Arizona Department of Water Resources

A Groundwater Flow Model of the Sierra Vista Subwatershed of the Upper San Pedro Basin - Southeastern Arizona

By

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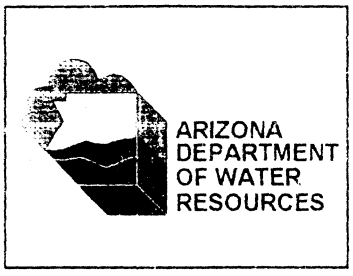

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Chapter 1: Introduction

The purpose of this report is to present the results of the Arizona Department of Water Resources Sierra Vista Subwatershed Upper San Pedro Basin groundwater flow model. The report outlines a brief description of the modeling approach, hydrogeologic framework, surface water system, the numerical model, steady-state and Transient-state model results, and sensitivity analysis. The modeling results indicate that the model provides a reasonably comprehensive simulation tool that can adequately represent the response of the Sierra Vista Subwatershed of the Upper San Pedro Basin to groundwater withdrawal stress.

Purpose and Goals of Model

The purpose of the Upper San Pedro modeling effort was to expand the model area from previous studies to incorporate new areas of concern. Also, to develop an analytical tool capable of providing answers to the questions listed below. The questions are oriented towards answering the effects on the San Pedro and Babocomari Rivers and their associated riparian areas and floodplain alluvial aquifers, as well as on the regional groundwater system. Departmental regulatory programs that may be supported by the model include the Water Adequacy Program and the adjudication of the Gila River watershed. Pertinent questions are:

1. What effect will various levels of municipal and non-agricultural growth in the basin at Sierra Vista, Fort Huachuca, and other areas have?

2. What will be the effects of retirement of agricultural lands or increased agricultural activity?

3. What will be the effects of municipal and agricultural conservation measures?

4. Will recharge projects be useful in mitigating undesired effects. If so, where would they be useful?

5. How will future development adjacent to the San Pedro River affect optimum base flow and seasonal variation in groundwater levels for the San Pedro riparian habitat? Seasonal variation in groundwater levels can not be answered with the model as it is currently developed.

6. What are the downstream effects of river flows of a fully restored riparian system?

7. What will be the effects of a long term drought?

8. What effect will increased Mexican groundwater use have?

The following are questions the Upper San Pedro model is not designed to answer;

1. Site-specific problems.

2. Seasonal behavior, as the model is currently developed.

3. Precise water level elevations and changes in elevation.

Description of Model Area

The Upper San Pedro study area includes Sierra Vista, Huachuca City, Fort Huachuca, Palominas, Hereford, Charleston, and Fairbank areas. The Upper San Pedro model grid is expanded further to the east towards the Mule Mountains in comparison to the Freethey (1982) model. Also, the Upper San Pedro model simulates mountain front recharge on the west side of the basin closer to the Huachuca Mountains in comparison to the Freethey (1982) model. The modeled area was divided into an orthogonal grid consisting of 72 rows by 67 columns. The total model domain is 22 miles in the east-west direction and 32 miles in the north-south direction. The model area includes a small northern portion of Sonora, Mexico beginning approximately 6 miles south of the International Boundary with Mexico and extending north to Fairbank (Figure 1). Model cell sizes range from 40 acres to 160 acres. The model area

is bounded on the west by the Huachuca Mountains, on the east by the Mule Mountains and Tombstone Hills, and to the south by the Sierra San Jose Mountains.

Previous Groundwater Modeling Investigations

The following discussion of previous groundwater modeling investigations is excerpted from Vionnet and Maddock (1992).

" The first groundwater flow model of the Upper San Pedro Basin was developed by the Arizona Water Commission (AWC, 1974). The purpose of the modeling study was to analyze water conditions at Fort Huachuca. The AWC model was a one layer model with a regular grid of one square mile model cells extending from Mexico to St. David. The aquifer was simulated as unconfined with recharge supplied by the mountain front. The San Pedro River was simulated with constant head cells.

Freethey (1982) developed a groundwater flow model for the Upper San Pedro Basin, the model area was from the Mexico border to Fairbank. A conceptual model of the hydrology of the Upper San Pedro Basin was developed by Freethey. The Freethey model utilized a finite difference model developed by the U.S. Geological Survey (Trescott, 1975). The aquifer system was simulated by two layers, one layer representing the upper unconfined, and the second layer representing the lower confined aquifer. The model grid was variable in size, with cell widths ranging from 0.6 mile to 1.0 mile.

Villnow (1986) modeled the Upper San Pedro Basin using a multi-objective groundwater management model as a primary decision making tool. The model was used to generate feasible alternative management policies using the multi objective constraint

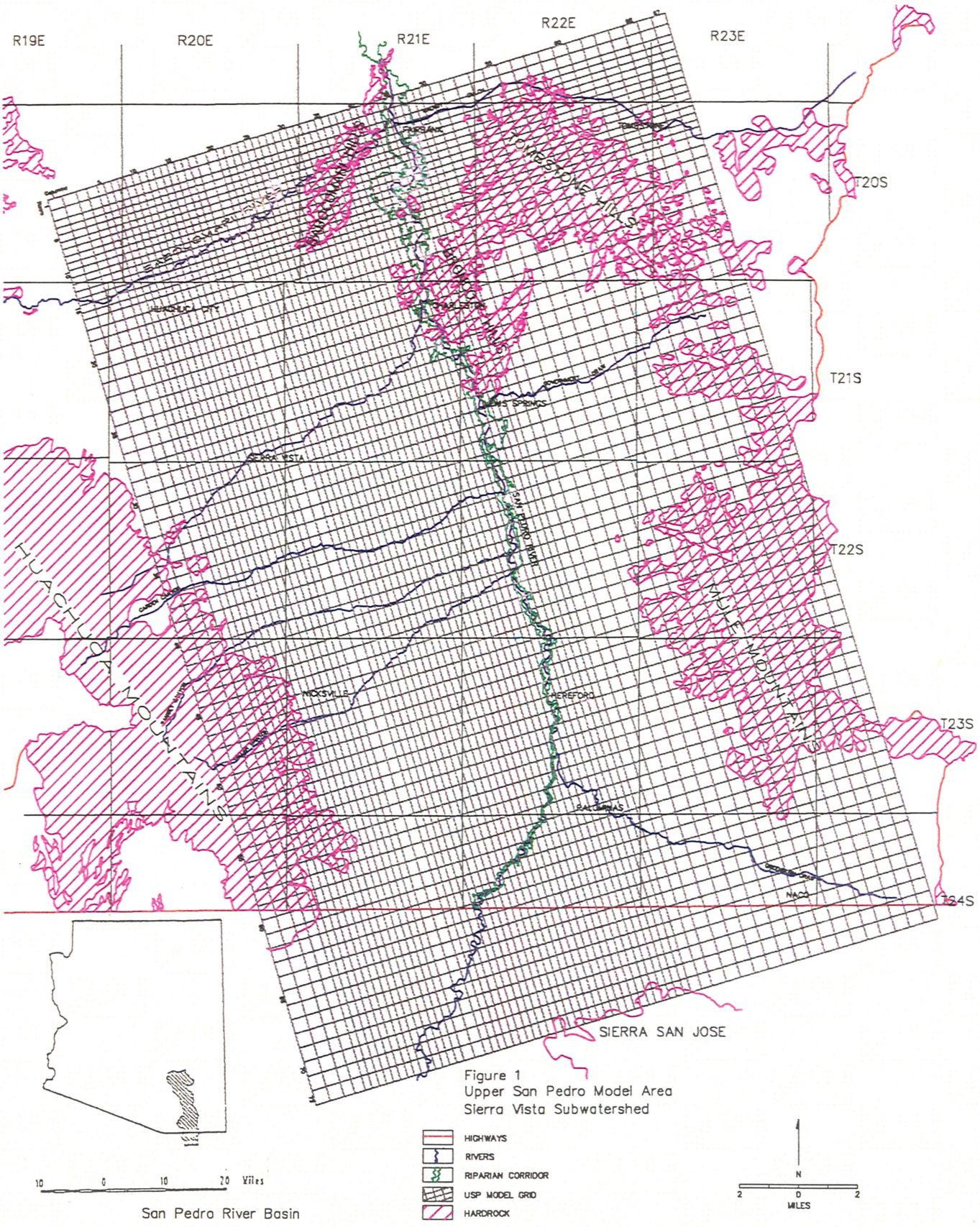


Figure 1
Upper San Pedro Model Area
Sierra Vista Subwatershed

technique. The hydrology of the basin was incorporated into the management models by means of the response function method. The response function method requires a linear groundwater model, the model area coincided with the Freethey model, the Villnow conceptual model did not.

In 1987, the U.S. Corps of Engineers, Los Angeles District completed a groundwater flow model of the Upper San Pedro Basin. The Freethey (1982) model was used as a base, the Corps analyzed the groundwater system to evaluate existing and future conditions around Fort Huachuca.

In 1988, Putman et al utilized the Freethey (1982) model and applied the Modular Three Dimensional Finite Difference Groundwater Flow Model (MODFLOW), developed by McDonald and Harbaugh (1984). The purpose of this modeling effort was to update and project future hydrologic conditions in the Sierra Vista area. Model input data was unchanged from that of Freethey with the exception of updated pumpage.

Rovey (1989) extended the modeled area to include the entire San Pedro Basin, from the Mexico border to Winkelman. The grid size ranges from 1 mile along streams to 4 miles in remote areas. Although the general characteristics of the Rovey model are published in draft reports, the model study is still in progress and final results are yet to be published."

In addition to the work summarized above, Vionnet and Maddock (1992) constructed a MODFLOW model of a portion of the Upper San Pedro Basin that incorporated a newly available stream-aquifer interaction package (Prudic, 1989), as well as new data on pumpage, aquifer properties from other interpretive studies.

Chapter 2: Hydrogeologic Framework

Geologic Setting

The Sierra Vista Subwatershed of the Upper San Pedro Basin is located within the Basin and Range physiographic province. The San Pedro River occupies a relatively broad structural trough or valley bounded by mountains on the east and west. The impermeable mountains form hard rock boundaries of the aquifers of the Upper San Pedro Basin. The Upper San Pedro Basin is bounded to the east by the Tombstone Hills and Mule Mountains. The Upper San Pedro Basin is bounded on the west by the Huachuca Mountains. Mountain crest elevations range from 5,000 feet to nearly 10,000 feet above mean sea level. The elevation of the San Pedro River is 4,275 feet above mean sea level at the Mexican border and about 3,800 feet above mean sea level near the USGS Tombstone stream gage.

The San Pedro River channel is slightly incised into the broad valley. Currently the river is in a state of widening, bar development, and accretion of floodplain (Jackson and others, 1987). The San Pedro River is perennial within much of the Upper San Pedro study area, most of the tributaries are ephemeral with the exception of certain reaches of the Babocomari River that are perennial.

Previous reports describe the non-bedrock aquifers of the Upper San Pedro Basin as follows. The bottom-most aquifer is a mid-Tertiary cemented conglomerate called the Pantano Formation (Brown and others, 1966) which may be present both in outcrop and below the ground surface only on the northeastern edge of the Huachuca Mountains. Above the Pantano lies the Basin Fill Unit, which forms the regional aquifer of the basin. The Basin Fill Unit is commonly divided into lower basin-fill and upper basin-fill. The lower basin-fill consists of

sand, gravel, silt, and clay layers and lenses, and possibly evaporites, and generally shows some degree of cementation. The upper basin-fill is predominantly sandy, silty clay, often intercalated with scattered sand, gravel, and boulder layers, but does not exhibit cementation. Overlying the basin-fill is the floodplain alluvium, which is limited to the floodplain of the San Pedro River and its major tributaries.

Geologic Units Defined for the Numerical Model

For modeling purposes the aquifers of the Upper San Pedro are divided into three hydrogeologic units with each unit corresponding to a model layer. The floodplain alluvium of the San Pedro and Babocomari Rivers are included in model layer 1. This unit is termed the Floodplain Alluvium Unit. Model layer 2 consists of upper basin-fill and uncemented portions of the lower basin-fill. This unit represents the regional aquifer of the basin and is called the Basin-Fill Unit. Model layer 3 is made up of the Pantano Formation and the cemented portions of the lower basin-fill. This unit is referred to as the Conglomerate Unit.

The thickness and lateral extent of the hydrogeologic units have been determined from structure contour maps prepared for the Upper San Pedro modeling project that indicate the top of the bedrock basement, the top of the overlying Conglomerate Unit, and the lateral extent of the Floodplain Alluvial Unit. The thickness of the Floodplain Alluvial Unit ranges from 10 to 65 feet and was determined from modified drillers' logs provided in Roeske and Werrell (1973). The thickness of model layer 2, the Basin-Fill Unit ranges from 12 to 1125 feet. The thickness of model layer 3, the Conglomerate Unit ranges from 15 to 1340 feet. The structure contour maps are based on approximately 400 drillers logs submitted to the Arizona

Department of Water Resources, logs in Brown and others (1966), and recent gravity anomaly data (Gettings and Houser, 1994). The geometry of the bedrock basement is illustrated in the structure contour map of Figure 2. Refer to Brown and others (1966), and Putman and others (1988) for a more detailed discussion of the geology of the basin. Figure 3 illustrates a general hydrogeologic cross-section (Drewes, 1980) of the southern Upper San Pedro basin indicating groundwater flow directions.

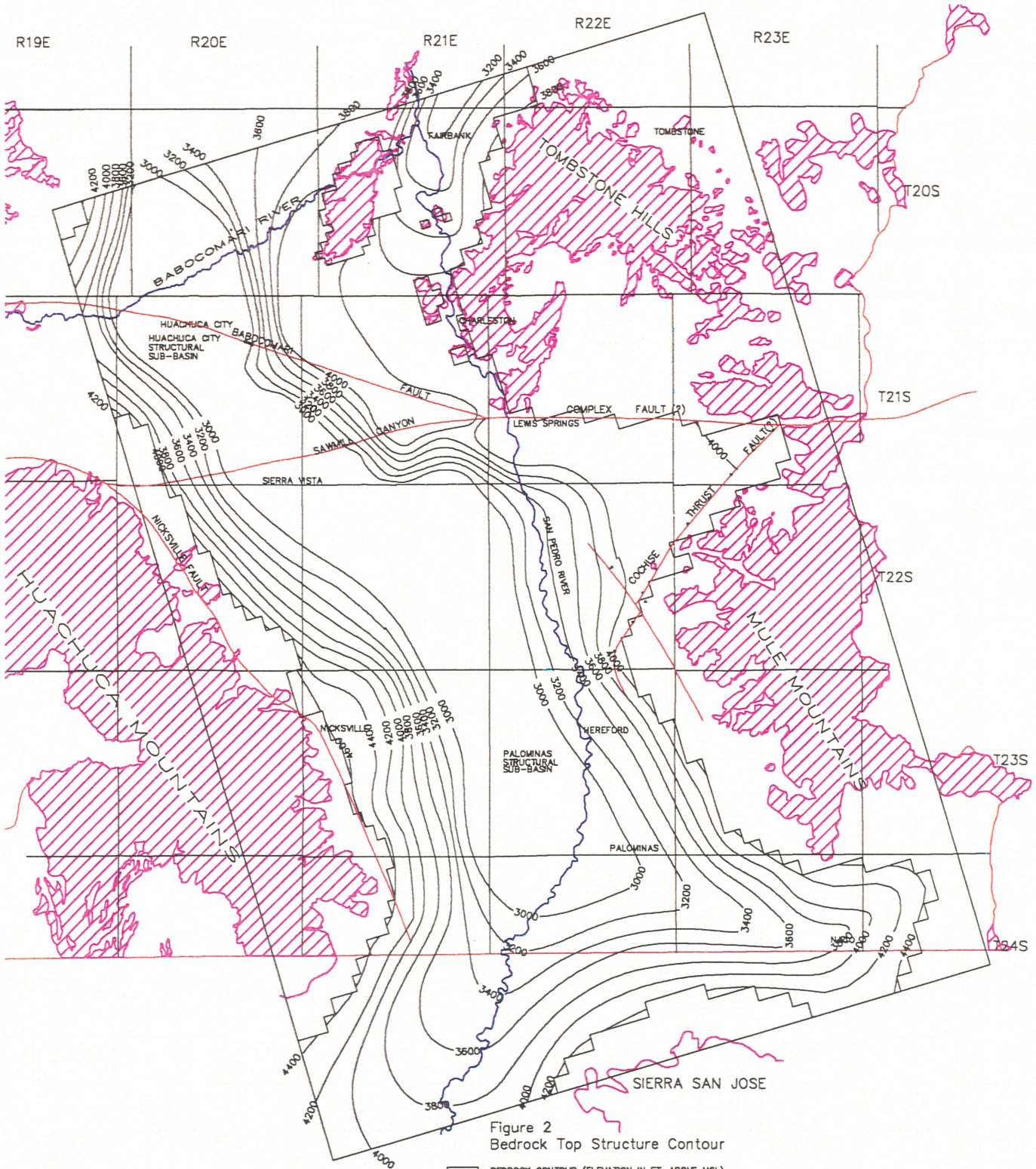


Figure 2
Bedrock Top Structure Contour

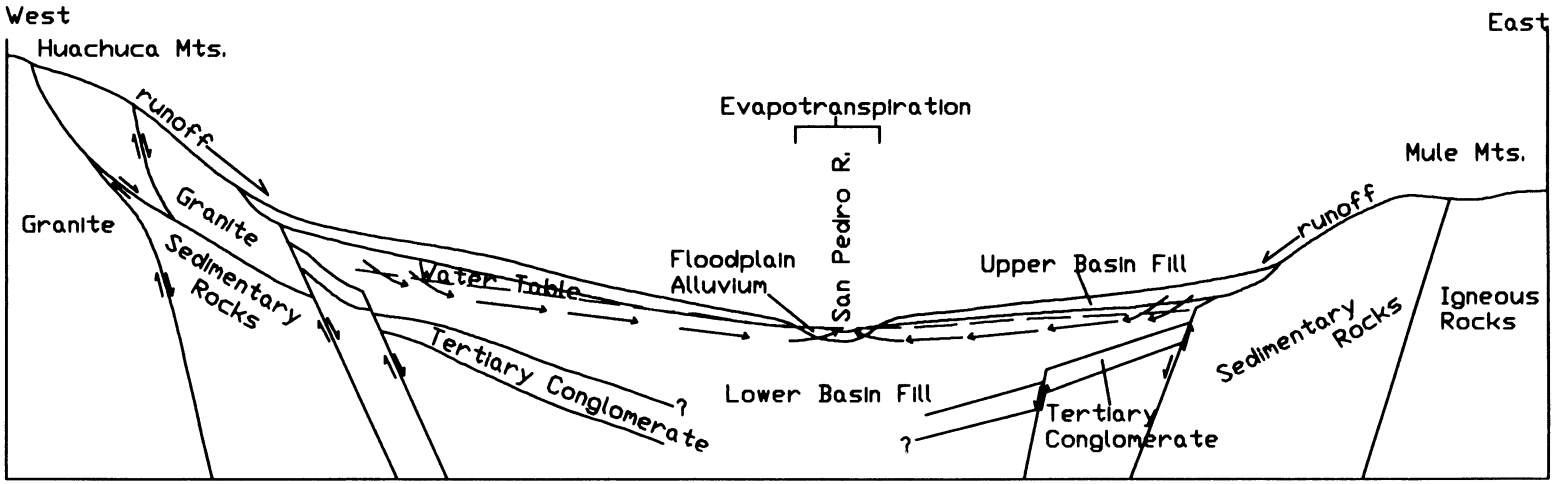


Figure 3: General Hydrogeologic Cross Section of the Southern USP Basin Modified from Drewes, 1980.

The Groundwater Flow System

Groundwater Movement

The Upper San Pedro basin consists of two main aquifers, the regional aquifer (Basin Fill Unit) and the floodplain alluvial aquifer. The regional aquifer is the primary source of groundwater in the Upper San Pedro and is generally unconfined except in the Palominas-Hereford area. The regional aquifer is made up of two units, the upper basin fill and lower basin fill. Artesian conditions occur in the regional aquifer in the Palominas-Hereford area with a head approximately 20 feet higher in the confined regional aquifer than in the overlying floodplain alluvial aquifer (Roeske and Werrell, 1973). The confining beds consist of silt and clay lenses of limited areal extent.

The regional aquifer is recharged primarily along the mountain fronts to the east and west, some recharge also occurs as streamflow infiltration first recharging the Floodplain Alluvial Unit then percolating to the regional aquifer. The Upper San Pedro basin also receives approximately 3,000 acre-feet/year as underflow across the International Boundary from Mexico (Harshbarger and Associates, 1974 estimate 3,500 acre-feet/year underflow).

The rate and direction of groundwater movement in the regional aquifer is controlled by the hydraulic gradient and permeability of the aquifer. Groundwater moves from the mountain front recharge areas to the San Pedro River where it may be discharged along gaining reaches of streams or by evapotranspiration. Groundwater flow lines are predominantly perpendicular to the San Pedro River on the west side. Some hardrock outcrops alter this general pattern, an example being the Babocomari Hills that acts as a hydrogeologic dam causing the Babocomari River to gain groundwater. Another example being the hardrock

outcrops near Charleston which have the same effect forcing groundwater eventually to the San Pedro River channel.

More recent unconsolidated alluvium of silt, sand, and gravel comprise the floodplain alluvial aquifer of the San Pedro River and its tributaries. The Floodplain Alluvial Unit ranges in thickness from 40 to 150 feet (Roeske and Werrell, 1973).

The Floodplain Alluvial Unit receives groundwater from the surrounding Basin Fill Unit, from underflow from Mexico, recharge from agriculture, and infiltration of storm runoff.

The Floodplain Alluvial Unit contains the contact area between the surface water and groundwater systems. It is also an important source of groundwater for irrigation wells along the San Pedro River and also supports the phreatophytes within the riparian area.

Pre-Development Groundwater System

The pre-development hydrologic system of the Upper San Pedro has been studied to serve as the time-frame for the steady-state calibration of the groundwater flow model. 1940 was chosen as the steady-state time frame on the basis of limited groundwater development and availability of water level and stream gage data. The period prior to 1940 was pre-groundwater development, but was not a true steady-state time. The San Pedro River had recently finished a down-cutting episode (Hereford, 1993) and the groundwater system was still equilibrating to a new stream level. In addition, the riparian community was adjusting to changed streamflow regimes. Insufficient data exist however to quantify hydrologic conditions for earlier periods of time. For this reason 1940 was chosen in this report and others (Freethey, 1982, Vionnet and Maddock, 1992) as representative of steady-state conditions.

In the pre-development groundwater system, discharge from the groundwater system is equal to recharge and there is no change in groundwater storage. The various components of groundwater inflow and outflow have been identified and analyzed for the pre-development hydrologic system (circa 1940). The components include groundwater underflow, perennial and ephemeral stream channel infiltration, mountain front recharge, streamflow (baseflow), and evapotranspiration. A pre-development groundwater budget developed for the Upper San Pedro study area is presented in Table 1.

Table 1
Conceptual Pre-Development Groundwater Budget
Upper San Pedro Study Area (1 Year)

INFLOW	**Conceptual Budget (ac-ft/yr)**
Mountain Front Recharge	15,000
Underflow from Mexico	3,000
Greenbush Draw ephemeral recharge	1,000
TOTAL INFLOW	19,000
OUTFLOW	
Underflow @ Fairbank	440
Evapotranspiration	8,020
Net San Pedro and Babocomari R. Groundwater Baseflow Discharge	9,540
Wells (Arizona Water Company Bisbee)	1,000
TOTAL OUTFLOW	19,000
IN - OUT	0

Also, for comparison purposes, Table 2 converted to acre-feet per year from Vionnet and Maddock (Table 4-2, 1992) is presented comparing the conceptual model and the numerical models steady-state (circa 1940).

Table 2

Comparison Between Recharge & Discharge Values from the Conceptual Model & the Numerical Models Steady-state

(Data Source: Freethey 1982)

INFLOW	CONCEPTUAL (ac-ft/yr)	Vionnet & Maddock MODEL ESTIMATES (ac-ft/yr)
Mountain Front Recharge	9,629 to 11,004	12,546
Underflow from Mexico	724 to 3,475	3,728
San Pedro River Losses	796 to 2,823	1,086
Babocomari River Losses	0 to 1,448	825
	Total In "low" = 11,149	**Total Inflow = 18,185**
	Total In "high" = 17,303	
OUTFLOW		
San Pedro River Gains	1,882 to 9,267	7,522
Babocomari River Gains	0 to 5,068	2,396
Evapotranspiration	3,620 to 12,307	7,898
Underflow @ Fairbank	0	651
Underflow @ NE Corner	--	282
	Total Out "low" = 5,502	**Total Outflow = 18,099**
	Total Out "high" = 26,642	

Post-Development Groundwater Flow System

The post-development groundwater flow system of the Upper San Pedro (1941 to 1990) has been studied to serve as the time-frame for the Transient groundwater flow model. 1990 was selected as the end of the Transient period due to the availability of wide-spread water level data and water use data (the Arizona Department of Water Resources Basic Data Section conducted a basin- wide water level survey in this year). The various components of groundwater inflow and outflow have been identified and analyzed for the post-development groundwater flow system. The components include underflow, mountain front recharge, agricultural recharge, pumpage, and evapotranspiration. A conceptual groundwater budget for the Upper San Pedro study area Transient period (1941 to 1990) is presented in Table 3.

Table 3

Conceptual Groundwater Budget -Upper San Pedro Study Area Transient State (1941 to 1990)

INFLOW	Conceptual Budget Transient conditions (ac-ft)	Conceptual Budget Steady-state conditions (ac-ft)
Mountain Front Recharge[1]	950,000	950,000
TOTAL INFLOW	950,000	950,000
OUTFLOW		
Underflow @ Fairbank	22,000	22,000
Pumpage	449,700	50,000
Evapotranspiration	353,750	401,000
Net San Pedro & Babocomari R. Groundwater Baseflow Discharge	314,580	477,000
TOTAL OUTFLOW	1,140,030	950,000
IN - OUT	-190,030	0

[1] Mountain Front Recharge includes 3,000 ac-ft/yr groundwater underflow in from Mexico. Also includes 1,000 ac-ft/yr ephemeral stream recharge along Greenbush Draw.

Hydraulic Characteristics

Horizontal Hydraulic Conductivity

Initial transmissivity values were developed from flow net analysis of the 1940 steady-state water level map and the amount of groundwater moving through the system as determined from the steady-state water budget. Hydraulic conductivity values for each model cell and layer were then calculated based on 1940 saturated thicknesses. The steady-state calibration served to refine the original estimates of hydraulic conductivity. Hydraulic conductivity values for all layers developed in steady-state modeling were incorporated into the Transient model. The final calibrated hydraulic conductivity values for Layer 1 are 40 ft/d, Layer 2 values range from 0.1 ft/d to 20 ft/d, and Layer 3 values range from 0.2 ft/d to 20 ft/d.

