DRAFT

RIPARIAN PROTECTION PROGRAM

LEGISLATIVE REPORT

VOLUME B

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CASE STUDIES REPORT

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INTRODUCTION

The purpose of this chapter of the report was to conduct indepth evaluations of some important riparian systems in the State. Due to time constraints associated with this project, evaluations were limited to three stream segments; the upper San Pedro River, the upper Santa Cruz River, and the Verde Valley portion of the Verde River. These river reaches are similar in some respects, particularly the upper Santa Cruz and San Pedro Rivers, but differences associated with ecology, climate, land and water use impacts, potential future growth and development, and available ecologic and hydrologic data made each evaluation unique. Specific reasons for individual site selections are discussed in each case study section.

Methodologies used to evaluate riparian ecosystem and hydrologic interactions included the application of (1) numeric, analytic, and hydrologic models, (2) ecologic field studies and response models, (3) remote sensing (satellite imagery), aerial photography, and Geographic Information Systems, and (4) existing hydrologic, climate, and land and water use information. Surface water, groundwater, climate, and land and water use information was available, in variable amounts, for all case study areas. However, time constraints and data availability precluded the development and/or application of models, satellite imagery, aerial photography, and GIS information to all three case study areas. Therefore, a second objective of these studies was to demonstrate the role the different approaches could play in assessing ecologic impacts resulting from groundwater and surface water depletions.

The individual approaches applied to each case study area are as follows:

Upper San Pedro River - numeric and ecologic groundwater models

Upper Santa Cruz River - remote sensing, aerial photography, and ecologic and analytic groundwater models

Verde River - instream flow and analytic groundwater models

The remaining portion of this chapter is divided into three individual, detailed case study sections. The San Pedro River study is presented first, followed by the Santa Cruz and Verde River studies, respectively. Each case study section contains an individual discussion of conclusions and recommendations.

UPPER SAN PEDRO CASE STUDY

INTRODUCTION

This section of the report provides a hydrologic assessment of surface water and groundwater in the Upper San Pedro (USP) basin and uses the available information in this area to study the effects of groundwater pumping on riparian areas in this basin. This site was chosen for the following ecologic and hydrologic reasons:

- The San Pedro River is perennial or very nearly so for the entire reach through the study area.
- Presence of a healthy riparian ecosystem, including cienega vegetation, cottonwood-willow forests, and other vegetation types associated with the San Pedro River in the study area.
- A numerical groundwater flow model has been developed for this area; currently it is in the process of being revised and updated to include more of an interactive surface water/groundwater system. It is a tool that will be used as part of the water resources planning process within the basin.
- Much ecologic and hydrologic data exists for this area.

This site was chosen for the following institutional reasons:

- The San Pedro Technical Committee, a local planning group made up of various constituents throughout the USP basin, is actively working towards collective management of the area's water resources. This is a diversified group of people who have a vested interest in the water resources of the basin.
- The USP basin is outside of an Active Management Area (AMA), with virtually no departmental regulation of the water resources within this area.
- It is one of the first watersheds within the state of Arizona being adjudicated.
- The Bureau of Land Management (BLM) has a certificated instream flow water right for the San Pedro River within the study area.
- There is a high potential for future development within the basin.

DESCRIPTION OF THE AREA

The USP basin is located in southeastern Arizona about 50 miles southeast of Tucson, (Figure 1, Chapter II, and Plate 1). The basin boundaries are defined by ADWR (1982) as "the surface watershed of the San Pedro River from the Republic of Mexico downstream to the area referred to as "The Narrows" north of Benson, and in addition, the upper drainage areas of Hot Springs and Kelsey Canyons which enter the San Pedro River north of "The Narrows"." The basin can be split into the Sierra Vista and Allen Flat sub-basins (Putman and others, 1988). The sub-basins are bounded to the east by the Mule, Dragoon, Little Dragoon, John Lyon, and Winchester mountains and on the west by the Huachuca, Mustang, Whetstone, Little Rincon, and Santa Catalina mountains. The elevations of the mountains range in height from 5,000 feet to nearly 10,000 feet above mean sea level (msl). Elevations along the river varies from 4,275 feet above msl at the international border to approximately 3,300 feet at "The Narrows" north of Benson.

For this project the study area was limited to the USP basin between the international border to approximately 3 miles north of the Tombstone Gage located northwest of Tombstone, Arizona (total drainage area upstream of the gage of 1,730 square miles). The San Pedro River, within the study area, is approximately 30 miles long and slightly incised into the broad alluvial valley. Roeske and Werrell (1973) calculated the slope of the river at 16 feet per mile. The San Pedro River is largely perennial in the USP basin and is intermittent in most other reaches. Intermittent stream reaches flow seasonally in response to climatic variations and water use. The major tributary to the San Pedro River, within the study area, is the Babocomari River which is ephemeral except for certain perennial reaches.

Currently, the San Pedro River is in a state of widening, including sand bar development, and accretion of sediments on floodplains (Jackson and others, 1987). However, entrenchment of the river is believed to have occurred between 1880 to 1926 (Jackson and others, 1987). Hereford (1993) stated that a series of large floods in the late 1800s to the early 1900s was the primary cause of entrenchment in this area. Other factors that probably contributed to this entrenchment were cattle grazing and regional settlement around the turn of the century.

The major population center within the USP basin is the city of Sierra Vista including Ft. Huachuca. The 1992 population of Sierra Vista (including Fort Huachuca) was estimated at 33,725 people (Arizona Department of Economic Security, 1993). There are no major diversionary structures on the San Pedro River within the study area. However, two major diversions divert flow of the river downstream of the study area. These include the St. David Ditch and the Pomerene Canal. At times of low flows, these diversions take the entire flow of the river.

Riparian Vegetation

The riparian vegetation that grows along the San Pedro River today is a product of present environmental influences as well as past influences. In the late 1980s, much of the Upper San Pedro River was designated by Congress as a Riparian National Conservation Area (SPRNCA). It is now managed for its natural riparian values. Cattle grazing, which occurred on most of the San Pedro floodplain, is now restricted from the SPRNCA. Large portions of the upper floodplain terrace were cleared for agriculture, but these agricultural lands were purchased and retired from farming. Sand and gravel mining, which had taken place in localized areas, are no longer allowed within the SPRNCA. Groundwater was pumped from the floodplain aquifer, but such pumping has been discontinued within the SPRNCA.

The San Pedro River floodplain is vegetated by a complex mosaic of species, each of which is adapted to different environmental conditions. Species that have similar distribution in the floodplain can be grouped into associations. Each species in the floodplain has its own tolerance range for factors such as depth to groundwater, flood disturbance, drought, soil saturation, soil salinity, soil nutrient level, soil texture, temperature, light availability, herbivory and grazing, and competition from other plants. Moisture gradients, including gradients of depth to groundwater, are of primary influence in structuring the riparian community, that is, in influencing which plants grow where they do within the floodplain and in what abundance and vigor.

One of the dominant riparian associations along the Upper San Pedro River is the Fremont cottonwood- Goodding willow (*Populus fremontii- Salix gooddingii)* series of the Warm Temperate Interior Riparian Deciduous Forest (Brown, 1982). Because of the relatively high elevation of the Upper San Pedro River (about 1300 m, or 4000 ft), this association also contains several warm-temperate mixed broadleaf trees including Arizona walnut (*Juglans major*). The Upper San Pedro River supports one of the best remaining examples of this formerly widespread riparian vegetation type. Intermixed with the cottonwoods and willows, however, are relatively extensive stands of riparian scrub (shrublands) vegetated by such species as burro-brush (*Hymenoclea monogyra*) and rabbit-brush (*Chrysothamnus nauseosus*). Although a natural component of the San Pedro riparian zone, a high abundance of this riparian type is indicative of degraded conditions (Brown, 1982).

The Upper San Pedro River also is notable for supporting marsh (cienega) associations in places along the river. The San Pedro floodplain also supports the most extensive remaining stands of riparian sacaton (*Sporobolus wrightii*) grasslands in Arizona, as well as woodlands (bosques) of velvet mesquite and netleaf hackberry (*Prosopis velutina-Celtis reticulata).*

Local Climate

Due to its relatively higher elevation, this area usually does not experience the extreme summer heat as do other areas in the southern part of the state. The temperatures within the Sierra Vista sub-basin generally average 63° F, with an overall range between 6° F and 113° F. Summers are moderately warm. Table 1 provides average monthly precipitation and temperature data (for the period of record: 1954-1962, 1964, 1966-1967, 1970-1992) for Tombstone, Arizona.

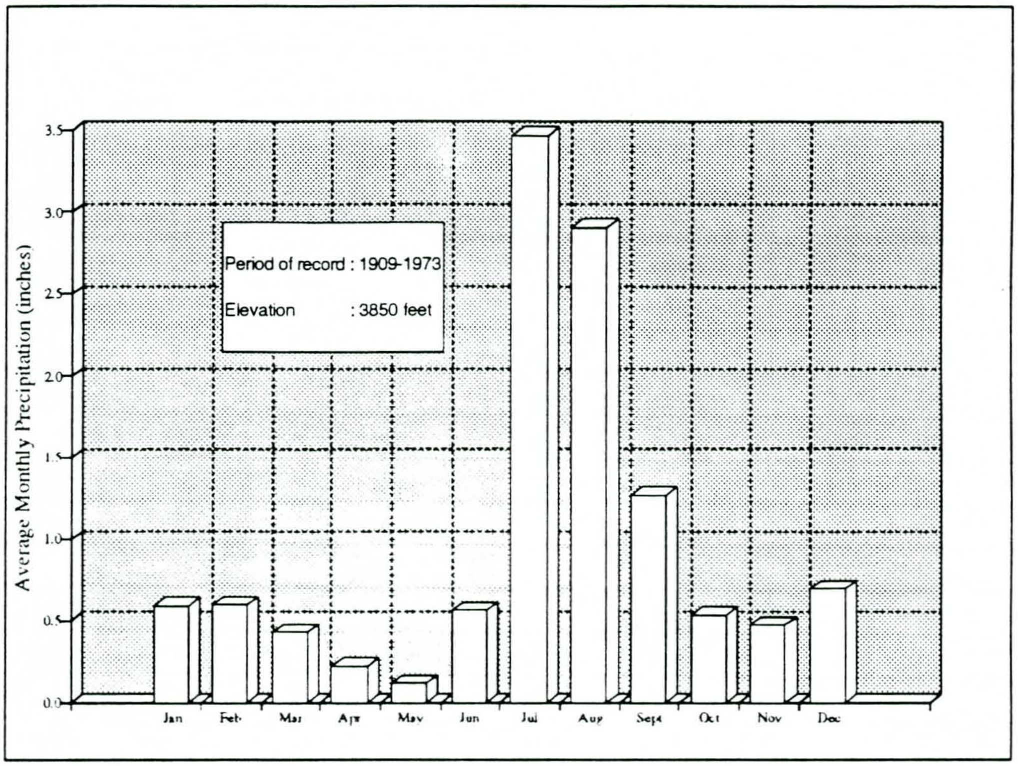
Table 1
Summary of Climatological Data for Tombstone, Arizona

Month	Precipitation (Inches)	Degrees Fahrenheit	
		Maximum Temperature	Minimum Temperature
JAN	0.87	59.8	34.4
FEB	0.75	63.4	36.7
MAR	0.65	68.7	40.2
APR	0.27	77.1	46.3
MAY	0.20	85.0	53.5
JUNE	0.48	94.2	62.1
JULY	3.54	92.8	65.5
AUG	3.35	90.0	64.2
SEP	1.52	87.6	60.4
OCT	0.81	79.4	51.4
NOV	0.60	68.4	41.3
DEC	.093	60.1	35.3
ANNUAL	14.3	77.6	49.6

Source: National Climatic Data Center, 1993

Precipitation in this area follows the general pattern for much of Arizona with most of the moisture accumulating during the winter months and the summer monsoons. The winter precipitation is from large cyclonic storms originating over the North Pacific Ocean. The summer monsoons are localized intense thunderstorms deriving their moisture from the Gulf of Mexico and the Gulf of California (Sellers and Hill, 1974). The basin receives 50% to 60% of the annual rainfall from July to September and 21% from December to February (Schwartzman, 1990). Figure 1 shows the average precipitation on a monthly basis for the period of record at Fairbank, Arizona. This data is representative of the climate in the study area near the San Pedro River.

Figure 1. Average monthly precipitation at Fairbank, Arizona.



This graph shows the seasonal variations in the amount of precipitation for each year, indicating that the months of July through September are months of high precipitation and the months of April and May have low precipitation. The higher elevations of the Huachuca, Rincon, and Santa Cruz mountains have a mean annual average precipitation ranging between 25 to 30 inches. At Fort Huachuca the mean annual precipitation is about 15 inches per year, however, the mean annual precipitation is usually below 12 inches per year along the San Pedro river (Putman and others, 1988; ADWR, 1991). The mean monthly runoff as a percentage of the annual runoff for the San Pedro River at Palominas and at Charleston is shown in Figure 2. Although the period of records are dissimilar, generally, most of the runoff occurs during the summer monsoonal season (July, August, and September) and correlates well to the precipitation data presented Figure 1.

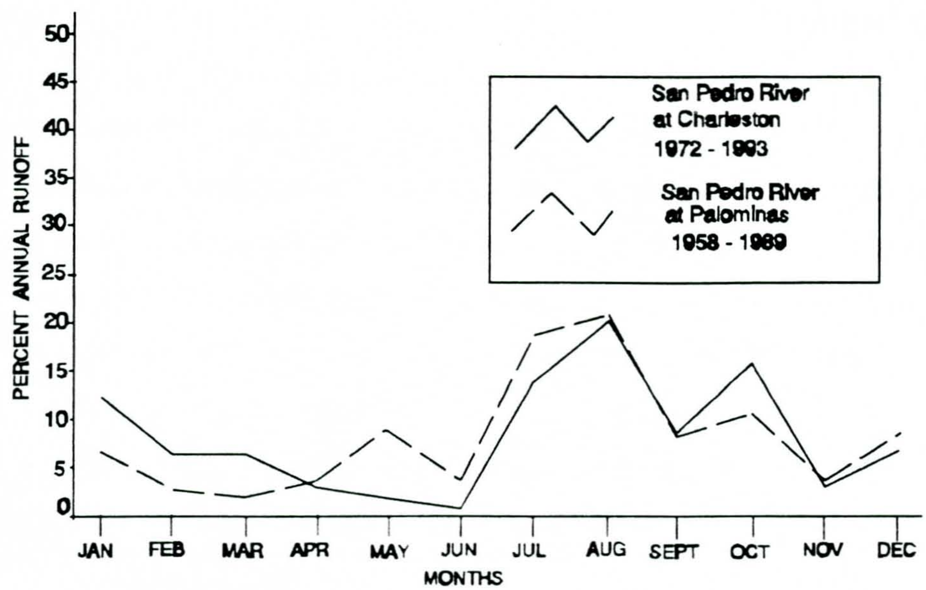
Geologic Setting

The USP basin lies within a major northwest structural trough that is bounded by mountain ranges on both sides (Drewes, 1980). These mountain ranges and the crystalline basement rocks are generally composed of Precambrian to Tertiary age schists, granites, diorites, monzonites, quartzite, shale, limestone, dolomite, sandstone, and volcanics (Gullily, 1956; Drewes, 1980; Usunoff, 1984; Putman and others, 1988). Crystalline basement rocks generally have relatively low porosity and primary permeability, making them poor aquifers. In areas where jointing, fracturing, or faulting have increased porosity and permeability, these rocks may produce a significant amount of water (Putman and others, 1988).

These rocks also form the structural basin of the San Pedro River valley. Unconsolidated alluvial material unconformably overlies the basement rocks and consists of lacustrine valley fills and stream deposited sediments eroded from the adjacent mountains (Melton, 1965, Jackson and others, 1987). The alluvial deposits that fill the basin and make up the water bearing units in ascending order, consist of the Pantano Formation, and the basin fill, which can be divided into a lower and upper unit, and the floodplain alluvium.

Rocks of the Pantano Formation form the lower aquifer in the Sierra Vista-Fort Huachuca area and is in direct hydraulic connection with the overlying basin fill deposits (Putman and others, 1988). It is generally a semiconsolidated conglomerate with a matrix grain size ranging from coarse sandstone to silt, with clasts of granite,

Figure 2. Mean Monthly Runoff as a Percent of Annual Runoff for the San Pedro River at Palominas and at Charleston.



limestone, volcanics, and other rock types, ranging from pebbles to boulders in size (up to 4 ft. in diameter) (Brown and others, 1966; Putman and others, 1988). The individual beds, usually exhibiting lenticular bedding can range in thickness from a few inches to a few feet (Brown and others, 1966). Within the study area the Pantano Formation ranges between 500 and 1,200 feet thick (Putman and others, 1988). In the Sierra Vista-Fort Huachuca area the Pantano Formation produces relatively small to moderate amounts of water that are generally limited to fractured zones (Brown and others, 1966).

Unconsolidated to semi-consolidated basin fill alluvium lies unconformably above the Pantano Formation. The basin fill is usually divided into two units, an upper basin fill and a lower basin fill. The lower basin fill is upper Pliocene to middle Pleistocene in age and consists of interbedded sandy clay, silty sand, sandstones and gravels, ranging from fine to coarse grained with occasional pebbles (Usunoff, 1984; Putman and others, 1988). This unit lies below the regional water table in the Sierra Vista-Fort Huachuca area and is in direct hydraulic connection with the overlying saturated portion of the upper basin fill (Putman and others, 1988) These sediments generally fine upward and laterally toward the center of the valley. Reported thicknesses of the lower basin fill range between 150 to 500 feet (Brown and others, 1966; Harshbarger and Associates, 1979; Jackson and others). The lower basin fill is estimated to be over 1,000 feet thick in the center of the valley and generally thins towards the mountains and the Narrows north of Benson (Roeske and Werrell, 1973; ADWR, 1991). Hydraulic properties of the lower basin fill are extremely variable from place to place in the basin due to poorly sorted and cemented sediments.

The upper basin fill unit is of middle to late Pleistocene in age and composed of very permeable flat-lying sediments. These consist of weakly cemented and compacted clay, gravel, sand, and silt. This unit grades from permeable alluvial fan gravels near the mouths of streams issuing from the Huachuca mountains to relatively impermeable well-bedded, limey clay in the central part of the basin (Brown and others, 1966; Roeske and Werrell, 1973; ADWR, 1991). The upper unit normally ranges in thickness from less than 10 feet in the center of the valley to 800 feet in the upper part of the valley, but typically pinches out within 3 miles of the river (Brown and others, 1966; Worthington, 1987). In the northern part of the San Pedro River valley, outside the study area, erosion has removed most of this unit (Roeske and Werrell, 1973; Harshbarger and Associates, 1979).

The floodplain alluvium is of Quaternary age and unconformably overlies the basin fill alluvium. It consists of highly permeable unconsolidated gravel, sand, and occasionally silt along the channels, floodplains, and terraces of the San Pedro River (Roeske and Werrell, 1973; Putman and others, 1988). These deposits can range from 40 to 150 feet thick and from a few hundred yards to several miles in width (Roeske and Werrell, 1973; Putman and others, 1988). The floodplain alluvium varies from 5 to 30 feet thick along minor tributaries (Brown and others, 1966). It forms a very productive aquifer along the San Pedro and Babocomari Rivers. The floodplain alluvium is commonly underlain by clay lenses in the basin fill, which may create local confining beds. This occurs and has been documented in the Palominas-Hereford area within the study area.

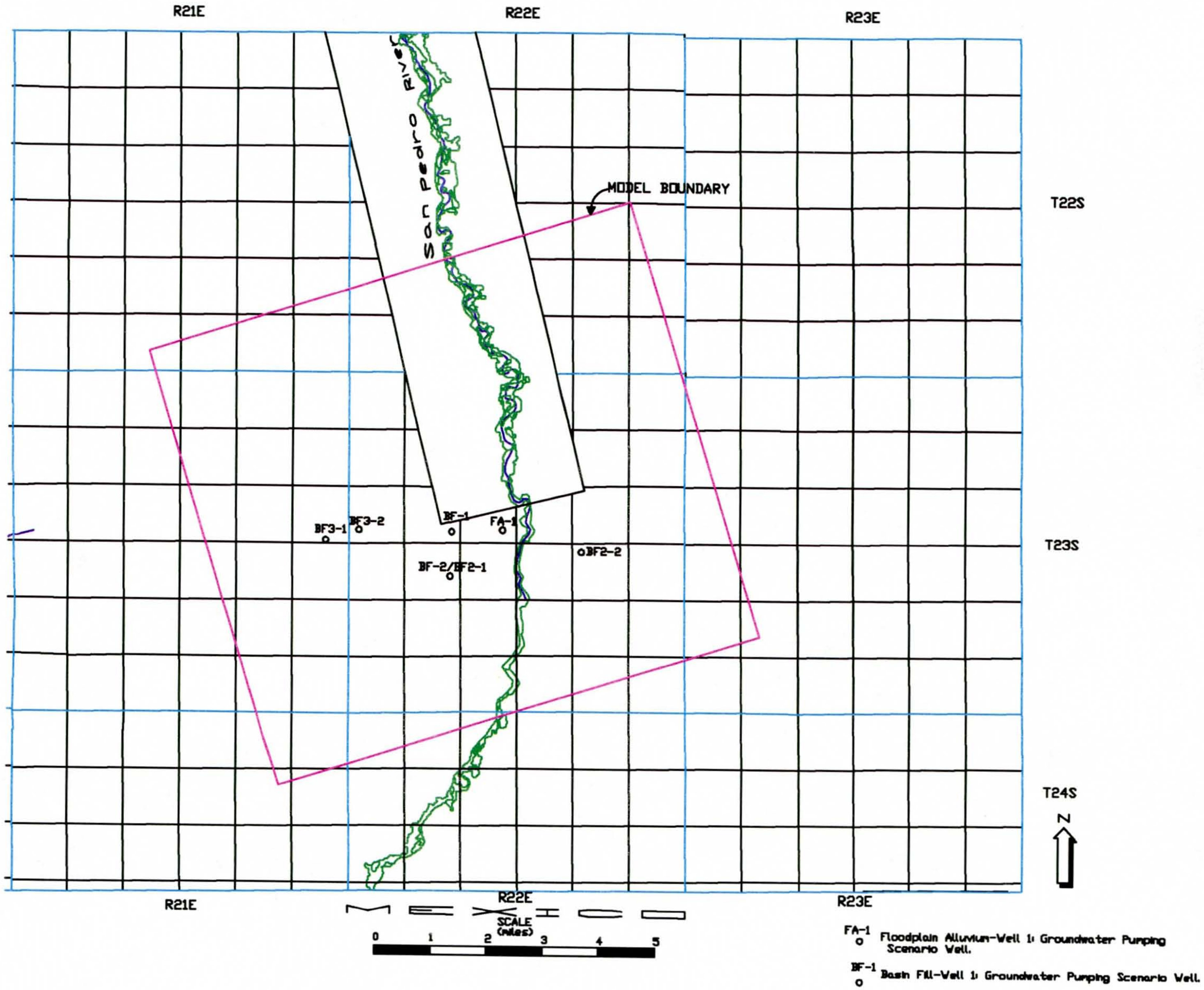
METHODS

Ecological consequences of groundwater decline along the upper San Pedro River were predicted from two types of models, used in conjunction: (1) hydrological models that use numerical techniques to predict rate and extent of groundwater decline associated with various rates of pumping from wells located in the floodplain and basin fill aquifers, and (2) ecologic models, that use quantified relationships between depth to groundwater and plant composition and stand structure as the basis for predicting future change.

Numerical Groundwater Flow Model

A numerical finite-difference groundwater flow model code (MODFLOW) developed by the USGS (McDonald and Harbaugh, 1988) was used to evaluate four different pumping scenarios within a portion of the USP basin (Figure 3; and Plate 1). For ease of discussion it will be called a vertical slice model as it represents a sub-area of a regional model and it extends from the mountain fronts to the river (i.e., representing a "slice" of the basin) The vertical slice model also incorporated a Streamflow Routing

FIGURE 3
LOCATION MAP OF THE VERTICAL SLICE
MODEL AREA



Package by Prudic (1989) that allows interactive simulation of streamflow (i.e., it accounts for gaining or losing streamflow reaches between the stream and the aquifer). The majority of the data used in the model was taken from a report by Freethey (1982), who previously developed a regional numerical groundwater flow model for the USP basin. A complete presentation of the vertical slice model development is given in appendix E.

