CHAPTER

2

Overview of Water Resources

2.1 INTRODUCTION

The Tucson Active Management Area (AMA) covers 3,866 square miles in southeastern Arizona and includes the Avra Valley Subbasin and the northern part of the Upper Santa Cruz Valley Subbasin (Figure 1-2). The Avra Valley Subbasin includes Avra Valley in the north and Altar Valley in the south (these are typically divided by the line between township 15 south and township 16 south). The AMA is in the basin and range physiographic province, characterized by broad, gently sloping alluvial basins separated by north to northwest trending fault block mountains. Elevations in the Tucson AMA range from 1,860 feet above mean sea level at the northwestern end of the AMA near Red Rock to 9,453 feet above mean sea level at Mount Wrightson in the southeastern portion of the AMA.

On July 1, 1994, the Santa Cruz AMA was formed. This new AMA consists of 716 square miles made up of the southern portion of the Upper Santa Cruz Valley Subbasin, an area formerly within the borders of the Tucson AMA. The Pima/Santa Cruz County line marks the approximate location of the divide between the Tucson AMA and the Santa Cruz AMA (Figure 1-2).

Average precipitation in the Tucson AMA ranges from 11 inches at the lower elevations to as much as 28 inches in the surrounding mountains (Brazil, et al., 1981, Arizona Meteorological Network (AZMET), 1995). Rainfall is seasonal, occurring in the winter months from frontal storms and in the summer from thunderstorm or "monsoon" activity. Average high temperatures in Tucson range from 67 degrees in January to 103 degrees in July. Summer rainfall activity coincides with the period of greatest evaporation potential. Average annual evapotranspiration is approximately 77 inches per year.

There are a number of factors that influence groundwater conditions in the Tucson AMA. These include the hydrogeologic characteristics of the two subbasins in the AMA, surface water flows, groundwater withdrawals, natural and artificial recharge, subsidence potential, and quality of groundwater in different locations. To avoid further damage from groundwater level declines and increasing subsidence, reliance on groundwater supplies needs to be reduced. Long-term stability of the AMA's water supply depends on conversion to effluent and Central Arizona Project (CAP) water, the primary renewable water sources available in this AMA.

Factors affecting groundwater conditions in the AMA and a description of available renewable water supplies are discussed in the following sections:

- Data sources
- Surface water conditions
- Geologic and aquifer characteristics
- Groundwater conditions
- Subsidence
- Water quality limitations
- Availability and utilization of renewable supplies

2.2 DATA SOURCES

Data sources describing hydrologic conditions in the AMA are available from the Arizona Department of Water Resources (Department), other state agencies, federal agencies, and water utilities. Some of the major data sources are described below.

2.2.1 Arizona Department of Water Resources Basic Data and Hydrology Divisions

The Department's Basic Data Division conducts annual water level measurements during periods of relatively low water demand in the late fall, winter, and early spring at 106 designated index wells

throughout the AMA. More in-depth analysis occurs every five years when approximately 600 wells are measured for water levels during this cooler time period when water levels in wells are more likely to be representative of regional water levels. Water samples are collected from approximately 12 wells each year in the spring or summer when wells are typically actively pumped and are analyzed for common inorganic constituents and selected trace metals. These data are periodically used to prepare hydrologic maps addressing water levels and water quality. Tucson AMA maps were published showing 1981/82 data for the Upper Santa Cruz Valley Subbasin and 1981 data for the Avra Valley Subbasin (Murphy and Hedley, 1984, Reeter and Cady, 1982, respectively). A map series updating water levels with 1994/95 data for both subbasins was published in 1997 (Hammett and Sicard, 1997).

The Department's Hydrology Division is participating in a cooperative subsidence monitoring effort with the United States Geological Survey (USGS), Tucson Water and Pima County using Global Positioning System monitoring equipment. This equipment tracks changes in land surface elevation over a broad area using a ground-to-satellite measurement system. Baseline data will be collected in 1998 followed by annual monitoring at stations throughout the area to detect year-to-year changes. In conjunction with subsidence monitoring activities, gravity meters will be used to generate data on the volume of groundwater in storage in the aquifer.

2.2.2 Arizona Department of Water Resources Computer Model

A three dimensional transient flow groundwater model of the Tucson AMA is being prepared as a tool to evaluate water resources in the AMA. The Department's Hydrology Division is preparing the model using information from previous groundwater models prepared by the Department and the USGS, and using additional water resources data on past and current groundwater conditions. The model will be completed in 1999. The Tucson AMA model can be used to project the regional impacts of CAP water recharge and recovery, future pumpage, and other supply and demand factors on water levels, groundwater storage, potential land subsidence, and aquifer productivity.

2.2.3 Other Agencies

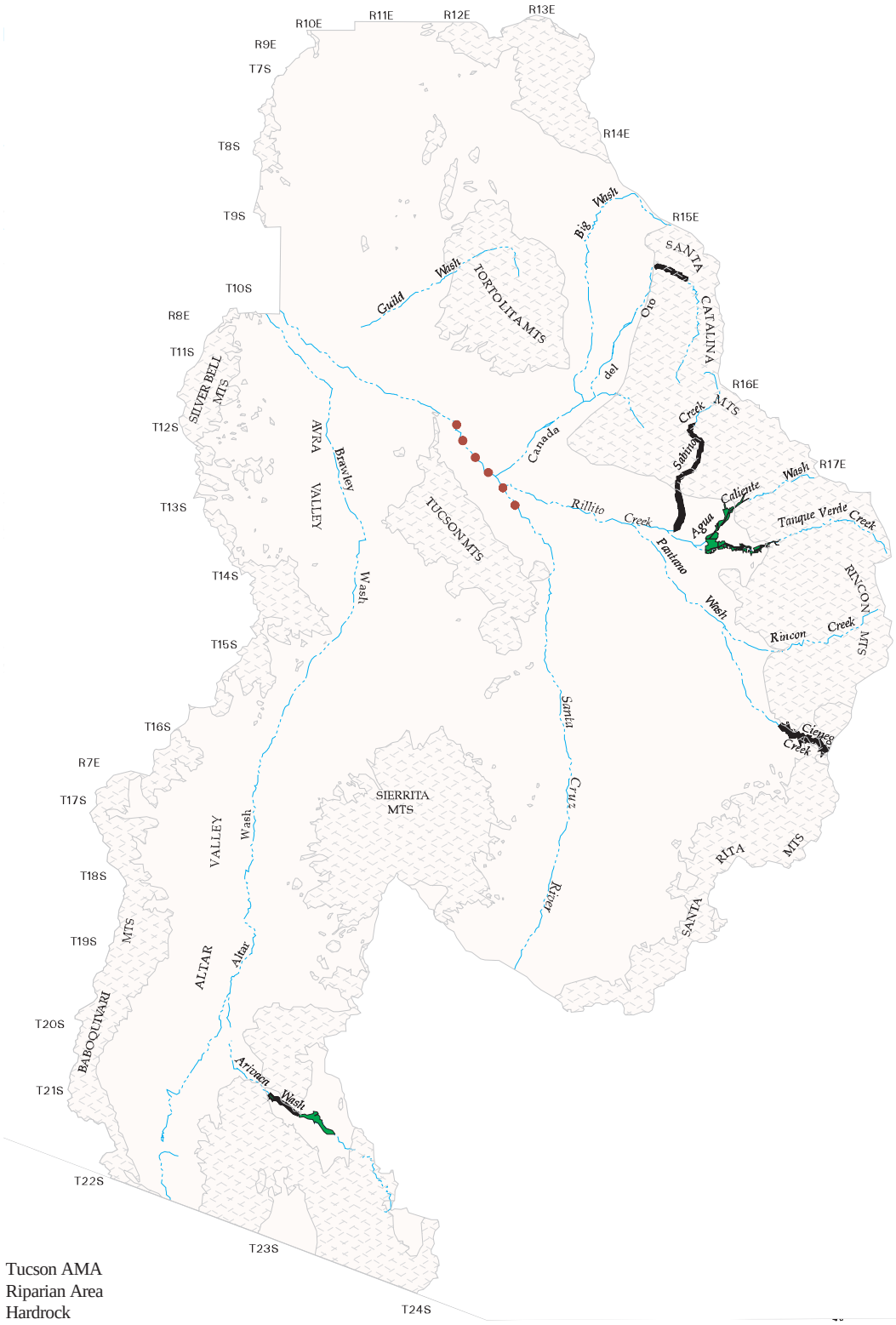
Water resources information is compiled by federal, state, and local entities in addition to the Department. Water quality sampling for organic and inorganic constituents is required by the Arizona Department of Environmental Quality (ADEQ) under the federal Clean Water Act. Results of this sampling are available in compiled databases at ADEQ.

The USGS has published numerous reports on water resources including recent reports on subsidence potential in the subbasins of the AMA (Hanson and Benedict, 1994; Hanson, Anderson and Pool, 1990; Anderson, 1988) and effluent recharge in the Santa Cruz River (Galyean, 1996). Basic hydrogeologic and water quality conditions were the subject of several reports in 1973 (Davidson, 1973; Laney, 1972). A network of stream gages is maintained by the USGS to monitor flow on a number of streams in the AMA including the Santa Cruz River, Rillito Creek, Sabino Creek, Tanque Verde Creek, Pantano Wash, Rincon Creek, and Arivaca Wash (Tadayon, et al., 1998).

The Pima Association of Governments has published 52 documents on water quality issues in the AMA (Pima Association of Governments, 1995). Tucson Water, the City of Tucson's water utility, compiles annual static water level reports for its wellfields and service area, and reports subsidence readings from a network of 13 extensometers monitored on a cooperative basis with the USGS (Tucson Water, 1997).

2.3 SURFACE WATER CONDITIONS

The main surface water drainage in the Tucson AMA is the Santa Cruz River which is about 60 miles long within the AMA (Figure 2-1). The Santa Cruz River originates in Arizona, then flows south into Mexico



Tucson AMA
Riparian Area
Hardrock
Rivers and Streams
Perennial Reach
Effluent-Dominated Reach

Figure 2- 1

Surface Water Features

ORIGINAL SOURCE
Arizona Department of Water Resources
Geographic Information System
Pima County Flood Control District

0 3 6 9 12
Miles
North

before bending west and north and reentering the United States east of Nogales, Arizona. The river flows north through both the Santa Cruz and Tucson AMAs in the Upper Santa Cruz Valley Subbasin, then flows northwest into the Avra Valley Subbasin. Surface water is present during some time periods in the reach of the river located within the Santa Cruz AMA as a result of precipitation events and effluent discharges from the Nogales International Wastewater Treatment Plant, which is located about 20 miles south of the Santa Cruz/Tucson AMA boundary. Under some conditions, surface water flows cross the Santa Cruz AMA boundary into the Tucson AMA. Within the Tucson AMA, the nine mile reach of the Santa Cruz River that flows north of the two regional wastewater treatment plants is perennial due to the volume of treated effluent discharged into the channel at Roger and Ina Roads. With the exception of this Tucson-area effluent-dominated reach, the remainder of the Santa Cruz River within the Tucson AMA is ephemeral and flows in response to rainfall events. In large precipitation events, the Santa Cruz River channel may carry sufficient surface water flows to cross the boundary into the adjacent Pinal AMA.