Vertical Leakance

The vertical leakance between Layers 1 and 2, and between Layers 2 and 3 was modeled using MODFLOW's VCONT option. MODFLOW requires VCONT to be calculated independently, and input as an array in the Block Centered Flow (BCF) package. VCONT between Layers 1 and 2 was calculated by the following equation:

$$VCONT_{1-2} = \frac{1}{\frac{(V_1)/2}{K_{v1}} + \frac{(V_2)/2}{K_{v2}}}$$

Where:

$VCONT_{1-2}$ = Vertical leakance between Layers 1 and 2 (1/day)
V_1 = Saturated thickness of Layer 1 (feet)
V_2 = Saturated thickness of Layer 2 (feet)
K_{v1} = Vertical hydraulic conductivity of Layer 1 (feet/day)
K_{v2} = Vertical hydraulic conductivity of Layer 2 (feet/day)

The ratio of horizontal to vertical hydraulic conductivity used to calculate VCONT between Layers 1 and 2, and between Layers 2 and 3 is given below.

Layer 1 Horizontal: Vertical hydraulic conductivity ratio = 10:1

Layer 2 Horizontal: Vertical hydraulic conductivity ratio = 100:1

Layer 3 Horizontal: Vertical hydraulic conductivity ratio = 40:1

Storage Coefficients and Specific Yield

Values of storage coefficient and specific yield for the Transient simulations were obtained from published data. Estimates of specific yield and storage coefficient were input as constant values to the model. The constant values of specific yield for the Floodplain Alluvial Unit (Layer 1), Basin Fill Unit (Layer 2), and Conglomerate Unit (Layer 3) were 0.15, 0.08, and 0.08 respectively. The constant values of storage coefficients for the Basin Fill Unit and Conglomerate Unit were 10^{-5}.

Recharge Along Mountain Fronts

Mountain front recharge is the surface water flow that infiltrates into the sediments of the basin-fill during runoff eventually reaching the water table. Mountain front recharge is controlled primarily by the amount of precipitation occurring in the mountain areas. The total amount of mountain front recharge for the Upper San Pedro study area was determined from steady-state (circa 1940) baseflow analysis of the San Pedro and Babocomari Rivers. It was assumed that all mountain front recharge eventually is discharged to the San Pedro and Babocomari Rivers and thus the baseflow rates of the San Pedro River in the winter of each

year are reflective of the rate of groundwater flux from the mountain front areas to the rivers. Mountain front recharge was estimated as about 19,000 acre-feet/year. This figure includes 3,000 acre-feet/year underflow from Mexico, and 1,000 acre-feet/year ephemeral stream recharge along Greenbush Draw. The baseflow analysis is discussed in the Surface Water Section of this report. The total mountain front recharge was then distributed among the Huachuca, Sierra San Jose, Mule Mountains, and Tombstone Hills based on the differences in annual precipitation for the different areas. The annual precipitation was weighted by areal coverage over bedrock areas on the east and west sides of the basin, this resulted in approximately 2/3 of the mountain front recharge occurring on the west side of the Upper San Pedro basin and 1/3 on the east side. The recharge volumes simulated in steady-state model simulations were also maintained in the Transient model simulation.

Discharge

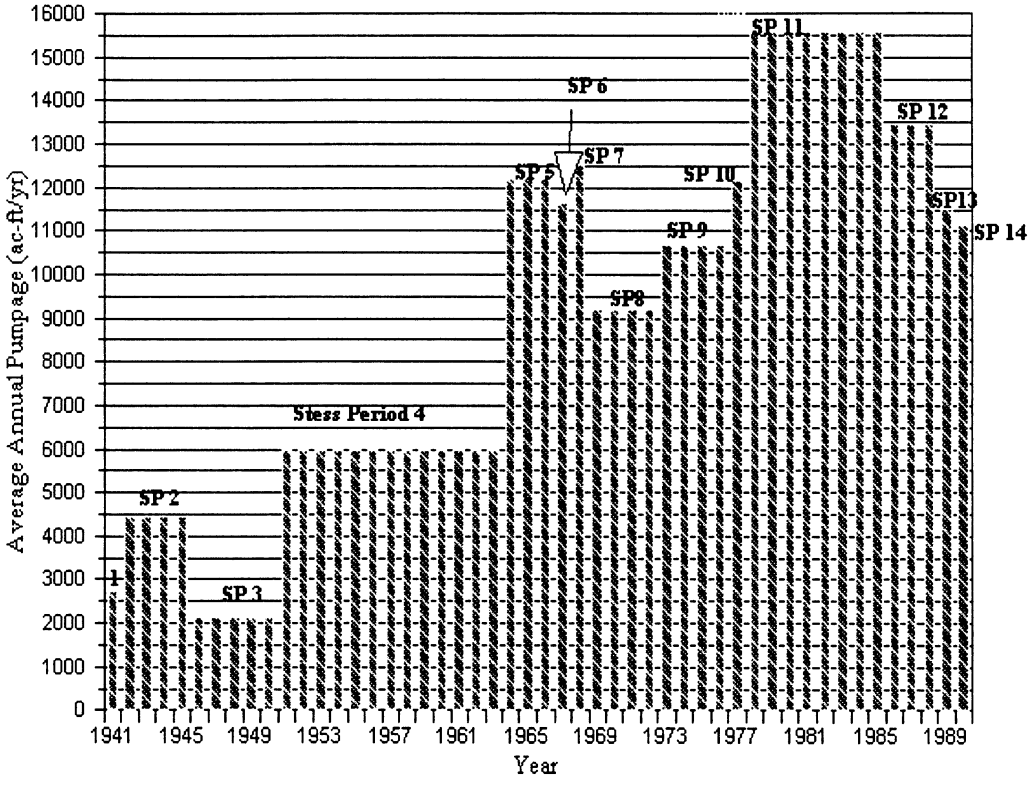
Pumpage

The Upper San Pedro pumpage databases and MODFLOW well package were developed as follows. Groundwater pumpage is simulated in the Upper San Pedro Transient model for the period 1941 through 1990 (stress periods 1 through 14). Historically, the major categories of groundwater use have included agricultural, military, municipal, and industrial pumpage. In recent years, domestic pumpage has also become a significant source of groundwater withdrawal as the number of registered domestic wells has increased. The total annual pumpage volume increased from about 2,750 acre-feet per year in stress period 1 (1941) to about 11,150 acre-feet per year in stress period 14 (1990). Total annual pumpage peaked

during the period 1978-1985 (stress period 11) at a level of about 15,600 acre-feet per year. The high pumpage reflected the increase in irrigated acreage which occurred during that period. Annual pumpage totals per model stress period are presented in Figure 4. The total cumulative pumpage from 1941 through 1990 was about 450,000 acre-feet.

Pumpage data for the period 1941 through 1977 (stress periods 1-10) were derived from the pumpage data compiled by Freethey (1982). Pumpage data for the period 1978-1986 (stress periods 11 and 12) were derived from Putman and others, Arizona Department of Water Resources, 1988. Pumpage for 1987-1988 was from the Arizona Department of Water Resources Hydrographic Survey Report (HSR) for the San Pedro River Watershed. Modifications were made to the 1978-1988 agricultural pumpage data listed in the HSR-MODFLOW well package (Freethey, 1982 MODFLOW well package updated to include 1978 to 1988 stresses) to account for the return of excess applied irrigation water to the groundwater system. The modifications consisted of reducing the original HSR agricultural pumpage totals by 30 percent. The reduction was consistent with the 30 percent reduction of agricultural pumpage made by Freethey (1982, p.18).

Figure 4
Annual Pumpage in USP Area: 1941 - 90



Pumpage data for 1989 and 1990 (stress periods 13 and 14) for municipal and industrial groundwater users were obtained from records from the Arizona Corporation Commission (ACC). Military pumpage data was obtained from Fort Huachuca. All 1989 and 1990 municipal, industrial, and military pumpage was assigned on a well-specific basis, and located in the Upper San Pedro model cells which corresponded to the specific well locations.

Agricultural pumpage was estimated for 1989 and 1990 based on the distribution of irrigated land determined from examination of June 1993 Landsat imagery (Earth Satellite Info, 1993). Although some agricultural acreage was retired between 1989-1990 and 1993, it was assumed that the 1993 distribution was generally representative of the earlier period. Based on the 1993 Landsat image analysis it was estimated that approximately 540 acres were cropped along the San Pedro River in the Palominas to Hereford area. Assuming an average annual consumptive use of 3.0 acre-feet per acre (a net figure that considers irrigation inefficiency and recharge of excess irrigation water), the total annual agricultural pumpage for 1989 and 1990 was estimated to be about 1,600 acre-feet per year. The agricultural pumpage was distributed to the Upper San Pedro model cells in proportion to the estimated irrigated acreage per cell.

Domestic pumpage was estimated and simulated in the model for all 14 stress periods. The average domestic pumpage per stress period was estimated from annual counts of registered domestic wells listed in the Arizona Department of Water Resources 55-Wells Registry Database. It was assumed that each domestic well pumped at a rate of 0.5 acre-feet per year. The average domestic pumpage increased from less than 10 acre-feet per year in stress period 1 (1941) to more than 650 acre-feet per year in stress period 14 (1990).

Translation of 1941-1988 pumpage data from the Freethey-HSR model grid to the Upper San Pedro model grid was accomplished using a model grid translation program which converted Freethey-HSR model cell locations to the corresponding Upper San Pedro model cells. In most areas, the Freethey-HSR model cells were larger than the Upper San Pedro model cells, therefore the Freethey-HSR cell pumpage totals were apportioned uniformly over the corresponding Upper San Pedro model cells.

Pumpage was vertically distributed to all three model layers. In the floodplain area of the San Pedro and Babocomari Rivers (where model Layer 1 exists) pumpage was apportioned between model Layers 1 and 2 on a 50:50 percent basis, all return flows were applied to Layer 1. It should be noted that larger vertical pumping percentages were initially assigned to model Layer 1. However, preliminary Transient model simulations indicated that the larger Layer 1 pumpage percentages caused excessive drawdowns and de-watering of Layer 1 cells. In areas away from the floodplain pumpage was assigned to the uppermost active model layer (either Layer 2 or 3). In most areas this resulted in assigning pumpage entirely to Layer 2, except near the mountain fronts where model Layer 2 was in some locations unsaturated.

Evapotranspiration

The riparian corridor of the Upper San Pedro Basin largely owned by the Bureau of Land Management, includes such vegetation species as the cottonwood, Gooding Willow, Seep Willow, mesquite, and various grasses. Many reaches have been invaded by Salt Cedar especially in the northern part of the Bureau of Land Management property (Vionnet and Maddock, 1992).

Evapotranspiration estimates were made as part of the baseflow analysis for this study, and are contained in Table 4 in the section entitled Surface Water System. The evapotranspiration estimates made for this report are estimates of the amount of groundwater discharge to the San Pedro and Babocomari Rivers that is intercepted by riparian use, by agricultural pumping, and to a lesser extent by other pumpage in the basin. Because the estimate includes only the groundwater-supplied portion of evapotranspiration, the values in Table 4 are less than would be calculated using a method that estimates the total use by riparian vegetation. The evapotranspiration rates outlined in Table 4 were the rates used for the Transient model, 1941 to 1990.

Seepage to Rivers

The Floodplain Alluvial Unit receives both surface water and groundwater. The regional aquifer supplies groundwater to the floodplain aquifer through lateral and upward migration. The floodplain aquifer also receives groundwater through upward migration from the confined portion of the regional aquifer in the Palominas-Hereford area. Groundwater reaching the floodplain aquifer supplies both evapotranspiration of phreatophytes and the baseflow in the stream channels. During the summer when phreatophytes are active, or in areas of groundwater pumpage the water table may drop sufficiently to a point at which the stream loses water to the floodplain aquifer and there is no flow in river.

Streamflow is represented in the model in the Streamflow-Routing package (Prudic, 1989). In the Streamflow-Routing package streams are represented by segments and each segment is divided into reaches. The San Pedro River contains 3 segments with a total of 113

reaches, Government Draw contains 1 segment and 1 reach, the Babocomari River contains 1 segment and 28 reaches. The Babocomari River joins the San Pedro River at its last segment. All of the river reaches of the discretized river system are illustrated on Figure 13. The San Pedro River was modeled with a constant width of 25 feet, the Babocomari River was modeled with a constant width of 3 feet. The San Pedro River, Babocomari River, and Government Draw adopted a Manning's roughness coefficient of 0.022.

Subsurface Outflow

Groundwater outflow occurs at a small portion of the northern boundary of the Upper San Pedro model within the San Pedro River valley where groundwater in the Floodplain Alluvium moves north across the model boundary. This value was approximately 440 acre-feet/year based on steady-state modeling results. The remainder of the northern boundary parallels flow lines and no groundwater outflow is assumed.

Groundwater Pumpage

In pre-development or steady-state conditions (circa 1940) the hydrologic system of the Upper San Pedro basin was assumed to be in balance. No change in storage is occurring and the total recharge was equal to the total discharge of the system. Since the 1940's the Upper San Pedro basin has grown to a current population of approximately 51,400 people (1990), and the increased population has led to increased development of groundwater.

There are many water users in the Upper San Pedro basin; however, the primary water users are the City of Sierra Vista and Fort Huachuca with a 1990 combined pumpage of 8,000

acre-feet/year for municipal, industrial, and military uses. The Palominas-Hereford agricultural area in the southern part of the model area, had an annual pumpage of 1,600 acre-feet/year in 1990. Other wells outside of these two areas supply water for domestic and livestock uses. Groundwater pumpage in the Sierra Vista/Fort Huachuca area since the 1940's has caused a cone of depression with water level declines of 20 to 90 feet. The Sierra Vista/Fort Huachuca cone of depression trends northwest to southwest, paralleling the Huachuca Mountains. The pumping center captures water that would have reached the San Pedro River in pre-development conditions. There is concern that without mitigation, present groundwater withdrawals will diminish flows in the San Pedro River.

A second, smaller cone of depression exists along the Babocomari River in the area of Huachuca City (Harshbarger and Associates, 1974).

Chapter 3: Surface Water System

Baseflow Analysis

In order to obtain an estimate of the annual contribution of mountain front recharge to the system an analysis of base flow was conducted to determine the net gain in streamflow during months when the riparian vegetation and agricultural pumpage was not intercepting groundwater before it could enter the stream. In addition, another means of estimating the quantities of groundwater consumed by riparian vegetation and agricultural uses near the river can be developed by comparing these baseflows with baseflows from other months when these consumptive uses are intercepting the groundwater before it can reach the river.

Base flows are defined as the groundwater discharge to a stream. Base flow estimates were used to develop a conceptual water budget (circa 1941 to 1990), calculate mountain front recharge, evapotranspiration estimates, for development of initial transmissivity estimates, and for calibration of the streamflow module of MODFLOW. In order to determine base flow it was necessary to do a base flow separation to find that portion of total stream flow contributed by groundwater discharge. That portion of stream flow due to runoff following precipitation events is not part of the groundwater system and therefore was eliminated from groundwater modeling considerations.

Procedure

USGS daily mean streamflow at the Palominas, Charleston, and Tombstone gages were examined and streamflow hydrographs were plotted for each gage for various time periods. Generally the intervals 1935-40, 1951-56, 1958-63, 1968-73, 1976-81, 1981-86, and 1986-91

were used, based on consideration of periods of record and available water level maps.

Base flows were determined by visually examining monthly hydrographs of streamflow and estimating the sustained streamflow at the gage. For summer months this was more difficult to do and sustained flow levels were determined using shorter stable periods of flow or by using preceding and following months' data. Base flow in January and December, when natural and cultural uses of water were minimal, was assumed to be equal to the amount of regional groundwater discharge to the river upstream of the gage. The amount of base flow in the river decreased in the summer and increased again in the fall. The decrease was assumed to be due to increased riparian and agricultural uses and increased evaporative losses, and thus the difference between winter base flows and spring, summer, and fall baseflows provided an estimate of the use of groundwater by riparian vegetation, agricultural use, and evaporation. One consequence of this method is that the near-stream pumpage was slightly over-estimated, since there were separate estimates made for agricultural pumpage in the model. The result of this over-estimate is that the model may have over-estimated the effects of groundwater pumping on river inflows and outflows.

The estimates of riparian, agricultural and evaporative losses may be smaller than prior estimates because these estimates only include the portion of riparian, agricultural and evaporative uses derived from the groundwater discharge to the San Pedro River, and not the additional amount of use supplied by flood flows, tributary inflows, and rainfall.

Steady-State (Circa 1940)

The analysis of the data for steady-state conditions is discussed in detail below as an example of the methodology used. Data from USGS stream gages at Palominas and Charleston were

examined to determine groundwater discharge to the San Pedro River and to determine the use of water by riparian vegetation, agricultural pumping, and evaporation. Mean daily flows were plotted by month for the period 1935-1940 for each gage and examined to determine the base stream flow in each month. Although the mean daily flows are subject to scatter, reflecting the high degree of natural variability of streamflow in southern Arizona, some patterns of flow emerge which allow analysis.

Model Boundary-Palominas Reach

Base flow at Palominas in January and December, when natural and cultural uses of water were minimal, was about 7.5 cfs or about 5,400 acre-feet per year when this rate of flow is carried for an entire year. This base flow was assumed to be equal to the amount of regional groundwater discharge to the river upstream of the Palominas gage. The amount of base flow in the river decreased in the summer and increased again in the fall. The decrease was assumed to be due to a combination of riparian and agricultural uses and to evaporative losses. These losses totaled about 2,100 acre-feet per year (2.9 cfs), leaving about 3,300 acre-feet of base flow in the San Pedro River to enter the Palominas-Charleston reach. See Figures 5 and 6 for examples of baseflow hydrographs.

Palominas-Charleston Reach

The reach of the San Pedro River between Palominas and Charleston received 3,300 acre-feet of base streamflow from the Model Boundary-Palominas reach and also showed large gains in flow due to groundwater discharge to the river. Streamflow records show a gain of

about 13.5 cfs in the winter, or an annualized gain due to groundwater discharge of 9,800 acre-feet per year. The base flow data again show a seasonal pattern of decrease and increase due to riparian and agricultural use and to evaporation. The losses totaled an average of 3,600 acre feet, leaving about 9,500 acre-feet of base flow leaving this reach.

Charleston-Tombstone Reach

The Charleston-Tombstone reach received 9,500 acre-feet of base flow at the Charleston gage as well as about 2,600 acre-feet of groundwater discharge to the San Pedro and Babocomari Rivers. This estimate of groundwater discharge is based on stream gage data from 1967-86, for which similar estimates of groundwater discharge and base flow abstractions were made, and on limited data in Schwartzman (1990). It was assumed due to the lack of data for this time period, that available data for 1967-87 was representative of steady state times. The isolated nature of this reach and the geologic features which borders the area help support the assumption that there was no significant change in groundwater discharge between 1940 and the 1970's.

Groundwater discharge directly to the San Pedro River in the Charleston-Tombstone reach was estimated at 600 acre-feet per year, and occurred as flux through the gap between the Bronco Hills and the Babocomari Hills (Figure 1). Groundwater discharge to the Babocomari River was estimated at 2,000 acre-feet per year, based on data in Schwartzman (1990). Evapotranspiration losses on the Babocomari River above the canyon were estimated at 600 acre feet, leaving the net discharge of the Babocomari River to the San Pedro River at about 1,400 acre-feet per year. Riparian uses and evaporative losses totaled about 2,800 acre-feet from the riparian corridor of the San Pedro River, and were calculated as the residual.

There is no farming activity in this reach. About 9,200 acre-feet of base flow was estimated to leave this reach of the river and the model area. An additional 300 acre-feet of groundwater underflow associated with the San Pedro River was estimated to leave the model area, for a total outflow of 9,500 acre-feet. Figure 7 shows a schematic water budget for steady-state times.

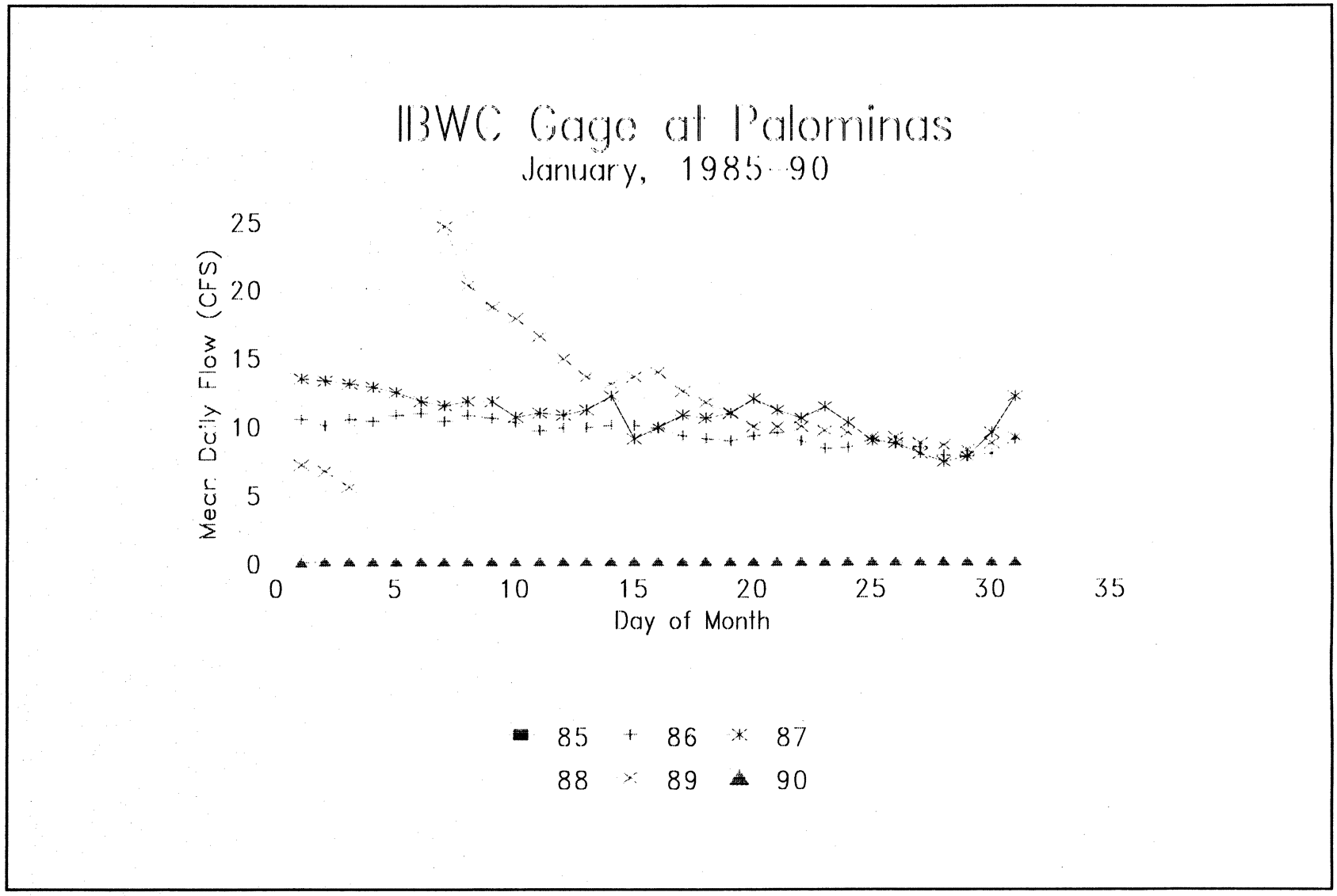


Figure 5 Daily Flows, Palominas Gage, January 1985-90

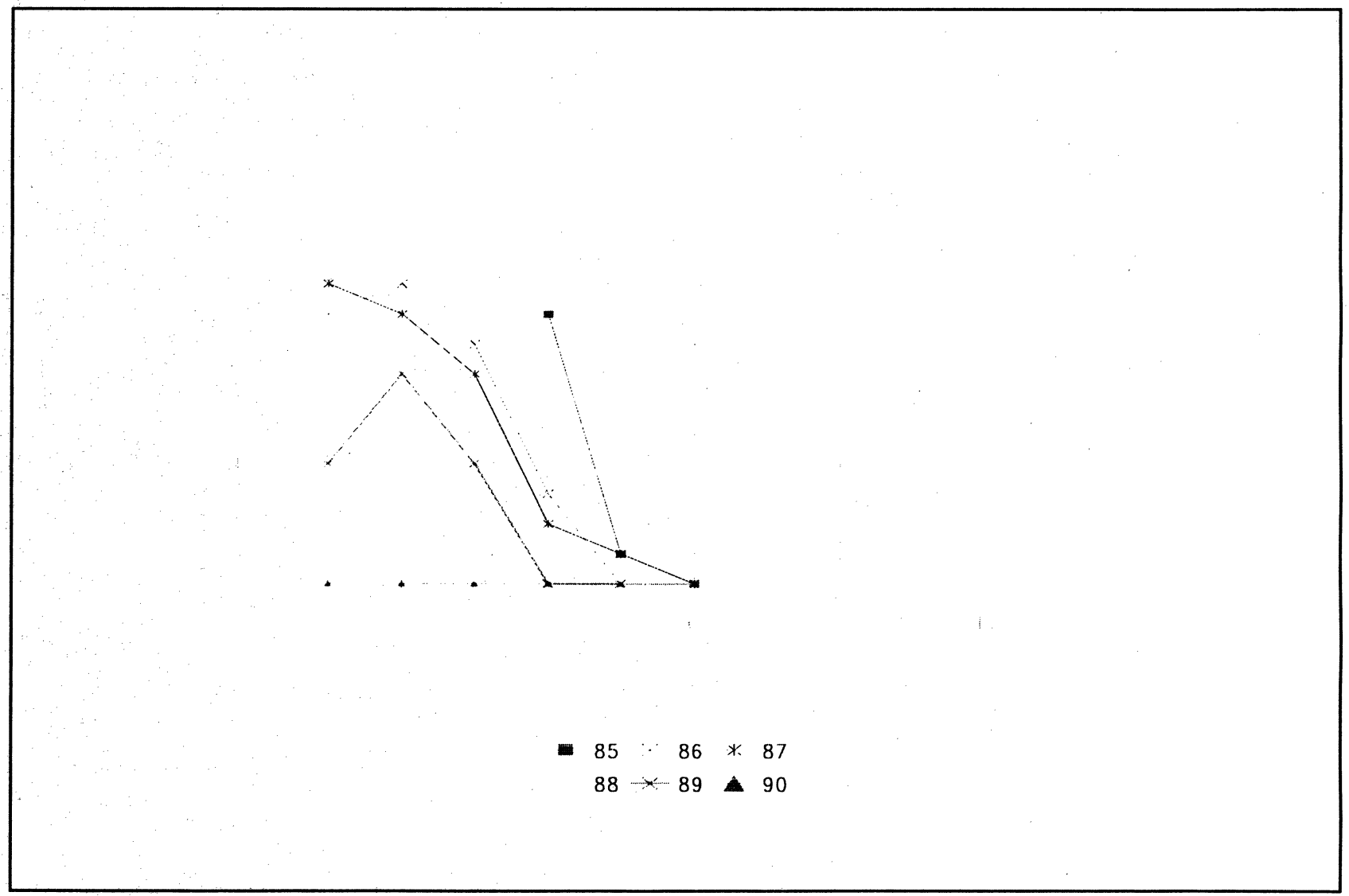


Figure 6 Palominas Seasonal Baseflow Trends, 1985-90

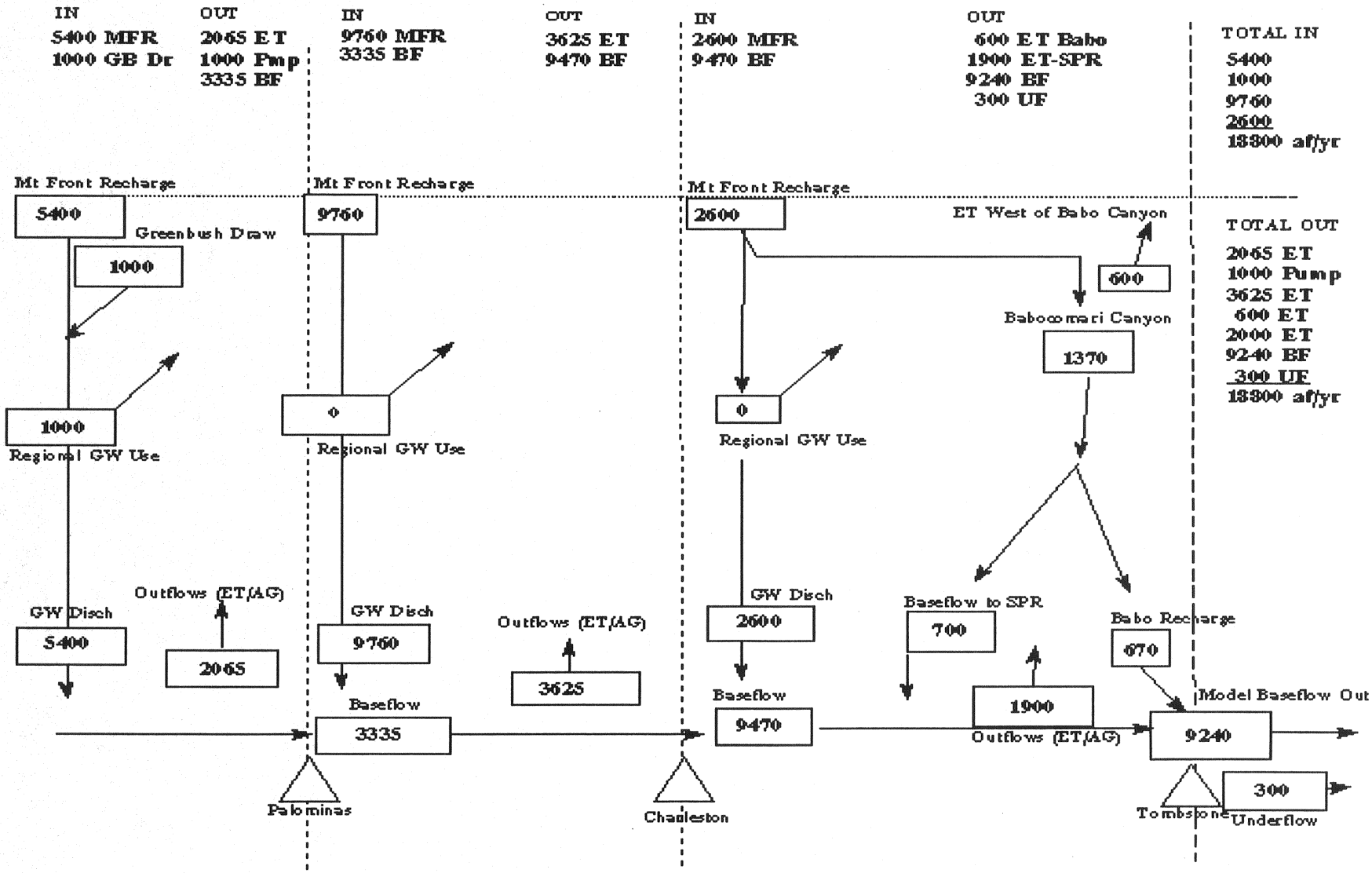


Figure 7: Upper San Pedro Schematic Steady-state Water Budget

Transient Period (1940-1990)