As shown in Figure 3, (and Plate 1) the model encompassed an area west of Nicksville extending in a northeasterly direction to the San Pedro River near Palominas and Hereford covering an area of 72 square miles. This area was chosen because there is a streamgage at Palominas, the streamflow has a gaining nature in the model reach, because it is the lower extent of the SPRNCA, and because there is potential for future growth in this area. The vertical slice model incorporates mountain front recharge, underflow into the basin from Mexico, underflow out of the model domain, gaining streamflow conditions, evapotranspiration due to the riparian area within the model boundaries, and pumpage (for further information see Appendix E). The model consists of 38 rows, 28 columns, and 3 layers. A variable grid size was used to obtain better resolution in the riparian area (i.e., the floodplain alluvium). Model cells in this area are 1,320 feet long by 660 feet wide. The layers replicate the younger alluvium, and two layers of basin fill material. Layer 1, the uppermost layer corresponds to the floodplain alluvium, and layer 2 corresponds to the part of the basin fill for which data are available (i.e., to a depth of 1,000 feet). Layer 2 can switch from confined to unconfined conditions dependant on whether the overlying floodplain alluvium is fully saturated or not (confined if fully saturated, unconfined if not). Layer 3 represents the basin fill aquifer at depths below land surface greater than 1,000 feet.

Water levels for the model area were constructed based on data from the Groundwater Site Inventory (GWSI) and are representative of the predevelopment system, circa

1940 (refer to Appendix E). The same water level elevations were used for all three layers as it was assumed there was little vertical hydraulic gradient in the predevelopment era. The vertical slice model was calibrated to steady state conditions that characterized the predevelopment era. The ending heads (water levels) of the final calibrated steady state model runs were used to predict changes in groundwater levels for the pumping scenarios under transient conditions. Transient conditions allow for a change in aquifer storage. The model was used to simulate transient state groundwater flow conditions between 1940 and 1990, however, additional impacts due to existing well pumpage for that time period were not incorporated in the analysis. The model was used to predict a change in water level due to pumping in order to determine what ecological effects that change would have on riparian areas. The ADWR is currently working on numerical groundwater models for the San Pedro watershed that will be useful in projecting hydrologic changes in the future due to existing and projected water demands in addition to predicting impacts to the riparian area.

Ecological Model

Ecological models were developed that indicate changes in structure, composition, and abundance of the riparian vegetation anticipated from various groundwater decline scenarios. The ecological models are based on a space-for-time substitution approach, in which riparian vegetation changes measured across natural spatial groundwater gradients are assumed to be indicative of changes that would occur over time in response to groundwater changes. The ecological models are based on several simplifying assumptions including: (1) groundwater changes will be uniform throughout the floodplain aquifer, (2) groundwater is the primary factor influencing plant distribution, and (3) depth to groundwater will change independently of other variables.

The first step in developing the ecological model involved quantifying relationships between plant community traits and depth to groundwater. To this end, eleven riparian transects were established within the floodplain of the Upper San Pedro River in the SPRNCA. Transects were aligned perpendicular to the stream and spanned the width of the floodplain. In many cases, however, transects did not extend to the floodplain perimeter because many of the higher floodplains have been extensively altered by agriculture. Nested plots were established along the transect line within different plant associations. The larger plots (5 m x 20 m [16 x 66 ft], with the long axis parallel to the stream) were sampled for several measures of woody plant abundance, species composition, and community structure. Canopy foliage area (also known as leaf area index, which is the ratio of foliage area to ground surface area) was measured with a LICOR 2000 plant canopy analyzer. Woody plant basal area and stem density, by species and size class, were measured using standard vegetation sampling techniques. Canopy height was measured with a clinometer. Cover of herbaceous plants, by species, was measured in smaller plots (1 x 1 m [3 x 3 ft]) in July (pre-monsoon) and September (post-monsoon).

Each riparian transect was located adjacent to a BLM monitoring well located within the floodplain alluvium. Depth to groundwater has been monitored in the wells since 1987 (see hydrographs on Plate 1, and groundwater system discussion). Groundwater data were not obtained directly for each study plot. Rather, transect lines and plot locations were topographically surveyed (using standard techniques) for elevation above the stream thalweg (low point in the channel). Survey data, in conjunction with groundwater data for the transect well, were used to calculate depth to groundwater from the floodplain surface at each plot. Depth to groundwater did not decline with distance from the stream, and a uniform water level was assumed (for the distance of the transect). Riparian variables were analyzed in relation to mean depth to groundwater over the last five years for woody plants (which typically are long-lived) and mean depth during the 1993 growing season for herbaceous plants (which typically are shorter-lived and more responsive to short-term groundwater changes). Relationships for some variables were analyzed with univariate regression.

Data from the vegetation-groundwater studies as described above were used to construct predictive models based on the following calculations. First, plant associations growing in distinct groundwater zones were identified, based on measurements of plant abundances within the study plots. Some species occurred in more than one zone, but each zone contains at least one species (or life stage) that occurs only in that zone. The width of each of these vegetation groundwater zones within the floodplain was then calculated. Zone width calculations were based on topographical surveys and represent average values for the five vegetation transects located in the pumpage simulation area. The area of each vegetation zone was calculated as it exists today, and for various water table drawdown scenarios. For example, if groundwater was expected to decline by a given amount over a one mile length of the river, the changing area of each vegetation zone was calculated within an area that encompassed the width of the present floodplain vegetation over a one mile length of the river. The models in essence are showing the changing potential of the study area relative to various plant associations, based on their known requirements for various depths to groundwater. In addition, regression equations relating groundwater to structural straits were used to predict the extent and nature of structural changes expected from groundwater decline.

Preliminary versions of these models are applied in this report. Both the hydrologic and ecological models are being refined to increase their accuracy. For example, attempts are being made to refine the model grids of the numerical groundwater models, allowing changes to be predicted for more site specific areas within the floodplain. The ecological models are being refined by incorporating knowledge of relationships between species distribution and inundation frequency (frequency of flood disturbance) and soil texture (which influences soil moisture holding capacity and extent of capillary water rise above the water table) and by incorporating more detail on seedling establishment requirements. Although groundwater is a primary factor affecting riparian plant communities, it is clear that other factors such as flood disturbance and soil texture also play a role. For example, floodplains adjacent to the channel have shallow water tables, are frequently inundated by flood waters, and often have coarse soil textures. As a result of groundwater decline, floodplains adjacent to the stream channel would have deep groundwater tables. Floodplains with deep groundwater levels normally are on high terraces some distance from the channel, are infrequently flooded, and often have fine soil texture. The models at present may not accurately predict the combined effects of decreased water tables, increased flood frequency, or altered soil texture on the riparian vegetation.

GROUNDWATER SYSTEM

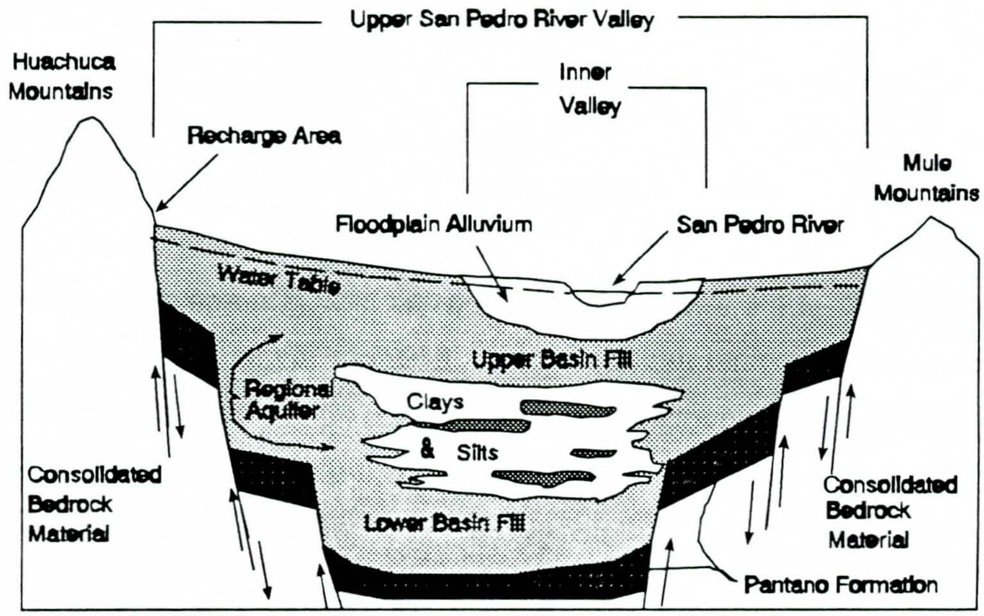
Aquifer Description

The groundwater system in the USP basin is comprised of two main aquifers, the regional aquifer and the floodplain aquifer. The regional aquifer within the study area consists primarily of the lower and upper basin fill, and in some areas, the Pantano Formation. Stream channel and floodplain alluvium associated with the San Pedro River forms the floodplain aquifer within the basin. The relationship of these aquifers and the San Pedro River are shown in a generalized cross-section of the USP valley (Figure 4).

Regional Aquifer

The regional aquifer is the primary source of groundwater within the USP basin. It is mostly unconfined with some locally confined areas in the southern part of the basin along the San Pedro River. The clays and silts of the basin fill alluvium deposited in the center of the valley act as an aquitard and form a barrier to the vertical movement of groundwater (Usunoff, 1984; Worthington, 1987), refer to Figure 4. Wells penetrating the regional aquifer near Palominas indicate confined conditions. The confined (or artesian) aquifer near Palominas is approximately 10 miles long and a mile wide in the basin fill alluvium (Roeske and Werrell, 1973). The artesian aquifer is generally encountered below 200 feet (Jackson and others, 1987; Putman and others, 1988). In these areas, the head in the confined aquifer is higher than the head in the surrounding aquifer. This provides a driving force for the upward leakage of water from the confined aquifer to the floodplain alluvium.

Figure 4. Generalized Hydrogeologic Cross-section of the Upper San Pedro Basin.



Groundwater in storage in the basin fill alluvium within the Sierra Vista subwatershed, which roughly equates to the study area, is approximately 31.8 million acre-feet (ADWR, 1991). This is the total estimated volume of recoverable water in storage to a depth of 1,200 feet. It is based on a saturated aquifer thickness of 800 feet and an estimated specific yield of 0.08. Most of the water available in the basin fill alluvium is above 1,200 feet due to greater compaction of the aquifer at that depth.

Recharge to the regional aquifer is from mountain front recharge and stream channel infiltration (Jackson and others, 1987; ADWR, 1991). Infiltration of precipitation on the valley floor is insignificant considering the relatively low amounts of precipitation and high rates of evaporation in the valley. Discharge of the aquifer occurs from groundwater pumping within the study area, discharge into the San Pedro River or the floodplain alluvium (i.e., baseflow), underflow out of the study area near Fairbank, and evapotranspiration.

Flow of groundwater from the regional aquifer to the floodplain aquifer can occur by upward leakage from the basin fill alluvium and lateral flow of water from the regional aquifer to the floodplain aquifer (Jackson and others, 1987).

Floodplain Aquifer

The floodplain alluvium forms a long, narrow, and shallow aquifer along the San Pedro River and its tributaries. Because of the limited aerial extent and thickness of the floodplain alluvium, only limited amounts of water can be stored in this aquifer. It is estimated that the floodplain alluvium stores approximately 160,000 acre-feet of water in the Sierra Vista subwatershed. This storage figure is based on an estimated saturated alluvium thickness of 60 feet and a specific yield of 0.12 percent (ADWR, 1991).

Groundwater levels fluctuate rapidly in response to natural and cultural uses, changes in the river stage (height), and infiltration of surface runoff due to the highly permeable nature of the materials (Jackson and others, 1987; ADWR, 1991). However, groundwater levels within the floodplain alluvium rarely fluctuate more than a few feet below the riverbed. As a result of this proximity between the groundwater and the surface water, the groundwater level has a pronounced effect on the amount of flow in the stream (Brown and Aldridge, 1973). There appear to be no long-term declines in the ground water levels within the floodplain aquifer (ADWR, 1991), although significant seasonal variations occur in some reaches and may be considered normal.

The floodplain aquifer is recharged from infiltration of surface water, especially during periods of high streamflow, discharge from the regional aquifer, deep percolation from agricultural areas, and underflow within the floodplain alluvium (Jackson and others, 1987; ADWR, 1991).

Occurrence and Movement of Groundwater

Groundwater flows generally from the mountain fronts or valley margins to the San Pedro River. Water levels range from approximately 5,100 feet above mean sea level (msl) near the mountain fronts to 3,900 feet above msl near the confluence of the Babocomari and San Pedro Rivers. The most recent groundwater elevation contour map for the study area is found on Plate 1. This water level contour map is based on winter data (December and January) for the period 1985 through 1990. An exception to the general flow pattern occurs in the Sierra Vista-Ft. Huachuca area. Groundwater pumping in the vicinity of Sierra Vista-Ft. Huachuca changes local gradients and causes water to flow toward the cone of depression (Plate 1). As reported in Putman and others (1988), the cone of depression within the 4,150 foot contour interval trends in a northwest-southeast direction, and includes an area of approximately 7.5 square miles. Water levels in this area have been reported to decline approximately 1.4 feet per year for the 20 year period 1966-1986 (Putman and others, 1988).

The data from wells that are presented as hydrographs were chosen on the basis of their period of record (for wells in the basin fill alluvium) and their proximity to riparian zone vegetation transects (for wells in the floodplain alluvium). On Plate 1, a hydrograph was constructed using water level data from well D(21-21) 29cca located approximately 4 miles east of the Sierra Vista-Fort Huachuca boundary, and approximately 6 miles west of the San Pedro River. This well shows a continuous decline rate of approximately 0.6 feet/year (1941 to 1978). Another hydrograph was constructed using data from well D(21-21) 27cbd which is located in the vicinity of the first well, approximately 4 miles due east of the San Pedro River. Although this well showed historic declines of approximately 1 foot/year, water levels have recovered to nearly the same elevation when data was first collected in 1941. Longer term records and more recent information are provided by the data from well D(23-22) 18bbb. This data illustrates a long term decline rate of approximately 0.3 feet/year through 1989, for an overall decline of 14 feet, however, in the last few years water levels have recovered approximately 5 feet.

Water levels in wells located in the floodplain alluvium are provided on Plate 1. The wells, from south to north, are Palominas No. 5 (D(24-22) 17bdc), Hereford No.2 (D(23-22) 9ada), Moson Springs (D(21-21) 13bba), and Contention Well (D(19-21) 21acc). Water levels recorded at Palominas Well No. 5 have a range of approximately 3 feet, and show a consistent seasonal decline during late spring to early summer with water levels recovering throughout the late summer and fall. At the Hereford Well No. 2 site, although there is a seasonal variation, data indicate a downward trend over time. Water levels have decreased approximately one foot in this well since monitoring began in 1987. Data collected at the Moson Springs Well indicate water levels fluctuate a little more than a foot. The Contention Well indicates water levels decrease, however data from this well shows the same seasonal fluctuations as seen in the Palominas Well No.5. Water levels from the Contention Well fluctuate approximately 6 feet every year, going dry when there is no flow in the river.

Floodflows during the summer and winter recharge the floodplain aquifer, often filling the available storage space to capacity (Putman and others, 1986; ADWR, 1991). The net result from this recharge has been no long-term declines in the water levels of the floodplain alluvium (Putman and others, 1986; ADWR, 1991). However, Brown and others (1966) calculated an average annual ground water decline rate of 1 ft/year even in areas of no pumping possibly due to downcutting of the San Pedro River. Incision has resulted in a decline in local water tables and the drying of former floodplain features such as ox-bow lakes and marshes (Jackson and others, 1987). Downcutting of the river causes a drop in the level of the stream. This in turn causes groundwater from the adjacent alluvial aquifer to drain to the river further lowering the water table.

Water Yielding Characteristics

The ability of the regional and floodplain aquifers to transmit water varies greatly throughout the study area. Due to heterogeneities of the aquifer materials a wide range of transmissivity and storage coefficient values have been reported by various researchers and are presented in Table 2. Several aquifer tests were conducted on test wells at Fort Huachuca in the early 1970s. Transmissivity values based on these aquifer tests range from approximately 2,670 to 9,360 ft^2/d. Other aquifer tests were conducted on wells perforated in the basin fill alluvium in the vicinity of Sierra Vista. Tests from these wells yield values of 5,750 to 21,390 ft^2/d. Putman and others (1988) estimated average transmissivity values in the USP basin to range from 4,000 to 8,000 ft^2/d. Values for storage coefficient are estimated to range from 0.05 to 0.12 for the unconfined portions of the regional aquifer (Arizona Water Commission, 1973) and from 0.00005 to 0.003 for portions of the confined regional aquifer.

Transmissivity values for the floodplain alluvium are even less well documented. Values are reported to range from 1,000 to 8,000 ft^2/d (Putman and others, 1988). A value of 10,700 ft^2/d was estimated from specific capacity data of 40 gpm/ft by Roeske and Werrell (1973). Values of storage coefficient were reported to range from 0.05 to 0.15 (Putman and others, 1988).

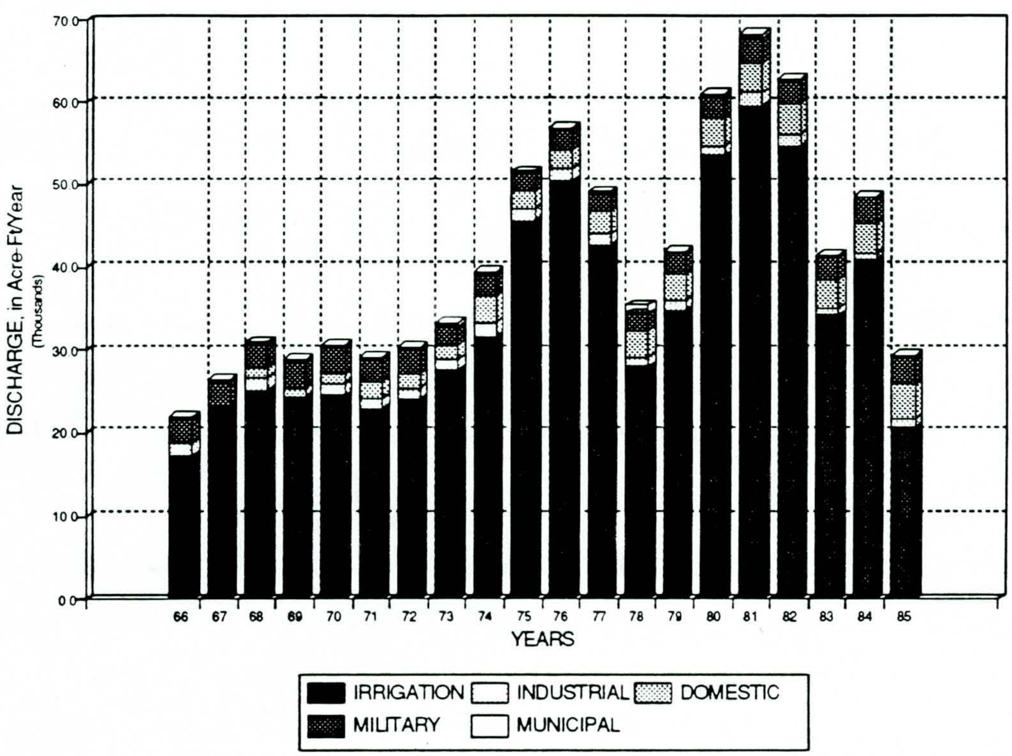
Table 2
Hydrologic properties of water bearing units in the upper San Pedro study area

Geologic Unit	Transmissivity (Ft^2/d)	Well Location	Storage Coefficient	Reference
Younger Alluvium	1,000 to 8,000	-	0.05 to 0.15	Putman and Others (1988)
	~ 10,700	-	-	Roeske and Werrell (1973)
Older Alluvium	6,020 9,360 2,670 1,740	D(21-20) 35ccb D(21-20) 11bcd D(21-20) 13cbb D(21-21) 17bcc	0.1	Harshbarger and Associates (1974)
	21,390 5,750	D(22-21) 6cba D(22-20) 36abb	- -	Arizona Water Commission (1973)
	1,340 to 13,370	-	0.05 to 0.12	Arizona Water Commission (1974)
	100 to 15,000	-	1E-05 to 1E-03	Freethey (1982)

Well yields in the regional aquifer range from 100 to 2,800 gallons per minute (gpm), with an average of 590 gpm (Roeske and Werrell, 1973). Specific capacities of these wells ranged from 1 to 40 gallons per minute per foot (gpm/ft), averaging 13 gpm/ft. Yields from wells at Fort Huachuca, ranged from 130 to 900 gpm, averaging 430 gpm (Harshbarger and Associates, 1979). Within the floodplain aquifer, well yields have been reported as high as 2,000 gpm, however, most range from 200 to 1,500 gpm, with an average specific capacity of 40 gpm/ft (Roeske and Werrell, 1973; Worthington, 1987).

Historic pumpage values for the USP basin are included here to provide an idea of the amount and type of groundwater withdrawals that have occurred. Figure 5 represents pumpage data from Putman and others (1988) for the case study area, and is separated out into the various categories of use. This data covers the time period from 1966 through 1985, the last year in which comprehensive data were available. Irrigation pumpage, presented in Figure 5, represents the total volume of water pumped for the entire USP basin including the Palominas-Hereford area as well as the

Figure 5. Historic groundwater pumpage in the upper San Pedro basin.



St. David, Pomerene, and Benson areas. However, this information is still useful in relaying trends in water use throughout the basin. For instance, from the early 1960s through 1981, there was a general increase in water use and groundwater pumpage throughout the basin. However, groundwater pumpage declined significantly from 1981 through 1985. Groundwater pumpage due to agriculture has declined significantly relative to other uses, but still constitutes the largest use in the basin. ADWR (1991) reported that, for the Sierra Vista subwatershed, 13,450 acre feet of groundwater was withdrawn in 1990. Of that total, only 4,590 acre feet of water was used for agriculture, while 7,190 acre feet was withdrawn for municipal and domestic uses. Essentially, the trends in water use have been reversed between agriculture, and municipal (i.e., water company) and domestic (other domestic) use.

Groundwater Quality

The groundwater quality in the regional aquifer and the floodplain aquifer within the study area is suitable for most uses. Thompson (1984) and Konieczki (1980) noted that the water in the regional aquifer is predominantly a calcium-bicarbonate type with total dissolved solids (TDS) in the 200-400 milligrams per liter (mg/l) range. In the vicinity of Palominas and Hereford, however, the primary inorganic constituents change to sodium-bicarbonate and sodium-sulfate, and TDS levels are found to rise over 1,000 mg/l. Putman (1988) noted that this generally corresponds to the confined areas of the regional aquifer beneath the San Pedro River and to the agricultural areas adjacent to the river. Fluoride levels in the regional aquifer and the floodplain aquifer generally were less than or rarely exceeded the 1.6 mg/l standard (Konieczki, 1980). In the Tombstone area, cyanide contamination has been reported due to the operations of the Contention Mine where cyanide is leached from silver ore causing groundwater contamination at one of the mine's industrial wells. This is believed to be a result of seepage from one of the two holding ponds containing cyanide-rich solutions (Kennett, 1985).

SURFACE WATER SYSTEM

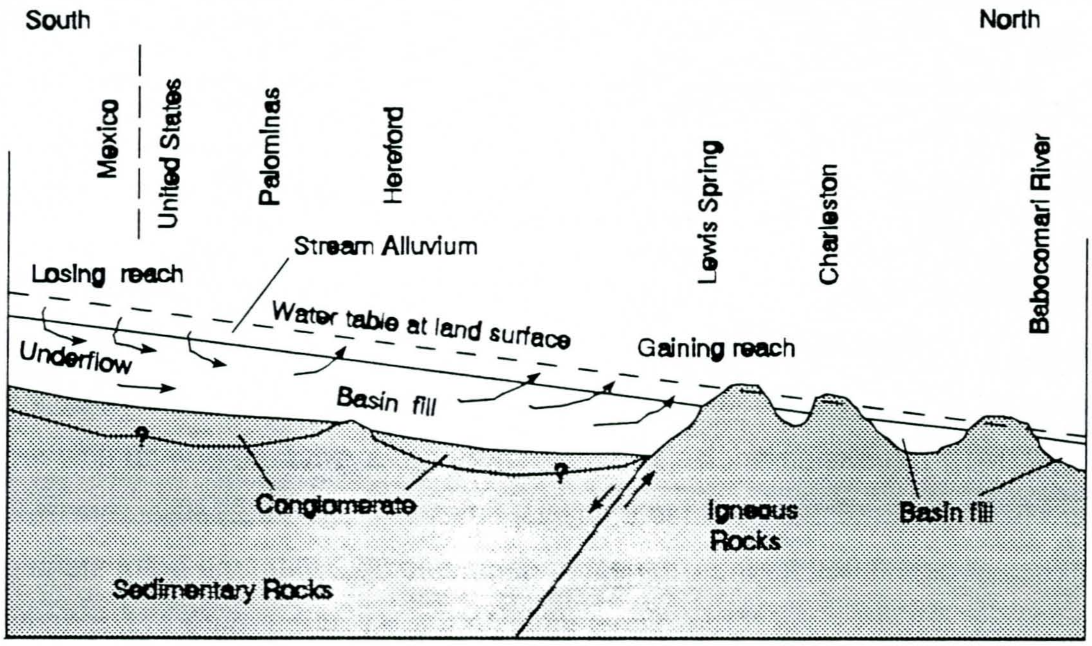
Watershed Description

The San Pedro River drains approximately 1,730 square miles at the Tombstone gage within the study area. Its headwaters originate in Sonora, Mexico approximately 30 miles south of the international border. The San Pedro River flows north for approximately 125 miles to its confluence with the Gila River near Winkelman. Tributary watersheds drain approximately 54 square miles of the western slopes of the Huachuca Mountains, entering Mexico in T24S, R19E (Putman and others, 1988). From Mexico, the San Pedro River drains approximately 696 square miles before entering the United States near Palominas, Arizona, in Section 18, T24S, R22E (Plate 1). The only major tributary to the San Pedro River within the study area is the Babocomari River. Other tributaries that contribute significant runoff to the San Pedro River include Garden Canyon, Miller Canyon, Greenbush Draw, and Walnut Gulch.