Major tributaries to the Santa Cruz River in the Upper Santa Cruz Valley Subbasin include the Cañada del Oro, which makes up the northern part of the Upper Santa Cruz Valley Subbasin, and Rillito Creek and its tributaries, which drain the area north and east of Tucson. Tributaries to Rillito Creek include the Pantano Wash and Tanque Verde Wash, which in turn receive flow from Sabino Creek, Rincon Creek, and Cienega Creek. In the Avra Valley Subbasin, Altar Wash originates in the southern portion and flows northward to become Brawley Wash. Brawley Wash flows to the north and northwest through Avra Valley to its confluence with the Santa Cruz River. A portion of Arivaca Wash in the southeastern portion of the Avra Valley Subbasin is perennial. Cienega Creek, Sabino Creek, and the Cañada del Oro have small perennial reaches within their lengths. Continued surface water flows in perennial reaches of Cienega Creek and Arivaca Wash depend on the maintenance of high groundwater tables in these areas.

Surface water flow recharges the Tucson AMA aquifer after infiltrating down through stream channel sediments. Stream channel recharge is a component of net natural recharge as discussed in section 2.5.3 and is incorporated into water supply estimates in the water budget as described in Chapter 11.

2.4 GEOLOGIC AND AQUIFER CHARACTERISTICS

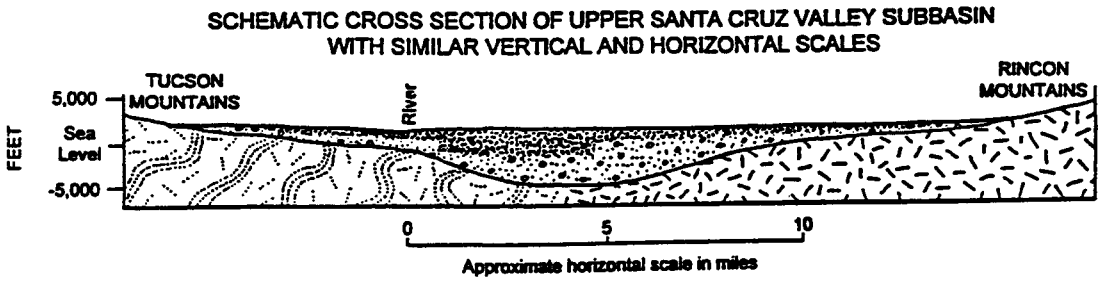
The Upper Santa Cruz Valley Subbasin and the Avra Valley Subbasin consist of alluvial basins and the surrounding mountains. The alluvial basins are composed of deep layers of sediments containing substantial volumes of groundwater. The composition and productivity of these sediment layers differs in the two subbasins of the Tucson AMA.

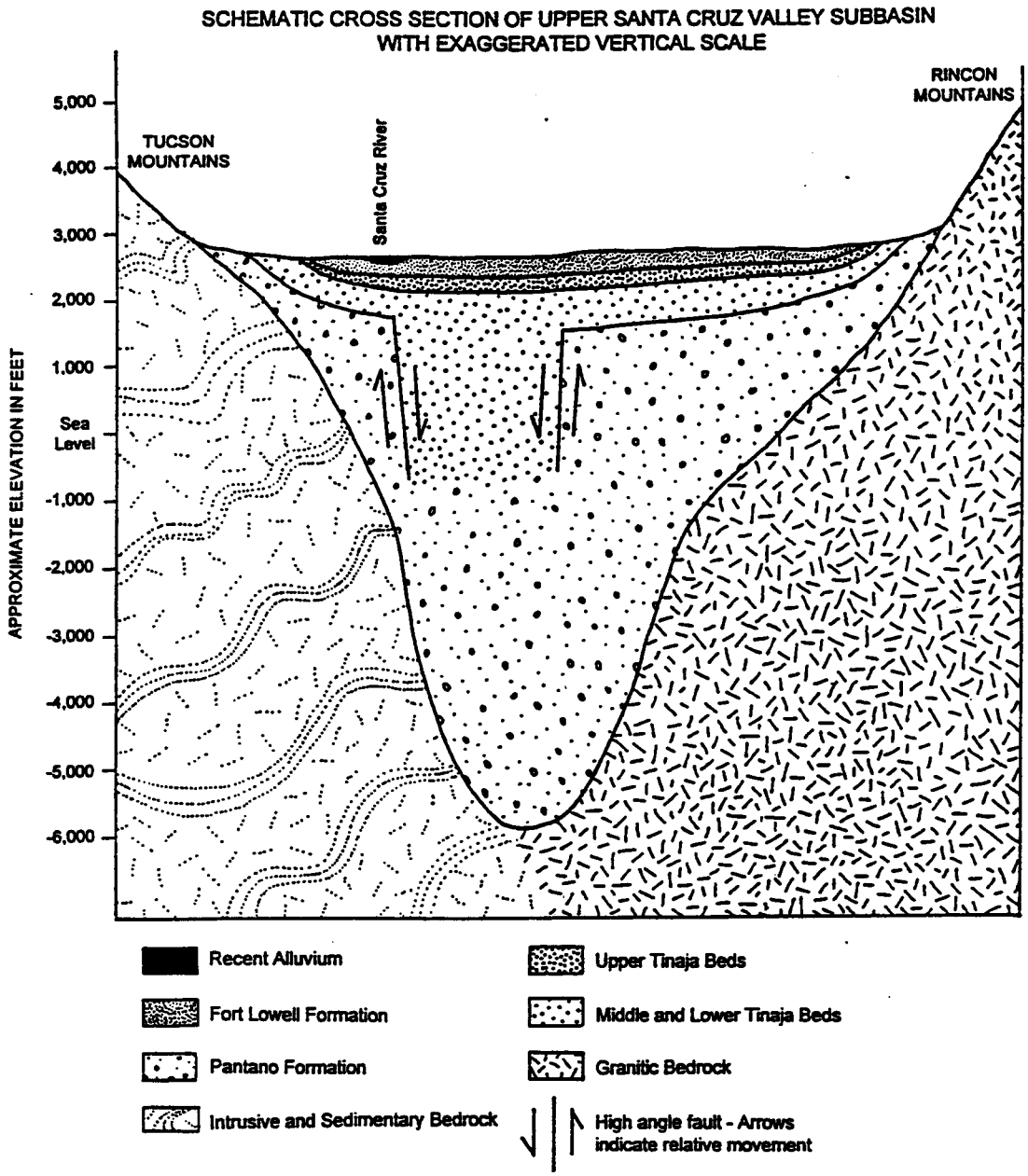
2.4.1 Upper Santa Cruz Valley Subbasin

The depth to bedrock at the center of the Upper Santa Cruz Valley Subbasin is in excess of 11,000 feet (Hanson and Benedict, 1994). Alluvial sediments in this basin have been divided into four hydrogeologic units that are, in descending order: (1) surficial or recent alluvial deposits, (2) the Fort Lowell Formation, (3) the Tinaja Beds, and (4) the Pantano Formation (Davidson, 1973) (Figure 2-2). These four units are hydrologically connected to varying degrees and form the main regional aquifer of the subbasin. Below the basin-fill sediments is the Basement Unit, which forms the impermeable bedrock floor of the basin and extends to the surrounding mountain sides. This bedrock has little groundwater storage and low production capacity and is not considered to be a reliable aquifer.

Each of the four units in the Upper Santa Cruz Valley Subbasin have unique geologic and water bearing characteristics. Recent alluvial deposits occupy the streambed channels of the Santa Cruz River and its major tributaries. These deposits are usually less than 100 feet thick (Davidson, 1973). The recent alluvium consists of predominantly unconsolidated sand and gravel and generally has high infiltration

FIGURE 2-2
SCHEMATIC CROSS SECTION OF THE UPPER SANTA CRUZ VALLEY SUBBASIN
TUCSON ACTIVE MANAGEMENT AREA





rates. The Fort Lowell Formation underlies the recent alluvial deposits and consists of unconsolidated to moderately consolidated sands and silts 300 to 400 feet thick throughout most of the basin (Davidson, 1973). In the past, the Fort Lowell Formation supplied most of the water used in the Tucson basin. Portions of this formation are now partially or completely dewatered (Tucson Water, 1998).

The Tinaja Beds underlying the Fort Lowell Formation consist of sandstones and conglomerates ranging to siltstones and mudstones with a total thickness of up to 5,000 feet in the center of the basin (Davidson, 1973). The Tinaja Beds consist of upper, middle, and lower units, and have become the principal supply source of groundwater in the Tucson Basin. The upper Tinaja Beds yield groundwater more readily than the middle and lower Tinaja Beds. The Pantano Formation underlies the Tinaja Beds and is up to 6,400 feet thick on the far eastern border of the AMA near Davidson Canyon (Davidson, 1973). It is composed of consolidated sandstones, conglomerates, and mudstones. Because of its great depth and the degree of cementation, it has relatively low well yields. The Pantano Formation is not widely used as a source of groundwater.

2.4.2 Avra Valley Subbasin

Alluvial sediments in the Avra Valley Subbasin have been divided into two units known as the upper alluvial unit and the lower alluvial unit (Hanson et al., 1990). The upper alluvial unit is composed of silt and gravel, and includes streambed deposits that occupy Altar and Brawley Washes and their major tributaries. The thickness of the upper unit ranges from less than 100 feet to as much as 1,000 feet (Hanson et al., 1990). The lower alluvial unit is thousands of feet thick and consists of gravel and conglomerates along the margins of the subbasin grading to silts and mudstones along the subbasin's central axis (Hanson et al., 1990). Most groundwater production in the Avra Valley subbasin is from the upper unit.