Streamflow data were analyzed in a similar fashion for the period 1940-1990 to encompass the period of time that the groundwater resources were being developed in the basin. Results are discussed in the next section.

Analysis of Results

The baseflow estimates discussed above are subject to scatter and uncertainty, but do show some patterns that help understand the behavior of the San Pedro River and the associated groundwater system over the last 50 years. The major change has been the decrease in groundwater discharge to the river between the 1935-40 period and the 1951-56 period. The baseflows at Palominas and Charleston changed greatly in a short period of time, presumably in response to an increase in agricultural activity in the upper part of the basin near the Palominas-Hereford area. Table 4 summarizes the results of the baseflow analysis. This analysis was also used to estimate the volumes of groundwater discharge intercepted by agriculture, riparian consumption, and other users.

Winter baseflows at Palominas, considered to be indicative of maximum groundwater discharge rates to the San Pedro River, decreased from about 7.5 cfs (annualized to about 5,400 AF per year) in steady state times (1935-40) to about 3.5 cfs (2,500 AF per year) for the 1951-56 period. Total average annual stream flows for these two periods remained relatively unchanged. The amount of baseflow at Palominas gradually declined through the 1970's, but appears to have increased in the 1980's. At Charleston, winter base flows decreased from about 21 cfs (15,000 AF per year) to about 14 cfs (10,000 AF per year) for the same period. At Charleston the winter

baseflow of the river has been more stable since the 1950's, at around 13-15 cfs (9,400 to 10,800 acre-feet per year). At Tombstone the winter baseflow for the 1967-86 period shows a consistent level of 14-16 cfs.

Use of baseflow by riparian vegetation and by agriculture has also decreased, but not at such a high rate. Figures 8-11 show these use rates for the area upstream of Palominas, the area between Palominas and Charleston, and the area between Charleston and Tombstone. Volumes of agricultural, riparian, and other uses generally declined through the 1970's and may have increased in the 1980's.

Table 4. Summary of Analysis of Baseflow Gains & Losses (Ac-Ft/Yr.[1])

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	
Year	GW Discharge[3]	GW Use[4]	Palominas Base Flow	GW Discharge[3]	GW Use[4]	Charleston Base Flow	GW Discharge[3]	GW Use[4]	Tombstone Base Flow[2]	Total GW Use
1935-40	5424	2085	3335	9763	3621	9470	2600	2800	9238	8506
1951-56	2531	1474	1057	7412	2734	5735	2600	2500	5767	6708
1958-63	1807	1002	805	8136	2609	6332	2600	2900	6003	6511
1968-73	1446	872	574	9401	3392	6583	2600	3512	5671	7776
1976-81	1446	916	530	7955	2831	5648	2600	3127	5127	6874
1981-86	4300	2400	1900	7250	4400	4750	2600	900	6450	7750
1985-91	4300	2400	1900	7250	4400	4750	2600	900	6450	7700

GW = Groundwater

1. (2)-(3)=(4); (4)+(5)-(6)=(7); (7)+(8)-(9)=(10)

2. Average values for the period 1968-86 for the Charleston-Tombstone reach were used for the periods 1935-63 for this reach.

3. GW Discharge represents winter baseflow rates expressed as an annual total.

4. GW Use is the total annual difference between GW Discharge and the estimated monthly baseflows. It represents the decrease of baseflow caused by phreatophytes and near-stream pumping.

Average baseflows have also decreased through time. Average baseflow is considered to be the groundwater discharge to the stream less the abstractions of water from the aquifer by riparian vegetation, agriculture, and evaporation. Average baseflow is a measure of the total annual baseflow discharged by the stream. At Palominas, average baseflow decreased from about 3,300 acre-feet per year in steady-state times to less than 1,000 acre-feet per year for the period 1951-1980 but has increased to about 1,900 acre-feet per year over the last decade. At Charleston, the average stream baseflow decreased from about 9,500 acre-feet per year to about 4,800 acre-feet per year. A similar reduction was assumed to take place at the Tombstone gage. There may have been an increase in average baseflows for the period 1981-90.

The interception of groundwater moving from mountain front recharge areas to the stream has also increased through time, as shown in Figures 8-11 as "Regional Groundwater Use". The amount of this interception has been estimated as the difference between the amount of steady state groundwater discharge to the stream and the maximum amount of discharge estimated to occur at later periods of time, and is due to interception of groundwater by regional groundwater withdrawals. Figure 12 shows the concept used to estimate use of baseflow by agriculture, the riparian community, domestic, and other users.

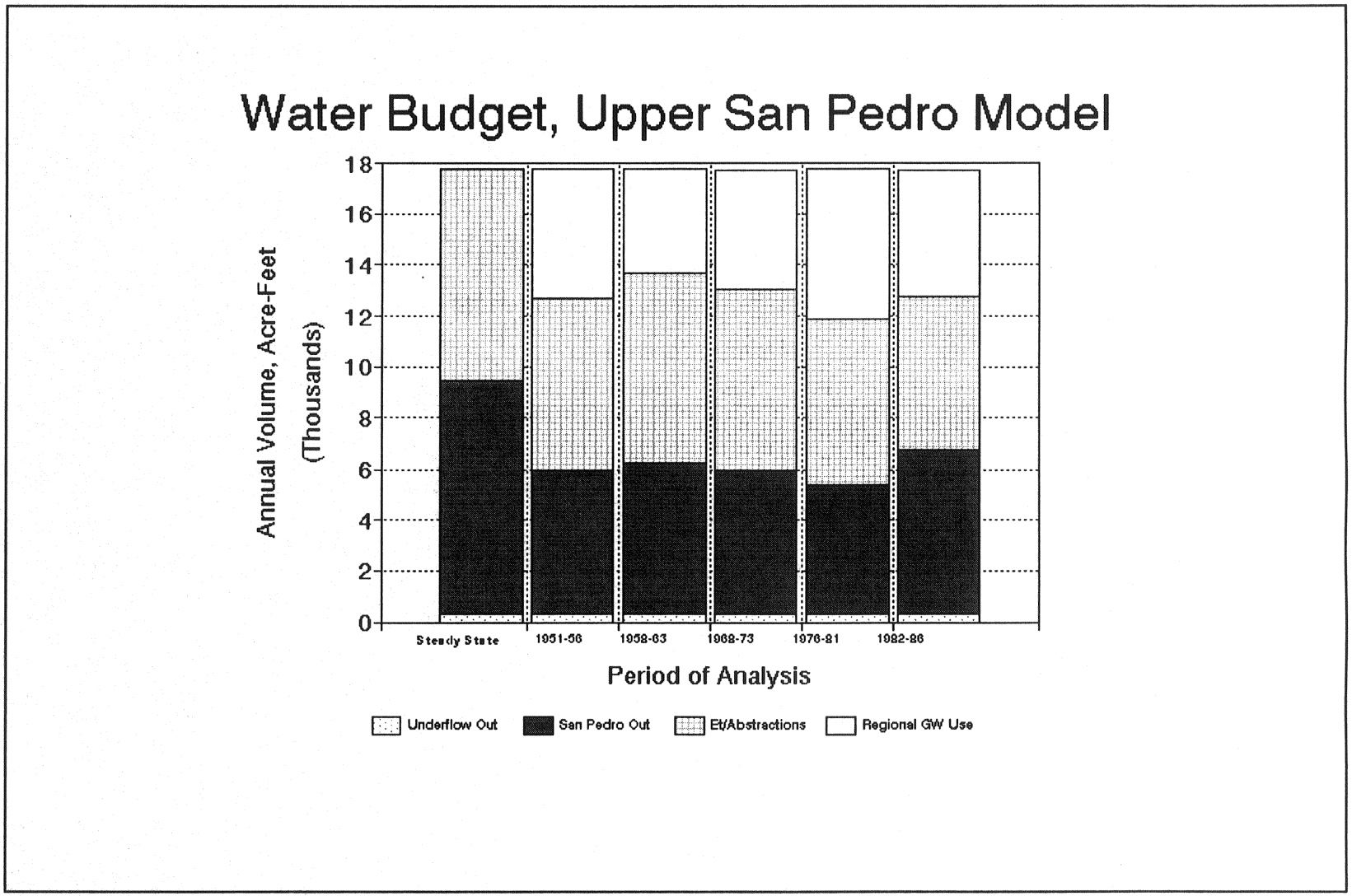

Water Budget, Upper San Pedro Model
Annual Volume, Acre-Feet
(Thousands)
18
16
14
12
10
8
6
4
2
0
Steady State
1951-58
1958-63
1968-73
1976-81
1982-86
Period of Analysis
Underflow Out
San Pedro Out
Et/Abstractions
Regional GW Use

Figure 8

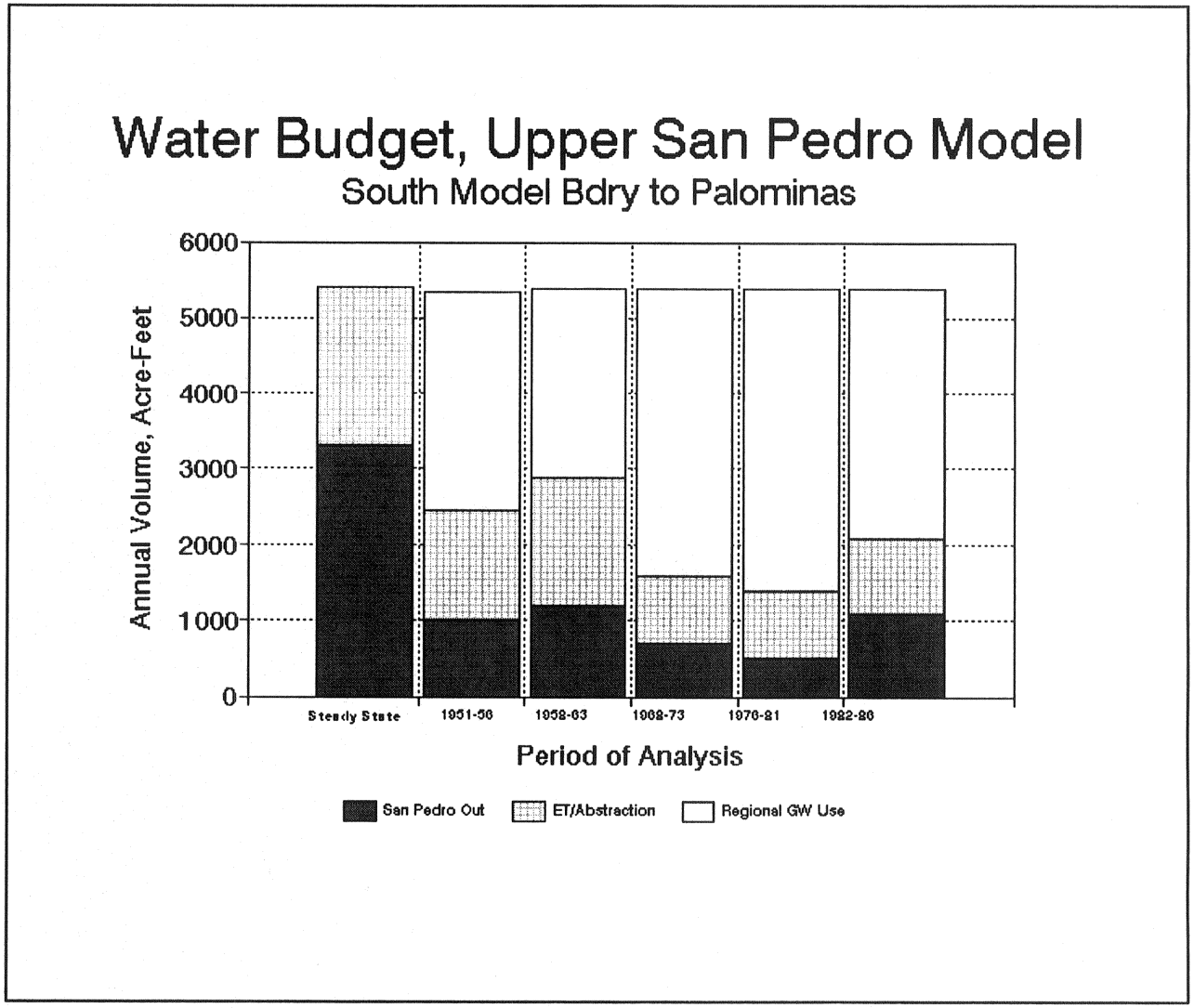

Water Budget, Upper San Pedro Model
South Model Bdry to Palominas
Annual Volume, Acre-Feet
6000
5000
4000
3000
2000
1000
0
Steady State
1951-58
1958-63
1968-73
1976-81
1982-86
Period of Analysis
San Pedro Out
ET/Abstraction
Regional GW Use

Figure 9

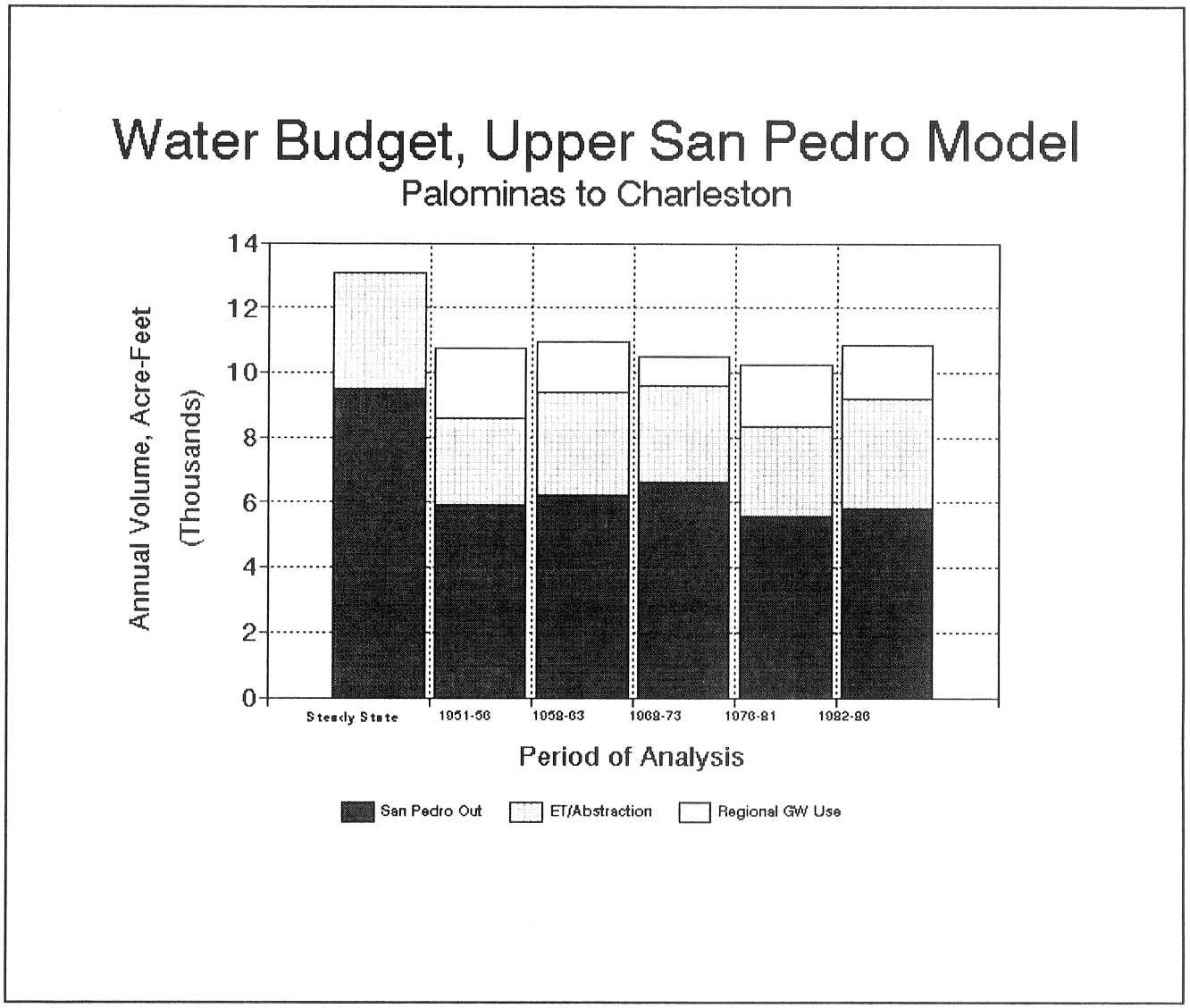

Water Budget, Upper San Pedro Model
Palominas to Charleston
Annual Volume, Acre-Feet
(Thousands)
14
12
10
8
6
4
2
0
Steady State
1951-58
1958-63
1968-73
1976-81
1982-86
Period of Analysis
San Pedro Out
ET/Abstraction
Regional GW Use

Figure 10

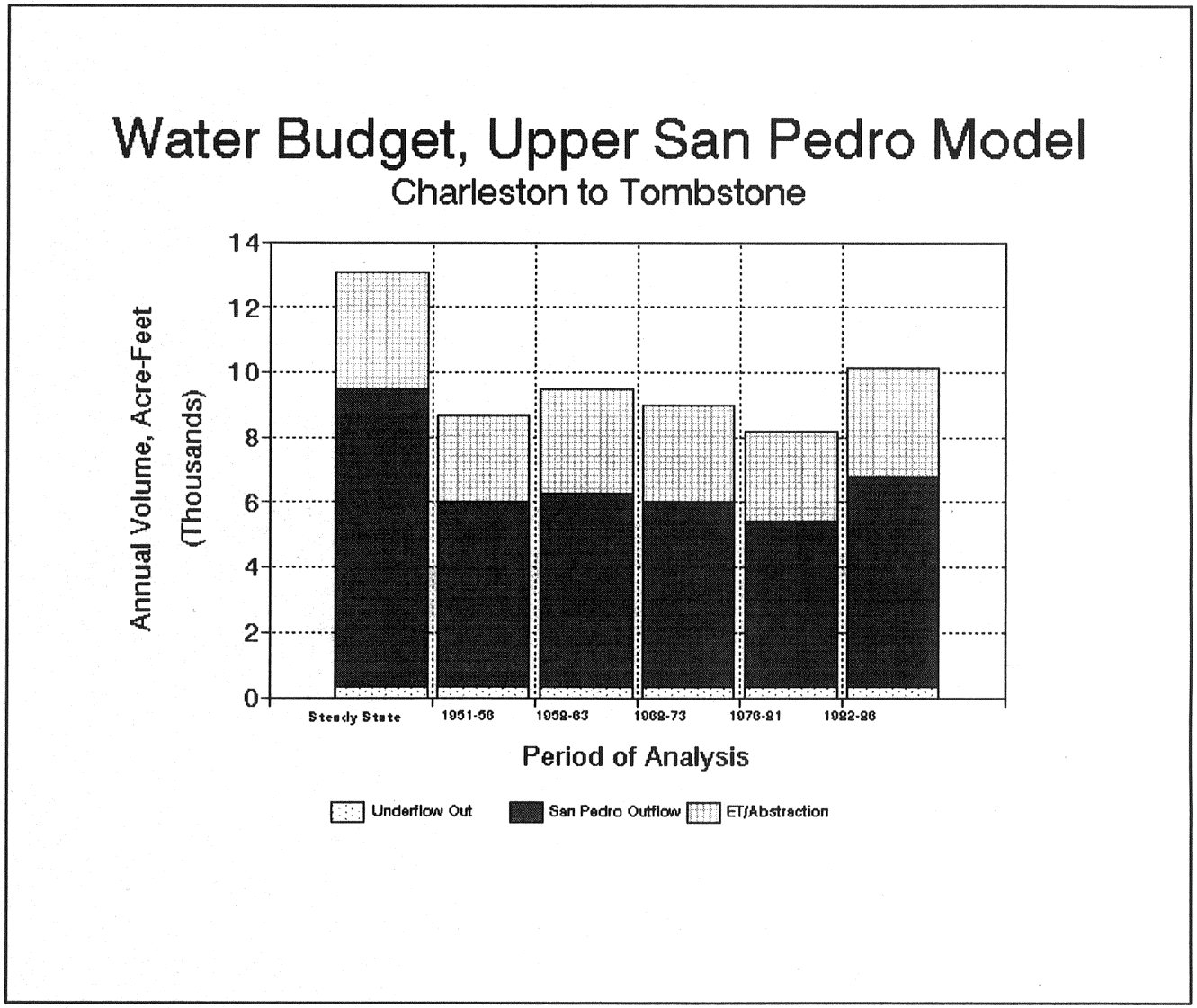

Water Budget, Upper San Pedro Model
Charleston to Tombstone
Annual Volume, Acre-Feet
(Thousands)
14
12
10
8
6
4
2
0
Steady State
1951-58
1958-63
1968-73
1976-81
1982-86
Period of Analysis
Underflow Out
San Pedro Outflow
ET/Abstraction

Figure 11

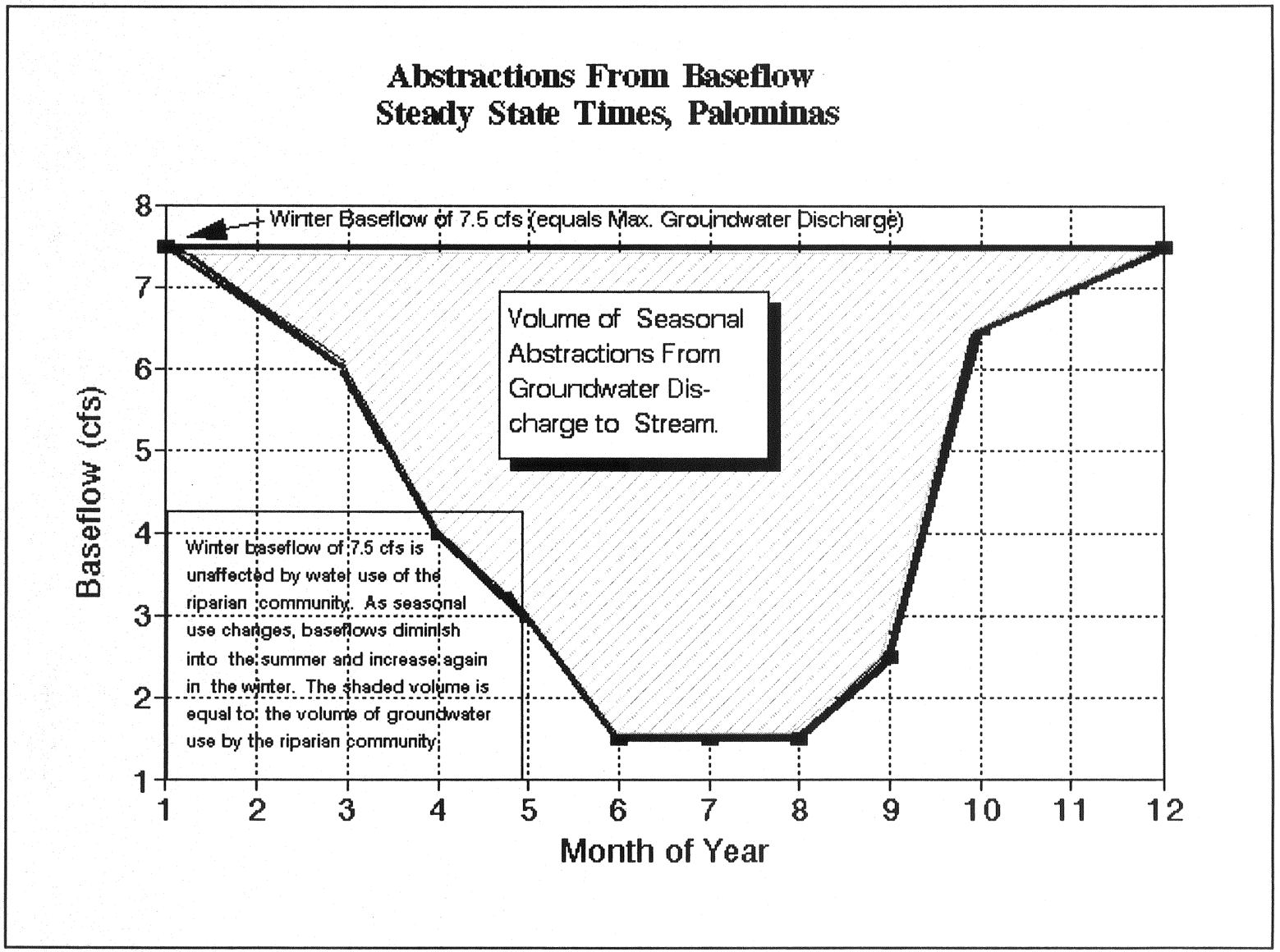

Abstractions From Baseflow
Steady State Times, Palominas
Winter Baseflow of 7.5 cfs (equals Max. Groundwater Discharge)
Volume of Seasonal Abstractions From Groundwater Discharge to Stream.
Winter baseflow of 7.5 cfs is unaffected by water use of the riparian community. As seasonal use changes, baseflows diminish into the summer and increase again in the winter. The shaded volume is equal to the volume of groundwater use by the riparian community.
Baseflow (cfs)
Month of Year
1
2
3
4
5
6
7
8
9
10
11
12

Figure 12

Chapter 4: Numerical Model of the Groundwater Flow System

General Features of the Model

Model Code and Model Packages

The model code selected to simulate groundwater flow was the Modular Three-Dimensional Finite Difference Groundwater Flow Model, or MODFLOW, developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). The model has been used to simulate the steady-state groundwater flow conditions of 1940 and Transient groundwater flow conditions between 1941 and 1990. The model unit of length was feet, and of time was days. The model was constructed using seven packages offered by MODFLOW. The packages used included; 1) the Basic package, 2) the Block Centered Flow 2 (BCF2) package, 3) the Well package, 4) the Recharge package, 5) the Streamflow-Routing package (STR), 6) the Evapotranspiration package (ET), and 7) the Preconjugate solver (PCG). A brief description of each MODFLOW package and how they relate to the modeling of the hydrogeologic system follows. The model data sets are located in Appendix B.

