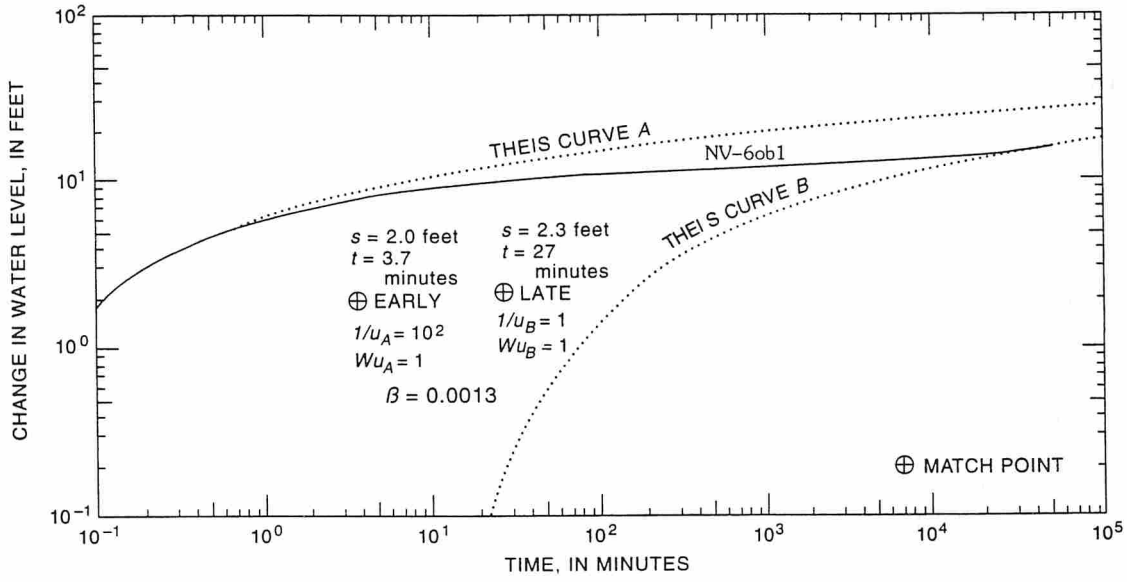


Figure 13. Neuman type-curve analysis for well NV–6ob1.

$$S_y = \frac{4Tu_B t}{r^2}, \qquad (12)$$

therefore,

$$S_y = \frac{4\,(16,300)\,(1)\left(\frac{27}{1,440}\right)}{82^2} = 0.18.$$

The ratio of K_z *to* K_r is calculated from a match of the "flat part" of the drawdown curve of $\beta = 0.0013$ and is about 0.07 or about 1:14 from equation 8:

$$\frac{K_z}{K_r} = \frac{(601)^2}{(82)^2}0.0013 = 0.07.$$

Data from these analyses of the water-level response to the pumping of well NV–6p indicate that the multiple-aquifer system exhibits the following hydraulic properties:

Transmissivity	16,300 ft²/d
Specific yield	0.18
K_z:K_r	1:14

On the basis of the interpretations of the geological and geophysical data available, the transmissivity value calculated for the confined, high-yielding zone in well V–5 is applied to the equivalent zone penetrated by well NV–6ob1 and gives an estimated transmissivity of about 14,500 ft²/d for the unconfined system at site NV–6. If this interpretation and extension of the T for the confined aquifer is valid, the analysis of data obtained for wells NV–6ob2 and NV–6ob3 that follows should corroborate these results.

Wells NV–6ob2 and NV–6ob3

Wells NV–6ob2 and NV–6ob3 were installed in the unconfined part of the aquifer system so that the aquifer properties for that part of the system could be determined. Both wells, however, were constructed with only 20-foot screens to lessen the cost of well construction. Consequently, both wells partially penetrate the aquifer and the effects caused by this partial penetration must be considered if a realistic analysis is to be made of the hydraulic properties of the aquifer.

Knowing, for purposes of the aquifer-test analysis that NV–6p fully penetrates an anisotropic, water-table aquifer and that observation wells NV–6ob2 and NV–6ob3 only partially penetrate that aquifer, the duration that the partial penetration affects the observed response in NV–6ob2 and NV–6ob3 may be determined by using the methods by Stallman (1965) and Neuman (1974).

The method is an analysis of water-level changes caused by a partially penetrating observation well that is affected by the (1) placement of the screen of that well, (2) radial distance between the pumped well and the observation well, and (3) ratio of vertical to horizontal hydraulic conductivity. The method of calculating the partial-penetration factor (Z/b) caused by the placement of the screen (z) of an observation well in an aquifer having a thickness (b) is illustrated in figure 14.

Then, using Stallman's (1965) method for a fully penetrating pumped well and an observation well having a specific value of Z/b at a distance (r) from the pumped well in an aquifer, with a known or estimated ratio of K_z:K_r, a value for y is calculated using equation 6. Using this value of y and a dimensionless, partial-penetration type curve for Z/b, (Stallman, 1965; and fig. 10, Lohman, 1972, pl. 6), a value for x is obtained using equation 7.

Finally, a solution for the time when the partial-penetration effects disappear for the specific test conditions can be made by rearranging equation 7:

$$t = \frac{xr^2 S_y}{T}. \qquad (13)$$

The values obtained as outlined above may then be corroborated using type curves drawn as described by Neuman (1974) and Moench (1993). This method produces type curves for specific field conditions that include the partial-penetration effects of those conditions and allows the transmissivity and specific-yield values to be calculated directly. This method was used to corroborate the values obtained using Stallman's (1965) technique.

As mentioned above, wells NV–6ob2 and NV–6ob3 were installed in the unconfined part of the aquifer system so that the properties for that aquifer could be determined. Both wells only partially penetrate the aquifer because they were constructed with only 20-foot screens set between depths of 529 and 549 ft to lessen the cost of well construction.

The water table was measured at 345 ft below land surface, and the bottom of the aquifer (b_b) was measured at 946 ft, which indicates that the unconfined aquifer is 601 ft thick (b). Because of the 20-foot lengths of screen (Z_{os}) installed in each well, the wells only penetrate about 3 percent of the aquifer. In order to use the observed time-drawdown information to calculate hydraulic properties of the unconfined aquifer, the time at which the effects of partial penetration will disappear must be determined.

The partial-penetration factor Z/b was calculated for both wells NV–6ob2 and NV–6ob3 using the midpoint of their screens.

$$Z/b = \frac{b_b - \left(d5 + \frac{Z_{os}}{2}\right)}{b}, \qquad (14)$$

and

$$Z/b = \frac{946\text{ ft} - 427\text{ ft}}{601} = 0.86.$$

Then, using Stallman's (1965) method for a fully penetrating pumped well and the observation wells having $Z/b = 0.86$ at distances (r) of 278 and 567 ft in an anisotropic aquifer where K_z/K_r is in the range of 0.06 from the match of type curve B (Neuman, 1974) for NV–6ob1 using equation 6:

$$\beta = \frac{r}{b}\sqrt{\frac{K_z}{K_r}}.$$

Then, for well NV–6ob2:

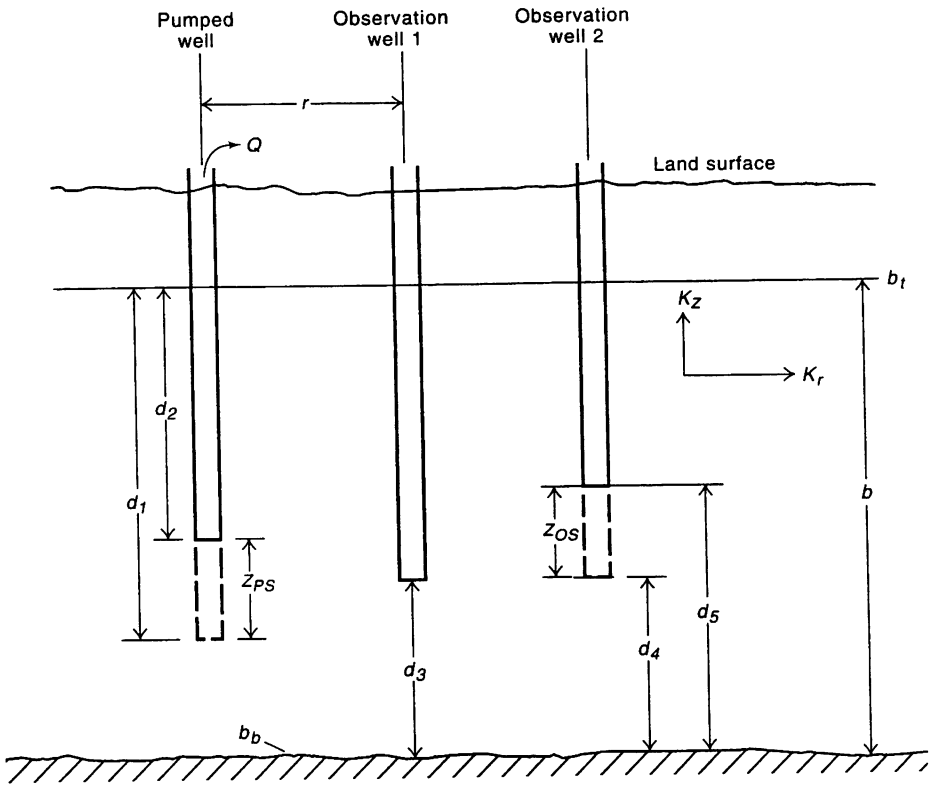
$$\beta = \frac{278\text{ ft}}{601\text{ ft}}\sqrt{0.06} = 0.113,$$

and for well NV–6ob3:

$$\beta = \frac{567\text{ ft}}{601\text{ ft}}\sqrt{0.06} = 0.231.$$

Using these values and the dimensionless, partial-penetration type curve for $Z/b = 0.86$ (fig. 15), a value for each well is obtained from the curve for equation 7. These values are 5 and 3.3 respectively for wells NV–6ob2 and NV–6ob3.

Solving for the time when the effects of partial penetration disappear at each well for well NV–6ob2 gives:



EXPLANATION

K_z — Vertical hydraulic conductivity

K_r — Horizontal hydraulic conductivity

b — Initial saturated thickness, in feet

b_b — Bottom of aquifer

b_t — Top of aquifer

d_1 — Distance from initial water table to bottom of screen in pumped well

d_2 — Distance from initial water table to top of screen in pumped well

d_3 — Vertical distance from bottom of aquifer to bottom of open-end pipe used as observation well

d_4 — Vertical distance from bottom of aquifer to bottom of screen in the observation well

d_5 — Vertical distance from bottom of aquifer to top of screen in the observation well

Q — Discharge from pumped well

r — Distance from pumped well to observation well

Z_{OS} — Length of screen in observation well

Z_{PS} — Length of screen in pumped well

Equations

$PD = d_1 / b$

$DD = d_2 / b$

$ZD = d_3 / b$

$ZD_1 = d_4 / b$

$ZD_2 = d_5 / b$

$BD = b / r$

$CD = K_z / K_r$

$Z/b = (b_b) - (d_5 + Z_{OS} / 2) / b$

Figure 14. Relation of well-screen placement (z) to aquifer thickness (b) of pumped and observation wells.

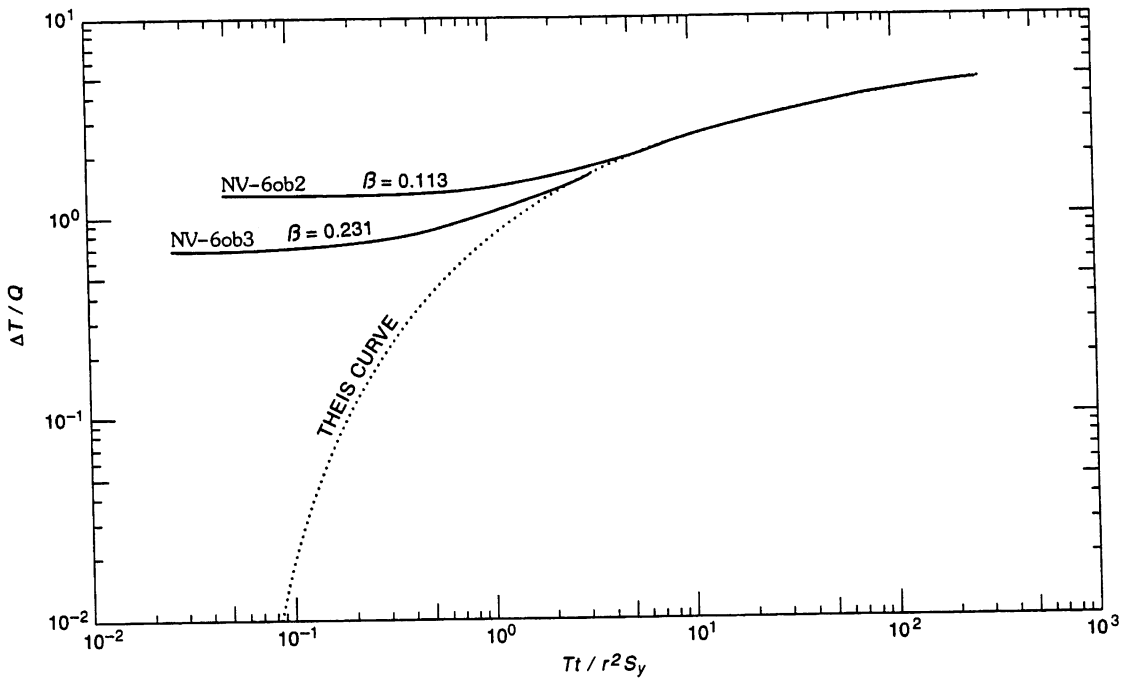


Figure 15. Partial-penetration type curve for $Z/b = 0.86$.

$$t = \frac{5r^2S_y}{T} = \frac{5\,(278\ \text{ft})^2\,(0.10)}{14,500\ \text{ft}^2/\text{d}} = 2.66\ \text{d} \sim 3{,}800\ \text{min},$$

and for well NV–6ob3:

$$t = \frac{3.3r^2S_y}{T} = \frac{3.3\,(567\ \text{ft})^2\,(0.10)}{14,500\ \text{ft}^2/\text{d}} = 7.32\ \text{d} \sim 10,500\ \text{min}.$$

The effects disappear for well NV–6ob2 at about 3,800 minutes and for well NV–6ob3 at about 10,500 minutes.

Using the observed time-drawdown data plots for wells NV–6ob2 and NV–6ob3 after the partial-penetration effects have disappeared, as shown on figure 16, gives the following hydraulic properties for the unconfined aquifer using equations 9, 12, and 8.

Property	NV–6ob2	NV–60b3
Transmissivity	13,000 ft²/d	14,000 ft²/d
Specific yield	0.13	0.08
Ratio of K_z:K_r	1:9	1:12

These computed hydraulic properties, showing: (1) an increase in transmissivity values with radial distance from the pumped well are diagnostic of a "delayed gravity response" and (2) the decreasing specific-yield values are diagnostic of an anisotropic aquifer. These conditions are indicated by the geology at the NV–6 aquifer-test site. Then using these computed aquifer characteristics, a value for K_z was calculated by the following method. First, using the equation:

$$K_r = \frac{T}{b},$$

and the aquifer characteristics obtained for well NV–6ob2:

1. $K_r = \frac{13,000\ \text{ft}^2/\text{d}}{601\ \text{ft}} = 21.6\ \text{ft/d}$,

2. K_z:K_r = 1:9, and

3. $K_z = \frac{K_r}{9} = 2.4\ \text{ft/d}$.

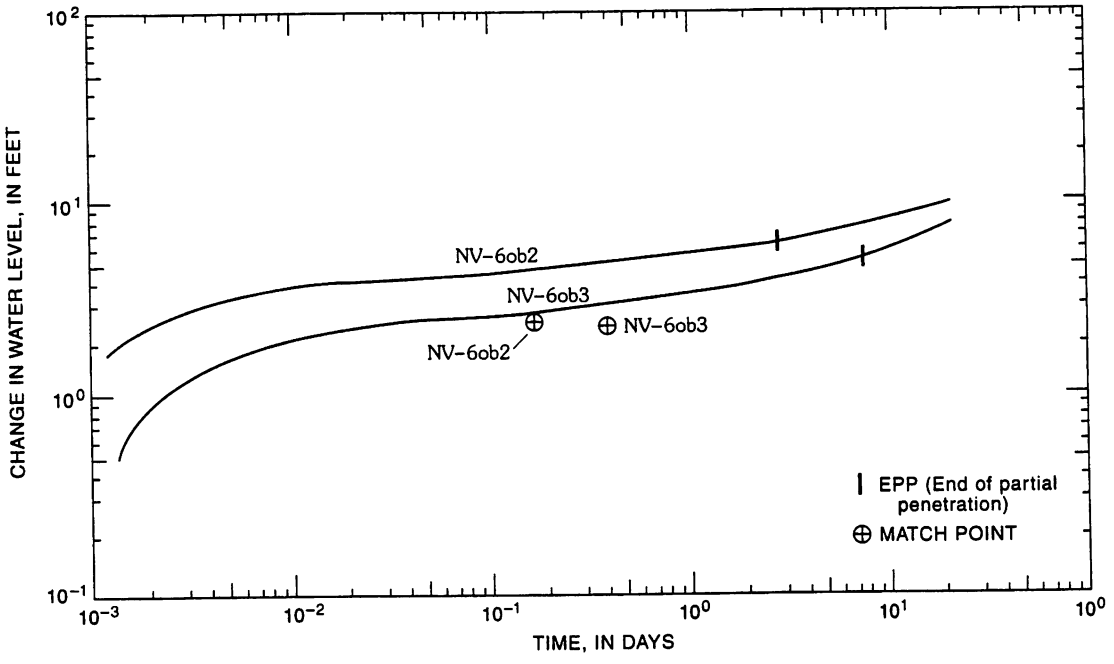


Figure 16. Analyses of time-drawdown data for wells NV–60b2 and NV–60b3 after partial-penetration effects disappear.

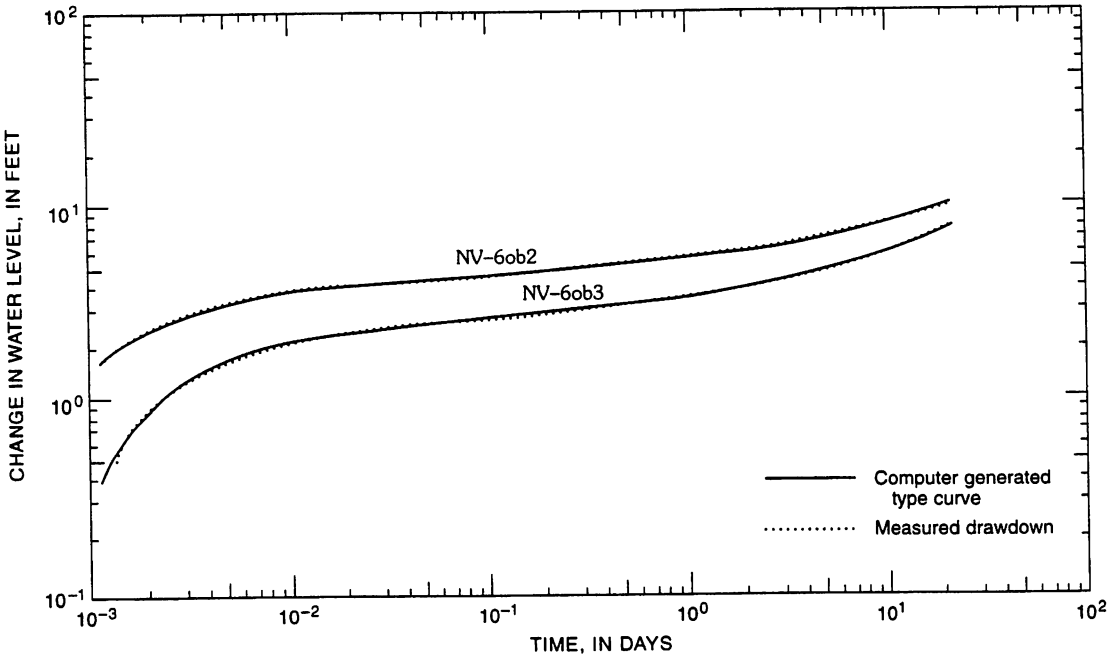


Figure 17. Site-specific type-curve analyses for wells NV–60b2 and NV–60b3.

Using the same method and the aquifer characteristics for well NV–6ob3 gives a K_z value of 1.9 ft/d. An average value for K_z is 2.2 ft/d.

The second approach to corroborate the aquifer properties used assumed aquifer-property values of T = 13,500 ft²/d, S_y = 0.12, and K_z:K_r = 1:10 to 1:12 along with other calculated and measured values that characterize the system to generate a site-specific type curve for wells NV–6ob2 and NV–6ob3. These type curves then were matched to the complete data plot of s and t for those wells to re-evaluate the aquifer properties. The match of the site-specific type curves and the data plots are good for the entire drawdown period, especially for the K_z:K_r value of 1:12 indicating that the computed and subsequently assumed values based on the computations above are realistic (fig. 17).

From this analysis of the water-level response of the unconfined aquifer to the pumping of well NV–6p, the conclusion was drawn that the unconfined aquifer at the NV–6 site has hydraulic properties of:

Property	Site NV–6
Transmissivity	13,500 ft²/d
Specific yield	0.12
Ratio of K_z:K_r	1:12

On the basis of these calculated aquifer characteristics, a value for K_z was calculated using the relation $T/b = K_r$ and K_z:K_r = 1:12. The value for K_z is 1.9. In addition, another technique that employs curve matching, but using a plot of observed drawdown (s) and the ratio of time (t) to the distance from the pumped well to the observation well squared (r^2), commonly referred to as a "continuity test," was used to verify that previously calculated T and S_y values for all data sets were consistent and reasonable. Finally, the semilogarithmic method (Cooper and Jacob, 1946) was used to obtain transmissivity values that would corroborate those values previously obtained.

Continuity Method

A continuity evaluation of aquifer-test data consists of plotting observed drawdown data against the ratio of time (t) to the distance from each observation well to the pumped well squared (r^2) for all observation wells on the same logarithmic graph. The plot illustrates the degree of areal continuity of the aquifer properties (T, S_y, K_z, and K_r) by the closeness of the fit of the data plots to the set of type curves for an aquifer having those hydraulic properties. This evaluation may be the most important analysis of the entire aquifer test because the aquifer properties that are determined can be verified as truly consistent for all observed data.

The graph for s and t/r^2 was plotted for wells NV–6ob1, NV–6ob2, and NV–6ob3 (fig. 18). Well NV–6ob1 is included to illustrate the correspondence of the entire aquifer system with the unconfined aquifer. This correspondence would be expected to be good because of the great effect the unconfined aquifer has on the drawdown observed for the entire system.The data plots appear to be consistent (fig. 18),

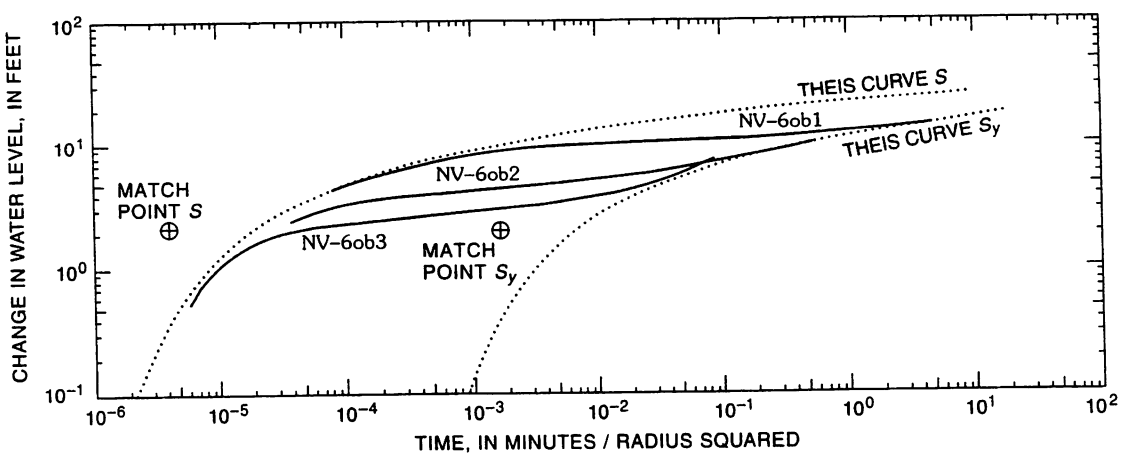


Figure 18. Analysis using the continuity method for wells NV–60b1, NV–609b2, and NV–60b3.

and calculations using equations 8, 9, 10, and 12 for both the "confined early" and "unconfined late" match points give values of:

Property	Confined early	Unconfined late
Transmissivity	17,500 ft²/d	15,800 ft²/d
Storage (S or S_y)	2.0×10^{-4}	0.09
Ratio of K_z:K_r	-----	1:12

This evaluation of the areal continuity of the aquifer properties indicate that the observed water-level declines reasonably depict a consistent, unconfined aquifer system because the observed drawdown plots match well with the family type-curve set of the aquifer system and the computed values compare well with values computed from the individual analyses. An estimate of the average K_z also was calculated and is 2.2.

Straight-Line Method

A final technique, commonly referred to as the "straight-line method" (Cooper and Jacob, 1946) was used to calculate the aquifer-system properties for the NV–6 aquifer test. A thorough discussion of the method is beyond the scope of this report; however, Lohman (1972, p. 22–23) discusses the precautions that should be considered when applying the method. The crux of the problem in application of the method was emphasized by Neuman (1975, p. 335):

> The hydrologist will do well to heed Prickett's (1965, p. 9) advice: "The effects of delayed gravity drainage must dissipate in all observation wells before using distance-drawdown data to compute the hydraulic properties of the aquifer. During the time when delayed gravity drainage is influencing drawdown in observation wells...an analysis of distance-drawdown data...will lead to erroneous results."

The drawdown data for observation wells NV–6ob1, NV–6ob2, and NV–6ob3 plot along the Theis curve for $1/u_B$ (fig. 18) of Neuman (1975) indicating that delayed gravity response has dissipated in those wells by the end of the test. Consequently, distance drawdown plots can be analyzed using the straight-line method (fig. 19). The solution for well NV–6ob1 gives a value for transmissivity of about 16,100 ft²/d for the entire aquifer system. The solution using wells NV–6ob2 and NV–6ob3 gives a value for transmissivity of 14,800 ft²/d for the unconfined aquifer. The solution for well V–5 gives a value of transmissivity of 2,500 ft²/d for the confined aquifer. These values are consistent with solutions derived earlier using the other methods.

In summary, the three techniques used to calculate the aquifer-system properties at site NV–6 gave reasonably consistent results as shown in the following table:

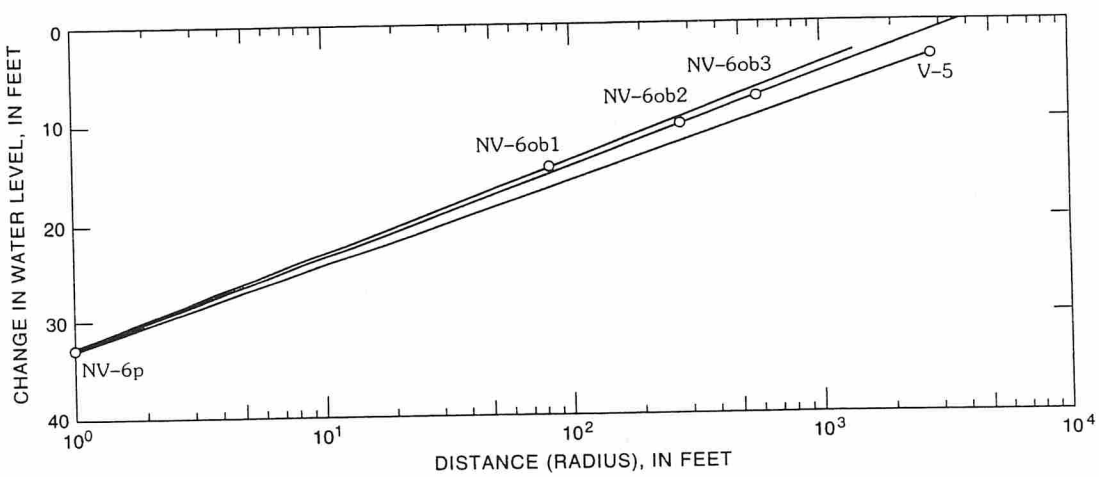


Figure 19. Analyses of drawdown with distance at t = 32,832 minutes for selected wells at site NV–6.

Method	Unconfined aquifer	Composite aquifer	Confined aquifer
Neuman (1975)	$T = 13{,}500$ ft²/d $S_y = 0.12$ $K_z:K_r = 1:12$	$T = 16{,}300$ ft²/d $S_y = 0.18$ $K_z:K_r = 1:14$	[1]2,800 ft²/d
Continuity		$T = 15{,}800$ ft²/d $S_y = 0.09$ $K_z:K_r = 1:12$	
Cooper and Jacob (1946)	$T = 14{,}800$ ft²/d	$T = 16{,}100$ ft²/d	$T = 2{,}500$ ft²/d

[1]Difference of composite minus unconfined.

AQUIFER SYSTEM UNDERLYING SOUTH VEKOL VALLEY

Studies of the southern part of Vekol Valley that were conducted during 1979–83 show that the aquifer system underlying this part of the valley is composed primarily of a thick sequence of silt, sand, and gravel units deposited in a structurally controlled basin (fig. 20; also figs. 2–4). These units grade from a thick silt at or near the surface into underlying sand and gravel units that, in turn, grade from unconsolidated to well cemented with depth in the basin. These basin-fill sediments are intercalated with and underlain by a sequence of volcanic rocks unconformably overlying older rocks that compose the faulted blocks of the Basin and Range Province.

The upper unit of the basin-fill sedimentary deposits is comprised of silt to sandy silt that ranges from a few feet to about 600 ft thick. This unit exists in much of the central part of the southern valley; however, it is absent almost everywhere around the edge of the valley. This unit is overlain by the younger alluvium of the stream courses that is composed of thin beds of sand and gravelly sand. Underlying the upper silty unit is a sequence of sand, gravel, and conglomerate that can be divided into two aquifers. The upper aquifer consists of unconsolidated sand and gravel that ranges in thickness from a few feet near the perimeter of the basin to about 1,100 ft at site SV–11 in the central part of the valley. Underlying the upper aquifer throughout most of the southern valley is a lower gravel and conglomerate aquifer that is about 1,000 ft thick at site SV–8. The gravel and conglomerate aquifer, however, was not present in core holes to the north and northwest at sites SV–1, SV–9, and SV–10. Underlying the lower aquifer in much of the southern valley and contemporaneous, at least in part, with the lower aquifer, is a sequence of volcanic rocks that are as much as 925 ft thick at site SV–6. The volcanics, like the overlying conglomerate, are not present at sites SV–1 and SV–10; however, the volcanic rocks are about 700 ft thick at site SV–9 where the conglomerate is absent.

Depths to ground water in wells in the southern part of the valley range from about 330 to 670 ft below land surface (table 4). Outflow from the southern part of the valley cannot be determined from the water-level data for existing wells. The water-level contours indicate that the direction of ground-water movement generally is from the mountains surrounding the valley toward the center of the valley. Ground water probably does not flow northward from the southern part of the valley because the top of the buried fault block that separates the valley into two distinct aquifer systems extends more than 200 ft above the water level and probably prevents flow to the north. Only one well (X on fig. 20) is known to be drilled into the unconsolidated rocks in the extreme southern end of the valley. The water level in this well was reported to be about 300 ft higher than the water levels in wells V–2, SV–6, and SV–11 farther north. Geologic mapping by Dockter and Keith (1978) show that the southern part of Vekol Valley is completely surrounded by rocks that are nearly impermeable at or near the surface. The presence of outcropping nearly impermeable rocks and available water-level data that show a northward gradient of about 4 ft/mi toward the center of the basin and a depth greater than 400 ft indicate that the southern part of the valley may be a closed ground-water basin. Water-level data are not available to determine if vertical-head differences exist in the various aquifers underlying the southern part of the valley. Data do not indicate whether the ground water flows northward through the buried fault block or toward an exit at the southern end of the valley as hypothesized by Robertson (1991) using geochemical data or if the discharge from the southern part of the valley is by evapotranspiration or some combination of these and other conditions.

TEST HOLES AND WELLS INSTALLED IN SOUTH VEKOL VALLEY

As part of an extensive well-drilling program that was undertaken in Vekol Valley from 1978–84,

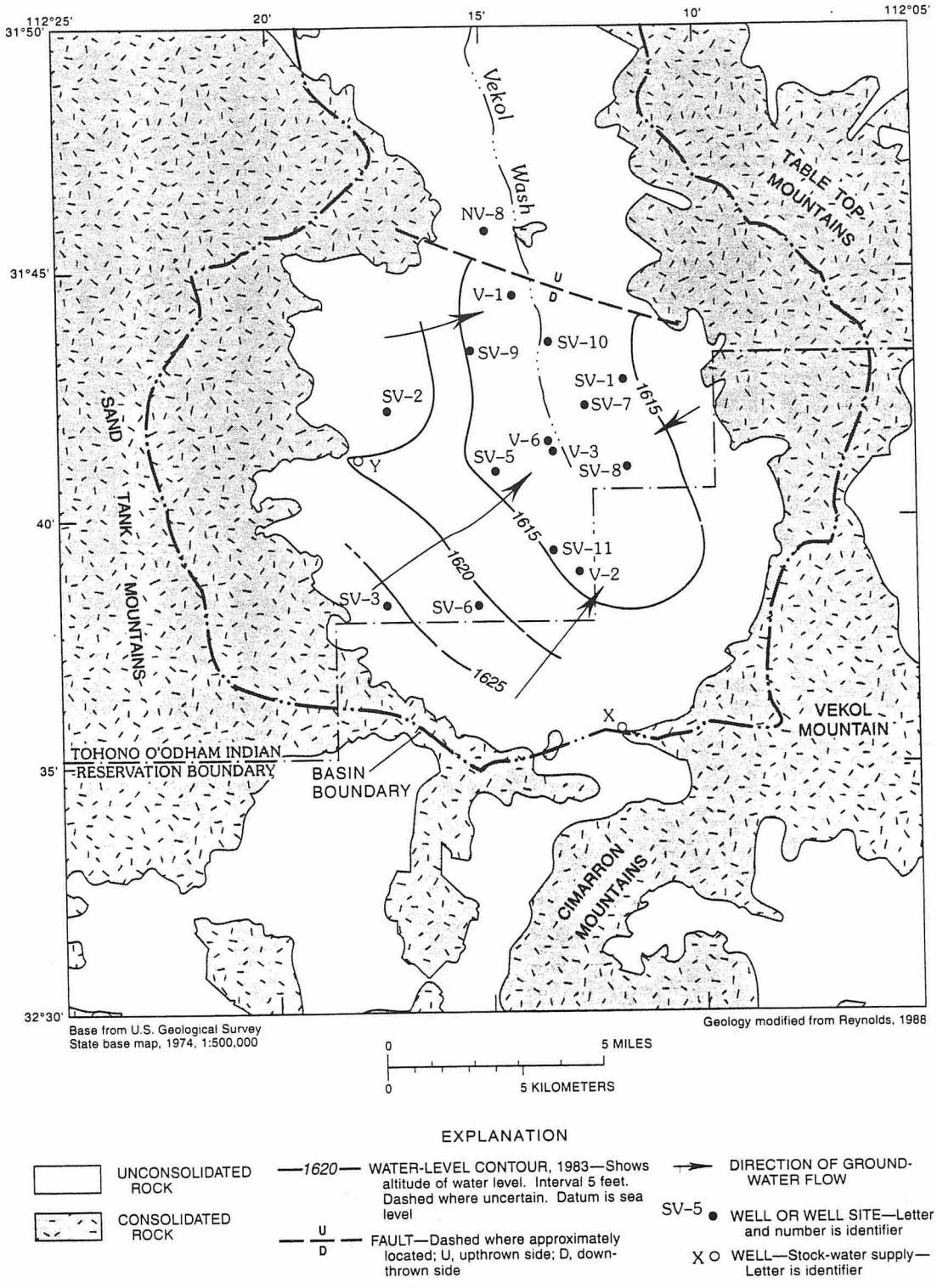


Figure 20. Configuration of the water table in south Vekol Valley.

Table 4. Test holes drilled and wells installed in south Vekol Valley

[Dashes indicate no data]

Well number	Location			Land-surface altitude, in feet above sea level	Depth, in feet below land surface	Screen or open hole, in feet below land surface		Water level, below land surface	
	Township	Range	Section			From	To	Depth, in feet	Date
Production									
V–2	9S	1E	13	2,048	1,983	-----	-------	436	1983
V–6	8S	1E	35	1,002	1,474	-----	-------	389	1983
SV–8	8S	2E	31	2,050	1,947	602	1,955	438	1983
SV–11	9S	1E	11	2,050	1,740	699	1,720	436	1983
Observation									
V–1	8S	1E	11	1,946	1,313	-----	-------	334	1983
V–3	8S	1E	35	2,004	1,981	-----	-------	390	1983
SV–1	8S	2E	19	2,092	1,050	-----	-------	479	1983
SV–2	8S	2E	30	2,165	981	-----	-------	532	1983
SV–3	9S	1E	18	2,296	960	-----	-------	669	1983
SV–8ob1	8S	2E	31	2,050	2,000	657	1,980	438	1983
SV–8ob2	8S	2E	31	2,050	2,007	663	1,987	438	1983
SV–11ob1	9S	1E	11	2,050	1,979	406	1,959	436	1983
SV–11ob2	9S	1E	11	2,050	1,741	700	1,720	436	1983
Core									
SV–5c	8S	1E	34	2,070	1,924	20	1,924	455	1983
SV–6c	9S	1E	15	2,150	2,000	20 871	261 2,000	533	1983
SV–7c	8S	1E	25	2,025	1,984	104 1,117	817 1,984	410	1983
SV–8c	8S	2E	31	2,050	2,000	30 1,024	344 2,000	438	1983
SV–9c	8S	1E	21	2,020	1,460	60	1,460	413	1983
SV–10c	8S	1E	14	1,960	1,747	60 1,000	100 1,747	349	1983
Extensometer									
SV–11ext1	9S	1E	11	2,050	1,660	1,060	1,119	438	1983
SV–11ext2	9S	1E	11	2,050	700	560	660	438	1983

21 test holes and wells were drilled at 14 sites in the southern part of the valley north of the Tohono O'Odham Indian Reservation (fig. 21). The test holes included two core holes that were drilled through the entire aquifer system and into the underlying granite or schist—one to a depth of 1,924 ft, the other to a depth of 2,000 ft. Two core holes—one to a depth of 1,460 ft, the other to a depth of 1,747 ft—were drilled through the aquifer system and into the underlying green shale and dolomite that is typical of rocks of early Paleozoic age. The other two core holes were terminated in the aquifer system—one at a depth of 1,984 ft in the sand and gravel of the upper alluvial aquifer, the other at a depth of 2,000 ft in the conglomerate of the lower part of the aquifer system. Core recovery from these holes, as in the northern part of the valley, was better than 90 percent. All six

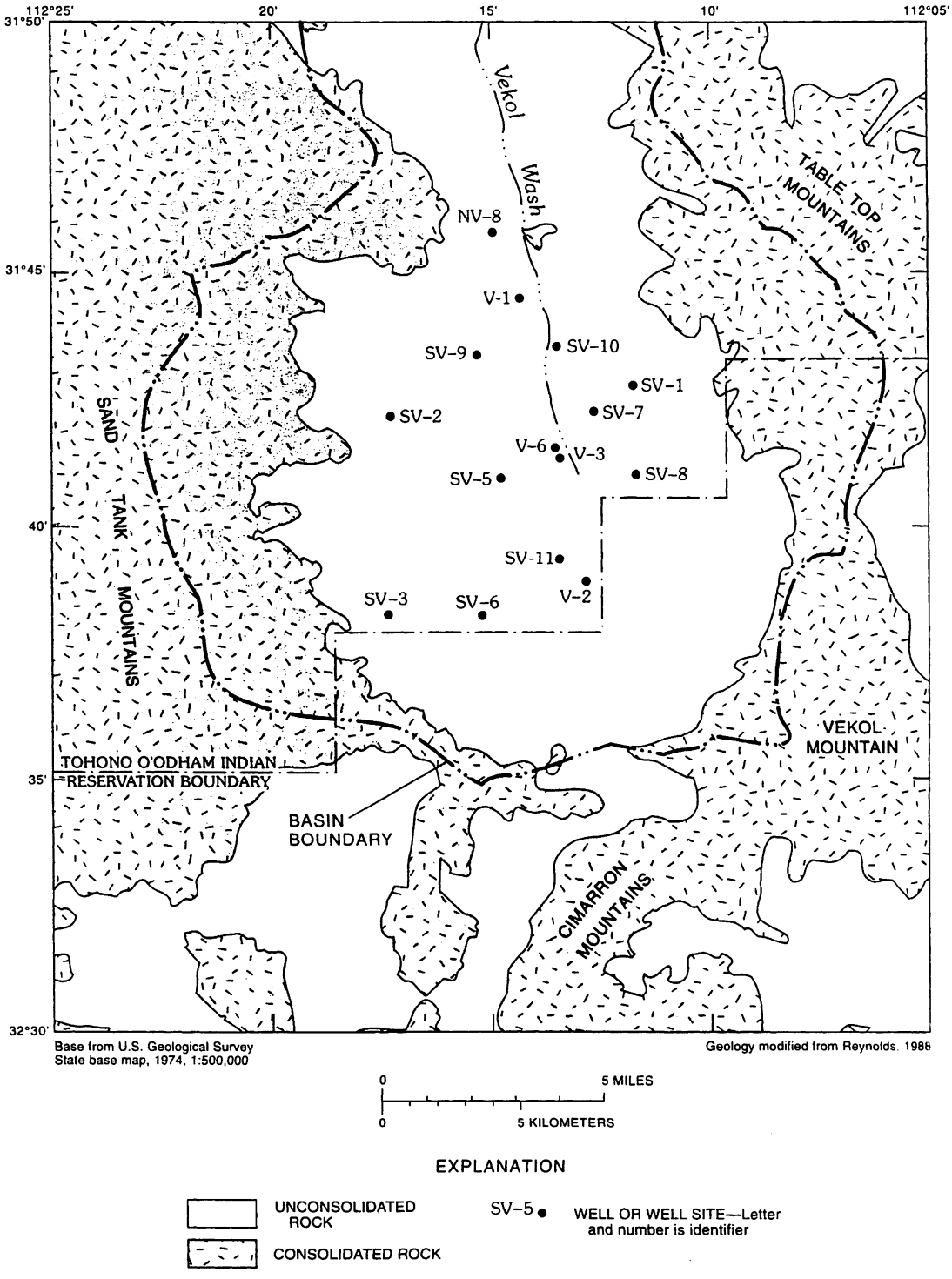


Figure 21. Location of selected wells and well sites in south Vekol Valley.

of the core holes were used as observation wells—two were left open; the other four holes were partially cased.