2.4.3 Effects on Recharge

The zone below land surface and above the water table is known as the vadose zone. In cases where groundwater levels have declined, the vadose zone can include sediments that were formerly saturated with water. In the case of natural recharge and various forms of managed recharge, variations in the way water moves through these sediments affects where and how water recharges the aquifer. In some locations, layers of silt or clay in the vadose zone may impede the downward migration of the water so that even though this water infiltrates through surface sediments it may not reach the groundwater aquifer. The movement of water once it has reached the groundwater table is affected by the direction of groundwater flow in that location, the characteristics of the aquifer material, the volume of water that has been recharged, and other site-specific variables. Variations in vadose zone and aquifer layers that affect the velocity and path of recharging water need to be taken into consideration in water management and recharge efforts.

2.5 GROUNDWATER CONDITIONS

Several types of maps are used in the following discussion to illustrate groundwater conditions in the Tucson AMA. These maps are based on the location of the water table–the "surface" of the groundwater–relative to either land surface, sea level, or the water table at a different point in time (Figure 2-3). When this information is known for a number of wells in an area, lines of equal elevation (contour lines) can be drawn showing the water table surface. Depth-to-water maps indicate how deep the top of the water table is beneath the surface of the land at different locations (Figure 2-3A). Water level elevation maps are used to show the level of the water table relative to average (mean) sea level (Figure 2-3A). The slope of the water table and the direction of groundwater flow can normally be determined using a water level elevation map. Water level change maps show areas where the water table has fallen or risen during a given time period (Figure 2-3B). Groundwater conditions change over time due to natural and human-

induced changes in the amount of water being added to, or removed from, the groundwater system. Because groundwater flows very slowly underground, the effects of pumping and recharge can alter the shape of the water table for long periods of time. Water that is naturally or artificially recharged can mound up underground, while pumping can create a cone of depression in the water table (Figure 2-3C). The current status and long-term changes in groundwater levels in the Tucson AMA are discussed in the following sections.

2.5.1 Depth to Groundwater

Depths to water in the AMA vary substantially depending, in part, on land surface elevations and proximity to natural drainage areas. In 1995, the depth to water in the Upper Santa Cruz Valley Subbasin ranged from less than 100 feet to over 600 feet below land surface (ft bls) (Figure 2-4). In 1995, depths to water in the Avra Valley Subbasin ranged from less than 200 to over 700 ft bls in Altar Valley, and from less than 200 to greater than 500 ft bls in Avra Valley (Figures 1-2 and 2-4). In general, depths to water tend to be shallower near rivers and major washes and deeper near mountain fronts where land surface elevations are higher.

2.5.2 Groundwater Levels

Groundwater levels in the Tucson AMA have changed substantially in the last 50 years as a result of groundwater pumping for municipal, agricultural, and industrial uses. Current and historical water level elevations, and changes in these elevations over time, are discussed and illustrated in the following sections.

2.5.2.1 Past Groundwater Levels

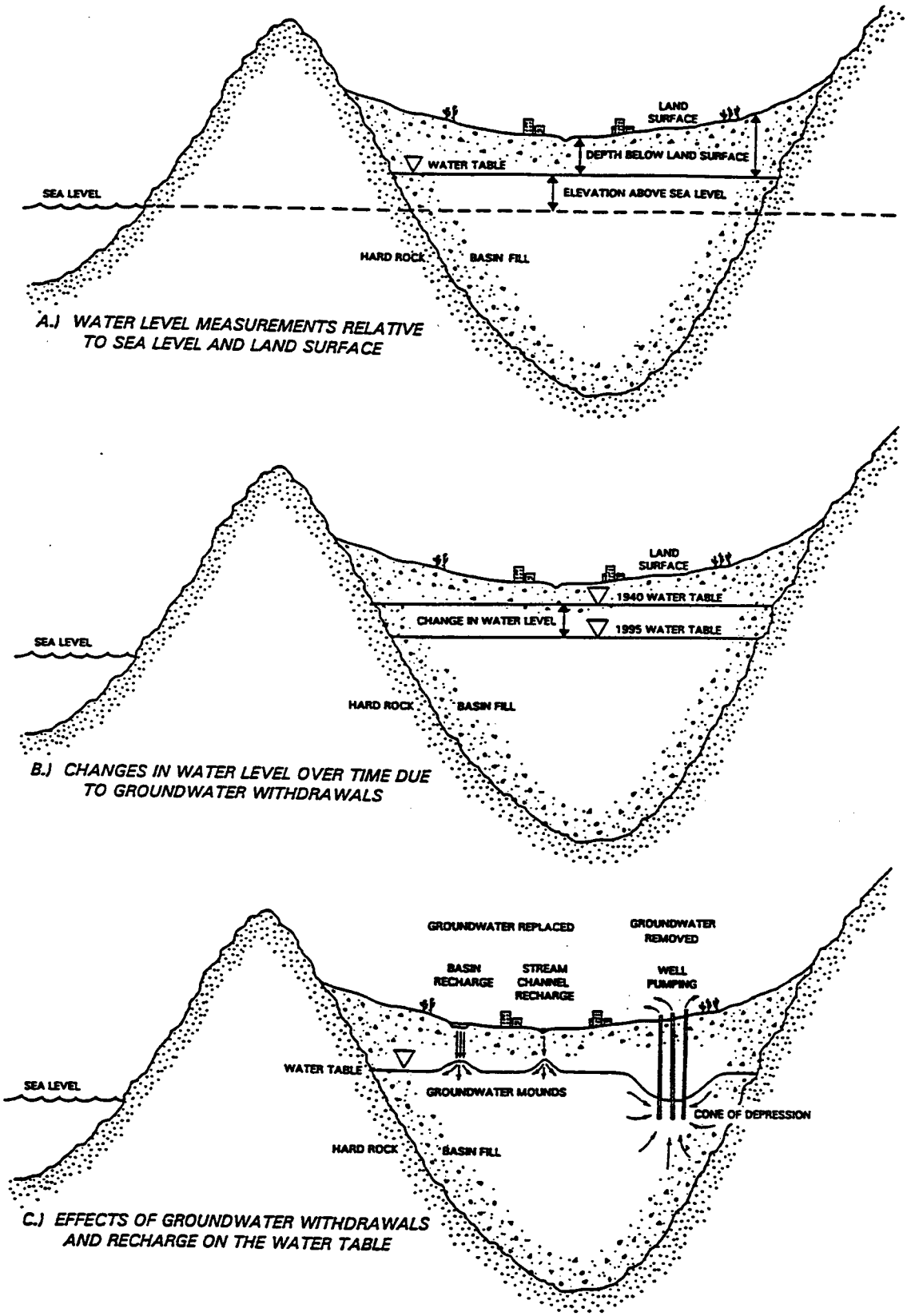
Water level elevations prior to major groundwater development in the AMA indicate that groundwater flowed toward the north and northwest at a fairly constant slope (Figure 2-5). Groundwater development intensified beginning in the late 1940s and early 1950s and has continued since that time. By 1965, water level contours were deflected by groundwater pumping for municipal use in the City of Tucson's Central Wellfield. By 1982, a cone of depression had developed in the Green Valley/Sahuarita area due to groundwater pumping by local copper mines (Figures 1-2 and 2-6).

2.5.2.2 Current Groundwater Levels

The deflection of groundwater elevation contours continued to increase between 1982 and 1995 in the City of Tucson's Central Wellfield and in the vicinity of pumping by metal mines in the Green Valley/Sahuarita area (Figures 2-6 and 2-7).

Water level elevations in the Upper Santa Cruz Valley Subbasin in 1995 generally decreased from 2,950 feet above mean sea level (ft above msl) in the southern portion of the subbasin, and from 3,050 ft above msl in the northern Cañada del Oro drainage, to around 1,900 ft above msl in the northwest portion of the subbasin where groundwater flows into the Avra Valley Subbasin (Figure 2-7). In the Avra Valley Subbasin, water level elevations ranged from 3,100 ft above msl in southern Altar Valley to 1,600 ft above msl at the northwest border of the Tucson AMA where groundwater flows into the adjacent Pinal AMA. With the exception of the Cañada del Oro area where groundwater flows south and then west, groundwater in both AMA subbasins generally flows north and northwest toward the northwest boundary of the AMA. The water table is presently at land surface and results in flowing surface water in Cienega Creek and Arivaca Wash. Other streams in the AMA generally flow as a result of snowmelt and stormwater flow.

FIGURE 2-3
CONCEPTS IN MAPPING GROUNDWATER LEVELS



2.5.2.3 Change in Groundwater Levels Over Time

Declines in groundwater levels reaching 200 feet in the City of Tucson's Central Wellfield and 150 feet in the Green Valley/Sahuarita area are indicated on a map of water level changes between around 1940 and 1995 (Figure 2-8).

A cone of depression is a "bowl" shape created in the groundwater table as a result of groundwater pumpage from a well (Figure 2-3C). Once a cone of depression is created, groundwater in the vicinity of the cone stops moving with the regional flow pattern and instead moves toward the center of the depression. If the rate of pumping continues, the cone of depression grows, getting deeper and broader. If multiple wells are being pumped, regional water level declines can occur as shown in Figure 2-8.

Water level hydrographs have been compiled to show water level changes between 1950 and 1995 at individual wells in the AMA (Figure 2-9). The location of these wells is shown on Figure 2-8. These hydrographs generally indicate that long-term water level declines have occurred in most locations. Groundwater levels have declined as much as 200 feet in the City of Tucson's Central Wellfield due to municipal pumpage, with declines averaging up to 4 to 5 feet per year. Declines have occurred steadily in the Central Wellfield since the 1950s (Figure 2-9A). Northwest of the Green Valley/Sahuarita area, pumping by copper mines has resulted in a 160-foot water level decline (Figure 2-9B). Additional areas of groundwater decline include 90 feet in southern Avra Valley due to municipal pumping by the City of Tucson, 70 feet in northwest Avra Valley due to agricultural pumping, and 50 feet in the lower Cañada del Oro area due to municipal uses (Figures 2-9C, D, and E, respectively).