The Basic package establishes the orientation of the active model area, boundary conditions, initial water levels, and the discretization of time. The model also incorporates the BCF2 (Block Centered Flow) package which provides a method of converting no-flow cells to variable head cells (McDonald and others), effectively allowing the re-wetting of dry model cells. The BCF2 package computes the conductance components of the finite-difference equation which determine flow between adjacent cells. It also computes the terms that determine the rate of movement of water to and from storage.

The Well package simulates groundwater pumpage from the aquifer at specified volumetric rates during specific stress periods. The Recharge package simulates the areal distribution of recharge. Recharge simulated was primarily from mountain front recharge. The Streamflow-Routing (STR) package (Prudic, 1989) simulates the San Pedro and Babocomari Rivers. This package is not a true surface water flow model but rather an accounting system that tracks flow in one or more streams that interact with the groundwater system (Prudic, 1989). The ET package simulates the effects of plant transpiration and direct evaporation in removing water from the saturated groundwater regime. The PCG package was used to implement the Preconjugate gradient solver, a numerical method for solving the large system of simultaneous linear equations by iteration. For a complete discussion of each MODFLOW package refer to McDonald and Harbaugh (1988).

The model was constructed using 6 time-steps per year with varying lengths of time for the stress periods. The stress periods were intended to correspond with changes in total annual pumpage. There are 14 stress periods simulated in the Transient-state model between 1941 and 1990. Stress periods 1 through 10 incorporate the same time frames as Freethey (1982).

Model Grid

The Upper San Pedro model grid is expanded further to the west towards the Huachuca Mountains in comparison to the Freethey (1982) model. The model is oriented in a southeast to northwest direction, paralleling the San Pedro River similar to the Freethey (1982) model. The modeled area was divided into an orthogonal grid consisting of 72 rows by 67 columns with high resolution along the San Pedro and Babocomari Rivers, along the mountain front with steep hydraulic gradients, and in the Sierra Vista-Fort Huachuca area where large groundwater

withdrawals occur. The total model domain is 22 miles in the east-west direction and 32 miles in the north-south direction. The model area extends from approximately 6 miles south of the International Boundary with Mexico and north to Fairbank, Arizona (Figure 1). Model cell sizes range from 40 acres to 160 acres. The model is bounded on the west by the Huachuca Mountains and on the east by the Mule Mountains and Tombstone Hills and to the south by the Sierra San Jose Mountains. The Upper San Pedro study area includes the Sierra Vista, Huachuca City, Fort Huachuca, Palominas, Hereford, Charleston, and Fairbank areas.

Aquifer Conditions

Three model layers were used to represent the hydrogeologic system. The uppermost layer, Layer 1, corresponds to the Floodplain Alluvial Unit. The Floodplain Alluvial Unit is modeled as an unconfined aquifer. The middle layer, Layer 2, corresponds to the Basin-Fill Unit. The Basin Fill Unit is modeled as a confined/unconfined aquifer--confined when the overlying Floodplain Alluvial Unit is saturated and unconfined when the Floodplain Alluvial Unit is unsaturated or absent. The bottom layer, Layer 3, represents the Pantano Formation, a conglomerate. The Conglomerate Unit is also modeled as a confined/unconfined aquifer--confined when the overlying Basin Fill Unit is saturated and unconfined when the Basin Fill Unit is unsaturated or absent.

Boundary and Initial Conditions

The selection of proper model boundary cell types is essential to the accuracy of the model. Boundary cells define the hydrologic conditions along the model borders. There are two

fundamental types of model cells, inactive and active model cells. Inactive model cells simulate no-flow conditions, where groundwater flow into or out of the model cell is not allowed. In the Upper San Pedro model no-flow cells generally correspond to impermeable bedrock outcrops of the Huachuca and Mule Mountains. There are two types of active cells used in the model, 1) variable head, and 2) constant head. Variable head cells comprise the active simulated region within the model. Constant head cells fix the water level elevation at a constant specified elevation. The Floodplain Alluvial Unit, Basin Fill Unit, and Conglomerate Unit are bounded on the east, west, and northern sides by no-flow cells with the exception of constant head cells simulated at the model boundary north of Fairbank and by no-flow cells on the southern boundary at the hardrock outcrop of the Sierra San Jose Mountains. Mountain front recharge and groundwater underflow into the model area are simulated using the MODFLOW Recharge package. No-flow cells are also present within the model domain in the area referred to as the "Babocomari Hills". Figure 13 illustrates the different model cell types and the location. A brief discussion of each model boundary follows.

The northern boundary to the Basin Fill Unit and Conglomerate Unit is simulated primarily as a no-flow boundary, since the groundwater flow paths parallel most of the northern boundary. Groundwater outflow is simulated north of Fairbank with constant head cells. Mountain front recharge is simulated along the entire reach of the western boundary. Mountain Front recharge is also simulated on the northern slopes of the Sierra San Jose Mountains. Mountain front recharge, which includes groundwater underflow from Mexico, is also simulated in the southwest model area in the gap between the Huachuca Mountains and the Sierra San Jose Mountains. Mountain front recharge is also simulated along the eastern model boundary along the Mule

Mountains and Tombstone Hills. Initial values of mountain front recharge were determined from analysis of steady state streamflow records and precipitation data, and were adjusted during the steady-state calibration process.

Bedrock at depth is considered to be a no-flow boundary. The bedrock configuration presented in Figure 2 together with an elevation of 3,000 feet above mean sea level for the bottom of the model is considered satisfactory as few wells are completed near this elevation and no wells are completed below this elevation (maximum model depth = 1,600 feet).

Aquifer Parameters

Initial estimates of transmissivity and hydraulic conductivity were developed from flow net analysis of the 1940 steady-state water level map. Values of hydraulic conductivity were backed out from the initial estimates of transmissivity based on saturated thicknesses. Hydraulic conductivity values of all model layers were then adjusted during the steady-state model calibration process. The total transmissivity of Freethey, 1982 were used as a general guide during the steady-state calibration of hydraulic conductivity's. Total transmissivity values range from 20 ft^2/d to 14,000 ft^2/d. Storativity estimates (specific yield and storage coefficient), for Transient simulations were obtained from published data. Estimates of specific yield and storage coefficient were input as constant values to the model. The constant values of specific yield for the Floodplain Alluvial Unit, Basin Fill Unit, and Conglomerate Unit were 0.15, 0.08, and 0.08 respectively. The constant values of storage coefficients for the Basin Fill Unit and Conglomerate Unit were 10^{-5}.

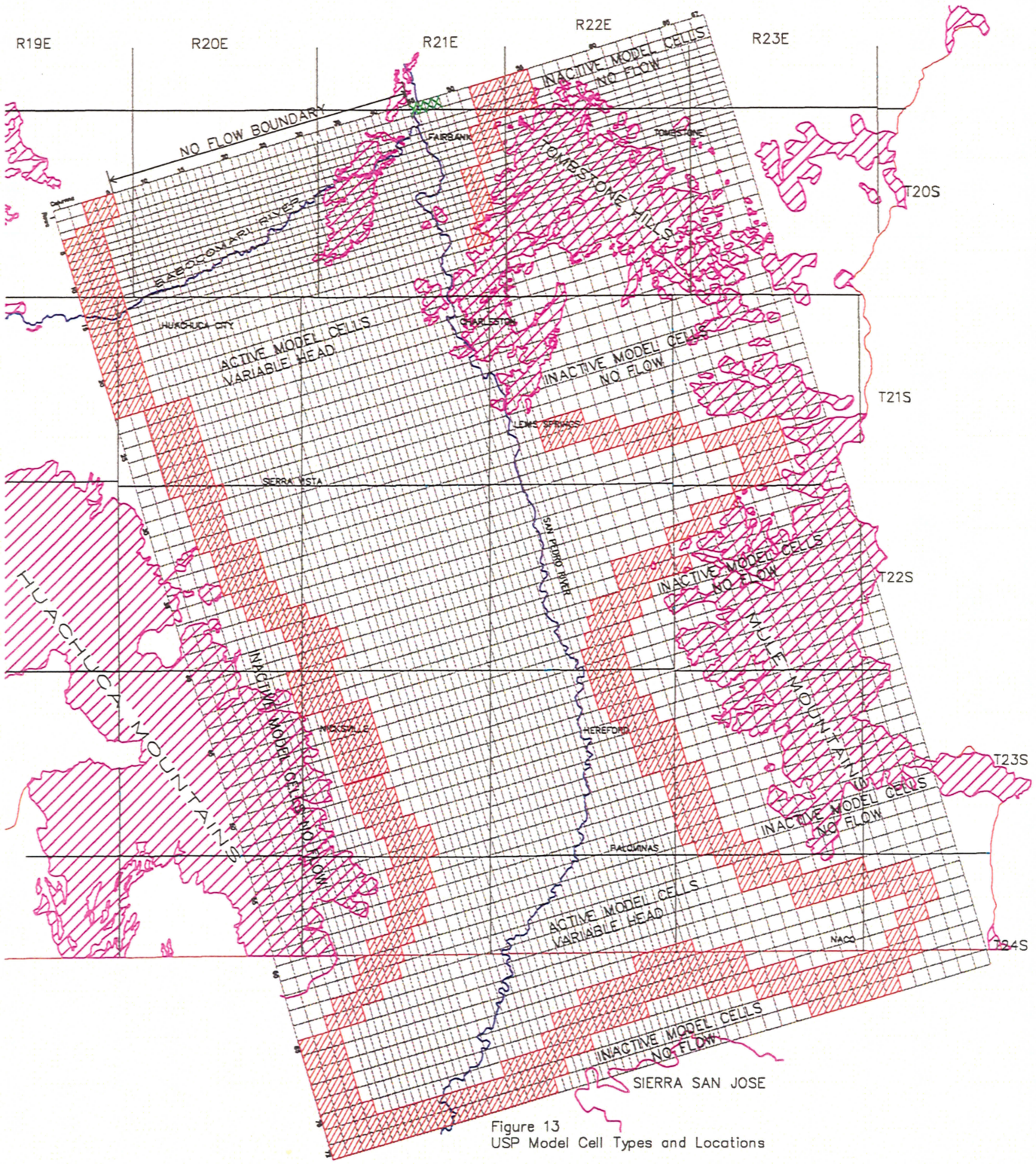


Figure 13
USP Model Cell Types and Locations

Leakage between model layers in MODFLOW is controlled by the term "VCONT", which is defined as the vertical hydraulic conductivity between two layers divided by the distance between the midpoint between the two layers (McDonald and Harbaugh, 1988). Values of VCONT between Layers 1 and 2 range from 10^{-3} to 10^{-7}, and between Layers 2 and 3 values range from 10^{-4} to 10^{-7} (units are day^{-1}).

Inflows and Outflows

Inflows to the Basin Fill Unit and Conglomerate Unit as modeled are comprised by leakage from overlying hydrogeologic units, groundwater underflow, and recharge from surface water infiltration (primarily mountain front recharge). Outflows from the Basin Fill Unit and Conglomerate Unit occur as pumpage, groundwater underflow, and as leakage to overlying units, the Basin Fill Unit and Floodplain Alluvial Unit. Inflows to the Floodplain Alluvial Unit occur as both stream leakage and as groundwater underflow and leakage from the underlying Basin Fill Unit and Conglomerate Unit. Outflows of the Floodplain Alluvial Unit are comprised of pumpage, evapotranspiration, groundwater underflow, leakage to underlying units, and leakage to streams.

Initial Steady-State Heads

A steady-state (circa 1940) water level map was constructed to provide initial heads of the three hydrogeologic units (Figure 14). Due to the limited availability of 1940 water level data points, the 1940 water level map was constructed as follows. A 1990 water level map was prepared using data from an Arizona Department of Water Resources Basic Data Section basin survey in 1990 which provided a greater number of data points with which to construct a water

level map. The 1940 water level data points were then posted on the 1990 water level map and a 1940 to 1990 change in water level map was constructed. To reconstruct the 1940 water level map, the 1940 to 1990 change in water level map was added to the 1990 water level map. 1940 water levels were posted on the derived steady-state map for further guidance. Starting heads for the Basin Fill Unit and Conglomerate Unit include confined aquifer conditions in the Palominas to Hereford area underlying the Floodplain Alluvial Unit. The initial heads for the Transient (1941 to 1990) model simulation were the model simulated ending heads from the final calibrated steady-state model run.

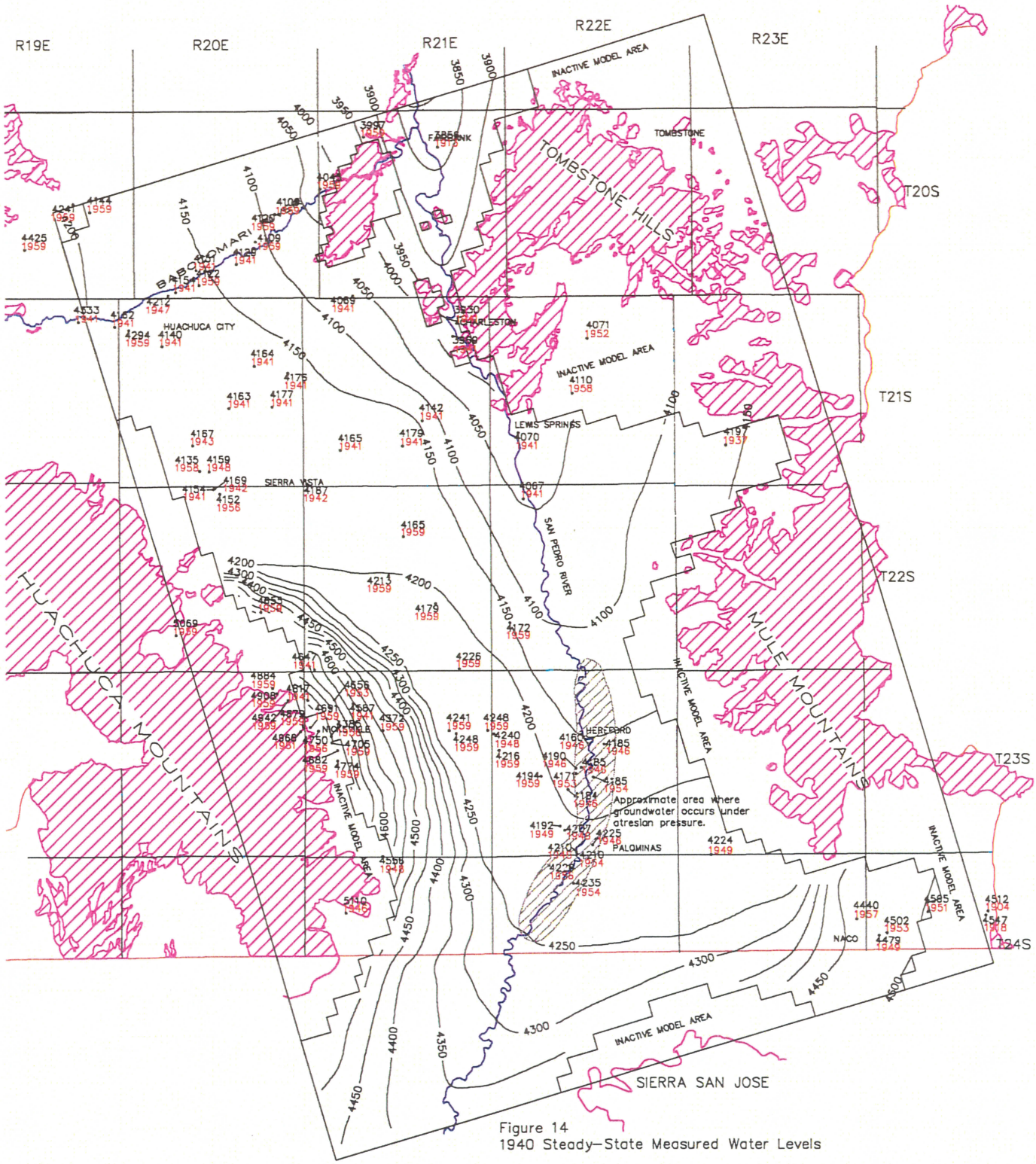


Figure 14
1940 Steady-State Measured Water Levels

Pre-Development Model Results

Water Levels

The Upper San Pedro groundwater flow model was initially calibrated to the steady-state conditions which characterized the pre-development era (circa 1940). The primary purpose of the steady-state calibration was to refine the original estimates of hydraulic conductivity. The steady-state calibration also provided initial heads for the Transient model.

Initial values of transmissivity were developed from flow net analysis of the 1940 steady-state water level map (Figure 14). The hydraulic conductivity values were then backed out from the initial transmissivity estimates based on saturated thicknesses. The final calibrated total transmissivity values are presented in Figure 15. Initial estimates of river conductances were calculated for each river cell which contained reaches of the San Pedro and Babocomari Rivers. The initial estimates of river conductance per river cell were equal to the product of the reach length, width, and estimated vertical hydraulic conductivity divided by the estimated river bed thickness.

Identical steady-state water level arrays were used for the initial heads for all model layers with the exception of confined conditions simulated in the Palominas to Hereford area. Heads in Layer 2 in this area were 10 feet higher than those in Layer 1 based on previous studies. Figure 14 illustrates the steady-state water levels circa 1940 used for initial heads in the steady-state calibration.

The steady-state calibration process involved making adjustments to the distribution of mountain front recharge, hydraulic conductivity values, VCONT, and river conductance values to obtain an acceptable match between model simulated water levels and measured water levels.

In addition water budget fluxes were compared to the conceptual estimates to ensure that inflows and outflows were maintained within an acceptable range. Figures 16, 17, and 18 show the model simulated steady-state water levels compared to the measured steady-state water levels. In most areas a reasonable head match was obtained.

An error analysis was performed by subtracting the final model-simulated water levels from the initial water levels. Being steady-state, the initial water levels should closely match the final model-simulated water levels. The analysis consisted of determining the mean absolute difference in head per model cell (the error), the standard deviation, and the maximum absolute head difference. The results of the analysis showed that the mean absolute head error per model cell was 2.3 feet for Layer 1, 12.4 feet for Layer 2, and 14.1 feet for Layer 3. This magnitude of mean absolute head error per model cell was regarded as acceptable. In addition, the ratio of the standard deviation to the total head loss in the system is small, indicating that the errors are only a small part of the overall model response (Anderson and Woessner, 1992). Table 5 presents an error analysis of heads for all three model layers.

Table 5

Steady-State Calibration Head Error Analysis (feet)

Layer	Mean Absolute Head Error	Standard Deviation	Maximum Absolute Head Error
1	2.3	2.2	13.6
2	12.4	11.4	87.7
3	14.1	11.9	91.6

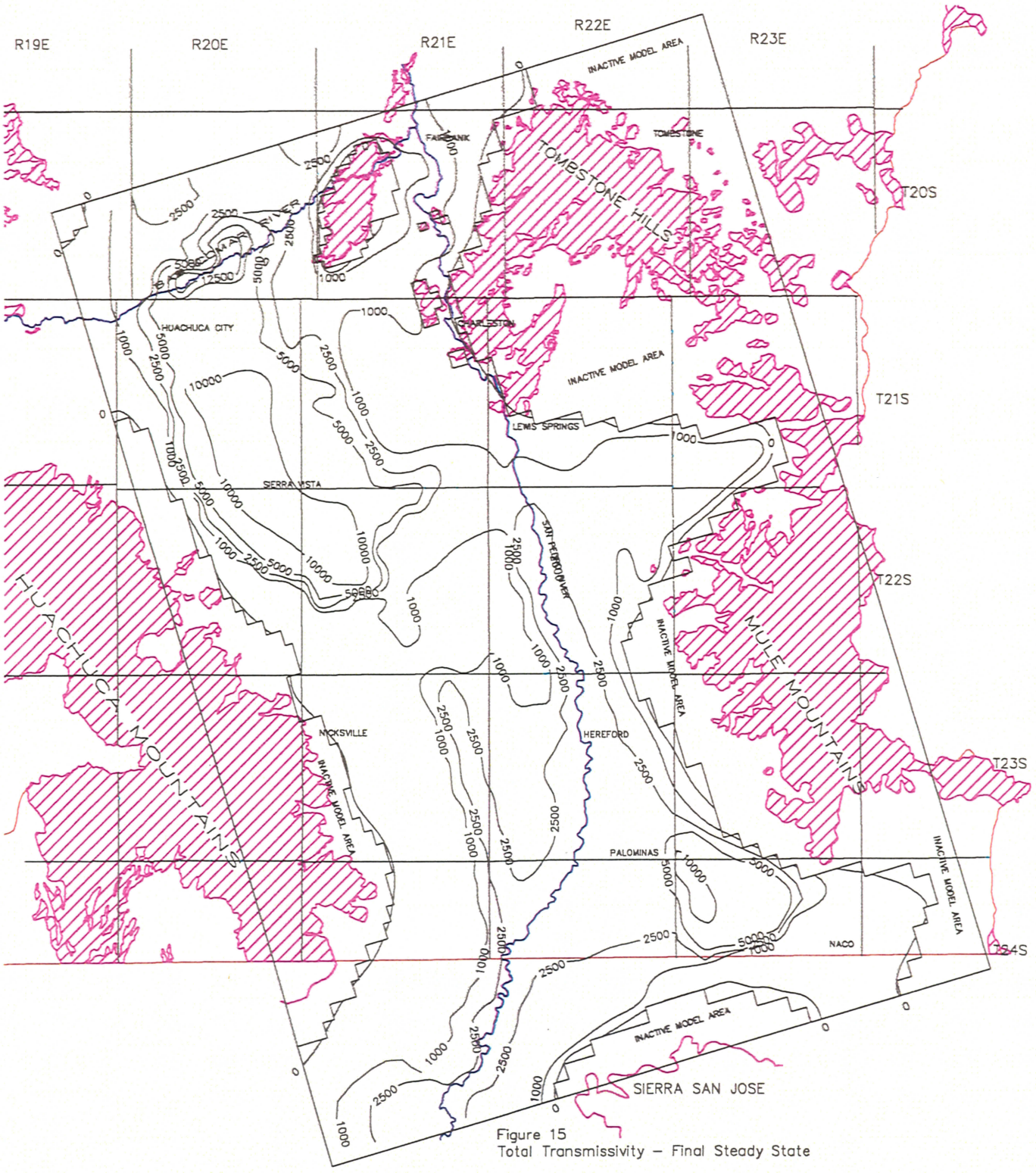


Figure 15
Total Transmissivity – Final Steady State

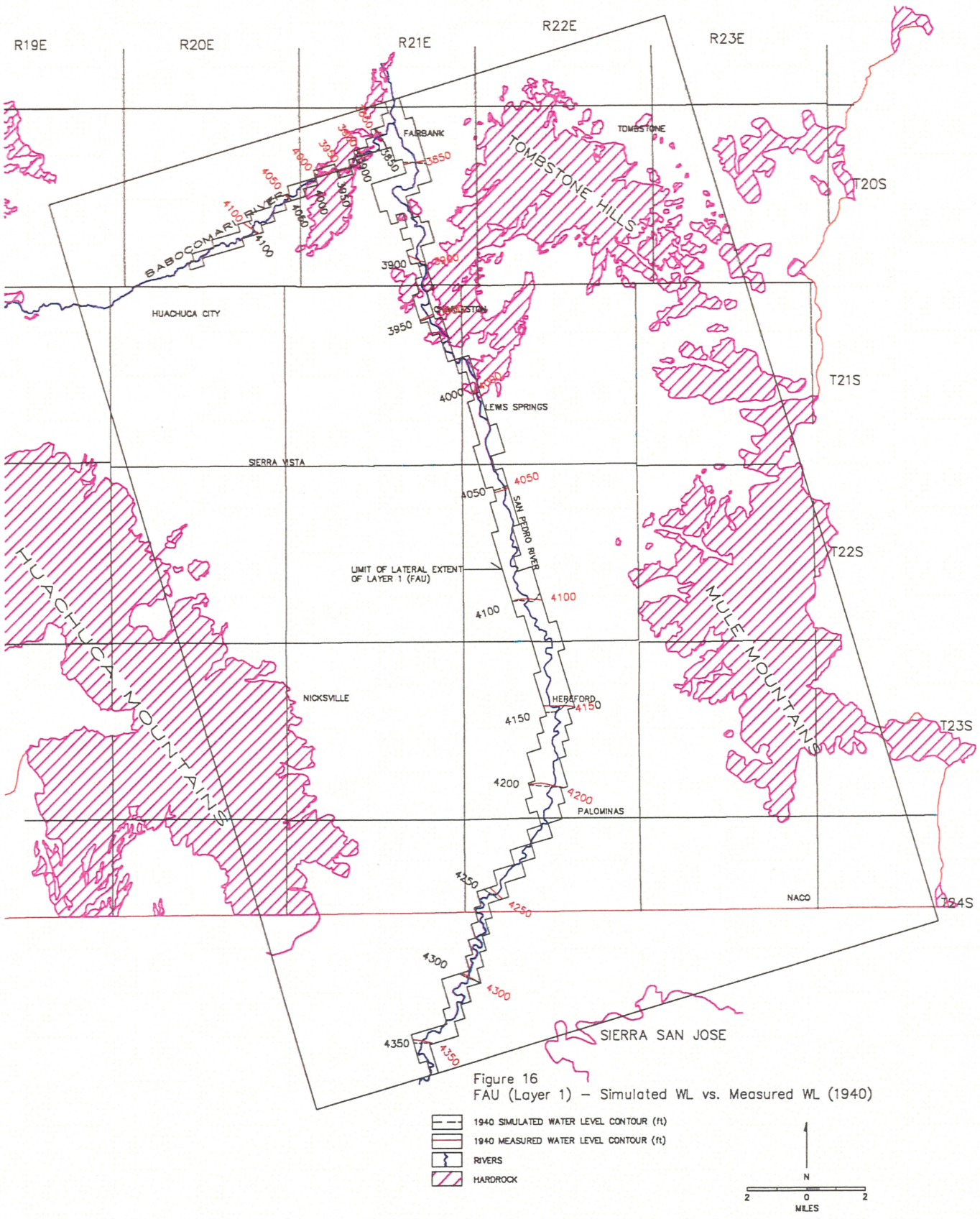


Figure 16
FAU (Layer 1) – Simulated WL vs. Measured WL (1940)