In addition to the core holes, 13 wells were drilled, cased, and (or) screened, fully developed, and tested, and included 4 production wells and 9 observation wells. Some of the wells are screened throughout the aquifer system. Others are screened only in specific aquifers. Most of the wells were finished using wire-wrapped, high-flow, stainless-steel screen. The wells range in diameter from 2 to 26 in. and in depth from 526 to 2,020 ft.

Two extensometers were constructed at site SV–11. Extensometer SV–11ext1 was designed to measure the compaction of the aquifer system. SV–11ext1 was completed at a depth of 1,660 ft on top of a 20-foot cement plug set in the top of the volcanics, which is principally basalt and underlies the aquifer system. SV–1ext1 also was designed to be used to measure heat flow in the aquifer system. Extensometer SV–11ext2 was designed to measure the compaction occurring in the silty confining unit. SV–11ext2 was completed at a depth of 660 ft on top of a 20-foot cement plug set in the top of the upper confined aquifer.

Aquifer tests were conducted using wells V–6, SV–8, and SV–11 as pumped wells. All other available wells, including the two extensometers, were used as water-level or heat-flow observation wells during these tests (table 4; fig. 21). Well-construction information is shown in table 4 and in the section entitled "Well-Construction Information" at the end of this report.

AQUIFER TESTS IN SOUTH VEKOL VALLEY

Hydrologic information was based on exploration drilling, standard methods of estimating aquifer properties, and the results of testing similar aquifer materials in north Vekol Valley. The aquifer system underlying south Vekol Valley was expected to be a leaky, confined system with the possibility of converting to an unconfined system depending on the amount of water-level decline actually caused by the pumped wells. The pretest estimates of transmissivity and storage coefficient for well sites SV–8 and SV–11 were used to help design the aquifer tests (fig. 22).

The aquifer system at well site SV–8 is comprised of three zones. From the surface to about 800 ft is a silt to sandy silt. From about 800 to 1,000 ft is an unconsolidated sand and gravel. From about 1,000 ft to the bottom of the well at 1,955 ft is a sequence of interbedded gravel and conglomerate. The 200-foot-thick unconsolidated sand and gravel was estimated to have a transmissivity of 3,050 ft^2/d and a storage coefficient of $2x10^{-4}$.

The aquifer system at well site SV–11 is much different from that underlying site SV–8. The unconsolidated sand and gravel at site SV–11 is about 1,100 ft thick; however, it is overlain by the same silt and sandy silt that is at site SV–8. The assumption was that the early-time response during the aquifer test at site SV–11 would be as a confined system and as the water level declined, the aquifer would become unconfined. The test results at SV–11 were expected to give a specific-yield value of about 0.12 or about what was calculated for site NV–6.

Before the aquifer tests, production wells SV–8 and SV–11 were tested using a 950-horsepower, diesel-driven turbine pump rated at a discharge of 4,000 gal/min against 600 ft of head. The tests in each well consisted of a three- or four-increment step-discharge, drawdown test and a short-term instrument calibration test before the long-term, constant-discharge, drawdown and recovery test was made. Discharge rates were measured using a totalizing flowmeter and an orifice plate coupled with a pressure transducer activated by a nitrogen manometer that, in turn, was coupled to a continuous recorder. All available wells were used to obtain water-level data during these tests. Drawdown and recovery water levels in the pumped wells were measured using an electric sounder. Water levels in the observation wells, including the extensometers, were measured using recorders and steel tapes.

Methods Used for Analysis

On the basis of the geology of south Vekol Valley, aquifer tests conducted at sites SV–8 and SV–11 were expected to show that the aquifer received considerable water from the overlying silty unit and that the analysis of the tests would require that a "leaky aquifer" approach be used for the solution.

A preliminary evaluation of the drawdown data confirmed this by showing the characteristic and diagnostic increasing transmissivity values for each observation well further from the pumped well when

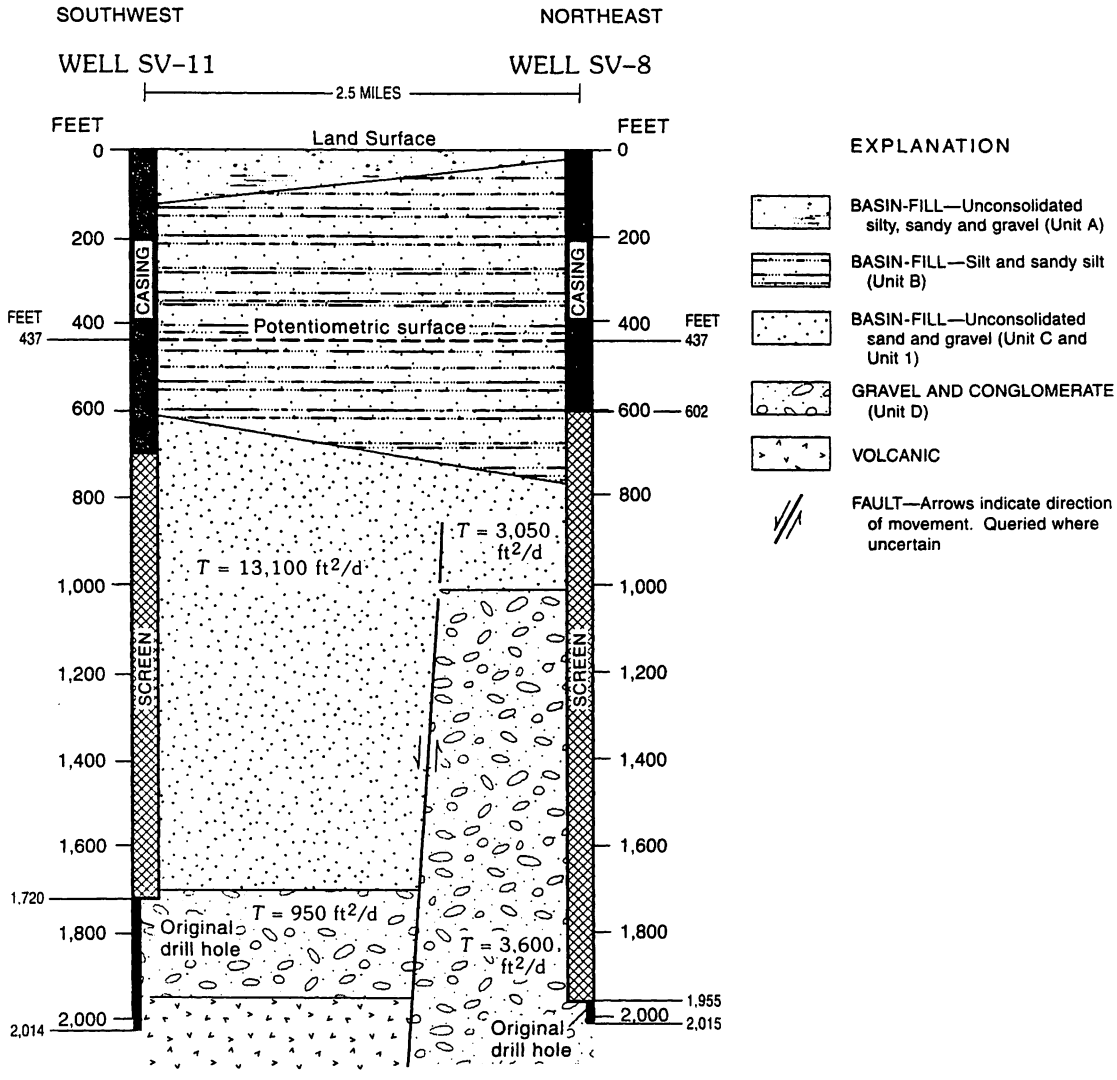


Figure 22. Estimated aquifer-system properties used to design the aquifer test at sites SV–8 and SV–11.

calculated using the Theis type-curve method. The values obtained from this preliminary evaluation were:

Well number	Radial distance, in feet	Transmissivity, in feet squared per day
SV–8ob1	200	7,000
SV–8ob2	500	7,800
SV–11ob1	200	9,100
SV–11ob2	500	10,300
V–2	3,650	24,300

Consequently, the analyses of the constant-discharge drawdown tests were made using a technique that would allow solution for a "leaky artesian aquifer" to which water was contributed from an overlying confining bed. This technique is based on a combination of methods described by Cooper (1963) and Neuman (1975) that includes plotting all drawdown and recovery data for each test against t/r^2 on one graph. The analysis then consists of the usual observed data and type-curve matching procedure for a "continuity analysis," but uses the additional matches for each individual data curve with the flat part of the intermediate type curve to calculate the

value of vertical hydraulic conductivity (K_z) of the confining bed using equation 8:

$$\beta = \frac{r^2 K_z}{b^2 K_r}.$$

If the geology is relatively uniform in the area of water-level decline caused by the pumping during the aquifer test, the values calculated for the K_z of the confining bed for each observation well should be the same because the K_z/b^2K_r part of the equation above should approximate a constant value.

After calculating values for transmissivity and storage coefficient, the values of β obtained from the matched type curve are used along with the aquifer thickness (b); the radial distance to each observation well (r); and the estimated value of K_r (= T/b) in equation (8) to solve for the vertical hydraulic conductivity (K_z) of the confining bed at each observation well. As stated before, these values for K_z should be approximately the same if the geology is fairly uniform.

The additional matches of the data with the family of type curves allows for the validation of the calculated values of transmissivity and storage coefficient if the expected uniformity of the vertical hydraulic conductivity of the confining bed is found. In addition, an evaluation of the leakage from the overlying confining bed in response to the withdrawal from the confined aquifer also can be made.

Test at Site SV–8

Two constant-discharge, drawdown and recovery tests were conducted at well site SV–8. The first test was run for about 22 hours at 3,770 gal/min to test all equipment and obtain preliminary data. The main test was run for about 9 days at 3,400 gal/min. All available wells in south Vekol Valley (fig. 23), including the pumped well, were used to collect water-level data during the tests. However, in addition to the pumped well, only observation wells SV–8ob1 and SV–8ob2 showed water-level changes caused by pumping from well SV–8.

The aquifer test conducted at site SV–8 was expected to show that the aquifer received large amounts of water from the overlying silty unit. The preliminary evaluation of the drawdown data did show the characteristic increasing transmissivity values for each observation well that is further from the pumped well, which is diagnostic of leaky conditions. The values obtained from this preliminary evaluation were:

Well number	Radial distance, in feet	Transmissivity, in feet squared per day
SV–8ob1	200	6,500
SV–8ob2	500	7,700

The analysis of the 9-day, constant-discharge test was made using the technique based on a combination of methods described individually by Cooper (1963) and Neuman (1975). Again, the method consists of plotting all drawdown and recovery data for the test against t/r^2 on one graph. The analysis consists of the usual data/type-curve matching procedure and calculations of transmissivity and storage coefficient and then uses the additional match of each individual data curve with the flat part of the intermediate type curve to obtain an β value and to calculate the K_z for the overlying confining bed at each observation well. The calculated K_z values for each observation well should be the same, that is the value for:

$$\frac{\beta}{r^2} = \frac{K_z}{b^2 K_r} = \text{Constant.} \qquad (15)$$

The data obtained are plotted on figure 24 along with the type curves. Analysis of drawdown and recovery data using equations 6 and 8 and the match points shown on figure 24 are given below. Well SV–8 was pumped at 3,770 gal/min on October 26, 1983, and at 3,420 gal/min on November 9, 1983. The match points and calculations for well SV–8ob1 (r = 200 ft) are as follows:

Well	Date of drawdown	Match points and calculations
SV–8ob1	10–26–83	t = 7.2 min s = 8.3 ft $1/u_A$ = 10 Wu_A = 1

$$T = \frac{Q}{4\pi s} Wu_A = \frac{7.26x10^5}{4\pi\,(8.3)} = 6,960\ (7,000)\ \text{ft}^2/\text{d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(6,960)\,(5x10^{-3})\,(0.1)}{200^2} = 3.48x10^{-4}.$$

Well	Date of recovery	Match points and calculations
SV–8ob1	11–9–83	t = 12.5 min s = 8.0 ft $1/u_A$ = 10 Wu_A = 1

$$T = \frac{Q}{4\pi s} Wu_A = \frac{6.58x10^5\,(1)}{4\pi\,(8.0)} = 6,549\,(6,500)\ \text{ft}^2/\text{d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(6,549)\,(8.7x10^{-3})\,(0.1)}{200^2} = 5.7x10^{-4}.$$

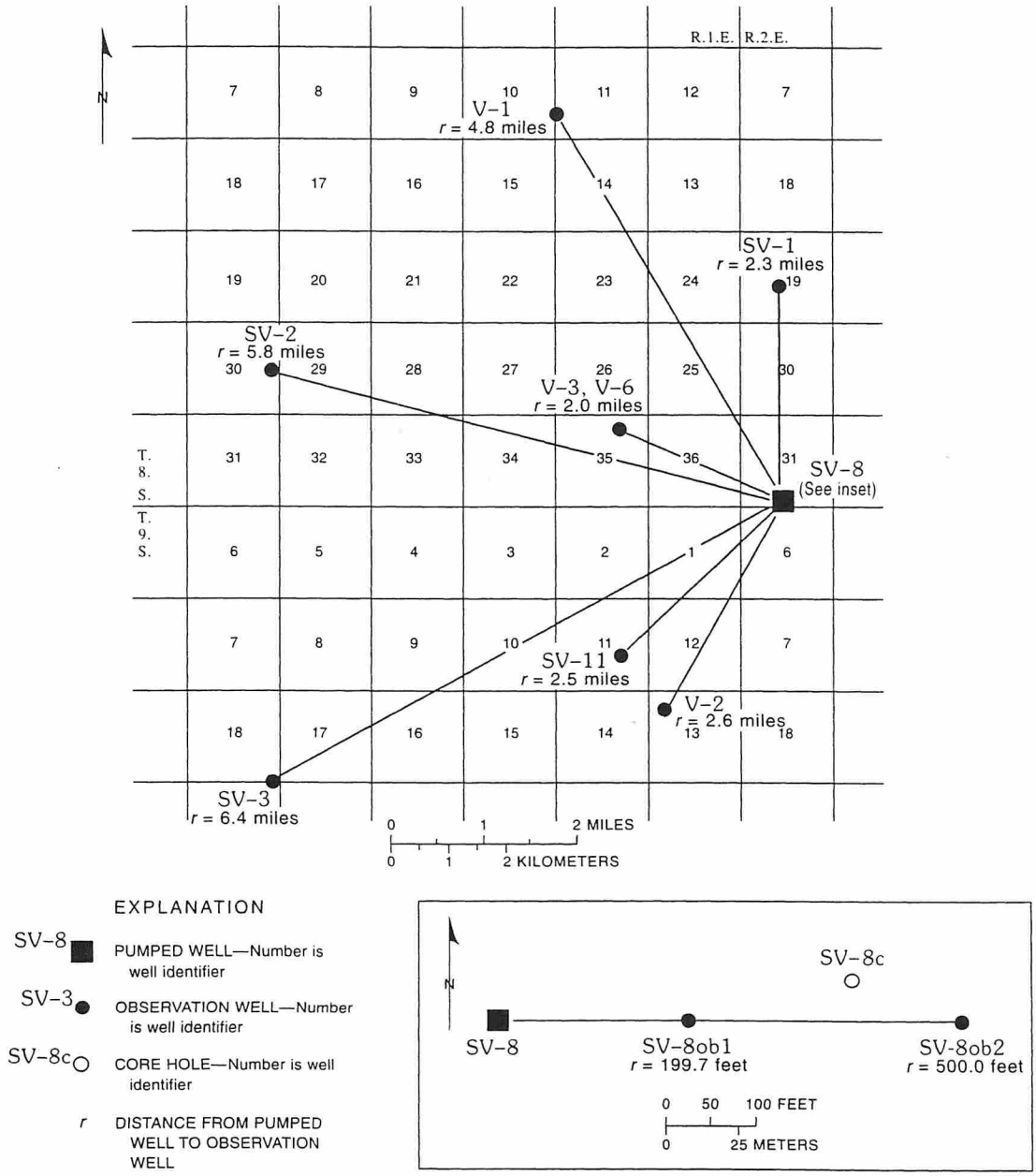


Figure 23. Layout for aquifer test at site SV–8. (Source: Modified from the Bureau of Indian Affairs, 1984.)

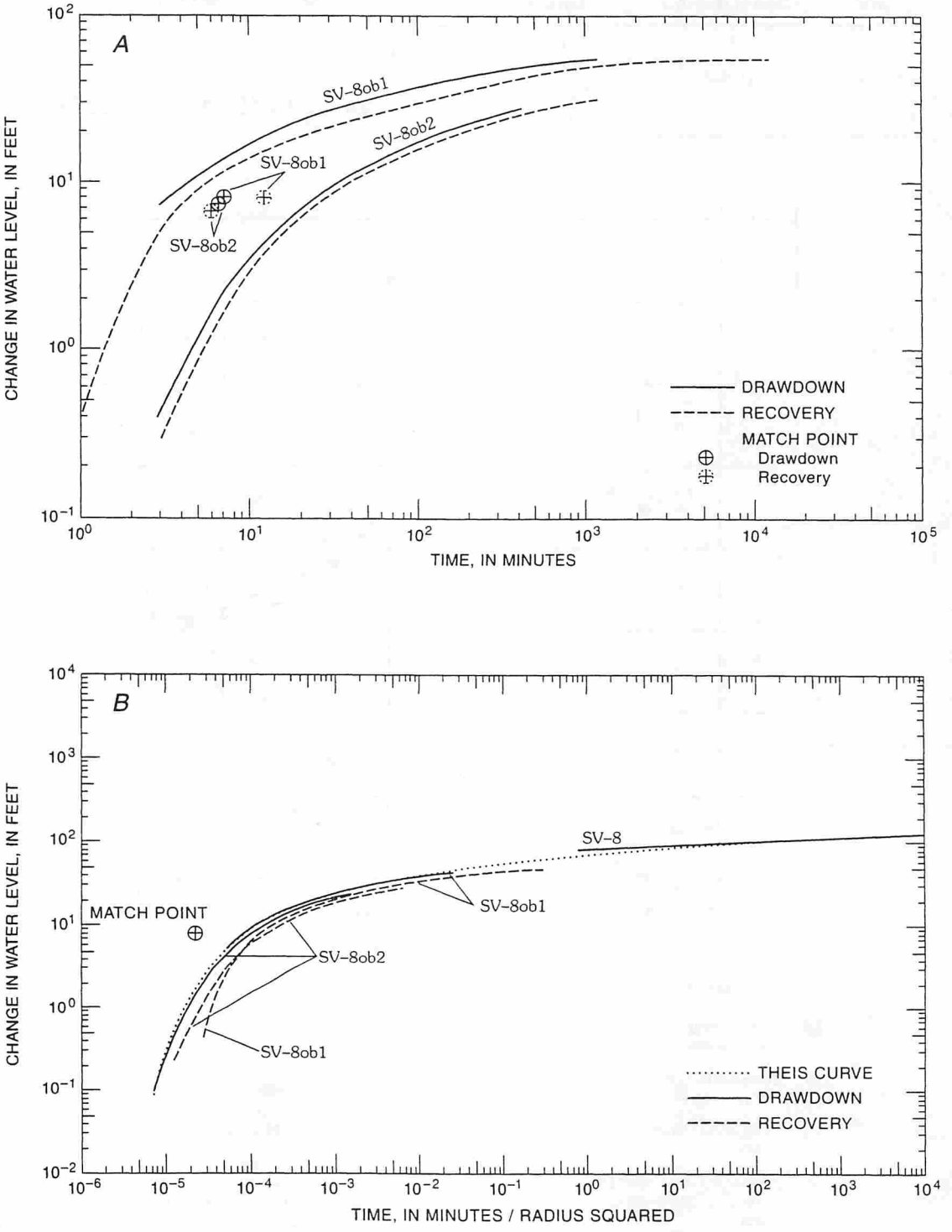


Figure 24. Analyses of aquifer-test data at site SV–8. A, Drawdown and recovery and match points for solution of Theis equation; B, Drawdown and Theis type curve and match point for the continuity method.

The match points and calculations for well SV–8ob2 (r = 500 ft) are as follows:

Well	Date of drawdown	Match points and calculations
SV–8ob2	10–26–83	t = 5.8 min s = 7.4 ft $1/u_A = 1$ $Wu_A = 1$

$$T = \frac{Q}{4\pi s} Wu_A = \frac{7.26x10^5\,(1)}{4\pi\,(7.4)} = 7,807\,(7,800)\ \mathrm{ft^2/d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(7,807)\,(4.03x10^{-3})\,(1)}{500^2} = 5.03x10^{-4}.$$

Well	Date of recovery	Match points and calculations
SV–8ob2	11–9–83	t = 6.0 min s = 6.8 ft $1/u_A = 1$ $Wu_A = 1$

$$T = \frac{Q}{4\pi s} Wu_A = \frac{6.58x10^5\,(1)}{4\pi\,(6.8)} = 7,700\,(7,700)\ \mathrm{ft^2/d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(7,700)\,(4.2x10^{-3})\,(1)}{500^2} = 5.17x10^{-4}.$$

The match points and calculations for the continuity method are as follows:

Well	Match points and calculations
Continuity method	$t/r^2 = 2.2x10^{-5}$ min/ft^2 s = 8.3 ft $1/u_A = 1$ $Wu_A = 1$

$$T = \frac{Q}{4\pi s} Wu_A = \frac{7.26x10^5\,(1)}{4\pi\,(8.3)} = 6,960\,(7,000)\ \mathrm{ft^2/d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(6,960)\,(2.2x10^{-5})\,(1)}{1,440} = 4.25x10^{-4}.$$

Well	Drawdown	Recovery	Continuity
SV–8ob1	T = 7,000 ft^2/d $S = 3.48x10^{-4}$	T = 6,500 ft^2/d $S = 5.7x10^{-4}$	T = 7,000 ft^2/d $S = 4.25x10^{-4}$
SV–8ob2	T = 7,800 ft^2/d $S = 5.03x10^{-4}$	T = 7,700 ft^2/d $S = 5.17x10^{-4}$	

The transmissivity values calculated using these methods are within 10 percent of the average value (7,200 ft^2/d). On the basis of the analysis outlined above, the following properties can be assigned to the aquifer underlying site SV–8:

Transmissivity	7,200 ft^2/d
Storage coefficient	$5.5x10^{-4}$
Ratio of K_z:K_r	1:63
Thickness of the high transmissive zone	220 ft
Given a maximum aquifer thickness	1,260 ft
Average aquifer hydraulic conductivity, K_r	5.6 ft/d
β	0.0004
Constant	$1.0x10^{-8}$
K_z	0.09

The storage coefficient calculated for the aquifer underlying site SV–8 is $5.5x10^{-4}$ and is only slightly higher than that calculated for the expansion of water in an aquifer that has a porosity of 30 percent. The value calculated for the expansion of water is $5.04x10^{-4}$.

Test at Site SV–11

A constant-discharge drawdown and recovery-aquifer test was conducted at site SV–11 during December 1983 and January 1984. Well SV–11 was pumped at a constant rate of 4,450 gal/min for about 21 days. All available wells in south Vekol Valley (fig. 25), including the pumped well, were used to collect water-level data. In addition to the pumped

well, only wells SV–11ob1, SV–11ob2, and V–2 and extensometers SV–11ext1 and SV–11ext2 showed water-level changes caused by pumping from well SV–11. Well V–2, about 3,600 ft from SV–11, was the farthest well from SV–11 that showed water-level responses to the pumping.

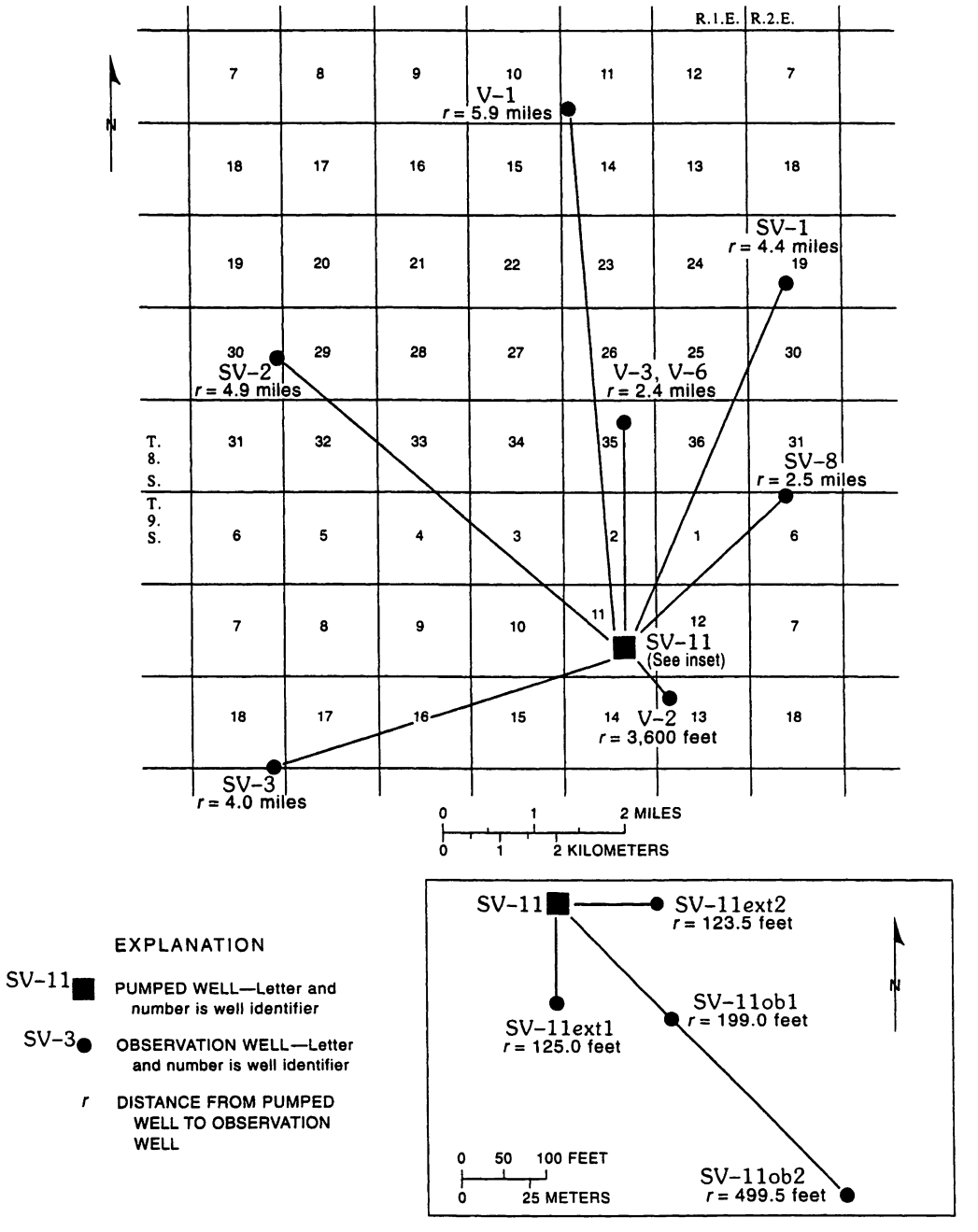


Figure 25. Layout for aquifer test at site SV–11. (Source: Modified from the Bureau of Indian Affairs, 1984.)

As at site SV–8, the aquifer test conducted at site SV–11 was expected to show that the aquifer received considerable water from the overlying silty unit and that it would convert from confined to unconfined during the pumping period. A preliminary evaluation of the data did show the characteristic increasing transmissivity values for each observation well further and further from the pumped well that is diagnostic of leaky conditions. The values obtained from this preliminary evaluation were as follows:

Well number	Radial distance, in feet	Transmissivity, in feet squared per day
SV–11ob1	200	9,100
SV–11ob2	500	10,300
V–2	3,650	24,300

As at site SV–8, the analysis of the aquifer-test data was made using the technique based on a combination of methods described individually by Cooper (1963) and Neuman (1975) as discussed in the section entitled "Methods Used for Analysis for South Vekol Valley." The data/type-curve plots are shown on figure 26. The analysis was done in the same manner as was the analysis for SV–8 and produced the following results:

Well number	Radial distance, in feet	Transmissivity, in feet squared per day	Storage coefficient
SV–11	([1])	8,960	0.12
SV–11ob1	200	9,100	1.9×10^{-3}
SV–11ob2	500	10,300	4.8×10^{-4}
V–2	3,650	24,300	9.1×10^{-4}

Well number	β	Constant	K_z
SV–11	--------	----------	-------
SV–11ob1	0.0004	1.000×10^{-8}	0.113
SV–11ob2	.0026	1.040×10^{-8}	.121
V–2	.1400	1.051×10^{-8}	.123

[1]Pumping well.

On the basis of this analysis, the following properties can be assigned to the aquifer system underlying site SV–11:

Transmissivity	9,000 ft^2/d
Storage coefficient (before conversion)	3×10^{-4}
Specific yield (after conversion)	0.12
Ratio of K_z:K_r	1:56
Given an aquifer thickness of	1,320 ft
Average aquifer hydraulic conductivity	6.8 ft/d

RECHARGE EXPERIMENT

A recharge experiment was conducted in conjunction with the 23-day aquifer test at site NV–6 to determine: (1) water loss from a natural channel, (2) flow rate through the 330-foot-thick unsaturated zone, and (3) the quantity of water reaching the unconfined aquifer. The recharge experiment (fig. 27) used the 2,450 gal/min (5.46 ft^3/s) of water pumped from well NV–6p during the aquifer test. The water was transported through a 2,000-foot pipeline and discharged into a dry, ephemeral channel. A recording circular orifice weir was installed at the end of the pipeline to record discharge. Four Cipolletti weirs with recorders were used to monitor flow in the channel. The channel was about 4 to 12 ft wide and 2 to 7 ft deep and had a thin layer, less than 1 ft, of alluvial sand and gravel covering the bottom of the channel. The basin-fill material underlying the alluvium is a poorly consolidated, silty to gravelly sand. In addition to the weirs, two wells were installed adjacent to the channel and downstream from the first weir in which borehole-geophysical logs (neutron, natural gamma, and temperature) and water-level measurements were made. Flow had not occurred in the ephemeral channel for at least 30 days before the experiment, except for the short-term pumping of well NV–6p during the equipment test.

The discharge records showed that water losses increased steadily to a maximum but a lower rate for each successive channel reach. The water losses decreased in succession from the upstream reach, which stabilized at 1.09 ft^3/s per 1,000 ft of channel length after 14 days, to the downstream reach, which stabilized at 0.64 ft^3/s per 1,000 ft after 20 days. These flow losses were directly related to flow depth and channel geometry. Flow extended for about 7,000 ft downstream from the end of the pipeline. The flow widened the channel for about 900 ft, removed most fine-grained alluvial material for about 3,500 ft, and

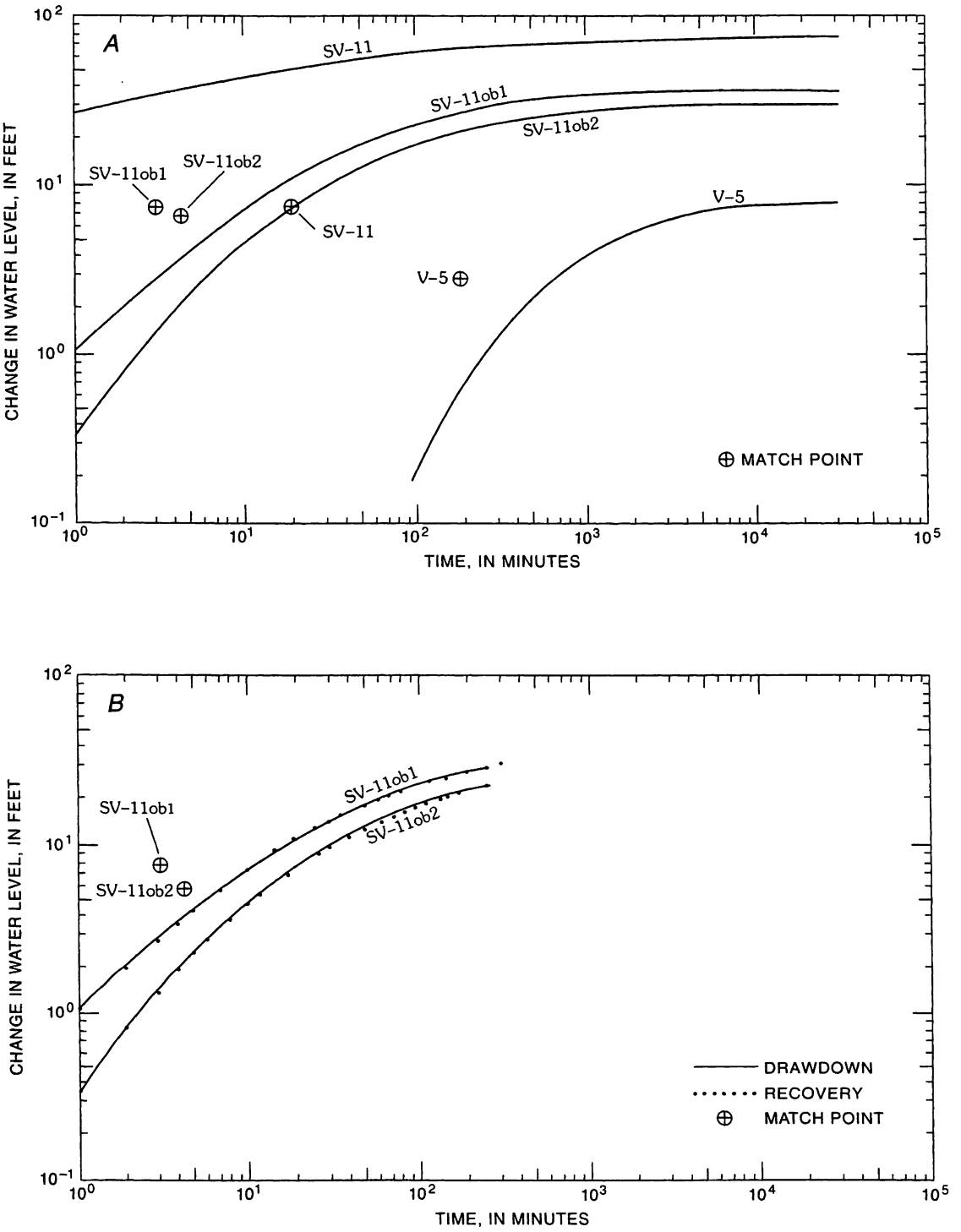


Figure 26. Analyses of aquifer-test data at site SV–11. A, Drawdown at wells SV–11p, SV–11ob1, SV–11ob2, and V–2; B, Drawdown and recovery at wells SV–11ob1 and SV–11ob2; C, Drawdown and Theis type curve and match point for the continuity method.

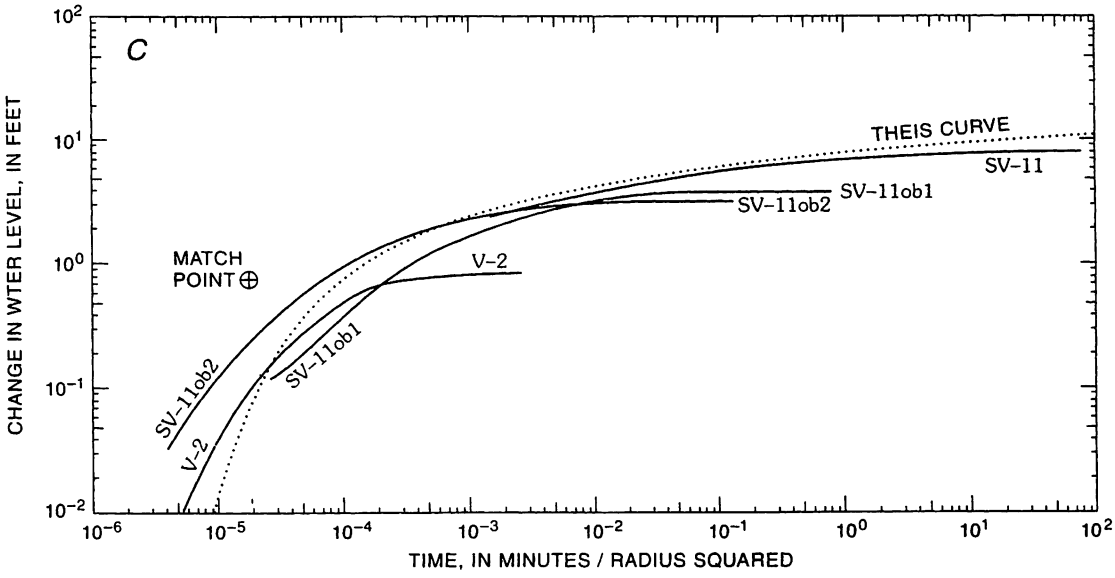


Figure 26. Continued

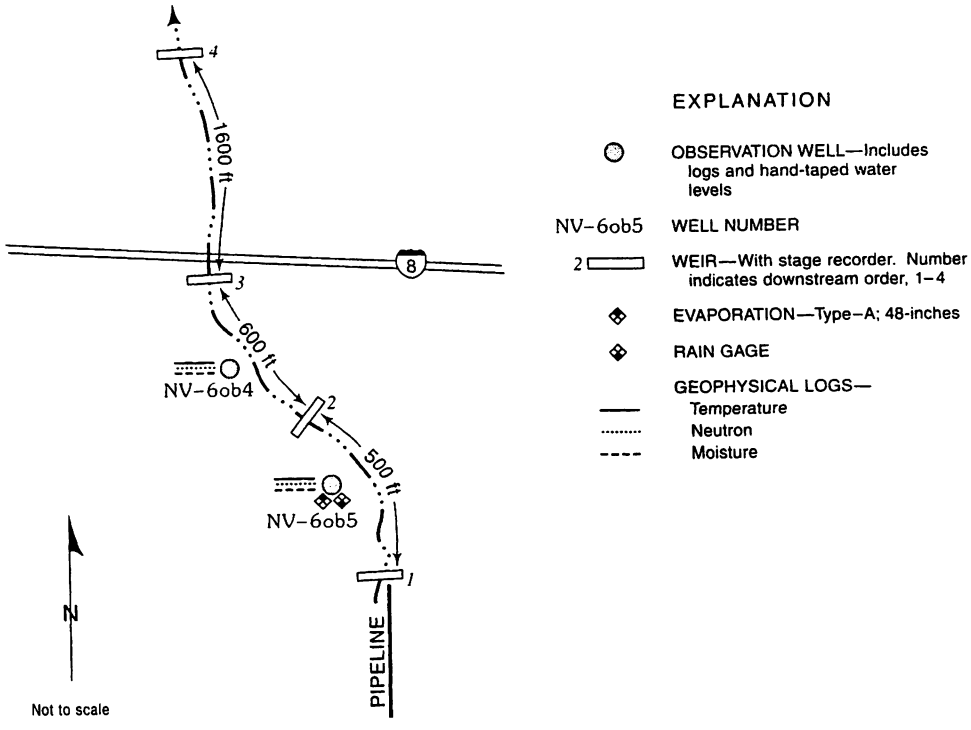


Figure 27. Recharge experiment conducted during the aquifer test at site NV–6.

deposited intermittent layers of sand and silt farther downstream. These channel changes were related to the water discharge and velocity in each reach.

Values calculated for vertical hydraulic conductivity using steady, channel-loss rates for each reach ranged from 2.9 to 7.1 ft/d. The average value calculated from the aquifer test was 2.2 ft/d.

Two sets of neutron logs were made before the tests at site NV–6 were started to document the relative moisture content between the saturated material (aquifer) and the overlying 330-foot-thick unsaturated zone (fig. 28). Dates of the logs were July 26 and 29; August 12, 17, 26, and 31; and September 7 and 23. The second set of neutron logs, made after the short-term equipment tests, showed a slight increase in relative moisture content in several individual beds between the surface and a depth of about 70 ft. Subsequent logs showed a moisture increase in the unsaturated zone progressing from the surface toward the water table and a mound of water (almost to saturation) developing above the water table. This mound expanded to a thickness of about 50 ft between the eighth and seventeenth day of the test. During the next 5 days, the mound continued to expand and was about 100 ft thick on the twenty-second day (fig. 28). Meanwhile, on the fourth day of the experiment, the ground-water level began to rise under the channel in response to the water being recharged through the unsaturated zone. By the tenth day, the ground-water level increased 1.04 ft. By the sixteenth day, an additional 0.07-foot rise had occurred. After pumping was stopped, the mound of water dissipated in less than 5 days, and the relative moisture content of the entire unsaturated section returned to almost pre-experiment conditions in 20 days.