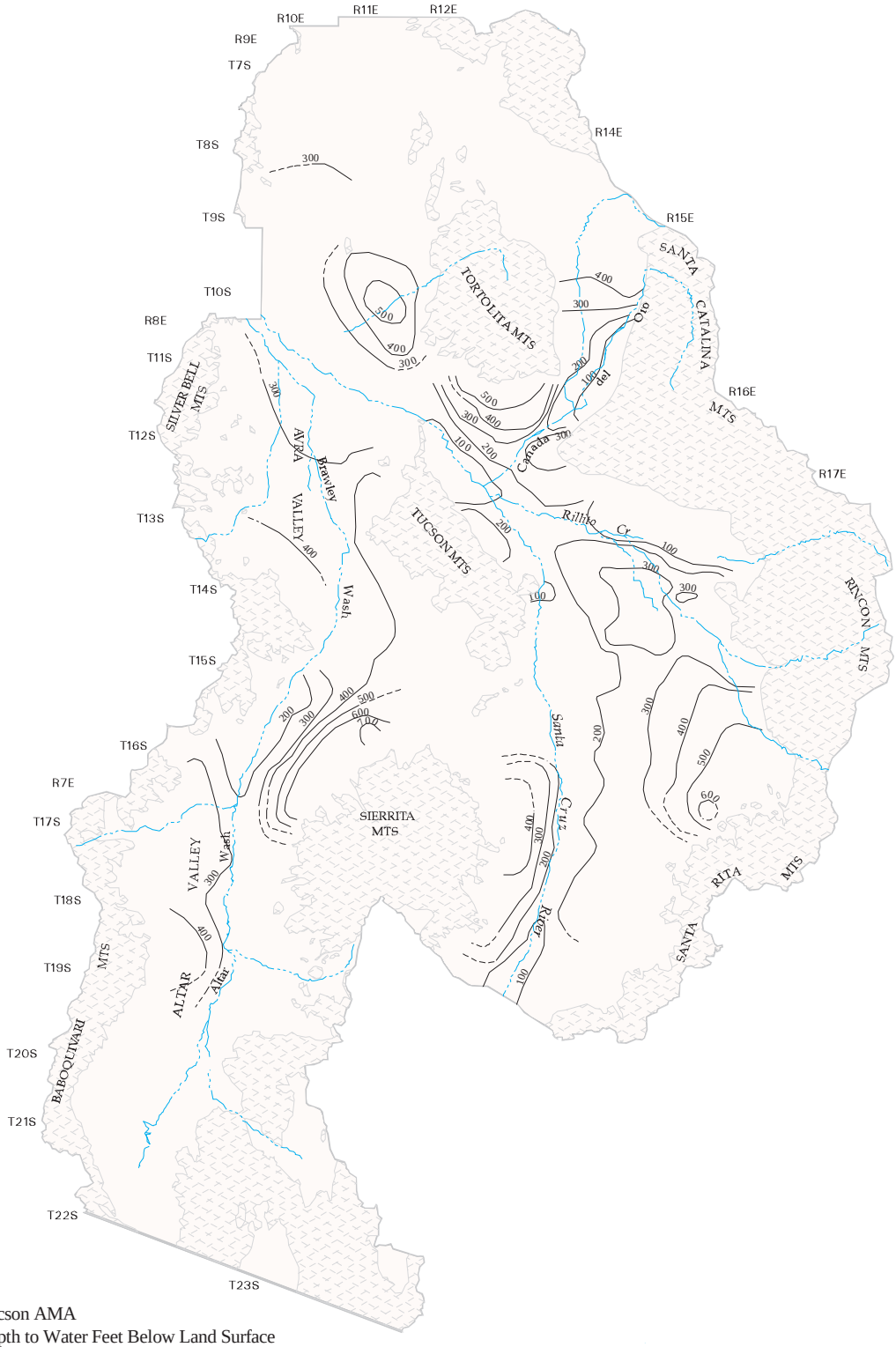
While overall water levels have continued to decline in much of the AMA, some areas have experienced water level rises since the late 1970s. The greatest rises have occurred along the Santa Cruz River where larger than average flood flows since the late 1970s resulted in increased natural recharge. Rises of up to 80 feet have occurred along the Santa Cruz River just north of the Santa Cruz/Tucson AMA boundary resulting from increased infiltration of flood flows and effluent discharges, and decreased agricultural and mine pumpage during this period (Figure 2-9F). Under some conditions there is sufficient surface water in the Santa Cruz River to flow from the Santa Cruz AMA into the Tucson AMA.

Since the late 1970s, water levels have risen 60 feet in the area southeast of Marana due to increased natural recharge from the Santa Cruz River and decreased agricultural pumpage (Figures 2-9G). Effluent discharges to the Santa Cruz River have also contributed to rising water levels along the river. Rises of 30 feet in the upper reaches of the Cañada del Oro since the late 1970s may be due to increased mountain front recharge and infiltration of stream channel runoff occurring during years of high precipitation (Figure 2-9H.). In several of these areas, water levels have recovered to water levels present around 1940.

Groundwater levels in the future will depend on the amount and location of groundwater pumping; recharge of CAP water; direct use of CAP water by agriculture, industry, and municipal users; direct use and recharge of treated effluent; and changes in water demand. The Tucson AMA groundwater model will be used to project water level changes in the future based on various supply, demand, and recharge scenarios.

2.5.3 Net Natural Recharge

Average net natural recharge resulting from infiltration of precipitation and groundwater underflow is estimated at 60,800 acre-feet per year in the Tucson AMA (Table 2-1). Of this total, an estimated 51,300 acre-feet of net natural recharge occurs in the Upper Santa Cruz Valley Subbasin and 9,500 acre-feet occurs in the Avra Valley Subbasin.



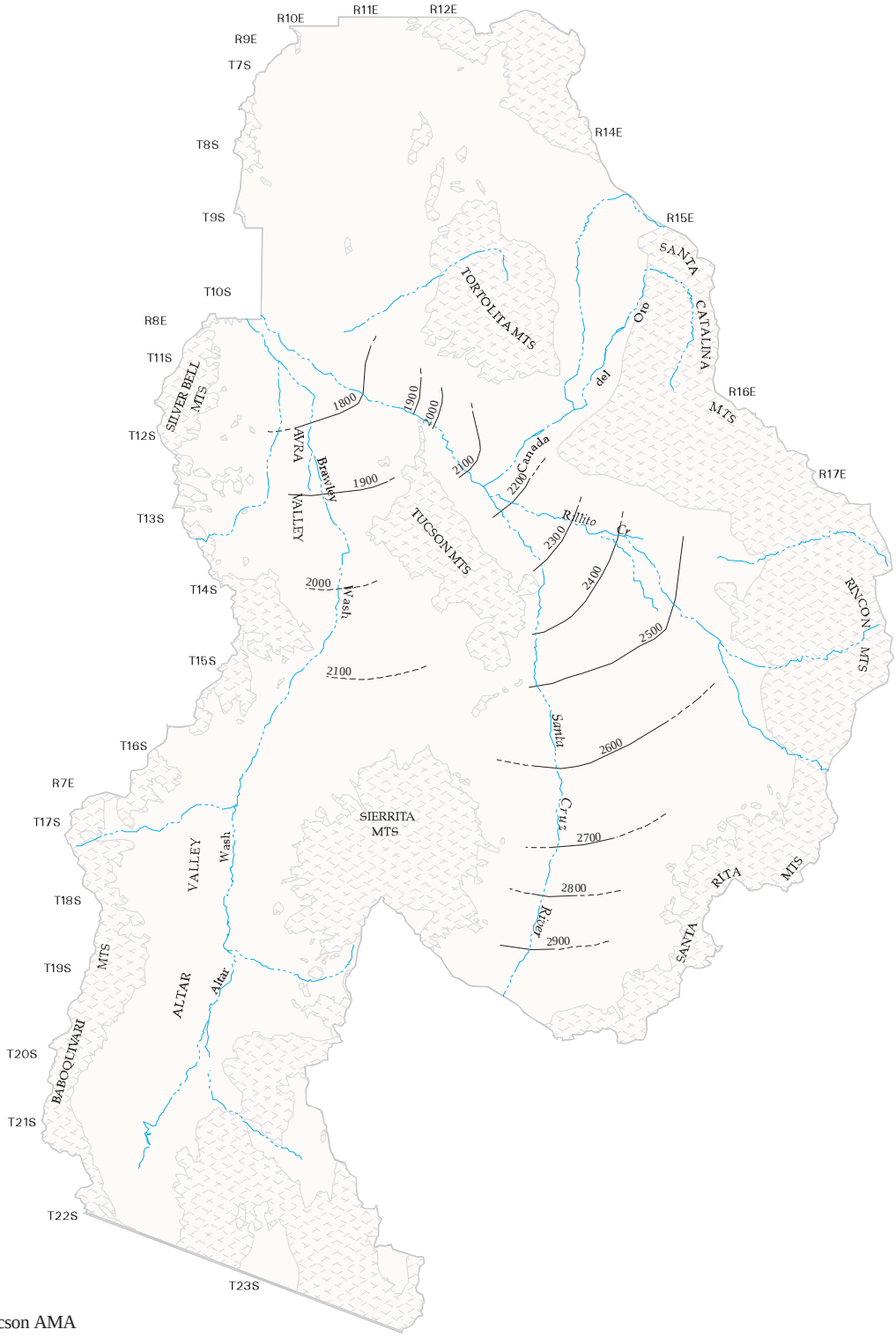
Tucson AMA
Depth to Water Feet Below Land Surface
Approximate Depth to Water Feet Below Land Surface
Hardrock
Rivers and Streams

Figure 2- 4

Depth to Water
1995

0 3 6 9 12
Miles
North

ORIGINAL SOURCE
Arizona Department of Water Resources
Hydrology Division



Tucson AMA
Water Elevation Feet Above Mean Sea Level
Approximate Elevation Feet Above Mean Sea Level