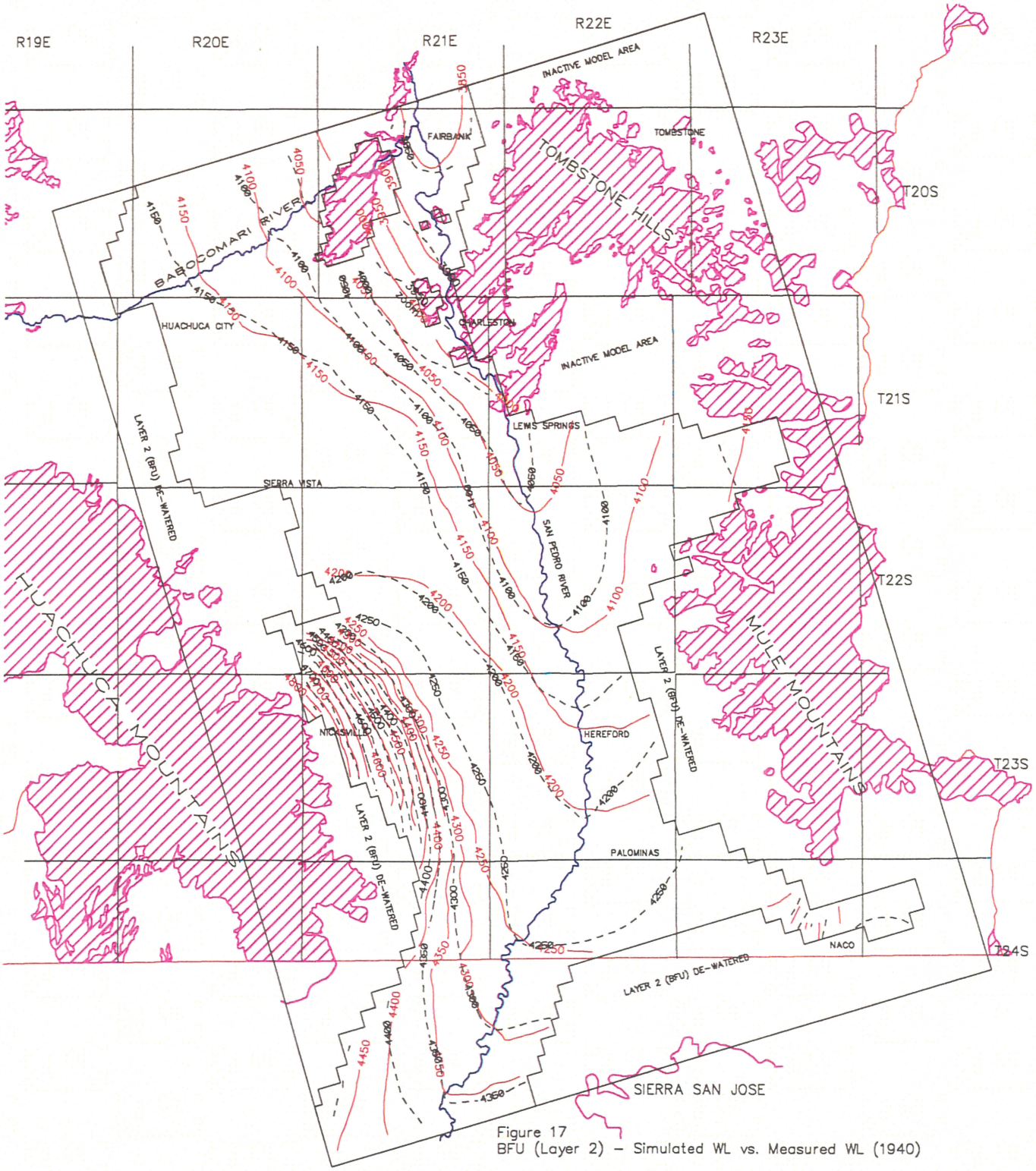


Figure 17
BFU (Layer 2) – Simulated WL vs. Measured WL (1940)

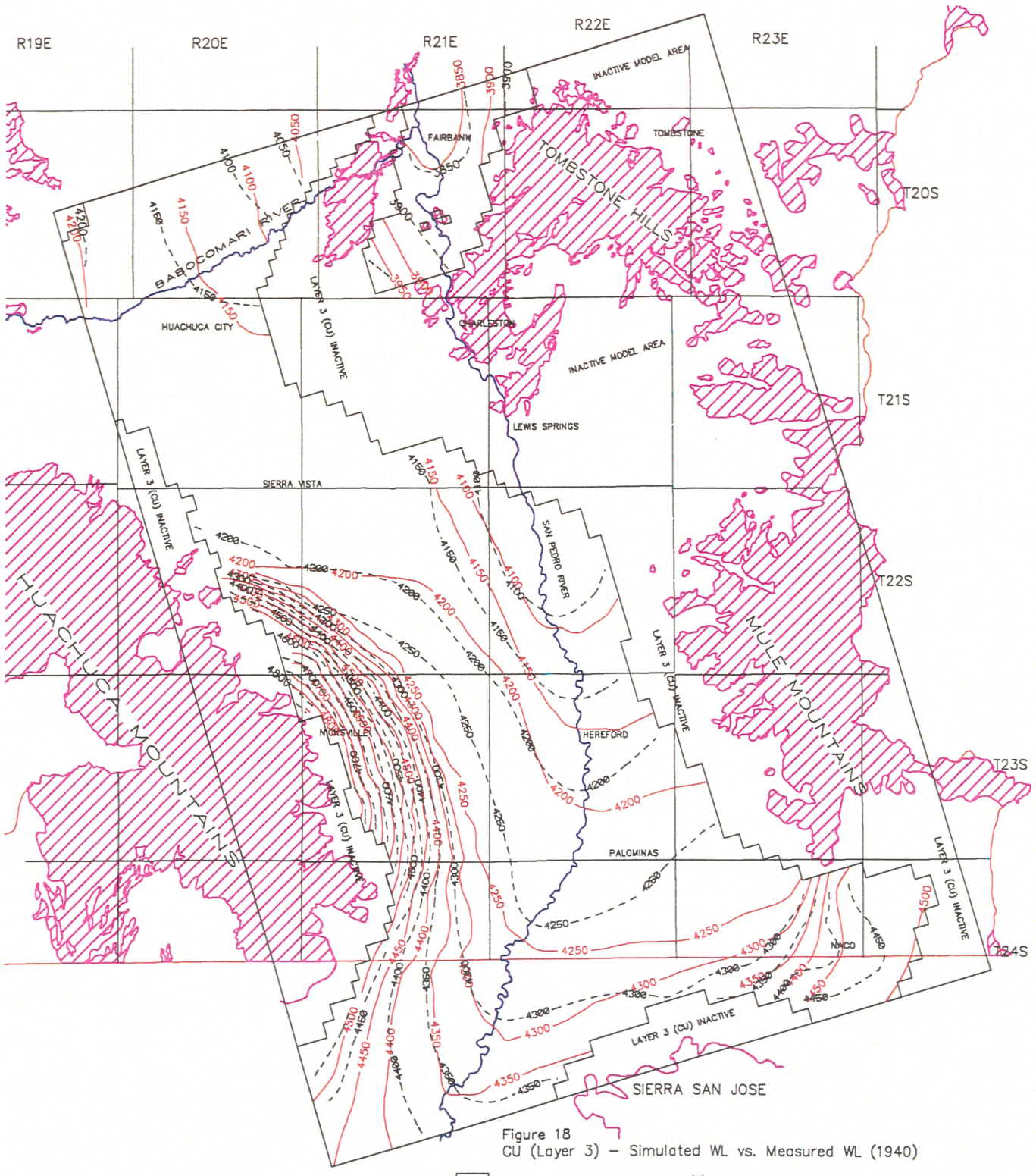


Figure 18
CU (Layer 3) – Simulated WL vs. Measured WL (1940)

Scatterplot Results: Steady-State

A scatterplot of measured versus simulated water levels is another way of showing the calibrated fit. The deviation of points from the straight line should be randomly distributed. The results of the steady-state (1940) scatterplot (simple linear regression analysis) of measured and simulated water levels are presented on the following page. The results indicate a high degree of correlation with a coefficient of correlation (r) of 0.989. The squared value of the correlation coefficient is the coefficient of determination and indicates the proportion of the variance in Y (simulated water levels) explained by the knowledge of X (measured water levels). Table 6 provides a listing of measured and simulated water levels and the Coefficient of Correlation, Coefficient of Determination, Mean Error, Mean Absolute Error, and Standard Deviation. The Mean Error is the mean difference between measured water levels and simulated water levels. The Mean Absolute Error is the mean of the absolute value of the differences in measured and simulated water levels. The Standard Deviation is the average of the squared differences in measured and simulated water levels.

Fig. A

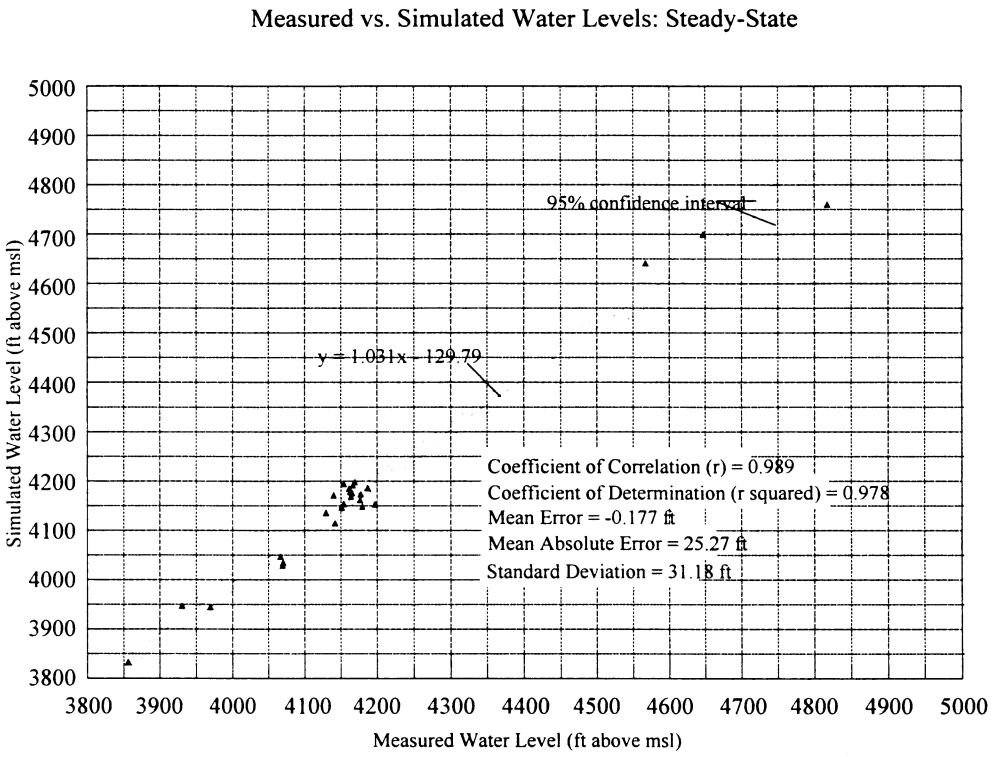

Measured vs. Simulated Water Levels: Steady-State
Simulated Water Level (ft above msl)
Measured Water Level (ft above msl)
95% confidence interval
y = 1.031x - 129.79
Coefficient of Correlation (r) = 0.989
Coefficient of Determination (r squared) = 0.978
Mean Error = -0.177 ft
Mean Absolute Error = 25.27 ft
Standard Deviation = 31.18 ft
5000
4900
4800
4700
4600
4500
4400
4300
4200
4100
4000
3900
3800
3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000

Table 6: Measured and Simulated Water Levels: Steady-State (1940)

Row	Col	Location	Measured Water Level	Simulated Water Level
6	46	D-20-21 10AAC	3856.0	3833.4
12	13	D-20-20 32AAA	4151.2	4146.3
13	18	D-20-20 27CDC	4129.4	4135.9
14	10	D-20-20 32CDB	4153.8	4153.6
15	2	D-21-19 01DDD	4161.5	4184.2
19	6	D-21-20 08CA	4140.0	4171.3
19	31	D-20-21 32CCC	4069.1	4029.0
22	16	D-21-20 14BAC	4163.6	4167.9
23	20	D-21-20 13BDA	4176.3	4161.9
23	41	D-21-21 11AA	3969.3	3944.4
23	42	D-21-21 02D	3930.0	3947.1
24	12	D-21-20 22ACC	4163.0	4178.5
25	6	D-21-20 28CAC	4166.6	4191.6
25	17	D-21-20 23ADD	4177.4	4173.6
28	8	D-21-20 34CC	4154.0	4194.6
28	23	D-21-21 29CCA	4165.0	4176.0
28	34	D-21-21 22DDC	4141.8	4114.4
29	7	D-22-20 03BBB1	4169.2	4198.2
29	31	D-21-21 27CBD	4179.3	4148.0
30	19	D-21-21 31CCC2	4186.8	4186.1
31	46	D-21-22 30ADA	4070.0	4035.3
35	44	D-22-22 05BC	4066.6	4046.9
35	61	D-21-23 29DBC	4197.0	4153.0
42	13	D-22-21 31CDC1	4646.9	4700.0
43	11	D-23-21 06CCC1	4817.3	4759.7
45	16	D-23-21 08ABB	4566.8	4641.5

Coefficient of Correlation (r) = 0.989
Coefficient of Determination (r squared) = 0.978
Mean Error = -0.177ft
Mean Absolute Error = 25.27 ft
Standard Deviation = 31.17 ft

Water Budgets

The volumetric water budget serves as an independent check of the overall acceptability of the model solution (McDonald and Harbaugh, 1988). Acceptable steady-state model solutions should have small differences between total inflows and outflows. The water budget from the final calibrated steady-state model run had a near zero percent discrepancy between total inflows and outflows. The final steady-state model water budget is compared to the conceptual water budget for the pre-development era (circa 1940) in Table 7.

Table 7
Upper San Pedro Steady-State Water Budget Comparison,
Final Steady-State Model Run vs. Conceptual
(Figures rounded to nearest 10 acre-feet)

INFLOW:	**Conceptual Budget (ac-ft)**	**Final Steady-State Model Run (ac-ft)**
Mountain Front Recharge[1]	19,000	18,870
TOTAL INFLOW	19,000	18,870
OUTFLOW		
Underflow @ Fairbank	440	440
Evapotranspiration	8,020	7,900
Net San Pedro and Babocomari R. Groundwater Baseflow Discharge	9,540	9,530
Wells	1,000	1,000
TOTAL OUTFLOW	19,000	18,870
IN - OUT	0	0
Percent Discrepancy	0.0	0.0

[1] Mountain Front Recharge includes 3,000 ac-ft/yr groundwater underflow in from Mexico. Also includes 1,000 ac-ft/yr ephemeral recharge along Greenbush Draw.

Streamflow-Routing Package Results

Another criteria for evaluating the steady-state calibration was the output of stream flows from the streamflow-routing package. Table 8 presents the comparison of measured stream flow with model-simulated streamflow for stream gage location and selected locations where stream baseflows have been estimated. The model-simulated streamflows compare reasonably with the stream gage data. Stream gage data are further discussed in the surface water section of the report.

Table 8
Conceptual vs. Model Estimated Stream Baseflow for Selected Locations, Steady-State (cfs)

Stream Locations	Conceptual	Model Estimated
San Pedro River @ S. Model Boundary	0.00	0.00
Palominas Gage	4.61	4.35
Government Draw	0.50	0.40
Charleston Gage	13.08	11.80
Babocomari River @ Canyon Entrance[1]	1.90	1.94
Babocomari River. @ San Pedro River[1]	0.96	1.57
Tombstone Gage	12.76	13.65

[1] Analysis by Arizona Department of Water Resources, with reference to Schwartzman (1990).

Post-Development Model Results

Water Levels

Following the steady-state calibration the model was run using Transient groundwater flow stresses of the period 1941 to 1990. Model parameters adjusted in the Transient calibration included the vertical distribution of pumpage within Layer 1, evapotranspiration extinction depths, VCONT's, and evapotranspiration rate array multipliers. Evapotranspiration rate array multipliers were used in the Transient model to calibrate the model simulated evapotranspiration to evapotranspiration totals in the conceptual water budget.

Initial water levels for the Transient simulation were obtained from the final calibrated steady-state model run. Other inputs to the Transient model include the hydraulic conductivity arrays developed during the steady-state calibration. River conductances developed during the steady-state model calibration were used for the Transient model inputs.

In the current Transient model calibration the final model simulated water levels and flow directions reasonably match the final measured water levels. 1990 water level data was plotted and contoured to serve as a calibration target for the Transient calibration (Figure 19). Figures 20, 21, and 22 show the model simulated Transient water levels compared to the 1990 measured water levels. In most areas a reasonable head match was obtained. Figures 23, 24, and 25 show the model simulated drawdown compared to the measured drawdown (1940 to 1990) for all three model layers.

An error analysis of model accuracy was also conducted for the Transient model. Two measures of model error were tested for the Transient simulation. This analysis measured the difference between the 1990 simulated water levels and the measured 1990 water levels. The

results of this analysis showed that the mean absolute head error per model cell was 2.9 feet for Layer 1, 13.6 feet for Layer 2, and 15.3 feet for Layer 3 (Table 9).

Table 9
Transient Calibration Head Error Analysis (Ft.)

Layer	Mean Absolute Head Error	Standard Deviation	Maximum Absolute Head Error
1	2.9	2.8	14
2	13.6	12.0	89
3	15.3	12.5	107

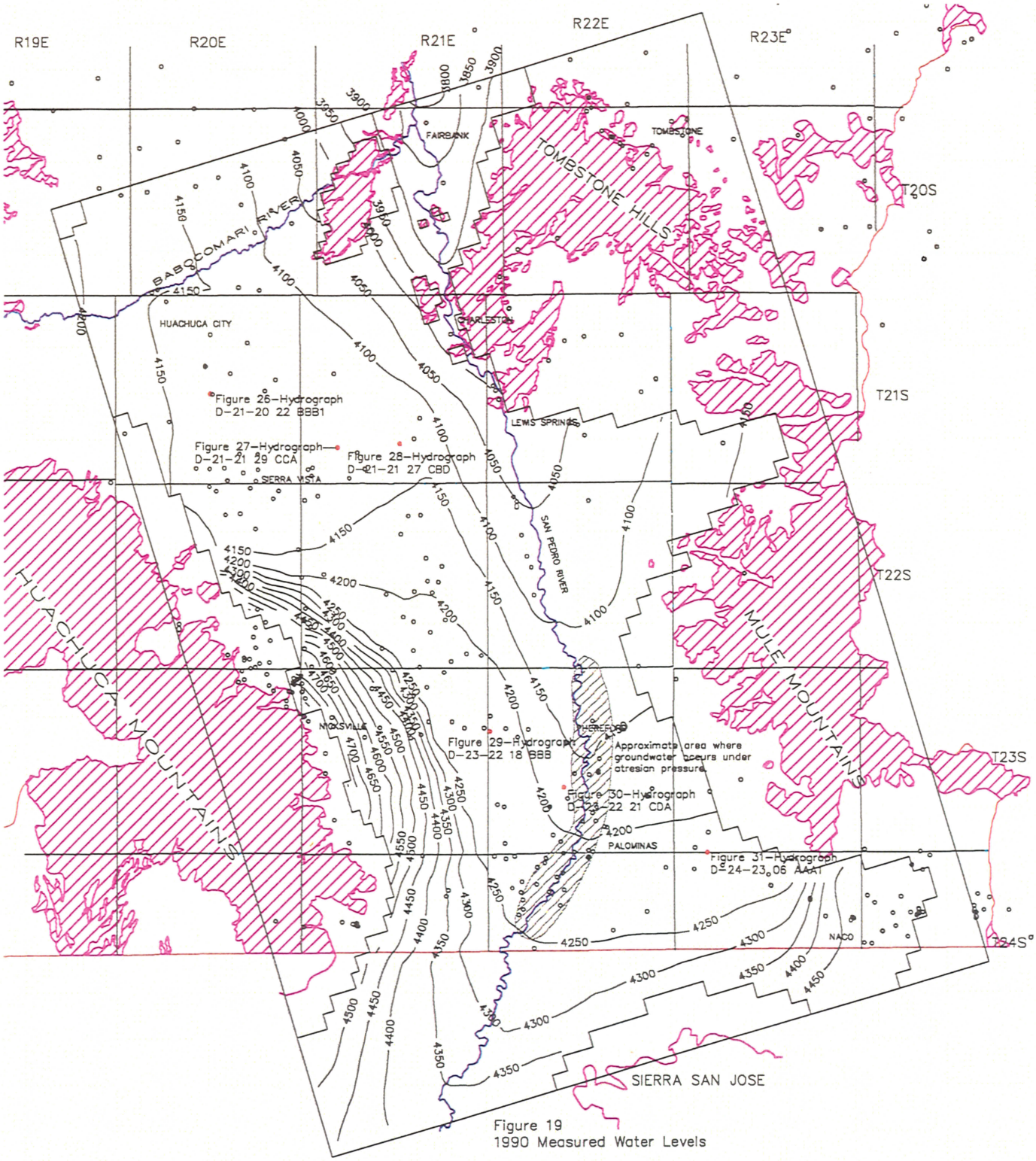


Figure 19
1990 Measured Water Levels

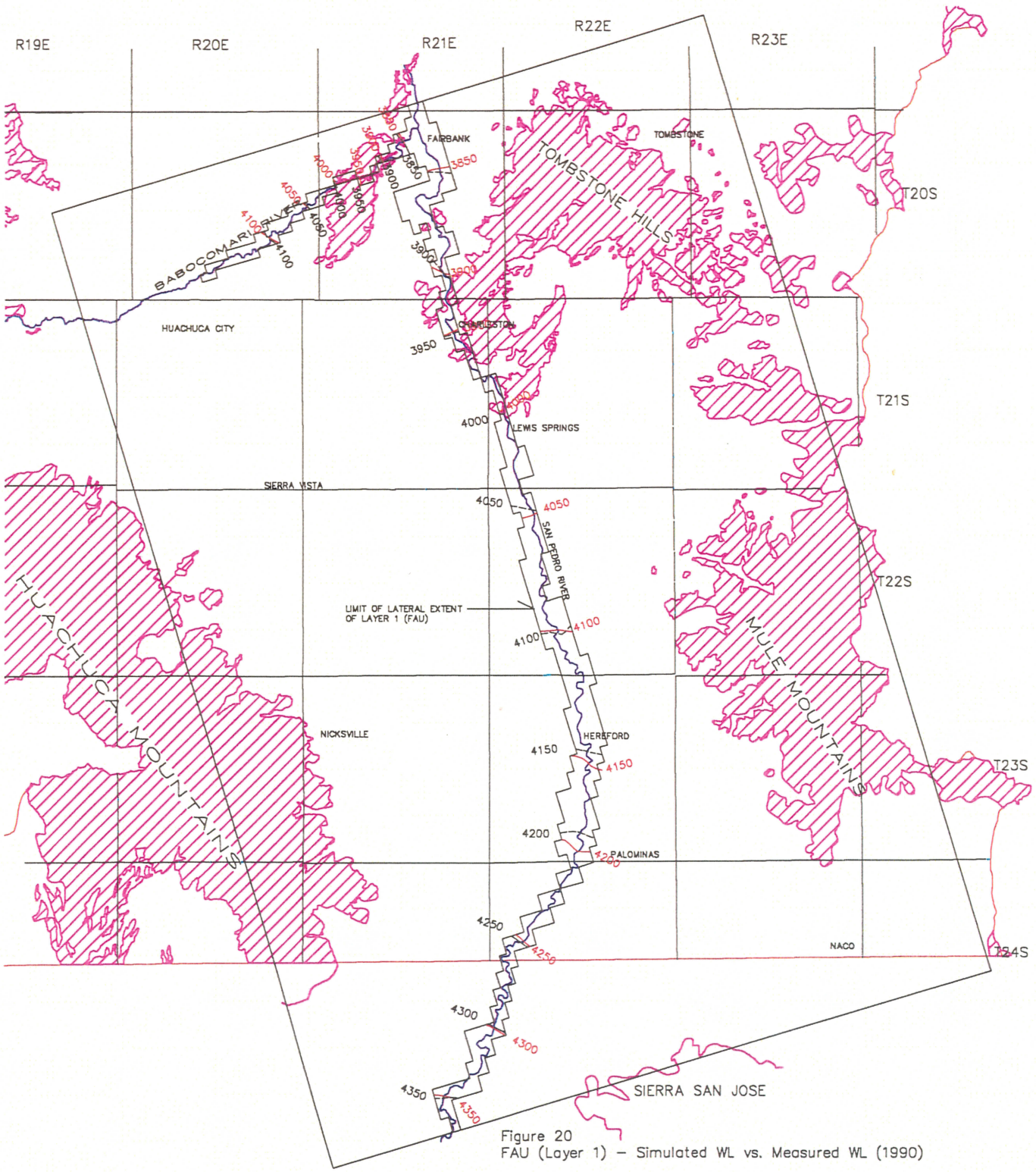


Figure 20
FAU (Layer 1) – Simulated WL vs. Measured WL (1990)

Figure 21
BFU (Layer 2) – Simulated WL vs. Measured WL (1990)