Figure 29 shows the observed water-level response in wells NV–6ob2 and NV–6ob3 along with the measured water elevation at weir 3 during part of August and September 1982. Using these observed water levels and assuming that the aquifer underlying the area is an ideal, homogeneous, and isotropic medium, the theoretical drawdown that would have occurred in well NV–6ob5 under these conditions and without any recharge reaching the water table was calculated. This ideal response of well NV–6ob5 is shown on figure 29 along with the observed response. Drawdown in well NV–6ob5 caused by the pumping of well NV–6p was measurable at about 2 days (point A). The water-level response in NV–6ob5 to the pump failure in NV–6p (point B) and the restart of

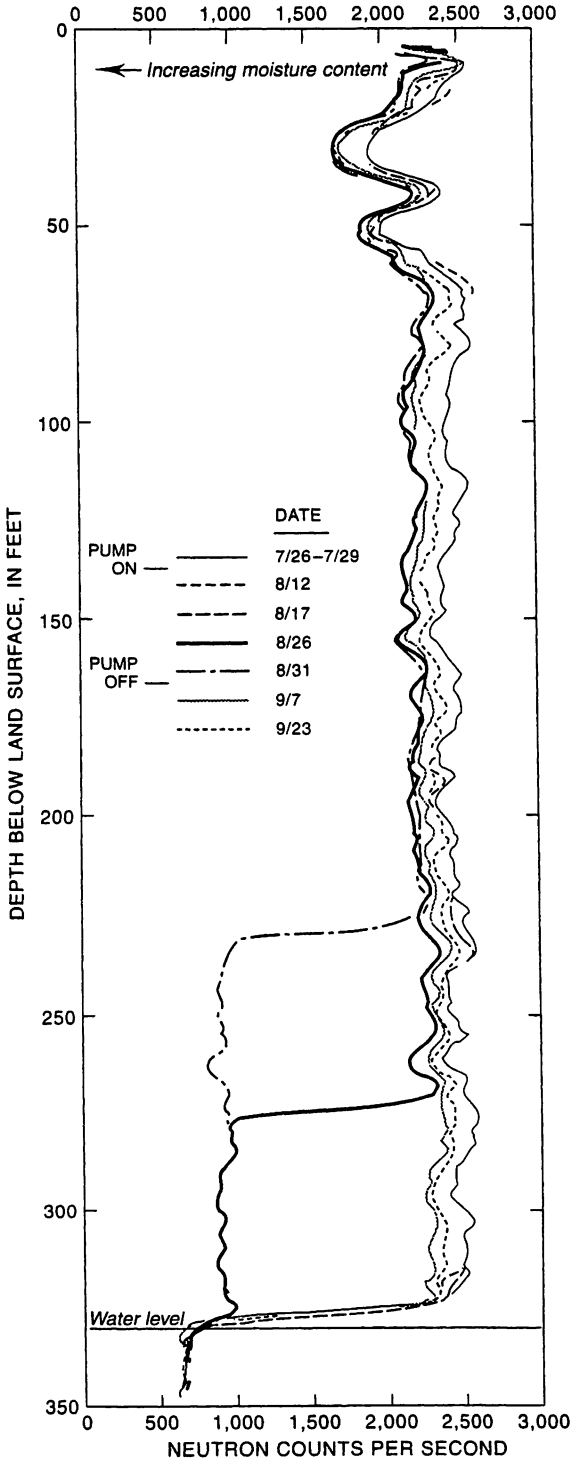


Figure 28. Relative change in moisture content in the unsaturated zone as interpeted using neutron logs.

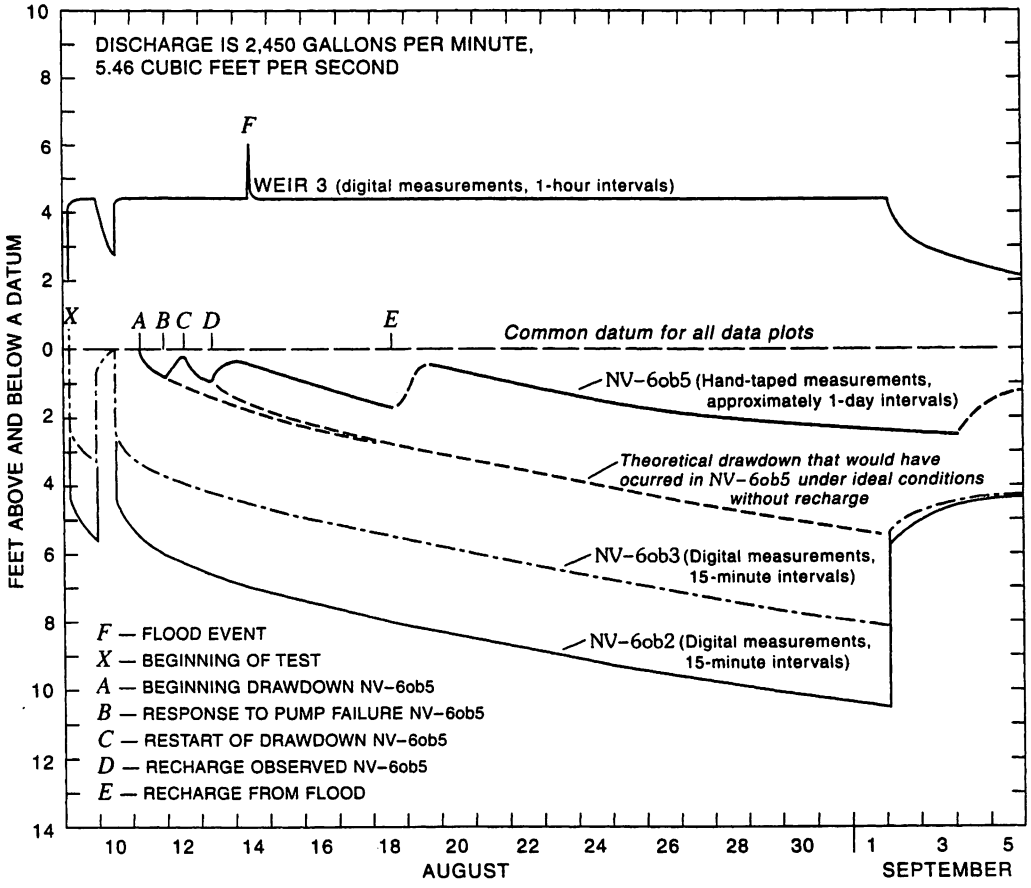


Figure 29. Wells and weirs used during the recharge experiment during 1982.

the pumping in NV–6p (point C) also are shown. The water-level rise in well NV–6ob5 (point D) was not observed in wells NV–6ob2 and NV–6ob3 and is attributed to recharge reaching the water table from the flow in the ephemeral channel caused by the discharge from well NV–6p. This water-level rise occurred in just over 4 days on August 13. On August 14, an intense thunderstorm caused flooding in this area of the valley. The flood peak (point F) was measured as it overtopped weir 3. The water level in well NV–6ob5 rose sharply (point E) in just over 4 days after the flood. This water-level rise is attributed to the recharge from the flood.

The movement of water from the land surface to the water table through the 330-foot-thick unsaturated zone and the consequent water-level rise shows that recharge can occur much more quickly than commonly estimated for Basin and Range unconsolidated, valley-fill deposits. Typically, estimates of downward velocity had ranged from 20 to 40 years for water to reach the water table at depths of 400 ft (Bouwer, 1980, p. 17). Estimates of 50 years/100 ft were common (Evans and Warrick, 1980, p. 58). Results from this recharge experiment drastically alter previously estimated vertical-flow velocities by documenting that water moved from the surface to the water table at a depth of about 330 ft in less than 5 days and that the moisture content increased throughout the unsaturated section and then returned to almost pre-experiment conditions in about 20 days.

SUMMARY AND CONCLUSIONS

The Ak-Chin Indian Community Water Rights Settlement Act directed the Secretary of the Interior to deliver a permanent water supply of 85,000 acre-ft/yr of water to the Ak-Chin Indian Reservation no later

than 25 years from the date (July 28, 1978) of the enactment. The Settlement Act further directed the Secretary of the Interior to determine if sufficient ground water was available beneath Federal Lands near the Reservation to meet the interim emergency needs of the community and, if sufficient quantities of ground water were available, to construct a well field and pipeline to deliver the emergency supply.

Initial studies indicated that the emergency supply could be obtained near the Ak-Chin Community. On the basis of these studies and other information, the Secretary of the Interior selected Vekol Valley as the area to be developed. The Secretary directed that a well field and pipeline capable of delivering the interim emergency supply of 30,000 acre-ft of water annually to the Ak-Chin Indian Community be constructed and work began in 1981 and was conducted in two phases. Vekol Valley is naturally divided into two distinct areas by a low, bedrock ridge that extends across the valley at about its mid-point. Consequently, a study of the northern part of the valley, which is closer to the Ak-Chin Reservation, was undertaken to determine if the ground-water resource underlying this area could be developed to supply the emergency water needs of the Community. When it was determined that the entire emergency supply could not be developed from the northern part of Vekol Valley, the study was expanded to include the southern part of Vekol Valley.

Study of the aquifer system underlying the northern part of Vekol Valley included drilling 19 boreholes at 10 sites and constructing 17 wells, three of which were high-capacity production wells designed as part of the proposed well field. The results of the study show that the aquifer system underlying the valley is composed of a thick sequence of sand and gravel units deposited in a structurally controlled basin. These sand and gravel units grade from unconsolidated to well cemented with depth in the basin. The upper units contain two aquifers: an upper, unconfined aquifer that ranges in thickness from about 550 to 650 ft in the central 12-square mile area of the valley and a lower, confined aquifer that ranges in thickness from about 50 to 300 ft. These aquifers are separated by a well-cemented conglomerate that ranges in thickness from about 210 to 300 ft.

Depth to ground water in the northern part of the valley ranges for about 270 to 430 ft. The direction of ground-water movement generally is from the mountains surrounding the valley on the east, south, and west toward the center of the valley, and then toward the north along the axis of the valley to an exit point at the north end of the valley. The water level in the upper aquifer is a few feet higher than in the lower aquifer around the edge of the valley and indicates downward movement of water in these areas. The water levels are about the same in the central part of the valley, and the water level in the lower aquifer is slightly higher than it is in the upper aquifer in the northern part of the valley. This difference in water levels indicates upward movement of water from the lower aquifer in the discharge area in the north end of the valley.

Analysis and evaluation of the data obtained during the aquifer test conducted in the northern part of Vekol Valley indicate that the aquifer system underlying the area has the following hydraulic characteristics.

Upper unconfined aquifer	T	=	13,500 ft^2/d
	S_y	=	0.12
	$K_z:K_r$	=	1:12
Lower confined aquifer (most productive zone)	T	=	2,000 ft^2/d
	S	=	4×10^{-4}

A recharge experiment conducted in conjunction with the aquifer test used the 2,450 gal/min (5.46 ft^3/s) of water pumped during the test. The water was transported from the test site through a 2,000-foot pipeline and discharged into a dry, ephemeral channel. Water discharge was measured using a recording orifice-manometer installed at the end of the pipeline and four Cipolletti weirs with recorders along the channel. The channel was about 4 to 12 ft wide, 2 to 7 ft deep, and had a thin layer—less than 1 ft—of alluvial sand and gravel. The basin-fill material underlying the alluvium is a poorly consolidated, silty to gravelly sand. Two wells were installed adjacent to the channel and downstream from the first weir in which geophysical logs and water-level readings were made. Natural flow had not occurred in the channel for at least 30 days before the experiment.

The results of the experiment indicated that water losses increased steadily to a constant rate. Each successive downstream channel reach had a lower loss rate. The water losses decreased in succession from the most upstream reach, which stabilized at 1.09 ft^3/s per 1,000 ft of channel length after 14 days,

to the most downstream reach, which stabilized at 0.64 ft^3/s per 1,000 ft after 20 days. These flow losses were directly related to flow depth and channel geometry. Flow extended for about 7,000 ft downstream from the end of the pipeline. The flow widened the channel for about 900 ft, removed most fine-grained alluvial material for about 3,500 ft, and deposited intermittent layers of sand and silt farther downstream. These channel changes were related to the discharge and velocity in each reach.

Several sets of water levels and two set of geophysical logs were made before the experiment was started and daily water levels and six additional sets of logs were made during the experiment to document water-table changes and moisture changes in the 330-foot thick unsaturated zone. The second set of logs showed a slight increase in moisture in several individual beds between the surface and a depth of about 70 ft. This slight increase in moisture is attributed to the short-term pumping of well NV–6p for the equipment test. Subsequent logs made during the aquifer test showed moisture increases in additional beds between the surface and the water table and a mound of moisture (almost to saturation) developing above the water table. This mound expanded to a thickness of about 50 ft between the seventh and sixteenth days of the experiment. During the next 5 days, the mound continued to expand and was about 100 ft thick on the twenty-first day.

Meanwhile, on the fourth day of the experiment, the ground-water level began to rise in response to the water being recharged through the unsaturated zone. By the tenth day, the ground-water level increased 1.04 ft. After pumping was stopped, the high moisture content above the water table dissipated in less than 5 days and the moisture content in the entire unsaturated section returned to about pre-experiment conditions in 20 days.

The movement of water from the land surface to the water table through the 330-foot-thick unsaturated zone shows that recharge can occur much more quickly than commonly estimated for Basin and Range, unconsolidated, basin-fill deposits. Typically, estimates of downward velocity had ranged from 20 to 40 years for water to reach the water table at depths of 400 ft. Estimates of 50 years/100 ft were common. Vertical velocities of about 65 ft/d were observed during the recharge experiment.

Values calculated for vertical hydraulic conductivity (K_z) using steady, channel-loss rates for each reach ranged from 2.9 to 7.1 ft/d. The value calculated from the aquifer test was 2.2 ft/d. Values calculated using the average vertical velocity observed during the recharge experiment ranged from 6 to 11 ft/d.

The results of the tests conducted in the northern part of Vekol Valley were used to construct a numerical ground-water flow model of that area to evaluate well-field design and projected water-level declines caused by the proposed long-term pumping to supply the Ak-Chin Community's water needs (Hollett and Marie, 1987).

The study of the southern part of Vekol Valley included drilling 21 test holes at 14 sites and constructing 13 wells, 4 of which were high-capacity production wells designed as part of the proposed well field. The results of the study show that the aquifer system underlying south Vekol Valley is composed primarily of a thick sequence of silt, sand, and gravel units deposited in a structurally controlled basin. These units grade from a thick silt at the surface into sand and gravel units, which in turn, grade from unconsolidated to well cemented with depth in the basin. These basin-fill sediments unconformably overlie various rocks of Tertiary to Precambrian age that comprise the faulted blocks of the Basin and Range province. The upper unit is comprised of silt to sandy silt that ranges from a few feet to about 600 ft thick. This unit forms an effective, leaky confining unit in much of the southern part of the valley. The sequence of sand, gravel, and conglomerate that underlie the silty unit can be divided into two aquifers: an upper, unconsolidated sand and gravel aquifer that ranges in thickness from a few feet near the perimeter of the basin to about 1,100 ft in the central part of the valley. Underlying the upper aquifer in most of the southern valley is a lower gravel and conglomerate aquifer that is about 1,000 ft thick in the center of the valley but was not present in the north and northwest. Underlying the lower aquifer in much of the southern valley and possibly, at least in part, contemporaneous with it, is a sequence of volcanic rocks that are as much as 925 ft thick in the southwestern part of the valley. The volcanics, like the overlying conglomerate is not present in the northeast; however, the volcanic rocks are about 700 ft thick in the northern part of the valley where the conglomerate is not present.

Depths to ground water in the southern part of the valley range from about 330 to 670 ft where measured. Analysis of available hydraulic data indi-

cate that the southern part of Vekol Valley may be a closed ground-water basin. Data are not available to show vertical-head differences in the aquifer system underlying the southern valley. Analysis and evaluation of the two aquifer tests conducted in the thicker part of the aquifer system in the southern part of the valley give similar aquifer-system characteristics.

Property	Site SV–8 test	Site SV–11 test
Transmissivity	7,200 ft^2/d	9,000 ft^2/d
Storage coefficient	5.5×10^{-4}	3×10^{-4}
Specific yield	Not applicable	0.12
Hydraulic conductivity	5.6 ft/d	6.8 ft/d
Ratio of K_z:K_r	1:63	1:56

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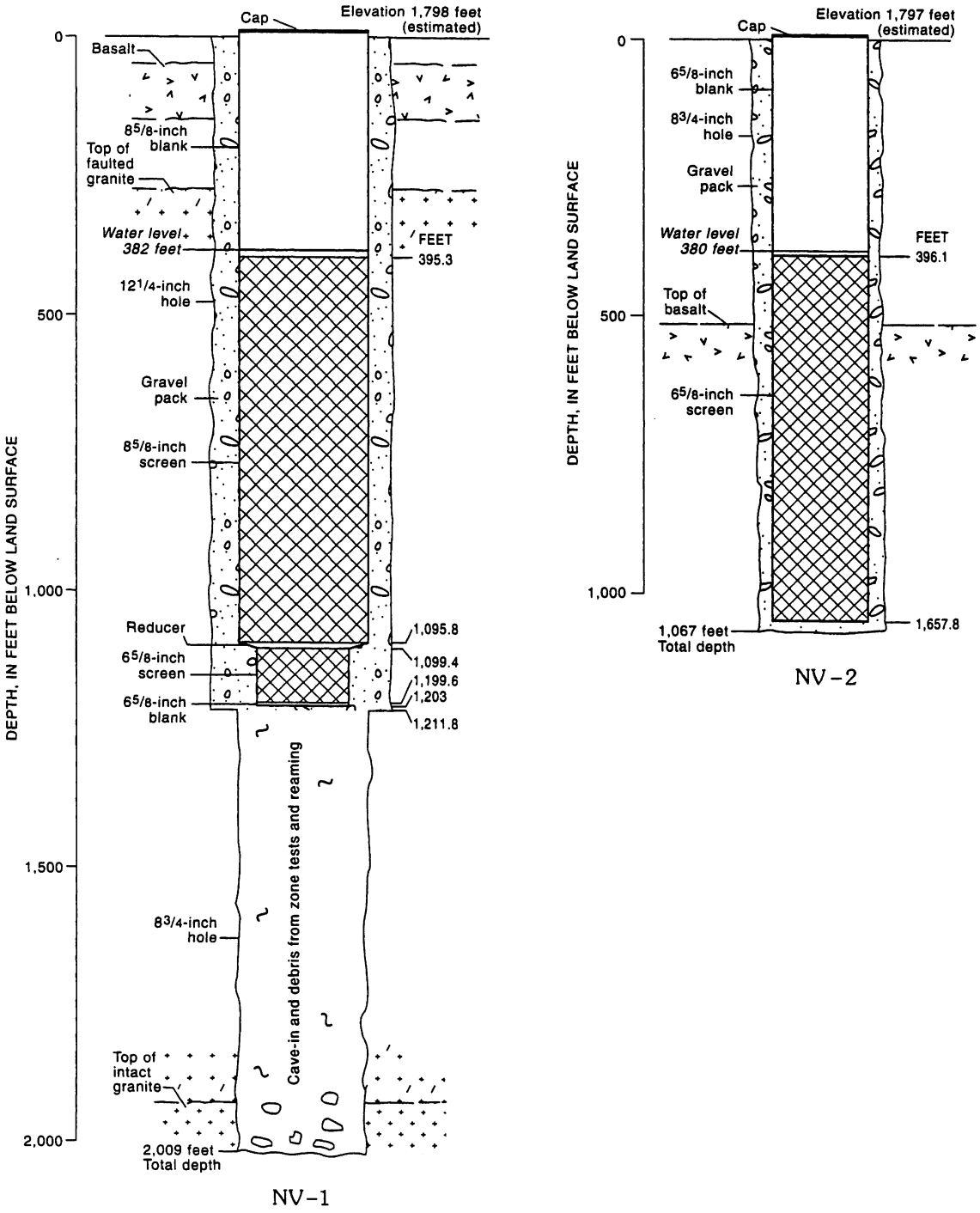
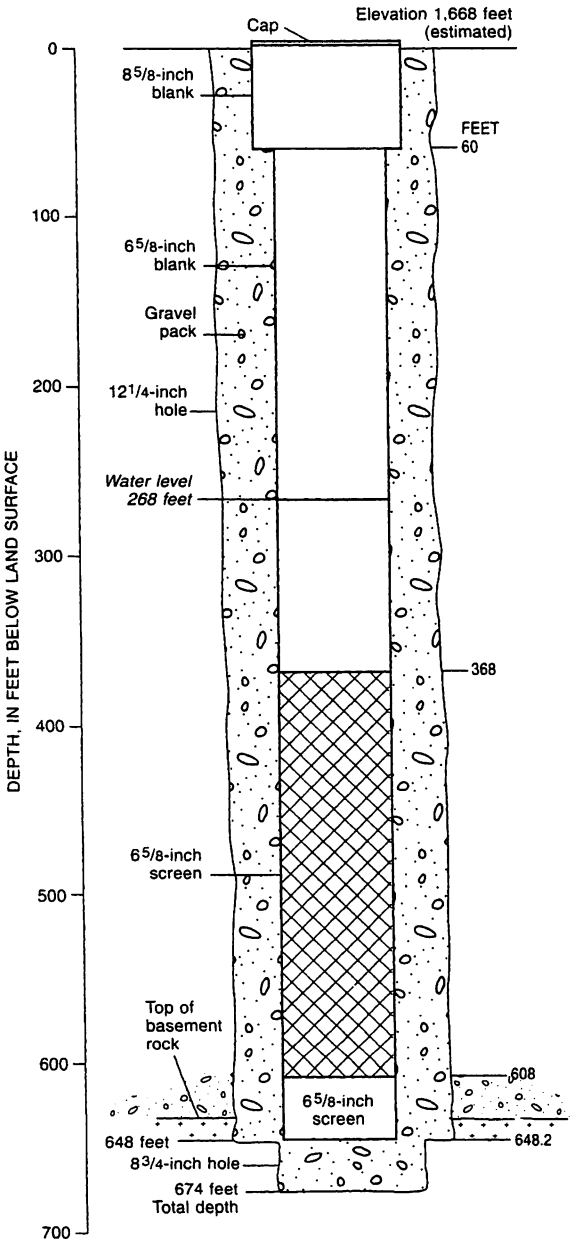
WELL CONSTRUCTION INFORMATION



Construction information for wells NV–1 and NV–2 installed in north Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1983.)



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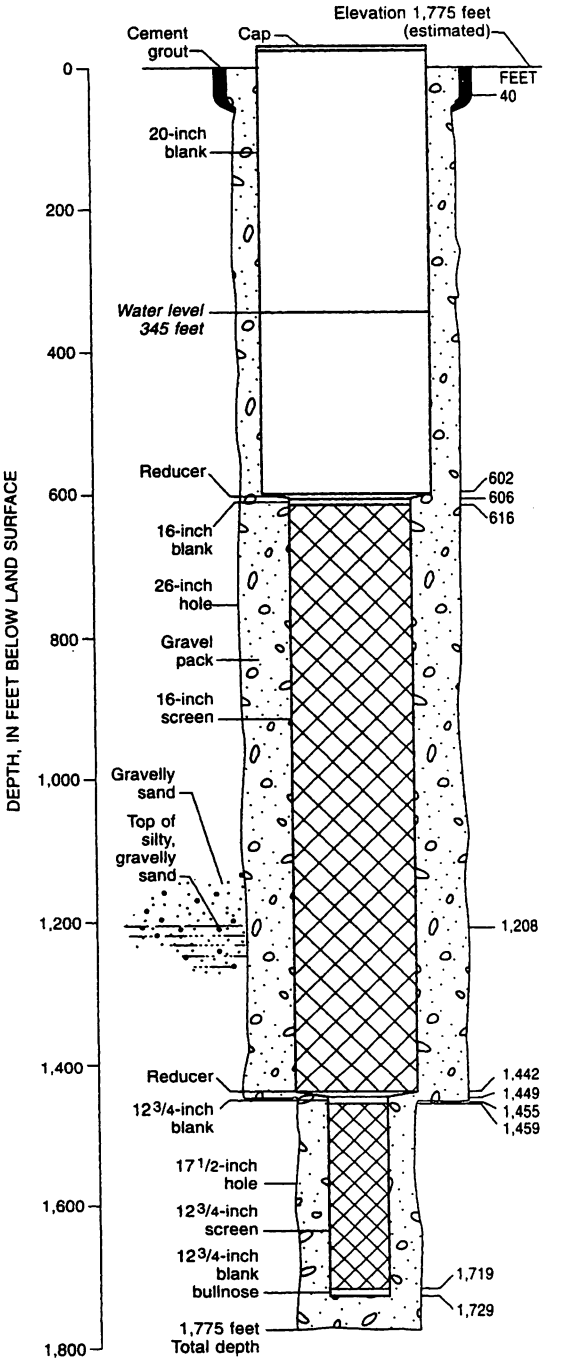

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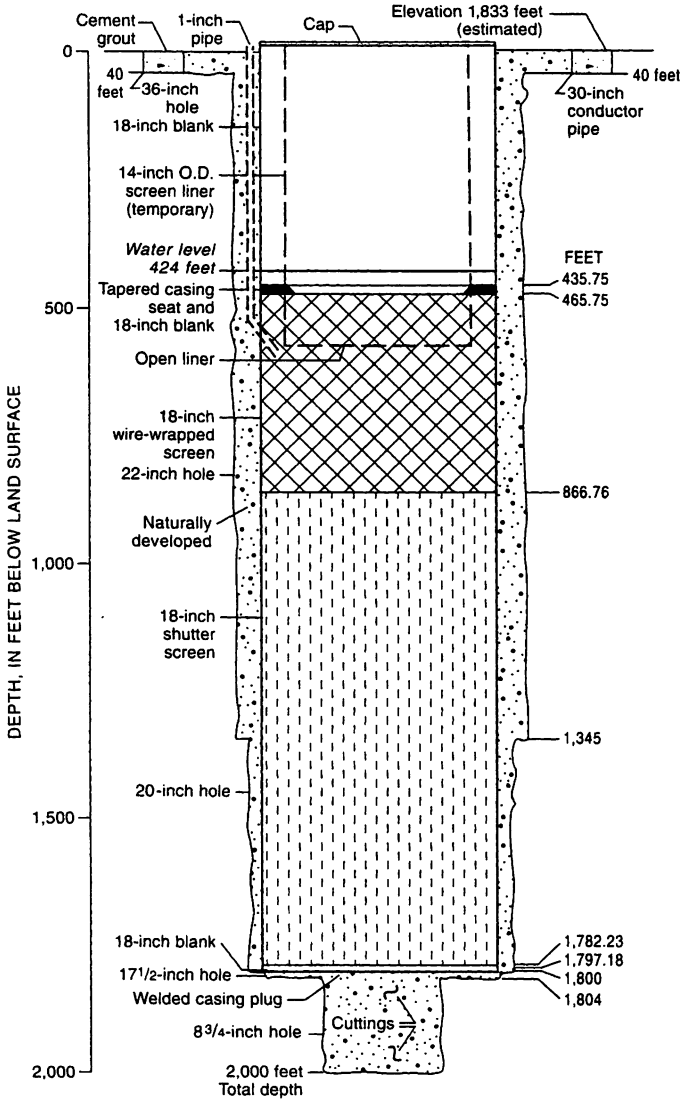

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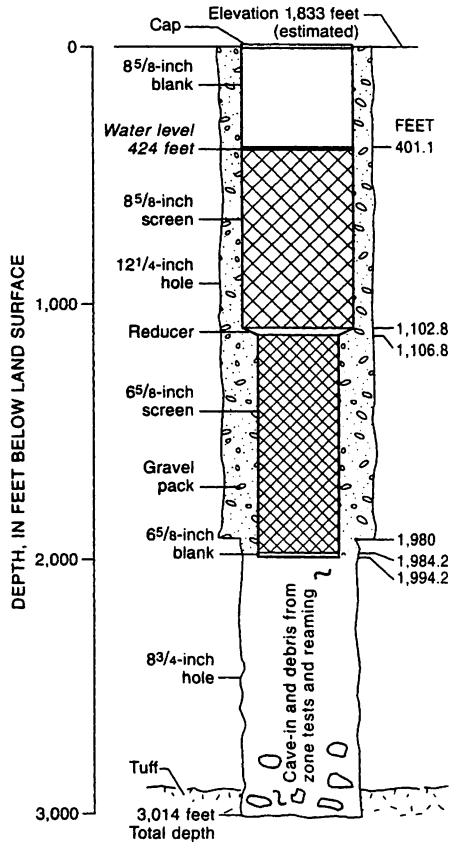

NV-5ob1

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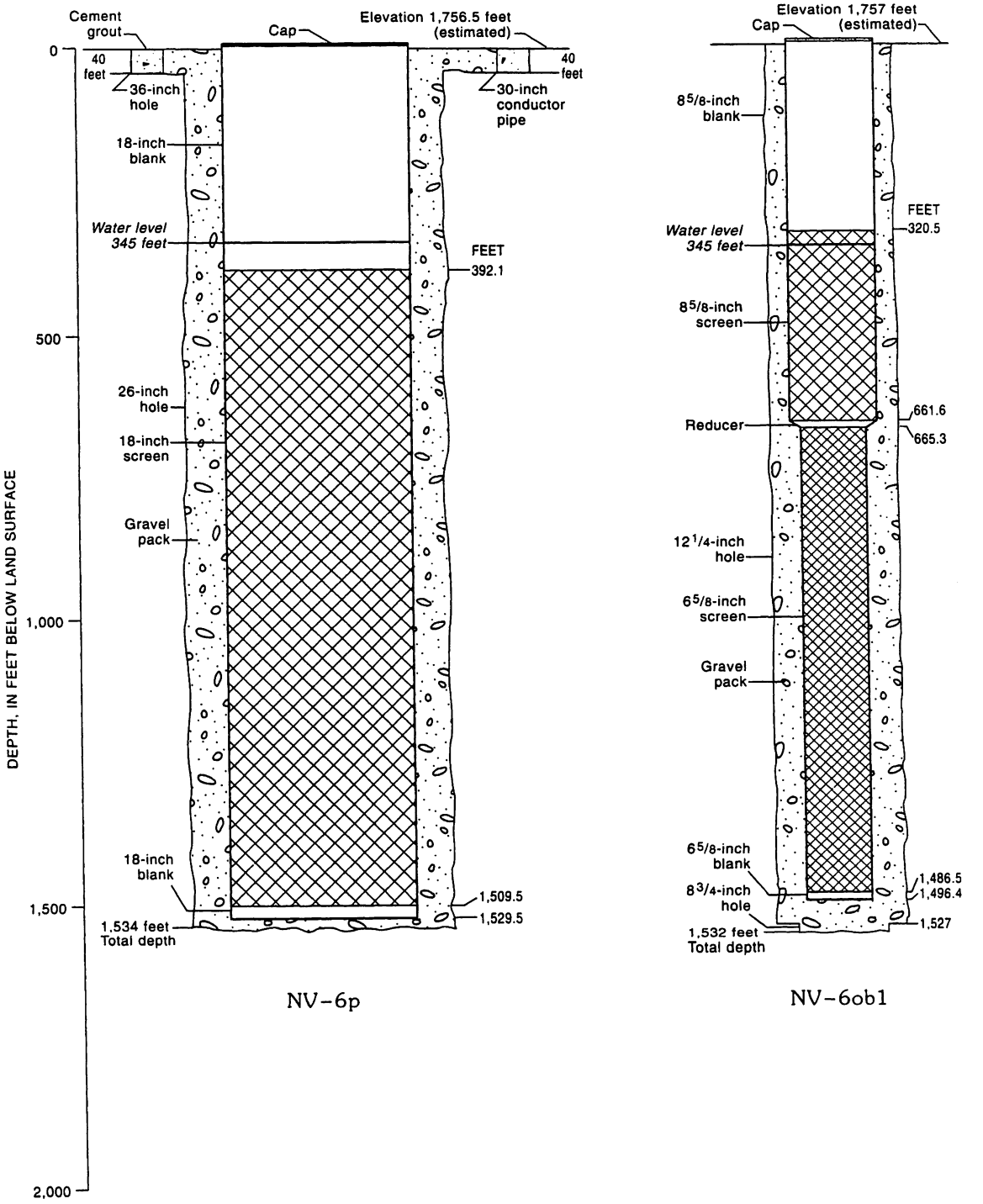

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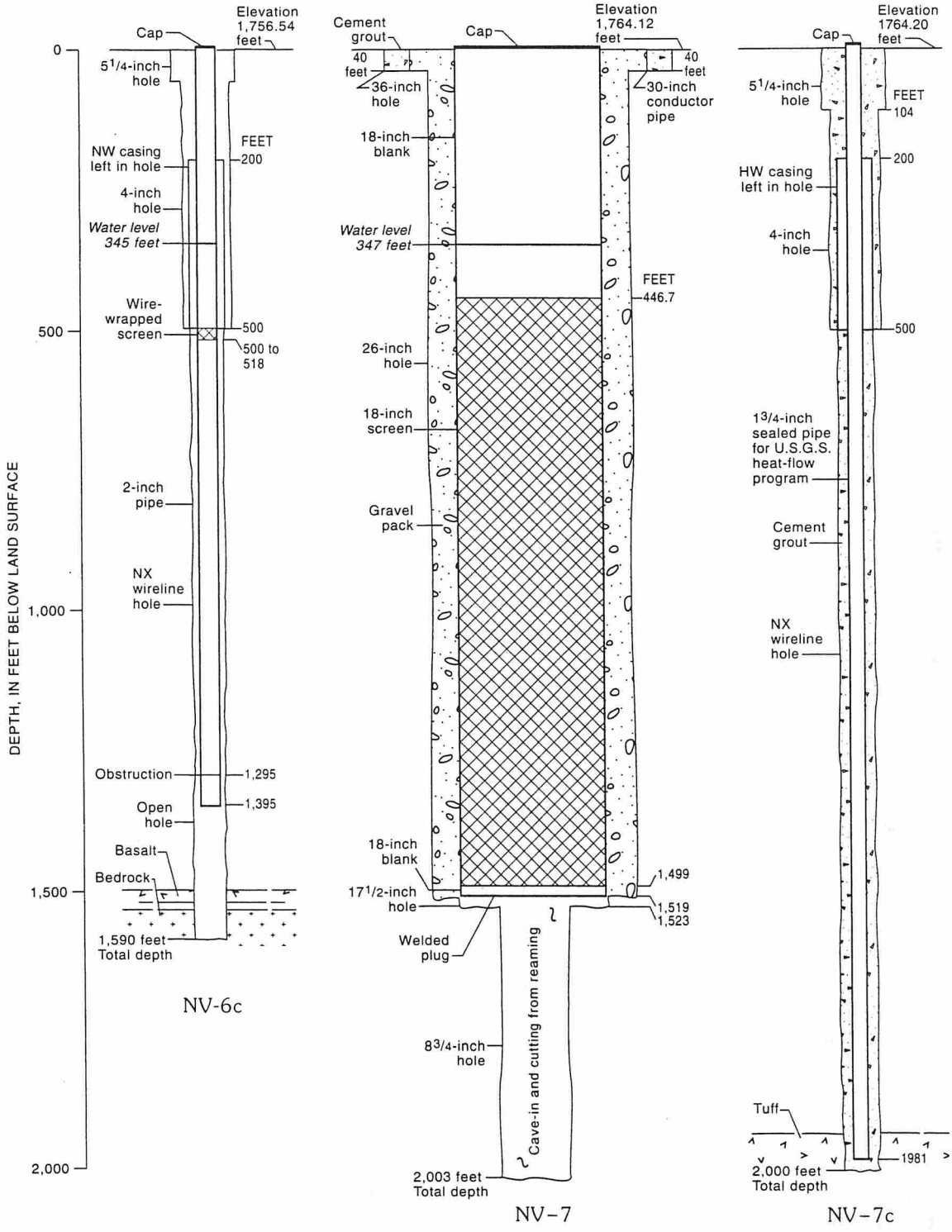

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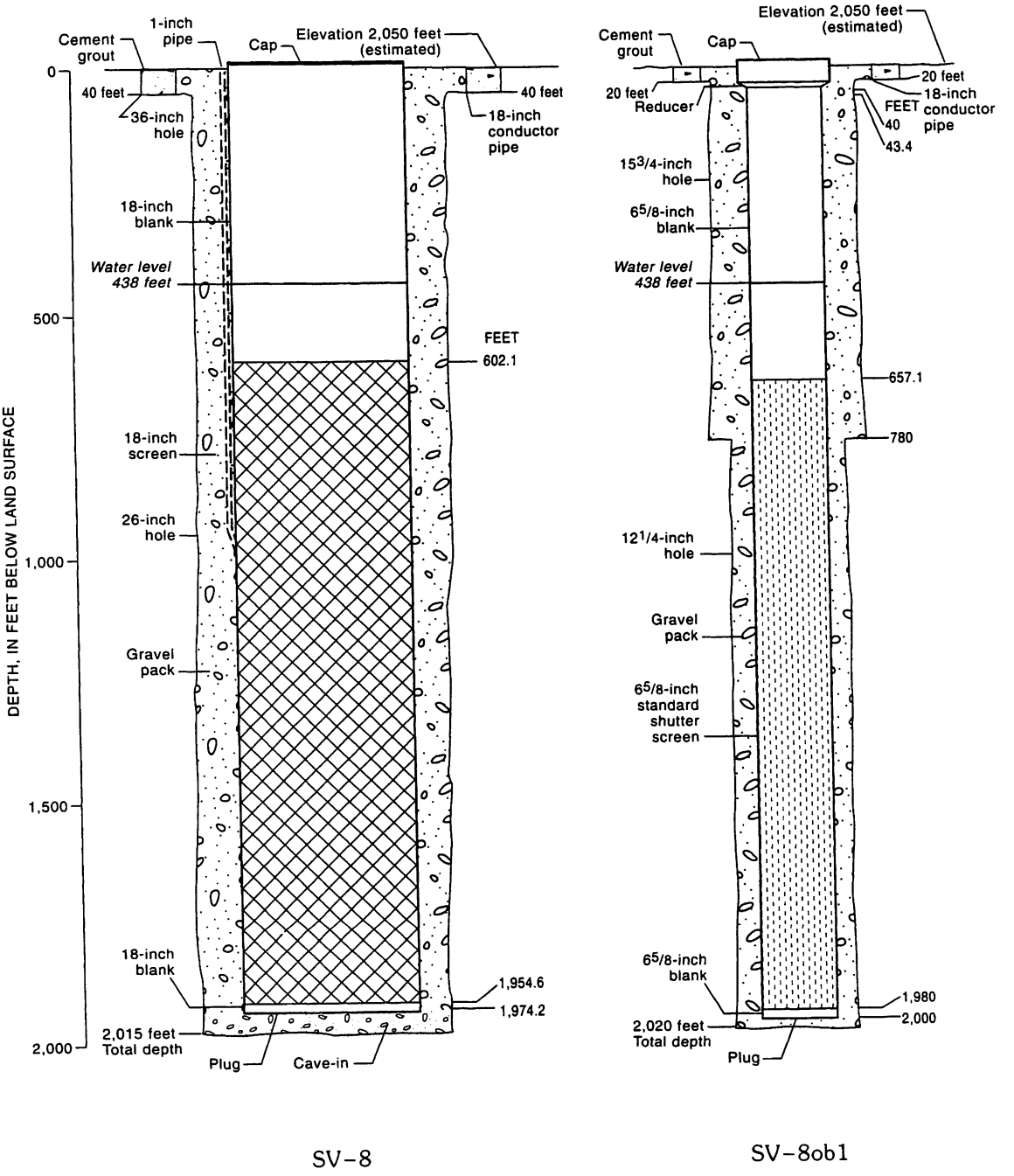
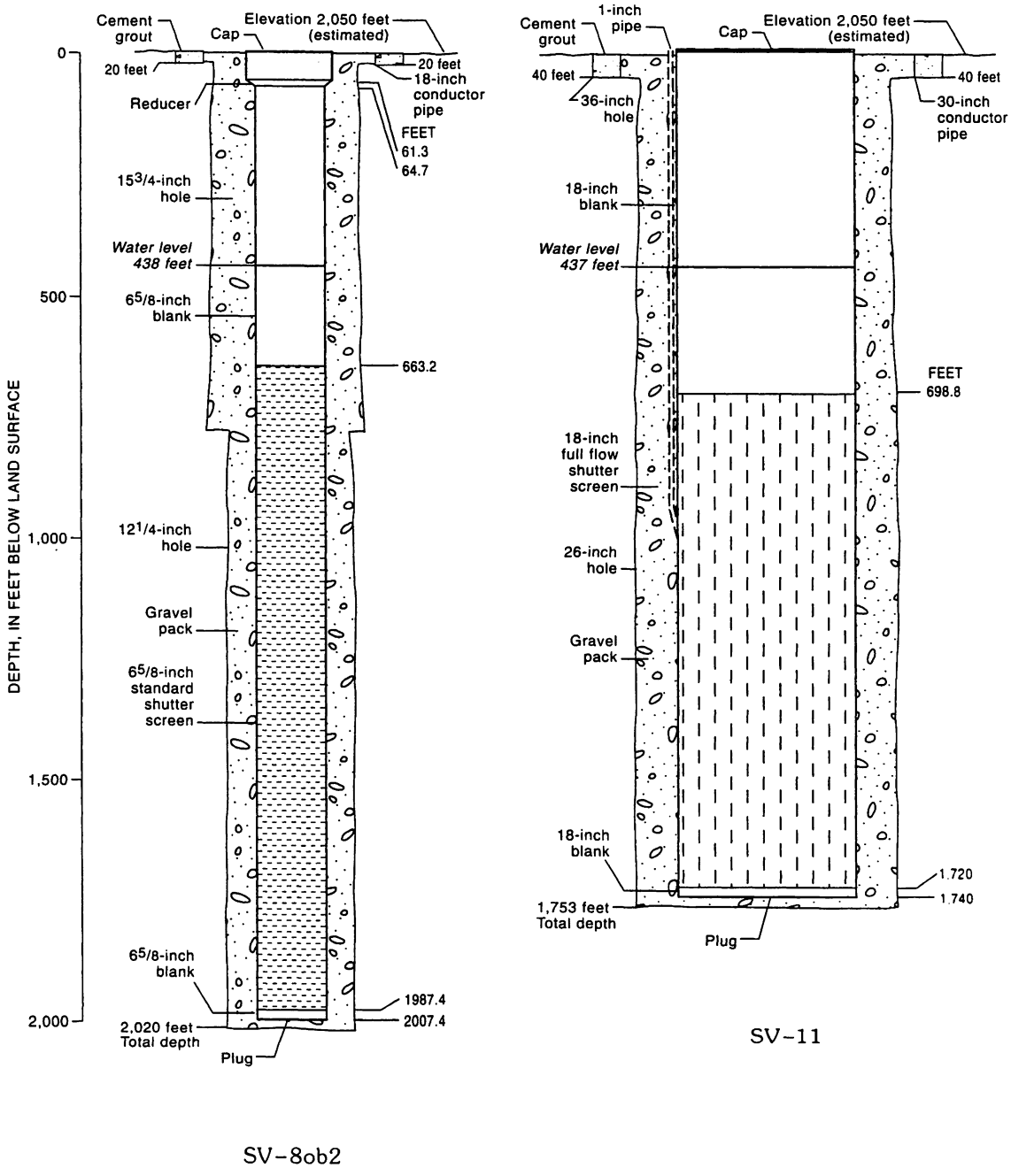


Construction information for wells SV–8 and SV–8ob1 installed in south Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1984.)