Hardrock
Rivers and Streams

Figure 2- 5

Water Elevations
1940

0 3 6 9 12
Miles

North

ORIGINAL SOURCE
Arizona Department of Water Resources
Hydrology Division

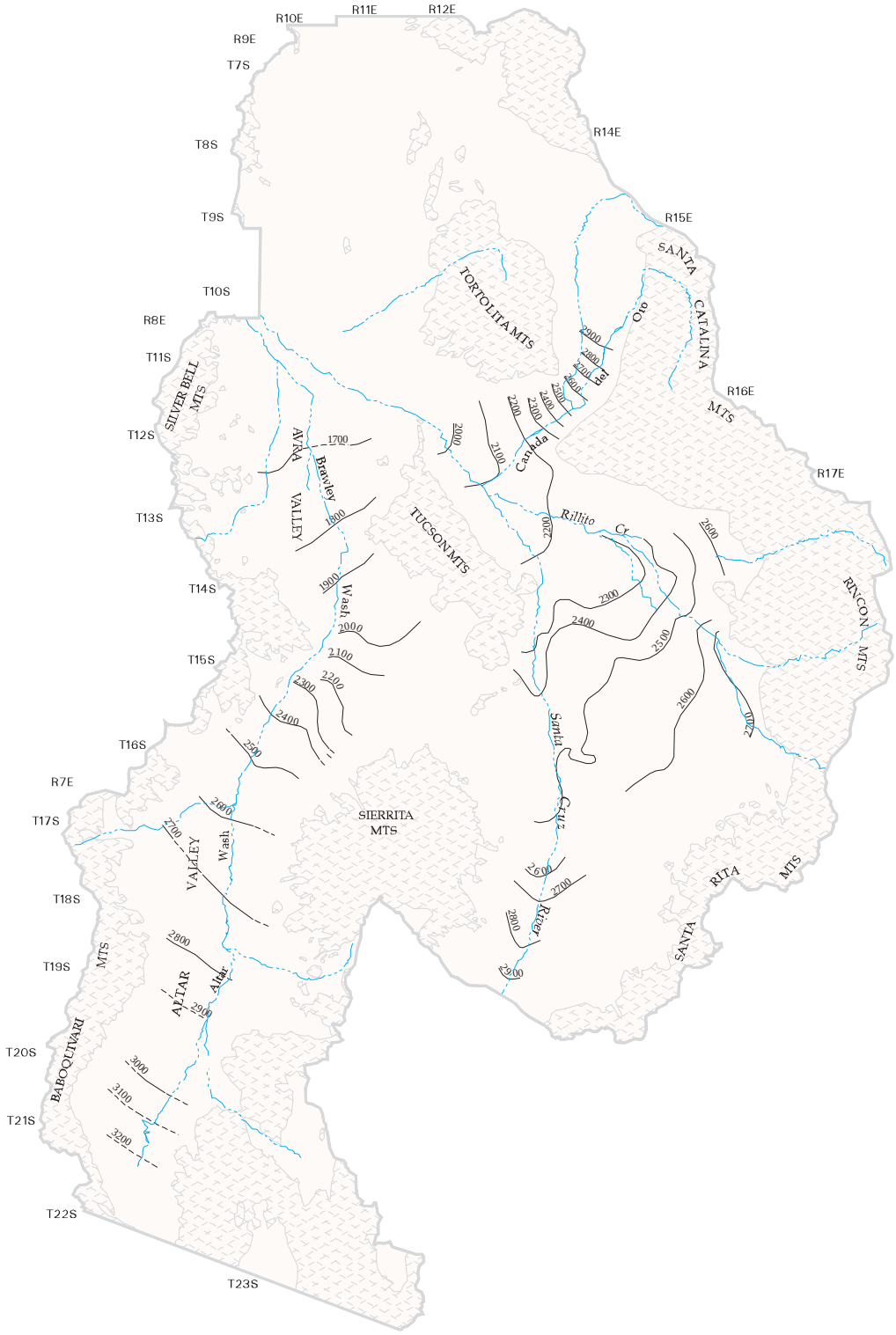


Figure 2- 6

Water Elevations
1981 - 1982

- Tucson AMA
- Water Elevation Feet Above Mean Sea Level
- Approximate Elevation Feet Above Mean Sea Level
- Hardrock
- Rivers and Streams

0 3 6 9 12
Miles

North

ORIGINAL SOURCE

Arizona Department of Water Resources
Hydrology Division

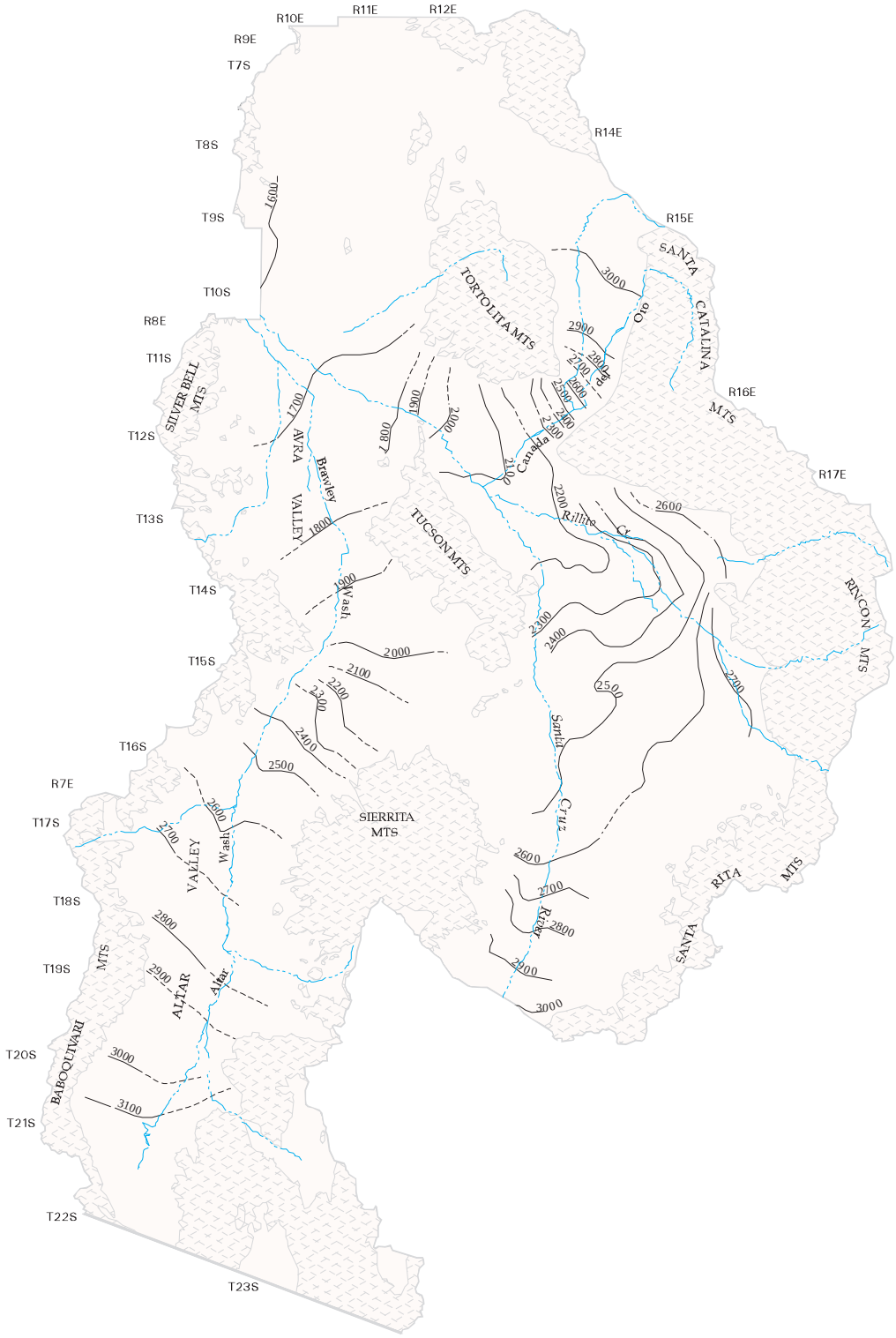


Figure 2- 7

Water Elevations
1995

- Tucson AMA
- Water Elevation Feet Above Mean Sea Level
- Approximate Elevation Feet Above Mean Sea Level
- Hardrock
- Rivers and Streams

0 3 6 9 12 Miles

North

ORIGINAL SOURCE

Arizona Department of Water Resources
Hydrology Division

TUCSON AMA

MAP	HYDROGRAPH
A	D-14-14 24BAA
B	D-16-13 34AAB2
C	D-15-11 05CCD
D	D-10-10 05DAD
E	D-12-13 22BBB
F	D-19-13 09CAA
G	D-12-11 20AAA
H	D-10-14 29DCA

Tucson AMA
Water Elevation Changes in Feet
Hardrock
Rivers and Streams
Wells Used for Hydrographs