1990 SIMULATED WATER LEVEL CONTOUR (ft)
1990 MEASURED WATER LEVEL CONTOUR (ft)
RIVERS
HARDROCK

N
2 0 2
MILES

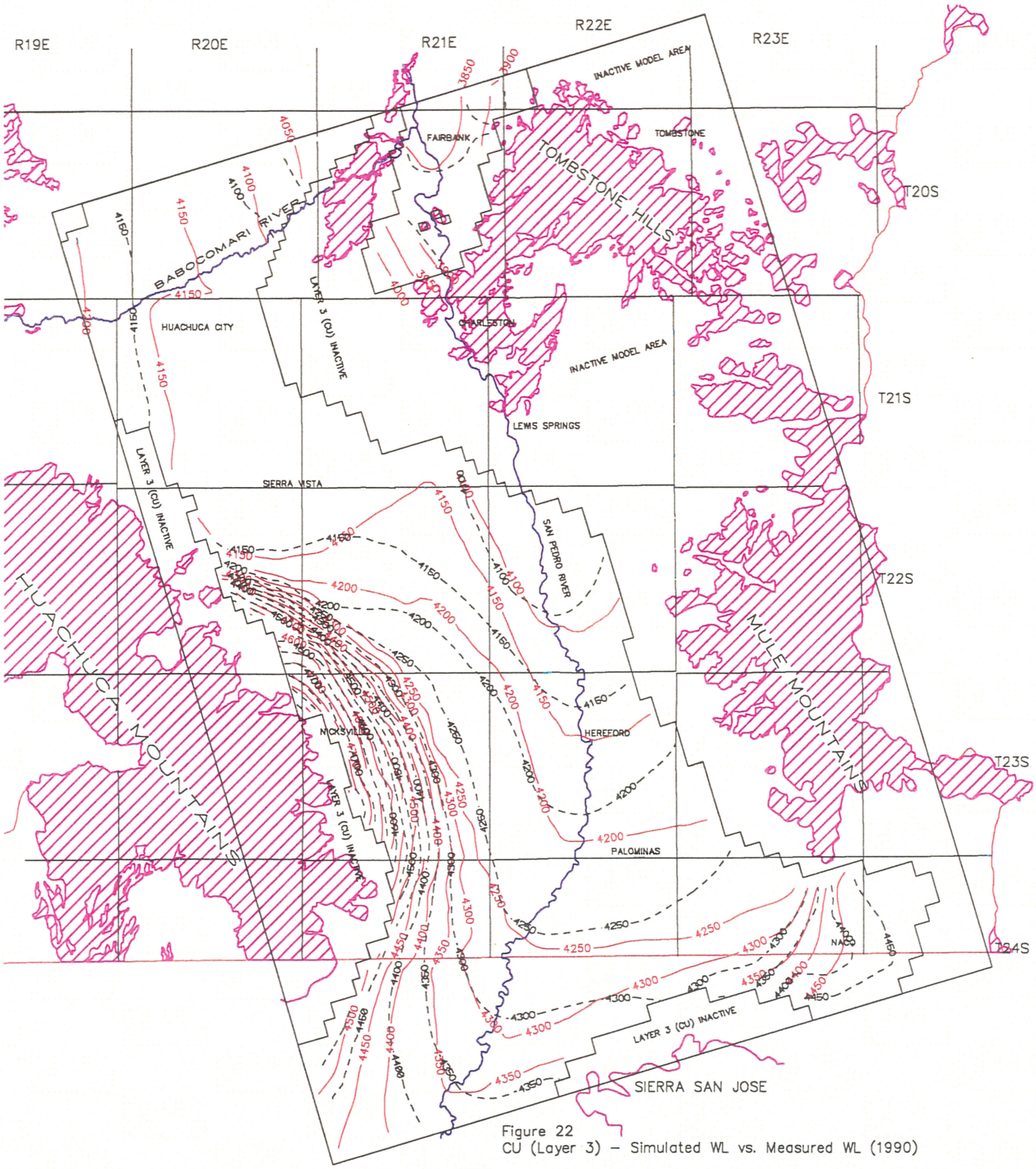


Figure 22
CU (Layer 3) – Simulated WL vs. Measured WL (1990)

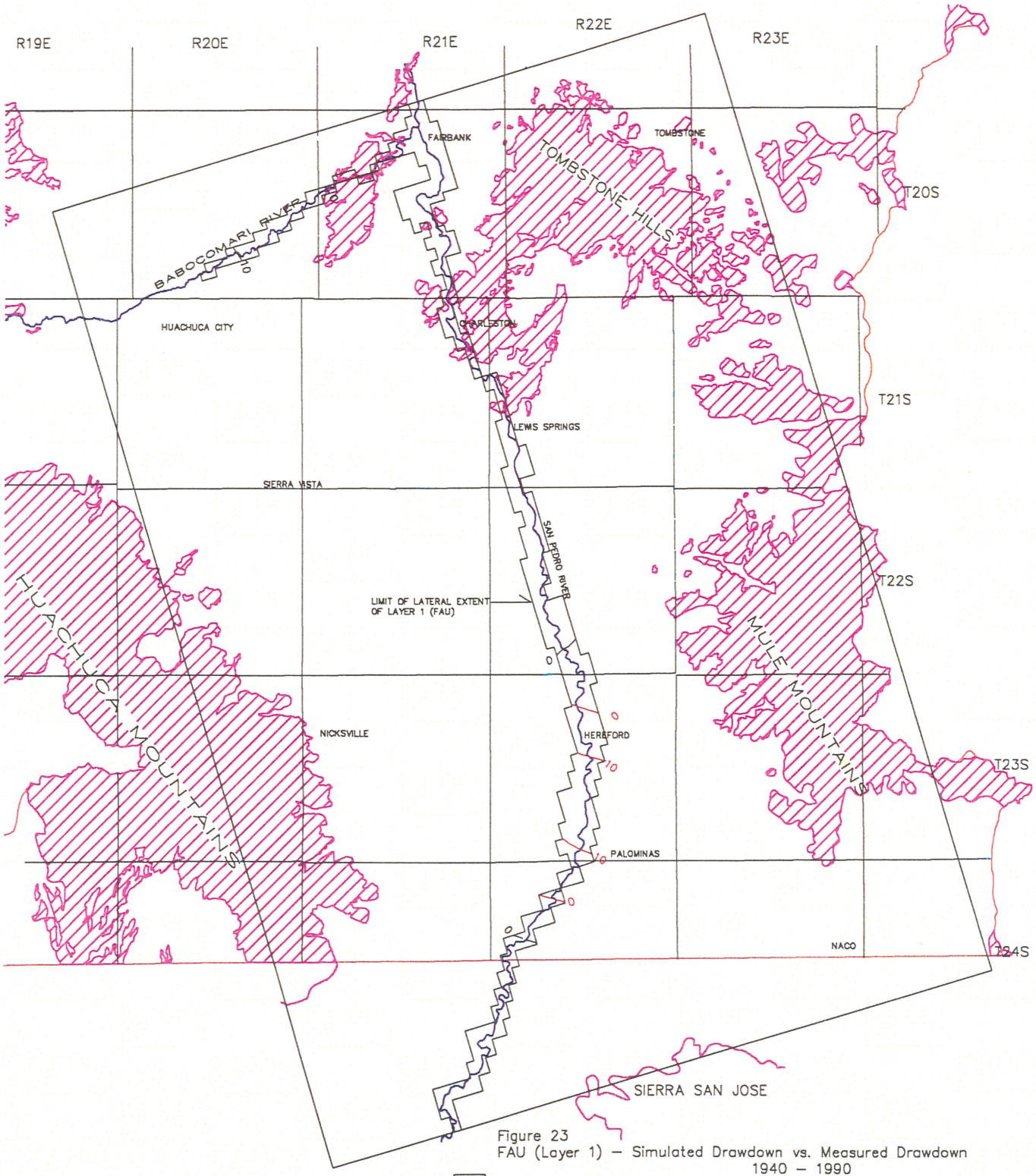


Figure 23
FAU (Layer 1) – Simulated Drawdown vs. Measured Drawdown
1940 – 1990

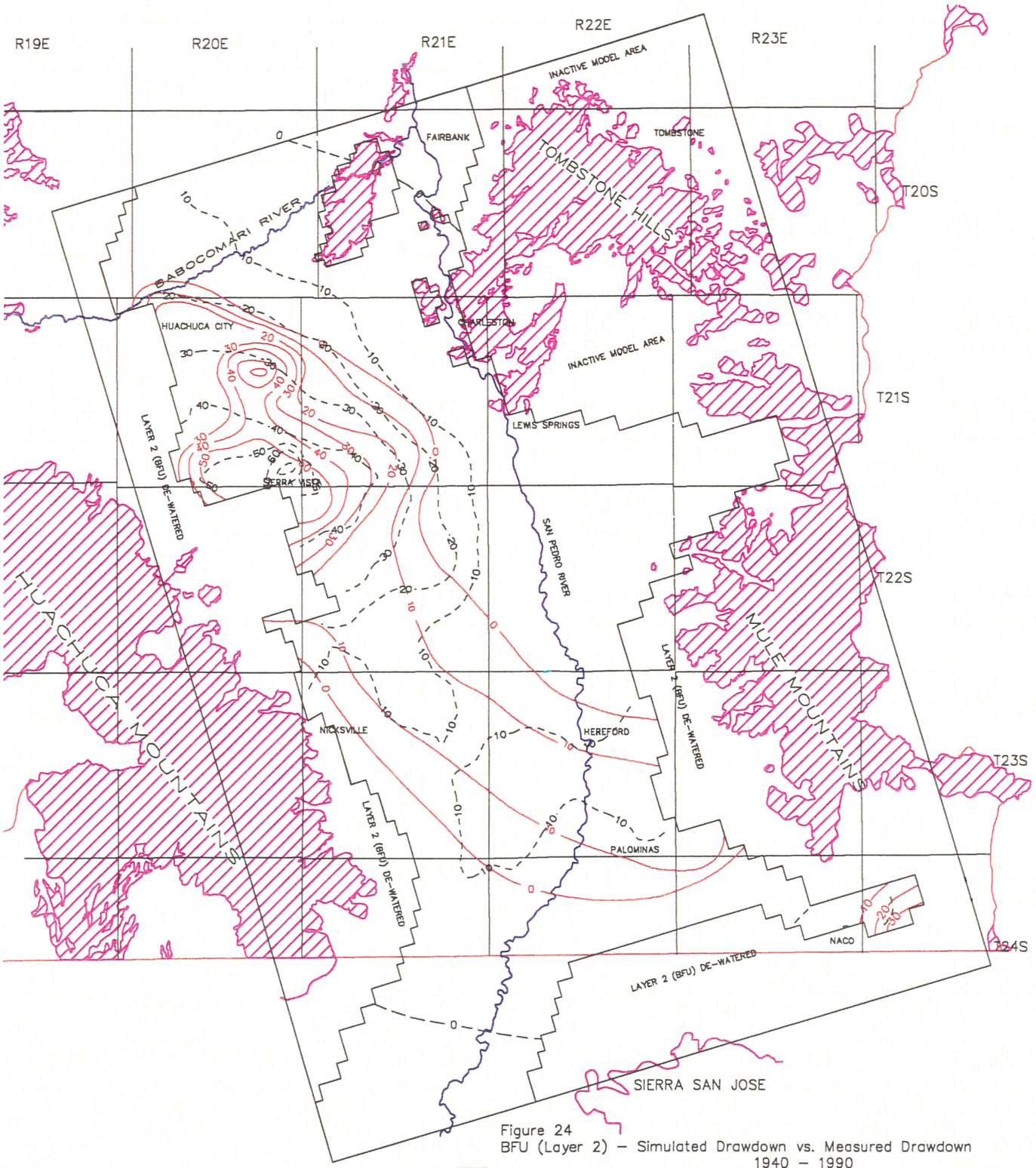


Figure 24
BFU (Layer 2) – Simulated Drawdown vs. Measured Drawdown
1940 – 1990

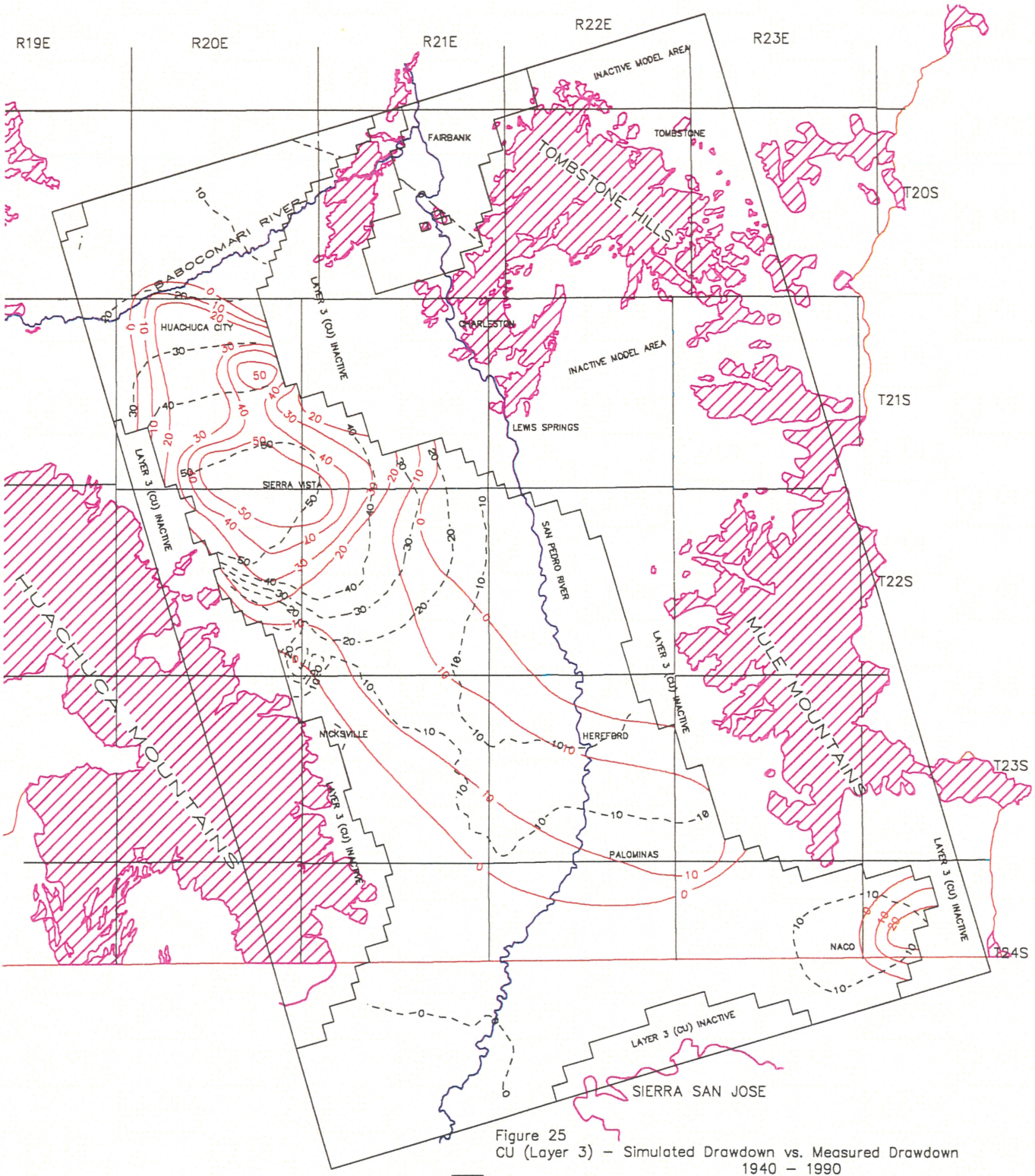


Figure 25
CU (Layer 3) – Simulated Drawdown vs. Measured Drawdown
1940 – 1990

Scatterplot Results: 1990

A scatterplot of measured versus simulated water levels is another way of showing the calibrated fit. The deviation of points from the straight line should be randomly distributed. A scatterplot of 1990 measured water levels versus 1990 simulated water levels was prepared. The results of the scatterplot (simple linear regression analysis) of measured and simulated water levels are presented on the following page. The results indicate a high degree of correlation with a coefficient of correlation of 0.969. The squared value of the correlation coefficient is the coefficient of determination and indicates the proportion of the variance in Y (simulated water levels) explained by the knowledge of X (measured water levels). Table 10 provides a listing of 1990 measured and simulated water levels and the Coefficient of Correlation, Coefficient of Determination, Mean Error, Mean Absolute Error, and Standard Deviation. The Mean Error is the mean difference between measured water levels and simulated water levels. The Mean Absolute Error is the mean of the absolute value of the differences in measured and simulated water levels. The Standard Deviation is the average of the squared differences in measured and simulated water levels.

Fig. B

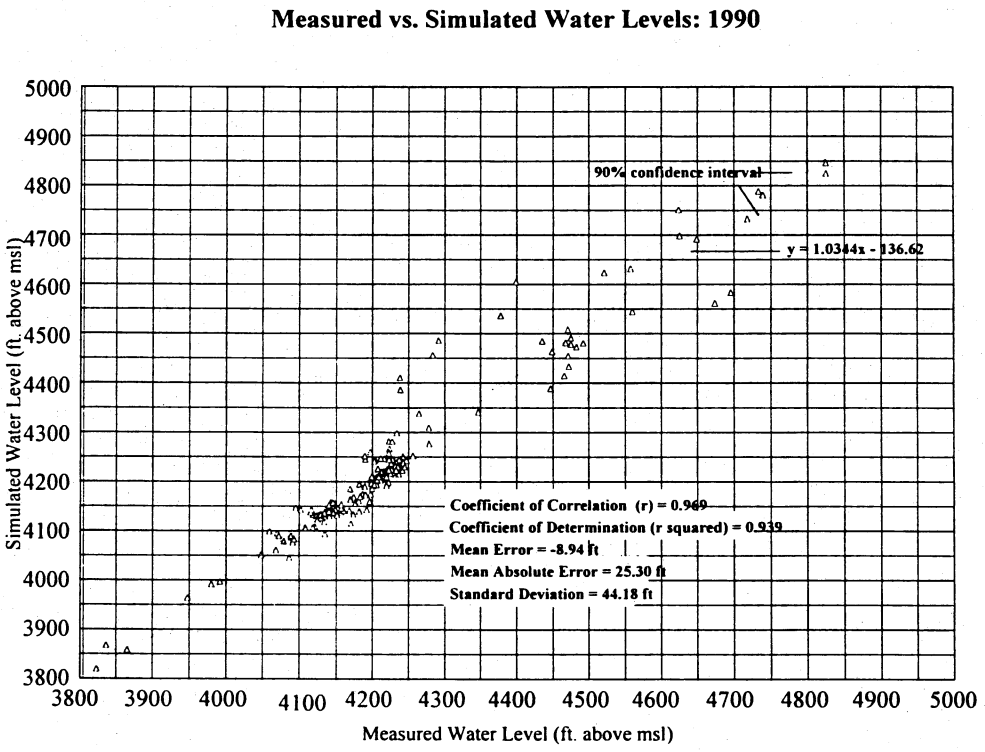

Measured vs. Simulated Water Levels: 1990
Simulated Water Level (ft. above msl)
Measured Water Level (ft. above msl)
5000
4900
4800
4700
4600
4500
4400
4300
4200
4100
4000
3900
3800
3800
3900
4000
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
90% confidence interval
y = 1.0344x - 136.62
Coefficient of Correlation (r) = 0.969
Coefficient of Determination (r squared) = 0.939
Mean Error = -8.94 ft
Mean Absolute Error = 25.30 ft
Standard Deviation = 44.18 ft

Table 10: Measured and Simulated Water Levels: 1990

Row	Col	Location	Measured Water Level	Simulated Water Level
1	7	D-20-19 13DBD	4139.3	4145.0
1	10	D-20-20 18DBC	4133.6	4134.0
1	28	D-20-20 02DDD	4086.5	4045.0
1	52	D-19-21 36BCA	3836.0	3868.0
2	16	D-20-20 16CBB	4124.9	4124.0
2	19	D-20-20 16AAC	4121.2	4109.0
3	46	D-20-21 03BDD	3822.5	3820.0
6	20	D-20-20 22ABB	4118.5	4107.0
8	24	D-20-20 23ACB	4089.5	4087.0
9	21	D-20-20 22DDD1	4108.2	4106.0
10	26	D-20-20 24CBD	4079.1	4079.0
11	46	D-20-21 14BCC	3865.4	3859.0
12	13	D-20-20 32AAA	4140.7	4130.0
13	7	D-20-20 31DCD	4142.6	4141.0
13	8	D-20-20 31DDA	4139.0	4137.0
15	8	D-21-20 05ABC	4118.4	4133.0
17	20	D-20-20 35CCB	4133.7	4118.0
19	13	D-21-20 10BBC	4129.7	4134.0
20	17	D-21-20 11BCD	4122.9	4131.0
21	11	D-21-20 16AAC1	4115.1	4138.0
22	14	D-21-20 15ACD	4149.2	4136.0
23	11	D-21-20 22BBB1	4142.1	4139.0
23	19	D-21-20 13CBB1	4134.0	4133.0
24	4	D-21-20 20DCD	4148.6	4143.0
24	17	D-21-20 23AAB	4146.3	4136.0
24	26	D-21-21 17BCC	4129.2	4127.0
24	41	D-21-21 11AAC	3947.2	3964.0
27	6	D-21-20 33ACC	4094.8	4147.0
27	8	D-21-20 34CBB2	4102.0	4143.0
28	12	D-21-20 35CBC	4126.6	4132.0
28	14	D-21-20 35ABB	4134.4	4130.0
28	35	D-21-21 22DDC	4134.6	4094.0
28	45	D-21-22 18CCA	3979.8	3992.0
29	9	D-21-20 34DCC1	4116.4	4143.0
29	12	D-22-20 02BAC	4134.1	4135.0
29	13	D-21-20 35CDD	4128.9	4133.0
29	20	D-21-21 31BDC	4151.0	4132.0
29	25	D-21-21 29DDC	4156.6	4138.0
29	33	D-21-21 27CAA	4169.9	4115.0
29	45	D-21-22 19BDB	3991.8	3997.0

Row	Col	Location	Measured Water Level	Simulated Water Level
30	14	D-22-20 01BCC	4144.5	4139.0
30	15	D-22-20 01BBD	4134.9	4138.0
30	19	D-21-21 31CAC	4134.0	4137.0
30	26	D-21-21 33CBB1	4145.3	4138.0
31	8	D-22-20 10ABB	4140.9	4143.0
31	18	D-22-21 06CBB	4139.7	4140.0
31	24	D-21-21 32DCB	4160.3	4141.0
31	52	D-21-22 28ABA	4070.1	4095.0
32	11	D-22-20 11BDD	4156.8	4146.0
32	52	D-21-22 27BCD	4059.0	4099.0
34	16	D-22-20 13AAC	4176.2	4156.0
34	29	D-22-21 10BAA	4168.0	4141.0
34	31	D-22-21 10AAB	4173.6	4134.0
35	43	D-22-22 06ADC	4047.5	4051.0
35	61	D-21-23 29DBC	4142.3	4159.0
36	18	D-22-21 18DCD	4196.7	4158.0
36	51	D-22-22 03CBA	4071.7	4090.0
37	8	D-22-20 26ABB1	4673.5	4562.0
37	30	D-22-21 15ADD	4191.8	4143.0
37	43	D-22-22 08CBC	4067.8	4061.0
38	9	D-22-20 26ADC	4695.5	4584.0
38	14	D-22-21 30BBB	4264.2	4338.0
38	29	D-22-21 23BBC	4195.8	4160.0
38	32	D-22-21 14CAD	4181.7	4140.0
39	14	D-22-21 30BCC	4291.0	4486.0
39	24	D-22-21 21DBA	4205.5	4209.0
39	27	D-22-21 22DBB	4200.0	4191.0
39	29	D-22-21 23CBA	4197.1	4175.0
39	31	D-22-21 23BAC	4180.9	4161.0
39	43	D-22-22 17CBA	4091.1	4077.0
40	13	D-22-21 31BCB2	4398.7	4605.0
40	25	D-22-21 27BCA	4215.6	4220.0
40	43	D-22-22 17CDB	4093.0	4083.0
41	26	D-22-21 27ACC	4207.3	4226.0
41	30	D-22-21 26ACC1	4205.9	4193.0
41	42	D-22-22 20CAD	4088.7	4090.0
42	10	D-23-20 01ACA	4739.0	4781.0
42	11	D-23-20 01AAD	4717.8	4733.0
42	13	D-22-21 31CDC1	4648.5	4692.0
42	16	D-23-21 06AAA	4559.7	4545.0
42	21	D-22-21 33ACB	4222.8	4282.0

Row	Col	Location	Measured Water Level	Simulated Water Level
42	25	D-22-21 34ACC	4216.6	4246.0
42	28	D-22-21 26CCB	4212.3	4220.0
43	10	D-23-20 01DBA	4825.0	4825.0
43	11	D-23-20 01ADD	4733.3	4789.0
44	11	D-23-21 06CCC2	4825.1	4846.0
44	19	D-23-21 04CBD	4237.7	4411.0
44	22	D-23-21 04AAB	4227.5	4281.0
44	25	D-22-21 34DCD	4223.5	4251.0
44	28	D-23-21 02ABB	4226.4	4230.0
44	29	D-22-21 35DCD	4220.2	4224.0
44	31	D-22-21 36CBA	4213.8	4209.0
44	33	D-22-21 36DBA	4220.3	4196.0
45	14	D-23-21 07DAA	4625.0	4699.0
45	23	D-23-21 03DCC	4223.3	4266.0
45	25	D-23-21 03DAA	4228.1	4245.0
46	13	D-23-21 07DDD	4623.9	4752.0
46	17	D-23-21 08DDD	4520.6	4624.0
47	17	D-23-21 17AAD	4557.0	4632.0
47	19	D-23-21 09CDD	4377.6	4536.0
47	24	D-23-21 11CBC	4222.8	4258.0
48	21	D-23-21 15BDA	4238.6	4386.0
48	23	D-23-21 15AAB	4233.6	4299.0
48	27	D-23-21 11DAC	4240.9	4241.0
48	29	D-23-21 12CCD	4238.0	4235.0
48	32	D-23-22 07CBB	4236.3	4215.0
49	31	D-23-21 12DDC	4241.6	4223.0
49	32	D-23-22 18BBB	4231.2	4215.0
49	34	D-23-22 07DCC	4222.1	4199.0
50	35	D-23-22 18AAD	4219.4	4192.0
50	36	D-23-22 17BBA2	4168.9	4185.0
50	43	D-23-22 09DDD	4140.0	4153.0
50	45	D-23-22 10CDB	4156.6	4154.0
51	41	D-23-22 16BDD	4169.1	4164.0
51	44	D-23-22 10CDC	4145.4	4158.0
53	40	D-23-22 21ADC	4185.9	4175.0
53	42	D-23-22 22BCD	4183.0	4170.0
53	43	D-23-22 22BDA	4173.9	4169.0
53	44	D-23-22 15DCC	4190.4	4173.0
54	30	D-23-22 30BCD	4227.5	4231.0
55	19	D-24-21 03AAB	4282.9	4456.0
55	36	D-23-22 29DAA	4198.2	4196.0