Flow in the San Pedro River is generated from rainfall runoff and baseflow or groundwater discharge to the stream from the floodplain alluvium. Runoff is due to snowmelt from the surrounding mountains in late spring, and precipitation. Precipitation during the winter is from long duration frontal storms and during the late summer and early fall is due to the short duration thunderstorms during the monsoon season. Baseflow provides the majority of flow during periods of low flows. The San Pedro River is perennial throughout most of the study area, however, where the river crosses the international border near Palominas, it is a losing stream and exhibits an intermittent flow pattern. Flows begin to gain through the reach between Hereford to a point just south of Fairbank (Putman and others, 1988). This is illustrated in Figure 6, a longitudinal profile of the San Pedro River, which shows the gaining and losing reaches within the case study area. The perennial flow in the San Pedro River within the study area is due to two factors, baseflow discharge to the stream and a geologic restriction near Charleston. The San Pedro River cuts through Bronco Hill which forces water from the floodplain alluvium associated with the river to the surface where it appears as streamflow.

The Babocomari River has two perennial reaches that total approximately 12 miles, however, at its confluence with the San Pedro River it is ephemeral. Other tributary streams in the case study area are ephemeral in nature and flow only in response to rainfall events. Some of these tributaries may flow near their headwaters, however, they are ephemeral in their lower reaches.

Figure 6. Longitudinal profile of the San Pedro River within the case study area (after: Jackson and others, 1987).



Streamflow Characteristics

Table 3 lists the streamgages on the San Pedro River within the case study area, operated by the U.S. Geological Survey (USGS). The Palominas gage is currently maintained by the U.S. Section of the International Boundary and Water Commission (IBWC). The streamgage locations are shown on Plate 1.

The Palominas gage can be used to represent the amount of water entering the USP basin from Mexico (i.e. the case study area), whereas, the Tombstone gage can be used to represent the volume of water leaving the case study area.

Table 3
USGS streamgages within the case study area

Gage	Location	Period of Record	Drainage Area (square miles)
San Pedro River at Palominas (09470500)	T23S, R22E, Sec.33	1926; 1930-1933; 1935- 1941; 1950-1989	737
San Pedro River at Charleston (09471000)	T21S, R21E, Sec.11	1912-1992	1,234
San Pedro River near Tombstone (09471550)	T19S, R21E, Sec. 28	1968-1986	1,730

Putman and others (1988) provided an analysis of annual streamflow data for all three gages within the study area plus the Benson gage (located downstream near "The Narrows"). Because the common period of record for all four gages was only 9 years (1965-1976), a regression analysis was performed to extend the annual flow records from 1936 to 1983. Based on this analysis, flows averaged 22,380 acre feet at the Palominas gage, 36,360 for the Charleston gage, and 38,200 for the Tombstone gage. Mean annual flows for the three gages indicate the variable nature of streamflow at different locations on the stream and further illustrate the gaining and losing nature of the San Pedro River within the study area. Annual flows of the San Pedro River are highly variable from year to year and although lower than average flows predominate, high flows may occur several years in succession. Although annual flows may vary from year to year, the gages usually exhibit the same pattern of rising or falling together (Putman and others, 1988).

Mean monthly flow values were determined for the Palominas and Charleston gages. These data are presented in Tables 4 and 5, respectively. The entire period of record was used for the Palominas gage and the latest 20 years were used for the average monthly flow values for the Charleston gage. The monthly flow statistics are useful in illustrating when the minimum and maximum flows can be expected to occur throughout the year. These tables were used to construct the runoff hydrograph illustrated in Figure 2.

Table 4
Monthly streamflow statistics USGS streamgage 09470500, San Pedro River at Palominas, 1958-1989 (values in cfs)

Month	Mean	Median	Maximum of Record	Minimum of Record	Percent of Annual Runoff
October	36.9	2.7	770.0	0.0	10.5
November	12.9	2.5	43.0	0.0	3.7
December	30.2	4.9	414.0	0.1	8.6
January	24.8	13.9	452.0	0.0	7.1
February	9.6	9.0	74.0	0.1	2.7
March	7.6	7.0	76.0	0.2	2.1
April	11.7	1.7	15.0	0.0	3.3
May	30.9	0.6	7.0	0.0	8.8
June	14.9	0.3	23.0	0.0	4.3
July	67.2	10.4	280.0	3.0	19.2
August	75.3	31.1	591.0	2.7	21.5
September	28.0	5.7	275.0	0.2	8.0

The data from Table 4 indicate that the lowest flows occur often at the Palominas gage during the months of April through June, and October and November. These minimum flow periods correspond to the driest season that includes the months of April to June. The months with the highest probability of rainfall include December through late March, however, these storm events are usually of low intensity and are not predictable (Hereford, 1993). This is evident by the maximum and minimum flow data shown in Tables 4 and 5. For the Palominas gage, this explains why December and

January experience high monthly flows yet minimum flows are zero or very nearly so. A second high monthly flow season occurs during the monsoon season, June through September, as indicated by the high monthly maximum and mean flow values for these months. Hereford (1993) noted that both the mean and maximum values for these months were consistently large and resulted in high sediment loads.

Table 5
Monthly streamflow statistics USGS streamgage 09471000 San Pedro River at Charleston, 1972-1993 (values in cfs)

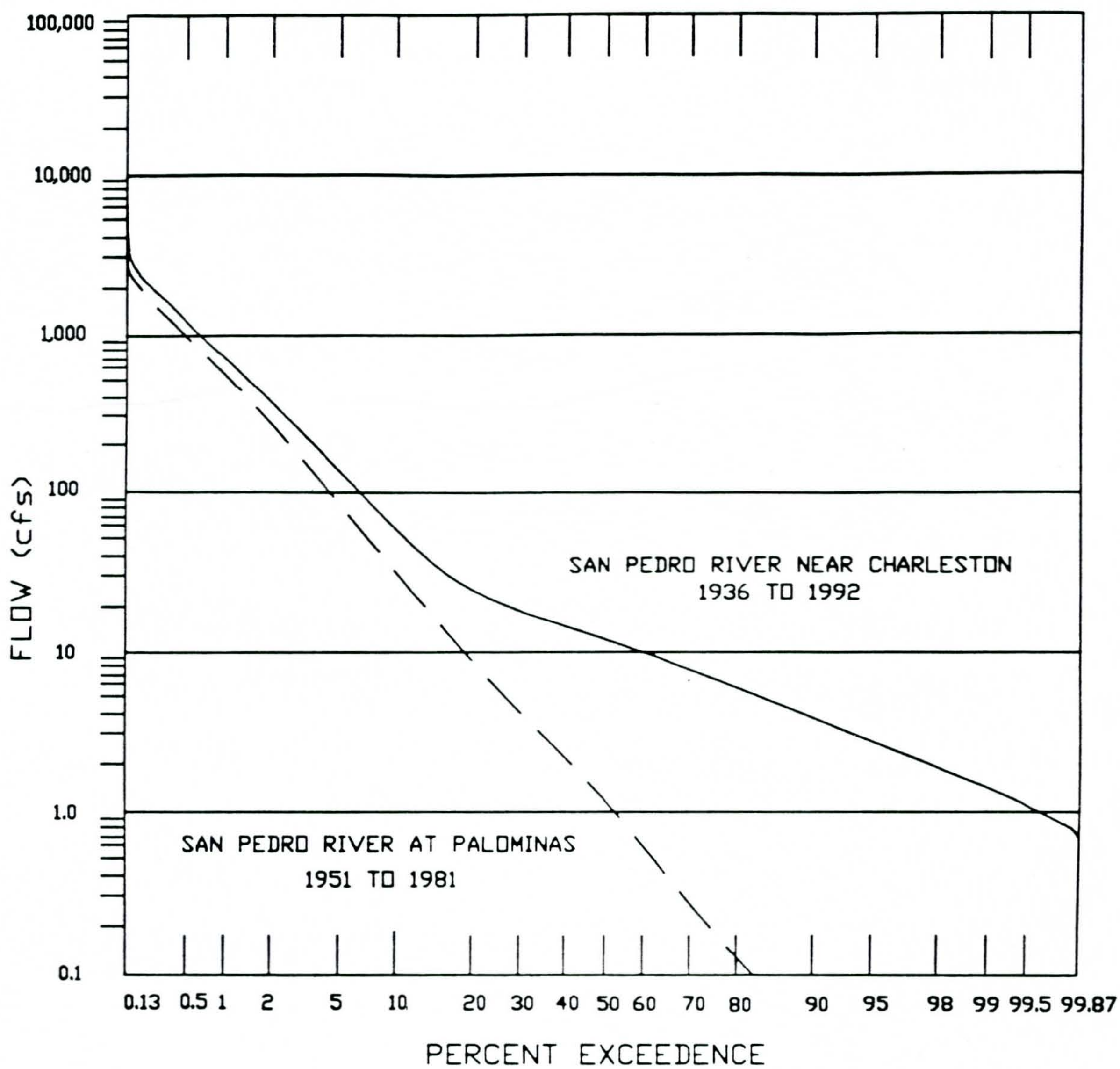
Month	Mean	Median	Maximum of Record	Minimum of Record	Percent of Annual Runoff
October	89.0	16.9	1,090.0	2.9	16.8
November	16.2	13.5	128.0	5.0	3.1
December	37.6	16.4	1,230.0	6.0	7.1
January	66.4	32.5	507.0	9.5	12.5
February	30.7	23.9	217.0	7.2	5.8
March	30.9	24.5	160.0	8.1	5.8
April	14.0	13.5	67.0	3.0	2.6
May	7.9	7.3	37.0	2.4	1.5
June	5.9	3.4	167.0	1.3	1.1
July	75.0	17.7	876.0	3.1	14.1
August	111.0	41.5	968.0	10.0	20.9
September	46.1	14.5	1,890.0	4.1	8.7

Streamflow data from the Charleston gage (Table 5) displays the same pattern as Palominas gage data, with one main exception. Minimum flow values indicate that streamflow is perennial at this location. Also, mean monthly flows are larger at the downstream gage. This is apparent by comparing the mean and median monthly flow values presented in each table. Figure 2 also illustrates that the trends or cycles in flows are similar at both sites.

Streamflow Availability

Streamflow availability can be determined from a plot of the daily flow values compared with the percent of time these flows were equalled or exceeded. The flow duration curves presented in Figure 7 were generated from mean daily flow values obtained from the Palominas and Charleston gages. Median daily flow values can be discerned from these curves for the period of record. For example, 99.5 percent of the time flows of 1.0 cfs are either equalled or exceeded at the Charleston gage. At Palominas however, a value of 1.0 cfs represents the annual median flow value, while 20 percent of the time no flow is present in the river at this location.

Figure 7. Flow duration curves for the San Pedro River at Palominas and at Charleston.



RIPARIAN VEGETATION - GROUNDWATER RELATIONSHIPS

Factors Influencing Depth to Groundwater in the Floodplain Aquifer

Depth to groundwater is a primary determinant of riparian vegetation composition and structure, and varies within the floodplain alluvium of the San Pedro River for several reasons. The first reason has to do with ongoing fluvial processes. The San Pedro, typical of low-gradient alluvial desert rivers, is a dynamic river. The main channel of the river migrates and meanders within a large floodplain. During small flood flows, the river carries much sediment which is trapped by the vegetation to form floodplain terraces. As time passes, the elevation of the terraces increases with each new flood event. Data from other rivers including the Hassayampa River and Gila River indicate that several inches of sediment, on average, can be deposited per year (Minckley and Clark, 1984; Stromberg et. al., 1991). Very large floods periodically scour away the accumulated sediment, again returning them to a low elevation. As a consequence of this ongoing process of terrace building (aggradation) and destruction (degradation), the soil surface varies throughout the floodplain in elevation above the water table. Although the position of the root crown of mature trees is not changed by the sedimentation process, other rooting characteristics are changed. Sedimentation directly affects the position of the root crown relative to the water table for annual plants and for newly germinating perennial plants. Many established perennial riparian plants produce adventitious roots (i.e., roots from the buried stem) that extend into the new alluvium. Floodplain habitats that are infrequently inundated by floods (e.g., highest terraces) undergo the least amount of aggradation and degradational change. Soil particles on these infrequently flooded areas tends to be very fine (e.g., have small grain size), because flood waters have dropped most of the larger particles by the time they reach the outermost floodplain areas.

Depth to groundwater within the San Pedro River floodplain also has varied as a result of historical fluvial events. Over a long period of time (centuries), the channel of the

San Pedro River has undergone periodic episodes of incision, or downcutting below the floodplain. The most recent episode of incision occurred near the turn of the century, in response to a suite of interacting factors that may have included human-caused activities related to the extensive mining activities occurring at the time (e.g., timber harvest from floodplains and uplands in the watershed, diking and draining of the river channel, groundwater pumping, overgrazing) as well as climatic factors (drought followed by high intensity floods) (Hastings and Turner, 1965; Bahre, 1991). Climatic flux and variations in hydro-geological conditions also cause depth to groundwater to vary over time and between reaches of the San Pedro River. For example, losing reaches of the river (such as those near Palominas) show greater seasonal fluctuation in depth to groundwater than do gaining reaches (see Occurrence and Movement of Groundwater above). The effect of high intensity floods on a devegetated and unstable floodplain was to cause the channel of the San Pedro and many other rivers in the Southwest to drop rapidly over a period of years to an elevation several feet below its initial location. Water tables dropped simultaneously as the channel cut below the floodplain surface. As a consequence, much of the floodplain was left "high and dry" above the water table.

Over the last 80 years or so, the San Pedro river floodplain has been slowly recovering from this past dramatic episode (Hereford, 1993). The "new" post-entrenchment floodplain adjacent to the channel has been widening ever since, and in many areas is now several hundred feet in width. The "old" pre-entrenchment floodplain still remains connected to the river and is also several hundred feet in width. The net result has been formation of a "two-tiered" floodplain, with depth to groundwater being much greater on the pre-entrenchment floodplain (about 6 m [20 ft] or more) than on the post-entrenchment floodplain. Figures 8 through 12 are cross-sections of the San Pedro River floodplain at locations beginning at Palominas and progressing downstream to Contention. These figures include a description of the community type

Figure 8. Cross-section of the San Pedro River floodplain near Palominas

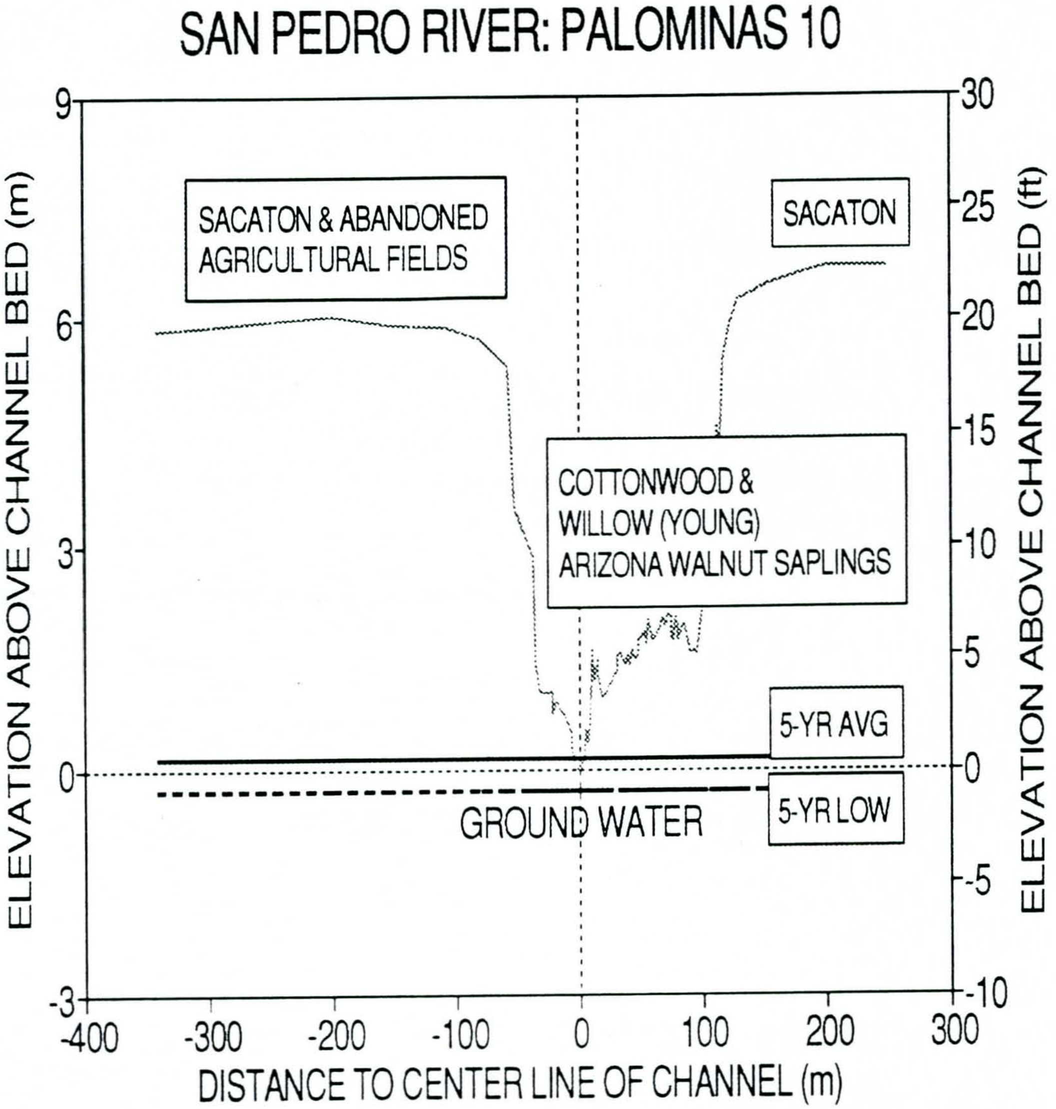


Figure 9. Cross-section of the San Pedro River floodplain near Hereford

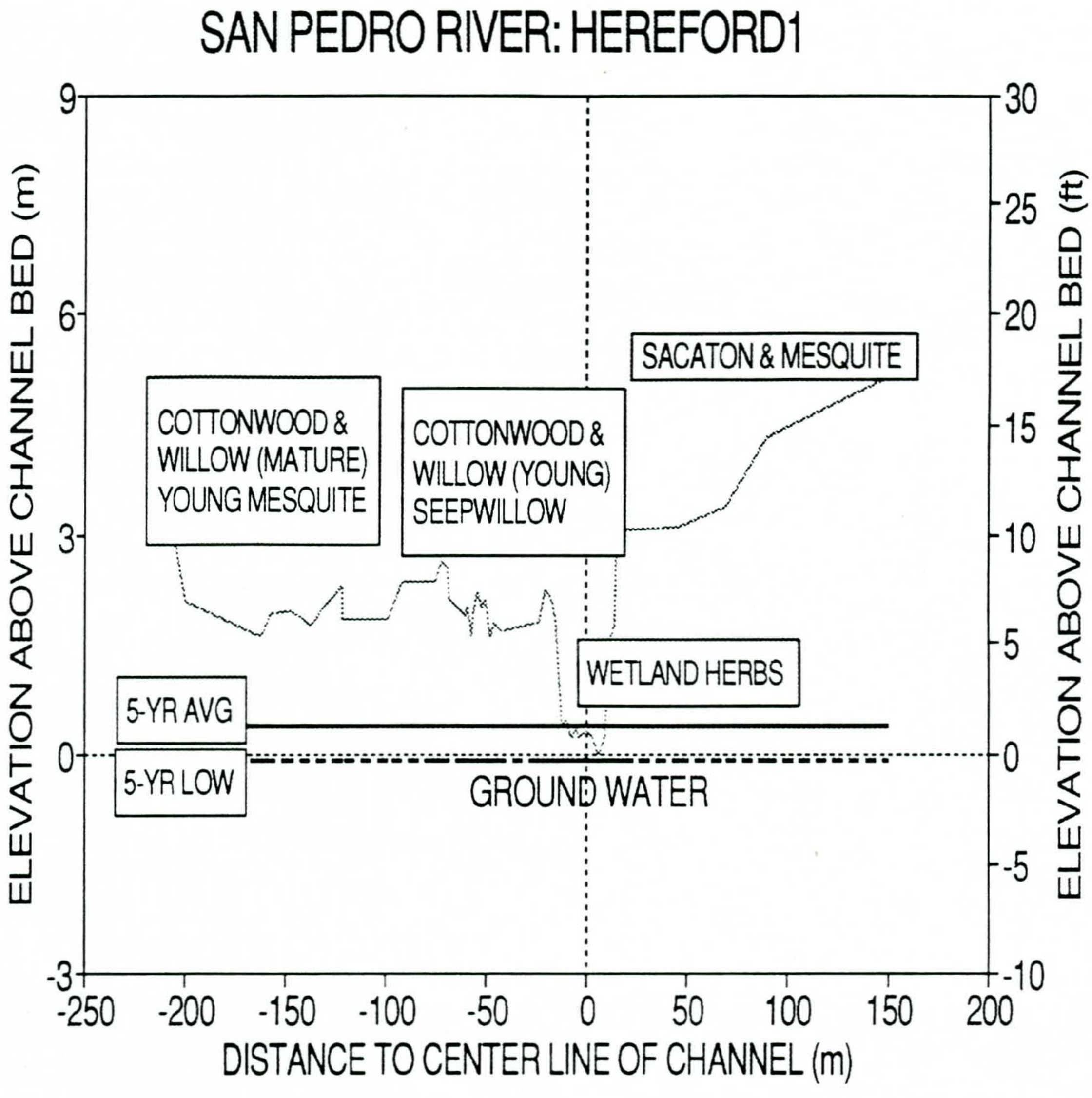


Figure 10. **Cross-section of the San Pedro River floodplain near Moson Springs**