Figure 2- 8

Water Elevation Changes
1940 - 1995

0 3 6 9 12
Miles
North

ORIGINAL SOURCE
Arizona Department of Water Resources
Hydrology Division

FIGURE 2-9
WATER LEVEL HYDROGRAPHS AT SELECTED LOCATIONS
TUCSON ACTIVE MANAGEMENT AREA

FIGURE 2-8A. WELL D-14-14 24BAA
CENTRAL WELLFIELD

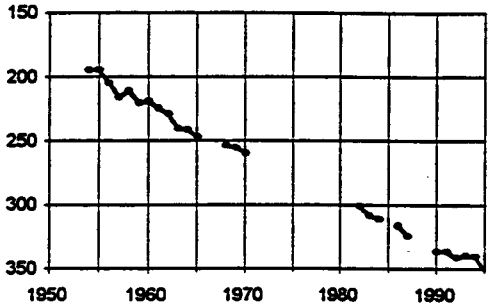


FIGURE 2-8B. WELL D-16-13 34AAB2
NORTHWEST OF SAHUARITA

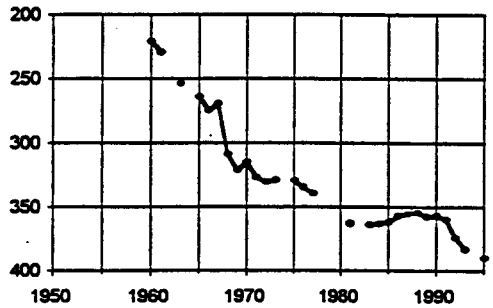


FIGURE 2-8C. WELL D-15-11 5CCD
SOUTHERN AVRA VALLEY

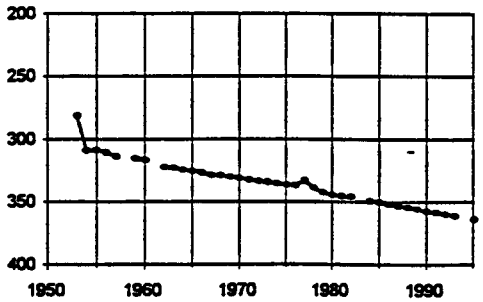


FIGURE 2-8D. WELL D-10-10 5DAD
NORTHWEST AVRA VALLEY

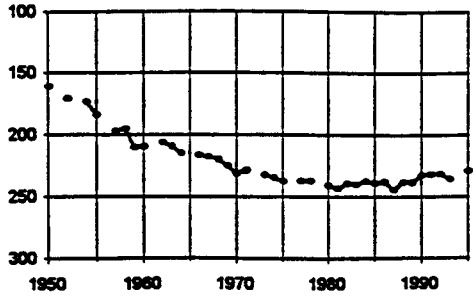


FIGURE 2-8E. WELL D-12-13 22BBB
LOWER CANADA DEL ORO

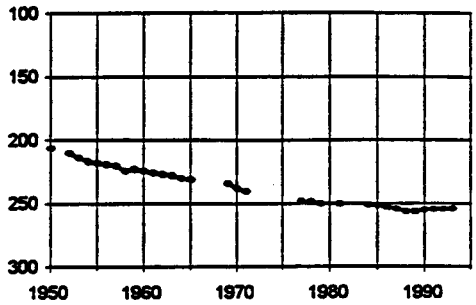


FIGURE 2-8F. WELL D-19-13 9CAA
SOUTHERN GREEN VALLEY AREA

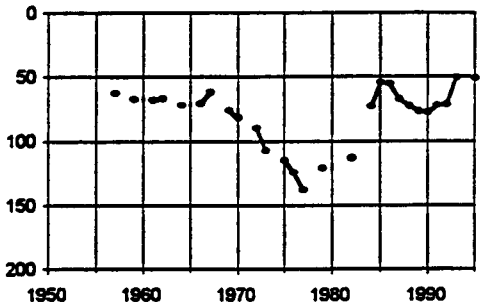


FIGURE 2-8G. WELL D-12-11 20AAA
SOUTHEAST OF MARANA

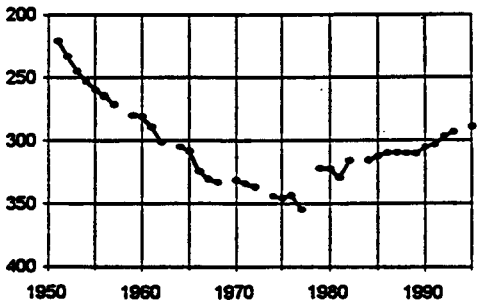
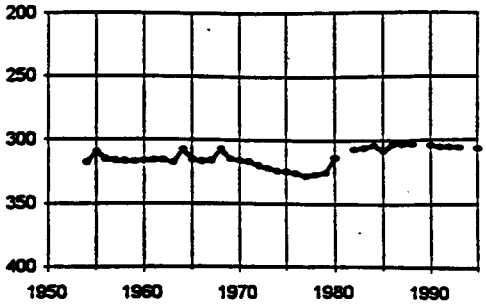


FIGURE 2-8H. WELL D-10-14 29DCA
UPPER CANADA DEL ORO



Rainfall and snowmelt replenish the aquifer as mountain front recharge, which occurs in channels at the margins of mountain ranges. Mountain front recharge in the Upper Santa Cruz Valley Subbasin is estimated at 27,000 acre-feet each year. In the Avra Valley Subbasin, mountain front recharge is around 11,900 acre-feet per year.

TABLE 2-1
NET NATURAL RECHARGE COMPONENTS IN THE WATER BUDGET
TUCSON ACTIVE MANAGEMENT AREA

Elements of Net Natural Recharge	Volume (acre-feet)
UPPER SANTA CRUZ VALLEY SUBBASIN	
Mountain Front Recharge	27,000
Stream Channel Recharge[1]	31,000
Groundwater Inflow from Santa Cruz Active Management Area[2, 3]	8,700
Groundwater Outflow to Avra Valley Subbasin[3]	(15,400)
Total Net Natural Recharge in Upper Santa Cruz Valley Subbasin	**51,300**
AVRA VALLEY SUBBASIN	
Mountain Front Recharge	11,900
Stream Channel Recharge	6,700
Groundwater Inflow from Upper Santa Cruz Valley Subbasin[3]	15,400
Groundwater Outflow to Pinal Active Management Area[3]	(24,500)
Total Net Natural Recharge in Avra Valley Subbasin	**9,500**
TOTAL NET NATURAL RECHARGE IN TUCSON ACTIVE MANAGEMENT AREA	**60,800**

[1] Surface water that flows in the Santa Cruz River from the Santa Cruz AMA into the Tucson AMA is accounted for in the Tucson AMA water budget only if it infiltrates into the groundwater aquifer within the boundary of the Tucson AMA, in which case it is accounted for as stream channel recharge in the Upper Santa Cruz Subbasin.
[2] Surface water that infiltrates into the groundwater aquifer within the boundary of the Santa Cruz AMA can eventually flow as groundwater into the Tucson AMA, in which case it is accounted for as groundwater inflow in the Tucson AMA water budget.
[3] Groundwater inflow and outflow can vary over time due to changes in effluent discharge conditions, artificial recharge conditions, and groundwater pumping at or near the AMA boundaries.

Groundwater conditions in the Tucson AMA are greatly affected by intermittent but occasionally large surface water flows in the Santa Cruz River and its tributaries originating from precipitation. Surface water flows recharge the groundwater system in the vicinity of the stream as water infiltrates through the stream channel sediments to the underlying aquifer. Under some conditions, surface water in the Santa Cruz River flows out of the Santa Cruz AMA and into the Tucson AMA. While flow across the boundary varies substantially from year-to-year, the long-term median streamflow exiting the Santa Cruz AMA into the Tucson AMA is about 13,800 acre-feet per year as measured at the USGS Continental streamgage located about ten miles north of the Tucson AMA boundary. This surface water flow is accounted for in the Tucson AMA water budget only if it infiltrates into the groundwater aquifer within the boundary of the Tucson AMA, in which case it is accounted for as stream channel recharge in the Upper Santa Cruz Subbasin. Stream channel recharge in the Upper Santa Cruz Valley Subbasin is estimated at 31,000 acre-

feet per year and in the Avra Valley Subbasin at about 6,700 acre-feet per year. Infiltration of treated effluent discharged to the Santa Cruz River from Pima County's regional wastewater treatment plants in the Tucson AMA is not a component of net natural recharge calculations.

Groundwater inflow to the Tucson AMA occurs as a result of the northward flow of groundwater from the Santa Cruz AMA into the Tucson AMA in the Upper Santa Cruz Valley Subbasin. Estimates of groundwater inflow at this location range from 6,800 to 10,600 acre-feet per year. A long-term mean inflow of 8,700 acre-feet per year is used in the net natural recharge calculation. Within the boundary of the Tucson AMA, an estimated 15,400 acre-feet of groundwater flows out of the Upper Santa Cruz Valley Subbasin into the adjacent Avra Valley Subbasin in the area north of the Tucson Mountains. Groundwater exits the Tucson AMA and flows north into the Pinal AMA at the northwestern border of the Avra Valley Subbasin in the vicinity of Picacho Peak. Estimates of this outflow range from 19,000 to 30,000 acre-feet per year, with a long-term mean outflow of 24,500 acre-feet used in net natural recharge calculations.

Mean groundwater inflow and outflow volumes could vary in the future. One important variable is the volume of effluent discharged to the Santa Cruz River from wastewater treatment plants located along the river in the Santa Cruz and Tucson AMAs. Mexico has the right, at any time, to retain that country's portion of wastewater before it goes to the Nogales International Wastewater Treatment Plant or to recapture the effluent before it is discharged to the river. A portion of the effluent discharged from this plant infiltrates back to the aquifer and can affect groundwater inflow to the Tucson AMA. At the regional Pima County wastewater treatment plants at Roger Road and Ina Road in the Tucson AMA, the volume of effluent being released could vary due to changes in direct use of effluent or recharge activities with effluent. Effluent flowing from these regional plants affects water levels in the Marana area and subsequent groundwater outflow to the Pinal AMA. Other factors that could affect groundwater inflow and outflow are precipitation events, flood flows, and water-related activities at or near the AMA boundaries including CAP recharge and recovery and groundwater pumping levels.

2.5.4 Groundwater Storage Trends

The perception that there is a vast and effectively inexhaustible supply of readily available groundwater in Tucson AMA aquifers is inaccurate. Water users in the Tucson AMA pump more groundwater from the aquifers than is replenished by natural or artificial recharge, resulting in groundwater overdraft and a decrease in the volume of groundwater stored in aquifers in the AMA. Based on estimates of historical pumpage, evapotranspiration, and net natural and incidental recharge in the Tucson AMA, a preliminary estimate has been made that groundwater removed from AMA aquifers since around 1940 ranges from 6 to 8 million acre-feet depending on assumptions made about aquifer characteristics. This constitutes a range of from 7 percent to 9 percent of the estimated 70 million acre-feet of groundwater in storage down to 1,200 feet below land surface around 1940.

While a relatively small percentage of groundwater has been removed from storage, it represents the depletion of groundwater from the most productive and easily accessible layers of the aquifer. Future depletions will occur in deeper and less productive layers of the aquifer, with a corresponding increase in costs and detrimental effects. In general, the quality of the water decreases with depth due to increasing mineral content with depth.

The Tucson Water service area covers a fraction of the land area of the AMA but provides water service to 80 percent of the municipal population. It is estimated that 12.7 million acre-feet of groundwater storage remains down to 1,000 feet in depth in those portions of the Upper Santa Cruz Valley and Avra Valley that are within the Tucson Water service area (Malcolm Pirnie, 1996). This area includes the Central Wellfield where water level declines of as much as 200 feet have occurred. Tucson Water has observed decreasing productivity in many of its wells due to declining water levels (Tucson Water, 1998).

Estimates of groundwater in storage in Arizona have typically been made to depths of 1,000 to 1,200 feet below land surface. While extraction of water is possible to a depth of 1,200 feet or more below land surface, this can result in substantial damage to the aquifer and overlying land. The water table in the most heavily pumped areas of the aquifer is still generally within 400 feet of the land surface, but this has already resulted in negative consequences. The lowering of water levels has destroyed riparian habitat, caused erosion, displaced existing groundwater users, and reduced stream flows. As overdraft continues, a number of problems can result. Groundwater must be withdrawn from deeper levels of the aquifer resulting in a loss of productivity in wells and a corresponding need to deepen or replace existing wells. Pumping costs increase as the depth to water increases. Because the total dissolved solids content of the groundwater tends to increase with depth, the quality of pumped groundwater may decrease as older groundwater from deeper zones is pumped. Enlarging areas of water level decline and changes in regional groundwater flow patterns can increase the chance that contaminated groundwater moves from current locations. A recent computer modeling study indicates that aquifer compaction, land subsidence, land fissuring, and loss of aquifer capacity may occur in the Tucson AMA as water levels continue to decline (Hanson and Benedict, 1994). As land subsides, aquifer layers are compressed and can permanently lose some of their capacity to store water.