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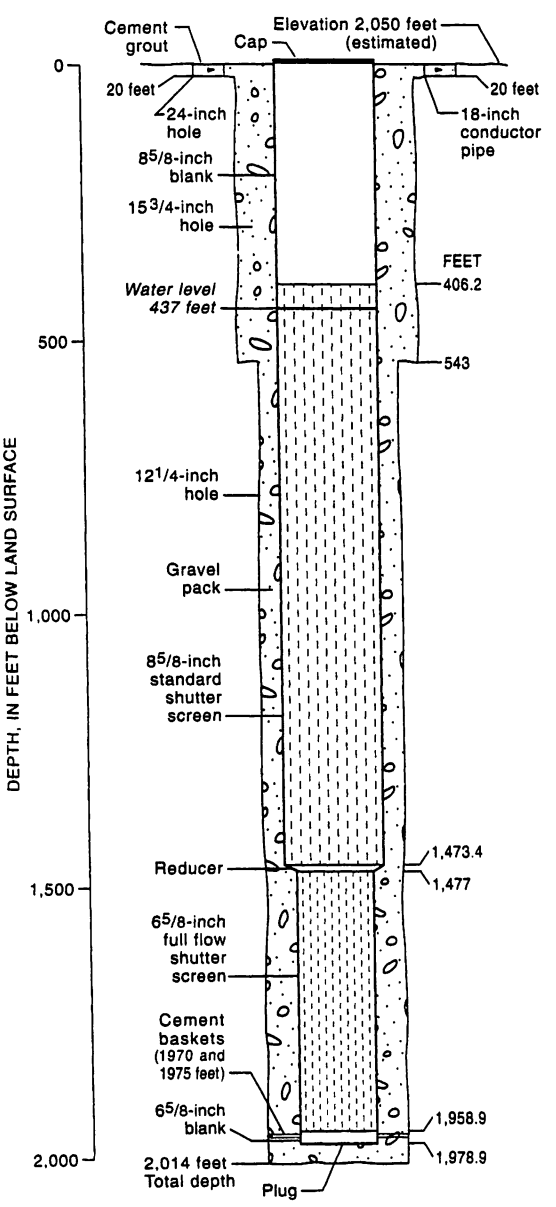
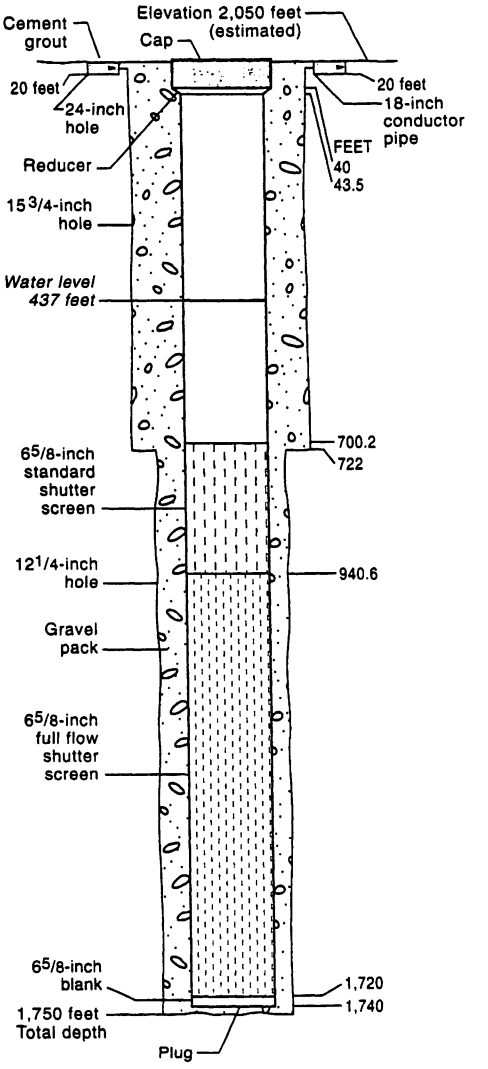


SV-11ob1



SV-11ob2

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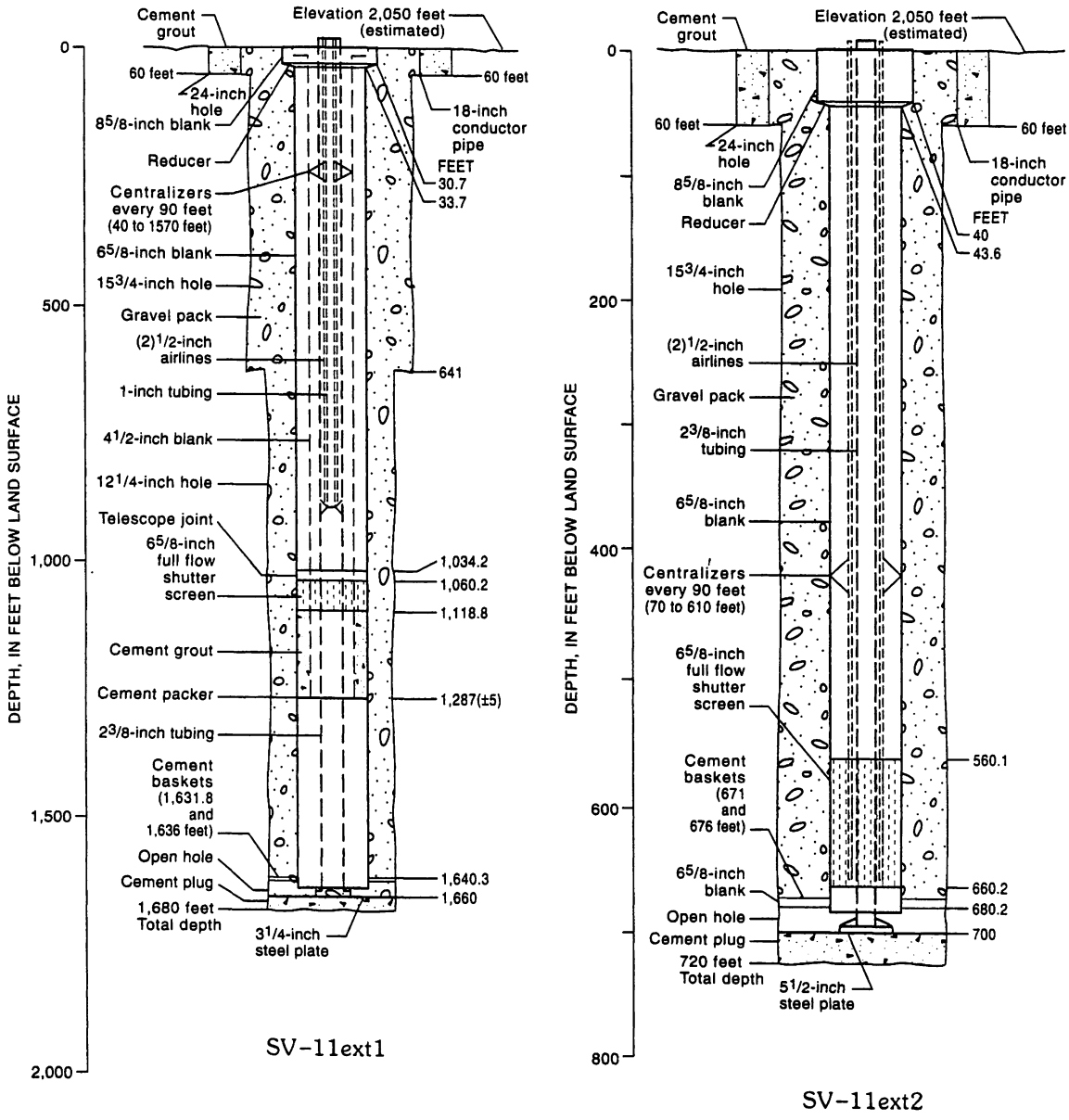

Construction information for wells SV–11ext1 and SV–11ext2 installed in south Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1984.)

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APPENDIX G

GROUND WATER MODELING SOFTWARE

THWELLS

Flow in an Confined, Leaky Confined or Unconfined Aquifer with Regional Uniform Flow and Multiple Wells

by

P.K.M. van der Heijde
Boulder, Colorado

IGWMC - BAS 04
Version 4.01
Released: May 1996

distributed by:

INTERNATIONAL GROUND WATER MODELING CENTER

Colorado School of Mines
Golden, CO 80401, USA

THWELLS: PROGRAM IDENTIFICATION

Program Name:	THWELLS
Title:	Flow in Confined or Unconfined Aquifer with Multiple Wells
Version:	4.01
Released:	May 1996
Author:	P.K.M. van der Heijde, Boulder, Colorado
Language:	Microsoft QuickBASIC version 4.5
IGWMC Number:	BAS 04
Legal status:	Proprietary (some restrictions apply)
Distributor:	International Ground Water Modeling Center Colorado School of Mines Golden, Colorado 80401-1887 phone: (303) 273-3103 fax: (303) 384-2037 e-mail: IGWMC@MINES.EDU

THWELLS: PROGRAM DESCRIPTION

The program 'THWELLS' calculates the drawdown or buildup of piezometric head due to the combined effect of up to 100 discharge or recharge wells in a confined, leaky-confined or unconfined aquifer. The calculations of total drawdown are based on either the Theis equation for non-steady state flow in an isotropic, homogeneous confined aquifer of infinite extent or the Hantush-Jacob equation for the same conditions in leaky-confined aquifers. The model can be used for water-table aquifers in case the calculated drawdowns are less than half the saturated thickness of the aquifer. The correction applied for water-table conditions is based on the following expression:

```
Drawdown  S(Theis) = S(Watertable) - (S(Watertable)^2 / (2 * H0))
```

This expression is evaluated using the quadratic formulae. The computed effects of individual wells are superposed on a regional, horizontal or sloping groundwater surface. Boundary effects can be included through the use of image well theory.

This menu-driven program facilitates interactive data entry and editing. It includes tabular and graphic screen display of results. Graphic display includes both time-drawdown curves for selected locations and contour plots for a user-specified time. The program can be used with either metric (meter, day) or English units (foot, US gallon, day). Data can be entered manually or from an external disk file, prepared in an earlier session. For instructional purposes the program contains a set of realistic default values.

The program has the option to prepare a SURFER (1) compatible ASCII file, containing grid information and calculated drawdowns for contour generation and other post-processing tasks. Furthermore, THWELLS provide

ASCII tabular output directly to an on-line printer, or to an ASCII file for word-processing.

(1) SURFER is a trade mark of Golden Software Inc., P.O. Box 281, Golden, Colorado 80402.

THWELLS: SYSTEM REQUIREMENTS

This program is a DOS application running in conventional memory. It requires:

- Intel 80i86 based computer with 640 Kb RAM and math coprocessor
- about 0.5 Mb disk space to install and run the program
- DOS 3.1 or higher
- CGA, EGA or VGA graphics

The programs run as a DOS application under MS Windows 3.1.

THWELLS: DISK CONTENTS

This program is distributed by IGWMC on a high density (HD), DOS-formatted disk. The disk contains the following files:

THWELLS.EXE	- Executable, compiled, ready-to-run version
THWELLS.DOC	- ASCII documentation file
README.BAT	- batch file to read the documentation file
GWDISP.COM	- utility to read the documentation file

In addition, the diskette contains a number of test data files; these problems have been verified using the tabulated W(u) function values given by Walton (1983; see documentation):

THW4D-1C.DAT	- Test 1: confined, 1 well, metric units
THW4D-1U.DAT	- Test 1: unconfined, 1 well, metric units
THW4D-2C.DAT	- Test 2: confined, 1 well, English units
THW4D-2U.DAT	- Test 2: unconfined, 1 well, English units
THW4D-3C.DAT	- Test 3: confined, 6 wells, English units
THW4D-3U.DAT	- Test 3: unconfined, 6 wells, English units

An extended example using the various program options present is described in the documentation. This example uses English units and applies to a confined aquifer. The data pertinent to this example are included in the following files:

THW4-2C1.DAT	- 1 real well; no regional groundwater flow (horizontal piezometric reference surface)
THW4-2C2.DAT	- 1 real well, 4 image wells; no regional flow
THW4-2C3.DAT	- 1 real well, 16 image wells; no regional flow
THW4-2C4.DAT	- no wells; regional flow present (sloping piezometric surface specified)
THW4-2C5.DAT	- 1 real well, no image wells; regional flow specified
THW4-2C6.DAT	- 1 real well, 4 image wells; regional flow specified
THW4-2C7.DAT	- 1 real well, 16 image wells; regional flow specified

Finally, there are six simple data sets provided containing the default values embedded in the software itself; these data sets were used to check the functionality of the program:

THW4-CM1.DAT	- 1 real well; no regional ground-water flow (horizontal piezometric reference surface); confined aquifer; metric units.
THW4-CE1.DAT	- 1 real well; no regional ground-water flow; confined aquifer; english units.
THW4-LM1.DAT	- 1 real well; no regional ground-water flow; leaky confined aquifer; metric units.
THW4-LE1.DAT	- 1 real well; no regional ground-water flow; leaky confined aquifer; english units.
THW4-UM1.DAT	- 1 real well; no regional ground-water flow; water-table aquifer; metric units.
THW4-UE1.DAT	- 1 real well; no regional ground-water flow; water-table aquifer; english units.

THWELLS: INSTALLATION PROCEDURE

(1) Review all documentation.

(2) Make sure that the disks supplied are write-protected, and prepare a backup copy of the disks.

(3) Copy all files from the distribution disk to a designated subdirectory on your hard drive using the DOS COPY command. To create the designated subdirectory use the DOS MD command (Make Directory).

THWELLS: TO RUN THE PROGRAM

To run the program, simply enter: THWELLS. THWELLS is operated from a main menu. This main menu provide options for entering a new data set, reading in a previously prepared data set, editing and saving data sets, calculating time-drawdown pairs using a user-defined time scale, and calculating spatially distributed drawdowns at a particular time using a user-defined, regular grid. Note that the program does not start a calculation or enter the edit/save modes if not first one of the two data-entry options have been completed. At any time, you can modify the data through the editing option.

The results of the calculations can be viewed in table format and graphically on screen, routed to a file or on-line printer, or saved for postprocessing. These options are selected from sub-menus which are displayed after the calculation is completed.

Selecting a file for data entry is facilitated interactively. It can be operated with a mouse, or by using the cursor and tab keys. Make sure to click on the file of choice; the name appears in the file name box. Then, click on the OK button to activate the file reading procedure.

THWELLS: PROGRAM DOCUMENTATION

Van der Heijde, P.K.M. (1992). THWELLS - Version 4.0: Calculating Drawdown Resulting from Multiple Discharge or Recharge Wells in an Isotropic Homogeneous Aquifer with Regional Flow. BAS-04, IGWMC, Colorado School of Mines, Golden, Colorado.

PROGRAM STATUS, SUPPORT AND MAINTENANCE

THWELLS is a proprietary program subject to restrictions on copying and redistribution of software and documentation. The software is distributed without source code. If you are interested in the source code, you should contact the developer. You may make copies for backup purposes and install the software on different computers within your office. You may not transfer the software to or make copies for users outside your company or institute without written permission from the developer. You are not allowed to (re)sell the software without written permission from the developer.

The IGWMC provides limited technical support for this program to its clients. Support is provided in the form of written or verbal communication, and covers assistance in program installation and operation only.

Although IGWMC staff members may often respond to questions about the use of a given program, the software support provided by the Center does not cover consulting services to assist users in the solutions to groundwater problems. The IGWMC does not support and disclaims any responsibility for use of software not purchased directly from the Center unless such support is covered by a written agreement with requester's organization.

The Center provides maintenance for its software through periodic updates provided at a discounted price to registered users only.

IGWMC WARRANTY/DISCLAIMER

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INTERNATIONAL GROUND WATER MODELING CENTER

The International Ground Water Modeling Center is an international information, education, and research center for ground water modeling, established to advance the qualified use of computer-based decision-support technology in groundwater resource management and pollution prevention.

The Center provides information on a variety of modeling related topics, distributes groundwater modeling software, and maintains extensive databases on ground water modeling peripheral software. It organizes an annual series of short courses, provides assistance in conducting workshops and seminars, and cooperates with national and international organizations in organizing modeling conferences.

Furthermore, the IGWMC conducts an extensive research program aimed at advancing and improving the use groundwater models as an integral part of regulatory and management decision-making, and in support of the informative and educational activities of the Center.

SPECIAL INSTRUCTION FOR PROGRAMS RUNNING UNDER 640 Kb RAM (LOW MEMORY ONLY)

Some of the older or simpler programs distributed by the IGWMC have been compiled for IBM PC/XT and PC/AT compatible computers running under MS-DOS or PC-DOS and will only run in conventional or low memory requiring less than 640 Kb RAM, e.g., WHPA, BIOPLUME II, THWELLS and SOLUTE. These programs will not use extended or expanded memory, even if its is available, nor do they access Intel 80386/80486 protected mode. They are often designed to use the maximum available memory after DOS has been loaded and compete for this limited memory with other system software (e.g., disk-cache), memory-resident programs, memory managers, and device drivers (including network drivers). This may cause some problems, such as:

- Inability to run the program; the program returns to DOS without proper execution.
- Computer locks up after starting the program requiring a warm or even a cold reboot.
- The program will run correctly until functions or program modules are called which require more memory, such as graphics, additional executables called from the program's main module or shell, and creating graphics output files. The program may abort, lock-up the keyboard, or returns to DOS while the output created is incomplete, or even not saved at all.
- Other runtime errors may occur, such as inability to open files, too many open files, too many units connected, stack overflow, not enough space for environment, abnormal program termination, and unexpected heap error, preventing correct running or continuation of the program.

Although these errors are frustrating, often, they can be easily solved. Often, installing IGWMC programs require the user to check, and when necessary, to make changes in the AUTOEXEC.BAT and CONFIG.SYS files on the boot disk of your computer system. In addition, when problems, as listed above, occur, additional modification of these system files may be necessary to free up memory for the IGWMC program. Some of these changes are specified in the IGWMC-produced documentation file distributed with each program. This file can be viewed by making the distribution disk (or the work directory) current and typing "readme" at the DOS prompt. A hardcopy version of this documentation file is included in the front of each IGWMC-prepared documentation package.

Typical changes in the CONFIG.SYS file include modification of the FILES and BUFFERS statements in the CONFIG.SYS file, adding a STACK statement to the CONFIG.SYS file, and including the statement DEVICE=[path]ANSI.SYS where path refers to the DOS directory on your hard drive. If this does not solve the problem, ram cache, memory managers and other programs using low memory need to be removed or loaded in high memory (under DOS 5.0 or higher). Programs requiring maximum low memory resources may not run on a network or as a DOS application under MS WINDOWS.

Sometimes, an IGWMC-distributed program require changes to the AUTOEXEC.BAT file. Possible modifications include the PATH statement, and addition of SET statements. Newer PC's often come with many peripherals requiring many device drivers, complex PATH statements, and memory-resident programs. It might be necessary to detach some of these devices to allow the IGWMC software to run. If you are not familiar with these DOS options, it is advisable to confer with your system manager or the person/organization who have set up your computer to determine the specifics of such modifications.

Before you make any changes to your CONFIG.SYS and AUTOEXEC.BAT files, make a backup copy, e.g., "COPY AUTOEXEC.BAT AUTOEXEC.OLD" and "COPY CONFIG.SYS CONFIG.OLD". These backup copies can be copied back to the AUTOEXEC.BAT and CONFIG.SYS files when the runs with the IGWMC-provided program have been completed. After creating the back up copies, the existing AUTOEXEC.BAT and CONFIG.SYS files can be modified using a line editor, e.g., the DOS program EDIT. After saving the

changed files, the computer needs to be rebooted (CTL-ALT-DEL) to make the changes effective. To see how much low memory is available, type the DOS command "MEM" at the DOS prompt. For older versions of DOS (3.0 or earlier) you need to use "CHKDSK" command instead. In an optimal configuration, close to 600 Kb of low RAM may be available for the IGWMC-distributed program, especially when DOS is loaded high (DOS 5.0 or later). The maximum memory requirement for any of the IGWMC conventional memory programs is about 580 Kb of low RAM.

If the above mentioned modifications are not successful:

- make sure that you have the correct number of disks;
- the disks contain all files on the packing list (see "readme" file)
- you have followed the installation instructions correctly
- the disks have not been damaged in shipping; this may be checked by using NORTON, PCTOOLS or other disk utilities.

If problems persist, or you expect a bad or incomplete disk, call IGWMC user support at 303-273-3107 with specifics and nature of the problem. If possible, provide the error message(s) displayed when trying to run the program, as well as the results of the memory check. Note that obtaining new disks will not solve low memory problems, so check the memory usage first before contacting IGWMC.

An example of generic CONFIG.SYS and AUTOEXEC.BAT files that will work for most applications and leave much of the low memory available for application programs is presented below. Individual systems may differ, so confer with your system manager when using these examples.

Sample CONFIG.SYS

```
Shell=C:\COMMAND.COM /p /e:1024
Dos=High
Device=C:\DOS\ANSI.SYS
Files=50
Buffers=30
```

Sample AUTOEXEC.BAT

```
@ECHO OFF
Loadhigh C:\DOS\DOSKEY
Path=c:\;c:\dos;c:\(your program name)
@PROMPT $P$G
```

It should be noted that some of the mentioned problems might not be caused by shortage of memory, but by incorrect data entry. Often, this results in "divide by zero", "integer overflow", "real math overflow", "invalid integer", "invalid real", or "end of file encountered" error messages. Other typical problems are "no space left on device" (no storage space on current disk or hard drive; use other disk or free-up space on your hard drive), and "file not found" (program expects a file with a particular name and can not find it; consult the program documentation for file requirements and conventions).

International Ground Water Modeling Center
Colorado School of Mines, Golden, CO 80401
phone: 303/273-3103, fax: 303/384-2037
email: "igwmc@mines.colorado.edu"

1/25/95

IGWMC NOTES ON THE THWELLS MODEL

1. There are two ways to print graphics: 1) Before entering the program type "GRAPHICS" at the DOS prompt. Then when the desired graphic appears in the program, type "Shift/Print Screen"; 2) Save model output to an external file then use a program like Golden Software's SURFER (TM) to contour output.

Colorado School of Mines, Golden, Colorado 80401-1887, USA
Phone: 303/273-3103. FAX 303/384-2037. Email: igwmc@mines.colorado.edu
Toll-free in Colorado - 800/245-1060 Toll-free outside Colorado - 800/446-9488

THWELLS

Calculating Drawdown Resulting from Multiple Discharge or Recharge Wells in an Isotropic Homogeneous Aquifer with Regional Flow

by

Paul K. M. van der Heijde
International Ground Water Modeling Center
Colorado School of Mines
Golden, Colorado

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INTERNATIONAL GROUND WATER MODELING CENTER

Institute for Ground-Water
Research and Education
Colorado School of Mines
Golden, Colorado

INTRODUCTION

The program **THWELLS** calculates the drawdown or buildup of piezometric head due to the combined effect of up to 100 discharge or recharge wells. The calculation of total drawdown is based on the Theis and Hantush-Jacob equations for non-steady state flow in an isotropic, homogeneous aquifer of infinite extent under confined or leaky confined conditions, respectively. The computed effects of individual wells are superposed on a regional, horizontal or sloping ground-water surface. The model can be used for water-table aquifers in case the calculated drawdowns are less than half the saturated thickness of the aquifer. Boundary effects can be included through the use of image well theory. This menu-driven program facilitates interactive data entry and editing. It includes tabular and graphic screen display of results. Graphic display includes both time-drawdown curves for selected locations and contour plots for a user-specified time. The program can be used with either metric (meter, day) or English units (foot, US gallon, day). Data can be entered manually or from an external disk file, prepared in an earlier session. For instructional purposes the program contains a set of realistic default values.

The program has the option to prepare a SURFER[1] compatible ASCII file, containing grid information and calculated drawdowns for contour generation and other post-processing tasks (e.g., using IGWMC's GWREFORM program to add and subtract gridded values for files having identical grid definition). Furthermore, THWELLS provide ASCII tabular output directly to an on-line printer or to an ASCII file for word-processing.

MATHEMATICAL MODELS

Confined Aquifers

The mathematical model for confined aquifers is based on the Theis equation for horizontal, transient, radial flow in a homogeneous, isotropic, nonleaky confined aquifer (figure 1.). Theis noted that when a well penetrating an extensive confined aquifer is continuously pumped, the area of influence of the well (i.e. the area where drawdowns occur) increases with time, forming a growing cone of depression (Theis 1935). The rate of decline of head, multiplied by the storage coefficient of the aquifer and summed over the area of influence, equals the discharge of the well. Because the water must come from a reduction of storage within the aquifer, the heads will continue to decline as long as the cone of depression does not reach a feeding boundary. However, the rate of decline decreases continuously as the area of influence (which under these conditions is the same as the area covered by the cone of depression) expands and eventually becomes so small that for all practical purposes it may be neglected (Kruseman and De Ridder 1970).

The Theis equation is given by (Walton 1983) (see Figure 1) as:

$$s = \frac{Q}{4\pi T} W(u)$$

with

$$u = \frac{r^2 S}{4Tt}$$

[1]SURFER is a trade mark of Golden Software Inc., P.O. Box 281, Golden, CO 80402. SURFER is a menu-driven program to create contour plots and surface graphs of two-dimensionally defined variables.

in which

s	=	drawdown [L]
Q	=	pumping rate of production well [$L^3 T^{-1}$]
W(u)	=	Theis well-function [dimensionless]
r	=	radial distance from production well to observation well [L]

$$r^2 = (x_p - x_o)^2 + (y_p - y_o)^2$$

x_p	=	x-coordinate of production well [L]
y_p	=	y-coordinate of production well [L]
x_o	=	x-coordinate of observation well [L]
y_o	=	y-coordinate of observation well [L]
S	=	storage coefficient [dimensionless]
T	=	transmissivity [$L^2 T^{-1}$]
t	=	time duration of operation of production well before time of monitoring [T]

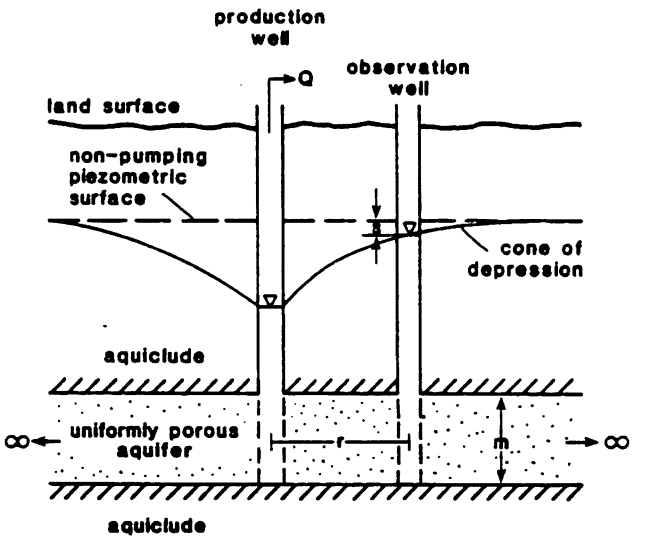

Figure 1. Definition of Theis condition aquifer

In deriving the Theis solution it is assumed that the aquifer is homogeneous, isotropic, of uniform thickness, and of infinite extent. Water is released instantaneously from storage by compaction of the aquifer matrix and by expansion of the water itself. The pumping well is fully penetrating and no water is stored in the well bore or the confining layer. Prior to pumping, the piezometric surface is horizontal over the entire area; that is, no regional flow is present.

The exponential integral W(u), called the Theis well function, is approximated by (Todd 1959):

$$W(u) = -.57721566 - \ln(u) + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + ...$$

or (Walton 1983):

$$W(u) = -\ln(u) - A_1 + A_2 u - A_3 u^2 + A_4 u^3 - A_5 u^4 + A_6 u^5 \quad for \quad 0 \le u \le 1$$

and

$$W(u) = \frac{1}{ue^4} \; \frac{u^4 + B_1 u^3 + B_2 u^2 + B_3 u + B_4}{u^4 + C_1 u^3 + C_2 u^2 + C_3 u + C_4} \quad for \; 0 \le u \le \infty$$

with

A_1 =	.57721566	A_4 =	.05519968
A_2 =	.99999193	A_5 =	.00976004
A_3 =	.24991055	A_6 =	.00107857
B_1 =	8.5733287401	C_1 =	9.5733223454
B_2 =	18.0590169730	C_2 =	25.6329561486
B_3 =	8.6347608924	C_3 =	21.0965308270
B_4 =	.2677737343	C_4 =	3.9584969228

The model for multiple wells is derived by superposition of the Theis solution for individual wells and is given by (Walton 1983):

$$s_t = \sum_{i=1}^{n} \frac{Q_i}{4\pi T} W_i(u_i)$$

$$u_i = \frac{r_i^2 S}{4\pi T t_i}$$

in which

s_t	=	total drawdown [L]
Q_i	=	pumping rate of production well i [$L^3 T^{-1}$]
W_i	=	well-function for production well i [dimensionless]
r_i	=	radial distance from production well i to observation well [L]

$$r_i^2 = (x_i - x_o)^2 + (y_i - y_o)^2$$

x_i	=	x-coordinate of production well i [L]
y_i	=	y-coordinate of production well i [L]
t_i	=	time duration of operation of well i before time of monitoring [T]

Water-table Conditions

The model can be used for water-table aquifers when the calculated drawdowns are small compared to the saturated thickness H_o of the aquifer. The correction applied for water-table conditions is based on (Jacob 1946; see Bear 1979, p.311):

$$s_c = s_{wt} - s_{wt}^2 / 2H_o$$

This expression is evaluated using the quadratic formulae:

$$s_{wt} = H_0 - \sqrt{H_0^2 - 2H_0 s_c}$$

with

s_{wt}	=	drawdown for water-table conditions (affected by gravity drainage)
s_c	=	drawdown for equivalent confined conditions (not affected by gravity drainage)

Leaky-Confined Aquifers

When a leaky-confined (or semi-confined) aquifer is pumped, water withdrawn not only from the aquifer but also from the overlying semi-confining (or semi-pervious) layer, assuming that the latter is (at least partly) saturated (Kruseman and De Ridder 1970). The pumping causes a lowering of the heads in the aquifer, resulting in a head gradient between the semi-confining layer and the aquifer. Due to this head gradient water from the confining layer will flow towards the aquifer. The amount of water moving into the aquifer is proportional to this gradient and inversely proportional to the hydraulic resistance of the saturated part of the confining layer.

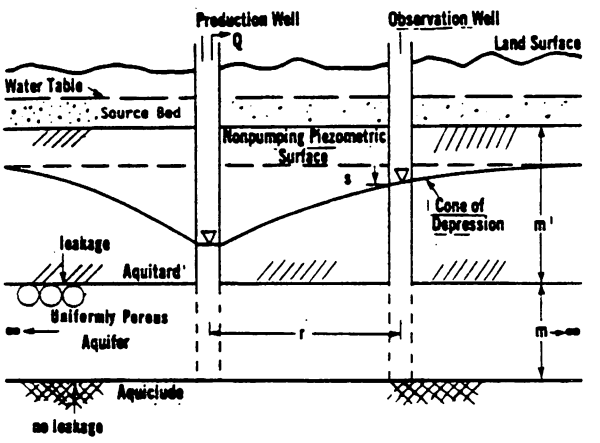

Figure 2. Definition of Hantush-Jacob condition aquifer

Assuming that the hydraulic head in the semi-confining layer is constant in time, the drawdown in the aquifer resulting from pumping the well can be expressed as (Hantush and Jacob 1955) (see Figure 2)

$$s = \frac{Q}{4\pi T} W(u, r/L)$$

with

$$u = \frac{r^2 S}{4Tt}$$

in which

W(u,r/L)	=	leaky-aquifer well-function [dimensionless]
L	=	√(Tc), leakage factor [L]
c	=	D'/K', hydraulic resistance of confining layer [T]
D'	=	saturated thickness of confining layer [L]
K'	=	hydraulic conductivity of confining layer [L/T]

The other variables have been defined before.

In deriving the Hantush-Jacob solution it is assumed that the aquifer is homogeneous, isotropic, of constant thickness, and of infinite extent. Furthermore, the confining bed is homogeneous and isotropic with respect to the hydraulic conductivity and the head in the confining bed does not change in time. Water is released instantaneously from storage by compaction of the aquifer matrix and by expansion of the water in the aquifer. The pumping well is fully penetrating and no water is stored in the well bore or the confining layer. Prior to pumping, the piezometric surface is horizontal over the entire area; that is, no regional flow is present.

The exponential integral W(u,r/L) is approximated by (Walton 1983):

When r/L < 2 and u > 1

$$W(u,r/L) = I_o(r/L)\,W(u) - \exp(u)\,[0.5772 + \ln(\frac{r^2}{4L^2u}) + W(\frac{r^2}{4L^2u})]$$

$$- [\frac{r^2}{4L^2u} + \frac{I_o(r/L) - 1}{u}] + \frac{\exp(u)}{u^2} \sum_{n=1}^{8} \sum_{m=1}^{n} \frac{(-1)^{n+m}(n-m+1)!}{(n+2)!^2 u^{n-m}} (\frac{r^2}{4L^2})^n$$

When r/L ≤ 2 and u ≤ 1

$$W(u,r/L) = 2K_o(r/L) - [I_o(r/L)\,W(\frac{r^2}{4L^2u})$$

$$- \exp(\frac{r^2}{4L^2u}) \left[0.5772 + \ln(u) + W(u) - u + \frac{I_o(r/L) - 1}{r^2/(4L^2u)}\right]$$

$$+ u^2 \sum_{n=1}^{8} \sum_{m=1}^{n} \frac{(-1)^{n+m}(n-m+1)!}{(n+2)!^2 u^{m-n}} (\frac{r^2}{4L^2})^m]$$

When r/L > 2

$$W(u,r/L) = (\frac{\pi L}{2r})^{1/2} \exp(-r/L)\ erfc(-\frac{r/L - 2u}{2u^{1/2}})$$

The effects of multiple wells on the drawdown distribution in the aquifer is obtained by superposition of the Hantush-Jacob solution for individual wells in the same fashion as for confined aquifers.

REGIONAL GROUND-WATER FLOW

The program allows calculation of drawdowns with respect to a sloping regional piezometric surface. It uses both a local and a global coordinate system. Regional flow is defined with respect to the global coordinate system; pumping and observation wells may be specified with respect to a separate local coordinate system which may have its horizontal axis rotated with respect to the global system. The user needs to specify the vertical angle α from the global x-axis (taken as the projection of the regional flow vector on the horizontal X-Y surface) downward to the regional flow vector (see figure 3). Furthermore, the counterclockwise horizontal angle ϕ from the local x-axis towards the global x-axis needs to be given (figure 4). Finally, the user needs to alter the vertical offset z_0 at the joint origin of the coordinate systems (figure 3). It should be noted that because the program calculates drawdowns, the effect of the regional piezometric surface is represented as a drawdown with respect to a horizontal surface through the point of origin chosen by the user.

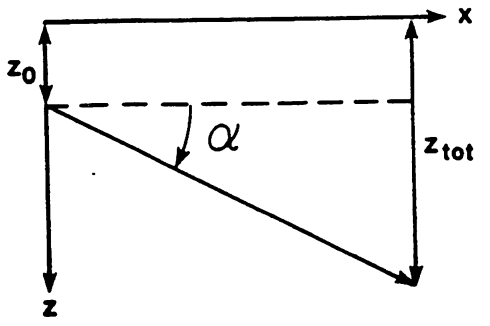

Figure 3. Definition of vertical (cross-sectional) geometry for a sloping regional piezometric surface.

$$x = x' \cos\phi - y' \sin\phi \qquad \text{and} \qquad y = x' \sin\phi + y' \cos\phi$$

x' and y' are local coordinates; x and y are global coordinates.

$$z = x \operatorname{tg}\phi = x(-i)$$

Substitution gives:

$$z = (x' \cos\phi - y' \sin\phi)\,(-i)$$

Finally: $$z_{tot} = z + z_0'$$

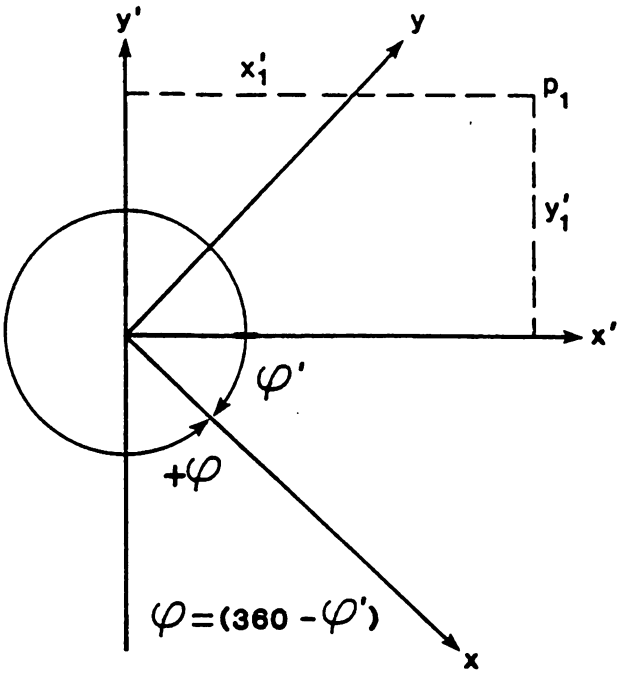

Figure 4. Definition of horizontal geometry for a sloping regional piezometric surface.

MODEL VERIFICATION

A large number of test runs have been made to verify the computational accuracy of the program. Tests included comparison with other programs based on the Theis equation such as **IMAGEW-1** (Texas Water Development Board 1973) and **WALTON35** (Walton 1983), or the Hantush-Jacob equation such as **WALTON35**, **CAPZONE** (Bair et al. 1992), and **GWFLOW** (van der Heijde 1991). One of the test series for the confined option is discussed below, others are included as example data files and presented in the appendix.

Bouwer (1978, p. 75) presents a series of calculations of drawdowns in a Theis condition aquifer for a single well. In Table 1 the results using **THWELLS** are compared with the results presented by Bouwer (1978). The following data were used:

Transmissivity	=	1000 m^2/day
Storage coefficient	=	.0001
Discharge of pumping well	=	1000 m^3/day
Duration of pumping	=	10 days
Location of well	=	origin (x=0, y=0)
Distance to observation wells	=	100, 200 m

The water-table option has been checked against the program **IMAGEW-1** (Texas Water Management Board 1973). This program is based on the same water-table correction as **THWELLS**. Table 2 presents the results. The following data were used:

Transmissivity	=	75000 gpd/ft
Storage coefficient	=	.200
Discharge of pumping wells	=	500 gpm (720,000 gpd)
Duration of pumping	=	.08 year (29.2 days), .17 year (62.05 days), .24 year (87.6 days), .5 year (182.5 days)
Location of well	=	origin (x=0, y=0)

The aquifer thickness is 250 feet. The results of the comparison are presented in table 2.

Testing the leaky-confined option of THWELLS was performed by comparison with **CAPZONE** version 1.1 of April 1992, and **GWFLOW** version 2.01 of October 1991. The results were compared with those published in tabular form by Hantush (1956). The data used for these tests are:

$T = 1000\ m^2/d$	$S = .004$	$Q = 1000\ m^{3/d}$
$k' = .01\ m/d$	$b' = 10\ m$	

Results are presented in table 3.

USER INSTRUCTIONS

THWELLS is a user-interactive menu-driven program which provides the user with options to create, edit and save data sets, run the simulation program both for individual observation wells (to calculate a time-drawdown curve) and for a regular grid of computational points (to calculate the spatial drawdown or head distribution), display the results on screen in tabular or graphic form, and reformat the results for additional post-processing (e.g. using a commercial graphing or contouring program).

The program is started by typing **THWELLS** from the appropriate subdirectory. The program is run through a main menu and various sub-menu's. The user may select to create a new data set. In that case the program prompts for selecting the confined, leaky-confined or water-table option, and for selecting English (ft U.S. gallon, day) or metric (m, day) units. The data input is facilitated through a sequence of screens. Each screen provides the option to redo the data (e.g., if a mistake has been made) before moving on to the next screen. The program contains a set of realistic default values for instructional purposes. When entering new data, these default values may be modified. Separate options are available to edit/modify the aquifer parameters and the pumping well characteristics. When a data set has been modified or a new data set been created, the user should save this data using the 'save input data' option of the main menu.

Calculations are performed either for individual observation wells or for locations defined by a user-specified horizontal rectangular grid. If the individual observation well option is selected, the program can compute a series of drawdown values for user-specified times (see section on time specification below). The results, in the form of a time-series, can be displayed as a time-drawdown graph or in tabular form. The results may be routed directly to an on-line printer or stored for external post-processing.

t Bouwer (days)	Timeperiod (days) input	Timestep (days) input	Drawdown for r = 100m		Drawdown for r = 200m	
			Bouwer	Calculated	Bouwer	Calculated
10	0.0001	0.0001	0.797	0.797	0.687	0.687
5	5	5	0.742	0.742	0.632	0.632
1	9	9	0.614	0.614	0.504	0.504
0.5	9.5	9.5	0.559	0.559	0.449	0.449
0.1	9.9	9.9	0.431	0.431	0.322	0.321
0.05	9.95	9.95	0.376	0.376	0.267	0.267
0.01	9.99	9.99	0.249	0.250	0.145	0.145
0.005	9.995	9.995	0.196	0.196	0.097	0.097
0.001	9.999	9.999	0.083	0.083	0.017	0.017

Table 1. Test 1: verification of confined aquifer option for a single well

well I.D.	x-coordinate (feet)	y-coordinate (feet)				
pumping wells						
PW 01	12000	15000				
IP 01	4000	23000				
observation wells			drawdown (feet)			
			period 1 29.2 days	period 2 62.05 days	period 3 87.6 days	period 4 182.5 days
OW 01	7000	14000	.0 (.002)	.0 (.033)	.1 (.079)	.3 (.300)
OW 02	11000	13000	.2 (.216)	.5 (.535)	.7 (.723)	1.2 (1.186)
OW 03	17000	14000	.0 (.002)	.0 (.033)	.1 (.079)	.3 (.280)
OW 04	16000	19000	.0 (.001)	.0 (.017)	.0 (.048)	.2 (.210)

Table 2. Test 2. Verification of water-table aquifer option; numbers between parenthesis are for **THWELLS**, other numbers for **IMAGE-I**.