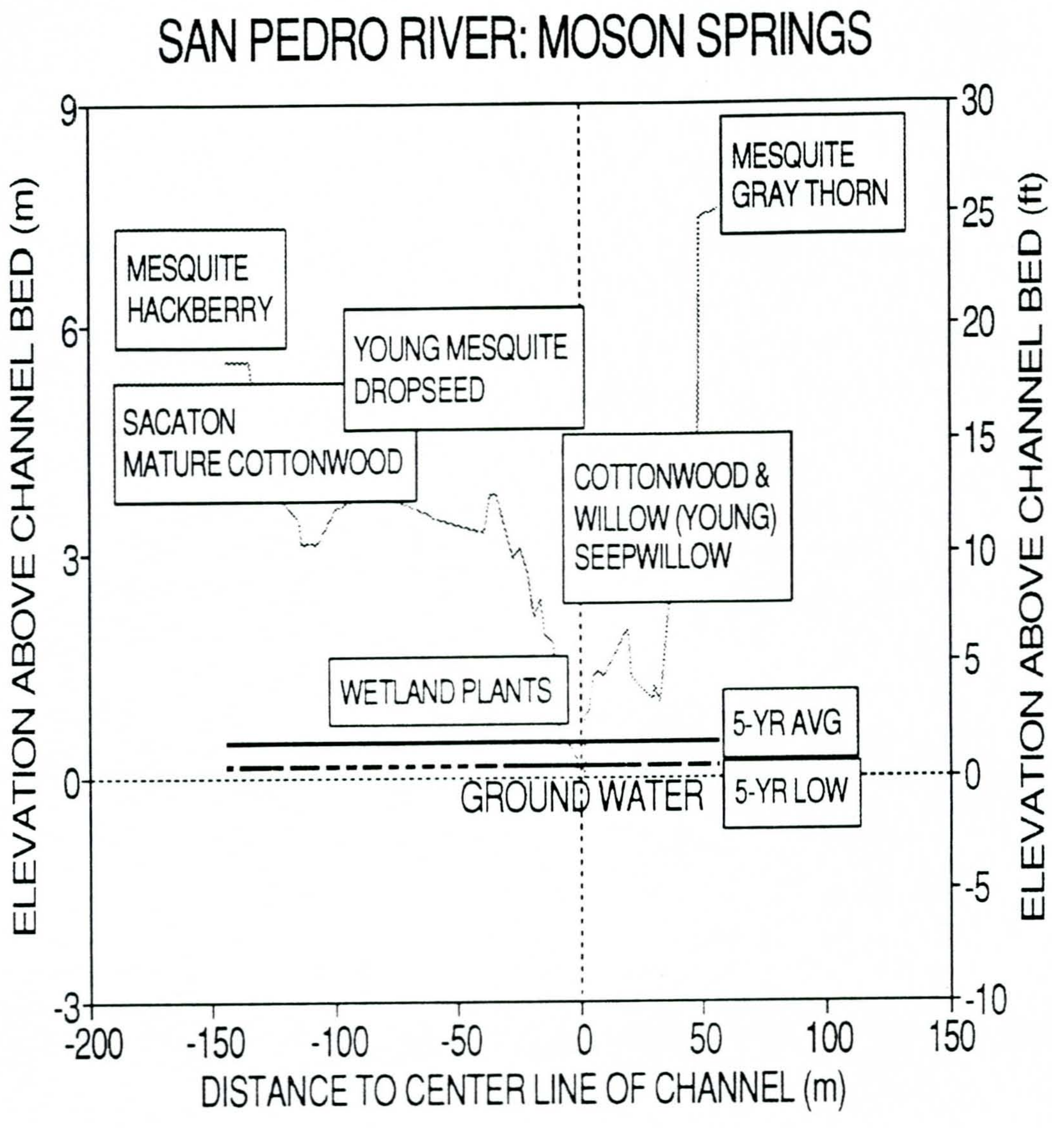


Figure 11. Cross-section of the San Pedro River floodplain near Boquillas Ranch

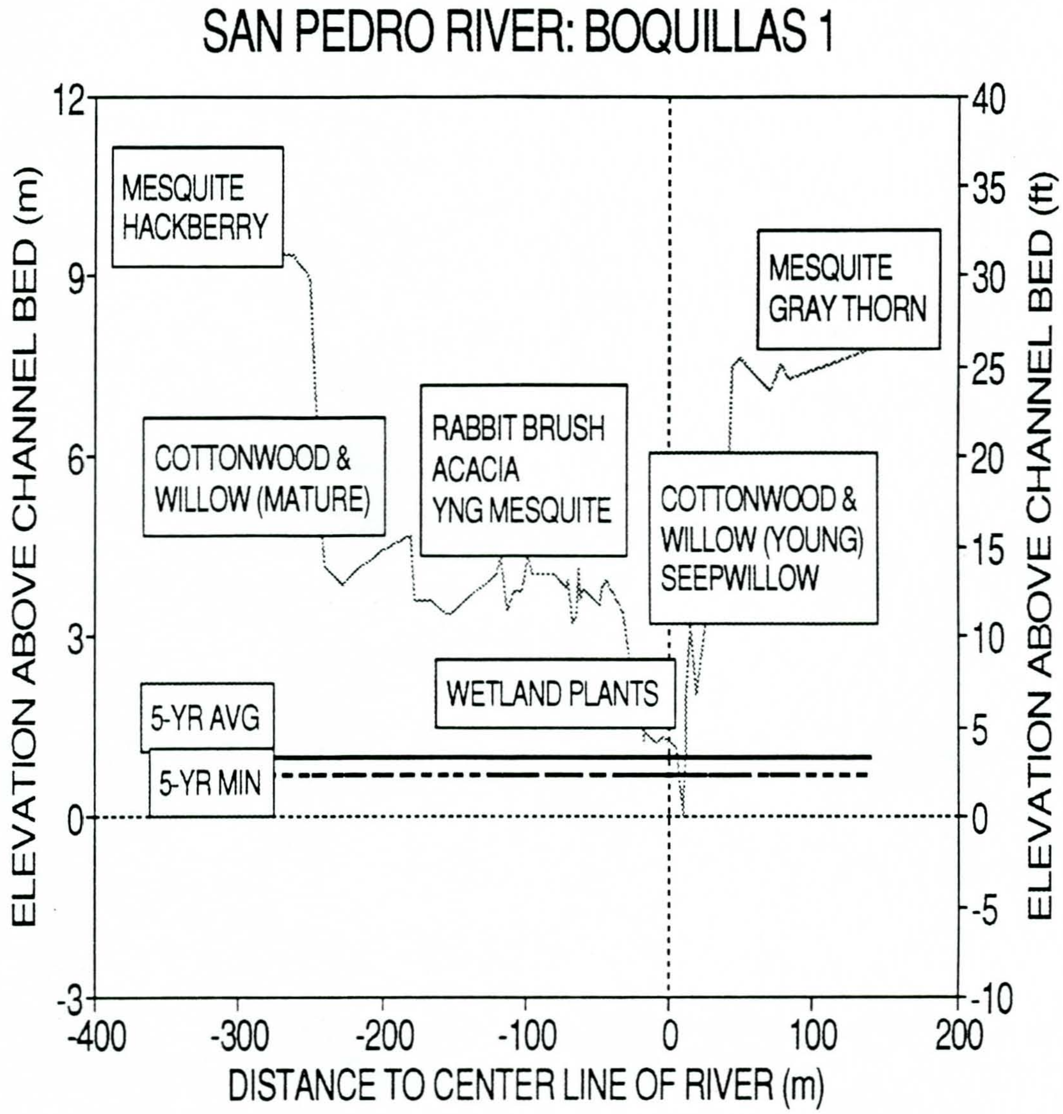
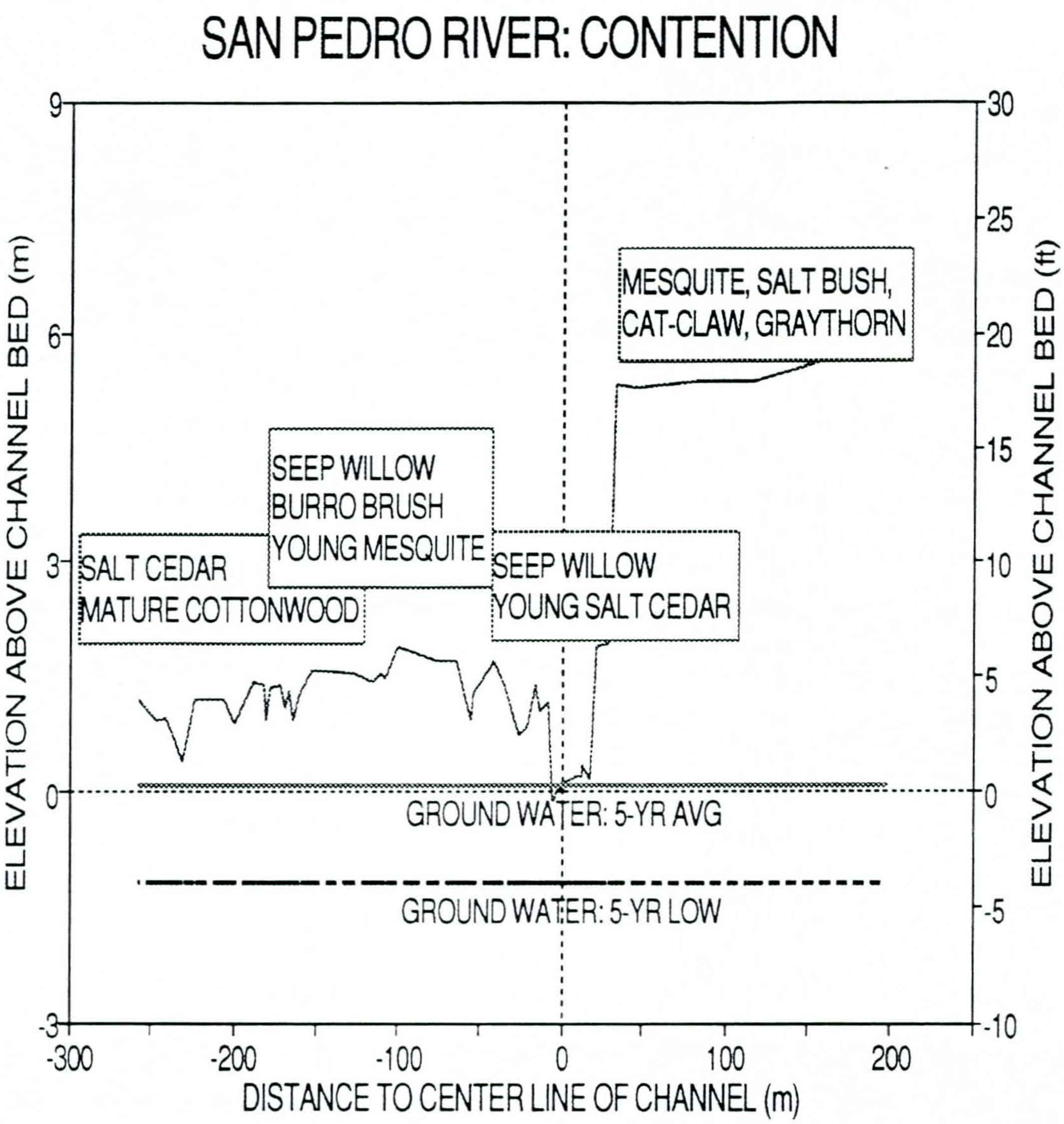


Figure 12. Cross-section of the San Pedro River floodplain near Contention



and general age class of cottonwood-willow forests. Also, the 5-year average and 5-year low groundwater level are plotted. Figure 8 (cross-section of the San Pedro River near Palominas) shows a fairly narrow and incised channel. The floodplain and recent channel become broader downstream as shown in figures 1-9 through 1-12.

Species Change Across Groundwater Gradients

Plant species within the San Pedro River floodplain are distributed across gradients of depth to groundwater. In this discussion, these relationships are described for tree species and exotic tree species, followed by shrub species, herbaceous plant species, and finally exotic herbaceous plant species.

Tree Species

The dominant trees in the upper San Pedro River floodplain are Goodding willow, Fremont cottonwood, and velvet mesquite. Velvet ash *(Fraxinus velutina)*, Arizona walnut, net-leaf hackberry, mulberry (*Morus* spp.), saltcedar (*Tamarix chinensis*), and others also are present. These tree species are arrayed in the floodplain across gradients of depth to groundwater and flood disturbance. Different age classes and size classes of each species also are arrayed across groundwater gradients. This is because juveniles tend to establish on lower floodplains than those on which adults grow, and because of ongoing terrace-building processes, as described above.

Of all the San Pedro tree species, Goodding willow requires the shallowest groundwater. Goodding willow is an obligate wetland species (Reed, 1988). Along the San Pedro River it grew on floodplains where depth to groundwater ranged from about 0.5 m to 2 m (2 to 7 feet). Average depth to water for the largest Goodding willow tree (about 60 cm [2 ft] trunk diameter) was 1.8 m (6 feet) (Figure 13). Figure 13 shows size classes of the dominant tree species of the Upper San Pedro River floodplain

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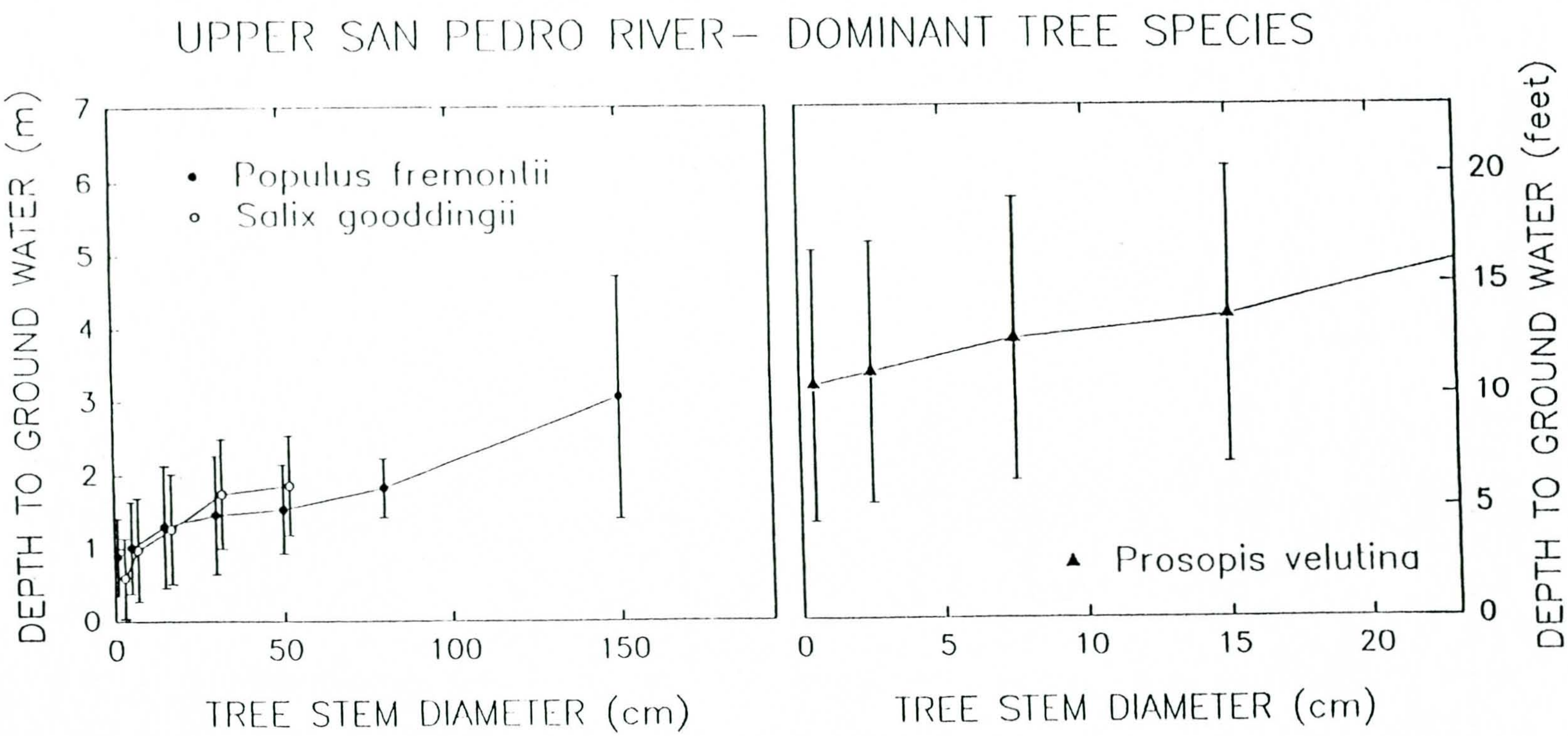
Figure 13. **Distribution of various size classes of the three dominant trees of the upper San Pedro River floodplain in relation to depth to groundwater**



(groundwater in this graph represents the mean depth to groundwater over the last 5 year period).

Goodding willow is often closely associated with Fremont cottonwood, a facultative wetland plant (but riparian obligate). Both of these species form linear groves that contain same-aged plants that established in the same year (i.e., cohorts). Generally, several cohorts are present at any one time, resulting in several bands of different-sized trees within the floodplain. Generally, the oldest cohorts are farther from the active channel and on higher floodplains than younger cohorts. Most of the mature cottonwood trees were on floodplains that were between 0.5 and 3 meters (2 to 10 ft) above the water table, consistent with maximum reported rooting depth for the species [7 ft+] (Zimmerman, 1969). A few large trees with maximum trunk diameter of 1.6 m [5 ft] (age determination is still in progress) grew in scattered locations on the "old" floodplain where depth to groundwater was 5 to 6 m [16 to 20 ft] and distance from the channel was about 100 to 300 m (300 to 1000 ft) (Figure 13). It is unknown if perched water table conditions exist in these areas.

The few mature trees of mulberry and velvet ash that were present grew on floodplains of intermediate height (about 1.5 to 4 m, or 5 to 13 ft) (Figure 14). Figure 14 shows the distribution of mature tree species of the Upper San Pedro River floodplain in relation to depth to groundwater. Arizona walnut also grew on floodplains of intermediate height but too few individuals were present to determine the extent of its range.

Velvet mesquite is a facultative riparian plant. Mesquite grew where depth to groundwater was between 2 and 7 m (7 to 23 ft), but was most abundant on the higher terraces where depth to groundwater was > 5 m (16 ft) (Figure 13). Mesquite bosques were most abundant on the high floodplain terraces at the downstream (northern) end of the SPRNCA area, where they extended for up to several hundred feet away from the channel. Net-leaf hackberry grew interspersed with mesquite in the bosques as did, occasionally, little-leaf sumac (*Rhus microphylla*).

The distribution of tree saplings in relation to groundwater provides an approximation of the conditions needed for establishment of new generations of the trees (Figure 15). Figure 15 shows the distribution of juvenile tree species of the Upper San Pedro River floodplain in relation to depth to groundwater. Saplings (defined here as plants less than 1 m [3 ft] tall) were arrayed across the groundwater gradient in generally the same sequence as were the mature trees. Goodding willow saplings were on low floodplains that averaged 0.6 m (2 ft) above the water table. Fremont cottonwood and velvet ash saplings grew on floodplains that averaged less than 1 m (3 ft) above the water table. Juveniles of willow and cottonwood tended to grow near the active channel.

Arizona walnut saplings grew where depth to groundwater was about 1 to 3 m (3 to 10 ft). Saplings of the high floodplain terrace species (velvet mesquite, netleaf hackberry, little-leaf sumac) grew where depth to groundwater was between about 1.5 and 4.5 m (5 to 15 ft). Juvenile netleaf hackberry were common in the understory of young and old cottonwood stands. Juvenile mesquite grew in cottonwood understories as well as in more open areas of the floodplain.

Exotic Tree Species

Saltcedar is an exotic tree species that has become prevalent on many Arizona rivers, but presently has low abundance on the Upper San Pedro River. Saltcedar seedlings have grown on floodplains where depth to groundwater was about 1 to 2 m (3 to 7 ft), values that are somewhat deeper than those for cottonwood and willow saplings (Figure 15). Saltcedar trees also grew on relatively low floodplains (depth to

Figure 14. Distribution of mature tree species of the Upper San Pedro River floodplain in relation to depth to groundwater

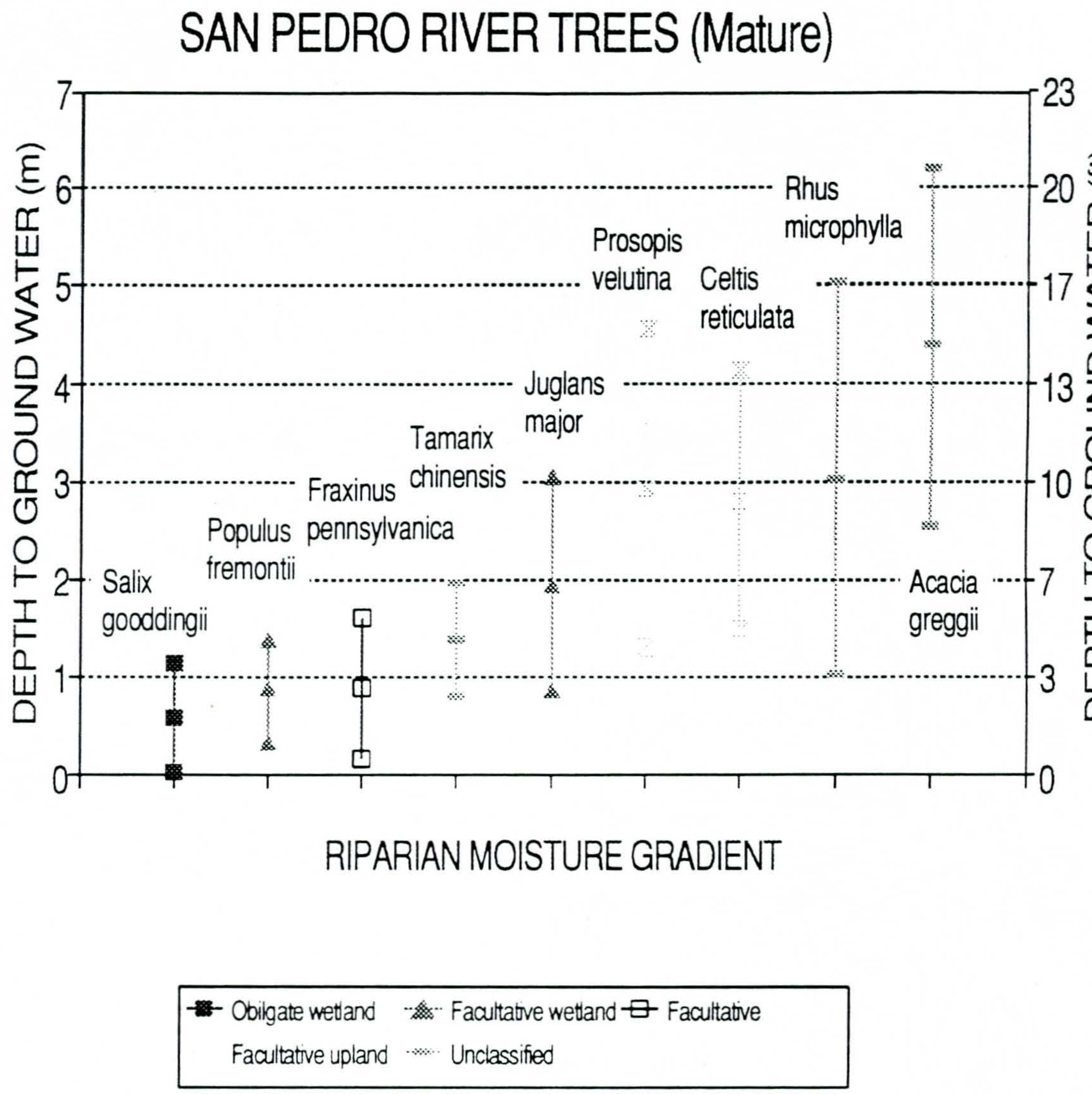
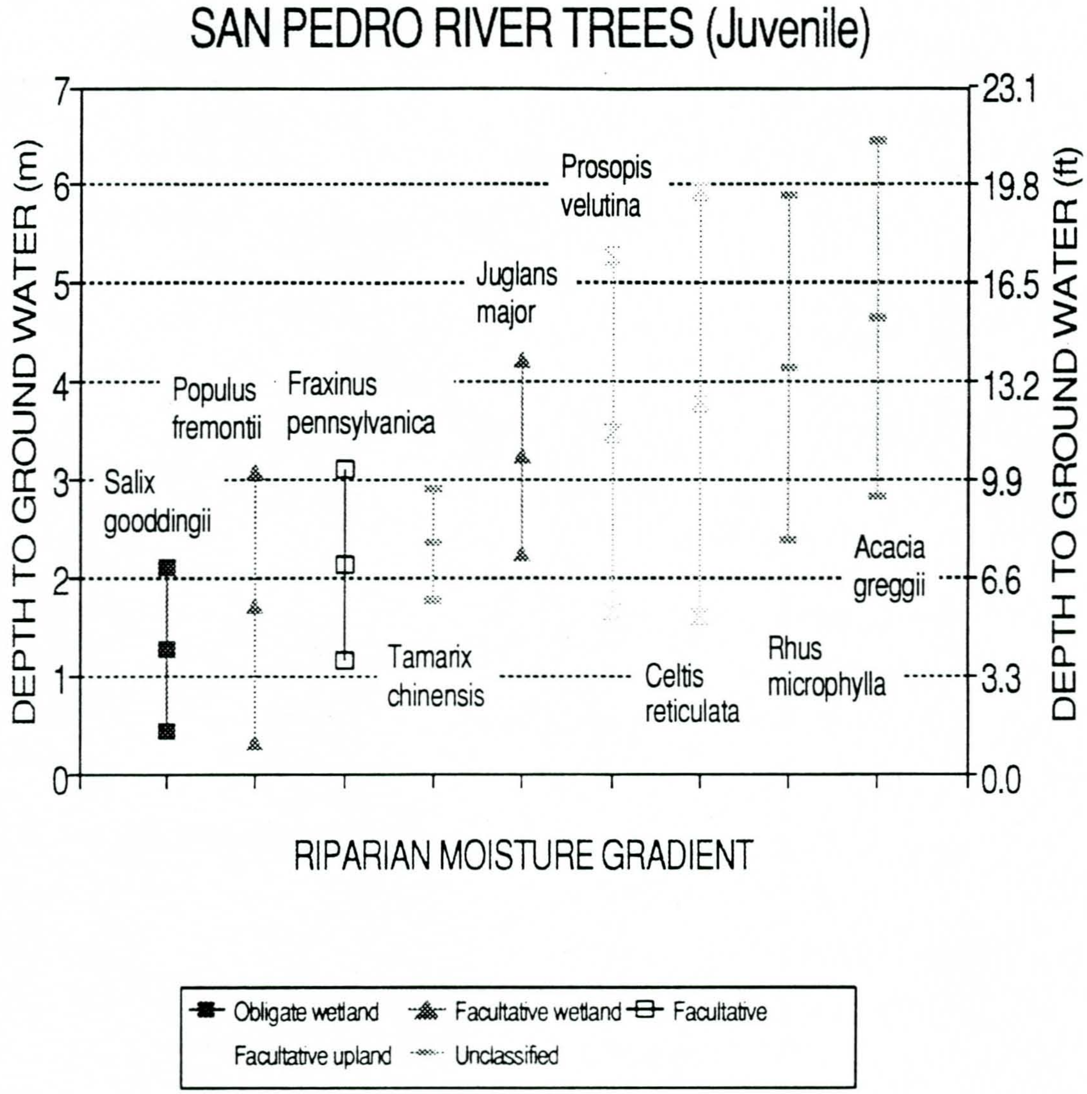


Figure 15. Distribution of juvenile tree species of the Upper San Pedro River floodplain in relation to depth to groundwater



groundwater of 2 to 3 m or 7 to 10 ft), reflective of the young age of the saltcedar stands. Mature saltcedar are known to grow where depth to groundwater is 10 m (33 ft) (see Ecology Chapter III).