Because of these negative consequences, estimates of groundwater storage need to be understood in a larger context than volume alone. The intricacies of the hydrogeologic system and the interconnected nature of groundwater flow makes all users vulnerable to these declines; and this vulnerability is increasing with time and further depletion. To project the possible impacts of further groundwater declines, the Tucson AMA computer model will be used to estimate groundwater storage for different aquifer layers and to project changes in storage over time using various pumping and recharge scenarios. The groundwater underlying the AMA has accumulated over many thousands of years, but is being depleted in the time frame of decades. Ultimately, the only way to avoid damages from groundwater decline is to stop groundwater overdraft.

2.6 SUBSIDENCE

Land subsidence can occur when groundwater is withdrawn to such a degree that portions of an aquifer become dewatered and, due to the weight of overlying land, this material becomes compacted. This results in a drop in elevation at the land surface and can result in cracks and fissures.

Land subsidence can cause considerable damage to sewer, water, and gas pipelines; canals; wells; roads; buildings and other infrastructure. In addition, when aquifer material compacts, several characteristics of the aquifer can change. The pore space available to store water is reduced. This in turn could reduce the ease with which water moves through the aquifer material and the productivity of wells in the area of compaction. If these changes occur, they are generally irreversible.

Computer models have been used by the USGS to estimate a range of maximum potential land subsidence in subbasins within the Tucson AMA (Hanson 1989; Hansen et al., 1990; and Hanson and Benedict, 1994). Results of the modeling studies indicate that by 2025, maximum potential land subsidence in the City of Tucson's Central Wellfield could reach 1.2 feet or 12 feet depending on the assumptions made about the characteristics of the aquifer materials being compressed (Hanson and Benedict, 1994). These subsidence estimates are based on the assumption that pumping and natural recharge rates continue at 1986 levels through the year 2025 and that water levels decline more than 400 feet below 1940 water levels. Potential subsidence in the City of Tucson's Santa Cruz Wellfield located north of Sahuarita could reach 0 feet or 4 feet during this time period depending on the assumptions used (Hanson and Benedict, 1994). Maximum potential subsidence in northern Avra Valley could reach 0.9 feet or 14.7 feet (Hanson, et al., 1990). The Avra Valley subsidence estimate is based on the assumption that pumping levels and natural recharge rates continue at levels experienced in the mid-1970s, and also depends on the assumptions made

about aquifer material characteristics. The highest estimates of maximum potential land subsidence are shown in Figure 2-10 (Hansen and Benedict, 1994; Hansen et al., 1990).

If land subsides at the same rate over a large area, there is less impact to surface activities than if adjacent land subsides at different rates. Such "differential subsidence" can occur when subsurface conditions change over a short distance. This can occur near bedrock, around faults, and in areas where the composition of subsurface sediments change abruptly. Based on the maximum subsidence potential projected in the USGS modeling studies, it appears the depth of land subsidence could vary from 2 feet to 10 feet in the vicinity of downtown Tucson by 2025 and from 2 feet to 14 feet in the central area of Avra Valley by 2025 (Figure 2-10).

In the Tucson AMA, there is already some evidence of aquifer compaction and associated land subsidence attributed to aquifer dewatering. Fissuring, aquifer compaction, and subsidence have been observed in northern Avra Valley. In 1988, an earth fissure in Avra Valley damaged the CAP aqueduct, costing about $50,000 in repairs (Slaff, 1993). Sink holes have been reported near the Santa Cruz River within the San Xavier District (Hoffman, et al., 1997). These sinkholes are not directly related to regional subsidence but may be related to localized water level declines.

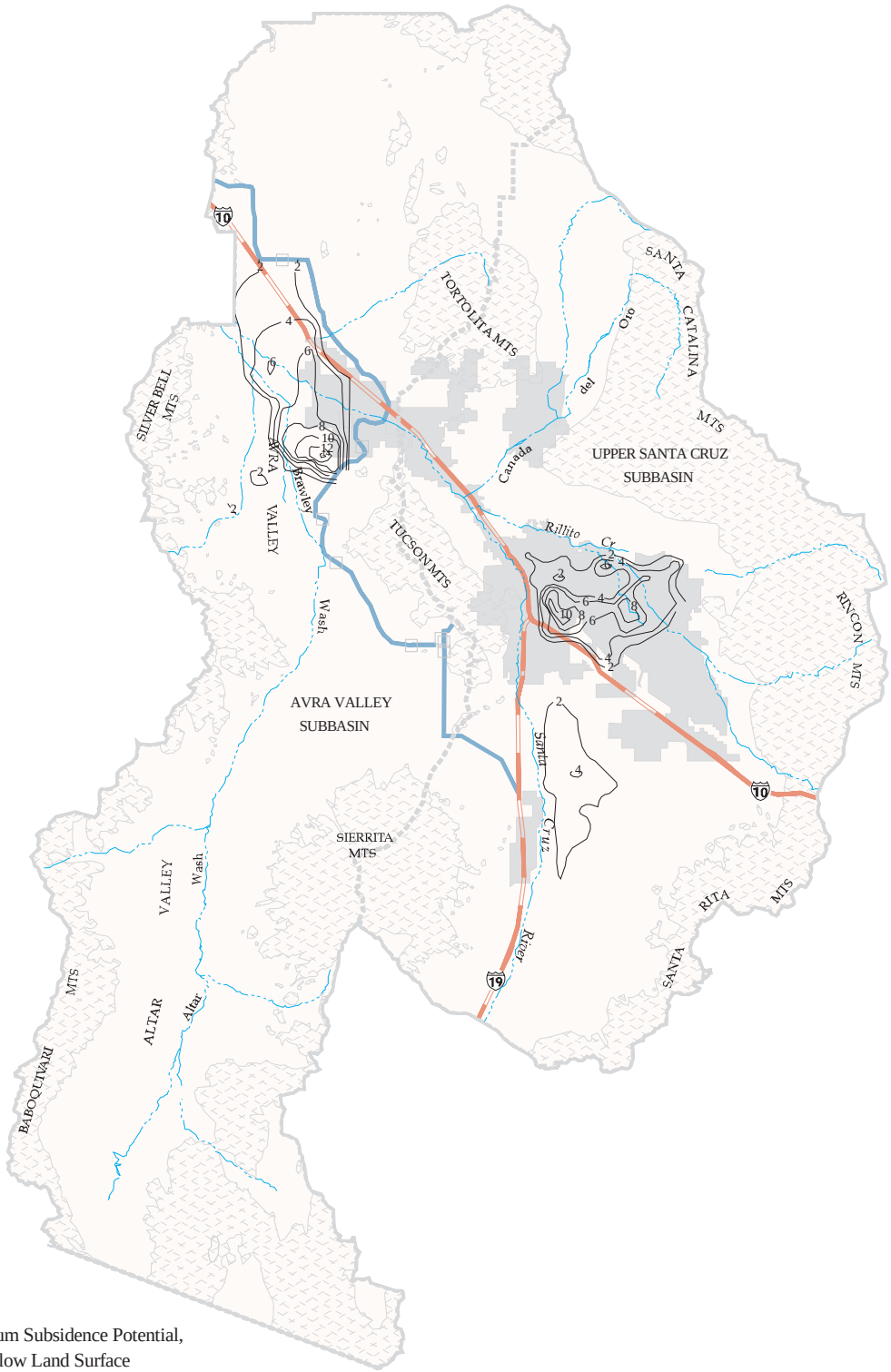
Aquifer compaction and associated land subsidence of nearly 0.5 feet had occurred south of Davis-Monthan Air Force Base by 1980 (Anderson, 1988). Subsidence monitoring has been conducted since the early 1980s by Tucson Water and the USGS using extensometers to measure aquifer compaction. In the northern Avra Valley subbasin, subsidence has been measured at 1.1 feet (Anderson, 1989). Measurement of compaction at specific locations in the time period between 1980 and 1995 were reported in the Tucson Water Annual Static Water Level Report for 1995 (Tucson Water, 1997). Results indicated compaction of from 0.02 feet to 0.18 feet at seven locations in the Upper Santa Cruz Subbasin and from 0.01 feet to 0.11 feet at seven locations in the Avra Valley Subbasin.

Future land subsidence can be minimized by halting groundwater pumping in vulnerable areas or by recharging water in the vicinity of the declining water table. Water should be recharged close to the compacting layer to be most effective, so well-injection recharge is a more useful strategy for addressing subsidence than basin recharge. Recharge could reduce the amount of compaction and could possibly result in the compacted layers rebounding to some extent. But in general, once subsidence has occurred, the addition of water to the subsurface cannot return land to its full original elevation (Slaff, 1993). Even though water levels may recover to previously high levels after subsidence occurs, because the aquifer material has been compacted, the space available for groundwater storage is reduced so less groundwater is available for pumping.

The Department currently monitors subsidence using extensometers and Global Positioning System (GPS) data. New technological developments in radar imaging from satellites shows promise for measuring changes in land surface elevation. This technology is known as radar interferometry. The combination of existing subsidence measuring approaches with the possible future use of radar interferometry could improve understanding of the areal extent and degree of land subsidence.

2.7 WATER QUALITY LIMITATIONS

The presence of elevated concentrations of inorganic and organic constituents can make water unacceptable for potable use prior to treatment due to health concerns or due to negative aesthetic characteristics. In some cases, this water may be acceptable for nonpotable uses in place of potable quality groundwater. Instances where the presence of elevated inorganic and organic constituents impact water supply are briefly addressed below. Water quality conditions in the Tucson AMA are discussed in depth in Chapter 7.



Maximum Subsidence Potential, Feet Below Land Surface
Incorporated Areas
Hardrock
Tucson AMA
Rivers and Streams
Interstates
Subbasins
CAP Canal
CAP Pumping Stations

Figure 2- 10

Maximum Projected Subsidence Potential by 2025

0 3 6 9 12
Miles

North

ORIGINAL SOURCE
U.S. Geological Survey
Water-Resources Investigations
Report 90-4178, 1990
Report 93-4196, 1994

2.7.1 Inorganic Constituents

Nitrates, sulfates, and total dissolved solids have been detected in groundwater in the Tucson AMA at concentrations exceeding established EPA primary and secondary maximum contaminant levels (Pima Association of Governments, 1994). Isolated areas of elevated sulfate and total dissolved solids concentrations have been detected near mining and agricultural operations in the AMA. Trace metals including silver, cadmium, chromium, lead, and selenium have been detected in groundwater in isolated areas. A few metals have been detected in groundwater samples associated with industrial waste disposal sites, airports, and mining areas. In most cases, these detections have not occurred in public supply wells and have not affected water supplies.