Test No. ->	1	2	3	4	5
r [m]	1000	1000	100	10	10
t [d]	1000	1	10	1000	1
u	10^{-3}	1	10^{-3}	10^{-7}	10^{-4}
r/B_k	1	1	.1	.01	.01
$W(u,r/B_k)$ *	.845	.186	4.829	9.450	8.398
s *	.067	.015	.384	.752	.668
s [GWFLOW]	.067	.015	.384	.751	.668
s [THWELLS]	.067	.015	.384	.751	.668
s [CAPZONE]	.067	.015	.384	.751	.668

Table 3. Test 3. Verification of leaky-confined aquifer option (* values form Hantush 1956).

If the "gridded calculation" option is chosen, the results may be displayed in tabular form or as a contour graph and may be saved in an XY-H file or directly printed using an on-line printer. When contouring the results on screen the user has the option to display the contours using a pixel coordinate system (positive to the right and downwards) or a cartesian system (positive to the right and upwards). The user needs to specify the contour bounds and the contour interval.

The program includes various error-checking routines to avoid crashing of the program while preparing data or executing options. Various variables are bounded internally (e.g., non-negativity requirements). Special attention should be given to the use of file names. When saving a data set, the program prompts for a file name. The user should provide the file name including the extension (maximum of 12 characters), and optionally the path. It should be noted that the file allocating routine used in various parts of the program has some limitations with respect to the number of directories it can handle. Running the program from within the user-created THWELLS subdirectory may prevent problems in path selection. The program can be exited by returning to the main menu and choosing the 'exit' option, or by hitting the <Ctrl> and <Break> keys simultaneously.

Appendix I provides examples of printouts of results. Appendix II contains a series of example problems illustrating the application of image well theory together with the program **THWELLS**, and the program's regional flow capabilities.

Time Specification in THWELLS

When using the rectangular grid option, the time for calculating the drawdown, T_0, is set as origin for the time axis (i.e., $t=0$; figure 5 and 6). The program then evaluates how long each well has been active (T_0-T_{pi}; see figure 5). In specifying the duration T_{pi} of the discharge/recharge for well i, we count backwards in time from T_0 to the start of the well activity (e.g., T_{p1} or T_{p2}; see figure 5).

This same principle is applied to the time series calculation for an individual observation well. T_0 is the last point in time for which we want to know the drawdown; this point is chosen as origin on the time axis (see figure 6). The duration of the time series, T_{tot}, is specified backwards in time till the first time for which we want to calculate the drawdown, i.e., $t=-T_t$ (figure 6). Note that the time duration between $t=0$ and $t=-T_t$ in figure 6 corresponds with T_{tot} in figure 5.

If $T_{pi}<T_{tot}$, no drawdowns are calculated during the time that the well is not yet active (e.g., left of $t=-T_{p1}$ in figure 6). Consequently, if $T_{pi}>T_{tot}$, the drawdown is calculated on the basis of the total time the well is active, T_{pi}, but the results are shown only for the period T_{tot} (see hatched lines between $t=-T_t$ and $t=-T_{p2}$ in figure 6).

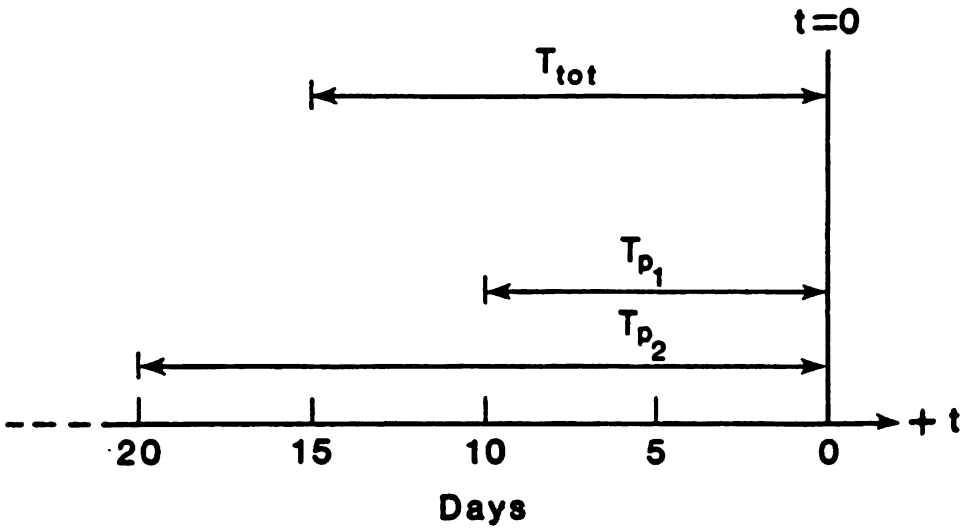

Figure 5. Definition of time-step specification

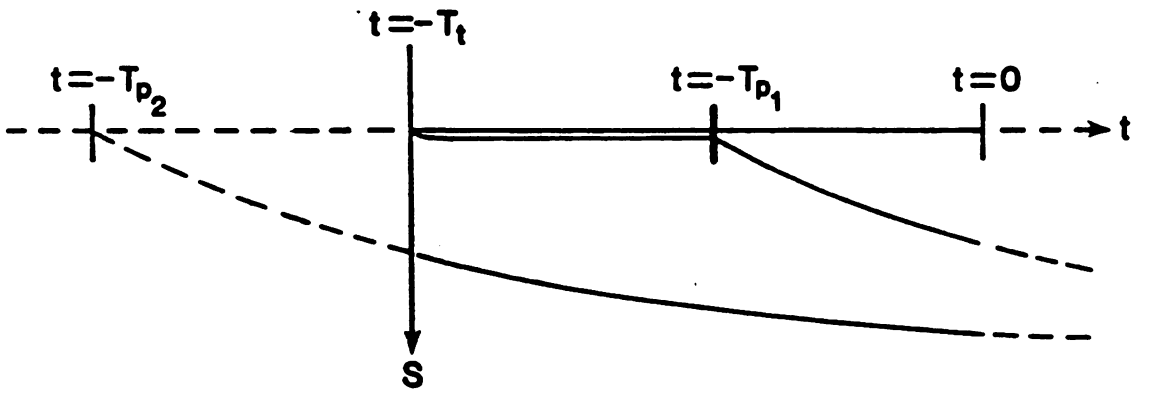

Figure 6. Drawdown versus time with definition of calculation window (solid lines)

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APPENDIX I

EXAMPLE PRINTOUT

Problem "Test"

Using default values included in program

```
******************************** THWELLS ********************************  PAGE 1

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED
AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

-------------------------------------------------------------------------------

test
-------------------------------------------------------------------------------


********************************** INPUT DATA **********************************

                                TRANSMISSIVITY  =  1000 [sq.m/day]

                             STORAGE COEFFICIENT  =  .1

                          REGIONAL FLOW GRADIENT
        (positive--downwards--in flow direction)  =  0

                        REGIONAL FLOW DIRECTION
                 (horizontal angle in degrees
         counter-clockwise from positive x-axis)  =  0

                 REGIONAL FLOW OFFSET AT ORIGIN
            (positive in downwards direction)  =  0 [m]


                         WATER TABLE CORRECTION APPLIED

                              AQUIFER THICKNESS  =  20 [m]

-------------------------------------------------------------------------------
```

WELL NO. 1

```
                          X-COORDINATE  =  100 [m]
                          Y-COORDINATE  =  100 [m]
                PUMPING/INJECTION RATE  =  1000 [cu.m/day]
  TIME SINCE START PUMPING/INJECTION    =  10 [day]
```

---------- Drawdown in [m] ----------

Y [m]	<- X [m] ->					
	0	100	200	300	400	500
0.00	0.1945E+00	0.2465E+00	0.1945E+00	0.1284E+00	0.8276E-01	0.5256E-01
100.00	0.2465E+00	0.1256E+01	0.2465E+00	0.1440E+00	0.8931E-01	0.5574E-01
200.00	0.1945E+00	0.2465E+00	0.1945E+00	0.1284E+00	0.8276E-01	0.5256E-01
300.00	0.1284E+00	0.1440E+00	0.1284E+00	0.9682E-01	0.6718E-01	0.4445E-01
400.00	0.8276E-01	0.8931E-01	0.8276E-01	0.6718E-01	0.4964E-01	0.3434E-01
500.00	0.5256E-01	0.5574E-01	0.5256E-01	0.4445E-01	0.3434E-01	0.2469E-01
600.00	0.3269E-01	0.3434E-01	0.3269E-01	0.2833E-01	0.2258E-01	0.1673E-01
700.00	0.1981E-01	0.2068E-01	0.1981E-01	0.1744E-01	0.1420E-01	0.1077E-01
800.00	0.1164E-01	0.1211E-01	0.1164E-01	0.1037E-01	0.8573E-02	0.6620E-02
900.00	0.6620E-02	0.6866E-02	0.6620E-02	0.5939E-02	0.4969E-02	0.3891E-02
1000.00	0.3631E-02	0.3759E-02	0.3631E-02	0.3277E-02	0.2766E-02	0.2189E-02

Y [m]	<- X [m] ->				
	600	700	800	900	1000
0.00	0.3269E-01	0.1981E-01	0.1164E-01	0.6620E-02	0.3631E-02
100.00	0.3434E-01	0.2068E-01	0.1211E-01	0.6866E-02	0.3759E-02
200.00	0.3269E-01	0.1981E-01	0.1164E-01	0.6620E-02	0.3631E-02
300.00	0.2833E-01	0.1744E-01	0.1037E-01	0.5939E-02	0.3277E-02
400.00	0.2258E-01	0.1420E-01	0.8573E-02	0.4969E-02	0.2766E-02
500.00	0.1673E-01	0.1077E-01	0.6620E-02	0.3891E-02	0.2189E-02
600.00	0.1164E-01	0.7667E-02	0.4797E-02	0.2861E-02	0.1629E-02
700.00	0.7667E-02	0.5149E-02	0.3277E-02	0.1983E-02	0.1142E-02
800.00	0.4797E-02	0.3277E-02	0.2118E-02	0.1299E-02	0.7573E-03
900.00	0.2861E-02	0.1983E-02	0.1299E-02	0.8063E-03	0.4754E-03
1000.00	0.1629E-02	0.1142E-02	0.7573E-03	0.4754E-03	0.2831E-03

APPENDIX II

EXAMPLE PROBLEMS

APPENDIX II

EXAMPLE PROBLEMS

Groundwater System

The example problem discussed concerns a square, isotropic, homogeneous, confined aquifer (see Figure III-1A/B).

The aquifer is bound on two opposite sides by impermeable bedrock hills constituting a no-flow boundary of 10,000 feet each. The third boundary is formed by a reservoir with a length of 10,000 ft and a water level of 200 ft. The fourth boundary is a river, 10,000 ft long and with a water level of 0 ft. The surface water stages remain constant; thus, a constant head is exerted at their contact surfaces with the aquifer (see Figure III-1A).

The transmissivity is 1.55×10^{-2} ft^2/sec (10018 gpd/ft). A well is located at 3500 ft from the origin in the positive x direction and 5000 ft from the origin in the positive y direction (see Figure III-1B). The pumping rate is 3.1 ft^3/sec (2003582 gpd).

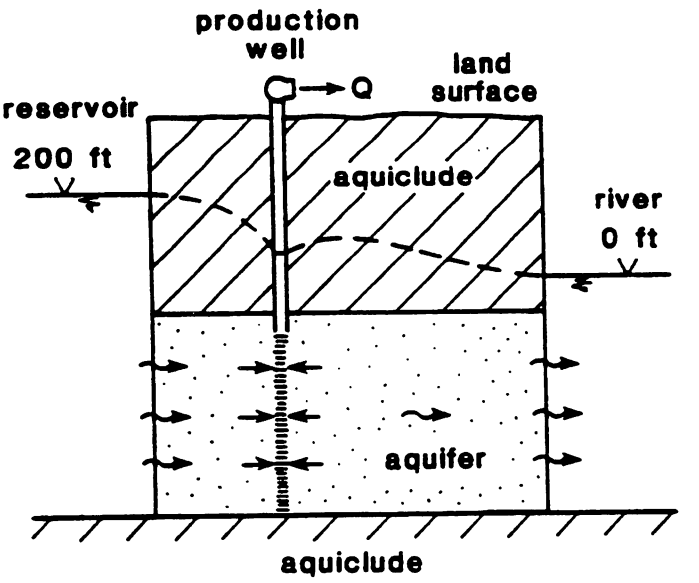


Figure III-1A. Cross-section of aquifer situation.

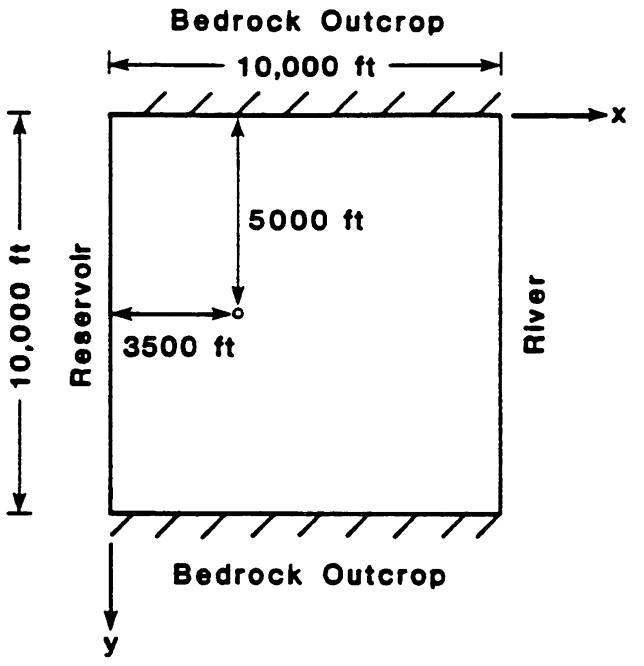


Figure III-1B. Position of pumping well in aquifer.

PROBLEM - Calculate areal distribution of drawdowns and heads. Then, contour the head values to decide whether the results are physically reasonable. (The problem is taken from Franke et al. 1987.)

SOLUTION - We wish to determine the head distribution and flows in the aquifer as the well is pumped. To do so, the principle of image well theory will be employed to account for the effects of no-flow and constant-head line-boundaries.

The image well theory states that for linear systems the effect of a barrier boundary on the drawdown in a well, as a result of pumping from another well, is the same as though the aquifer were infinite and a like discharging well were located across the real boundary as the pumping well. The principle is the same for a recharge boundary except that the image well is assumed to be recharging the aquifer instead of pumping from it (see Franke et al. 1987).

To determine where to place image wells, the following rules must be followed:

(1) At no-flow boundaries image well flow rates are equal in size and direction to the flow rate of the real well.
(2) At constant head boundaries the image well flow rates are opposite in direction and equal in size to the flow rate of the real well.
(3) The distance from the real well to the boundary is equal to the distance from the boundary to the image well.

For this problem, two groups of three sets of calculations (scenarios) were performed (see Table III-1). In the first group, drawdown calculations were made with respect to a horizontal regional water level. The second group concerned drawdown superposed on a sloping regional groundwater surface. The first calculation in each group involved drawdown of the real well only. Drawdowns range from 2.31 to 76.3 ft. The second calculation involves five wells: the real well and four primary image wells (see Figure III-2). Drawdowns range from 0.521 to 74.7 ft. In the third calculation, 17 wells are involved: the original well, 4 primary image wells, and 12 secondary image wells (see Figure III-2). Drawdowns range from -6.02 to 73.3 ft.

The contours near the constant head boundaries obtained in the second set of calculations most closely resemble actual boundaries. Comparing this with calculations of the same problems performed with a finite-difference model (Franke et al. 1987) shows that the results of using four image wells most closely resemble drawdown contours and changes in flow due to pumping. This means that one needs to go out only as far as the primary image wells location to assess the true effects of the pumping. Distances beyond that prove negligible. Differences noted between the THWELLS calculations and what these authors have obtained for set two could be attributed to conversion differences in the transmissivity and pumping rate values.

Note: plots on pages 61 and 67 are obtained in two steps:
Step 1: contour from 0 to 80 with interval of 10.
Step 2: create additional contours with interval of 1 between 0 and 10 using <C> option.

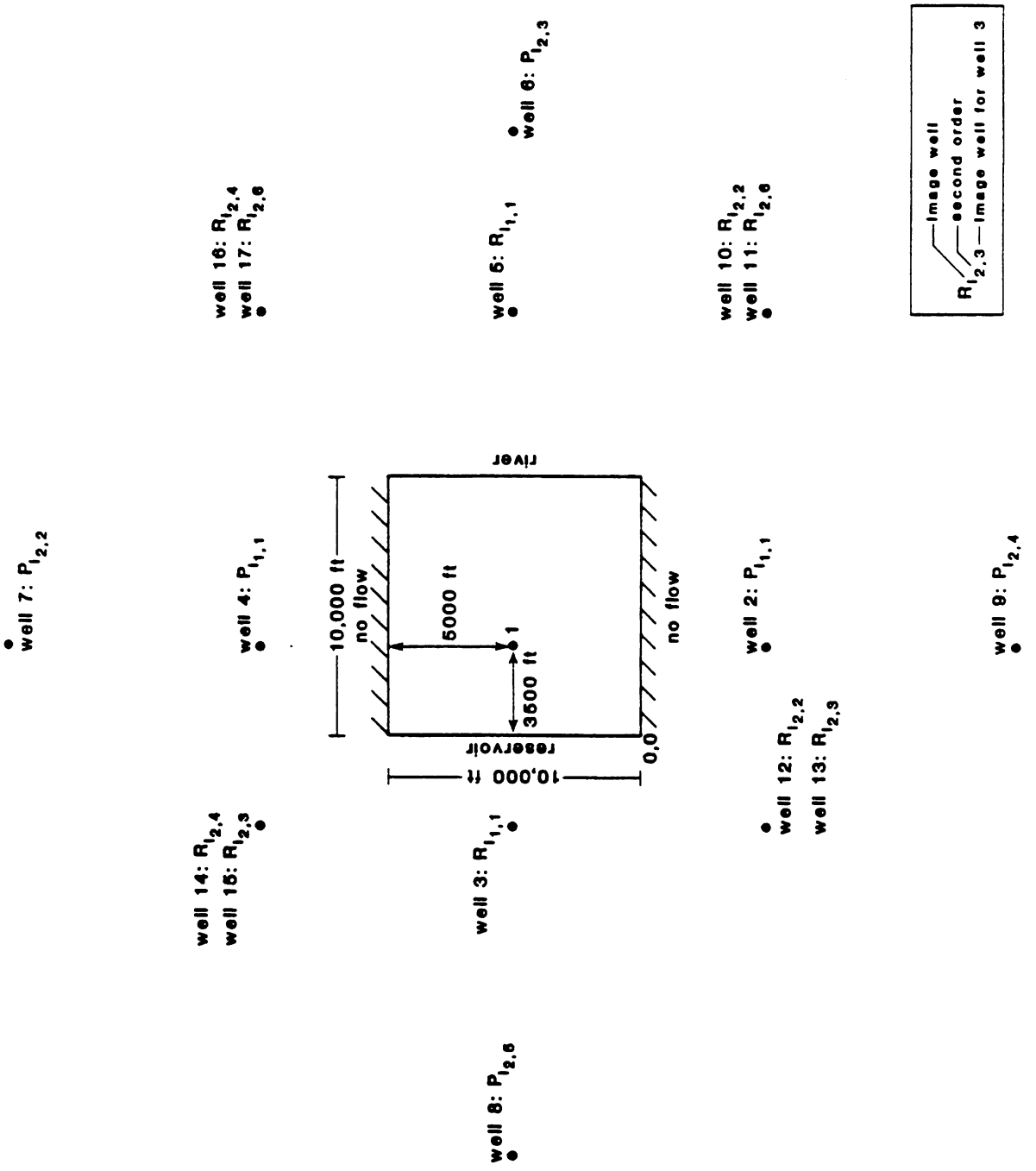


Figure III-2. Position of real well and image wells.

Table III-1.

Listing of Coordinates (in ft.)

Real Well			
#	x	y	
1	3500	5000	P+ *

1st order image wells			
#	x	y	
2	3500	-5000	P+
3	-3500	5000	R-
4	3500	15000	P+
5	16500	5000	R-

2nd order image wells			
#	x	y	
6	26500	5000	P+
7	3500	25000	P+
8	-16500	5000	P+
9	3500	-15000	P+
10	16500	-5000	R-
11	16500	-5000	R-
12	-3500	-5000	R-
13	-3500	-5000	R-
14	-3500	15000	R-
15	-3500	15000	R-
16	16500	15000	R-
17	16500	15000	R-

Scenarios

Scenario A:

calculation 1:	1 well
calculation 2:	5 wells
calculation 3:	17 wells

Scenario B:

calculation 1:	0 well
calculation 2:	1 well
calculation 3:	5 wells
calculation 4:	17 wells

---

* P denotes a pumping well, R an injecting/recharging well.
+ denotes a positive flux (pumping), - a negative flux (injecting).

The second series of calculations (scenario B) includes using the option for a regional sloping piezometric surface. Gradient is 200 ft/ 10,000 ft = 0.02. The results are presented on the following pages. For comparison, Figures III-3, 4 and 5 show the results presented by Franke et al. (1987).

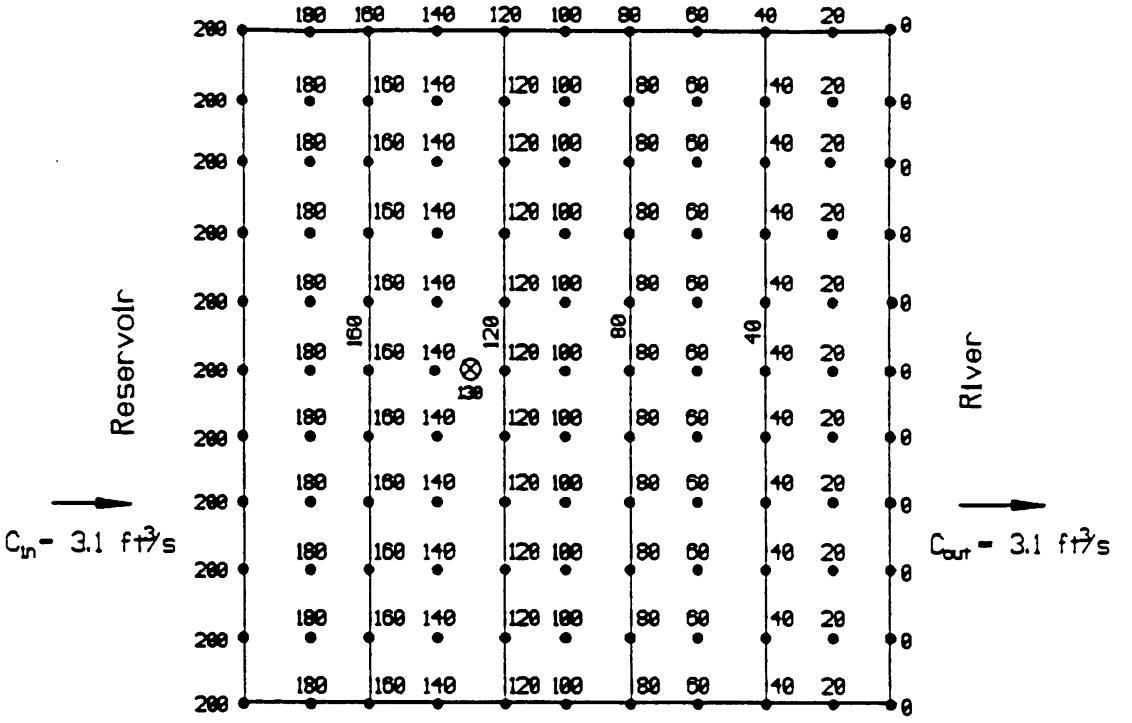


Figure III-3. Aquifer response without pumping as presented by Franke et al. 1987.

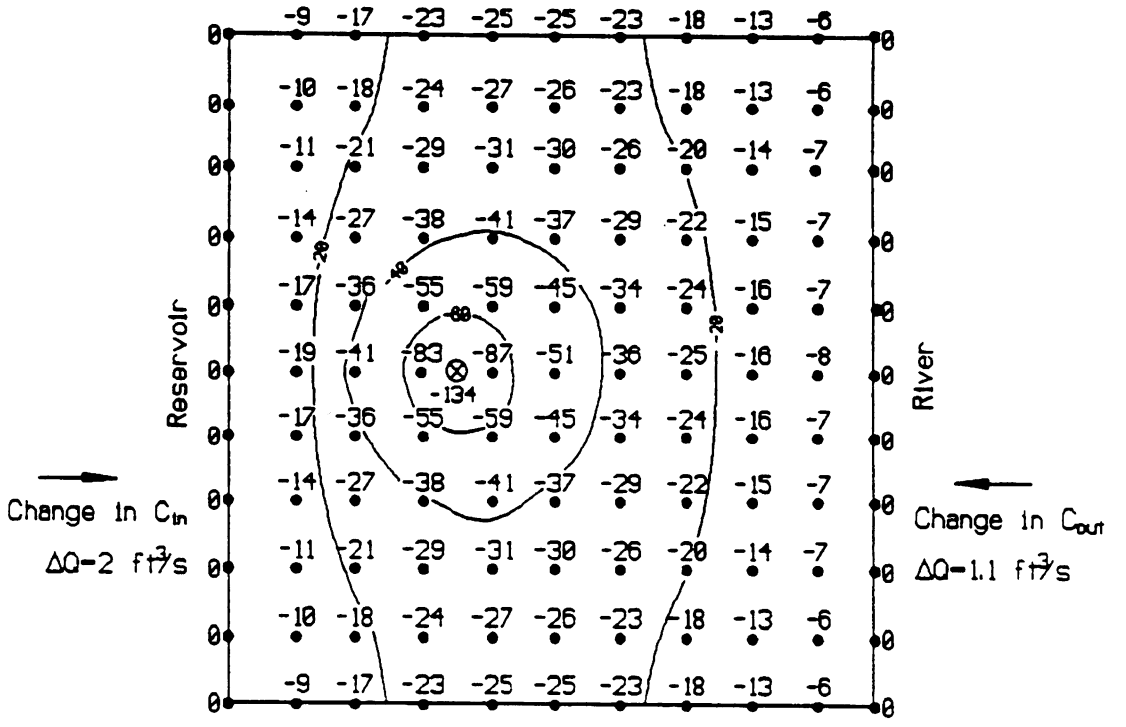
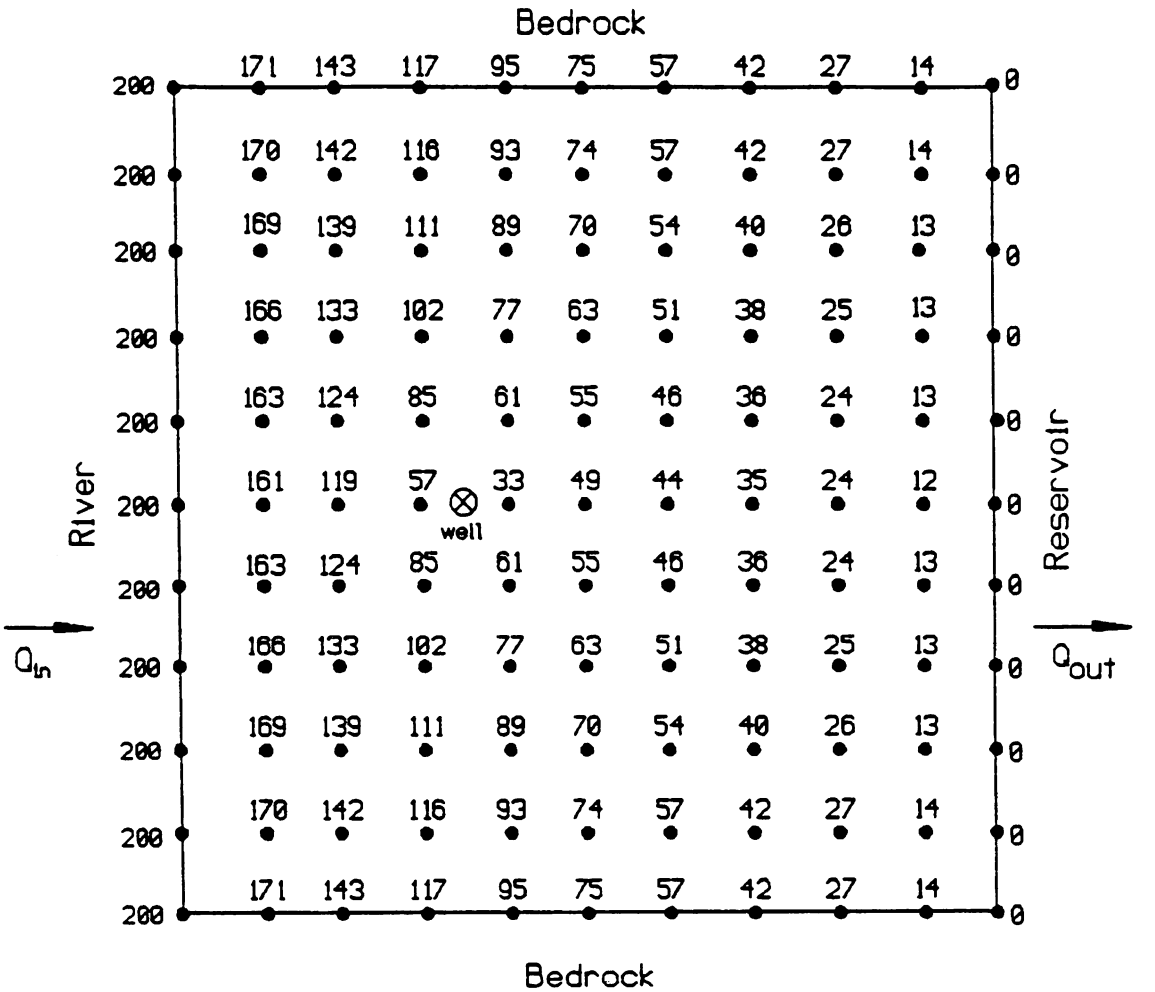


Figure III-4. Aquifer response for pumping as presented by Franke et al. 1987; assumes reservoir and river levels are both at 0 ft.



$$Q_{in} = Q_{in_C} + Q_{in_D} = 3.1\ ft^3/s + 2\ ft^3/s = 5.1\ ft^3/s$$

$$Q_{out} = Q_{out_C} + Q_{out_D} = 3.1\ ft^3/s + (-1.1)\ ft^3/s = 2.0\ ft^3/s$$

Figure III-5. Final superposed aquifer response as presented by Franke et al. 1987.

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

---

thw3-2c1.dat

********** INPUT DATA **********

TRANSMISSIVITY	=	10018 [gpd/ft]
STORAGE COEFFICIENT	=	.001
REGIONAL FLOW GRADIENT (positive--downwards--in flow direction)	=	0
REGIONAL FLOW DIRECTION (horizontal angle in degrees counter-clockwise from positive x-axis)	=	0
REGIONAL FLOW OFFSET AT ORIGIN (positive in downwards direction)	=	0 [ft]

WELL NO. 1

```
                    X-COORDINATE  =  3500 [ft]
                    Y-COORDINATE  =  5000 [ft]
          PUMPING/INJECTION RATE  =  2003582 [gpd]
TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

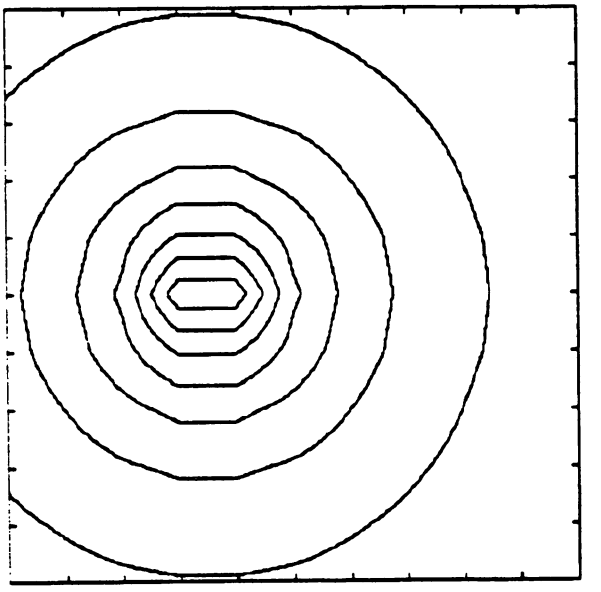
---------- Drawdown in [ft] ----------

Y [ft] <- X [ft] ->

	0	1000	2000	3000	4000	5000
0.00	0.6001E+01	0.7479E+01	0.8743E+01	0.9486E+01	0.9486E+01	0.8743E+01
1000.00	0.8401E+01	0.1078E+02	0.1294E+02	0.1428E+02	0.1428E+02	0.1294E+02
2000.00	0.1127E+02	0.1504E+02	0.1882E+02	0.2140E+02	0.2140E+02	0.1882E+02
3000.00	0.1428E+02	0.2004E+02	0.2681E+02	0.3238E+02	0.3238E+02	0.2681E+02
4000.00	0.1675E+02	0.2473E+02	0.3636E+02	0.5099E+02	0.5099E+02	0.3636E+02
5000.00	0.1774E+02	0.2681E+02	0.4193E+02	0.7631E+02	0.7631E+02	0.4193E+02
6000.00	0.1675E+02	0.2473E+02	0.3636E+02	0.5099E+02	0.5099E+02	0.3636E+02
7000.00	0.1428E+02	0.2004E+02	0.2681E+02	0.3238E+02	0.3238E+02	0.2681E+02
8000.00	0.1127E+02	0.1504E+02	0.1882E+02	0.2140E+02	0.2140E+02	0.1882E+02
9000.00	0.8401E+01	0.1078E+02	0.1294E+02	0.1428E+02	0.1428E+02	0.1294E+02
10000.00	0.6001E+01	0.7479E+01	0.8743E+01	0.9486E+01	0.9486E+01	0.8743E+01

Y [ft] <- X [ft] ->

	6000	7000	8000	9000	10000
0.00	0.7479E+01	0.6001E+01	0.4562E+01	0.3313E+01	0.2310E+01
1000.00	0.1078E+02	0.8401E+01	0.6219E+01	0.4414E+01	0.3021E+01
2000.00	0.1504E+02	0.1127E+02	0.8077E+01	0.5593E+01	0.3756E+01
3000.00	0.2004E+02	0.1428E+02	0.9891E+01	0.6687E+01	0.4414E+01
4000.00	0.2473E+02	0.1675E+02	0.1127E+02	0.7479E+01	0.4877E+01
5000.00	0.2681E+02	0.1774E+02	0.1179E+02	0.7770E+01	0.5045E+01
6000.00	0.2473E+02	0.1675E+02	0.1127E+02	0.7479E+01	0.4877E+01
7000.00	0.2004E+02	0.1428E+02	0.9891E+01	0.6687E+01	0.4414E+01
8000.00	0.1504E+02	0.1127E+02	0.8077E+01	0.5593E+01	0.3756E+01
9000.00	0.1078E+02	0.8401E+01	0.6219E+01	0.4414E+01	0.3021E+01
10000.00	0.7479E+01	0.6001E+01	0.4562E+01	0.3313E+01	0.2310E+01



11 rows 11 columns DX= 1000 DY= 1000 Drawdowns: 2.310415 <-> 76.30832

Enter <C> for additional contours: <X> to exit >>>

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

---

thw3-2c2.dat

********** INPUT DATA **********

TRANSMISSIVITY	=	10018 [gpd/ft]
STORAGE COEFFICIENT	=	.001
REGIONAL FLOW GRADIENT (positive--downwards--in flow direction)	=	0
REGIONAL FLOW DIRECTION (horizontal angle in degrees counter-clockwise from positive x-axis)	=	0
REGIONAL FLOW OFFSET AT ORIGIN (positive in downwards direction)	=	0 [ft]

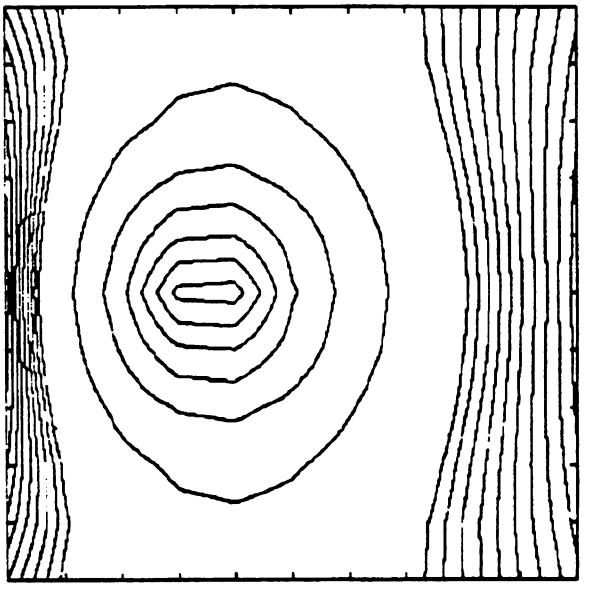
```
WELL NO. 1

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 2

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 3

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 4

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 5

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

********** RESULTS ********** THWELLS - PAGE 3

---------- Drawdown in [ft] ----------

Y [ft]	<- X [ft] ->					
	0	1000	2000	3000	4000	5000
0.00	0.6027E+01	0.1042E+02	0.1418E+02	0.1664E+02	0.1734E+02	0.1630E+02
1000.00	0.4193E+01	0.9661E+01	0.1436E+02	0.1748E+02	0.1843E+02	0.1726E+02
2000.00	0.2874E+01	0.1039E+02	0.1710E+02	0.2172E+02	0.2294E+02	0.2086E+02
3000.00	0.2001E+01	0.1250E+02	0.2273E+02	0.3068E+02	0.3216E+02	0.2732E+02
4000.00	0.1507E+01	0.1521E+02	0.3081E+02	0.4808E+02	0.4974E+02	0.3600E+02
5000.00	0.1348E+01	0.1658E+02	0.3586E+02	0.7300E+02	0.7473E+02	0.4128E+02
6000.00	0.1507E+01	0.1521E+02	0.3081E+02	0.4808E+02	0.4974E+02	0.3600E+02
7000.00	0.2001E+01	0.1250E+02	0.2273E+02	0.3068E+02	0.3216E+02	0.2732E+02
8000.00	0.2874E+01	0.1039E+02	0.1710E+02	0.2172E+02	0.2294E+02	0.2086E+02
9000.00	0.4193E+01	0.9661E+01	0.1436E+02	0.1748E+02	0.1843E+02	0.1726E+02
10000.00	0.6027E+01	0.1042E+02	0.1418E+02	0.1664E+02	0.1734E+02	0.1630E+02

Y [ft]	<- X [ft] ->				
	6000	7000	8000	9000	10000
0.00	0.1398E+02	0.1102E+02	0.7922E+01	0.4970E+01	0.2258E+01
1000.00	0.1463E+02	0.1133E+02	0.7927E+01	0.4681E+01	0.1636E+01
2000.00	0.1697E+02	0.1263E+02	0.8480E+01	0.4683E+01	0.1145E+01
3000.00	0.2068E+02	0.1456E+02	0.9352E+01	0.4875E+01	0.7962E+00
4000.00	0.2463E+02	0.1639E+02	0.1016E+02	0.5098E+01	0.5898E+00
5000.00	0.2647E+02	0.1717E+02	0.1049E+02	0.5195E+01	0.5216E+00
6000.00	0.2463E+02	0.1639E+02	0.1016E+02	0.5098E+01	0.5898E+00
7000.00	0.2068E+02	0.1456E+02	0.9352E+01	0.4875E+01	0.7962E+00
8000.00	0.1697E+02	0.1263E+02	0.8480E+01	0.4683E+01	0.1145E+01
9000.00	0.1463E+02	0.1133E+02	0.7927E+01	0.4681E+01	0.1636E+01
10000.00	0.1398E+02	0.1102E+02	0.7922E+01	0.4970E+01	0.2258E+01



11 rows 11 columns DX= 1000 DY= 1000 Drawdowns: .5215998 <-> 74.72702

Enter <C> for additional contours: <X> to exit >>>

```
****************************** THWELLS ******************************  PAGE 1

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED
AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

--------------------------------------------------------------------------------

thw3-2c3.dat
--------------------------------------------------------------------------------


********************************** INPUT DATA **********************************

                                 TRANSMISSIVITY  =  10018 [gpd/ft]

                              STORAGE COEFFICIENT  =  .001

                           REGIONAL FLOW GRADIENT
        (positive--downwards--in flow direction)  =  0

                          REGIONAL FLOW DIRECTION
                    (horizontal angle in degrees
         counter-clockwise from positive x-axis)  =  0

                   REGIONAL FLOW OFFSET AT ORIGIN
              (positive in downwards direction)  =  0 [ft]

--------------------------------------------------------------------------------
```

```
WELL NO. 1

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 2

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 3

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 4

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 5

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 6

                        X-COORDINATE  =  26500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

--------------------------------------------------------------------------------
```

```
WELL NO. 7

                        X-COORDINATE  =  3599 [ft]
                        Y-COORDINATE  =  25000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]


WELL NO. 8

                        X-COORDINATE  = -16500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]


WELL NO. 9

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  = -15000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]


WELL NO. 10

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]


WELL NO. 11

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]


WELL NO. 12

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

-------------------------------------------------------------------------------
```

WELL NO. 13

```
                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

WELL NO. 14

```
                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

WELL NO. 15

```
                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

WELL NO. 16