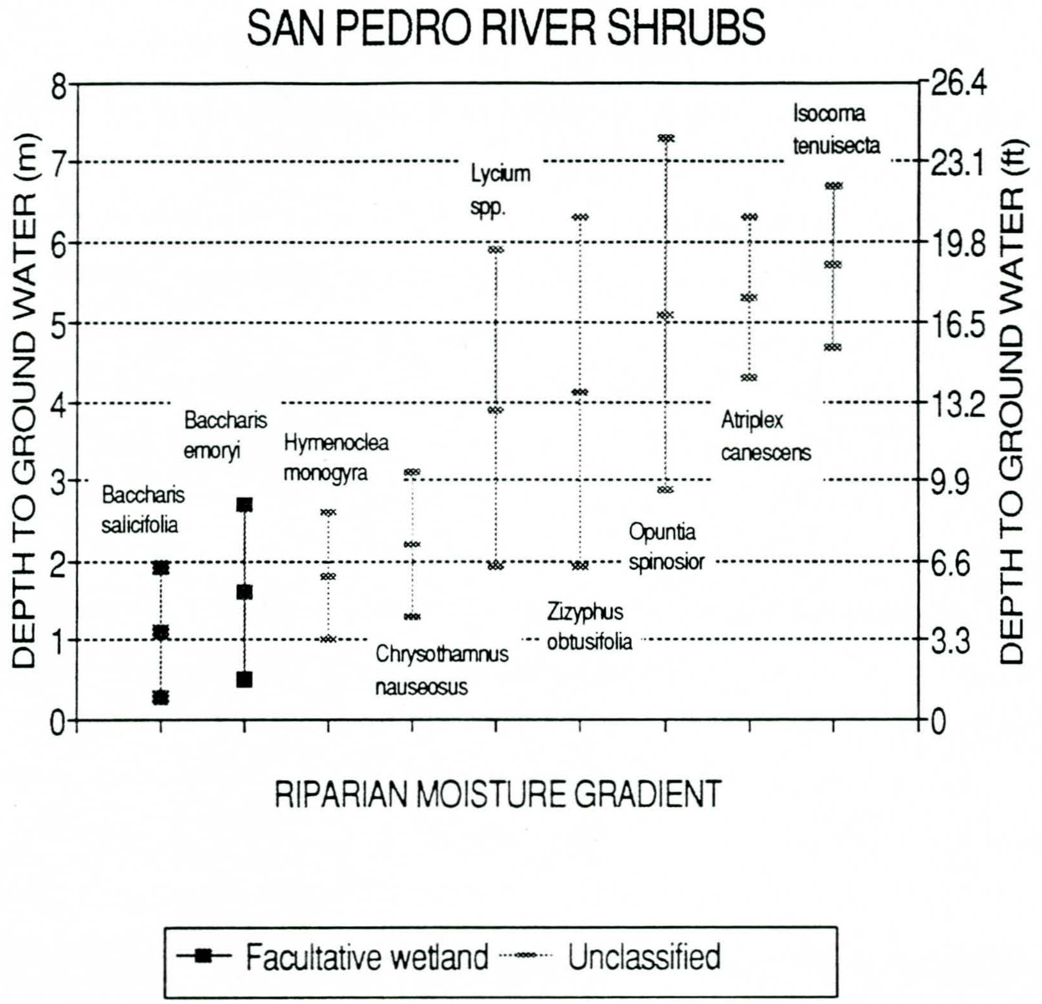
Shrub Species

Seepwillow (*Baccharis salicifolia*) and Emory seepwillow (*B. emoryi*) are obligate riparian shrubs, and also are classified as facultative wetland species (Reed 1988). Seepwillow grew on floodplains that were anywhere from about 0.3 to 2.8 m (1 to 9 ft) above the water table (Figure 16). Figure 16 shows the distribution of dominant shrub species of the Upper San Pedro River floodplain in relation to depth to groundwater. Seepwillow, like cottonwood and willow, tends to establish along the wet banks of the streams and forms thickets lining the stream banks. Seepwillow also grew on floodplains that were several feet away from the channel, due to channel movement that occurred after the plants became established. Seepwillow is seldom found away from perennial water courses, and produces vertical roots that extend to a shallow water table and lateral roots that proliferate in the zone of streambank recharge (Gary, 1963).

Burro-brush and rabbit-brush are facultative riparian plants that grow in floodplains of perennial rivers as well as in ephemeral washes and some upland habitats. Both species formed extensive stands on relatively low floodplains (about 1 to 3 m, or 3 to 10 ft above the water table) that contained coarse alluvial substrates deposited by flood waters. These shrublands had low plant density and essentially no tree canopy cover.

Wolfberry (*Lycium andersonii*), graythorn (*Zizyphus obtusifolia*), and cat-claw acacia (*Acacia greggii*, which can grow to tree size) are found in the understory of cottonwood forests and young mesquite stands on floodplains of intermediate height above the water table (2 to 5 m, or 7 to 16 ft), and in the understory of mature mesquite on high floodplains (5 to 7 m, or 16 to 23 ft). Several other facultative riparian shrubs including salt-bush (*Atriplex canescens*) and burro-weed (*Isocoma tenuisecta*) were essentially restricted to the higher floodplain terraces (>4 m, or 13 ft).

Figure 16. Distribution of dominant shrub species of the Upper San Pedro River floodplain in relation to depth to groundwater

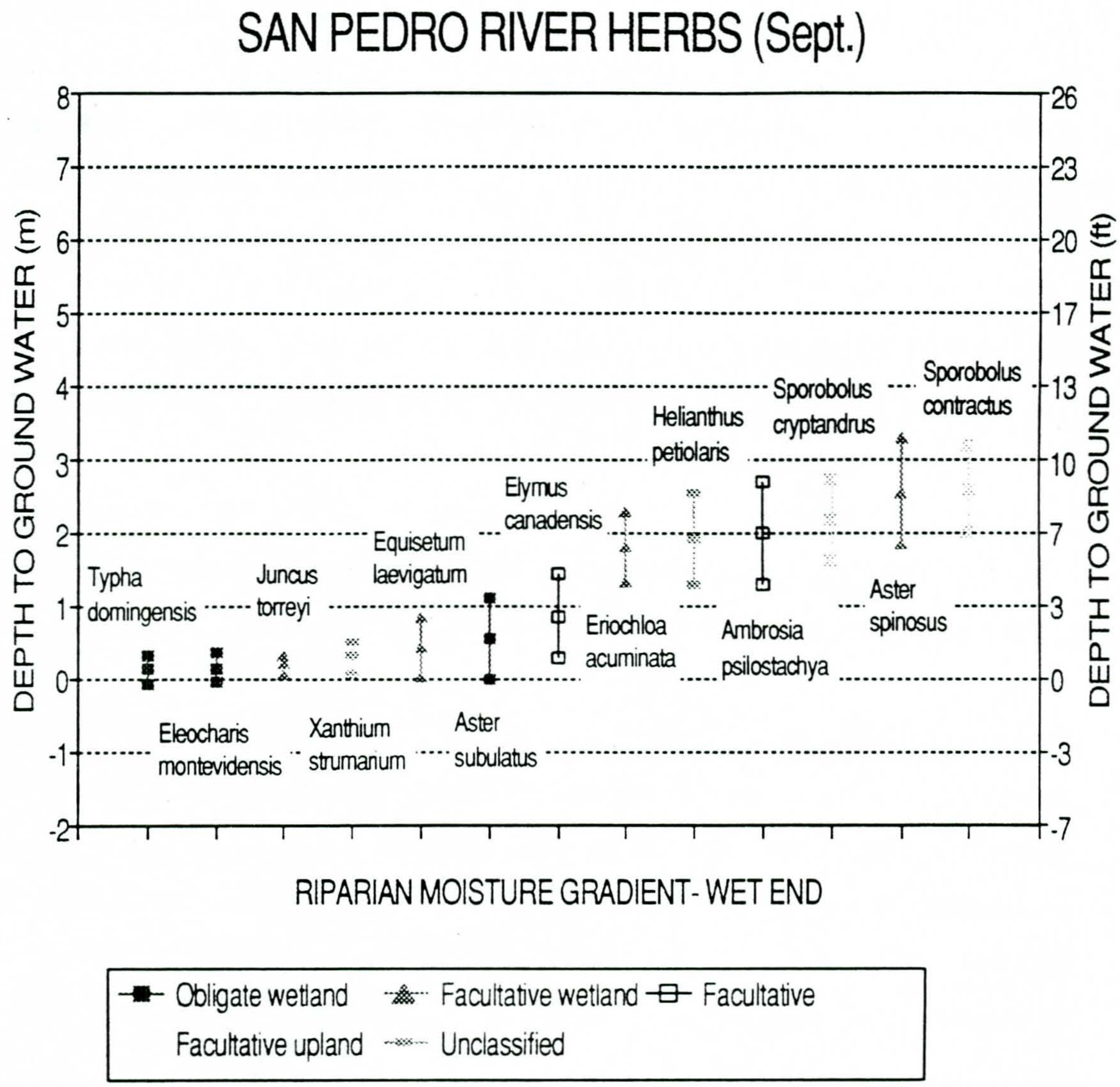


Herbaceous Plant Species

There are many more species of herbaceous plants in the San Pedro River floodplain than there are woody plants. The composition of the herbaceous community changes throughout the year as cool-season plants (e.g., annuals that complete their life cycle in the spring and early summer, and perennials that bloom and die-back by early to mid-summer) give way to warm-season plants (e.g., plants that germinate or bloom during the hot temperatures of mid-summer). Some perennial plants are present throughout the entire growing season. The following discussion applies to plants that are present in the San Pedro riparian zone during late summer.

As a general trend, plants that occurred on low floodplains grew over a narrow range of groundwater depths. Plants of higher floodplains had large ranges for depth to groundwater. This pattern was apparent for trees, but was even more pronounced for herbaceous plants (Figures 17 and 18). Figures 17 and 18 show the distribution of dominant herbaceous plant species of low floodplain terraces and of high floodplain terraces, respectively. There is a relatively large group of obligate and facultative wetland plants in the San Pedro floodplain, and these have a very narrow tolerance with respect to fluctuations in depths to groundwater. Some of these wetland plants include great bulrush (*Scirpus acutus)*, tropical cattail (*Typha domingensis*), spikerush (*Eleocharis montevidensis*), Torrey rush (*Juncus torreyi*), horsetail (*Equisetum laevigatum)*, and willow smartweed (*Polygonum lapathifolium*). Several of these marsh plants grew where water was above the ground surface or only a few inches below it, while others grew where groundwater was up to about 0.7 m (2 ft) below the ground surface. A mixture of facultative wetland, facultative, and facultative upland plants (Reed 1988) grew on floodplains that were about 1 to 3 meters (3 to 10 ft) above the water table. These included several members of the sunflower family: spiny aster (*Aster spinosus*), western ragweed (*Ambrosia psilostachya*), and sunflower (*Helianthus petiolaris*). They also included several members of the grass family: sand

Figure 17. Distribution of dominant herbaceous plant species of low floodplain terraces of the Upper San Pedro River floodplain in relation to depth to groundwater (September, 1993)

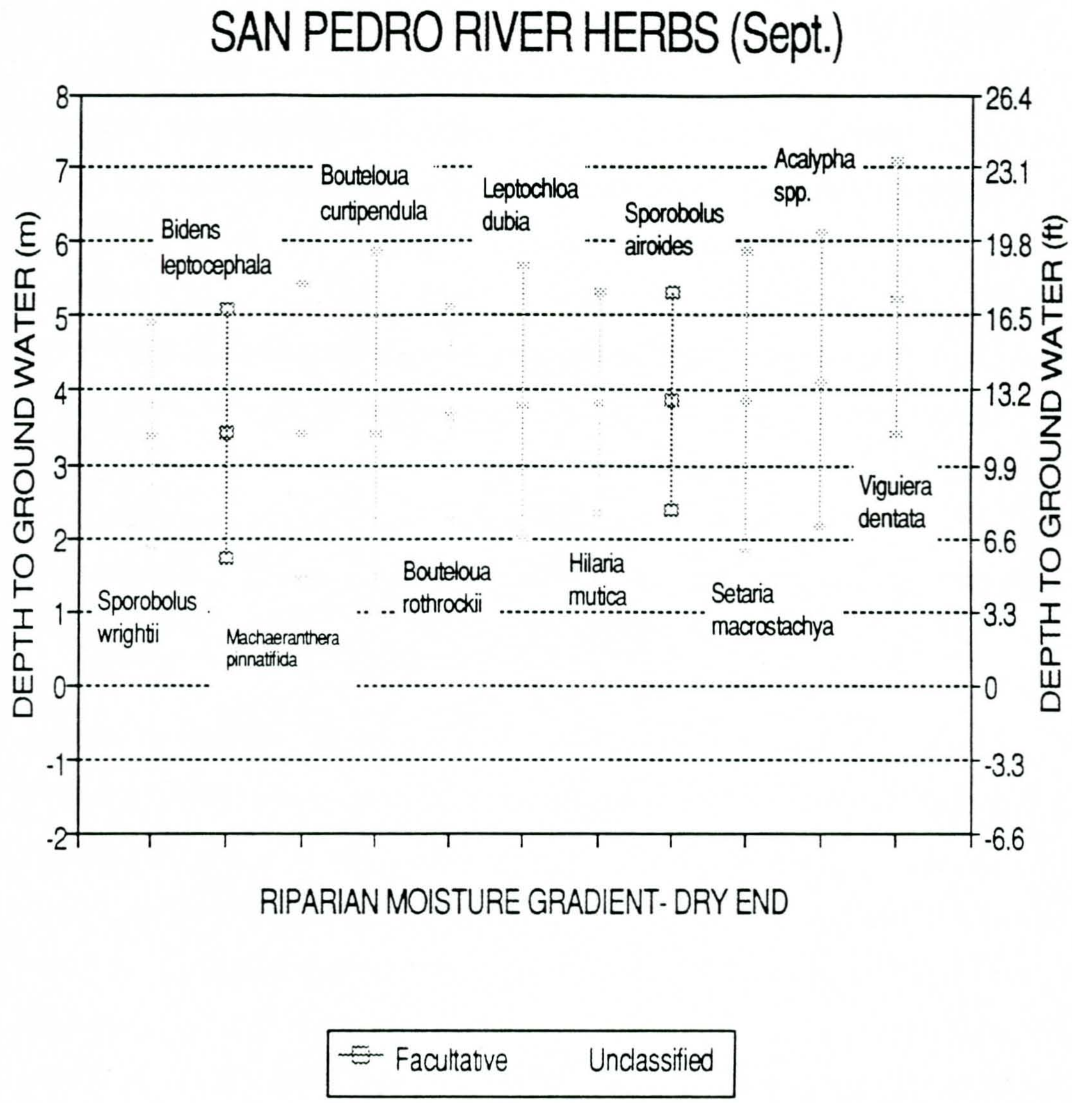


and spike dropseed (*Sporobolus cryptandrus* and *S. contractus*) and cupgrass (*Eriochloa aristata*). Some of these plants were associated with sunny open spaces (e.g., sunflower), while others tended to grow under cottonwood or willow canopy (e.g., western ragweed). Some were associated with coarse textured soils and others with fine textured soils.

On the highest floodplains, where depth to groundwater was about 2 to 6 m (7 to 20 ft), there occurred a variety of facultative riparian plants. Many of these also grow in the surrounding uplands. These high floodplains supported several grasses such as Plains bristlegrass (*Setaria macrostachya*), green sprangletop (*Leptochloa dubia*), and Rothrock grama (*Bouteloua rothrockii*) and sunflower family members including bur marigold (*Bidens leptocephala*). Many of these plants do not grow roots to the water table, but grow in the floodplain because the overstory trees create favorable growing conditions. For example, floodplain soils in bosques can have high fertility because mesquite add nitrogen to the soil and local flood events deposit nutrient-laden sediments. Also, dense tree canopies moderate temperature extremes. Deep-rooted trees also may increase moisture in surface soils by leaking groundwater from shallow roots (McQueen and Miller, 1972).

One riparian grass, giant sacaton (*Sporobolus wrightii*), is known to produce deep roots that extend to the zone of capillary water above the water table. Sacaton is a large, "showy" bunch grass up to 2 m (6 ft) in height that formed dense stands on large portions of the high floodplain terraces where groundwater was at a depth of about 2 to 5 m (7 to 16 ft). Sacaton grasslands are considered as a specific type of riparian community (Brown 1982). Several other plant species grew intermixed with giant sacaton, including tobosa grass (*Hilaria mutica*) and alkali sacaton (*Sporobolus airoides*). Sacaton grasslands were best developed at the upstream (southern) end of the SPRNCA, and generally gave way to mesquite bosques at the downstream end.

Figure 18. Distribution of dominant herbaceous plant species of high floodplain terraces of the Upper San Pedro River floodplain in relation to depth to groundwater (September, 1993)



Exotic Herbaceous Species

The herbaceous component of the San Pedro riparian plant community, like most such riparian areas in Arizona, contains a fair number of exotic plant species. Some of these exotics were purposely introduced into the riparian zones to help stabilize banks, while others arrived through other means. Several exotics were abundant on streambanks and floodplains of relatively low elevation above the water table (1 to 2 m, or 3 to 7 ft). These included white sweet clover (*Melilotus albus)*, Bermuda grass (*Cynodon dactylon*), and Johnson grass *(Sorghum halepense*). Generally, exotic plants were less abundant in the very wettest sites or where groundwater was deepest (e.g., mesquite bosque understories or dense sacaton grasslands). This is with the exception of those portions of the high floodplain terraces that have been extensively modified by humans, such as abandoned fields (e.g., former sacaton or mesquite sites) which in some areas support dense stands of tumbleweed (*Salsola kali*) and other non-native weeds.

Changes in Vegetation Structure Across Groundwater Gradients

Vegetation can be characterized by describing the species composition, and by describing changes in structural characteristics such as canopy height, number of vegetation "layers," or canopy density. Structural characteristics of the San Pedro riparian community also changed over a gradient of depth to groundwater (Figure 19), as well as across a gradient of flood disturbance. Figure 19 shows the relationship of canopy height and foliage density to groundwater depth for the Upper San Pedro River ecosystem. The change with groundwater is a product of two factors. First, structure changes because composition of the riparian plant species changes across the groundwater gradient. Tree species associated with shallow groundwater often are very tall. Fremont cottonwood, for example, can attain heights of up to 30 m (100 ft). Species that are characteristic of deeper groundwater, such as mesquite, invest more of their resources into root production and as consequence have shorter canopies. Second, structural characteristics of many facultative riparian plants change as availability of water changes. Mesquite, for example, forms only a small tree where water tables are deep, but has taller canopies in riparian zones with shallow groundwater (Stromberg, Wilkins and others, 1993). Flood disturbance affects stand structure because those areas that were most recently scoured by floods (which typically are near-channel sites with low elevation floodplains) support the youngest (and thus least structurally complex) vegetation types.

The greatest average canopy height (10 m, or 33 ft) occurred on floodplains that were about 1 to 2 m (3 to 7 ft) above the groundwater. Average canopy height declined to about 6 m (20 ft) as depth to groundwater increased to about 4 m (13 ft) or more. Maximum canopy height (i.e., height of the tallest tree found in a specific groundwater zone) occurred at groundwater depths of 2 to 5 meters (7 to 17 ft), which was the zone of mature cottonwood occurrence, and dropped sharply thereafter.

Canopy foliage area (leaf area index) also varied with groundwater depth. Foliage area was greatest on sites where groundwater was about 1 m (3 ft) below the surface, reflective of the high leaf density that occurred in relatively young, high density cottonwood stands. However, average foliage area decreased only slightly with depth to groundwater. This is because low elevation and high elevation floodplains both supported tall, dense riparian forests as well as short, open vegetation types. Low floodplains, for example, supported cottonwood and willow forests, as well as shrublands of rabbit-brush and burro-brush; while high floodplains supported mesquite bosques as well as sacaton grasslands. Although the forests on the low floodplains had higher foliage density than those on the high floodplains, they tended to form narrow "stringers" along the active and abandoned channels, whereas the mesquite bosques often covered large, contiguous areas.

ECOLOGICAL CONSEQUENCES OF FUTURE GROUNDWATER DECLINE

This section describes some of the potential consequences of groundwater decline for riparian vegetation along the upper San Pedro River. These consequences are based

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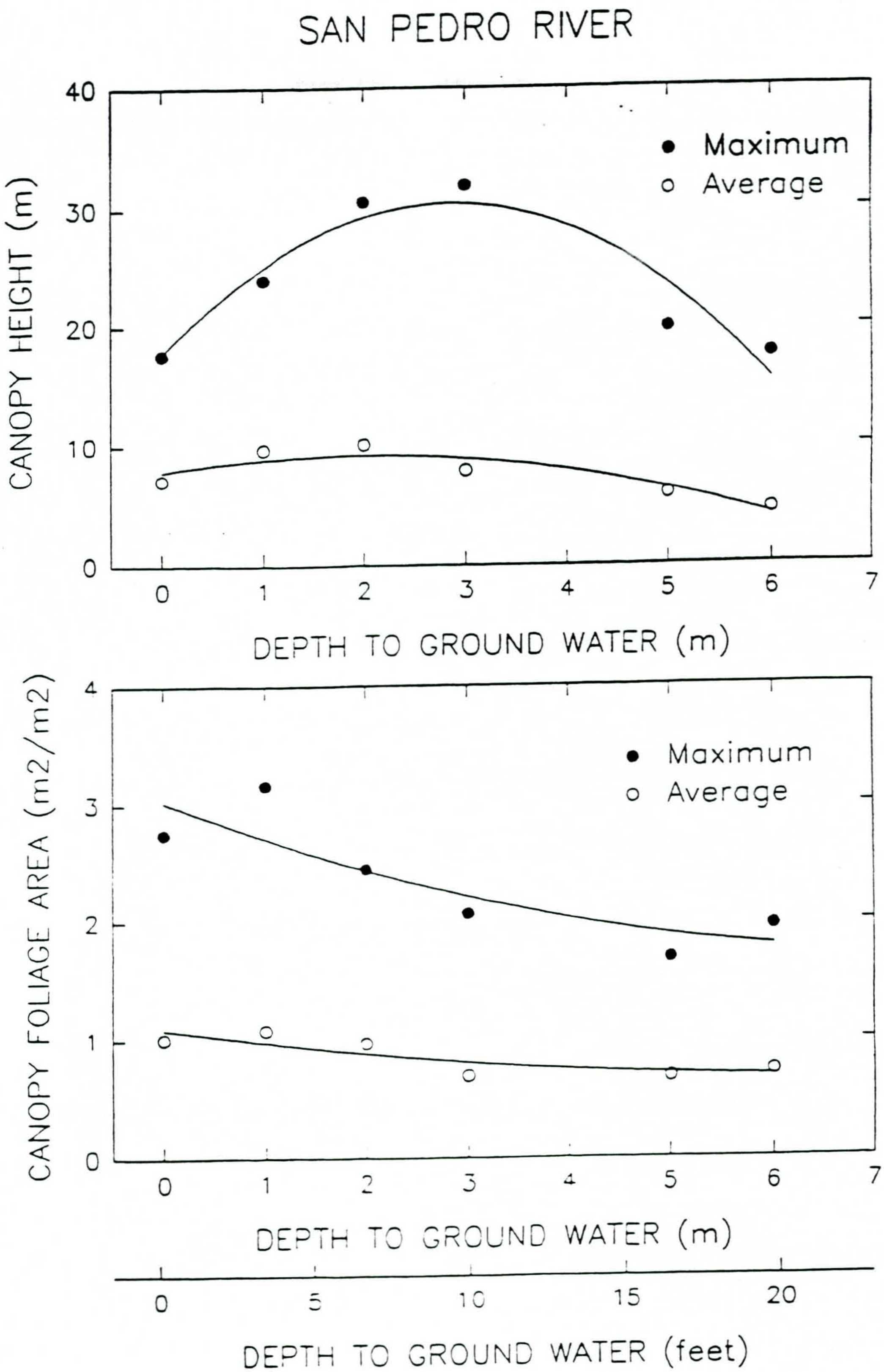


Figure 19. **Canopy height and foliage density of the Upper San Pedro River ecosystem in relation to depth to groundwater**

on predictions from two types of models, used in conjunction: (1) hydrological models, that use numerical techniques to predict extent of groundwater decline associated with various rates of pumping from wells located in the floodplain and regional aquifers, and (2) ecologic models, based on quantified relationships between plant distribution and depth to groundwater.