Row	Col	Location	Measured Water Level	Simulated Water Level
55	39	D-23-22 28ABC	4189.0	4190.0
55	41	D-23-22 27CAC	4199.3	4186.0
56	29	D-23-22 31CAD1	4226.1	4237.0
56	40	D-23-22 28DCC	4202.5	4194.0
56	42	D-23-22 27CAA2	4181.7	4195.0
56	49	D-23-22 24CCD	4200.1	4210.0
57	27	D-24-22 06BBB	4237.2	4245.0
57	29	D-24-22 06ABC	4233.2	4238.0
57	30	D-24-22 06AAB	4231.5	4232.0
57	34	D-24-22 04CCA	4218.6	4213.0
57	35	D-23-22 33BCC	4199.0	4210.0
57	36	D-23-22 33CAC	4214.8	4208.0
57	41	D-23-22 34BAA	4211.0	4202.0
57	42	D-23-22 34AAC	4206.2	4204.0
58	20	D-24-21 11ABD	4277.9	4310.0
58	32	D-24-22 05BDD	4233.8	4223.0
58	33	D-24-22 05ACA	4225.5	4221.0
58	34	D-24-22 05AAC	4228.5	4218.0
58	36	D-24-22 04BAB1	4210.1	4212.0
58	37	D-23-22 33DCD2	4208.4	4210.0
58	40	D-23-22 34CDC2	4219.7	4210.0
59	22	D-24-21 12CBD	4278.3	4276.0
59	28	D-24-22 18ACA	4242.4	4240.0
59	30	D-24-22 05CCC	4235.3	4230.0
59	32	D-24-22 08BAA	4226.6	4225.0
59	39	D-24-22 03BBC	4224.9	4217.0
59	53	D-23-23 32BCC	4203.9	4244.0
60	29	D-24-22 08CBB	4241.4	4236.0
60	30	D-24-22 07ADA	4243.9	4230.0
60	33	D-24-22 08ADA	4222.5	4224.0
60	35	D-24-22 09BAC	4232.8	4223.0
61	28	D-24-22 18AAA	4246.8	4243.0
61	29	D-24-22 08CCB	4242.5	4238.0
61	34	D-24-22 09CBD	4244.6	4230.0
61	48	D-24-22 01DBA	4202.5	4241.0
61	51	D-24-23 06DBB	4189.7	4245.0
61	52	D-24-23 06AAA1	4211.2	4247.0
62	53	D-24-23 05BDD2	4189.0	4252.0
63	29	D-24-22 20BBA	4256.0	4252.0
63	44	D-24-22 12CCC	4223.2	4245.0
63	55	D-24-23 04DDB	4197.0	4260.0

Row	Col	Location	Measured Water Level	Simulated Water Level
64	39	D-24-22 15DAA	4242.2	4250.0
65	58	D-24-23 11CAB	4346.4	4341.0
66	61	D-24-24 07BCC	4448.2	4464.0
66	65	D-24-24 05DAA	4491.6	4481.0
67	60	D-24-23 13ABC	4434.9	4485.0
67	62	D-24-24 07CAC	4467.0	4482.0
67	63	D-24-24 08CBA	4474.6	4479.0
68	62	D-24-24 18AAA	4470.5	4509.0
68	64	D-24-24 08DDC1	4482.3	4473.0
69	58	D-24-23 14AAB	4446.5	4389.0
69	60	D-24-23 13DDD	4465.2	4415.0
69	61	D-24-24 18DBB1	4471.4	4434.0
69	62	D-24-24 17BCC	4470.6	4455.0
69	63	D-24-24 17CDA	4474.5	4492.0

Coefficient of Correlation (r) = 0.969
Coefficient of Determination (r squared) = 0.939
Mean Error = -8.94 ft
Mean Absolute Error = 25.30 ft
Standard Deviation = 44.17 ft

Water Budgets

A comparison of volumetric water budgets also served as a check of model calibration. The volumetric water budget serves as an independent check of the overall acceptability of the model solution (McDonald and Harbaugh, 1988). An acceptable Transient model solution should have small differences between total inflows and total outflows including the changes in storage. The percent discrepancy between total inflows and total outflows is calculated using the following formula (McDonald and Harbaugh, 1988):

$$D = \frac{100(IN - OUT)}{(IN + OUT)/2}$$

Where:
D = Percent Error Term
IN = Total Inflow to the system
OUT = Total Outflow from the system

If the model equations are correctly solved, the percent error term should be small. The water budget from the final Transient model run had a percent discrepancy between total inflows and total outflows (adjusted for storage changes) of near 0.0 percent. The final Transient model budget is compared to the conceptual water budget for the period 1941 to 1990 in Table 11. The model simulated a decrease in groundwater in storage of approximately 232,000 acre-feet compared to approximately 190,000 acre-feet in the conceptual water budget (Table 11). It can be seen that the two budgets compare reasonably in most categories, and also indicates that the model reasonably simulated the applied stresses. Base flows of the river were projected higher by the model and led to most of the discrepancy between the conceptual and simulated water budget.

Table 11

USP Transient Water Budget Comparison 1941 to 1990, Model Simulated vs. Conceptual

Stress Period		Parameter	Model (ac-ft)	Conceptual (ac-ft)	Model (ac-ft/yr)	Conceptual (ac-ft/yr)
1	In:	Mountain Front Recharge	19,000	19,000	19,000	19,000
1941 (1 yr)		Total In	19,000	19,000		
	Out:	Underflow @ Fairbank	441	440	441	440
		Pumpage	2,754	2,754	2,754	2,754
		Evapotranspiration	8,485	8,506	8,485	8,506
		Net Stream Leakage	8,027	9,238	8,027	9,238
		Total Out	19,707	20,938		
2	In:	Mountain Front Recharge	95,002	95,000	19,000	19,000
1942-45 (4 yr)		Total In	85,002	95,000		
	Out:	Underflow @ Fairbank	2,206	2,200	441	440
		Pumpage	20,502	20,502	5,125	5,125
		Evapotranspiration	35,367	35,338	6,720	6,708
		Net Stream Leakage	46,531	46,190	9,626	9,238
		Total Out	104,606	10,4230		
3	In:	Mountain Front Recharge	190,004	190,000	19,000	19,000
1946-50 (5 yr)		Total In	190,004	190,000		
	Out:	Underflow @ Fairbank	4,413	4,400	441	440
		Pumpage	31,239	31,237	2,147	2,147
		Evapotranspiration	68,962	68,878	6,719	6,708
		Net Stream Leakage	94,619	75,025	9,617	5,767
		Total Out	199,234	179,540		
4	In:	Mountain Front Recharge	437,006	437,000	19,000	19,000
1951-63 (13 yr)		Total In	437,006	437,000		
	Out:	Underflow @ Fairbank	10,150	10,120	441	440
		Pumpage	109,107	109,120	5,990	5,991
		Evapotranspiration	156,116	156,082	6,704	6,708
		Net Stream Leakage	210,833	153,064	8,939	6,003
		Total Out	486,206	428,386		

Stress Period		Parameter	Model (ac-ft)	Conceptual (ac-ft)	Model (ac-ft/yr)	Conceptual (ac-ft/yr)
5	In:	Mountain Front Recharge	494,008	494,000	19,001	19,000
1964-66 (3 yr)		Total In	494,008	494,000		
	Out:	Underflow @ Fairbank	11,470	11,440	440	440
		Pumpage	145,645	145,756	12,179	12,212
		Evapotranspiration	175,743	175,615	6,543	6,511
		Net Stream Leakage	229,894	171,063	6,354	6,000
		Total Out	567,752	503,874		
6	In:	Mountain Front Recharge	513016	513000	19008	19,000
1967 (1 yr)		Total In	513016	513000		
	Out:	Underflow @ Fairbank	11,909	11,880	439	440
		Pumpage	157,266	157,406	11,621	11,650
		Evapotranspiration	183,574	183,391	7,831	7,776
		Net Stream Leakage	235,312	176,744	5,418	5,681
		Total Out	588,061	529,421		
7	In:	Mountain Front Recharge	532,002	532,000	18,985	19,000
1968 (1 yr)		Total In	532,002	532,000		
	Out:	Underflow @ Fairbank	12,347	12,320	441	440
		Pumpage	169,805	169,945	12,539	12,539
		Evapotranspiration	191,373	191,167	7,798	7,776
		Net Stream Leakage	240,521	182,415	5,209	5,671
		Total Out	614,046	555,847		
8	In:	Mountain Front Recharge	608,012	608000	19,003	19,000
1969-72 (4 yr)		Total In	608,012	608000		
	Out:	Underflow @ Fairbank	14,103	14,080	439	440
		Pumpage	206,669	206,813	9,216	9,217
		Evapotranspiration	222,672	222,271	7,825	7,776
		Net Stream Leakage	265,186	205,099	6,166	5,671
		Total Out	708,630	648,263		

Stress Period		Parameter	Model (ac-ft)	Conceptual (ac-ft)	Model (ac-ft/yr)	Conceptual (ac-ft/yr)
9	In:	Mountain Front Recharge	684,022	684,000	19,002	19,000
1973-76 (4 yr)		Total In	684,022	684,000		
	Out:	Underflow @ Fairbank	15,857	15,840	438	440
		Pumpage	249,403	249,573	10,684	10,690
		Evapotranspiration	253,719	253,375	7,762	7,776
		Net Stream Leakage	287,828	225,607	5,661	5,127
		Total Out	806,807	744,395		
10	In:	Mountain Front Recharge	703,007	703,000	18,985	19,000
1977 (1 yr)		Total In	703,007	703,000		
	Out:	Underflow @ Fairbank	16,294	16,280	437	440
		Pumpage	261,570	261,735	12,167	12,162
		Evapotranspiration	260,583	260,249	6,864	6,874
		Net Stream Leakage	293,322	230,734	5,494	5,127
		Total Out	831,769	768,998		
11	In:	Mountain Front Recharge	855,028	855,000	19,003	19,000
1978-85 (8 yr)		Total In	855,028	855,000		
	Out:	Underflow @ Fairbank	19,798	19,800	438	440
		Pumpage	386,364	386,575	15,599	15,605
		Evapotranspiration	315,565	315,241	6,873	6,874
		Net Stream Leakage	329,917	282,334	4,574	6,450
		Total Out	1,051,644	1,003,950		
12	In:	Mountain Front Recharge	912,029	912,000	19,001	19,000
1986-88 (3 yr)		Total In	912,029	912,000		
	Out:	Underflow @ Fairbank	21,118	21,120	440	440
		Pumpage	426,814	427,021	13,483	13,482
		Evapotranspiration	338,223	338,341	7,553	7,700
		Net Stream Leakage	346,878	301,684	5,653	6,450
		Total Out	1,133,032	1,088,166		

Stress Period		Parameter	Model (ac-ft)	Conceptual (ac-ft)	Model (ac-ft/yr)	Conceptual (ac-ft/yr)
13	In:	Mountain Front Recharge	931,015	931,000	18,985	19,000
1989 (1 yr)		Total In	931,015	931,000		
	Out:	Underflow @ Fairbank	21,556	21,560	439	440
		Pumpage	437,856	438,544	11,042	11,523
		Evapotranspiration	345,707	346,041	7,484	7,700
		Net Stream Leakage	352,573	308,134	5,696	6,450
		Total Out	1,157,693	1,114,279		
14	In:	Mountain Front Recharge	950,023	950,000	19,008	19,000
1990 (1 yr)		Total In	950,023	950,000		
	Out:	Underflow @ Fairbank	21,993	22,000	436	440
		Pumpage	448,531	449,700	10,675	11,156
		Evapotranspiration	353,260	353,741	7,553	7,700
		Net Stream Leakage	358,232	314,584	5,659	6,450
		Total Out	1,182,016	1,140,025		
		Change in Storage 1941-90	-231,993	-190,025		
			model	conceptual		

[1] Mountain Front Recharge includes 3,000 ac-ft/yr groundwater underflow in from Mexico. Also includes 1,000 ac-ft/yr ephemeral stream recharge along Greenbush Draw.

[2] Net San Pedro and Babocomari River groundwater baseflow discharge = (Total Gain - Total Loss)

Hydrographs

The final Transient model run was also evaluated by comparing model simulated water level data for selected model cells to hydrographs from wells located within the selected model cells. This provides a better understanding of model behavior in specific areas of the model domain. Figures 26 through 31 present hydrographs of measured water levels versus model simulated water levels for selected locations (refer to Figure 19 for hydrograph locations).

Figure 26: Hydrograph D-21-20 22 BBB1
Model Row 23 Col 11 Layer 2

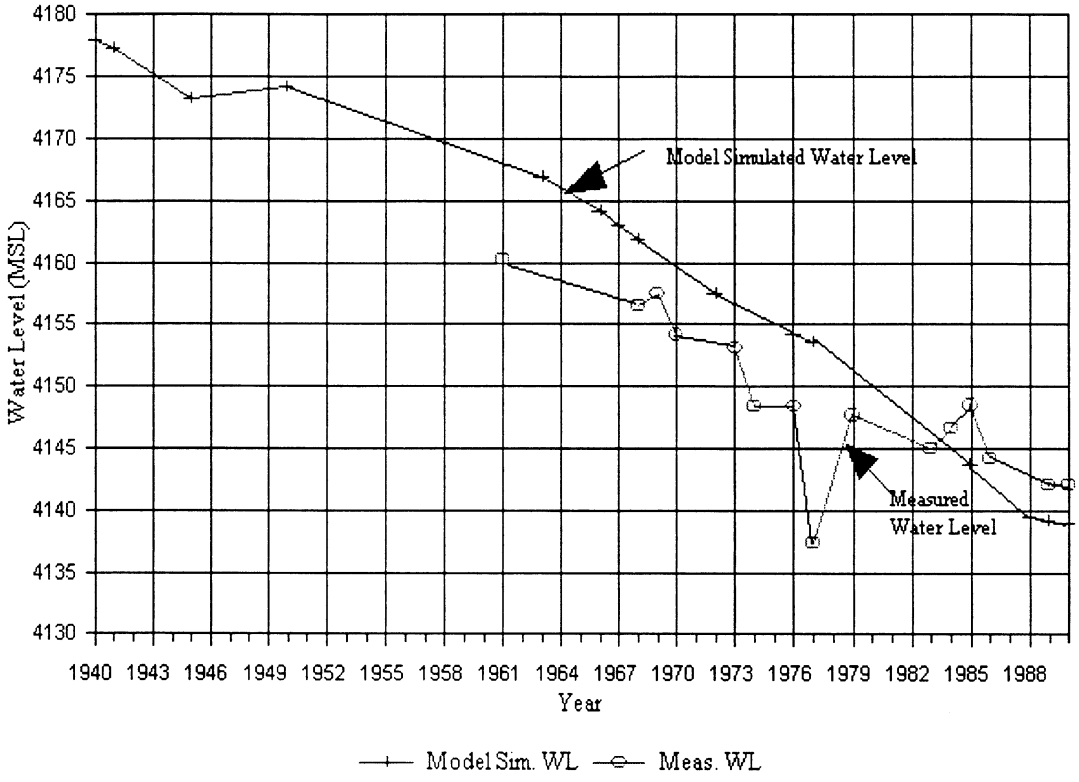


Figure 27: Hydrograph D-21-21 29 CCA
Model Row 28 Col 24 Layer 2

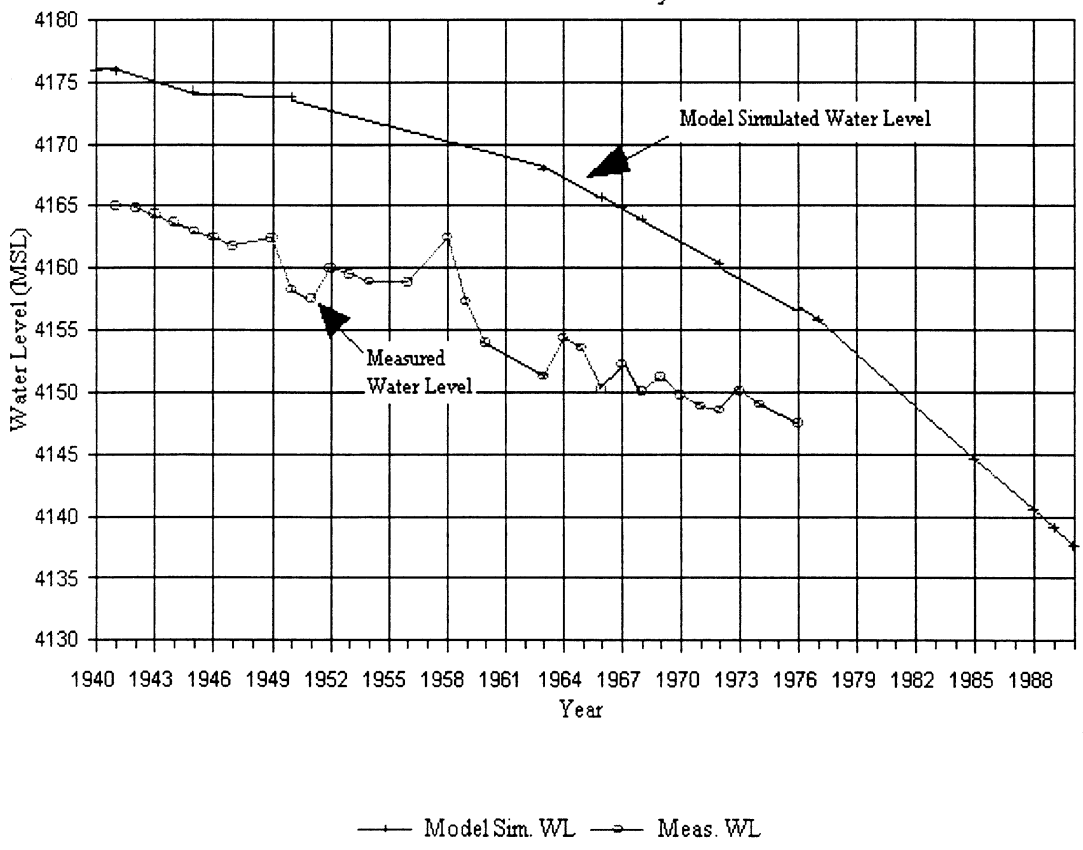


Figure 28: Hydrograph D-21-21 27 CBD
Model Row 29 Col 31 Layer 2

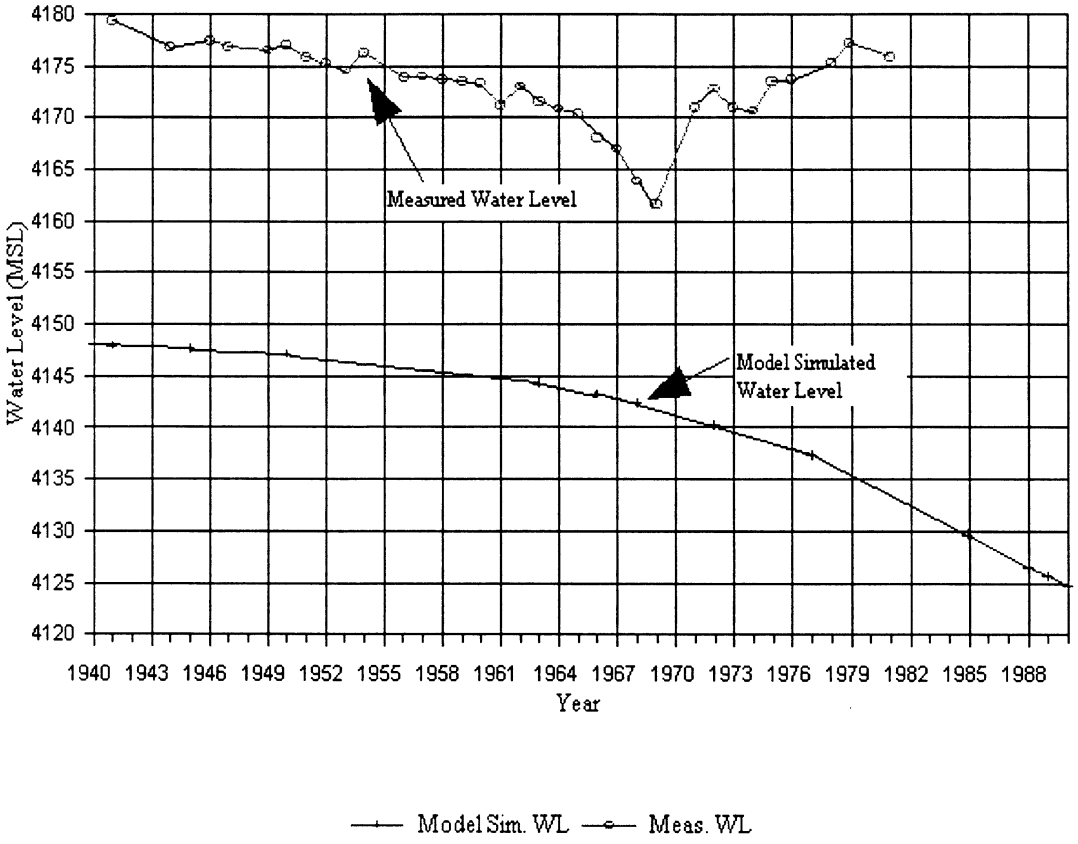


Figure 29: Hydrograph D-23-22 18 BBB
Model Row 49 Col 32 Layer 2

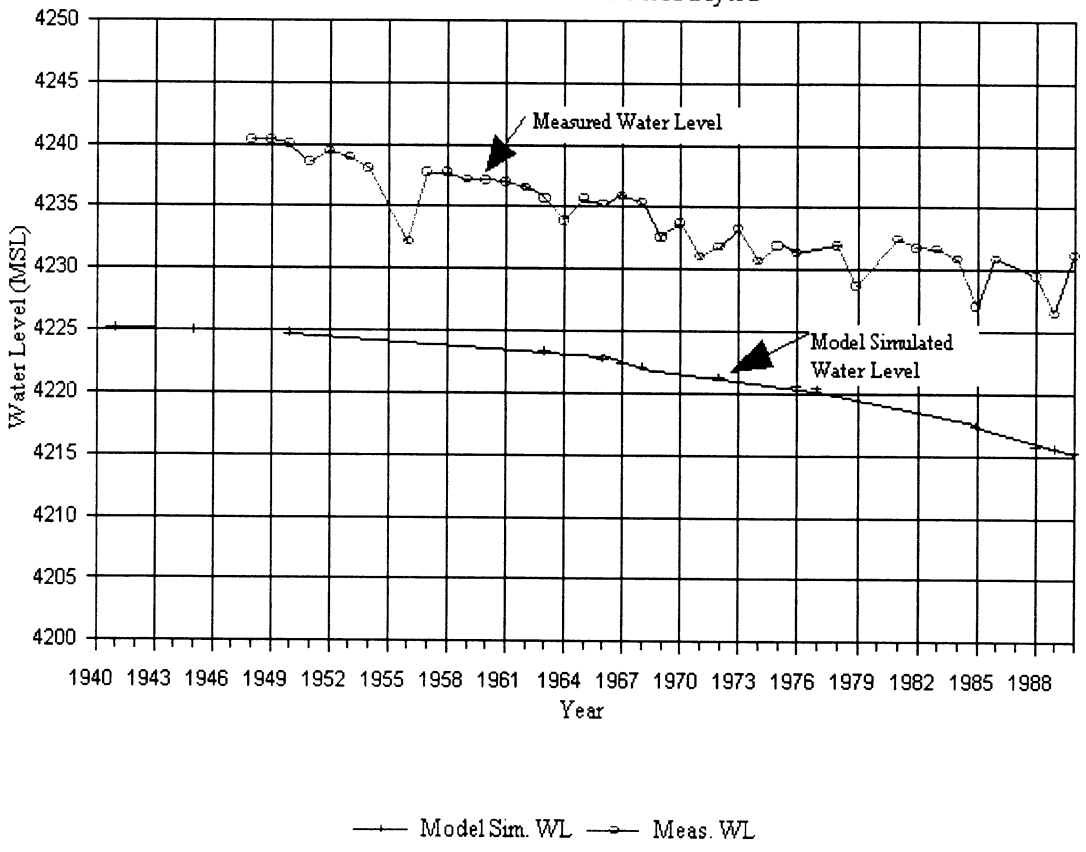


Figure 30: Hydrograph D-23-22 21 CDA
Model Row 54 Col 39 Layer 1

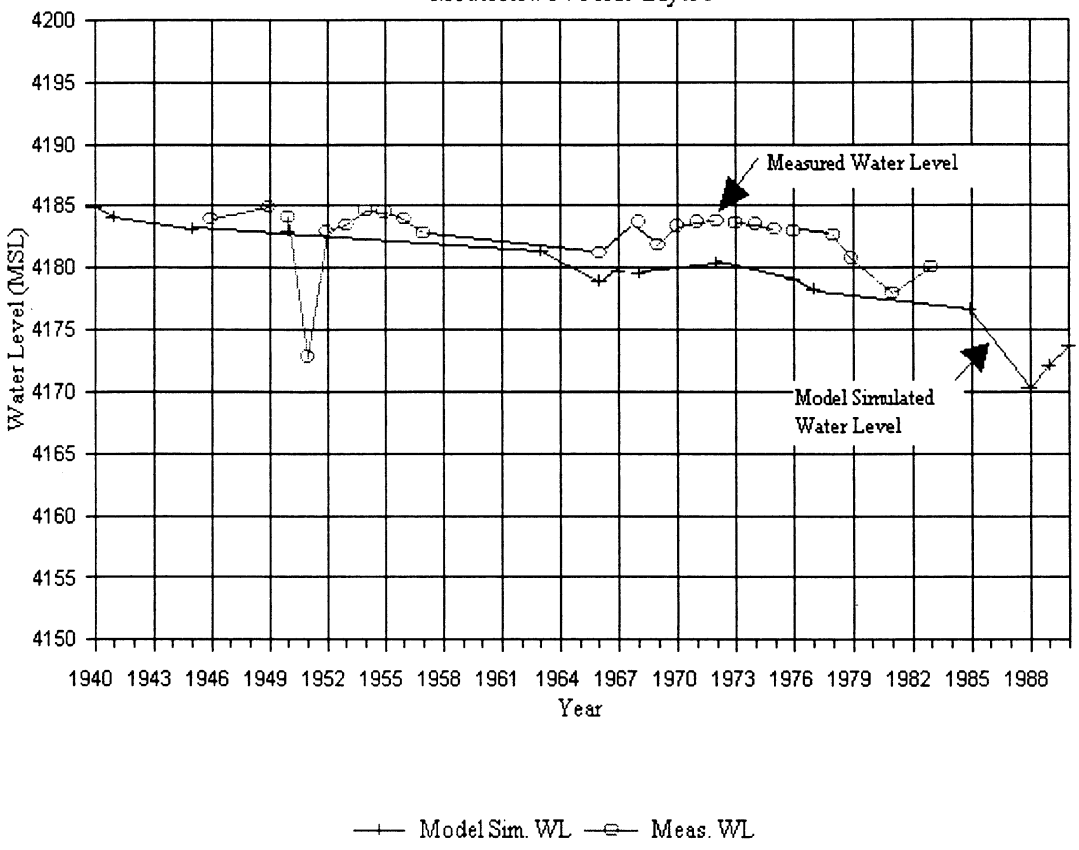
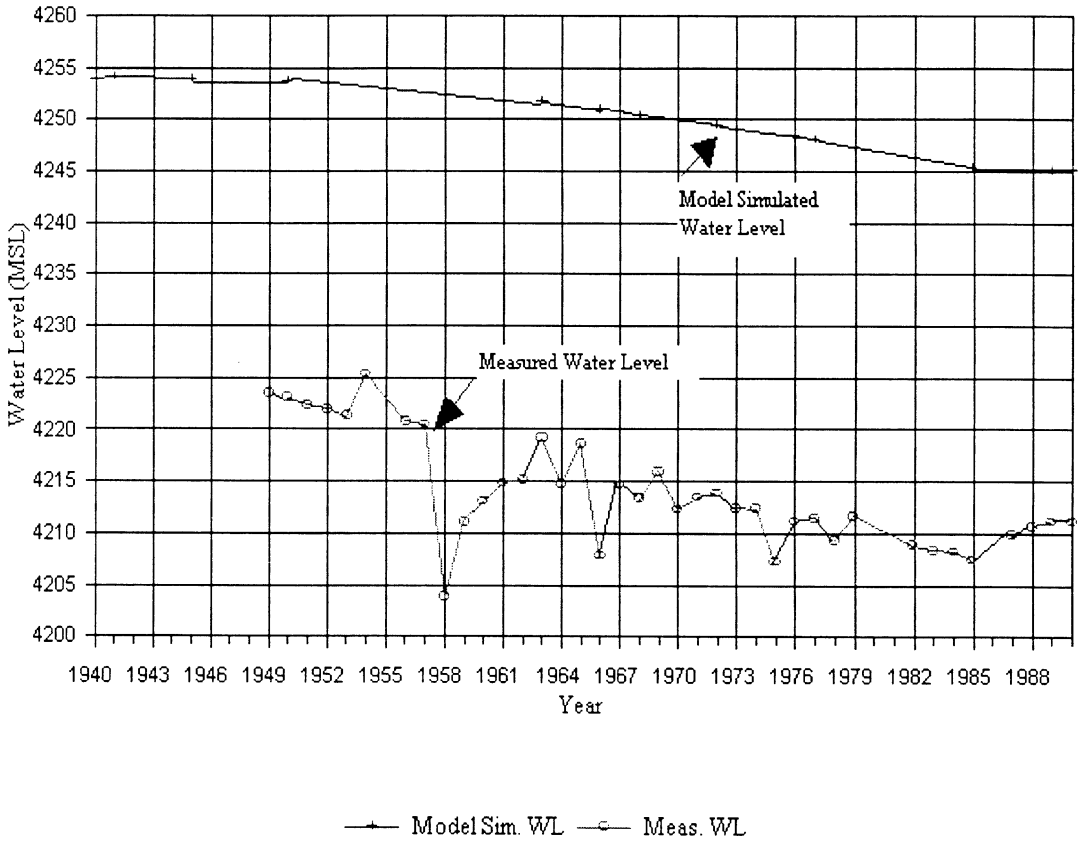


Figure 31: Hydrograph D-24-23 06 AAA1
Model Row 61 Col 51 Layer 2



Streamflow-Routing Package Results

Another criteria for evaluating the Transient calibration was the output of stream flows from the streamflow-routing package. Table 12 presents the comparison of measured streamflow with model-simulated streamflow for stream gage stations. The model-simulated stream flows compare reasonably to the stream gage data. Figures 32, 33, and 34 illustrate model simulated streamflow versus streamflow from the base flow analysis for stress periods 1 to 14 (1941 to 1990).