```
                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

WELL NO. 17

```
                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

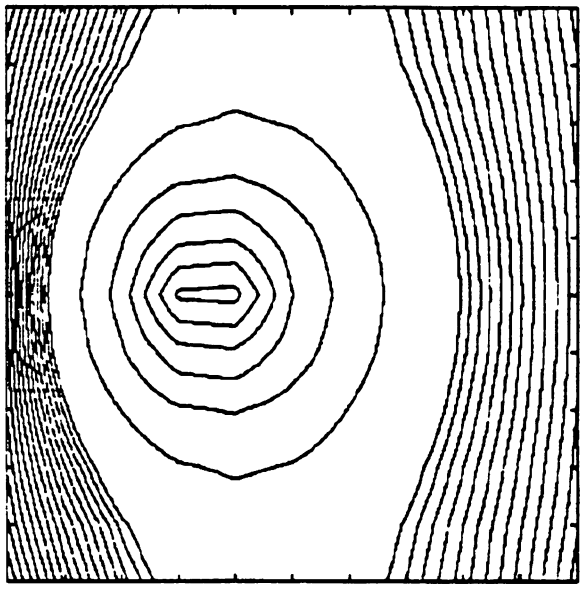
---------- Drawdown in [ft] ----------

Y [ft] <- X [ft] ->

	0	1000	2000	3000	4000	5000
0.00	-.6020E+01	0.1238E+01	0.7476E+01	0.1189E+02	0.1399E+02	0.1385E+02
1000.00	-.4202E+01	0.3116E+01	0.9477E+01	0.1395E+02	0.1590E+02	0.1538E+02
2000.00	-.2891E+01	0.5811E+01	0.1361E+02	0.1915E+02	0.2106E+02	0.1944E+02
3000.00	-.2022E+01	0.9252E+01	0.2022E+02	0.2880E+02	0.3076E+02	0.2625E+02
4000.00	-.1530E+01	0.1273E+02	0.2886E+02	0.4661E+02	0.4863E+02	0.3514E+02
5000.00	-.1371E+01	0.1435E+02	0.3410E+02	0.7166E+02	0.7371E+02	0.4049E+02
6000.00	-.1530E+01	0.1273E+02	0.2886E+02	0.4661E+02	0.4863E+02	0.3514E+02
7000.00	-.2022E+01	0.9251E+01	0.2022E+02	0.2880E+02	0.3076E+02	0.2625E+02
8000.00	-.2891E+01	0.5811E+01	0.1361E+02	0.1915E+02	0.2106E+02	0.1944E+02
9000.00	-.4202E+01	0.3116E+01	0.9477E+01	0.1395E+02	0.1590E+02	0.1538E+02
10000.00	-.6021E+01	0.1238E+01	0.7476E+01	0.1189E+02	0.1399E+02	0.1385E+02

Y [ft] <- X [ft] ->

	6000	7000	8000	9000	10000
0.00	0.1197E+02	0.9005E+01	0.5464E+01	0.1607E+01	-.2514E+01
1000.00	0.1306E+02	0.9763E+01	0.6039E+01	0.2141E+01	-.1902E+01
2000.00	0.1578E+02	0.1144E+02	0.7064E+01	0.2809E+01	-.1418E+01
3000.00	0.1978E+02	0.1365E+02	0.8284E+01	0.3483E+01	-.1076E+01
4000.00	0.2389E+02	0.1566E+02	0.9300E+01	0.3994E+01	-.8743E+00
5000.00	0.2579E+02	0.1649E+02	0.9701E+01	0.4187E+01	-.8079E+00
6000.00	0.2389E+02	0.1566E+02	0.9300E+01	0.3994E+01	-.8743E+00
7000.00	0.1978E+02	0.1365E+02	0.8284E+01	0.3483E+01	-.1076E+01
8000.00	0.1578E+02	0.1144E+02	0.7064E+01	0.2809E+01	-.1418E+01
9000.00	0.1306E+02	0.9763E+01	0.6040E+01	0.2142E+01	-.1901E+01
10000.00	0.1197E+02	0.9006E+01	0.5464E+01	0.1607E+01	-.2514E+01



11 rows 11 columns DX= 1000 DY= 1000 Drawdowns:-6.020808 <-> 73.71235

Enter <C> for additional contours: <X> to exit >>>

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

---

thw3-2c4.dat

********** INPUT DATA **********

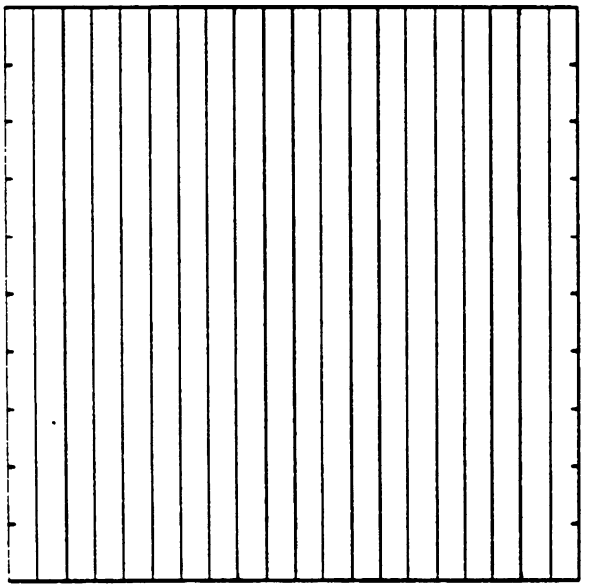
TRANSMISSIVITY	=	10018 [gpd/ft]
STORAGE COEFFICIENT	=	.001
REGIONAL FLOW GRADIENT (positive--downwards--in flow direction)	=	.02
REGIONAL FLOW DIRECTION (horizontal angle in degrees counter-clockwise from positive x-axis)	=	0
REGIONAL FLOW OFFSET AT ORIGIN (positive in downwards direction)	=	-200 [ft]

Note: No wells present, no data.

---------- Drawdown in [ft] ----------

Y [ft]	<- X [ft] ->					
	0	1000	2000	3000	4000	5000
0.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
1000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
2000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
3000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
4000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
5000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
6000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
7000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
8000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
9000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03
10000.00	-.2000E+03	-.1800E+03	-.1600E+03	-.1400E+03	-.1200E+03	-.1000E+03

Y [ft]	<- X [ft] ->				
	6000	7000	8000	9000	10000
0.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
1000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
2000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
3000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
4000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
5000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
6000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
7000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
8000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
9000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00
10000.00	-.8000E+02	-.6000E+02	-.4000E+02	-.2000E+02	0.0000E+00



11 rows 11 columns DX= 1000 DY= 1000 Drawdowns:-200 <-> 0

Enter <C> for additional contours: <X> to exit >>>

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

---

thw3-2c5.dat

********** INPUT DATA **********

TRANSMISSIVITY	=	10018 [gpd/ft]
STORAGE COEFFICIENT	=	.001
REGIONAL FLOW GRADIENT (positive--downwards--in flow direction)	=	.02
REGIONAL FLOW DIRECTION (horizontal angle in degrees counter-clockwise from positive x-axis)	=	0
REGIONAL FLOW OFFSET AT ORIGIN (positive in downwards direction)	=	-200 [ft]

WELL NO. 1

X-COORDINATE	=	3500 [ft]
Y-COORDINATE	=	5000 [ft]
PUMPING/INJECTION RATE	=	2003582 [gpd]
TIME SINCE START PUMPING/INJECTION	=	10 [day]

********** RESULTS ********** THWELLS - PAGE 3

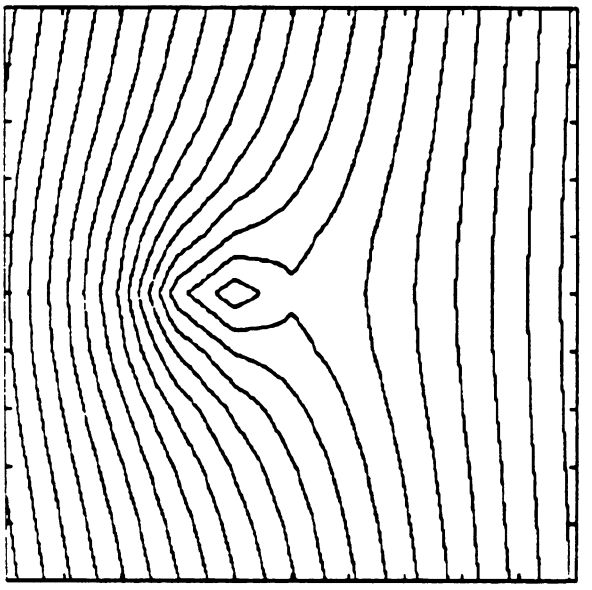
---------- Drawdown in [ft] ----------

Y [ft] <- X [ft] ->

	0	1000	2000	3000	4000	5000
0.00	-.1551E+03	-.1241E+03	-.9460E+02	-.6903E+02	-.4903E+02	-.3460E+02
1000.00	-.1372E+03	-.9936E+02	-.6317E+02	-.3315E+02	-.1315E+02	-.3170E+01
2000.00	-.1157E+03	-.6751E+02	-.1917E+02	0.2009E+02	0.4009E+02	0.4083E+02
3000.00	-.9315E+02	-.3010E+02	0.4056E+02	0.1022E+03	0.1222E+03	0.1006E+03
4000.00	-.7468E+02	0.4974E+01	0.1120E+03	0.2414E+03	0.2614E+03	0.1720E+03
5000.00	-.6732E+02	0.2056E+02	0.1536E+03	0.4309E+03	0.4509E+03	0.2136E+03
6000.00	-.7468E+02	0.4974E+01	0.1120E+03	0.2414E+03	0.2614E+03	0.1720E+03
7000.00	-.9315E+02	-.3010E+02	0.4056E+02	0.1022E+03	0.1222E+03	0.1006E+03
8000.00	-.1157E+03	-.6751E+02	-.1917E+02	0.2009E+02	0.4009E+02	0.4083E+02
9000.00	-.1372E+03	-.9936E+02	-.6317E+02	-.3315E+02	-.1315E+02	-.3170E+01
10000.00	-.1551E+03	-.1241E+03	-.9460E+02	-.6903E+02	-.4903E+02	-.3460E+02

Y [ft] <- X [ft] ->

	6000	7000	8000	9000	10000
0.00	-.2405E+02	-.1511E+02	-.5869E+01	0.4786E+01	0.1728E+02
1000.00	0.6385E+00	0.2848E+01	0.6523E+01	0.1302E+02	0.2260E+02
2000.00	0.3249E+02	0.2429E+02	0.2043E+02	0.2184E+02	0.2810E+02
3000.00	0.6990E+02	0.4685E+02	0.3400E+02	0.3002E+02	0.3302E+02
4000.00	0.1050E+03	0.6532E+02	0.4429E+02	0.3595E+02	0.3649E+02
5000.00	0.1206E+03	0.7268E+02	0.4818E+02	0.3813E+02	0.3774E+02
6000.00	0.1050E+03	0.6532E+02	0.4429E+02	0.3595E+02	0.3649E+02
7000.00	0.6990E+02	0.4685E+02	0.3400E+02	0.3002E+02	0.3302E+02
8000.00	0.3249E+02	0.2429E+02	0.2043E+02	0.2184E+02	0.2810E+02
9000.00	0.6385E+00	0.2848E+01	0.6523E+01	0.1302E+02	0.2260E+02
10000.00	-.2405E+02	-.1511E+02	-.5869E+01	0.4786E+01	0.1728E+02



11 rows 11 columns DX= 1000 DY= 1000 Drawdowns:-193.9993 <-> 5.045021

Enter <C> for additional contours: <X> to exit >>>

```
****************************** THWELLS ******************************  PAGE 1

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED
AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

-------------------------------------------------------------------------------

thw3-2c6.dat
-------------------------------------------------------------------------------


********************************** INPUT DATA **********************************

                                 TRANSMISSIVITY  =  10018 [gpd/ft]

                              STORAGE COEFFICIENT  =  .001

                         REGIONAL FLOW GRADIENT
        (positive--downwards--in flow direction)  =  .02

                        REGIONAL FLOW DIRECTION
                  (horizontal angle in degrees
         counter-clockwise from positive x-axis)  =  0

                  REGIONAL FLOW OFFSET AT ORIGIN
              (positive in downwards direction)  = -200 [ft]

-------------------------------------------------------------------------------
```

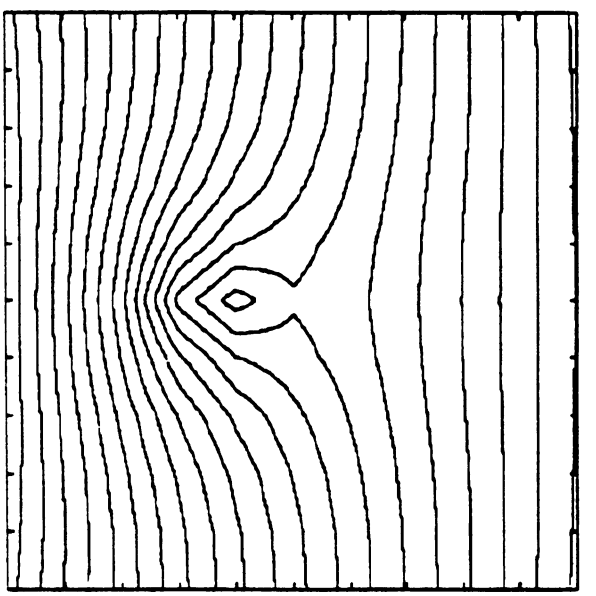
```
WELL NO. 1

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 2

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 3

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 4

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 5

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

********** RESULTS ********** THWELLS - PAGE 3

---------- Drawdown in [ft] ----------

Y [ft]	<- X [ft] ->					
	0	1000	2000	3000	4000	5000
0.00	-.1940E+03	-.1696E+03	-.1458E+03	-.1234E+03	-.1027E+03	-.8370E+02
1000.00	-.1958E+03	-.1703E+03	-.1456E+03	-.1225E+03	-.1016E+03	-.8274E+02
2000.00	-.1971E+03	-.1696E+03	-.1429E+03	-.1183E+03	-.9706E+02	-.7914E+02
3000.00	-.1980E+03	-.1675E+03	-.1373E+03	-.1093E+03	-.8784E+02	-.7268E+02
4000.00	-.1985E+03	-.1648E+03	-.1292E+03	-.9192E+02	-.7026E+02	-.6400E+02
5000.00	-.1987E+03	-.1634E+03	-.1241E+03	-.6700E+02	-.4527E+02	-.5872E+02
6000.00	-.1985E+03	-.1648E+03	-.1292E+03	-.9192E+02	-.7026E+02	-.6400E+02
7000.00	-.1980E+03	-.1675E+03	-.1373E+03	-.1093E+03	-.8784E+02	-.7268E+02
8000.00	-.1971E+03	-.1696E+03	-.1429E+03	-.1183E+03	-.9706E+02	-.7914E+02
9000.00	-.1958E+03	-.1703E+03	-.1456E+03	-.1225E+03	-.1016E+03	-.8274E+02
10000.00	-.1940E+03	-.1696E+03	-.1458E+03	-.1234E+03	-.1027E+03	-.8370E+02

Y [ft]	<- X [ft] ->				
	6000	7000	8000	9000	10000
0.00	-.6602E+02	-.4898E+02	-.3208E+02	-.1503E+02	0.2258E+01
1000.00	-.6537E+02	-.4867E+02	-.3207E+02	-.1532E+02	0.1636E+01
2000.00	-.6303E+02	-.4737E+02	-.3152E+02	-.1532E+02	0.1145E+01
3000.00	-.5932E+02	-.4544E+02	-.3065E+02	-.1512E+02	0.7962E+00
4000.00	-.5537E+02	-.4361E+02	-.2984E+02	-.1490E+02	0.5898E+00
5000.00	-.5353E+02	-.4283E+02	-.2951E+02	-.1480E+02	0.5216E+00
6000.00	-.5537E+02	-.4361E+02	-.2984E+02	-.1490E+02	0.5898E+00
7000.00	-.5932E+02	-.4544E+02	-.3065E+02	-.1512E+02	0.7962E+00
8000.00	-.6303E+02	-.4737E+02	-.3152E+02	-.1532E+02	0.1145E+01
9000.00	-.6537E+02	-.4867E+02	-.3207E+02	-.1532E+02	0.1636E+01
10000.00	-.6602E+02	-.4898E+02	-.3208E+02	-.1503E+02	0.2258E+01



11 rows 11 columns DX= 1000 DY= 1000 Drawdowns:-198.6519 <-> 2.258439

Enter <C> for additional contours: <X> to exit >>>

```
****************************** THWELLS ******************************  PAGE 1

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED
AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

-------------------------------------------------------------------------------

thw3-2c7.dat
-------------------------------------------------------------------------------


********************************** INPUT DATA **********************************

                                 TRANSMISSIVITY  =  10018 [gpd/ft]

                              STORAGE COEFFICIENT  =  .001

                          REGIONAL FLOW GRADIENT
        (positive--downwards--in flow direction)  =  .02

                         REGIONAL FLOW DIRECTION
                   (horizontal angle in degrees
         counter-clockwise from positive x-axis)  =  0

                   REGIONAL FLOW OFFSET AT ORIGIN
                (positive in downwards direction)  = -200 [ft]

-------------------------------------------------------------------------------
```

```
WELL NO. 1

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 2

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 3

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 4

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 5

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 6

                        X-COORDINATE  =  26500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

--------------------------------------------------------------------------------
```

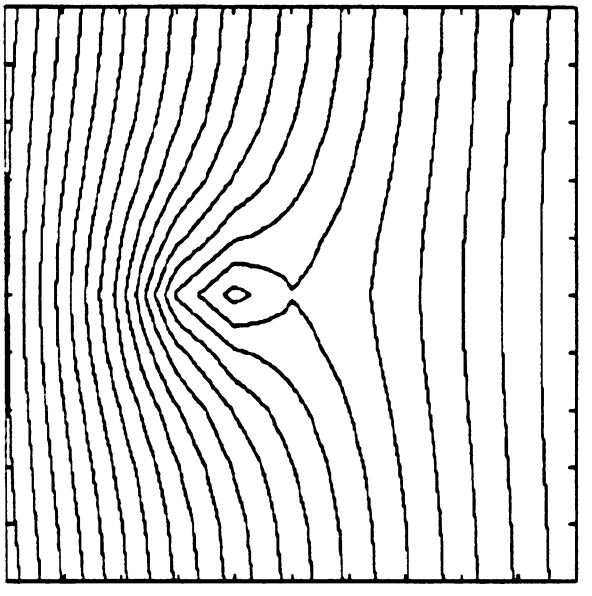
```
WELL NO. 7

                        X-COORDINATE  =  3599 [ft]
                        Y-COORDINATE  =  25000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 8

                        X-COORDINATE  = -16500 [ft]
                        Y-COORDINATE  =  5000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 9

                        X-COORDINATE  =  3500 [ft]
                        Y-COORDINATE  = -15000 [ft]
               PUMPING/INJECTION RATE  =  2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 10

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 11

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 12

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]
```

```
WELL NO. 13

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  = -5000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 14

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 15

                        X-COORDINATE  = -3500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 16

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

WELL NO. 17

                        X-COORDINATE  =  16500 [ft]
                        Y-COORDINATE  =  15000 [ft]
               PUMPING/INJECTION RATE  = -2003582 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  10 [day]

--------------------------------------------------------------------------------
```

---------- Drawdown in [ft] ----------

Y [ft]	<- X [ft] ->					
	0	1000	2000	3000	4000	5000
0.00	-.2060E+03	-.1788E+03	-.1525E+03	-.1281E+03	-.1060E+03	-.8615E+02
1000.00	-.2042E+03	-.1769E+03	-.1505E+03	-.1261E+03	-.1041E+03	-.8462E+02
2000.00	-.2029E+03	-.1742E+03	-.1464E+03	-.1209E+03	-.9894E+02	-.8056E+02
3000.00	-.2020E+03	-.1707E+03	-.1398E+03	-.1112E+03	-.8924E+02	-.7375E+02
4000.00	-.2015E+03	-.1673E+03	-.1311E+03	-.9339E+02	-.7137E+02	-.6486E+02
5000.00	-.2014E+03	-.1657E+03	-.1259E+03	-.6834E+02	-.4629E+02	-.5951E+02
6000.00	-.2015E+03	-.1673E+03	-.1311E+03	-.9339E+02	-.7137E+02	-.6486E+02
7000.00	-.2020E+03	-.1707E+03	-.1398E+03	-.1112E+03	-.8924E+02	-.7375E+02
8000.00	-.2029E+03	-.1742E+03	-.1464E+03	-.1209E+03	-.9894E+02	-.8056E+02
9000.00	-.2042E+03	-.1769E+03	-.1505E+03	-.1261E+03	-.1041E+03	-.8462E+02
10000.00	-.2060E+03	-.1788E+03	-.1525E+03	-.1281E+03	-.1060E+03	-.8615E+02

Y [ft]	<- X [ft] ->				
	6000	7000	8000	9000	10000
0.00	-.6803E+02	-.5099E+02	-.3454E+02	-.1839E+02	-.2514E+01
1000.00	-.6694E+02	-.5024E+02	-.3396E+02	-.1786E+02	-.1902E+01
2000.00	-.6422E+02	-.4856E+02	-.3294E+02	-.1719E+02	-.1418E+01
3000.00	-.6022E+02	-.4635E+02	-.3172E+02	-.1652E+02	-.1076E+01
4000.00	-.5611E+02	-.4434E+02	-.3070E+02	-.1601E+02	-.8743E+00
5000.00	-.5421E+02	-.4351E+02	-.3030E+02	-.1581E+02	-.8079E+00
6000.00	-.5611E+02	-.4434E+02	-.3070E+02	-.1601E+02	-.8743E+00
7000.00	-.6022E+02	-.4635E+02	-.3172E+02	-.1652E+02	-.1076E+01
8000.00	-.6422E+02	-.4856E+02	-.3294E+02	-.1719E+02	-.1418E+01
9000.00	-.6694E+02	-.5024E+02	-.3396E+02	-.1786E+02	-.1901E+01
10000.00	-.6803E+02	-.5099E+02	-.3454E+02	-.1839E+02	-.2514E+01



11 rows 11 columns DX= 1000 DY= 1000 Drawdowns:-206.0208 <->-.8078589

Enter <C> for additional contours: <X> to exit >>>

APPENDIX III

PRINTOUT OF TEST FILES

The program comes with two series of data files. The first series consists of three examples in either metric or English units. For each problem a confined and an unconfined case is given. The second series consists of two groups of problems representing various options to solve the problem described in Appendix II. The printout of input data and results for one problem of the first series is given in this Appendix, both for time-drawdown calculation in a single observation well as for the areal drawdown at a particular time. The data and results of the second series are given at the end of Appendix II.

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Dataset THW3D-3U.DAT

Time-drawdown Results for Single Observation Well

```
****************************** THWELLS ******************************  PAGE 1

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED
AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

-------------------------------------------------------------------------------

thw3d-3u.dat
-------------------------------------------------------------------------------


********************************** INPUT DATA **********************************

                                TRANSMISSIVITY  =  10000 [gpd/ft]

                             STORAGE COEFFICIENT  =  .1

                          REGIONAL FLOW GRADIENT
        (positive--downwards--in flow direction)  =  0

                       REGIONAL FLOW DIRECTION
                 (horizontal angle in degrees
         counter-clockwise from positive x-axis)  =  0

                 REGIONAL FLOW OFFSET AT ORIGIN
              (positive in downwards direction)  =  0 [ft]


                       WATER TABLE CORRECTION APPLIED

                             AQUIFER THICKNESS  =  60 [ft]

-------------------------------------------------------------------------------
```

WELL NO. 1

```
                    X-COORDINATE  =  7950 [ft]
                    Y-COORDINATE  =  5970 [ft]
          PUMPING/INJECTION RATE  =  1111680 [gpd]
TIME SINCE START PUMPING/INJECTION  =  179.8 [day]
```

WELL NO. 2

```
                    X-COORDINATE  =  10590 [ft]
                    Y-COORDINATE  =  5970 [ft]
          PUMPING/INJECTION RATE  = -1111680 [gpd]
TIME SINCE START PUMPING/INJECTION  =  179.8 [day]
```

WELL NO. 3

```
                    X-COORDINATE  =  7950 [ft]
                    Y-COORDINATE  =  30 [ft]
          PUMPING/INJECTION RATE  =  1111680 [gpd]
TIME SINCE START PUMPING/INJECTION  =  179.8 [day]
```

WELL NO. 4

```
                    X-COORDINATE  =  10590 [ft]
                    Y-COORDINATE  =  30 [ft]
          PUMPING/INJECTION RATE  = -1111680 [gpd]
TIME SINCE START PUMPING/INJECTION  =  179.8 [day]
```

WELL NO. 5

```
                    X-COORDINATE  =  7950 [ft]
                    Y-COORDINATE  =  11910 [ft]
          PUMPING/INJECTION RATE  =  1111680 [gpd]
TIME SINCE START PUMPING/INJECTION  =  179.8 [day]
```

WELL NO. 6

```
                    X-COORDINATE  =  10590 [ft]
                    Y-COORDINATE  =  11910 [ft]
          PUMPING/INJECTION RATE  = -1111680 [gpd]
TIME SINCE START PUMPING/INJECTION  =  179.8 [day]
```

---------- Drawdown in [ft] -- Time in [days] ----------

X-coordinate observation well = 100 [ft]
Y-coordinate observation well = 100 [ft]

time	drawdown	time	drawdown	time	drawdown	time	drawdown
0.000	0.001	0.200	0.001	0.400	0.001	0.600	0.001
0.800	0.001	1.000	0.001	1.200	0.001	1.400	0.001
1.600	0.001	1.800	0.001	2.000	0.001	2.200	0.001
2.400	0.001	2.600	0.001	2.800	0.002	3.000	0.002
3.200	0.002	3.400	0.002	3.600	0.002	3.800	0.002
4.000	0.002	4.200	0.002	4.400	0.002	4.600	0.002
4.800	0.002	5.000	0.002	5.200	0.002	5.400	0.002
5.600	0.002	5.800	0.002	6.000	0.002	6.200	0.002
6.400	0.002	6.600	0.002	6.800	0.002	7.000	0.002
7.200	0.002	7.400	0.002	7.600	0.002	7.800	0.002
8.000	0.002	8.200	0.002	8.400	0.002	8.600	0.002
8.800	0.002	9.000	0.002	9.200	0.002	9.400	0.002
9.600	0.002	9.800	0.002				

Dataset THW3D-3U.DAT

Areal Drawdown for Particular Time

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC NONLEAKY CONFINED AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS

---

thw3d-3u.dat

********** INPUT DATA **********

TRANSMISSIVITY = 10000 [gpd/ft]

STORAGE COEFFICIENT = .1

REGIONAL FLOW GRADIENT
(positive--downwards--in flow direction) = 0

REGIONAL FLOW DIRECTION
(horizontal angle in degrees
counter-clockwise from positive x-axis) = 0

REGIONAL FLOW OFFSET AT ORIGIN
(positive in downwards direction) = 0 [ft]

WATER TABLE CORRECTION APPLIED

AQUIFER THICKNESS = 60 [ft]

```
WELL NO. 1

                        X-COORDINATE  =  7950 [ft]
                        Y-COORDINATE  =  5970 [ft]
               PUMPING/INJECTION RATE  =  1111680 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  180 [day]

WELL NO. 2

                        X-COORDINATE  =  10590 [ft]
                        Y-COORDINATE  =  5970 [ft]
               PUMPING/INJECTION RATE  = -1111680 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  180 [day]

WELL NO. 3

                        X-COORDINATE  =  7950 [ft]
                        Y-COORDINATE  =  30 [ft]
               PUMPING/INJECTION RATE  =  1111680 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  180 [day]

WELL NO. 4

                        X-COORDINATE  =  10590 [ft]
                        Y-COORDINATE  =  30 [ft]
               PUMPING/INJECTION RATE  = -1111680 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  180 [day]

WELL NO. 5

                        X-COORDINATE  =  7950 [ft]
                        Y-COORDINATE  =  11910 [ft]
               PUMPING/INJECTION RATE  =  1111680 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  180 [day]

WELL NO. 6

                        X-COORDINATE  =  10590 [ft]
                        Y-COORDINATE  =  11910 [ft]
               PUMPING/INJECTION RATE  = -1111680 [gpd]
  TIME SINCE START PUMPING/INJECTION  =  180 [day]
```

---------- Drawdown in [ft] ----------

Y [ft]	<- X [ft] ->					
	0	100	200	300	400	500
0.00	0.1689E-02	0.2035E-02	0.2447E-02	0.2938E-02	0.3520E-02	0.4210E-02
100.00	0.1692E-02	0.2039E-02	0.2452E-02	0.2943E-02	0.3526E-02	0.4217E-02
200.00	0.1692E-02	0.2038E-02	0.2451E-02	0.2942E-02	0.3525E-02	0.4216E-02
300.00	0.1688E-02	0.2034E-02	0.2446E-02	0.2936E-02	0.3517E-02	0.4206E-02
400.00	0.1681E-02	0.2025E-02	0.2436E-02	0.2923E-02	0.3502E-02	0.4188E-02
500.00	0.1671E-02	0.2013E-02	0.2421E-02	0.2906E-02	0.3481E-02	0.4162E-02
600.00	0.1658E-02	0.1998E-02	0.2402E-02	0.2883E-02	0.3453E-02	0.4129E-02
700.00	0.1643E-02	0.1979E-02	0.2379E-02	0.2855E-02	0.3420E-02	0.4089E-02
800.00	0.1625E-02	0.1957E-02	0.2352E-02	0.2823E-02	0.3381E-02	0.4042E-02
900.00	0.1604E-02	0.1932E-02	0.2323E-02	0.2787E-02	0.3338E-02	0.3990E-02
1000.00	0.1582E-02	0.1905E-02	0.2290E-02	0.2747E-02	0.3290E-02	0.3932E-02
1100.00	0.1558E-02	0.1876E-02	0.2255E-02	0.2705E-02	0.3239E-02	0.3871E-02
1200.00	0.1532E-02	0.1845E-02	0.2217E-02	0.2660E-02	0.3184E-02	0.3805E-02
1300.00	0.1506E-02	0.1813E-02	0.2178E-02	0.2613E-02	0.3128E-02	0.3737E-02
1400.00	0.1479E-02	0.1780E-02	0.2139E-02	0.2565E-02	0.3070E-02	0.3668E-02
1500.00	0.1451E-02	0.1746E-02	0.2098E-02	0.2516E-02	0.3011E-02	0.3596E-02
1600.00	0.1423E-02	0.1713E-02	0.2057E-02	0.2466E-02	0.2951E-02	0.3525E-02
1700.00	0.1395E-02	0.1679E-02	0.2017E-02	0.2418E-02	0.2893E-02	0.3454E-02
1800.00	0.1368E-02	0.1646E-02	0.1977E-02	0.2370E-02	0.2835E-02	0.3385E-02
1900.00	0.1342E-02	0.1615E-02	0.1939E-02	0.2323E-02	0.2779E-02	0.3318E-02
2000.00	0.1317E-02	0.1584E-02	0.1902E-02	0.2279E-02	0.2726E-02	0.3254E-02
2100.00	0.1293E-02	0.1556E-02	0.1867E-02	0.2237E-02	0.2675E-02	0.3193E-02
2200.00	0.1271E-02	0.1529E-02	0.1835E-02	0.2199E-02	0.2629E-02	0.3137E-02
2300.00	0.1251E-02	0.1505E-02	0.1806E-02	0.2163E-02	0.2586E-02	0.3086E-02
2400.00	0.1234E-02	0.1483E-02	0.1780E-02	0.2132E-02	0.2548E-02	0.3040E-02
2500.00	0.1218E-02	0.1465E-02	0.1757E-02	0.2105E-02	0.2516E-02	0.3001E-02
2600.00	0.1205E-02	0.1449E-02	0.1739E-02	0.2082E-02	0.2488E-02	0.2968E-02
2700.00	0.1195E-02	0.1437E-02	0.1724E-02	0.2064E-02	0.2467E-02	0.2942E-02
2800.00	0.1188E-02	0.1428E-02	0.1713E-02	0.2051E-02	0.2451E-02	0.2924E-02
2900.00	0.1184E-02	0.1423E-02	0.1707E-02	0.2043E-02	0.2442E-02	0.2912E-02
3000.00	0.1182E-02	0.1421E-02	0.1705E-02	0.2041E-02	0.2439E-02	0.2909E-02
3100.00	0.1184E-02	0.1423E-02	0.1707E-02	0.2044E-02	0.2442E-02	0.2913E-02
3200.00	0.1188E-02	0.1428E-02	0.1713E-02	0.2051E-02	0.2452E-02	0.2924E-02
3300.00	0.1196E-02	0.1437E-02	0.1724E-02	0.2065E-02	0.2467E-02	0.2943E-02
3400.00	0.1206E-02	0.1450E-02	0.1739E-02	0.2083E-02	0.2489E-02	0.2969E-02
3500.00	0.1219E-02	0.1465E-02	0.1758E-02	0.2105E-02	0.2517E-02	0.3002E-02
3600.00	0.1234E-02	0.1484E-02	0.1781E-02	0.2133E-02	0.2550E-02	0.3042E-02
3700.00	0.1252E-02	0.1506E-02	0.1807E-02	0.2164E-02	0.2588E-02	0.3088E-02
3800.00	0.1272E-02	0.1530E-02	0.1836E-02	0.2200E-02	0.2630E-02	0.3139E-02

Y [ft]	<- X [ft] ->					
	0	100	200	300	400	500
3900.00	0.1294E-02	0.1557E-02	0.1869E-02	0.2239E-02	0.2678E-02	0.3196E-02
4000.00	0.1318E-02	0.1586E-02	0.1904E-02	0.2281E-02	0.2728E-02	0.3257E-02
4100.00	0.1344E-02	0.1616E-02	0.1941E-02	0.2326E-02	0.2782E-02	0.3322E-02
4200.00	0.1370E-02	0.1649E-02	0.1980E-02	0.2373E-02	0.2839E-02	0.3389E-02
4300.00	0.1398E-02	0.1682E-02	0.2020E-02	0.2421E-02	0.2897E-02	0.3460E-02
4400.00	0.1426E-02	0.1716E-02	0.2061E-02	0.2471E-02	0.2957E-02	0.3531E-02
4500.00	0.1454E-02	0.1750E-02	0.2102E-02	0.2521E-02	0.3017E-02	0.3604E-02
4600.00	0.1482E-02	0.1784E-02	0.2144E-02	0.2571E-02	0.3077E-02	0.3676E-02
4700.00	0.1510E-02	0.1818E-02	0.2185E-02	0.2620E-02	0.3137E-02	0.3748E-02
4800.00	0.1537E-02	0.1851E-02	0.2225E-02	0.2668E-02	0.3195E-02	0.3818E-02
4900.00	0.1564E-02	0.1883E-02	0.2263E-02	0.2715E-02	0.3251E-02	0.3885E-02

Y [ft]	<- X [ft] ->					
	600	700	800	900	1000	1100
0.00	0.5026E-02	0.5989E-02	0.7124E-02	0.8458E-02	0.1002E-01	0.1186E-01
100.00	0.5035E-02	0.5999E-02	0.7136E-02	0.8472E-02	0.1004E-01	0.1188E-01
200.00	0.5033E-02	0.5997E-02	0.7133E-02	0.8468E-02	0.1004E-01	0.1187E-01
300.00	0.5021E-02	0.5983E-02	0.7116E-02	0.8448E-02	0.1001E-01	0.1184E-01
400.00	0.4999E-02	0.5957E-02	0.7084E-02	0.8410E-02	0.9965E-02	0.1179E-01
500.00	0.4968E-02	0.5919E-02	0.7039E-02	0.8356E-02	0.9901E-02	0.1171E-01
600.00	0.4928E-02	0.5871E-02	0.6981E-02	0.8287E-02	0.9818E-02	0.1161E-01
700.00	0.4880E-02	0.5813E-02	0.6912E-02	0.8203E-02	0.9718E-02	0.1149E-01
800.00	0.4824E-02	0.5746E-02	0.6831E-02	0.8107E-02	0.9603E-02	0.1135E-01
900.00	0.4761E-02	0.5670E-02	0.6741E-02	0.7999E-02	0.9474E-02	0.1120E-01
1000.00	0.4692E-02	0.5587E-02	0.6642E-02	0.7880E-02	0.9333E-02	0.1103E-01
1100.00	0.4618E-02	0.5498E-02	0.6535E-02	0.7753E-02	0.9181E-02	0.1085E-01
1200.00	0.4539E-02	0.5404E-02	0.6423E-02	0.7618E-02	0.9020E-02	0.1066E-01
1300.00	0.4458E-02	0.5306E-02	0.6305E-02	0.7478E-02	0.8853E-02	0.1046E-01
1400.00	0.4374E-02	0.5206E-02	0.6185E-02	0.7334E-02	0.8681E-02	0.1026E-01
1500.00	0.4288E-02	0.5103E-02	0.6062E-02	0.7188E-02	0.8506E-02	0.1005E-01
1600.00	0.4203E-02	0.5001E-02	0.5939E-02	0.7041E-02	0.8331E-02	0.9839E-02
1700.00	0.4118E-02	0.4899E-02	0.5817E-02	0.6895E-02	0.8157E-02	0.9633E-02
1800.00	0.4034E-02	0.4799E-02	0.5698E-02	0.6753E-02	0.7987E-02	0.9430E-02
1900.00	0.3954E-02	0.4702E-02	0.5582E-02	0.6614E-02	0.7822E-02	0.9234E-02
2000.00	0.3877E-02	0.4610E-02	0.5472E-02	0.6482E-02	0.7665E-02	0.9046E-02
2100.00	0.3804E-02	0.4523E-02	0.5368E-02	0.6358E-02	0.7517E-02	0.8869E-02
2200.00	0.3737E-02	0.4442E-02	0.5271E-02	0.6242E-02	0.7379E-02	0.8706E-02
2300.00	0.3675E-02	0.4369E-02	0.5183E-02	0.6137E-02	0.7254E-02	0.8556E-02
2400.00	0.3621E-02	0.4303E-02	0.5105E-02	0.6044E-02	0.7142E-02	0.8424E-02
2500.00	0.3573E-02	0.4247E-02	0.5037E-02	0.5963E-02	0.7046E-02	0.8309E-02
2600.00	0.3534E-02	0.4199E-02	0.4980E-02	0.5895E-02	0.6965E-02	0.8213E-02
2700.00	0.3503E-02	0.4162E-02	0.4936E-02	0.5842E-02	0.6902E-02	0.8137E-02
2800.00	0.3480E-02	0.4135E-02	0.4904E-02	0.5804E-02	0.6856E-02	0.8083E-02

Y [ft]	<- X [ft] ->					
	600	700	800	900	1000	1100
2900.00	0.3467E-02	0.4119E-02	0.4884E-02	0.5781E-02	0.6828E-02	0.8050E-02
3000.00	0.3462E-02	0.4114E-02	0.4878E-02	0.5773E-02	0.6819E-02	0.8039E-02
3100.00	0.3467E-02	0.4119E-02	0.4885E-02	0.5781E-02	0.6829E-02	0.8050E-02
3200.00	0.3481E-02	0.4136E-02	0.4904E-02	0.5804E-02	0.6857E-02	0.8084E-02
3300.00	0.3504E-02	0.4163E-02	0.4937E-02	0.5843E-02	0.6903E-02	0.8139E-02
3400.00	0.3535E-02	0.4201E-02	0.4982E-02	0.5897E-02	0.6967E-02	0.8215E-02
3500.00	0.3575E-02	0.4248E-02	0.5039E-02	0.5965E-02	0.7048E-02	0.8312E-02
3600.00	0.3622E-02	0.4305E-02	0.5107E-02	0.6046E-02	0.7145E-02	0.8427E-02
3700.00	0.3677E-02	0.4371E-02	0.5186E-02	0.6141E-02	0.7257E-02	0.8561E-02
3800.00	0.3739E-02	0.4445E-02	0.5274E-02	0.6246E-02	0.7384E-02	0.8711E-02
3900.00	0.3807E-02	0.4526E-02	0.5372E-02	0.6363E-02	0.7522E-02	0.8876E-02
4000.00	0.3880E-02	0.4614E-02	0.5477E-02	0.6488E-02	0.7672E-02	0.9054E-02
4100.00	0.3958E-02	0.4708E-02	0.5588E-02	0.6621E-02	0.7831E-02	0.9243E-02
4200.00	0.4040E-02	0.4805E-02	0.5705E-02	0.6761E-02	0.7997E-02	0.9441E-02
4300.00	0.4124E-02	0.4906E-02	0.5826E-02	0.6905E-02	0.8169E-02	0.9646E-02
4400.00	0.4210E-02	0.5009E-02	0.5949E-02	0.7053E-02	0.8345E-02	0.9856E-02
4500.00	0.4297E-02	0.5114E-02	0.6074E-02	0.7202E-02	0.8523E-02	0.1007E-01
4600.00	0.4384E-02	0.5218E-02	0.6199E-02	0.7351E-02	0.8700E-02	0.1028E-01
4700.00	0.4470E-02	0.5321E-02	0.6322E-02	0.7498E-02	0.8876E-02	0.1049E-01
4800.00	0.4553E-02	0.5421E-02	0.6442E-02	0.7641E-02	0.9047E-02	0.1069E-01
4900.00	0.4634E-02	0.5518E-02	0.6558E-02	0.7780E-02	0.9212E-02	0.1089E-01

Y [ft]	<- X [ft] ->					
	1200	1300	1400	1500	1600	1700
0.00	0.1400E-01	0.1650E-01	0.1942E-01	0.2281E-01	0.2674E-01	0.3129E-01
100.00	0.1402E-01	0.1653E-01	0.1945E-01	0.2284E-01	0.2678E-01	0.3134E-01
200.00	0.1402E-01	0.1652E-01	0.1944E-01	0.2283E-01	0.2676E-01	0.3131E-01
300.00	0.1398E-01	0.1648E-01	0.1938E-01	0.2276E-01	0.2669E-01	0.3123E-01
400.00	0.1392E-01	0.1640E-01	0.1929E-01	0.2266E-01	0.2656E-01	0.3107E-01
500.00	0.1382E-01	0.1629E-01	0.1916E-01	0.2250E-01	0.2637E-01	0.3085E-01
600.00	0.1371E-01	0.1615E-01	0.1900E-01	0.2230E-01	0.2614E-01	0.3058E-01
700.00	0.1356E-01	0.1598E-01	0.1880E-01	0.2207E-01	0.2586E-01	0.3025E-01
800.00	0.1340E-01	0.1579E-01	0.1857E-01	0.2179E-01	0.2554E-01	0.2987E-01
900.00	0.1322E-01	0.1557E-01	0.1831E-01	0.2149E-01	0.2517E-01	0.2944E-01
1000.00	0.1302E-01	0.1533E-01	0.1803E-01	0.2115E-01	0.2478E-01	0.2897E-01
1100.00	0.1280E-01	0.1508E-01	0.1772E-01	0.2079E-01	0.2435E-01	0.2847E-01
1200.00	0.1257E-01	0.1481E-01	0.1740E-01	0.2041E-01	0.2391E-01	0.2794E-01
1300.00	0.1234E-01	0.1452E-01	0.1707E-01	0.2002E-01	0.2344E-01	0.2739E-01
1400.00	0.1209E-01	0.1424E-01	0.1673E-01	0.1961E-01	0.2296E-01	0.2683E-01
1500.00	0.1185E-01	0.1394E-01	0.1638E-01	0.1920E-01	0.2247E-01	0.2625E-01
1600.00	0.1160E-01	0.1365E-01	0.1603E-01	0.1879E-01	0.2199E-01	0.2568E-01
1700.00	0.1135E-01	0.1336E-01	0.1568E-01	0.1838E-01	0.2150E-01	0.2511E-01
1800.00	0.1111E-01	0.1307E-01	0.1534E-01	0.1798E-01	0.2103E-01	0.2455E-01