Groundwater Pumping Scenarios

The vertical slice model (previously discussed; presented in detail in Appendix E) was used to evaluate four different pumping scenarios to determine the effect well pumping would have on riparian areas. Each scenario simulated pumpage from either the floodplain or basin fill alluvium. The scenarios were based on one or two wells pumping at a rate of 500 gpm (2.21 acre-feet/day) continuously for the entire simulation period. The simulation periods were 6 months, 1 year, 10 years, and 20 years. The pumping rate and time periods were specifically chosen to impact the floodplain alluvium using the results in the ecologic model study. A rate of 500 gpm was chosen because it is representative of pumping rates found in the USP basins. The time periods were chosen to allow long term assessments of impacts. Also, these pumping scenarios assume new pumping at the specified rate would take place immediately, however, this additional pumpage would take place over time and would increase as the population in the basin grows in the future.

The results of each scenario are provided in Table 6 (and in appendix E). Figure 3 shows the well locations for each scenario within the model grid. The results of each model run was analyzed to determine the areal extent of drawdown greater than 1 foot, 3 feet, and 6 feet within the floodplain alluvium. The following pumping scenarios were evaluated:

<u>Scenario 1:</u>

A single well located in the floodplain alluvium (T23S R22E Sec 16d) pumping at a rate of 500 gpm (2.21 acre-feet/day). This well is located approximately 1,759 feet (~ ⅓ mile) from the San Pedro River (Figure 3). This well went dry after 3.7 years of continuous pumping.

Scenario 2:

Two wells located at 6,536 feet (~ 1¼ miles) from the San Pedro River in the basin fill alluvium (T23S R22E Secs 17d and 20d) adjacent to the floodplain alluvium. Each well is simulated pumping at a rate of 500 gpm (2.21 acre-feet/day).

Scenario 3:

Two wells located in the basin fill alluvium on each side of the river at a distance of 6,536 feet (~ 1¼ miles) from the channel (T23S R22E Secs 20d and 23b) pumping at a rate of 500 gpm (2.21 acre-feet/day) each.

Scenario 4:

Two wells located in the basin fill alluvium on the west side of the river closer to the mountain front, one at a distance of 18,855 feet (3.6 miles) from the river channel and another at a distance of 15,335 feet (2.9 miles) from the river channel (Figure 3) (T23S R21E Sec 13d and T23S R22E Sec 18c). Each well is simulated pumping at 500 gpm (2.21 acre-feet/day).

It can be seen from the Table 6 that the impacts to the riparian area and to the floodplain aquifer are immediate and direct when a well is withdrawing water from the floodplain aquifer. However, the effects of well pumping are less pronounced (and less direct) as groundwater withdrawals are moved from the floodplain aquifer to the basin fill alluvium or regional aquifer (scenarios 2, 3, and 4). Table 6 also shows the maximum drawdown due to the well pumping for both the floodplain and basin fill aquifers. Scenario 2 and 3 yielded very similar results for total acres within the 1 Ft drawdown. Scenario 4 had less of an impact and the effects took longer to reach the floodplain alluvium than with the other three scenarios. Also, scenario 4 showed the most drawdown of approximately 84 feet (in the regional aquifer) for any given cell.

Because the results of scenarios 2 and 3 were so similar, scenario 2 results were used in the ecologic model.

Table 6
Results of groundwater pumping scenarios 1 through 4

		Layer 1 Drawdown (DDN) Area >1ft, 3ft, 6ft (Acres)			Layer 1 (Floodplain Aquifer)	Layer 2 (Regional Aquifer)
Model Run	Time	>1Ft DDN	>3Ft DDN	>6Ft DDN	Maximum DDN (Ft)	Maximum DDN (Ft)
Scenario 1 (FA1)						
FA1-1	6 mos	473	211	139	40.8	N/A
FA1-2	1yr	666	253	167	47.7	N/A
FA1-3[1]	10yr					
Scenario 2 (BF)						
BF-1	6 mos	535	0	0	2.48	17
BF-2	1 yr	1,017	<1	0	3.5	18.9
BF-3	10 yr	2,382	677	0	6.72	23.6
BF-4	20 yr	2,431	729	<2	7.13	24.1
Scenario 3 (BF2)						
BF2-1	6 mos	402	0	0	2.4	9.5
BF2-2	1 yr	1,233	0	0	3.1	10.6
BF2-3	10 yr	2,343	323	0	4.9	13.6
BF2-4	20 yr	2,377	383	0	5.1	13.9
Scenario 4 (BF3)						
BF3-1	6 mos	0	0	0	1.2	24.2
BF3-2	1 yr	0	0	0	1.2	32.8
BF3-3	10 yr	1,262	0	0	3.0	73.8
BF3-4	20 yr	1,986	137	0	4.5	83.6

[1] Model Run FA1-3 pumping cell went dry 3.7 years into simulation;
FA - floodplain alluvium scenario 1
BF - basin fill alluvium scenario 2
BF2 - basin fill alluvium scenario 3
BF3 - basin fill alluvium scenario 4

Changes in Species Composition

One consequence of groundwater decline on riparian ecosystems is sequential loss of increasingly more sensitive plant species. As depth to groundwater increases, species composition changes from hydrophytic plants (i.e., obligate wetland plants) to more and more xerophytic plants (i.e., facultative riparian plants and ultimately upland plants).

Plants along the San Pedro River that are most sensitive to groundwater decline are herbaceous wetland plants (i.e., cienega or marsh plants). These plants occur within Vegetation Zone 1 (Table 7). This table shows the various groundwater zones used in the ecological groundwater decline model. The vegetation zones are separated into (1) obligate wetland herbs, (2) cottonwood seedlings, (3) mature cottonwood-willow (lower end), (4) mature cottonwood-willow (upper end), (5) sacaton-mesquite, and (6) mesquite.

With a groundwater decline scenario of 0.3 m (1 ft), the floodplain area that could support obligate wetland plants (i.e., Vegetation Zone 1) would decline by 28% (Table 8). Under a groundwater decline scenario of 1 m (3 ft) or more, this wetland community would be lost entirely from that portion of the floodplain undergoing such a decline. This would include the loss of marsh species such as tropical cattail, rushes, bulrushes, and rare species such as Huachuca water umbel (*Lilaeopsis schaffneriana* var. *recurva*) which is a Federal Category 1 listing candidate that has only recently been re-discovered along the San Pedro River (Warren and Gori, 1993). Greater rates of groundwater decline (e.g., 2 m, or 6 ft) would cause many facultative wetland plants such as Canada wild rye and horsetail (Vegetation Zone 2) to be lost or undergo decline. Such facultative wetland plants would undergo a 37% decline in potential habitat with 0.3 m (1 ft) groundwater decline in the floodplain aquifer; a 51% decline with 1 m (3 ft) decline, and 100% loss with a 2 m (6 ft) decline (Table 8 and Figure 20).

Specific pumpage scenarios show that wells located in the floodplain aquifer would cause greater loss of wetland vegetation than would those located with increasing distance from the floodplain in the basinfill aquifer. For example, one well pumping

Table 7
Vegetation groundwater zones used in ecological groundwater decline models.

		CHARACTERISTIC PLANTS- PARTIAL LIST		
VEGETATION ZONE	DEPTH TO Groundwater RANGE	WOODY SEEDLINGS	MATURE WOODY PLANTS	HERBACEOUS PLANTS
1 OBLIGATE WETLAND HERBS	-0.3 to 0.3 m (-1 to 1 ft)	Seepwillow		Torrey rush
		Goodding willow		Spike rush
				Great bulrush
				Tropical cattail
2 COTTON-WOOD SEEDLING ZONE	0.3 to 1 m (1 to 3 ft)	Fremont cottonwood		Canada wild rye
		Goodding willow		Horsetail
				Cocklebur
3 COTTON-WOOD- WILLOW ZONE-lower end	1 to 2 m (3 to 7 ft)	Saltcedar	Fremont cottonwood	Cup grass
			Goodding willow	Western ragweed
			Seepwillow	Sunflower
			Burro-brush	
			Rabbit-brush	
4 COTTON-WOOD WILLOW ZONE-upper end	2 to 3 m (7 to 10 ft)	Mesquite	Fremont cottonwood	Sand dropseed
		Hackberry	Goodding willow	Spiny aster
			Burro-brush	
			Rabbit-brush	
5 SACATON-MESQUITE ZONE	3 to 5 m (10 to 16 ft)		Mesquite	Giant sacaton
			Graythorn	Green sprangletop
			Cat-claw acacia	Tobosa grass
6 MESQUITE ZONE	5 to 8 m (16 to 26 ft)		Mesquite	Golden eye
			Salt bush	Copper-leaf
			Graythorn	
			Cat-claw acacia	

Table 8 Expected decline in marsh vegetation abundance and cottonwood-willow abundance under hypothetical groundwater declines of 1ft, 3ft, and 6ft.			
	PERCENTAGE DECLINE IN AREA COVERED BY VEGETATION TYPES		
Groundwater DECLINE	Marsh Vegetation (Zone 1)	Cottonwood and willow seedlings (Zone 2)	Cottonwood-willow forest (Zones 3 and 4)
1 ft (0.3 m)	28%	37%	14%
3 ft (1 m)	100%	51%	35%
6 ft (2 m)	100%	100%	79%

500 gpm (2.21 acre-feet/day) and located in the floodplain alluvium of the Upper San Pedro River (T23S, R22E, Section 16D) would be expected to cause a 64% reduction in marsh vegetation after one year (Zone 1 Vegetation) (Figure 21). Several years would be required for wells located in the regional aquifer to cause declines in marsh vegetation. Two wells located in the basin fill alluvium (T23S, R22E, Sec 17D and 20D) about 2 miles from the San Pedro floodplain edge, both pumping 500 gpm, would cause an 18% decline in marsh vegetation after one year; a 64% decline after ten years and a 68% decline after twenty years (Figure 22).

The greater the distance the regional aquifer wells are from the floodplain, the longer it takes for effects to be apparent in the floodplain aquifer. For example, wells located about four miles west of the floodplain edge would have no discernable effects after ten years but would cause 49% decline in marsh vegetation after twenty years (Table 9). Wells located about 2 miles from the floodplain would show major effects after ten years.

Loss of wetland plants already is apparent on portions of the SPRNCA where groundwater tables show seasonal groundwater declines of about 1 to 2 m (3 to 6 ft). Table 10 provides a comparison of the herbaceous plant composition in a section of the San Pedro River where water tables remain seasonally very high and flow is

Figure 20. Estimated change in area of riparian vegetation zones (see Table 8) in response to groundwater declines of 1ft, 3ft, and 6ft.

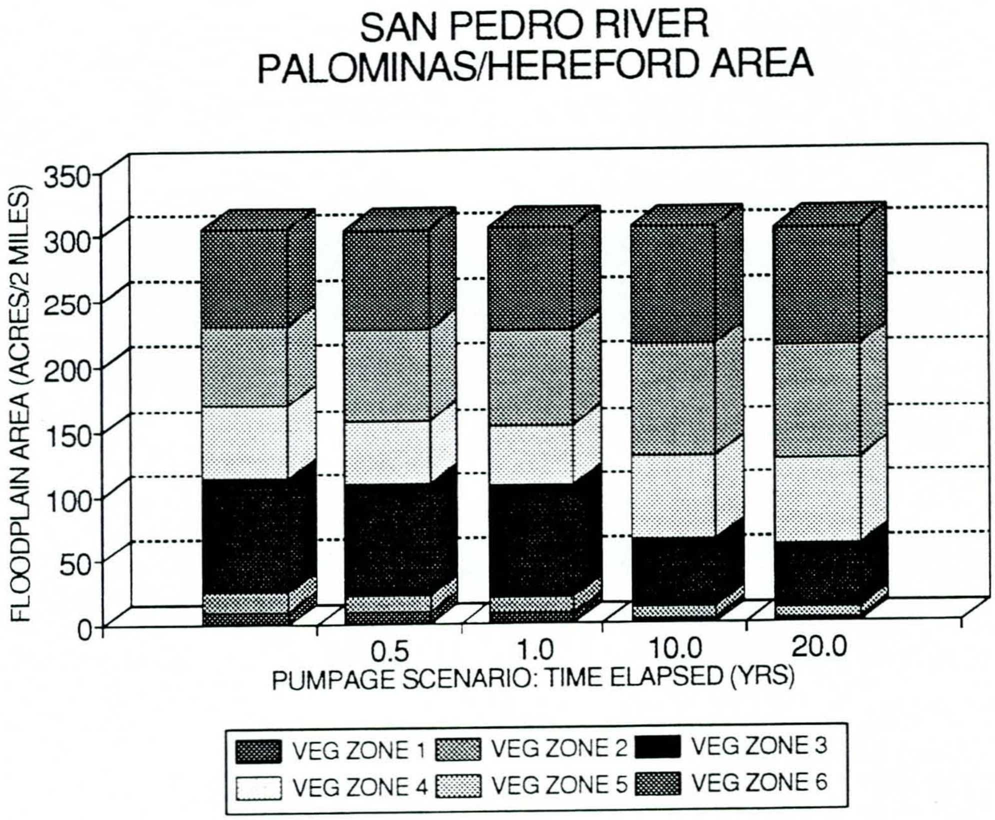


Figure 21. Estimated change in area of riparian vegetation zones in response to groundwater pumpage scenario 1 (well pumping in the floodplain aquifer)

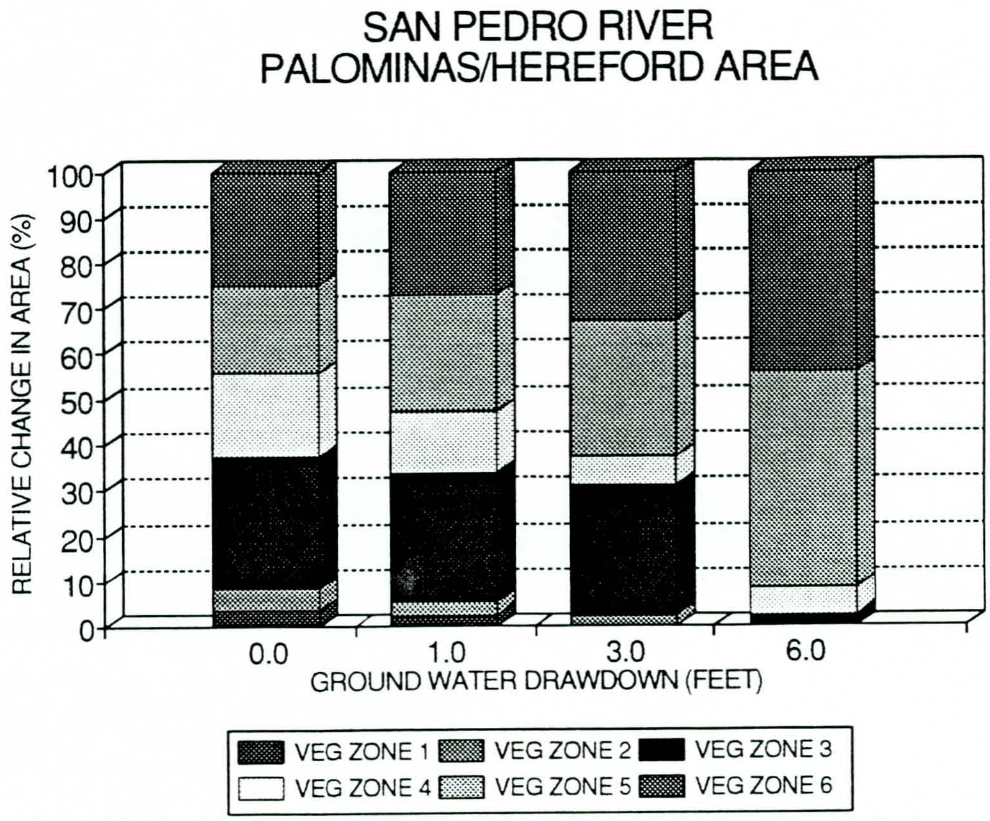
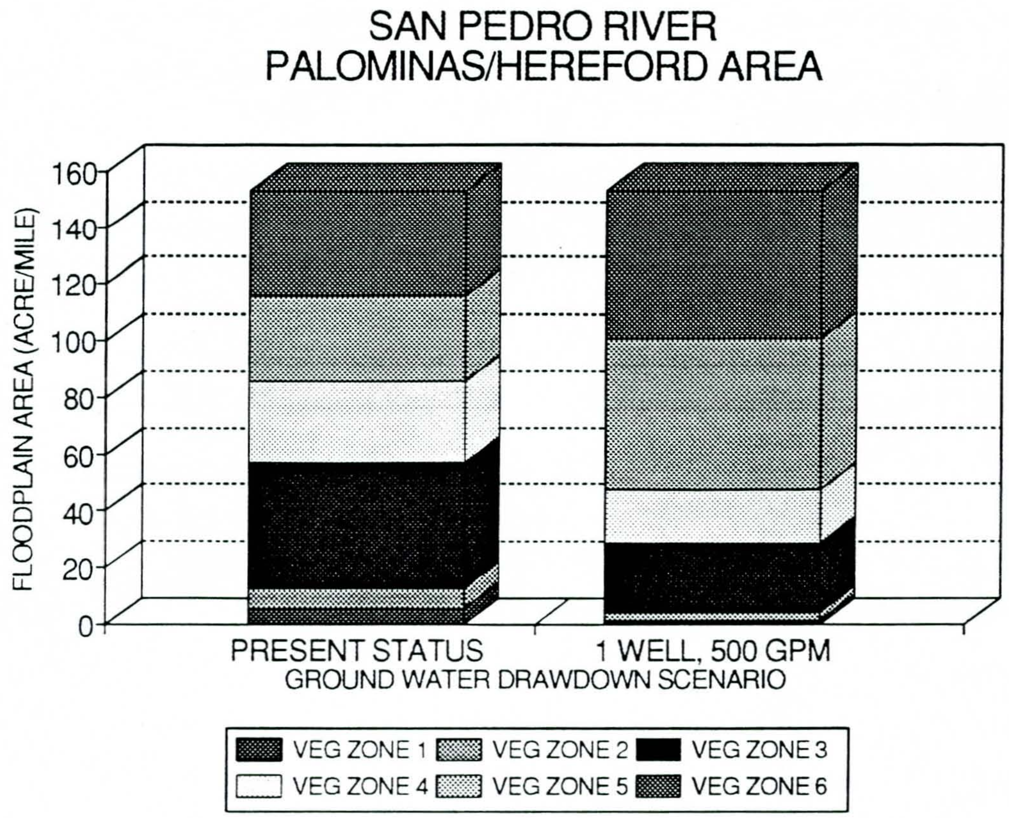


Figure 22. Estimated change in area of riparian vegetation zones in response to groundwater pumpage scenario 2 (two wells pumping from the regional basinfill aquifer)



perennial and sites in which groundwater has higher seasonal declines and flow is intermittent in the summer. Groundwater tables are shallowest at Hereford 1 and Moson Springs and deepest at Contention. At the Hereford 1 and Moson Springs sites, maximum groundwater flux has been 0.5 m, or 1.5 ft since 1987. These sites support several obligate wetland plants (Table 10). At Palominas 10, maximum groundwater flux has been 1 m [3 ft] since 1987. As a result of these moderate seasonal groundwater declines, the site supports facultative wetland plants but no obligate wetland species. At Contention (located between Tombstone and Benson), maximum groundwater flux has been 1.9 m [6 ft] since 1987. These groundwater declines have been great enough to cause loss of obligate wetland plants and facultative wetland plants.

Table 9
Expected decline in marsh vegetation and cottonwood-willow abundance under two basin fill pumpage scenarios

	PERCENTAGE DECLINE WITHIN A 2-MILE REACH OF THE FLOODPLAIN		
Groundwater PUMPAGE SCENARIO	Marsh Vegetation (Zone 1)	Cottonwood and willow seedlings (Zone 2)	Cottonwood-willow forest (Zones 3 and 4)
2: 10 yrs	64%	44%	14%
4: 10 yrs	0%	0%	0%
2: 20 yrs	68%	45%	14%
4: 20 yrs	49%	41%	14%

Changes in Population Structure and Plant Density

Seedlings of riparian tree species typically germinate and establish under conditions that are quite different from those tolerated by adults. In comparison to mature trees, seedlings of many obligate and facultative riparian trees and shrubs are highly sensitive to groundwater decline. Thus, another expected response to groundwater decline would be reduction in seedling establishment success and loss of population age class diversity. Seedlings of Fremont cottonwood, Goodding willow, and seepwillow, for example, establish in Vegetation Zones 1 and/or 2 (Table 7). Declines of about 0.3 m (1 ft) would reduce potential cottonwood establishment areas (Vegetation Zone 2) by about a third; declines of 1 m (3 ft) would reduce these areas by about half; and declines of 2 m (about 6 ft) would entirely eliminate seedling recruitment zones for this species. Under groundwater decline, then, cottonwood and willow establishment could be eliminated entirely from certain reaches of the river, or restricted to narrow bands within the floodplain.

Table 10
Herbaceous plant composition and cover at four sites adjacent to the San Pedro River, as measured in July 1993.

OBLIGATE WETLAND SPECIES	SAN PEDRO STREAMSIDE PLANT COVER, BY SPECIES (%)			
	Hereford 1	Moson Springs	Palominas 10	Contention
Aster subulatus	<1±<1	0±0	0±0	0±0
Juncus balticus	22±31	0±0	0±0	0±0
Polypogon interruptus	2±3	1±1	0±0	0±0
Polygonum punctatum	1±1	0±0	0±0	0±0
Rorippa Nasturtium-aquaticum	<1±<1	0±0	0±0	0±0
Scirpus acutus	0±0	2±2	0±0	0±0
Typha domingensis	0±0	<1±<1	0±0	0±0
Veronica anagallis-aquatica	<1±<1	0±0	0±0	0±0
SUBTOTAL	26	3	0	0
FACULTATIVE WETLAND SPECIES				
Eleocharis montevidensis	1±1	1±1	0±0	0±0
Equisetum laevigatum	3±5	0±0	12±13	0±0
Juncus torreyi	0±0	2±1	7±9	0±0
Polypogon monspeliensis	3±3	4±3	4±3	0±0
SUBTOTAL	7	7	23	0
FACULTATIVE SPECIES				
Ambrosia psilostachya	<1±<1	0±0	0±0	0±0
Cynodon dactylon	0±0	2±2	0±0	0±0
Melilotus albus	6±2	28±32	10±14	1±1
SUBTOTAL	6	30	10	1
OTHER SPECIES				
Helianthus petiolaris	0±0	0±0	<1±<1	0±0
Xanthium strumarium	<1±<1	<1±<1	<1±<1	0±0
AVERAGE TOTAL COVER[1]	38±30	40±40	28±34	1±1

[1] Total cover values sometimes exceed sum of individual species cover values because of overlapping plant cover layers.