Table 12
Conceptual vs. Model Estimated Stream Baseflow for Stream Gages, Transient - 1941 to 1990 (mean cfs)

Stream Gage	1941-90 Mean cfs, Conceptual	1941-90 Mean cfs, Model Estimated
Palominas Gage	1.94	2.36
Charleston Gage	8.62	6.97
Tombstone Gage	8.81	9.48

Figure 32 Palominas Gage
Simulated Baseflow vs Meas. Baseflow

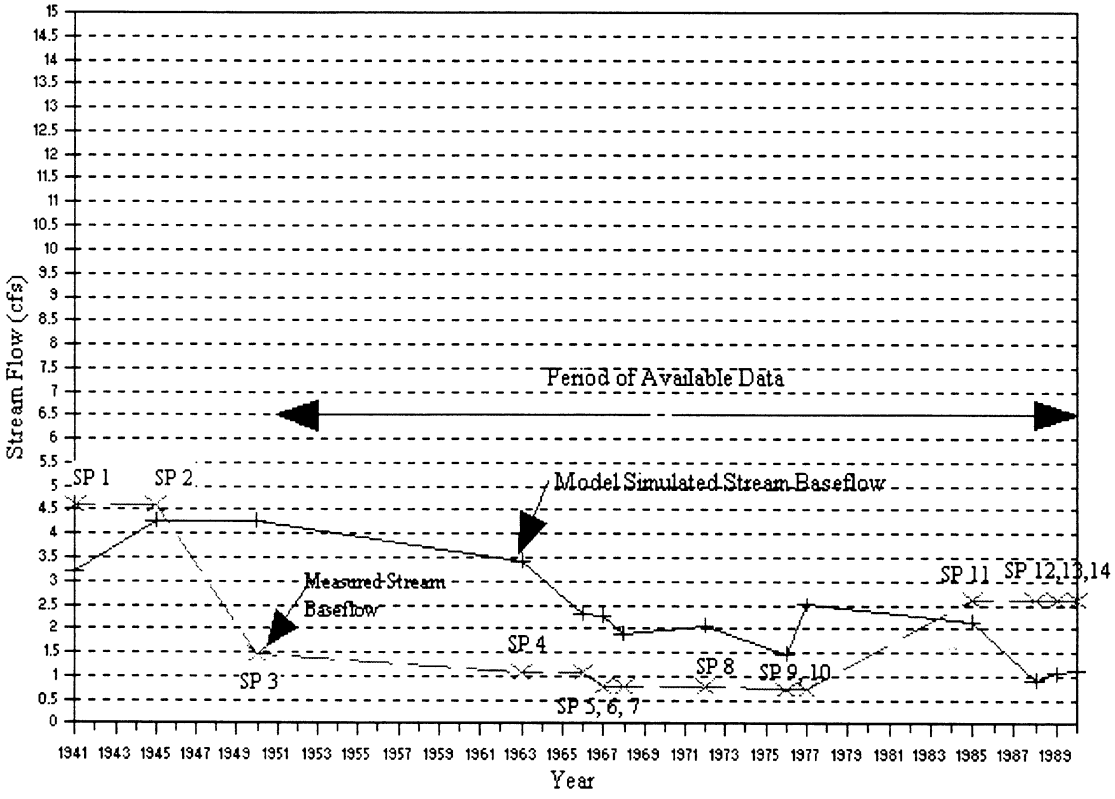


Figure 33 Charleston Gage
Simulated Baseflow vs Meas. Baseflow

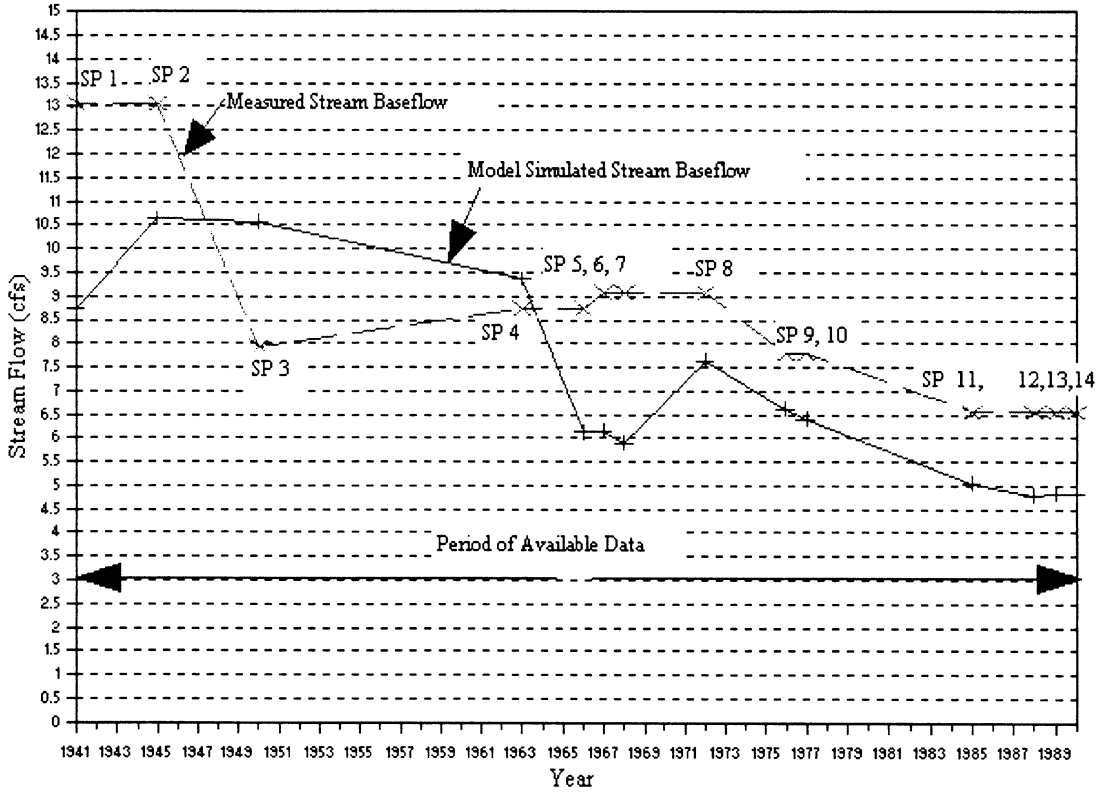
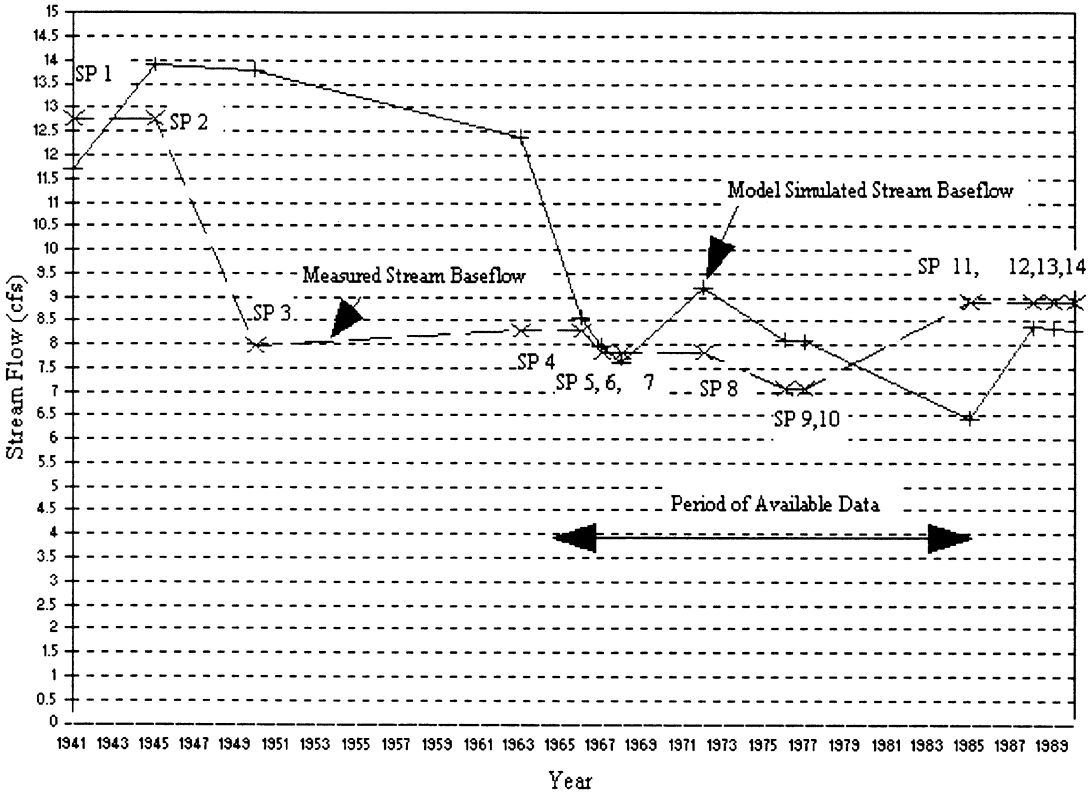


Figure 34 Tombstone Gage
Simulated Baseflow vs Meas. Baseflow



Chapter 5: Summary and Recommendations

Summary

The Upper San Pedro model provides a reasonably comprehensive simulation tool that can adequately represent the response of the Sierra Vista Sub-basin to groundwater withdrawal stress. The model should prove useful as a planning tool to study issues related to the Department's Water Adequacy program and the adjudication of the Gila River watershed, and may also serve to evaluate impacts of various groundwater management and conservation scenarios. It should be noted that the model is regional in scope and extent and therefore was not intended to evaluate site-specific problems or seasonal behavior.

The final report documents the Upper San Pedro model construction and calibration of both the steady-state (circa 1940) and Transient model (1941 to 1990). The purpose of the Upper San Pedro groundwater modeling effort was to expand the model area to incorporate new areas of concern. Also, to provide an analytical tool capable of quantifying the effects of various groundwater management and conservation scenarios and their effects on the San Pedro and Babocomari Rivers and associated riparian areas, floodplain alluvial aquifers, and on the regional aquifer system. The Upper San Pedro model provides a regional understanding of the interrelationships between the groundwater flow system and groundwater pumpage and recharge.

The Upper San Pedro steady-state model simulation attempted to replicate water levels and baseflows for the year 1940. The steady-state model reasonably simulates water levels as illustrated in the scatterplot of Figure A. The model simulated water levels in the final steady-state run served as initial water levels for the Transient model. The Transient model simulated the period from 1941 to 1990, with stress periods ranging from 1 to 13 years. The Transient

model reasonably simulates observed water levels as illustrated in the scatterplot, Figure B, and baseflows as shown in Figures 32, 33, and 34, although the baseflows were projected higher by the model. Improvements in model-estimated streamflow could be made with improved estimates of evapotranspiration and recharge. The conceptual estimates of baseflow may include some component of runoff not accounted for in the model and may include some effects of near-stream pumping.

Recommendations

1. Update the model as data becomes available to improve model calibration for use as a planning tool. The continuing acquisition of new field data is necessary for future improvements as many questions exist regarding aquifer parameters, mountain front recharge, evapotranspiration, and geology.

2. Conduct further analysis of the spatial and temporal distribution of pumpage for the Transient model simulation. As currently modeled agricultural pumpage is estimated based on aerial photo analysis. Model results could be improved by a more accurate location of agricultural pumpage in both time and space, as well as by better knowledge of the vertical distribution of pumpage within the aquifer.

3. Seasonalize model stresses, specifically pumpage, evapotranspiration, and streamflow. As the model is currently constructed, stress periods are as long as 13 years, with such time periods the model lacks the ability to account for seasonal variation in pumpage, streamflow, and evapotranspiration.

4. Continue monitoring and data collection activities related to groundwater levels, surface water flows, evapotranspiration measurements, and surface water/groundwater interactions. The work being done in the Upper San Pedro Basin presents an opportunity to refine our understanding of the hydrology of the basin and to allow better management of the groundwater system so that the many goals for the basin can be integrated.

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Appendix A: Sensitivity Analysis

An analysis of the Upper San Pedro model was conducted to determine how sensitive the model solution is to uncertainty of various hydraulic parameters. The sensitivity analysis analyzed similar hydraulic parameters as in Freethey (1982) and Vionnet and Maddock (1992). As is generally case with numerical models, not all of the input parameters are known completely (uncertainty of the original data). The purpose of the sensitivity analysis is to determine which hydraulic parameters exert the most control over the model solution and therefore, may generate the largest potential errors. Improved understanding (or reduction of uncertainty) of the most influential input components would yield the greatest improvement for future model inputs.

Procedure

The procedure to test the sensitivity of the model consisted of changing a single hydraulic parameter over a reasonable range of values during a series of model runs. Stream bed conductance, evapotranspiration extinction depths, evapotranspiration rates, and vertical conductance between aquifers were hydraulic parameters selected for sensitivity analysis. The model sensitivity to each selected parameter was measured in terms of the mean and standard deviation of the final Transient model run (1941 to 1990) water levels and the simulated water levels for each sensitivity run. The model sensitivity was also measured in terms of the percent change in volumetric budgets and the percent change from the mean stream baseflow (1941 to 1990) simulated in the Transient model. Table 13 compares the mean and standard deviation of water level changes, and the percent change in storage from the final Transient water budget, and the percent change in mean stream baseflow.

Stream bed Conductance

The Stream bed conductance controls the net exchange of water between the stream and the aquifer. The Stream bed conductance was increased by 70 percent, and decreased by 70 percent. When Stream bed conductance was increased above 70 percent the model failed to solve. An increase of 70 percent in Stream bed conductance resulted in an increased average base streamflow of 8.21 percent and increased the volume of water in storage by 11.20 percent. Absolute mean water levels changed by 0.53 feet in Layer 1 (Floodplain Alluvial Unit), 1.86 feet in Layer 2 (Basin Fill Unit), and 3.06 feet in Layer 3 (Conglomerate Unit). Decreasing Stream bed conductance by 70 percent resulted in an increase in the volume of water in storage by 7.04 percent and a change in absolute mean water levels in Layer 1 by 0.92 feet, Layer 2 by 1.64 feet, and Layer 3 by 2.57 feet. Average stream baseflow increased by 9.45 percent. The model sensitivity to changes of these parameters is relatively low for water levels. However, the model is moderately sensitive in terms of fluxes and stream baseflows.

Evapotranspiration Extinction Depth

The evapotranspiration extinction depth is the depth below land surface at which evapotranspiration ceases. The evapotranspiration extinction depth (EVD) was raised from 10 feet to 5 feet below land surface, and increased from 10 feet to 20 feet below land surface. The first simulation (EVD = 5 ft.) indicated a small depletion of the volume of water in storage and an increase in average stream baseflow of approximately 3 percent. Mean absolute water levels remained virtually unchanged (less than 0.5 feet of change in all Layers). Total evapotranspiration also decreased by 3 percent. The second simulation (EVD = 20 ft.) resulted

in a 1 percent increase in the volume of water in storage while average stream baseflows declined by an average of 3.5 percent. Water levels remained unchanged with a mean absolute change of less than 1 foot in all layers, while total evapotranspiration increased by 5 percent. The model sensitivity to changes of these parameters is low for water levels, however it is moderately sensitive in terms of fluxes and stream baseflows.

Evapotranspiration Rate

The evapotranspiration rate (EVT) is the maximum evapotranspiration loss per unit area per unit time. The evapotranspiration rate was increased by 25 percent and decreased by 25 percent. Increasing the evapotranspiration rate by 25 percent resulted in an increase in the volume of water in storage of 2 percent while average stream baseflows declined an average 22.29 percent. Mean absolute water levels changed by an average of 0.8 feet in Layer 1 and an average of 0.3 feet in Layers 2 and 3. Total evapotranspiration increased by 21 percent. Decreasing the evapotranspiration rate by 25 percent showed a decline in the volume of water in storage by approximately 2 percent and an increase in average stream baseflow by an average of 19 percent. Mean absolute water levels changed insignificantly, less than an average 0.5 feet for all Layers. The volume of water consumed by evapotranspiration decreased by 23 percent. The models sensitivity to changes in the evapotranspiration rate low in terms of water levels. However, the model is very sensitive to changes in the evapotranspiration rate in terms of fluxes and stream baseflow.

Vertical Conductance Layer 2 - Layer 1

The vertical conductance (Vcont) between the Basin Fill Unit and the overlying Floodplain Alluvial Unit (Layer 2 and Layer 1) was increased by factors of 10 and 100, and decreased by a factor of 0.5. The results from the first simulation (VCONT * 10) indicated an 8 percent increase in the volume of water in storage and a 3.7 percent increase in average stream baseflow. Mean absolute water levels changed an average of 0.5 feet for Layer 1 and an average 1.25 feet in Layers 2 and 3. Results from the second simulation (VCONT * 100) indicated a 9 percent increase in the volume of water in storage and a 4.8 percent average stream baseflow increase. Water levels changed less than 5 feet on average for Layer 1, and 1.4 feet on average for Layers 2 and 3. In addition to increasing Vcont a model simulation was run with Vcont between Layer 2 and 1 decreased by a factor of 0.5. This resulted in a decrease in the amount of water in storage by 6.6 percent as well as a decrease in average stream baseflow of 5.5 percent. Mean absolute water levels changed insignificantly, less than 1 foot in all Layers. The models sensitivity to changes in vertical conductance between layer 2 to layer 1 is low in terms of water levels and moderately sensitive in terms of fluxes and stream baseflows.

Vertical Conductance Layer 3 - Layer 2

The Vcont between the Conglomerate Unit and the overlying Basin Fill Unit (Layer 3 and Layer 2) was increased by factors of 10 and 100, and decreased by a factor of 0.5. The first simulation (VCONT * 10) indicated an increase in the volume of water in storage of 10.5 percent. Average stream baseflow increased by an average of 8.7 percent while mean absolute water levels changed by less than 0.5 feet in Layer 1, 1.8 feet in Layer 2, and 3 feet in Layer 3. The second

simulation (VCONT * 100) indicated an increase in the volume of water in storage of over 12 percent and an increase in average stream baseflow of 10.6 percent. Mean absolute water levels changed in Layer 1 by less than 0.5 feet, in Layer 2 by over 2 feet, and in Layer 3 by 3.5 feet. The final simulation (VCONT * 0.5) resulted in a decrease in the volume of water in storage of 7.8 percent and a decrease in average stream baseflow of 2.6 percent. The mean absolute water levels changed in Layer 1 by an average of 0.45 feet, Layer 2 by 1.3 feet, and Layer 3 by 2.3 feet. The models sensitivity to changes in Vcont between Layers 3 and 2 is low in terms of water levels, however, the model is moderately sensitive in terms of fluxes and stream baseflows.

Conclusions

The results of the sensitivity analysis indicate that the model is low to moderately sensitive to changes in Stream bed conductance, evapotranspiration extinction depth, and vertical conductance for the selected range of parameter changes. The model is more sensitive to changes in the evapotranspiration rate, especially in terms of fluxes and streamflows. The model is generally more sensitive in terms of the models simulated stream baseflows than in terms of the models simulated water levels. Changes in Stream bed conductance resulted in increased average stream baseflow and increases in the volume of water in storage. Increases in the evapotranspiration rate resulted in a significant decrease in average stream baseflow and an increase in storage while decreases in evapotranspiration rates resulted in an increase in average stream baseflow and a decrease in the volume of water in storage. Changes in vertical conductance demonstrate that the model is more sensitive to vertical conductance changes between Layers 2 and 3 than between Layers 1 and 2. Changes to vertical conductance between Layers

2 and 3 had the effect of significantly changing average stream baseflows as well as the volume of water in storage and the absolute mean water levels in Layer 2 and 3. Confining the 3 alluvial units, by decreasing the vertical conductance, demonstrated more sensitivity as compared with increasing the vertical conductance. Water levels in Layer 1 exhibit small changes during the sensitivity analysis which can be explained by Layer 1 being the flood plain aquifer and comprising a relatively small area of the model.

Future data collection efforts may improve the sensitive hydraulic parameters of the model. Analysis of a greater number of well logs may improve model inputs for vertical conductance. Remote sensing capabilities and field studies of vegetation along the model area will enhance of evapotranspiration rates reducing the sensitivity of the model.

Table 13

Summary of Sensitivity Statistical Analysis
Sensitivity Simulated Water Levels Minus Final Calibrated TR Water Levels (feet)

Model Input Parameters	Layer 1		Layer 2		Layer 3		Percent Change in Storage	Percent Change in Avg. Stream Baseflow		
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation		Palomin as	Charleston	Tombstone
Stream bed Conductance 70% Increase	.53	1.03	1.86	3.16	3.06	2.37	11.20	10.76	6.74	7.14
Stream bed Conductance 70% Decrease	.92	.95	1.64	3.04	2.57	2.45	7.04	16.06	6.84	5.44
EVT Extinction Depth raised to 5'	.17	.50	.04	.20	.03	.16	-.95	5.67	1.62	2.50
EVT Extinction Depth Deepened to 20'	.85	2.04	.20	.58	.20	.50	1.40	-3.94	-3.37	-3.78
EVT Rate Increased 25%	.82	1.84	.29	.69	.29	.60	2.11	-32.89	-15.55	-18.44
EVT Rate Decreased 25%	.24	.76	.11	.31	.11	.31	-1.93	35.28	19.59	2.34
Vertical Conductance L2 to L1 x 10	.49	1.05	1.24	1.93	1.26	1.81	8.10	-1.06	6.73	5.39
Vertical Conductance L2 to L1 x 100	.55	1.12	1.40	2.21	1.42	2.07	9.19	-1.27	9.01	6.57
Vertical Conductance L2 to L1 x .5	.57	1.23	.82	1.12	.82	1.06	-6.65	-7.64	-4.36	-4.64
Vertical Conductance L3 to L2 x 10	.41	.94	1.79	3.14	2.98	2.36	10.54	12.31	6.90	6.98
Vertical Conductance L3 to L2 x 100	.42	.94	2.13	3.63	3.49	2.68	12.42	15.22	8.04	8.50
Vertical Conductance L3 to L2 x .5	.45	1.14	1.28	2.40	2.32	1.98	-7.80	.09	-4.28	-3.71

Notes: All differences are changes between the final Transient water levels or water budget component and the sensitivity run.

EVT = Evapotranspiration
Percent Change in Storage = percent change in storage from the calibrated change in storage for the entire model

Appendix B: Model Input Data

The MODFLOW data files for the Arizona Department of Water Resources Upper San Pedro model for both steady-state and Transient-state are on diskette at the end of this report. All model packages are standard ASCII text format and can be read with most text editors. The files on diskette labeled "ADWR Upper San Pedro MODFLOW Model Packages" are as follows:

Steady-State Data Files:

BAS Data File	USPSSBAS.DAT
BCF Data File	USPSSBCF.DAT
WEL Data File	USPSSWEL.DAT
EVT Data File	USPSSEVT.DAT
RCH Data File	USPSSRCH.DAT
OCL Data File	USPSSOCL.DAT
STR Data File	USPSSSTR.DAT
PCG Data File	USPSSPCG.DAT

Transient-State Data Files:

BAS Data File	USPTRBAS.DAT
BCF Data File	USPTRBCF.DAT
WEL Data File	USPTRWEL.DAT
EVT Data File	USPTREVT.DAT
RCH Data File	USPTRRCH.DAT
SIP Data File	USPTRSIP.DAT
OCL Data File	USPTROCL.DAT
STR Data File	USPTRSTR.DAT