Y [ft]	<- X [ft] ->					
	1200	1300	1400	1500	1600	1700
1900.00	0.1088E-01	0.1279E-01	0.1502E-01	0.1759E-01	0.2057E-01	0.2401E-01
2000.00	0.1066E-01	0.1253E-01	0.1470E-01	0.1722E-01	0.2013E-01	0.2349E-01
2100.00	0.1045E-01	0.1228E-01	0.1441E-01	0.1687E-01	0.1972E-01	0.2301E-01
2200.00	0.1025E-01	0.1205E-01	0.1413E-01	0.1655E-01	0.1934E-01	0.2256E-01
2300.00	0.1007E-01	0.1184E-01	0.1388E-01	0.1625E-01	0.1899E-01	0.2215E-01
2400.00	0.9916E-02	0.1165E-01	0.1366E-01	0.1599E-01	0.1868E-01	0.2178E-01
2500.00	0.9780E-02	0.1149E-01	0.1347E-01	0.1576E-01	0.1841E-01	0.2147E-01
2600.00	0.9666E-02	0.1135E-01	0.1331E-01	0.1558E-01	0.1819E-01	0.2120E-01
2700.00	0.9576E-02	0.1125E-01	0.1318E-01	0.1543E-01	0.1801E-01	0.2099E-01
2800.00	0.9511E-02	0.1117E-01	0.1309E-01	0.1532E-01	0.1789E-01	0.2084E-01
2900.00	0.9472E-02	0.1112E-01	0.1304E-01	0.1525E-01	0.1781E-01	0.2075E-01
3000.00	0.9459E-02	0.1111E-01	0.1302E-01	0.1523E-01	0.1778E-01	0.2072E-01
3100.00	0.9473E-02	0.1112E-01	0.1304E-01	0.1525E-01	0.1781E-01	0.2076E-01
3200.00	0.9512E-02	0.1117E-01	0.1310E-01	0.1532E-01	0.1789E-01	0.2085E-01
3300.00	0.9578E-02	0.1125E-01	0.1319E-01	0.1543E-01	0.1802E-01	0.2100E-01
3400.00	0.9668E-02	0.1136E-01	0.1331E-01	0.1558E-01	0.1819E-01	0.2121E-01
3500.00	0.9783E-02	0.1149E-01	0.1348E-01	0.1577E-01	0.1842E-01	0.2147E-01
3600.00	0.9920E-02	0.1166E-01	0.1367E-01	0.1600E-01	0.1869E-01	0.2179E-01
3700.00	0.1008E-01	0.1184E-01	0.1389E-01	0.1626E-01	0.1900E-01	0.2216E-01
3800.00	0.1026E-01	0.1206E-01	0.1414E-01	0.1656E-01	0.1935E-01	0.2257E-01
3900.00	0.1045E-01	0.1229E-01	0.1442E-01	0.1688E-01	0.1974E-01	0.2302E-01
4000.00	0.1067E-01	0.1254E-01	0.1472E-01	0.1724E-01	0.2015E-01	0.2351E-01
4100.00	0.1089E-01	0.1281E-01	0.1503E-01	0.1761E-01	0.2059E-01	0.2403E-01
4200.00	0.1113E-01	0.1309E-01	0.1536E-01	0.1800E-01	0.2105E-01	0.2458E-01
4300.00	0.1137E-01	0.1337E-01	0.1570E-01	0.1841E-01	0.2153E-01	0.2514E-01
4400.00	0.1162E-01	0.1367E-01	0.1605E-01	0.1882E-01	0.2202E-01	0.2572E-01
4500.00	0.1187E-01	0.1397E-01	0.1641E-01	0.1924E-01	0.2251E-01	0.2630E-01
4600.00	0.1212E-01	0.1427E-01	0.1676E-01	0.1966E-01	0.2301E-01	0.2688E-01
4700.00	0.1237E-01	0.1456E-01	0.1711E-01	0.2007E-01	0.2350E-01	0.2746E-01
4800.00	0.1261E-01	0.1485E-01	0.1745E-01	0.2047E-01	0.2397E-01	0.2802E-01
4900.00	0.1285E-01	0.1513E-01	0.1778E-01	0.2086E-01	0.2443E-01	0.2856E-01

Y [ft]	<- X [ft] ->					
	1800	1900	2000	2100	2200	2300
0.00	0.3655E-01	0.4262E-01	0.4962E-01	0.5765E-01	0.6688E-01	0.7744E-01
100.00	0.3661E-01	0.4269E-01	0.4969E-01	0.5774E-01	0.6697E-01	0.7754E-01
200.00	0.3658E-01	0.4265E-01	0.4965E-01	0.5769E-01	0.6691E-01	0.7747E-01
300.00	0.3647E-01	0.4253E-01	0.4950E-01	0.5751E-01	0.6670E-01	0.7723E-01
400.00	0.3629E-01	0.4231E-01	0.4924E-01	0.5721E-01	0.6635E-01	0.7681E-01
500.00	0.3603E-01	0.4201E-01	0.4889E-01	0.5679E-01	0.6586E-01	0.7623E-01
600.00	0.3571E-01	0.4163E-01	0.4844E-01	0.5626E-01	0.6523E-01	0.7550E-01
700.00	0.3532E-01	0.4117E-01	0.4789E-01	0.5562E-01	0.6449E-01	0.7463E-01
800.00	0.3487E-01	0.4064E-01	0.4727E-01	0.5489E-01	0.6363E-01	0.7363E-01

Y [ft]	<- X [ft] ->					
	1800	1900	2000	2100	2200	2300
900.00	0.3437E-01	0.4004E-01	0.4658E-01	0.5408E-01	0.6267E-01	0.7251E-01
1000.00	0.3382E-01	0.3940E-01	0.4581E-01	0.5318E-01	0.6163E-01	0.7128E-01
1100.00	0.3322E-01	0.3870E-01	0.4500E-01	0.5223E-01	0.6051E-01	0.6997E-01
1200.00	0.3260E-01	0.3797E-01	0.4414E-01	0.5122E-01	0.5933E-01	0.6859E-01
1300.00	0.3195E-01	0.3721E-01	0.4324E-01	0.5017E-01	0.5810E-01	0.6716E-01
1400.00	0.3129E-01	0.3642E-01	0.4232E-01	0.4909E-01	0.5683E-01	0.6568E-01
1500.00	0.3061E-01	0.3563E-01	0.4139E-01	0.4800E-01	0.5556E-01	0.6419E-01
1600.00	0.2993E-01	0.3483E-01	0.4046E-01	0.4690E-01	0.5427E-01	0.6269E-01
1700.00	0.2926E-01	0.3404E-01	0.3953E-01	0.4582E-01	0.5300E-01	0.6120E-01
1800.00	0.2861E-01	0.3327E-01	0.3862E-01	0.4475E-01	0.5176E-01	0.5975E-01
1900.00	0.2797E-01	0.3252E-01	0.3775E-01	0.4373E-01	0.5056E-01	0.5835E-01
2000.00	0.2736E-01	0.3181E-01	0.3691E-01	0.4274E-01	0.4941E-01	0.5701E-01
2100.00	0.2679E-01	0.3114E-01	0.3612E-01	0.4182E-01	0.4833E-01	0.5574E-01
2200.00	0.2626E-01	0.3051E-01	0.3539E-01	0.4096E-01	0.4733E-01	0.5457E-01
2300.00	0.2578E-01	0.2995E-01	0.3472E-01	0.4018E-01	0.4642E-01	0.5351E-01
2400.00	0.2535E-01	0.2944E-01	0.3413E-01	0.3949E-01	0.4560E-01	0.5256E-01
2500.00	0.2498E-01	0.2900E-01	0.3362E-01	0.3889E-01	0.4490E-01	0.5174E-01
2600.00	0.2467E-01	0.2864E-01	0.3319E-01	0.3839E-01	0.4432E-01	0.5106E-01
2700.00	0.2442E-01	0.2835E-01	0.3285E-01	0.3800E-01	0.4386E-01	0.5052E-01
2800.00	0.2425E-01	0.2815E-01	0.3261E-01	0.3771E-01	0.4352E-01	0.5013E-01
2900.00	0.2414E-01	0.2802E-01	0.3246E-01	0.3754E-01	0.4332E-01	0.4990E-01
3000.00	0.2410E-01	0.2798E-01	0.3242E-01	0.3748E-01	0.4326E-01	0.4982E-01
3100.00	0.2414E-01	0.2802E-01	0.3247E-01	0.3754E-01	0.4333E-01	0.4990E-01
3200.00	0.2425E-01	0.2815E-01	0.3261E-01	0.3772E-01	0.4353E-01	0.5014E-01
3300.00	0.2443E-01	0.2836E-01	0.3286E-01	0.3800E-01	0.4386E-01	0.5053E-01
3400.00	0.2467E-01	0.2865E-01	0.3320E-01	0.3840E-01	0.4433E-01	0.5107E-01
3500.00	0.2498E-01	0.2901E-01	0.3363E-01	0.3890E-01	0.4492E-01	0.5176E-01
3600.00	0.2536E-01	0.2945E-01	0.3414E-01	0.3951E-01	0.4562E-01	0.5258E-01
3700.00	0.2579E-01	0.2996E-01	0.3474E-01	0.4020E-01	0.4644E-01	0.5353E-01
3800.00	0.2628E-01	0.3053E-01	0.3541E-01	0.4099E-01	0.4735E-01	0.5460E-01
3900.00	0.2681E-01	0.3116E-01	0.3614E-01	0.4185E-01	0.4836E-01	0.5578E-01
4000.00	0.2738E-01	0.3183E-01	0.3694E-01	0.4278E-01	0.4945E-01	0.5705E-01
4100.00	0.2800E-01	0.3255E-01	0.3778E-01	0.4377E-01	0.5060E-01	0.5840E-01
4200.00	0.2864E-01	0.3331E-01	0.3867E-01	0.4480E-01	0.5182E-01	0.5981E-01
4300.00	0.2930E-01	0.3409E-01	0.3958E-01	0.4587E-01	0.5307E-01	0.6128E-01
4400.00	0.2998E-01	0.3488E-01	0.4052E-01	0.4697E-01	0.5435E-01	0.6278E-01
4500.00	0.3067E-01	0.3569E-01	0.4146E-01	0.4808E-01	0.5565E-01	0.6429E-01
4600.00	0.3135E-01	0.3650E-01	0.4241E-01	0.4919E-01	0.5694E-01	0.6581E-01
4700.00	0.3203E-01	0.3729E-01	0.4334E-01	0.5028E-01	0.5823E-01	0.6730E-01
4800.00	0.3269E-01	0.3807E-01	0.4426E-01	0.5135E-01	0.5948E-01	0.6877E-01

Y [ft]	<- X [ft] ->					
	1800	1900	2000	2100	2200	2300
4900.00	0.3333E-01	0.3882E-01	0.4514E-01	0.5238E-01	0.6069E-01	0.7018E-01

Y [ft]	<- X [ft] ->					
	2400	2500	2600	2700	2800	2900
0.00	0.8951E-01	0.1033E+00	0.1190E+00	0.1368E+00	0.1570E+00	0.1800E+00
100.00	0.8963E-01	0.1034E+00	0.1191E+00	0.1370E+00	0.1572E+00	0.1802E+00
200.00	0.8954E-01	0.1033E+00	0.1190E+00	0.1368E+00	0.1571E+00	0.1800E+00
300.00	0.8925E-01	0.1030E+00	0.1186E+00	0.1364E+00	0.1565E+00	0.1793E+00
400.00	0.8877E-01	0.1024E+00	0.1179E+00	0.1356E+00	0.1556E+00	0.1782E+00
500.00	0.8809E-01	0.1016E+00	0.1170E+00	0.1345E+00	0.1543E+00	0.1768E+00
600.00	0.8723E-01	0.1006E+00	0.1158E+00	0.1331E+00	0.1528E+00	0.1750E+00
700.00	0.8621E-01	0.9942E-01	0.1145E+00	0.1315E+00	0.1509E+00	0.1728E+00
800.00	0.8504E-01	0.9806E-01	0.1129E+00	0.1297E+00	0.1487E+00	0.1703E+00
900.00	0.8373E-01	0.9653E-01	0.1111E+00	0.1276E+00	0.1463E+00	0.1675E+00
1000.00	0.8231E-01	0.9486E-01	0.1091E+00	0.1253E+00	0.1437E+00	0.1645E+00
1100.00	0.8078E-01	0.9308E-01	0.1071E+00	0.1229E+00	0.1409E+00	0.1612E+00
1200.00	0.7916E-01	0.9120E-01	0.1049E+00	0.1204E+00	0.1379E+00	0.1578E+00
1300.00	0.7749E-01	0.8925E-01	0.1026E+00	0.1177E+00	0.1349E+00	0.1542E+00
1400.00	0.7577E-01	0.8724E-01	0.1003E+00	0.1150E+00	0.1317E+00	0.1506E+00
1500.00	0.7402E-01	0.8521E-01	0.9791E-01	0.1123E+00	0.1286E+00	0.1469E+00
1600.00	0.7227E-01	0.8317E-01	0.9554E-01	0.1095E+00	0.1254E+00	0.1432E+00
1700.00	0.7054E-01	0.8116E-01	0.9319E-01	0.1068E+00	0.1222E+00	0.1396E+00
1800.00	0.6885E-01	0.7918E-01	0.9090E-01	0.1042E+00	0.1191E+00	0.1360E+00
1900.00	0.6721E-01	0.7728E-01	0.8868E-01	0.1016E+00	0.1161E+00	0.1325E+00
2000.00	0.6565E-01	0.7546E-01	0.8657E-01	0.9912E-01	0.1133E+00	0.1292E+00
2100.00	0.6418E-01	0.7374E-01	0.8457E-01	0.9681E-01	0.1106E+00	0.1261E+00
2200.00	0.6281E-01	0.7216E-01	0.8273E-01	0.9467E-01	0.1081E+00	0.1233E+00
2300.00	0.6157E-01	0.7071E-01	0.8105E-01	0.9272E-01	0.1059E+00	0.1207E+00
2400.00	0.6047E-01	0.6943E-01	0.7956E-01	0.9099E-01	0.1039E+00	0.1183E+00
2500.00	0.5951E-01	0.6831E-01	0.7827E-01	0.8949E-01	0.1021E+00	0.1163E+00
2600.00	0.5872E-01	0.6739E-01	0.7719E-01	0.8825E-01	0.1007E+00	0.1147E+00
2700.00	0.5809E-01	0.6666E-01	0.7634E-01	0.8726E-01	0.9955E-01	0.1133E+00
2800.00	0.5764E-01	0.6613E-01	0.7573E-01	0.8655E-01	0.9872E-01	0.1124E+00
2900.00	0.5736E-01	0.6581E-01	0.7536E-01	0.8612E-01	0.9823E-01	0.1118E+00
3000.00	0.5727E-01	0.6571E-01	0.7524E-01	0.8598E-01	0.9806E-01	0.1116E+00
3100.00	0.5737E-01	0.6582E-01	0.7536E-01	0.8613E-01	0.9823E-01	0.1118E+00
3200.00	0.5764E-01	0.6614E-01	0.7574E-01	0.8656E-01	0.9873E-01	0.1124E+00
3300.00	0.5810E-01	0.6667E-01	0.7635E-01	0.8727E-01	0.9956E-01	0.1134E+00
3400.00	0.5873E-01	0.6740E-01	0.7721E-01	0.8826E-01	0.1007E+00	0.1147E+00
3500.00	0.5953E-01	0.6833E-01	0.7829E-01	0.8952E-01	0.1022E+00	0.1164E+00
3600.00	0.6049E-01	0.6945E-01	0.7959E-01	0.9102E-01	0.1039E+00	0.1184E+00
3700.00	0.6160E-01	0.7074E-01	0.8109E-01	0.9276E-01	0.1059E+00	0.1207E+00
3800.00	0.6285E-01	0.7219E-01	0.8277E-01	0.9472E-01	0.1082E+00	0.1233E+00

Y [ft]	<- X [ft] ->					
	2400	2500	2600	2700	2800	2900
3900.00	0.6422E-01	0.7379E-01	0.8463E-01	0.9687E-01	0.1107E+00	0.1262E+00
4000.00	0.6570E-01	0.7551E-01	0.8663E-01	0.9920E-01	0.1134E+00	0.1293E+00
4100.00	0.6727E-01	0.7734E-01	0.8876E-01	0.1017E+00	0.1162E+00	0.1326E+00
4200.00	0.6892E-01	0.7926E-01	0.9099E-01	0.1043E+00	0.1192E+00	0.1361E+00
4300.00	0.7063E-01	0.8125E-01	0.9330E-01	0.1069E+00	0.1223E+00	0.1397E+00
4400.00	0.7238E-01	0.8329E-01	0.9567E-01	0.1097E+00	0.1255E+00	0.1434E+00
4500.00	0.7414E-01	0.8534E-01	0.9806E-01	0.1125E+00	0.1287E+00	0.1471E+00
4600.00	0.7591E-01	0.8740E-01	0.1005E+00	0.1152E+00	0.1320E+00	0.1509E+00
4700.00	0.7765E-01	0.8944E-01	0.1028E+00	0.1180E+00	0.1352E+00	0.1545E+00
4800.00	0.7936E-01	0.9142E-01	0.1051E+00	0.1207E+00	0.1383E+00	0.1581E+00
4900.00	0.8101E-01	0.9334E-01	0.1074E+00	0.1233E+00	0.1413E+00	0.1616E+00

Y [ft]	<- X [ft] ->					
	3000	3100	3200	3300	3400	3500
0.00	0.2059E+00	0.2351E+00	0.2680E+00	0.3051E+00	0.3466E+00	0.3931E+00
100.00	0.2061E+00	0.2354E+00	0.2683E+00	0.3054E+00	0.3470E+00	0.3935E+00
200.00	0.2058E+00	0.2351E+00	0.2680E+00	0.3049E+00	0.3464E+00	0.3929E+00
300.00	0.2051E+00	0.2342E+00	0.2669E+00	0.3037E+00	0.3451E+00	0.3913E+00
400.00	0.2039E+00	0.2327E+00	0.2653E+00	0.3018E+00	0.3428E+00	0.3887E+00
500.00	0.2022E+00	0.2308E+00	0.2630E+00	0.2992E+00	0.3398E+00	0.3852E+00
600.00	0.2000E+00	0.2283E+00	0.2601E+00	0.2959E+00	0.3360E+00	0.3808E+00
700.00	0.1975E+00	0.2254E+00	0.2568E+00	0.2920E+00	0.3315E+00	0.3757E+00
800.00	0.1946E+00	0.2220E+00	0.2529E+00	0.2875E+00	0.3263E+00	0.3697E+00
900.00	0.1914E+00	0.2183E+00	0.2486E+00	0.2825E+00	0.3206E+00	0.3631E+00
1000.00	0.1879E+00	0.2142E+00	0.2439E+00	0.2771E+00	0.3144E+00	0.3560E+00
1100.00	0.1841E+00	0.2099E+00	0.2389E+00	0.2714E+00	0.3077E+00	0.3483E+00
1200.00	0.1802E+00	0.2053E+00	0.2336E+00	0.2653E+00	0.3007E+00	0.3403E+00
1300.00	0.1760E+00	0.2006E+00	0.2281E+00	0.2590E+00	0.2935E+00	0.3319E+00
1400.00	0.1718E+00	0.1957E+00	0.2225E+00	0.2525E+00	0.2860E+00	0.3234E+00
1500.00	0.1676E+00	0.1908E+00	0.2168E+00	0.2460E+00	0.2785E+00	0.3148E+00
1600.00	0.1633E+00	0.1859E+00	0.2111E+00	0.2394E+00	0.2710E+00	0.3061E+00
1700.00	0.1591E+00	0.1810E+00	0.2055E+00	0.2330E+00	0.2636E+00	0.2976E+00
1800.00	0.1549E+00	0.1762E+00	0.2000E+00	0.2266E+00	0.2563E+00	0.2893E+00
1900.00	0.1509E+00	0.1716E+00	0.1947E+00	0.2205E+00	0.2493E+00	0.2812E+00
2000.00	0.1471E+00	0.1672E+00	0.1897E+00	0.2147E+00	0.2426E+00	0.2736E+00
2100.00	0.1436E+00	0.1631E+00	0.1849E+00	0.2092E+00	0.2363E+00	0.2664E+00
2200.00	0.1402E+00	0.1593E+00	0.1805E+00	0.2042E+00	0.2305E+00	0.2597E+00
2300.00	0.1372E+00	0.1558E+00	0.1765E+00	0.1996E+00	0.2252E+00	0.2537E+00
2400.00	0.1346E+00	0.1527E+00	0.1729E+00	0.1955E+00	0.2205E+00	0.2483E+00
2500.00	0.1322E+00	0.1500E+00	0.1699E+00	0.1919E+00	0.2165E+00	0.2436E+00
2600.00	0.1303E+00	0.1478E+00	0.1673E+00	0.1890E+00	0.2131E+00	0.2398E+00
2700.00	0.1288E+00	0.1460E+00	0.1653E+00	0.1867E+00	0.2104E+00	0.2367E+00
2800.00	0.1277E+00	0.1448E+00	0.1638E+00	0.1850E+00	0.2085E+00	0.2345E+00

Y [ft]	<- X [ft] ->					
	3000	3100	3200	3300	3400	3500
2900.00	0.1270E+00	0.1440E+00	0.1629E+00	0.1840E+00	0.2073E+00	0.2332E+00
3000.00	0.1268E+00	0.1438E+00	0.1627E+00	0.1837E+00	0.2070E+00	0.2327E+00
3100.00	0.1270E+00	0.1440E+00	0.1630E+00	0.1840E+00	0.2074E+00	0.2332E+00
3200.00	0.1277E+00	0.1448E+00	0.1638E+00	0.1850E+00	0.2085E+00	0.2345E+00
3300.00	0.1288E+00	0.1461E+00	0.1653E+00	0.1867E+00	0.2105E+00	0.2367E+00
3400.00	0.1303E+00	0.1478E+00	0.1673E+00	0.1890E+00	0.2131E+00	0.2398E+00
3500.00	0.1323E+00	0.1501E+00	0.1699E+00	0.1920E+00	0.2165E+00	0.2437E+00
3600.00	0.1346E+00	0.1527E+00	0.1730E+00	0.1955E+00	0.2206E+00	0.2484E+00
3700.00	0.1373E+00	0.1558E+00	0.1766E+00	0.1996E+00	0.2253E+00	0.2538E+00
3800.00	0.1403E+00	0.1593E+00	0.1806E+00	0.2043E+00	0.2306E+00	0.2598E+00
3900.00	0.1436E+00	0.1632E+00	0.1850E+00	0.2094E+00	0.2364E+00	0.2665E+00
4000.00	0.1472E+00	0.1673E+00	0.1898E+00	0.2148E+00	0.2428E+00	0.2738E+00
4100.00	0.1511E+00	0.1717E+00	0.1949E+00	0.2207E+00	0.2495E+00	0.2815E+00
4200.00	0.1551E+00	0.1764E+00	0.2002E+00	0.2268E+00	0.2565E+00	0.2895E+00
4300.00	0.1592E+00	0.1812E+00	0.2057E+00	0.2332E+00	0.2638E+00	0.2979E+00
4400.00	0.1635E+00	0.1861E+00	0.2114E+00	0.2397E+00	0.2713E+00	0.3065E+00
4500.00	0.1678E+00	0.1911E+00	0.2171E+00	0.2463E+00	0.2789E+00	0.3152E+00
4600.00	0.1721E+00	0.1960E+00	0.2229E+00	0.2529E+00	0.2865E+00	0.3239E+00
4700.00	0.1764E+00	0.2010E+00	0.2285E+00	0.2594E+00	0.2940E+00	0.3325E+00
4800.00	0.1806E+00	0.2058E+00	0.2341E+00	0.2658E+00	0.3013E+00	0.3410E+00
4900.00	0.1846E+00	0.2104E+00	0.2395E+00	0.2720E+00	0.3085E+00	0.3492E+00

Y [ft]	<- X [ft] ->					
	3600	3700	3800	3900	4000	4100
0.00	0.4452E+00	0.5033E+00	0.5679E+00	0.6399E+00	0.7197E+00	0.8082E+00
100.00	0.4456E+00	0.5037E+00	0.5685E+00	0.6404E+00	0.7203E+00	0.8088E+00
200.00	0.4449E+00	0.5029E+00	0.5675E+00	0.6393E+00	0.7189E+00	0.8072E+00
300.00	0.4430E+00	0.5007E+00	0.5649E+00	0.6364E+00	0.7156E+00	0.8034E+00
400.00	0.4400E+00	0.4973E+00	0.5610E+00	0.6318E+00	0.7104E+00	0.7974E+00
500.00	0.4360E+00	0.4926E+00	0.5557E+00	0.6257E+00	0.7034E+00	0.7893E+00
600.00	0.4310E+00	0.4868E+00	0.5490E+00	0.6181E+00	0.6946E+00	0.7793E+00
700.00	0.4250E+00	0.4800E+00	0.5411E+00	0.6091E+00	0.6843E+00	0.7676E+00
800.00	0.4182E+00	0.4722E+00	0.5322E+00	0.5988E+00	0.6726E+00	0.7542E+00
900.00	0.4106E+00	0.4635E+00	0.5222E+00	0.5874E+00	0.6596E+00	0.7393E+00
1000.00	0.4024E+00	0.4540E+00	0.5114E+00	0.5751E+00	0.6455E+00	0.7232E+00
1100.00	0.3936E+00	0.4440E+00	0.4999E+00	0.5619E+00	0.6304E+00	0.7061E+00
1200.00	0.3844E+00	0.4334E+00	0.4878E+00	0.5481E+00	0.6146E+00	0.6881E+00
1300.00	0.3748E+00	0.4224E+00	0.4753E+00	0.5337E+00	0.5983E+00	0.6694E+00
1400.00	0.3650E+00	0.4112E+00	0.4624E+00	0.5191E+00	0.5816E+00	0.6504E+00
1500.00	0.3551E+00	0.3999E+00	0.4495E+00	0.5043E+00	0.5647E+00	0.6312E+00
1600.00	0.3452E+00	0.3886E+00	0.4365E+00	0.4895E+00	0.5479E+00	0.6121E+00
1700.00	0.3355E+00	0.3774E+00	0.4238E+00	0.4749E+00	0.5313E+00	0.5932E+00
1800.00	0.3259E+00	0.3665E+00	0.4113E+00	0.4607E+00	0.5151E+00	0.5747E+00

Y [ft] <- X [ft] ->

	3600	3700	3800	3900	4000	4100
1900.00	0.3167E+00	0.3559E+00	0.3993E+00	0.4470E+00	0.4995E+00	0.5570E+00
2000.00	0.3079E+00	0.3459E+00	0.3878E+00	0.4340E+00	0.4846E+00	0.5401E+00
2100.00	0.2997E+00	0.3365E+00	0.3771E+00	0.4217E+00	0.4707E+00	0.5243E+00
2200.00	0.2921E+00	0.3278E+00	0.3671E+00	0.4104E+00	0.4578E+00	0.5096E+00
2300.00	0.2851E+00	0.3199E+00	0.3581E+00	0.4001E+00	0.4461E+00	0.4964E+00
2400.00	0.2790E+00	0.3128E+00	0.3501E+00	0.3910E+00	0.4357E+00	0.4846E+00
2500.00	0.2737E+00	0.3067E+00	0.3431E+00	0.3831E+00	0.4267E+00	0.4744E+00
2600.00	0.2692E+00	0.3017E+00	0.3374E+00	0.3765E+00	0.4193E+00	0.4660E+00
2700.00	0.2657E+00	0.2977E+00	0.3328E+00	0.3713E+00	0.4134E+00	0.4593E+00
2800.00	0.2632E+00	0.2948E+00	0.3296E+00	0.3676E+00	0.4092E+00	0.4545E+00
2900.00	0.2617E+00	0.2931E+00	0.3276E+00	0.3654E+00	0.4066E+00	0.4516E+00
3000.00	0.2612E+00	0.2925E+00	0.3269E+00	0.3646E+00	0.4058E+00	0.4506E+00
3100.00	0.2617E+00	0.2931E+00	0.3276E+00	0.3654E+00	0.4066E+00	0.4516E+00
3200.00	0.2632E+00	0.2949E+00	0.3296E+00	0.3676E+00	0.4092E+00	0.4545E+00
3300.00	0.2658E+00	0.2977E+00	0.3329E+00	0.3714E+00	0.4135E+00	0.4593E+00
3400.00	0.2693E+00	0.3017E+00	0.3374E+00	0.3766E+00	0.4194E+00	0.4660E+00
3500.00	0.2737E+00	0.3068E+00	0.3432E+00	0.3832E+00	0.4268E+00	0.4745E+00
3600.00	0.2791E+00	0.3129E+00	0.3502E+00	0.3911E+00	0.4358E+00	0.4847E+00
3700.00	0.2852E+00	0.3200E+00	0.3582E+00	0.4002E+00	0.4462E+00	0.4965E+00
3800.00	0.2922E+00	0.3279E+00	0.3673E+00	0.4105E+00	0.4580E+00	0.5098E+00
3900.00	0.2998E+00	0.3367E+00	0.3773E+00	0.4219E+00	0.4709E+00	0.5245E+00
4000.00	0.3081E+00	0.3461E+00	0.3880E+00	0.4342E+00	0.4849E+00	0.5404E+00
4100.00	0.3169E+00	0.3562E+00	0.3995E+00	0.4473E+00	0.4998E+00	0.5574E+00
4200.00	0.3262E+00	0.3668E+00	0.4116E+00	0.4611E+00	0.5155E+00	0.5752E+00
4300.00	0.3358E+00	0.3778E+00	0.4242E+00	0.4754E+00	0.5318E+00	0.5937E+00
4400.00	0.3456E+00	0.3890E+00	0.4370E+00	0.4900E+00	0.5485E+00	0.6127E+00
4500.00	0.3556E+00	0.4004E+00	0.4501E+00	0.5049E+00	0.5654E+00	0.6320E+00
4600.00	0.3656E+00	0.4118E+00	0.4631E+00	0.5198E+00	0.5824E+00	0.6513E+00
4700.00	0.3755E+00	0.4232E+00	0.4761E+00	0.5346E+00	0.5992E+00	0.6705E+00
4800.00	0.3852E+00	0.4343E+00	0.4887E+00	0.5491E+00	0.6158E+00	0.6893E+00
4900.00	0.3945E+00	0.4450E+00	0.5010E+00	0.5631E+00	0.6318E+00	0.7075E+00

Y [ft] <- X [ft] ->

	4200	4300	4400	4500	4600	4700
0.00	0.9060E+00	0.1014E+01	0.1133E+01	0.1264E+01	0.1407E+01	0.1564E+01
100.00	0.9067E+00	0.1015E+01	0.1134E+01	0.1264E+01	0.1408E+01	0.1565E+01
200.00	0.9048E+00	0.1012E+01	0.1131E+01	0.1261E+01	0.1405E+01	0.1561E+01
300.00	0.9004E+00	0.1007E+01	0.1125E+01	0.1255E+01	0.1397E+01	0.1553E+01
400.00	0.8935E+00	0.9995E+00	0.1116E+01	0.1245E+01	0.1385E+01	0.1539E+01
500.00	0.8843E+00	0.9890E+00	0.1104E+01	0.1231E+01	0.1370E+01	0.1521E+01
600.00	0.8729E+00	0.9760E+00	0.1089E+01	0.1214E+01	0.1350E+01	0.1500E+01
700.00	0.8595E+00	0.9607E+00	0.1072E+01	0.1194E+01	0.1328E+01	0.1474E+01
800.00	0.8442E+00	0.9433E+00	0.1052E+01	0.1172E+01	0.1302E+01	0.1445E+01

Y [ft]	<- X [ft] ->					
	4200	4300	4400	4500	4600	4700
900.00	0.8272E+00	0.9240E+00	0.1030E+01	0.1147E+01	0.1274E+01	0.1413E+01
1000.00	0.8089E+00	0.9031E+00	0.1007E+01	0.1120E+01	0.1244E+01	0.1378E+01
1100.00	0.7894E+00	0.8809E+00	0.9813E+00	0.1091E+01	0.1211E+01	0.1342E+01
1200.00	0.7689E+00	0.8576E+00	0.9548E+00	0.1061E+01	0.1177E+01	0.1303E+01
1300.00	0.7477E+00	0.8335E+00	0.9275E+00	0.1030E+01	0.1142E+01	0.1264E+01
1400.00	0.7260E+00	0.8089E+00	0.8996E+00	0.9986E+00	0.1106E+01	0.1223E+01
1500.00	0.7042E+00	0.7842E+00	0.8715E+00	0.9668E+00	0.1070E+01	0.1183E+01
1600.00	0.6824E+00	0.7595E+00	0.8435E+00	0.9351E+00	0.1035E+01	0.1142E+01
1700.00	0.6610E+00	0.7351E+00	0.8160E+00	0.9039E+00	0.9994E+00	0.1103E+01
1800.00	0.6401E+00	0.7114E+00	0.7891E+00	0.8736E+00	0.9651E+00	0.1064E+01
1900.00	0.6199E+00	0.6886E+00	0.7633E+00	0.8444E+00	0.9322E+00	0.1027E+01
2000.00	0.6008E+00	0.6669E+00	0.7388E+00	0.8167E+00	0.9010E+00	0.9918E+00
2100.00	0.5828E+00	0.6465E+00	0.7158E+00	0.7907E+00	0.8717E+00	0.9589E+00
2200.00	0.5662E+00	0.6278E+00	0.6945E+00	0.7668E+00	0.8447E+00	0.9286E+00
2300.00	0.5512E+00	0.6107E+00	0.6753E+00	0.7451E+00	0.8203E+00	0.9011E+00
2400.00	0.5378E+00	0.5956E+00	0.6582E+00	0.7258E+00	0.7987E+00	0.8768E+00
2500.00	0.5263E+00	0.5826E+00	0.6435E+00	0.7093E+00	0.7800E+00	0.8558E+00
2600.00	0.5167E+00	0.5717E+00	0.6313E+00	0.6955E+00	0.7645E+00	0.8384E+00
2700.00	0.5091E+00	0.5632E+00	0.6216E+00	0.6846E+00	0.7523E+00	0.8247E+00
2800.00	0.5037E+00	0.5571E+00	0.6147E+00	0.6768E+00	0.7435E+00	0.8149E+00
2900.00	0.5004E+00	0.5533E+00	0.6105E+00	0.6721E+00	0.7382E+00	0.8089E+00
3000.00	0.4993E+00	0.5521E+00	0.6091E+00	0.6705E+00	0.7364E+00	0.8069E+00
3100.00	0.5004E+00	0.5534E+00	0.6105E+00	0.6721E+00	0.7382E+00	0.8089E+00
3200.00	0.5037E+00	0.5571E+00	0.6147E+00	0.6768E+00	0.7435E+00	0.8149E+00
3300.00	0.5092E+00	0.5633E+00	0.6217E+00	0.6847E+00	0.7524E+00	0.8248E+00
3400.00	0.5168E+00	0.5718E+00	0.6314E+00	0.6956E+00	0.7646E+00	0.8386E+00
3500.00	0.5264E+00	0.5827E+00	0.6436E+00	0.7094E+00	0.7801E+00	0.8560E+00
3600.00	0.5380E+00	0.5958E+00	0.6584E+00	0.7260E+00	0.7988E+00	0.8770E+00
3700.00	0.5513E+00	0.6109E+00	0.6755E+00	0.7453E+00	0.8205E+00	0.9014E+00
3800.00	0.5664E+00	0.6280E+00	0.6948E+00	0.7671E+00	0.8450E+00	0.9289E+00
3900.00	0.5831E+00	0.6468E+00	0.7161E+00	0.7911E+00	0.8721E+00	0.9593E+00
4000.00	0.6011E+00	0.6672E+00	0.7391E+00	0.8171E+00	0.9014E+00	0.9923E+00
4100.00	0.6203E+00	0.6890E+00	0.7638E+00	0.8449E+00	0.9327E+00	0.1028E+01
4200.00	0.6405E+00	0.7119E+00	0.7897E+00	0.8742E+00	0.9658E+00	0.1065E+01
4300.00	0.6615E+00	0.7357E+00	0.8166E+00	0.9046E+00	0.1000E+01	0.1103E+01
4400.00	0.6831E+00	0.7602E+00	0.8443E+00	0.9360E+00	0.1035E+01	0.1143E+01
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4600.00	0.7270E+00	0.8100E+00	0.9007E+00	0.9998E+00	0.1108E+01	0.1225E+01
4700.00	0.7488E+00	0.8347E+00	0.9288E+00	0.1032E+01	0.1144E+01	0.1265E+01
4800.00	0.7702E+00	0.8591E+00	0.9564E+00	0.1063E+01	0.1179E+01	0.1305E+01

Y [ft]	<- X [ft] ->					
	4200	4300	4400	4500	4600	4700
4900.00	0.7909E+00	0.8826E+00	0.9831E+00	0.1093E+01	0.1213E+01	0.1344E+01

Y [ft]	<- X [ft] ->	
	4800	4900
0.00	0.1736E+01	0.1924E+01
100.00	0.1737E+01	0.1925E+01
200.00	0.1733E+01	0.1919E+01
300.00	0.1723E+01	0.1908E+01
400.00	0.1707E+01	0.1891E+01
500.00	0.1687E+01	0.1868E+01
600.00	0.1663E+01	0.1840E+01
700.00	0.1634E+01	0.1807E+01
800.00	0.1601E+01	0.1770E+01
900.00	0.1564E+01	0.1729E+01
1000.00	0.1525E+01	0.1685E+01
1100.00	0.1484E+01	0.1638E+01
1200.00	0.1440E+01	0.1589E+01
1300.00	0.1396E+01	0.1538E+01
1400.00	0.1350E+01	0.1487E+01
1500.00	0.1304E+01	0.1435E+01
1600.00	0.1259E+01	0.1384E+01
1700.00	0.1214E+01	0.1334E+01
1800.00	0.1171E+01	0.1285E+01
1900.00	0.1129E+01	0.1239E+01
2000.00	0.1090E+01	0.1194E+01
2100.00	0.1053E+01	0.1153E+01
2200.00	0.1019E+01	0.1115E+01
2300.00	0.9877E+00	0.1080E+01
2400.00	0.9604E+00	0.1050E+01
2500.00	0.9369E+00	0.1023E+01
2600.00	0.9174E+00	0.1002E+01
2700.00	0.9021E+00	0.9844E+00
2800.00	0.8910E+00	0.9720E+00
2900.00	0.8844E+00	0.9645E+00
3000.00	0.8821E+00	0.9621E+00
3100.00	0.8844E+00	0.9646E+00
3200.00	0.8911E+00	0.9721E+00
3300.00	0.9022E+00	0.9845E+00
3400.00	0.9176E+00	0.1002E+01
3500.00	0.9371E+00	0.1024E+01
3600.00	0.9607E+00	0.1050E+01
3700.00	0.9880E+00	0.1080E+01
3800.00	0.1019E+01	0.1115E+01

Y [ft] <- X [ft] ->

	4800	4900
3900.00	0.1053E+01	0.1153E+01
4000.00	0.1090E+01	0.1195E+01
4100.00	0.1130E+01	0.1239E+01
4200.00	0.1171E+01	0.1286E+01
4300.00	0.1215E+01	0.1335E+01
4400.00	0.1260E+01	0.1385E+01
4500.00	0.1306E+01	0.1437E+01
4600.00	0.1352E+01	0.1489E+01
4700.00	0.1397E+01	0.1540E+01
4800.00	0.1442E+01	0.1591E+01
4900.00	0.1486E+01	0.1640E+01

APPENDIX H

U.S. Department of the Interior
U.S. Geological Survey

Modeling Ground-Water Flow with MODFLOW and Related Programs

USGS
science for a changing world

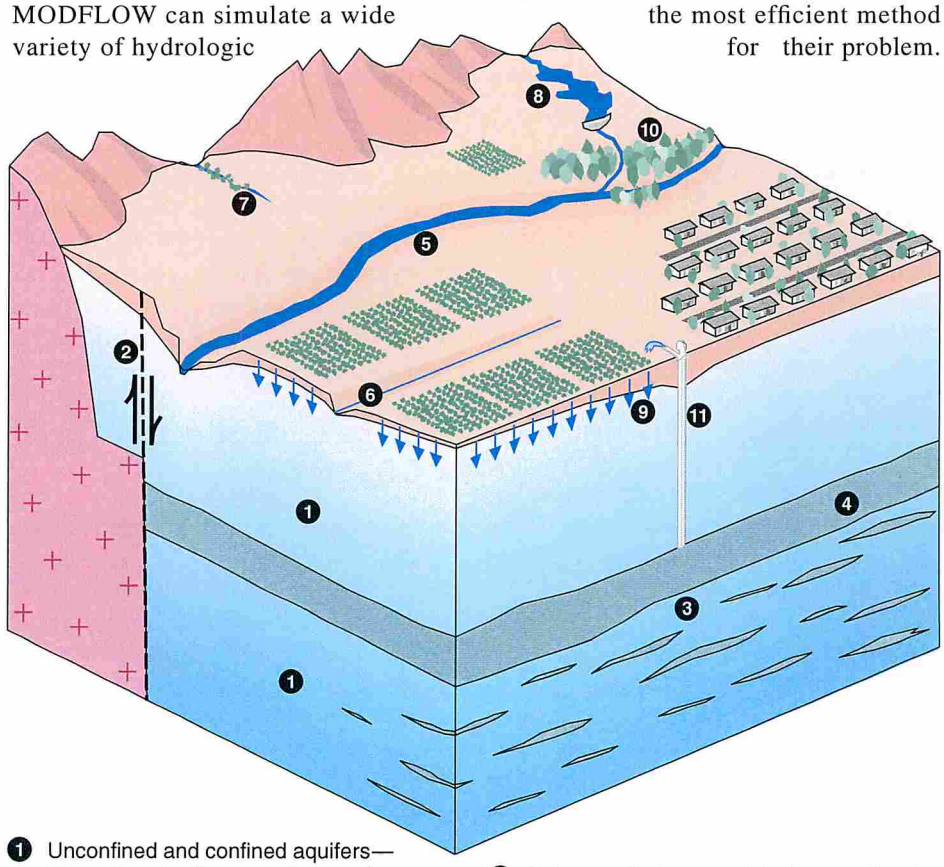
The modular finite-difference ground-water flow model (MODFLOW) developed by the U.S. Geological Survey (USGS) is a computer program for simulating common features in ground-water systems (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The program was constructed in the early 1980's and has continually evolved since then with development of many new packages and related programs for ground-water studies. Currently, MODFLOW is the most widely used program in the world for simulating ground-water flow. The popularity of the program is attributed to the following factors:

- *The finite-difference method used by MODFLOW is relatively easy to understand and apply to a wide variety of real-world conditions.*
- *MODFLOW works on many different computer systems ranging from per-sonal computers to super computers.*
- *MODFLOW can be applied as a one-dimensional, two-dimensional, or quasi- or full three-dimensional model.*
- *Each simulation feature of MODFLOW has been extensively tested.*
- *Data input instructions and theory are well documented.*
- *The modular program design of MODFLOW allows for new simulation features to be added with relative ease.*
- *A wide variety of computer programs written by the USGS, other federal agencies, and private companies are available to analyze field data and construct input data sets for MODFLOW.*
- *A wide variety of programs are available to read output from MODFLOW and graphically present model results in ways that are easily understood.*
- *MODFLOW has been accepted in many court cases in the United States as a legitimate approach to analysis of ground-water systems.*

This publication outlines the major features of MODFLOW and several related programs and gives information on obtaining programs and documentation.