Successful establishment of Fremont cottonwood and Goodding willow depends on a combination of factors. Floods are essential in this process. Flood peaks, which scour some vegetation and deposit new sediment, serve to create seed beds of bare alluvium required by the seedlings (which do not compete well with established vegetation). Flood waters also moisten the floodplain sites and stimulate germination. Slowly receding flood waters help to keep the seedling roots moist and promote good root growth. Shallow water tables (0.5 to 1 m, or about 1.5 to 3 ft) are essential for survivorship of the seedlings in their first year of life (Stromberg and others, 1991; Stromberg, 1993). High survivorship also depends upon a slow rate of post-flood spring and summer groundwater recession (no greater than 3 cm [1 inch] a day) (Mahoney and Rood, 1991; Segelquist and others, 1993).

Lack of recent Fremont cottonwood and Goodding willow establishment already is apparent in some reaches of the San Pedro River. During 1993, for example, floods created potential conditions for cottonwood seedling establishment. Sampling of the established vegetation at this site also indicted the presence of few young cottonwoods (i.e., few saplings or "pole-sized" trees) (Table 11). This contrasts with sites such as Moson Springs, at which cottonwood is abundant in many size (age) cohorts. Age structure at sites such as Moson Springs can be classified as "healthy" in the sense that there are many more young trees than old trees and many size (age) classes. At Contention, where seasonal groundwater flux is relatively high (about 2 m, or 6 ft) and flow is intermittent, monitoring of seedling establishment revealed that water tables declined too rapidly in summer to allow for survivorship of Fremont cottonwood seedlings.

Goodding willow and Fremont cottonwood thrive as adults on sites where groundwater is up to 3 m (10 ft) below the surface. Although mature Goodding willow and Fremont cottonwood trees would survive small groundwater declines, these declines would reduce the frequency of establishment and abundance of new generations of trees. Groundwater decline would initially result in a decrease in age structure diversity for these tree species, ultimately causing the eventual loss or reduction of the species from the groundwater depressed portion of the floodplain as the last remaining adults succumbed to old age at about 80 to 130 years.

Groundwater declines on the order of 2 to 4 m (6 to 10 ft) would cause depth to groundwater below the cottonwood-willow floodplain surface to drop 4 to 7 m (13 to 23 ft). This would effect existing cottonwood and willow stands by causing loss of vigor, tree death, decline in tree density, and loss of canopy foliage. As indicated by the Santa Cruz Case Study, stand foliage area and tree density would decline continuously as depth to groundwater declined below the surface from about 3 m (10 ft) to about 7 m (23 ft).

Table 11
Density of Fremont cottonwood and saltcedar at two sites along the Upper San Pedro River, as measured in 1993.

		FREMONT COTTONWOOD		SALTCEDAR	
COHORT CODE NUMBER	DISTANCE TO STREAM (m)	Stem Diameter Range (cm)	Stem Density (#/100m^2)	Stem Diameter Range (cm)	Stem Density (#/100m^2)
MOSON SPRINGS					
1E[3]	0	<1	132	-	0
1W	3	<1	10	-	0
2E	10	15-30	10	1-2	2
3E	140	30-60	23	2-6	6
4E	215	65-105	1	-	0
2W	60	160-260	1	-	0
CONTENTION					
1W	0	15-30	<1	-	0
1E	2	-	0	1-3	2
2E	30	-	0	1-7	16
3E	230	25-65	6	1-15	126
4E	180	90-105	1	-	0
2W	200	110-130	2	-	0

[1] Age-class determination is in progress
[2] Stem diameter in cm (one inch = 2.54 cm)
[3] Indicates whether cohort is growing on east or west side of stream

Reduction or loss of Fremont cottonwood or Goodding willow from the riparian zone could disrupt natural ecosystem processes such as soil development, terrace building, succession, and understory species establishment. For example, loss of Fremont cottonwood and Goodding willow stands may affect species such as netleaf hackberry, Arizona walnut, or giant sacaton that establish in the shade of cottonwood stands on aggraded floodplains where soils have greater nutrient content, more organic matter, and an abundance of silts and clays. This "domino effect" in which alterations in the abundance of one riparian plant species affect other riparian species has not been thoroughly studied.

Increase in Exotic Species

Another predicted consequence of lowered water tables on the San Pedro River is increased invasion of saltcedar. Saltcedar in its native land grows on mid to high floodplain terraces. It tolerates relatively deep water tables and is more drought tolerant as juveniles and adults than are Fremont cottonwood or Goodding willow. Like these two native species, however, it also is a flood-tolerant pioneer species.

As indicated in Figure 20, groundwater declines of up to 2 m (about 6-7 ft) would still allow for saltcedar seedling establishment (Vegetation Zone 3) while eliminating suitable establishment sites for cottonwood and willow seedling establishment (Vegetation Zone 2).

As water tables drop, recruitment bars will remain in the zone of frequent flood scour which will preclude establishment of native high floodplain tree species such as mesquite or hackberry, which are flood intolerant. Water tables will be too deep for cottonwood and willow seedlings. Saltcedar, however, can tolerate the combination of deeper water tables and periodic flood inundation. This new "niche" of deeper water tables and high flood frequency may be filled by saltcedar, and by riparian scrub species such as burro brush which also are both drought tolerant and flood tolerant.

Saltcedar is abundant on much of the lower San Pedro River below Benson, and is beginning to invade on hydrologically losing reaches of the downstream end of the SPRNCA where flows are intermittent and water tables show relatively high seasonal declines (i.e., between Tombstone and Benson) (Table 11). The saltcedar in this area is relatively young, but is occupying areas of the floodplain zones that typically would be occupied by cottonwood.

Contention, is a site in the downstream end of the SPRNCA in which cottonwoods are giving way to saltcedar on the young floodplains (Table 11). While, at Moson Springs, in contrast, cottonwood trees are abundant in a variety of size (and age) classes, including young age classes. Should groundwater declines occur throughout the SPRNCA, saltcedar would be likely to invade the lower floodplains of much of the Upper San Pedro River, replacing one of the last strongholds of cottonwood-willow forest.

Changes in Vegetation Structure

Burro-brush and rabbit-brush are native facultative riparian shrubs (often called riparian "scrub") that also are adapted to the niche of moderately deep groundwater, high frequency of flood disturbance, and coarse soils. With groundwater decline of about 2 m (6 ft) or more, these species likely would decline in abundance in the Upper San Pedro River floodplain (Figure 20; note decrease in both Vegetation Zones 3 and 4). With intermediate groundwater declines, however, these species would likely increase in relative abundance within what is now potential cottonwood-willow habitat. With groundwater declines of 1 m [3 ft], Vegetation Zone 3 habitat remains relatively abundant, while cottonwood-willow establishment zones decline.

These shrublands are a natural component of the riparian mosaic. However, they have short stature (<3 m, or 10 ft), form open stands with low plant density, and produce relatively small needle-like leaves. Saltcedar stands also are relatively short and produce tiny leaves. One result of increases in these species in the San Pedro River floodplain would be a reduction in canopy height, canopy foliage area, and structural diversity, as also predicted by vegetation structure models in response to groundwater decline (Figure 19).

Structural development of vegetation types adapted to relatively deep groundwater also would be affected by groundwater decline. Sacaton grasslands, for example, are known to have greatest "lushness" and vigor where depth to groundwater is about 2 to 5 m (6 to 16 ft) (Stromberg, 1993). Many of the sacaton grasslands along the Upper San Pedro floodplain grow on the pre-entrenchment floodplain where depth to groundwater is 5 or 6 m (16 to 20 ft). Groundwater declines of several feet would cause these stands to undergo declines in vigor or abundance. Giant sacaton tend to give way to the shorter alkali sacaton and may also give way to mesquite as groundwater levels decline to more than about 5 m (16 ft) below the surface (Lacey and others, 1975).

Similar to sacaton grasslands, mesquite bosques are most extensive on the pre-entrenchment floodplains where groundwater tables already are relatively deep. Although tolerant of a wide range of water tables, mesquite in these areas would be expected to under go continuous declines in canopy height and canopy foliage area as depth to groundwater increases (Stromberg and others, 1993). Mesquite would persist and potentially increase on the post-entrenchment floodplain in response to groundwater declines, but many years would be required for these young mesquite stands to attain the same size and density (and wildlife value) as the older stands on the higher floodplains.

DISCUSSION AND HISTORICAL PERSPECTIVE

Cienega Vegetation

The San Pedro River has been a site of human activity for centuries. Some of these activities are believed to have contributed to large-scale changes in the riparian vegetation over the last century. The Upper San Pedro River as of 100 years ago was unincised and marshy over much of its length, with an abundance of beaver dams. Cienega areas with "boggy banks" covered about half the length of the river, although riparian trees (cottonwood and willow) grew in the cienega reaches as well as in intervening reaches. These cienegas, now nearly nonexistent, historically were maintained by groundwater discharge as well by perhaps by the beaver impoundments.

The cienegas were vegetated by wetland species that included a wide mixture of rushes, spike rushes, bulrushes, and other plants that require shallow water tables and perennially wet soil. These wetlands were essentially eliminated from the San Pedro and other southern Arizona Rivers during the turn of the century. During 1890 to 1915, the San Pedro, San Simon, Santa Cruz, and many other southern Arizona rivers were converted from shallow-banked narrow rivers with high water tables to incised rivers with vertical cut-banks and water tables that were well below the original floodplain surface (Jordan and Maynard, 1970; Cooke and Reeves, 1976; Hendrickson and Minckley, 1984). Exact causes of this phenomenon are unknown, although land and water uses may have been contributing factors. Surface water was diverted through dikes and drains to supply irrigation water for floodplain agriculture as early as the 1870s (Bahre, 1991). Groundwater pumping, although not as extensive as in modern-day times, began in this area in the 1890s. Groundwater was pumped only in areas with shallow groundwater, and was fueled by steam-powered pumps that consumed large amounts of mesquite wood (e.g., one cord of wood to run a pump for 10 hours) that were harvested from the floodplain (Bahre, 1991).

Of all riparian vegetation types, cienegas were impacted to the greatest degree by a combination of these hydrological modifications because of their requirements for high water tables (Scurlock, 1988). Riparian forests persist along the San Pedro but the river no longer flows through lush riparian marshlands (Cooke and Reeves, 1976; Jackson and others, 1987). Small patches of wetland vegetation line the streambanks in some portions of the SPRNCA but these cover a small portion of the floodplain. Many rivers in Arizona, however, have no marsh vegetation. The presence of marsh plants along the San Pedro River has been interpreted as a sign that the cienega vegetation is recovering. Jackson and others (1987) observed that cienega (marsh) vegetation was rebuilding within the newly widened lower floodplain in river reaches of the San Pedro River that had shallow, stable water tables.

History tells us of the sensitivity of cienega vegetation to water table changes, as do the ecological relationships described in this report. It is essential to maintain high water tables on the San Pedro River to allow the existing cienega vegetation to continue on its road to recovery rather and to prevent cienega loss such as is evident on portions of the San Pedro as well as on many other rivers in the state (e.g., see Santa Cruz Case Study).

Impacts of loss of cienega vegetation are many. As rare wetland habitats within semiarid settings, cienegas provide critical habitat to many animal species. In summer, bird densities in cienega habitat near the San Pedro River were three to five times as high as bird densities in the surrounding uplands and about equal to that in cottonwood-willow forests (Krueper and Corman, 1988). In winter, bird densities in the cienega were higher than in the riparian forest although species richness was lower. Several bird species respond positively to the combination of cienega habitat and riparian forest habitat (Gori, 1992).

Reptiles and amphibians also are abundant in cienegas, and include Sonora mud turtles (*Kinosternon sonoriense*), garter snakes (*Thamnophis* sp.), and leopard frogs (*Rana pipiens* and *Rana yavapaiensis*), the latter of which are undergoing regional decline (Brown, 1982). Relict or endemic species of mollusc also may occur in spring-fed cienegas (Hendrickson and Minckley, 1984). The Huachuca spring snail (*Pyrgulopsis thompsoni*) is a rare snail that occurs in cienega habitat in southern Arizona, and is a candidate for listing under the Federal Endangered Species Act.

Cottonwood-Willow Forests

Although cienegas were historically abundant on the Upper San Pedro River, historical reports of the San Pedro bottomlands in the mid-1800s also describe the occurrence of thick forested groves (Davis, 1982). For example, the trapper and explorer James Ohio Pattie in the 1830s talks about an abundance of beaver and other wildlife and described "a thick grove of timber, extending about a hundred yards in width" in a reach of the river which is no longer perennial. He went on to describe river banks that were "plentifully timbered with cottonwood and willow (Davis, 1982). Others during this time period described areas of "heavy mesquite timber about one mile in width," dense sacaton grass, and "large quantities of cottonwood, ash and willow timber" (Davis, 1982).

Photographs of portions of the San Pedro River in the late 1800s and the early part of this century show few large trees (Hastings and Turner, 1965). This has been interpreted by some as indicating that the riparian ecosystem at this time was dominated by herbaceous vegetation (e.g., cienegas or sacaton grasslands). However, this was a period of active development in the San Pedro area and there was much mining and floodplain settlement. Timber harvest and floodplain clearing may have reduced the abundance of riparian forests (Bahre, 1991).

Today, Fremont cottonwood and Goodding willow in a large sense form the "heart" of the existing riparian ecosystem on the lower floodplains of the Upper San Pedro River. The cottonwood-willow forests that grow along the river today are reflections of the conditions of the past decades. It is unknown to what degree their status has been or will be affected by the only recently discontinued floodplain groundwater pumping, or from past land uses (e.g., cattle grazing). Scattered old cottonwood trees survive on the old, high floodplain of the San Pedro River, but are infrequent. The riparian forest of the post-entrenchment channel for the most part established after the late 1930s, in response to several flood events during the 1930s, 1960s, and other decades (Hereford, 1993). However, these younger cottonwood-willow stands are interspersed with extensive stands of riparian scrub (facultative riparian shrubs such as rabbit-brush), and only in a few places form wide, continuous forest stands. This may indicate that their potential coverage within the floodplain has been reduced by past conditions.

Age structure determination is underway for the Upper San Pedro Fremont cottonwood trees. This analysis will identify past establishment years, and allow determination of the floodplain width and area occupied by different age cohorts. These data will help to determine how Fremont cottonwood establishment and abundance has varied over time in response to changing hydrological conditions (e.g., flood flows and water tables) within different reaches of the San Pedro River.

Fremont cottonwood and Goodding willow are structural dominants that influence many ecosystem processes as well as riparian functions and values. Loss or reduction of these forests would modify the ecosystem as we know it now. For example, the San Pedro riparian area is a well-known birding spot in large part because of the cottonwood-willow groves. Cottonwood-willow forests in general support the highest densities of breeding birds of any vegetation type in Arizona as well as in much of the

U.S. (Ohmart and Anderson, 1986; Ohmart and others, 1988). Many bird species are "obligates" that survive no where but in cottonwood-willow forests (e.g., Blue-throated Hummingbird [*Lampornis clemenciae*]). Cottonwood-willow forests also provide critical habitat for several species of raptors (e.g. Common Black-Hawk [*Buteogallus anthracinus*] and Gray Hawk [*Buteo nitidus*]), many of which are rare or threatened Neotropical migrant species. Certain birds (e.g., Summer Tanager [*Piranga rubra*] and Yellow-billed Cuckoos [*Coccyzus americanus*]) are upper-canopy dwellers, dependent on tall, mature Fremont cottonwood or Goodding willow for foraging or nesting (Reiner and Griggs, 1989). Others, such as Bewick's Wren (*Thyromanes bewickii*) and Common Yellowthroat (*Geothlypis trichas*) are low-canopy specialists. Others, such as Gila Woodpecker (*Melanerpes uropygialis*), Lucy's Warbler (*Vermivora luciae*), and Elf Owls (*Micrathene whitneyi*) use dead "snags" and cavities in old cottonwood trees as nest sites, while others such as the Southwest Willow Flycatcher (*Empidonax trailli extimus*) depend on the presence of willow groves. This latter species has been proposed for listing as an endangered species by the U. S. Fish and Wildlife Service. Proposed critical habitat includes the San Pedro River between about Hereford and Benson, which of note, is the zone of the river that has been subject to the least groundwater fluctuation over time.

It is apparent, then, that reduction or loss of cottonwood and willow forests would have adverse effects on abundance and diversity of birds and mammals as well as on the aesthetic quality and recreational value of the San Pedro riparian zone. Loss of age class diversity of the cottonwood-willow forest would impact species that use particular height strata within the canopy, while reduction in stand density would impact species that depend on stands with a specific foliage density. Loss of Goodding willow, which is more sensitive to groundwater decline than is Fremont cottonwood (see Santa Cruz Case Study), would impact rare species such as the Southwest Willow Flycatcher.

Saltcedar

As ecosystems become stressed, the environmental factors that control the distribution and abundance of plant species become altered. Often, these new conditions are more favorable for exotic species, many of which have wide tolerance ranges for environmental conditions. Saltcedar, for example, is an invasive riparian exotic that has become the dominant tree on many desert rivers that are regulated by dams or that have large scale modification of their hydrological regime due to water withdrawal. Saltcedar invasion on the middle and lower San Pedro River may be due to water withdrawals as well as to salinity increases resulting from irrigation return flows. Salt cedar also is invading on lowing reaches of the Upper San Pedro River. This invasion most likely would increase as a result of increased groundwater decline.

The consequences of replacement of native riparian forests of cottonwood and willow by saltcedar are well documented. Among these impacts are loss of wildlife habitat; increased fire frequency in the riparian zone; and increased soil salinity and loss of diversity of understory plant species (Rosenberg and others, 1991; Busch and Smith, 1993). Saltcedar stands have low habitat value for most wildlife because they have low plant species diversity, low canopy height, and low vertical and horizontal complexity, and support few insect species which form the food base for many native bird species. Increased fire frequency can be destructive for native riparian habitats in part because fire further contributes to increased saltcedar invasion. Loss of understory diversity would be an unfortunate consequence in its own right. Riparian corridors are recognized as being focal points of regional biodiversity (Naiman and others, 1993) and the San Pedro presently is no exception with its great diversity of understory vines, herbs, and grasses.

Riparian Shrublands

Riparian "scrub" (i.e., shrublands composed of facultative riparian species such as burro-brush and rabbit-brush) are a natural part of the riparian mosaic, but have become more abundant in degraded riparian zones (Turner, 1974; Brown, 1982). Riparian scrub has increased at the expense of cottonwood-willow forests on several rivers of the Southwest which have been degraded not only by hydrologic change but by overgrazing (Turner, 1974; Brown, 1982; Rucks, 1984). It is unknown exactly how abundant riparian scrublands are in "pristine" riparian zones because no such areas exist. On the San Pedro River, relatively high abundance of riparian scrub may be a consequence of past agricultural groundwater pumping or cattle grazing. In the future, groundwater declines could result in relative increases in riparian scrub at the expense of cottonwood-willow forest.

These shrublands provide habitat for plant and animal species that prefer open sites with coarse soils and little canopy development. However, they provide less wildlife habitat than do riparian forests. The replacement of riparian forests by these shrublands would result in an overall loss of ecosystem biodiversity. Riparian ecosystems have tremendous value in part because they support such a rich diversity of habitat types.

Sacaton Grasslands

Sacaton grasslands historically were abundant on the floodplains of the San Pedro River and along other rivers in southern Arizona. These riparian grasslands today occupy only a small percentage of their original distribution which included millions of acres in the southwest (Humphrey, 1958). As early as 1915, Griffiths and others, (1915) reported that there were "but faint traces" left of the dense growths of sacaton that formerly covered southern Arizona floodplains. Primary causes of destruction of sacaton habitat are similar to generic causes of riparian destruction in Arizona: historical downcutting of rivers and associated dropping of water tables and reduction in lateral spread of floodwater, groundwater pumping and diversion of streamflow, clearing of floodplains for agriculture, and overgrazing. Much of the destruction occurred during the late 1800s when "... trappers exterminated the beaver, farmers plowed the sacaton bottoms, rivers were channeled to provide irrigation for crops, and ranchers overgrazed the grasslands" (Cox and others, 1984).

Although a larger portion of the San Pedro floodplain has been cleared for agriculture, the San Pedro River today supports a stronghold of riparian sacaton grasslands (Lacey and others, 1975). In some areas sacaton is reclaiming these abandoned fields. As a high floodplain species able to tap relatively deep groundwater, sacaton can survive some degree of groundwater decline. In the short term, however, moderate groundwater declines would stress and degrade the existing sacaton grasslands which grow on the high pre-entrenchment floodplain. Sacaton patches on the post-entrenched floodplains, most of which are associated with mature cottonwood forests, would not be effected by moderate groundwater declines. In the long term, however, development of new sacaton grasslands could be disrupted if groundwater declines caused changes in cottonwood establishment. Little is known about the dynamics of the establishment process, but there may be a need for Fremont cottonwood to serve as a "nurse plant" for sacaton seedlings on young floodplains where soils are poorly developed.

Mesquite Bosques

Like sacaton grasslands, mesquite bosques also are a riparian vegetation type which was formerly widespread in Arizona. These have been much reduced in abundance by floodplain clearing, timber harvesting, and groundwater decline. Mesquite can tolerate deep groundwater tables, but groundwater decline would result in loss of structural complexity of the bosques which form large woodlands along some portions of the SPRNCA. Previous studies indicate that groundwater decline causes internal water stress of mesquite, followed by canopy dieback and declines in canopy height and foliage cover (Stromberg, and others, 1992). Groundwater decline also would reduce the rate of recovery of both sacaton and mesquite on abandoned agricultural fields.

SUMMARY AND CONCLUSIONS

The upper San Pedro River supports a riparian ecosystem composed of wetland (cienega) vegetation, Goodding willow and Fremont cottonwood forests, riparian shrublands, sacaton grasslands, and mesquite bosques. These plant associations (each of which harbors many different species) are distributed along moisture gradients, in the sequence listed above. Cienega plants grow where water is near or above the ground surface, while mesquite bosques grow where water is several feet below the ground surface. Structural characteristics of the vegetation, such as canopy height and foliage area, also vary with depth to groundwater.

Although the riparian ecosystem of the San Pedro is among the best remaining example of its type in the state, it has been reduced from its historical potential as evidenced by low abundance of wetland (cienega) vegetation and high abundance of riparian scrub (facultative riparian shrubs) in potential cottonwood-willow habitat. Management actions taken in the recent past, including elimination of grazing, mining, and floodplain agriculture from portions of the San Pedro River floodplain, will contribute to increased ecological health of the riparian ecosystem in the future. Groundwater pumping, however, could reverse these anticipated gains.

Numerical groundwater flow models described in this report can be used to quantify the extent to which groundwater pumping in the floodplain aquifer or regional basin fill aquifer would cause groundwater decline in the San Pedro floodplain. Ecological data indicates that these groundwater declines would cause several changes to the riparian ecosystems of the SPRNCA, all of which would lower the value of the riparian habitat for wildlife. These changes include:

- Sequential loss of more and more sensitive plant species with increasing groundwater decline. Obligate wetland and obligate riparian plants are the most sensitive to groundwater decline and would be among the first species lost or reduced. Groundwater declines on the order of 0.3 m (1 ft) would result in declines in cienega (marsh) vegetation, while declines of 1 m (3 ft) or more would result in complete loss of this rare vegetation type from stretches of the river.
- Loss of biodiversity, including loss of rare and endangered wetland species.
- Changes in abundance and age structure of dominant plant species. Groundwater declines on the order of a few feet could reduce both the frequency of establishment and the abundance of new generations of Fremont cottonwood and Goodding willow trees, resulting in loss of age class diversity, reduction in forest density and canopy cover, and degradation of this now-dominant vegetation association.
- Increased invasion by exotic species, notably by saltcedar.
- Decreased structural diversity, as tall, towering cottonwoods and willows were reduced in abundance and/or replaced by saltcedar and facultative riparian shrubs, and as stature and foliage area of mesquite declined.

It must be recognized that vegetation changes from groundwater decline occur along a continuum. Although there are some thresholds that can be recognized (e.g., absolute depths to groundwater beyond which species or plant associations will not grow), it is also true that with increasing groundwater decline, there is a continuum of change in which more and more species are lost, structure declines continuously, and densities of individual species decline or increase. Some of these effects already can be seen on portions of the San Pedro River and nearby rivers that have been stressed from groundwater pumping or surface water diversion (e.g., see Santa Cruz Case Study).