2.7.2 Volatile Organic Compounds

Groundwater supply wells associated with industrial and transportation facilities have been shut down in several areas of the AMA due to contamination from volatile organic compounds and fuels. Remediation of groundwater from contaminated sites is proceeding in the AMA, and a portion of this remediated water is being delivered to potable customers. As a result of the Water Consumer Protection Act passed in 1995, direct delivery of remediated water might be halted and the remediated water discharged into the Santa Cruz River bed instead.

2.8 AVAILABILITY AND UTILIZATION OF RENEWABLE SUPPLIES

To achieve safe-yield in the Tucson AMA by 2025, it is necessary to decrease reliance on groundwater supplies. An important component of this reduced reliance is to increase the use of renewable water supplies. The major renewable water supplies available in the Tucson AMA are secondary-treated effluent, secondary-treated effluent that has undergone additional treatment and is delivered through the City of Tucson's reclaimed water distribution system, and CAP water used either directly or through recharge and recovery projects.

The use of renewable supplies by the agricultural, municipal, and industrial sectors is described in chapters 3, 4, 5, and 6. Issues associated with the availability and potential use of CAP water and effluent are discussed in the Augmentation and Recharge Program in Chapter 8. The projected reduction in overdraft due to the use of renewable water supplies is shown in the AMA water budget in Chapter 11.

2.8.1 Effluent

Total production of effluent from all wastewater treatment plants in the Tucson AMA was approximately 68,600 acre-feet in 1995. The majority of this effluent, 65,400 acre-feet, is treated by the Pima County Wastewater Management Department at two regional wastewater treatment plants located along the Santa Cruz River at Roger Road and Ina Road.

In 1995, around 1,800 acre-feet of the effluent produced at these plants was delivered directly to the Cortaro Marana Irrigation District for agricultural irrigation, 1,200 acre-feet was delivered directly to turf facilities, and 7,000 acre-feet was diverted to the City of Tucson's reclaimed system for delivery to turf facilities located throughout the City and County. The remaining 55,400 acre-feet of effluent was released into the Santa Cruz River channel where the majority infiltrated into the aquifer as incidental recharge. Outlying wastewater treatment plants in the Pima County wastewater treatment system produced around 2,800 acre-feet of treated effluent in 1995. This effluent was generally stored in ponds adjacent to the treatment plants where it then evaporated or infiltrated into the ground.

Under the terms of the Southern Arizona Water Rights Settlement Act (SAWRSA), 28,200 acre-feet per year of the effluent generated at the Pima County regional wastewater treatment plants is granted to the

United States Secretary of the Interior to be used for the benefit of the Tohono O'odham Nation. This water is not currently being used by the Secretary, but may be recharged or directly used in the future. Of the remaining effluent generated at the regional plants, the City of Tucson controls 90 percent and Pima County controls 10 percent.

The first artificial effluent recharge project operating in the Tucson AMA, the Sweetwater Recharge Facility, began recharging effluent treated at the City of Tucson's reclaimed plant in the late 1980s. This recharged effluent is pumped out annually for delivery through the City's reclaimed system. Future uses of effluent may include additional recharge projects. The City of Tucson and the Secretary of the Interior are applying for a "managed recharge facility" permit for their portions of the effluent being discharged into the Santa Cruz River. This permit would allow the City and the Secretary to accrue recharge credits for 50 percent of this passively recharging effluent. These credits could be recovered by pumping groundwater from locations in the AMA away from where the effluent recharge occurred. The implications of effluent recharge and recovery on the AMA water budget are addressed in Chapter 11.

Use of effluent is projected to increase in the future due to the City's extensive reclaimed water system and support for effluent use, and Pima County's ordinance requiring new golf courses to utilize renewable supplies. The dissolved solids content of effluent is expected to increase with the increased utilization of CAP water. This may have implications for future use of effluent supplies. Reuse of effluent reduces the burden on groundwater supplies and redistributes the effluent throughout the geographical area where groundwater levels are steadily dropping. By using effluent directly, higher quality groundwater can be retained to meet potable needs or can remain in the ground to stabilize groundwater declines.

2.8.2 CAP Supply

CAP water is the most abundant source of renewable supply available for use in the Tucson AMA. The available allocation and current use of CAP water in the Tucson AMA is discussed below, along with the key entities from outside the AMA that facilitate its use in the state.

2.8.2.1 CAP Allocation and Use in the Tucson Active Management Area

The Central Arizona Project was constructed to annually deliver 1.5 million acre-feet of Arizona's allocation of Colorado River water to central and southern Arizona through a series of aqueducts and pumping stations. The project is over 300 miles long, and lifts Colorado River water 2,400 feet to its final destination in Tucson. CAP water was originally allocated in 1983 among Indian users, non-Indian municipal users, industrial users, and agricultural users to parties who requested an allocation. Contracts for the allocations are made with the Central Arizona Water Conservation District, which is also responsible for operating and maintaining CAP infrastructure and managing the repayment of construction costs to the federal government.

CAP allocations available for importation into the Tucson AMA total 215,333 acre-feet per year, of which 138,920 acre-feet is allocated to the City of Tucson. More detail on CAP allocations in the Tucson AMA is available in Chapter 8. Planned large-scale importation of CAP water for direct delivery by Tucson Water was expected to reduce groundwater overdraft by the mid-1990's but was curtailed due to water quality problems experienced when CAP water was delivered directly to municipal users. The subsequent passage of the Water Consumer Protection Act in 1995 limits direct delivery and injection recharge of CAP unless stringent water quality criteria are met. As a result of curtailed CAP deliveries, groundwater overdraft has continued at high levels. The Water Consumer Protection Act is discussed in more detail in Chapter 8.

In 1995, 10,100 acre-feet of CAP was delivered in the AMA for use in recharge projects. In 1996 and 1997, CAP deliveries for direct and indirect recharge totaled 19,600 acre-feet and 33,300 acre-feet,

respectively. Recharge projects currently constitute the main use of CAP water within the Tucson AMA. Direct recharge allows water to infiltrate into underlying aquifer layers and can occur in basins, streambeds, or injection wells. Indirect recharge, through groundwater savings programs, allows existing groundwater to remain underground by physically replacing specific groundwater uses with CAP water. Recharge projects are administered statewide by the Department under the 1994 Underground Water Storage, Savings and Replenishment Program. Direct and indirect recharge projects that have received permits in the Tucson AMA are discussed in Chapter 8. Current permitted recharge capacity is not sufficient to utilize all of the available CAP water.

The ultimate use of the CAP allocations that are available for use in the Tucson AMA will significantly affect the AMA's ability to reach safe-yield. This use could include direct recharge, indirect recharge in cooperation with agriculture and mines, sufficient water quality treatment to make direct use acceptable to the public, or a combination of these. The future level of CAP utilization will depend on the success of recharge projects and studies on water quality treatment options.

2.8.2.2 Outside Entities Affecting CAP Use and Management

The Assured Water Supply Program (AWS Program), the Central Arizona Groundwater Replenishment District (CAGRD), the Central Arizona Water Conservation District (CAWCD), and the Arizona Water Banking Authority (AWBA) all encourage CAP use in the AMAs.

Under the 1995 Assured Water Supply Rules (AWS Rules), new residential development within the Tucson AMA must demonstrate that sufficient water supplies are available to meet proposed uses for 100 years, consistent with achieving the safe-yield goal. Because continued dependance on mined groundwater is not consistent with the safe-yield goal, renewable water use is required. This has been a major impetus behind the increasing use of CAP water in the AMA. The AWS Rules are described in more detail in Chapter 5.

Membership in the CAGRD is one way to demonstrate that sufficient water supplies are available to meet the requirements of the AWS Program. Under the AWS Program, the CAGRD acquires water supplies that it uses to replenish aquifers in the AMA from which groundwater has been pumped for use on member lands and in member service areas. To meet its replenishment obligations, the CAGRD can use several strategies including: (1) storing water at replenishment projects it constructs and operates on behalf of its members, (2) recharging water as a cooperator at a state demonstration project or other recharge facility, or (3) purchasing recharge credits that have previously been accrued by CAWCD or another entity.

The CAWCD establishes the pricing structure for CAP water and administers CAP contracts and subcontracts. The pricing structure created for CAP water by the CAWCD affects the volume of water other entities can afford to purchase for recharge or direct use. As part of its activities, the CAWCD operates state demonstration projects at which excess CAP water may be recharged for future withdrawal during canal outages, shortages on the Colorado River, or to meet CAGRD replenishment obligations.

Each year, the AWBA purchases a portion of Arizona's unused entitlement of Colorado River water and brings it into central Arizona via the CAP aqueduct for storage in AMAs. One of the objectives of the AWBA is to store water for recovery in years of shortage when Colorado River entitlements are reduced for the state of Arizona. This storage is necessary, in part, because Arizona may receive less than its full entitlement during years of shortage on the river. The AWBA, CAGRD, and CAWCD are addressed further in Chapter 8.

2.9 SUMMARY AND CONCLUSIONS

Water levels have declined substantially in the Tucson AMA since around 1940. The City of Tucson's Central Wellfield and the area of metal mine pumping in the Green Valley/Sahuarita area have experienced the greatest declines. Some recovery of groundwater levels has occurred since the mid-1980s along the Santa Cruz River and in northern Avra Valley due primarily to increased flood flows in the river and some localized decreases in groundwater pumping.

Net natural recharge of around 60,800 acre-feet replenishes the AMA's aquifers, but overdraft continues due to growing water demand. Groundwater in storage has decreased by an estimated 6 to 8 million acre-feet since around 1940. This decline has resulted in depletion of the upper layer of the aquifer and some land surface subsidence. The potential for additional subsidence exists as long as groundwater levels continue to decline. There have been some well closures due to groundwater contamination. The renewable supplies available for use in the Tucson AMA are effluent and CAP water. Use of both supplies will be necessary to offset groundwater pumping and achieve the AMA's safe-yield goal.

Hydrogeologic conditions in the AMA are deteriorating and make the need for achieving safe-yield increasingly urgent. Since the vulnerability to damage from continued water level declines varies from location to location in the AMA, it is necessary to focus water management efforts on addressing critical areas of the AMA as well as reaching an AMA-wide balance. It is essential that renewable supplies are put to use in the AMA in such a way that localized conditions are effectively addressed.

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