Simulation Capabilities of MODFLOW

MODFLOW is designed to simulate aquifer systems in which (1) saturated-flow conditions exist, (2) Darcy's Law applies, (3) the density of ground water is constant, and (4) the principal directions of horizontal hydraulic conductivity or transmissivity do not vary within the system. These conditions are met for many aquifer systems for which there is an interest in analysis of ground-water flow and contaminant movement. For these systems, MODFLOW can simulate a wide variety of hydrologic features and processes (fig. 1). Steady-state and transient flow can be simulated in unconfined aquifers, confined aquifers, and confining units. A variety of features and processes such as rivers, streams, drains, springs, reservoirs, wells, evapotranspiration, and recharge from precipitation and irrigation also can be simulated. At least four different solution methods have been implemented for solving the finite-difference equations that MODFLOW constructs. The availability of different solution approaches allows model users to select the most efficient method for their problem.



1. Unconfined and confined aquifers—Ground-water flow and storage changes
2. Faults and other barriers—Resistance to horizontal ground-water flow
3. Fine-grained confining units and interbeds
4. Confining units—Ground-water flow and storage changes
5. Rivers—Exchange of water with aquifers
6. Drains and springs—Discharge of water from aquifers
7. Ephemeral streams—Exchange of water with aquifers
8. Reservoirs—Exchange of water with aquifers
9. Recharge from precipitation and irrigation
10. Evapotranspiration
11. Wells—Withdrawal or recharge at specified rates

Figure 1. Features of an aquifer system that can be simulated by MODFLOW.

Application of MODFLOW

MODFLOW simulates ground-water flow in aquifer systems using the finite-difference method. In this method, an aquifer system is divided into rectangular blocks by a grid (fig. 2). The grid of blocks is organized by rows, columns, and layers, and each block is commonly called a "cell."

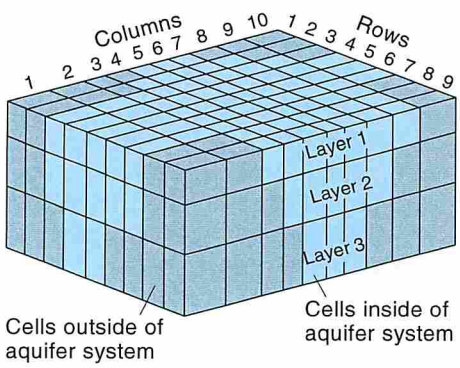


Figure 2. Example of model grid for simulating three-dimensional ground-water flow.

Model Input

For each cell within the volume of the aquifer system, the user must specify aquifer properties. Also, the user specifies information relating to wells, rivers, and other inflow and outflow features for cells corresponding to the location of the features. For example, if the interaction between a river and an aquifer system is simulated, then for each cell traversed by the river, input information includes layer, row, and column indices; river stage; and hydraulic properties of the river bed.

Model Output

MODFLOW uses the input to construct and solve equations of ground-water flow in the aquifer system. The solution consists of head (ground-water level) at every cell in the aquifer system (except for cells where head was specified as known in the input data sets) at intervals called "time steps." The head can be printed and (or) saved on a computer storage device for any time step. Hydrologists commonly use water levels from a model layer to construct contour maps for comparison with similar maps drawn from field data. They also compare computed water levels at individual cells with measured water levels from wells at corresponding locations to determine model error (fig. 3). The process of adjusting the model input values to reduce the model error is referred to as model calibration.

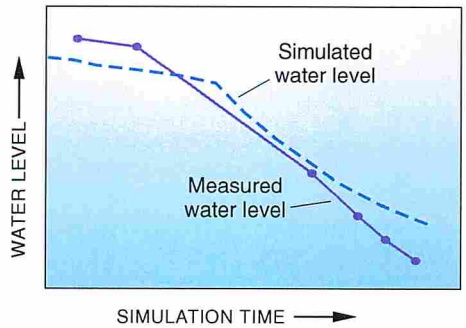


Figure 3. Example comparison of computed and measured water levels.

In addition to water levels, MODFLOW prints a water budget for the entire aquifer system. The budget lists inflow to and outflow from the aquifer system for all hydrologic features that add or remove water.

Other program output consists of flow rates for each model cell. MODFLOW can write the flow rates onto a computer storage device for any hydrologic feature in a simulation. These cell-by-cell flow rates commonly are read by post-processing programs for detailed analysis of the simulated ground-water system.

Inverse Modeling with MODFLOWP

In conventional or "forward modeling," model parameters (such as aquifer properties) are specified and water levels and flow quantities are computed (fig. 4). For most aquifer systems, however, more information is available from field data on water levels, flows, and advective transport or ground-water age than on input parameters. Typically, input parameters are adjusted during model calibration using a trial-and-error process. This calibration process can yield acceptable agreement between computed model results and field data but is time consuming, may not produce parameter values that result in the best fit of field data, and does not result in quantitative estimates of uncertainty in model results and estimated parameter values.

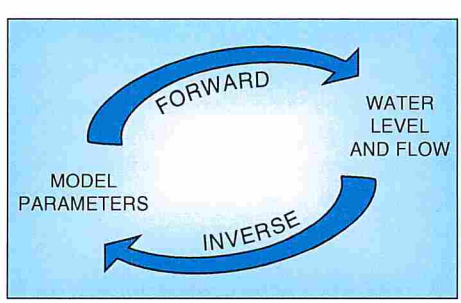


Figure 4. Forward and inverse approaches to modeling.

Inverse modeling is a more formal approach to model calibration that includes automatic parameter adjustment in order to match field data. Program MODFLOWP (pronounced MOD•FLOW•P) is the USGS version of MODFLOW that includes automatic parameter estimation (Hill, 1992). MODFLOWP uses a weighted least-squares objective function as a measure of how well model results agree with field measurements. Weights are used to reflect reliability of individual measurements. Parameters that can be estimated by MODFLOWP include transmissivity; hydraulic conductivity; storage coefficient; vertical leakance; vertical and horizontal anisotropy; hydraulic conductance between aquifer systems and rivers, drains and other features; areal recharge; maximum evapotranspiration; pumping; and water levels at constant-head boundaries. Measured or externally estimated information on parameters also can be included. Parameter values that minimize the objective function (fig. 5) are calculated by MODFLOWP using the modified Gauss-Newton method or the conjugate-direction method. The resulting parameter values are "best-fit" in that they provide the closest match between measured and simulated heads and flows, as measured by the objective function. The task of the modeler is to evaluate how well these calculated values represent the physical system being simulated.

Model output includes estimates of parameters and statistics relating to the parameter estimates. The statistics can be used to quantify the reliability of the resulting model, suggest changes in model construction, and compare results of models constructed in different ways. Post-processors can be used to calculate confidence intervals on predicted heads and flows to depict prediction uncertainty. To effectively use MODFLOWP, an understanding of principles of ground-water flow and basic statistics is needed.

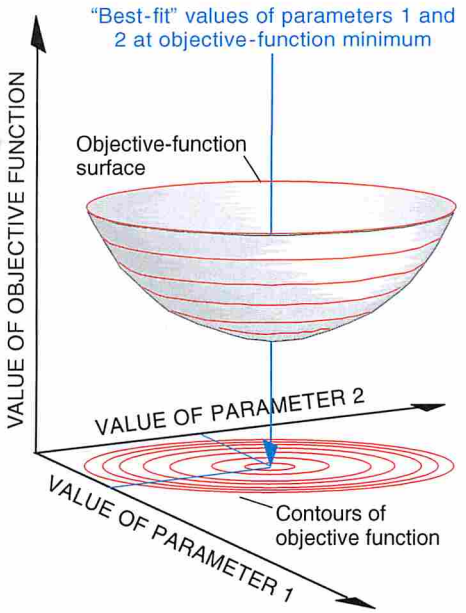


Figure 5. Example of an objective function and "best-fit" parameter values for a linear problem with two parameters.

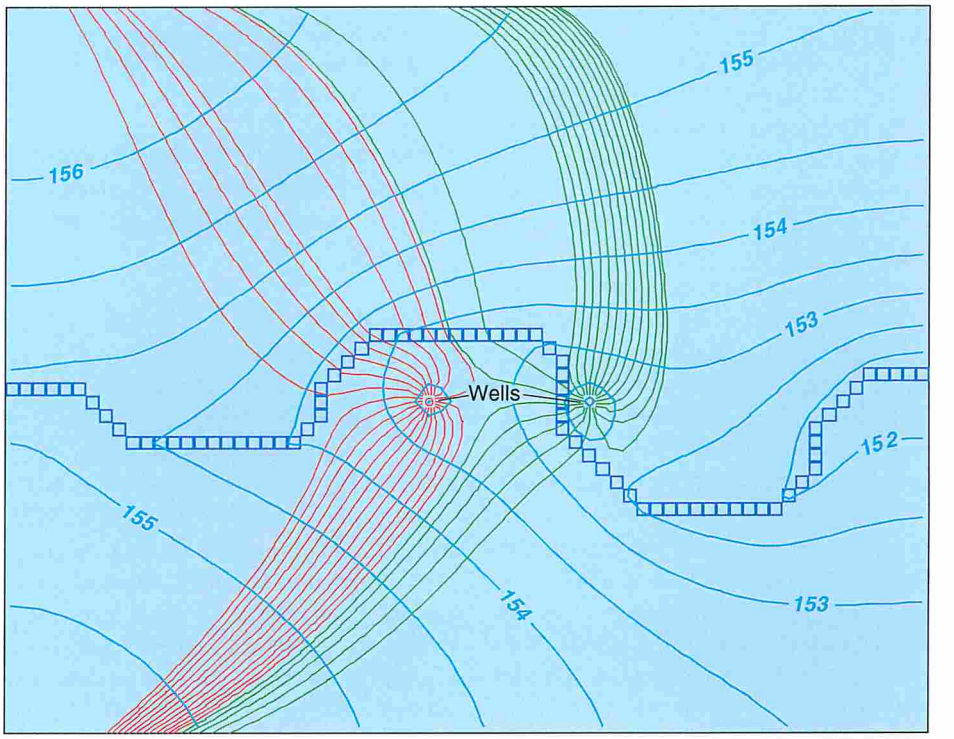


Figure 6. Flow paths of particles discharging at two wells. Pathlines were computed by MODPATH and are denoted by red and green lines. Blue squares are river cells and light blue lines are contours of water levels, in feet above sea level, computed by MODFLOW.

Particle Tracking with MODPATH

Many studies require information such as the average rate of movement of ground water and contaminants. Also, information often is needed on the recharge or capture areas for water discharging to wells, springs, stream reaches, and other features. Although MODFLOW does not compute this information directly, simulation with MODFLOW provides basic information needed for such analyses. The particle-tracking program, MODPATH, is a post-processing program for MODFLOW to estimate flow paths (fig. 6) and times of travel in ground-water systems. An accompanying program, MODPATH-PLOT, displays particle paths, contours, and model features.

MODPATH can be used for studies of steady-state and transient flows. Common applications include studies of paths and time of travel of contaminant movement (fig. 7); and source (recharge) areas of wells, springs, rivers, and other features.

MODPATH can place particles at specified locations or generate starting locations of arrays of particles in selected regions. Particles can be tracked forward from starting locations to calculate where water is going or backwards to map where it came from. Multiple particle-release times can be used to simulate "plumes" of contamination.

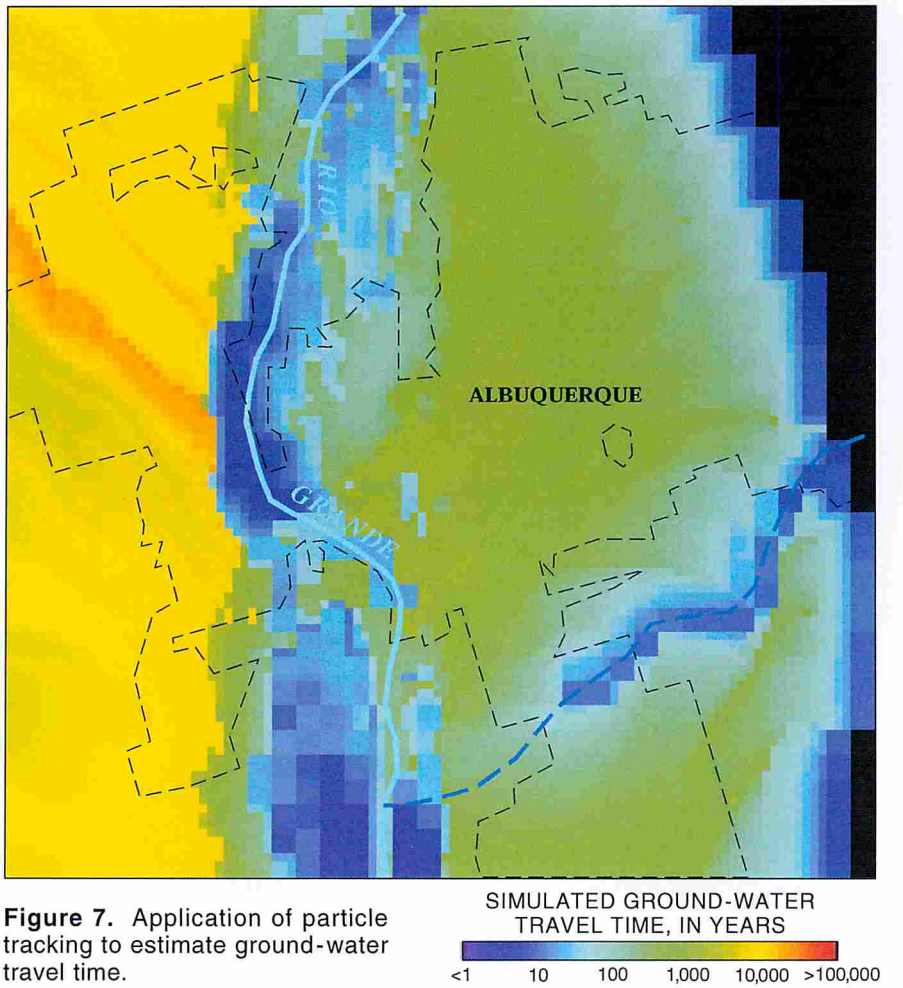


Figure 7. Application of particle tracking to estimate ground-water travel time.

Solute Transport with MOC3D

To evaluate or remediate contaminated aquifers, it is important to be able to compute the concentration of dissolved chemicals. Hydrologists and water managers need to know how contaminants will spread in the future, or how the concentration distributions will respond to changes in the flow field that might arise from new water-supply stresses, remediation efforts, or other management activities.

MOC3D is a solute-transport program that is integrated with MODFLOW and has the capability to calculate changes in concentration (fig. 8) of a single solute as affected by processes of advection, dispersion, diffusion, fluid sources, decay, and retardation. In addition to input data requirements for MODFLOW, the user must also define porosity, thickness, dispersivity, initial concentrations, and source-fluid concentrations. Model output includes the calculated concentration distribution in space and time.

MOC3D is based on a particle-tracking method coupled with an explicit finite-difference procedure. This numerical technique is optimal for advection-dominated problems. Alternative numerical methods are planned to broaden the range of types of field problems for accurate and efficient application of the model.

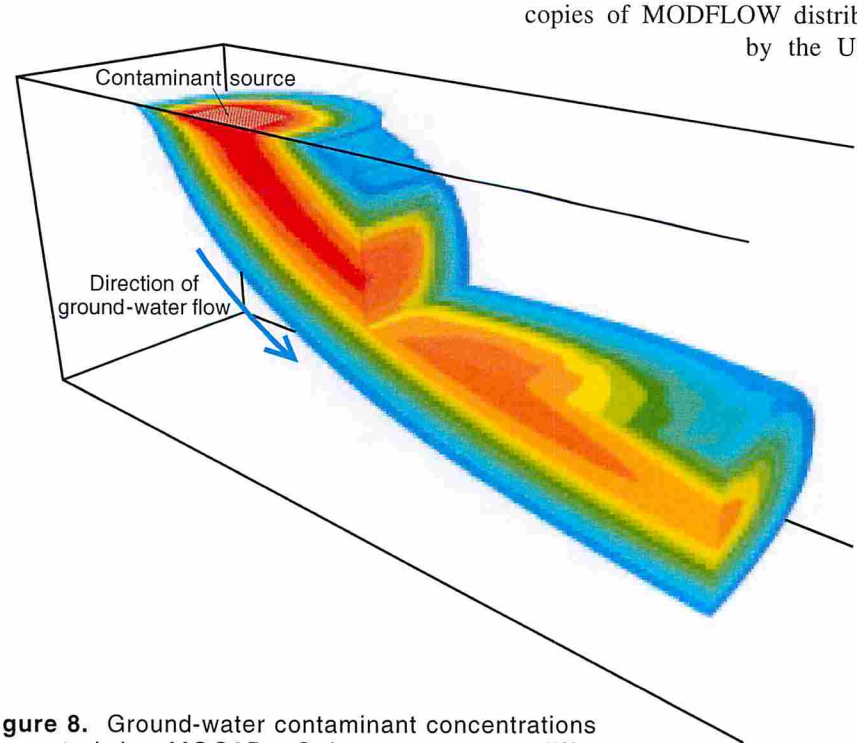


Figure 8. Ground-water contaminant concentrations computed by MOC3D. Colors represent different concentration ranges, with highest contaminant concentrations in red and lowest concentrations in blue.

How to Obtain Ground-Water Model Programs, Documentation, and Additional Information

Additional references for USGS computer programs for ground-water simulation are given by Appel and Reilly (1994). Many of the programs including MODFLOW, MODFLOWP, MODPATH, and MOC3D are available from the USGS at no cost at World Wide Web site *http://water.usgs.gov/software/*. The site includes links to download program source code and compiled versions for some computers. Also, some of the programs are available by anonymous ftp from Internet site *water.usgs.gov* in the directory *pub/software/ground_water/*.

The MODFLOW program obtained from the USGS includes most simulation capabilities currently documented by the USGS. Added features for MODFLOW have been documented in separate reports. A bibliography of the documentation reports is included with copies of MODFLOW distributed by the USGS.

Reports documenting USGS model programs can be purchased from
U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

For information on local USGS studies and research applications of the MODFLOW family of computer programs, contact the USGS state representative for the area of interest. A list of state representatives is available from the World Wide Web site *http://water.usgs.gov/public/wrd011.html/*.

—*S.A. Leake*

References

Appel, C.A., and Reilly, T.E., 1994, Summary of selected computer programs produced by the U.S. Geological Survey for simulation of ground-water flow and quality, 1994: U.S. Geological Survey Circular 1104, 98 p.

Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96–485, 56 p.

Hill, M.C., 1992, A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional, ground-water flow model using nonlinear regression: U.S. Geological Survey Open-File Report 91–484, 358 p.

Konikow, L.F., Goode, D.J., and Hornberger, G.Z., 1996, A three-dimensional method-of- characteristics solute-transport model (MOC3D): U.S. Geological Survey Water-Resources Investigations Report 96–4267, 87 p.

McDonald, M.C., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, version 3: a particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94–464, 234 p.

Water Resources Applications Software

Summary of MF2K

NAME

modflow - Modular three-dimensional finite-difference ground-water model

ABSTRACT

MODFLOW is a three-dimensional finite-difference ground-water model that was first published in 1984. It has a modular structure that allows it to be easily modified to adapt the code for a particular application. Many new capabilities have been added to the original model. OFR 00-92 (complete reference below) documents a general update to MODFLOW, which is called MODFLOW-2000 in order to distinguish it from earlier versions.

MODFLOW-2000 simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary block. MODFLOW is currently the most used numerical model in the U.S. Geological Survey for ground-water flow problems.

In addition to simulating ground-water flow, the scope of MODFLOW-2000 has been expanded to incorporate related capabilities such as solute transport and parameter estimation.

METHOD

The ground-water flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks in which the medium properties are assumed to be uniform. In plan view the blocks are made from a grid of mutually perpendicular lines that may be variably spaced. Model layers can have varying thickness. A flow equation is

written for each block, called a cell. Several solvers are provided for solving the resulting matrix problem; the user can choose the best solver for the particular problem. Flow-rate and cumulative-volume balances from each type of inflow and outflow are computed for each time step.

HISTORY

MODFLOW-2000 Version 1.6 2001/10/19 - Fixed two problems. The first caused simulation time to be truncated, for runs that involve calculation of sensitivities, to a simulation period one time step too short when the last flow observation in a transient simulation falls in a later time step than the final head observation. The second problem caused observation sensitivities for constant-head flow observations to be incorrect for log-transformed parameters.

In addition, support for new options for the name file was added to allow users to designate files of type DATA, DATA(BINARY), DATAGLO, or DATAGLO(BINARY) as either input or output files. Please see the Release Notes in the file release.txt for a description of these options.

MODFLOW-2000 Version 1.5 2001/08/16 - Added the LMT Package to support generation of the link file required by the contaminant-transport program MT3DMS.

MODFLOW-2000 Version 1.4 2001/07/10 - Added the LMG Package for solving matrix equations using an algebraic multigrid solver.

MODFLOW-2000 Version 1.3 2001/06/11 - Fixed problem in LPF where if a lower cell goes dry while the cell above is still wet, there is a non-zero vertical conductance to a dry cell, causing calculated heads and flows to be in error.

MODFLOW-2000 Version 1.2 2001/04/12 - Added support for using vendor-specific options for opening unformatted (binary) files. On personal computers, this can make it possible for programs compiled by different compilers to write files that have the same structure. The formula used to calculate dimensionless, scaled sensitivities of simulated equivalents to observations for log-transformed parameters is changed. Other changes include bug fixes and clarification of output. The MODFLOW-2000 distribution now includes Release Notes in the file release.txt in the doc directory -- this file describes in detail changes to MODFLOW-2000 for each version.

MODFLOW-2000 Version 1.1 2001/01/17 - Added IBS, HUF, LAK, ETS, and DRT Packages. Added HYDMOD option. The EVT Package was modified as described in the LAK documentation to include the option (NEVTOP=3) to apply ET to the uppermost wet cell in a vertical column of cells as done in the RCH Package.

MODFLOW-2000 Version 1.0 2000/07/20 - Enhanced modular structure that facilitates the addition of broader capabilities such as parameter estimation and solute transport. New data input methods are included to support parameter estimation. Vertical cell dimensions are specified in a separate discretization file. A new

package called the LPF Package has been added as an alternative to the BCF Package.

The MODFLOW-2000 documentation report (OFR 00-92) does not include the STR Package; however, this code has been upgraded to use parameters and is included in this version of MODFLOW-2000. Revised STR input instructions can be found in file str6.pdf, which is included in the doc directory that is part of the distribution for MODFLOW-2000.

The ADV Package has been modified for use with MODFLOW-2000. Changes in input instructions are contained in file adv.txt, which is also in the doc distribution directory.

The RES and FHB Packages are included in MODFLOW-2000 without modification. These will work as before, but they do not incorporate parameters or observations.

The IBS, TLK, and GFD Packages are not included in this release. They require modification in order to work within MODFLOW-2000.

Note that MODFLOW-2000 sends some messages to the computer display. Some Fortran compilers make use of a reserved file unit, for example unit 6, for output to the display. If such compilers are used, it is important to avoid using a reserved unit for any files in the MODFLOW name file.

MODFLOW-96 Version 3.3 2000/05/02 - Error fixed in IBS code that caused incorrect values for critical head to be written when the option is invoked to save these values in an external file (variable IHCSV>0). The error did not affect the actual interbed storage calculations, and none of the other model results, such as computed head and budget flows, are affected by the correction. There are no changes to any other packages.

MODFLOW-96 Version 3.2 1998/01/09 - The Flow and Head Boundary Package, Version 1, (FHB1) has been added. This package allows for assignment of transient specified-flow and specified-head boundaries in applications of MODFLOW-96. The FHB1 package is documented in U.S. Geological Survey Open-File Report 97-571.

MODFLOW-96 Version 3.1 1997/03/11 - Calls to the Horizontal Flow Barrier (HFB) Package have been corrected in the main program. The main program for Version 3.0 incorrectly calls the HFB1RP module where it should call the HFB1FM module.

MODFLOW-96 Version 3.0 1996/12/03 - Updated version of overall model, which is called MODFLOW-96. A number of changes were made to make MODFLOW easier to use and easier to enhance. MODFLOW-96 can use existing input data sets, and has the same computational methods. Any package added to the original model (now referred to as MODFLOW-88) will also work with MODFLOW-96.

The Preconditioned Conjugate Gradient Package, Version 2

(PCG2) has been updated. This requires a minor change in input data compared to the documentation in U.S. Geological Survey Water-Resources Investigations Report (WRIR) 90-4048 (full reference below). WRIR 90-4048 specifies two lines of input data. All of the data are the same except the seventh value on the 2nd line. This value is named IPCGCD in WRIR-4048, but it has been replaced by a value named DAMP. That is, IPCGCD is no longer part of the input data. DAMP can be used to reduce oscillation when the solver is having difficulty converging due to excessive oscillation. The value of DAMP is multiplied times the head change calculated each iteration at all cells. Thus, if DAMP is 0.5, the head change is cut in half. If DAMP is 1.0, then PCG2 behaves as it did prior to the addition of this capability. DAMP should be set equal to 1.0 except when there is indication of excessive oscillation. If the value of DAMP is specified as 0.0 or less, it is automatically changed to 1.0.

Also the sign of the C.B. STORAGE cell-by-cell budget data in the TLK1 Package was changed to match the standard sign convention in MODFLOW. The change to TLK1 does not impact computed heads or the overall volumetric budget; it only affects data written to a cell-by-cell budget file.

MODFLOW-88 Version 2.6 1996/09/20 - Added Reservoir package (RES1) as documented in U.S. Geological Survey Open-File Report 96-364. Problem fixed for IBS package. Although subsidence is only meant to be active for layers in which IBQ>0, sometimes MODFLOW performed subsidence calculations when IBQ<0. Note that this was a problem only if negative IBQ values were specified. That is, the code has always worked correctly for IBQ=0 and IBQ>0.

MODFLOW-88 Version 2.5 1995/06/23 - Added direct solution package (DE45).

MODFLOW-88 Version 2.4 1995/06/15 - Added transient leakage package (TLK1).

MODFLOW-88 Version 93/08/30 - Release with PCG2, BCF3, STR1, HFB1, ISB1, CHD1, and GFD1 additions.

MODFLOW-88 Version 87/07/24 - Fortran 77 version published in U.S. Geological Survey Techniques of Water-Resources Investigations 6-A1.

MODFLOW Version 83/12/28 - Fortran 66 version published in U.S. Geological Survey Open-File Report 83-875.

DATA REQUIREMENTS

In order to use MODFLOW, initial conditions, hydraulic properties, and stresses must be specified for every model cell in the finite-difference grid.

OUTPUT OPTIONS

Primary output is head, which can be written to the listing file or into a separate file. Other output includes the complete listing of all input data, drawdown, and budget data. Budget data are printed as a summary in the listing

file, and detailed budget data for all model cells can be written into a separate file.

SYSTEM REQUIREMENTS

MODFLOW-2000 is written in Fortran 77 with the following extensions: use of variable names longer than 6 characters, Fortran 90 statements for dynamic memory allocation, and a call to SUBROUTINE GETCL to retrieve command-line arguments. Generally, the program is easily installed on most computer systems. The code has been used on UNIX-based computers and DOS-based 386 or greater computers having a math coprocessor and 4 mb of memory.

PROCESSES

This version of MODFLOW includes the following processes:

GWF1 -- Ground-Water Flow Process
SEN1 -- Sensitivity Process
OBS1 -- Observation Process
PES1 -- Parameter-Estimation Process

PACKAGES

This version of MODFLOW includes the following packages:

BAS6 -- Basic Package
BCF6 -- Block-Centered Flow Package
LPF1 -- Layer-Property Flow Package
RIV6 -- River Package
DRN6 -- Drain Package
WEL6 -- Well Package
GHB6 -- General Head Boundary Package
RCH6 -- Recharge Package
EVT6 -- Evapotranspiration Package
CHD6 -- Time-Variant Specified-Head Package
HFB6 -- Horizontal Flow Barrier Package
SIP5 -- Strongly Implicit Procedure Package
SOR5 -- Slice Successive Over-Relaxation Package
PCG2 -- Version 2 of Preconditioned Conjugate Gradient Package
DE45 -- Direct solver
LMG1 -- Multigrid solver
STR6 -- Streamflow-Routing Package
ADV2 -- Advective-Transport Observation Package
RES1 -- Reservoir Package (RES is the file type in the MODFLOW name file)
FHB1 -- Flow and Head Boundary Package (FHB is the file type in the MODFLOW name file)
IBS6 -- Interbed Storage (subsidence) Package (IBS is the file type in the name file)
HUF1 -- Hydrogeologic-Unit Flow Package
LAK3 -- Lake Package
ETS1 -- Evapotranspiration with a Segmented Function Package
DRT1 -- Drains with Return Flow Package
LMT6 -- Link to MT3DMS contaminant-transport model

ADDITIONAL CAPABILITIES

HYDMOD -- Hydrograph option

DOCUMENTATION

The basic documentation is contained in the following five

reports:

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to the Observation, Sensitivity, and Parameter-Estimation Processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 210 p.

Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Harbaugh, A.W., and McDonald, M.G., 1996, Programmer's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-486, 220 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

The BCF6 code is documented in several places. It includes the capabilities of BCF1, BCF2, and BCF3 Packages. The primary documentation is in the basic model documentation (TWRI 6-A1, OFR 96-485, and OFR 96-486).

BCF2 documentation describes the addition of the capability to convert dry cells to wet:

McDonald, M.G., Harbaugh, A.W., Orr, B.R., and Ackerman, D.J., 1992, A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 91-536, 99 p.

BCF3 documentation describes the addition of alternate interblock transmissivities.

Goode, D.J., and Appel, C.E., 1992, Finite-difference interblock transmissivity for unconfined aquifers and for aquifers having smoothly varying transmissivity: U.S. Geological Survey Water-Resources Investigations Report 92-4124, 79 p.

Version 2 of Preconditioned Conjugate Gradient Package is documented in:

Hill, M.C., 1990, Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources

Investigations Report 90-4048, 43 p.

The Streamflow-Routing Package is documented in:

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

The Time-Variant Specified-Head Package is documented in:

Leake, S.A., and Prudic, D.E., 1991, Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A2, 68 p.

The Horizontal-Flow Barrier Package is documented in:

Hsieh, P.A., and Freckleton, J.R., 1993, Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 92-477, 32 p.

The DE45 Package is documented in:

Harbaugh, A.W., 1995, Direct solution package based on alternating diagonal ordering for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 95-288, 46 p.

The RES1 Package is documented in:

Fenske, J.P., Leake, S.A., and Prudic, D.E., 1996, Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Open-File Report 96-364, 51 p.

The FHB1 Package is documented in:

Leake, S.A., and Lilly, M.R., 1997, Documentation of a computer program (FHB1) for assignment of transient specified-flow and specified-head boundaries in applications of the modular finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Open-File Report 97-571, 50 p.

The ADV Package is documented in:

Anderman, E.R. and Hill, M.C., 1997, Advective-transport observation (ADV) package, a computer program for adding advective-transport observations of steady-state flow fields to the three-dimensional ground-water flow parameter-estimation model MODFLOWP: U.S. Geological Survey Open-File Report 97-14, 67 p.

HYDMOD is documented in:

Hanson, R.T. and Leake, S.A., 1999, Documentation of HYDMOD, a program for extracting and processing time-series data from the U.S. Geological Survey's modular three-

dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File report 98-564, 57 p.

The IBS Package is documented in:

Leake, S.A. and Prudic, D.E., 1991, Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chapter A2, 68 p.

The HUF Package is documented in:

Anderman, E.R., and Hill, M.C., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- Documentation of the Hydrogeologic-Unit Flow (HUF) Package: U.S. Geological Survey Open-File Report 00-342, 89 p.

The LAK Package is documented in:

Merritt, L.M. and Konikow, L.F., 2000, Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model: U.S. Geological Survey Water-Resources Investigations Report 00-4167, 146 p.

The ETS and DRT Packages are documented in:

Banta, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- Documentation of packages for simulating evapotranspiration with a segmented function (ETS1) and drains with return flow (DRT1): U.S. Geological Survey Open-File Report 00-466, 127 p.

The LMG Package is documented in:

Mehl, S.E. and Hill, M.C., MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to the LINK-AMG (LMG) Package for solving matrix equations using an algebraic multigrid solver: U.S. Geological Survey Open-File Report 01-177, 33 p.

The LMT Package is documented in:

Zheng, Chunmiao, Hill, M.C., and Hsieh, P.A., 2001, MODFLOW-2000, the U.S. Geological Survey modular ground-water model--User guide to the LMT6 package, the linkage with MT3DMS for multi-species mass transport modeling: U.S. Geological Survey Open-File Report 01-82, 43 p.

TRAINING

Modeling of Ground-Water Flow Using Finite-Difference Methods (GW2096TC), offered annually at the USGS National Training Center.

Advanced Finite-Difference Modeling of Ground-Water Flow (GW3099TC), offered annually at the USGS National Training Center.

Calibration and uncertainty of Ground-Water Models

(GW3089TC), offered annually at the USGS National Training Center.

CONTACTS

Operation:
U.S. Geological Survey
Office of Ground Water
Arlen Harbaugh
411 National Center
Reston, VA 20192

harbaugh@usgs.gov

The USGS MODFLOW fact sheet (a short description of the MODFLOW model) can be retrieved using the World-Wide Web at site:

http://water.usgs.gov/public/pubs/FS/FS-121-97/

See http://water.usgs.gov/software/ordering_documentation.html for information on ordering printed copies of USGS publications.

SEE ALSO

modpath(1) - Particle-tracking postprocessor program for the modular three-dimensional finite-difference ground-water flow model

zonebdgt(1) - Program for computing subregional water budgets for MODFLOW ground-water flow models

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The URL for this page is http://water.usgs.gov/cgi-bin/man_wrdapp?mf2k
Send questions or comments to h2osoft@usgs.gov
Page created: 03/19/2002

APPENDIX I

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC, CONFINED, LEAKY CONFINED OR UNCONFINED AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS AND UNIFORM REGIONAL FLOW

Simulated drawdown at municipal well from example 1

********** INPUT DATA **********

UNCONFINED AQUIFER - THEIS EQUATION WITH JACOB'S CORRECTION

WATER TABLE CORRECTION APPLIED; DRAWDOWNS EXCEED 10% OF SATURATED THICKNESS

AQUIFER THICKNESS	=	200 [ft]
TRANSMISSIVITY	=	14960 [gpd/ft]
STORAGE COEFFICIENT	=	.08
REGIONAL FLOW GRADIENT (positive--downwards--in flow direction)	=	.002
REGIONAL FLOW DIRECTION (horizontal angle in degrees counter-clockwise from positive x-axis)	=	0
REGIONAL FLOW OFFSET AT ORIGIN (positive in downwards direction)	=	0 [ft]

WATER TABLE CORRECTION APPLIED; DRAWDOWNS EXCEED 10% OF SATURATED THICKNESS

AQUIFER THICKNESS = 200 [ft]

PUMPING/INJECTION WELL DATA

WELL NO. 1

X-COORDINATE	=	10000 [ft]
Y-COORDINATE	=	10000 [ft]
PUMPING/INJECTION RATE	=	178600 [gpd]
TIME SINCE START PUMPING/INJECTION	=	14600 [day]

---------- Drawdown in [ft] -- Time in [days] ----------

X-coordinate observation well = 10000 [ft]
Y-coordinate observation well = 10000 [ft]

time	drawdown	time	drawdown	time	drawdown	time	drawdown
0.000	20.000	365.000	39.016	730.000	39.746	1095.000	40.174
1460.000	40.478	1825.000	40.714	2190.000	40.907	2555.000	41.071
2920.000	41.213	3285.000	41.338	3650.000	41.450	4015.000	41.552
4380.000	41.644	4745.000	41.730	5110.000	41.809	5475.000	41.882
5840.000	41.951	6205.000	42.016	6570.000	42.077	6935.000	42.135
7300.000	42.189	7665.000	42.242	8030.000	42.291	8395.000	42.339
8760.000	42.384	9125.000	42.428	9490.000	42.470	9855.000	42.510
%10220.000	42.549	%10585.000	42.587	%10950.000	42.623	%11315.000	42.658
%11680.000	42.692	%12045.000	42.725	%12410.000	42.757	%12775.000	42.788
%13140.000	42.819	%13505.000	42.848	%13870.000	42.877	%14235.000	42.904
%14600.000	42.932						

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC, CONFINED, LEAKY CONFINED OR UNCONFINED AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS AND UNIFORM REGIONAL FLOW

Simulated drawdown at jurisdictional subflow zone in Example 1

********** INPUT DATA **********

UNCONFINED AQUIFER - THEIS EQUATION WITH JACOB'S CORRECTION

WATER TABLE CORRECTION APPLIED

AQUIFER THICKNESS = 200 [ft]
TRANSMISSIVITY = 14960 [gpd/ft]

STORAGE COEFFICIENT = .08

REGIONAL FLOW GRADIENT
(positive--downwards--in flow direction) = .002

REGIONAL FLOW DIRECTION
(horizontal angle in degrees
counter-clockwise from positive x-axis) = 0

REGIONAL FLOW OFFSET AT ORIGIN
(positive in downwards direction) = 0 [ft]

WATER TABLE CORRECTION APPLIED

AQUIFER THICKNESS = 200 [ft]

PUMPING/INJECTION WELL DATA

WELL NO. 1

X-COORDINATE	=	10000 [ft]
Y-COORDINATE	=	10000 [ft]
PUMPING/INJECTION RATE	=	178600 [gpd]
TIME SINCE START PUMPING/INJECTION	=	14600 [day]

---------- Drawdown in [ft] -- Time in [days] ----------

X-coordinate observation well = 20000 [ft]
Y-coordinate observation well = 10000 [ft]

time	drawdown	time	drawdown	time	drawdown	time	drawdown
0.000	40.000	365.000	40.017	730.000	40.116	1095.000	40.242
1460.000	40.366	1825.000	40.481	2190.000	40.586	2555.000	40.682
2920.000	40.771	3285.000	40.852	3650.000	40.927	4015.000	40.997
4380.000	41.063	4745.000	41.124	5110.000	41.182	5475.000	41.237
5840.000	41.288	6205.000	41.337	6570.000	41.384	6935.000	41.429
7300.000	41.471	7665.000	41.512	8030.000	41.551	8395.000	41.589
8760.000	41.625	9125.000	41.660	9490.000	41.694	9855.000	41.727
%10220.000	41.758	%10585.000	41.789	%10950.000	41.818	%11315.000	41.847
%11680.000	41.875	%12045.000	41.902	%12410.000	41.929	%12775.000	41.954
%13140.000	41.979	%13505.000	42.004	%13870.000	42.027	%14235.000	42.051
%14600.000	42.073						

CALCULATION OF DRAWDOWN IN A HOMOGENEOUS, ISOTROPIC, CONFINED, LEAKY CONFINED OR UNCONFINED AQUIFER WITH MULTIPLE PRODUCTION AND INJECTION WELLS AND UNIFORM REGIONAL FLOW

Simulated drawdown at irrigation well from example 2

********** INPUT DATA **********

UNCONFINED AQUIFER - THEIS EQUATION WITH JACOB'S CORRECTION

WATER TABLE CORRECTION APPLIED; DRAWDOWNS EXCEED 10% OF SATURATED THICKNESS

AQUIFER THICKNESS	=	10 [ft]
TRANSMISSIVITY	=	3740 [gpd/ft]
STORAGE COEFFICIENT	=	.2
REGIONAL FLOW GRADIENT (positive--downwards--in flow direction)	=	.005
REGIONAL FLOW DIRECTION (horizontal angle in degrees counter-clockwise from positive x-axis)	=	0
REGIONAL FLOW OFFSET AT ORIGIN (positive in downwards direction)	=	0 [ft]

WATER TABLE CORRECTION APPLIED; DRAWDOWNS EXCEED 10% OF SATURATED THICKNESS

AQUIFER THICKNESS = 10 [ft]

PUMPING/INJECTION WELL DATA

WELL NO. 1

X-COORDINATE	=	3500	[ft]
Y-COORDINATE	=	3500	[ft]
PUMPING/INJECTION RATE	=	7200	[gpd]
TIME SINCE START PUMPING/INJECTION	=	3650	[day]

---------- Drawdown in [ft] -- Time in [days] ----------

X-coordinate observation well = 3500 [ft]
Y-coordinate observation well = 3500 [ft]

time	drawdown	time	drawdown	time	drawdown	time	drawdown
0.000	17.500	365.000	20.526	730.000	20.680	1095.000	20.771
1460.000	20.837	1825.000	20.889	2190.000	20.931	2555.000	20.967
2920.000	20.998	3285.000	21.026	3650.000	21.051		

---------- Drawdown in [ft] -- Time in [days] ----------

X-coordinate observation well = 7000 [ft]
Y-coordinate observation well = 3500 [ft]

time	drawdown	time	drawdown	time	drawdown	time	drawdown
0.000	35.000	365.000	35.001	730.000	35.012	1095.000	35.028
1460.000	35.044	1825.000	35.061	2190.000	35.076	2555.000	35.090
2920.000	35.103	3285.000	35.116	3650.000	35.127		