CONSIDERATIONS FOR RIPARIAN PROTECTION

To maintain or improve the condition of the San Pedro riparian ecosystems, the following hydrological conditions must be met:

- Cienegas are a rare riparian/wetland community type that presently occur on reaches of the San Pedro River where: (1) flow is perennial, (2) the river gains water from the groundwater (gaining reaches), (3) the water table in portions of the floodplain is above or only about 0.5 m (1 or 2 ft) below the ground surface, and (4) the water table fluctuates on a seasonal basis by less than 0.5 m (1.5 ft). To maintain these existing cienegas, these conditions must continue to be met in the future. To restore cienegas throughout the SPRNCA, these same conditions must occur on reaches in the north and south ends of the SPRNCA where flow is now intermittent, reaches lose surface flow to the groundwater, and water tables seasonally fluctuate by 1 m (3 ft) or more.
- Fremont cottonwood-Goodding willow forests are an ecologically important riparian forest type that are in degraded condition along many rivers in the state. This forest type occurs throughout the SPRNCA but in many areas is intermixed with extensive stands of riparian scrub and in the south end of the SPRNCA is being replaced by salt cedar. To maintain the existing cottonwood-willow forests, water tables should remain less than 3 m (10 ft) below the floodplain surface. To allow for new generations of these "pioneering" riparian trees, water tables during winter flood years should remain less than 1 m (3 ft) below the surface of seedling establishment zones and floods should be allowed to occur.

- Sacaton grasslands are also an ecologically important but rare riparian vegetation type that form extensive stands along the San Pedro River floodplain. This community persists on the pre-entrenchment floodplain, where depth to groundwater is about 5 to 6 m (16-20 ft) and also is reestablishing on the post-entrenchment floodplains under mature Fremont cottonwood stands where depth to groundwater is about 3 m (10 ft). To maintain the sacaton grasslands on the pre-entrenchment floodplain, groundwater should remain no more then 5 to 6 m (16-20 ft) below the floodplain surface. For optimum development of sacaton on the post-entrenchment floodplain, water tables should go no deeper than about 10 to 16 ft (3 to 5 m). Because of a possible need for cottonwood stands to allow for successful sacaton establishment, hydrological conditions for cottonwood establishment and maintenance also may need to be met.
- Mesquite bosques are the main riparian forest type on the higher floodplain terraces of the San Pedro floodplain. Mesquite tolerates a wide range of water table conditions but has greatest structural development where water tables are relatively shallow. To maintain vigorous mesquite bosques and to hasten recovery of mesquite on abandoned agricultural fields, groundwater under the high floodplain terraces should go no deeper than 5 to 8 m (16 to 26 ft).

To allow these various hydrological conditions to be met, it is imperative to continue to monitor hydrologic conditions in the San Pedro watershed and to refine numerical groundwater models that allow prediction of changes in groundwater and surface water. A sufficient number of wells should be monitored in both the floodplain aquifer and in the regional basin fill aquifer to allow floodplain aquifer declines to be predicted well in advance. Monitoring of floodplain aquifer wells should continue without interruption, as should monitoring of surface flows. Attention also should be paid to groundwater and surface water changes in the headwaters of the San Pedro as well as its major tributaries (e.g., Babocomari River).

Riparian vegetation also should be monitored directly. Long-term vegetation study plots in the San Pedro floodplain should be monitored on a periodic basis to detect changes in abundance or distribution of plants sensitive to groundwater decline (e.g., wetland plants and obligate riparian tree seedlings).

If changes in groundwater, surface water, or riparian vegetation are apparent, modifications should be made in water use practices. For example, groundwater pumping rates may need to be reduced, or well sites moved a far distance away from the floodplain aquifer. Changes in riparian vegetation resulting from groundwater pumping from the regional aquifer can be difficult to detect, but should continue to be a focus of study.

Additionally, riparian changes from groundwater pumping can be minimized by recycling treated water (effluent) directly to the floodplain aquifer. Because existing wetland vegetation along the San Pedro River may be sensitive to water quality changes, care should be taken that effluent is of high quality.

Other factors that influence floodplain groundwater, such as beaver dams, also should be a focus of study.

UPPER SANTA CRUZ RIVER CASE STUDY

INTRODUCTION

The Santa Cruz River represents a river that is undergoing a mixture of hydrologic changes, some with positive consequences for the riparian ecosystems and some with negative repercussions. Like several other rivers in Arizona, water and land uses in the relatively recent past have eliminated riparian vegetation from the lower reaches of the Santa Cruz River. Riparian vegetation remains in the upper reaches, but is degraded in some areas. Attention focused today on the Santa Cruz River and other river systems could help prevent further riparian degradation and loss along rapidly developing river reaches.

The towns of Nogales, Arizona and Nogales, Sonora obtain a large portion of their water supply from aquifers connected to the Santa Cruz River, as do many other smaller communities including Rio Rico. Irrigated agriculture also uses water from the floodplain aquifer. Effects of groundwater pumping from the floodplain aquifer can include reduction in groundwater levels and conversion of perennially flowing river reaches to intermittent or ephemeral reaches, both of which are changes that adversely affect riparian vegetation.

Some of the groundwater that is pumped from the upper Santa Cruz River stream alluvium (and from another river basin in Mexico) is returned to the Santa Cruz River farther downstream near Rio Rico as effluent. Effluent released from the Nogales International Wastewater Treatment Plant (NIWTP) is resulting in substantial increase in streamflow in the downstream reach and is contributing to groundwater recharge, both of which have beneficial effects on riparian vegetation. In recent years, for example, a large Fremont cottonwood (*Populus fremontii*)-Goodding willow (*Salix gooddingii*) forest has established downstream of the treatment plant.

This study site was selected, not only to assess effluent discharge to the river, but because a majority of the Santa Cruz River is located within the Tucson Active Management Area (AMA), where groundwater withdrawals and water use are monitored and managed by Arizona Department of Water Resources. In addition to its close proximity to the Tucson metropolitan area, the Santa Cruz River valley serves as a primary traffic corridor between the United States and Mexico. Therefore, extensive future development will likely occur.

The general objective of this case study was to assess the extent and causes of historical changes in surface flow and groundwater tables along the Santa Cruz River (with an emphasis on the upper Santa Cruz basin), and to relate these hydrologic changes to riparian vegetation changes. The study had a specific emphasis on understanding the relationship of hydrologic changes with changes in Fremont cottonwood-Goodding willow population dynamics, including changes in age structure, recruitment frequency, and stand density along the river and over time. Other riparian vegetation-types are also addressed. Related objectives were to compare the effectiveness of two riparian stress evaluation techniques for detecting and determining ecological impacts resulting from hydrologic changes, remote sensing of vegetation, and ground-based population studies.

DESCRIPTION OF THE AREA

The Santa Cruz River study site is located along an approximately 45 mile reach of the Santa Cruz River from the International Border at Nogales, Arizona to Continental, Arizona (Plate 2). The upper Santa Cruz River is primarily an intermittent desert stream that contains interrupted perennial and effluent dominated reaches. It drains a 13,790 square mile watershed located in southern Arizona and northern Mexico. From its headwaters in the San Rafael Valley, the river flows southward approximately 9 miles and enters Mexico. During its 35 mile course through Mexico, the river continues its southward flow a short distance and then bends northward and enters Arizona 5 miles east of Nogales. Within the United States, the Santa Cruz River continues northward for 65 miles from Nogales to Tucson. During major floods, the Santa Cruz River below Tucson can flow an additional 96 miles to converge with the Gila River near Phoenix. Generally, this reach remains dry except for municipal effluent discharges and flood flows.

The Santa Cruz River case study area is located in the Basin and Range physiographic province, which is characterized by broad, alluvial-filled basins bounded by steep, rugged, fault-block mountains. Halpenny (1964) described the river valley below the Santa Cruz/Pima County line as an inner valley located within a broad valley surrounded by mountains. The inner valley ranges from 0.3 miles in width to approximately 1 mile, while the river channel is incised 5 to 10 feet, and is 100 to 200 feet wide. The edges of the valley are terrace slopes which rise from approximately 10 to 15 feet above the valley floor. However, in some areas terraces are more than 100 feet above the valley floor (Halpenny and Halpenny, 1988). Upon entering the Tucson Basin, north of the county line, the inner valley and associated terraces disappear as the valley broadens.

The study area is bordered on the east by the Patagonia, San Cayetano and Santa Rita Mountains, while on the west it is bounded by the Pajarito, Atacosa and Tumacacori Mountains. Mountain peaks along the east side of the valley range from 6,000 to 8,600 feet above mean sea level, while those on the west side range from 4,900 to 5,300 feet.

Agricultural activities in the upper Santa Cruz River valley began with Spanish settlement, however, the area is too arid to support dryland farming. Early irrigation was accomplished by diverting surface flows from the river. Today, most irrigation water is obtained from wells withdrawing groundwater and subflow of the Santa Cruz River. Land use in the area primarily involves ranching, farming operations and homesite development. Currently, Nogales, Arizona supports a major portion of the population within the study area. Current statistics indicate a population of 19,489, an increase of 24% from 1980 statistics (ADES, 1993).

The NIWTP, currently located at the confluence of the Santa Cruz River and Nogales Wash (a.k.a., Potrero Creek), began discharging effluent generated from Nogales, Sonora and Nogales, Arizona in 1951. Initially the treatment facility was located along Nogales Wash, approximately two miles north of the international border. From 1951 through 1959, neither wastewater inflow or effluent discharge records were kept. Releases were made into Nogales Wash, however, in some years effluent was used directly for irrigation in the immediate area (International Boundary and Water Commission, personal communication). Since that time, Nogales, Sonora and Nogales, Arizona have continued to develop and effluent discharges have increased. Currently, Nogales, Sonora supports a population of approximately 250,000. The city currently obtains approximately 60% of its potable water supplies from the Santa Cruz River alluvium south of the border. However, due to the limited nature of the water in this system, additional supplies have been developed in another south-flowing watershed, the Magdalena River drainage basin. Currently, effluent augments perennial surface water and groundwater downstream of the discharge site and provides significant support to riparian communities located along the river.

Riparian Vegetation

The upper Santa Cruz River is vegetated by the Cottonwood-Willow Series of the Warm-Temperate Interior Riparian Deciduous Forest (Brown, 1982). Fremont cottonwood and Goodding willow dominate on low floodplains associated with the river, and these give way to "bosques" (woodlands) of velvet mesquite (*Prosopis velutina*), netleaf hackberry (*Celtis reticulata*), and Mexican elder (*Sambucus mexicana*). Other vegetation associations that are present include cienegas (marshes), sacaton (giant sacaton (*Sporobolus wrightii*) and alkali sacaton (*S. airoides*)) grasslands, as well as riparian shrublands of seepwillow (*Baccharis salicifolia*), rabbit brush (*Chrysothamnus nauseosus)*, and burro brush (*Hymenoclea* spp.).

Riparian vegetation along the Santa Cruz River has experienced significant historical change. In addition to groundwater and surface water availability, riparian vegetation composition and abundance continues to respond to changes in land use, and possibly changes in water quality.

Geologic Setting

The geological structure of the study area was developed during the mid-Tertiary phase of the Cordilleran orogeny and subsequent Basin and Range disturbances (Cella Barr Associates, 1990). The late Tertiary was a time of long continuous deposition of 7,500 feet of fanglomerate, conglomerate,and sandstone, referred to as the Nogales Formation. The Nogales Formation is a volcanic conglomerate containing many beds of sandstone and siltstone. It rests on and was derived from the Grosvenor Hills volcanics of the Oligocene age and is overlain by Quaternary alluvium in the valleys (Bradbeer, 1978). Quaternary alluvium in the area is composed of sand and gravels located along stream channels. These sediments are generally unconsolidated and provide the major water bearing formations. They are divided into the moderately consolidated older alluvium and the unconsolidated younger alluvium. The younger alluvium serves as the primary aquifer in the area. The surface of this unconsolidated sand and gravel formation is continually rearranged by flood flows (Bradbeer, 1978).

Local Climate

The Santa Cruz River Valley experiences a mild, semiarid climate with temperatures ranging from 27°F to 95°F (Table 12). The average annual temperature in the Nogales area is 61°F with the growing season typically beginning in March, when minimum monthly temperatures are above 32°F, and ending in October. The elevation of the river bed at the international boundary is 3,702 feet, while at Continental it is 2,836 feet. As with most areas in Arizona, the Santa Cruz Valley receives a majority of its annual precipitation in a bimodal pattern, during the summer monsoon season (July and August) and in the fall/winter (October, December and January). However, the amounts of precipitation and ultimately runoff, occurring during these time periods can vary.

Table 12
Summary of climatological data at Nogales

Month	Precipitation (Inches)	Degrees Fahrenheit	
		Maximum Temperature	Minimum Temperature
January	1.16	63.4	27.1
February	0.81	66.3	29.2
March	0.88	70.1	33.2
April	0.32	77.9	38.2
May	0.24	85.3	44.3
June	0.40	95.0	54.0
July	4.92	93.6	63.5
August	3.81	91.2	61.9
September	1.69	89.8	54.8
October	1.47	82.2	43.6
November	0.62	71.3	32.9
December	1.41	64.6	27.5
Annual	17.43	79.3	42.5

Source: National Climate Data Center (1992)

Precipitation magnitudes and occurrence have fluctuated over time in the Santa Cruz River (Webb and Betancourt, 1992). This variability is ultimately tied to long-term fluctuations in global weather patterns, including El Nino-Southern oscillation conditions. In particular, the period from about 1930 to 1960 was climatically distinct from preceding and following periods. During this time period, only 3% of the peak floods in the Santa Cruz River occurred in fall or winter, and maximum winter flood size of <2500 cfs was recorded at the Nogales gage. Flooding in this thirty-year period was dominated by July or August monsoonal floods, which typically occur frequently but are localized in extent. Table 12, showing monthly precipitation totals for 1928 to present, reflects some of that dominance. Since about 1960, increased activity of low-pressure Pacific frontal winter storms and of dissipating late summer and fall tropical cyclones (i.e., hurricanes and tropical storms) has resulted in increased magnitude of fall and winter floods in southern Arizona rivers (Figure 23). Surface flow in the Santa Cruz River was also greater during this time period. Winter storms sometimes produce regional flooding, such as occurred in southern Arizona in December 1967, December 1978, and winter of 1993. Prior to 1930, another large winter/fall flood period occurred, extending back for several decades. These trends are evident on other rivers of southern and central Arizona, but are particularly strong for the Santa Cruz River and a major tributary, Sonoita Creek (Webb and Betancourt, 1992).

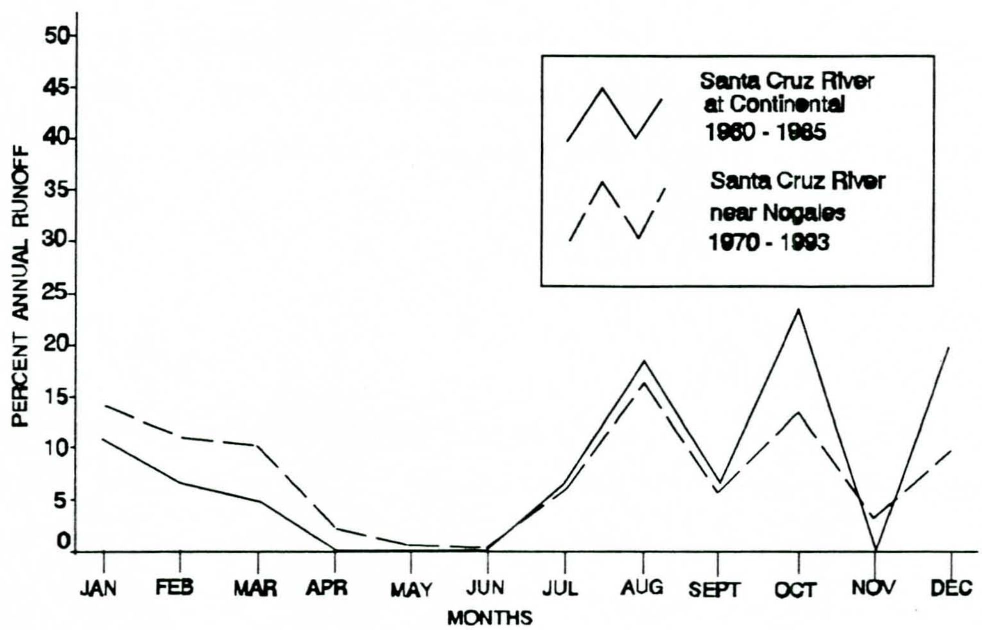
METHODS

Hydrologic Analyses

Existing hydrologic data were used to assess groundwater and surface water hydrology of the area. Assessment of the groundwater systems included determination of groundwater movement and occurrence, changes in groundwater levels, water yielding characteristics of associated aquifers, and groundwater/surface water interactions.
Hydrographs were constructed for index wells to assess groundwater level changes in riparian zones located along riparian vegetation transects established for this project. All of the wells were located on terraces of varying height above the stream channel. Land surface elevation was surveyed along each riparian transect, between the index well and the river channel. The water table within the riparian zone was assumed to be horizontal. Depth to water was determined at different points along the transect by subtracting the water level elevation from land surface elevation.

Monthly streamflow rates were quantified for the Santa Cruz River from USGS streamgage data to characterize the past and present streamflow regime. Two gages were of primary importance in describing surface water flows through the area. The upstream gage is the Santa Cruz River streamgage near Nogales (#9480500), and the

Figure 23. Mean annual runoff as percent of annual runoff for the Santa Cruz River at Continental and near Nogales



downstream gage is the Santa Cruz River streamgage at Continental (#9482000). No streamgages are installed between these two locations or on major tributaries located within the study area.

Analytical methods, developed by Theis (1935), were used to predict areas of impact associated with groundwater level declines resulting from pumping wells. Three sites, corresponding to three of the riparian transects, were selected for this analysis. One site was located in the Buena Vista area near Duquesne Road, another at Kino Bridge and a third in the vicinity of the Santa Cruz/Pima County line.

Riparian Vegetation Analyses

Cottonwood Population Demography

Riparian vegetation abundance and health were studied at sites along the Santa Cruz River located in Santa Cruz and southern Pima Counties. Ten sites were situated along a gradient extending downstream (north) of the NIWTP to southern Pima County, while six were located between the US/Mexico border and the NIWTP.

Riparian transects were established within the floodplain at each site. The transects were aligned perpendicular to the stream and spanned the width of the floodplain. Vegetation plots (5 m x 20 m, or about 16 x 66 ft) were located along the transect line within different plant associations, including cottonwood stands of varying stem diameter. The plots were sampled for density and stem diameter of the woody plants, using standard vegetation sampling techniques. Canopy foliage area, or leaf area index, was measured with a LICOR 2000 plant canopy analyzer within the lower floodplain (cottonwood-willow) zone of the riparian transect.

Increment cores were collected from 5 to 10 Fremont cottonwood trees from each discernable size class (cohort) at each site. Two cores were collected per tree, using Swedish increment borers, and core holes were plugged with wood dowels. In the laboratory, cores were mounted, sanded with a graded series of sandpaper (ranging to 900 grit, or 12 micron), and measured for ring-width with a Bannister-type incremental measuring system. The tree ring chronologies were cross-dated to identify false, indistinct, or missing rings. Age of the cored trees was determined by counting the number of annual rings and adding estimated time to grow to coring height (one year). The largest increment bore (0.62 m, or 2 ft) was not sufficiently long to reach the center of trees with trunk diameters >1.25 m (4 ft). For these trees, age of the uncored portion was estimated by assuming it had an annual growth rate equal to that of the oldest extractable growth rings.

Establishment date was determined for each cottonwood cohort, by identifying the establishment year for those trees which the core penetrated the exact center of the trunk. Establishment years were then related to past hydrologic events and conditions including flood flows and water table depths (Baker, 1990; Stromberg, Patten and others, 1991).

Remote Sensing Analysis

A Geographic Information System (GIS) was used to create a spatial database for the river and its watershed in the study area. The GIS database projects the study area basemap into the Universal Transverse Mercator (UTM) coordinate system. These coordinates represent real locations on the surface of the earth. Aerial photographs and satellite imagery in conjunction with the GIS database were used to analyze the presence and density of riparian vegetation associated with the river, as well as the land use that occurs in the floodplain.

A set of May, 1973 georeferenced orthophoto 7 1/2 minute quadrangles were obtained from the USGS. The orthophoto quads were used to georeference aerial photos taken in August of 1980 and October of 1990. Land use and vegetation within three sub-basins of the study area were digitized from the 1973 orthophotos and the 1990 photos. Data from the 1990 photos are presented in this report.

The GIS database was used to calculate the total acreage of the floodplain in different land use categories. The land use categories included developed land (industrial, and high and low density residential uses), active and inactive agriculture, high and low densities of riparian mesquite woodland, and high, medium, and low densities of cottonwood-willow forest and/or riparian shrub associations. The unvegetated portion of the river channel, and transportation routes (including highways and railroads), were digitized as separate land use classes.

A database cover of vegetation density based on satellite imagery was processed from a Landsat Thematic Map (TM) scene taken in July of 1987, and uses two of the seven TM bands to calculate a ratio between soil background (TM Band 3, visible red) and vegetation canopy cover (TM Band 4, near infra-red) . The satellite imagery cover indicates the location of low, medium and high density vegetation areas, but does not classify vegetation by type. Because the study area was located in the Tucson AMA, land with appurtenant grandfathered groundwater rights were mapped as a GIS cover. The database cover of irrigated agriculture fields and golf courses was overlaid on the satellite imagery cover to distinguish natural riparian vegetation from irrigated vegetation-types.

GROUNDWATER SYSTEM

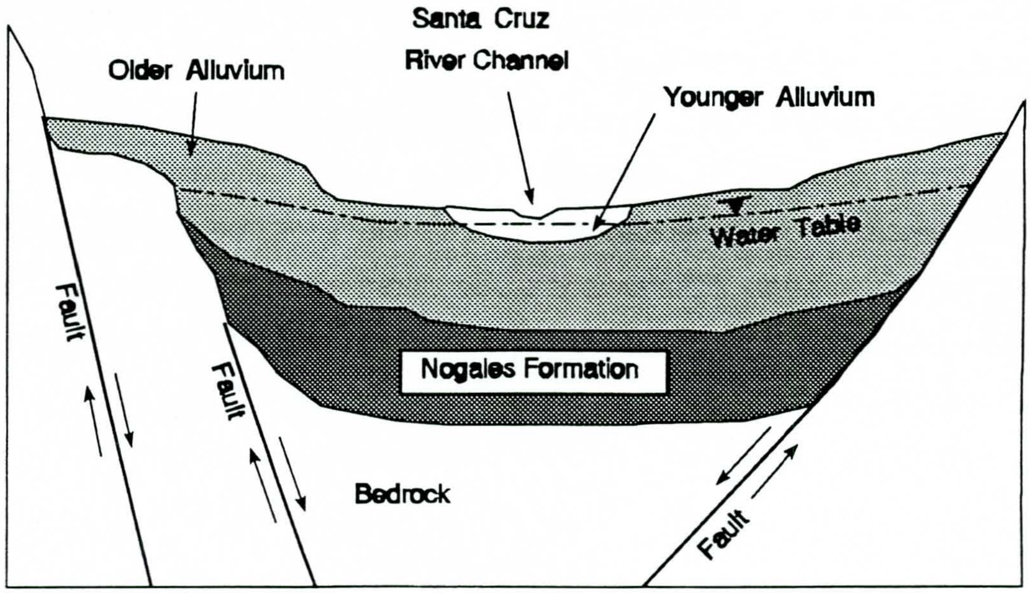
Aquifer Description

Basin-fill sediments in the upper Santa Cruz River valley form three aquifer units. Listed in ascending order they are: the Nogales Formation, and the older and the younger alluvium. All three units are unconfined, hydraulically connected and yield water to wells (Figure 24).

Nogales Formation

The Nogales Formation is composed of well-consolidated conglomerates with imbedded volcanic tuffs and is at least 5,000 feet thick (Simons, 1974). Little is known about the hydrologic characteristics of the Nogales Formation because it has poor water bearing characteristics and has not been widely developed. Groundwater occurs primarily in fracture zones and unconsolidated layers within the formation (Putman and others, 1983). Well yields of several hundred gallons per minute (gpm) have been obtained from this formation, however, average yields are about 30 gpm (Putman and others, 1983).

Figure 24. General stratigraphy of upper Santa Cruz Valley



Older Alluvium

The older, basin fill alluvium consists of locally stratified lenses of boulders, gravel, sand, silt and clays with cemented zones or caliche (Anderson, 1956; Schwalen and Shaw, 1957; Putman and others, 1983). Cella Barr Associates (1990) reported the older alluvium located near Nogales to be tightly cemented sands and gravels grading to a conglomerate at approximately 800 feet in depth. Although the older alluvium stores large amounts of water, it does not transmit water readily to wells. The thickness of the older alluvium in Santa Cruz County ranges from a few feet along the mountain ranges to 4,800 feet or more in the north-central portion of the valley (ADWR, 1989).

Younger Alluvium

The younger alluvium, sometimes referred to as floodplain or stream alluvium, is present along the Santa Cruz River and some of the larger tributaries. It ranges from 45 to 100 feet in depth and is up to one mile in width (Schwalen and Shaw, 1957; ADWR, 1989; Cella Barr Associates, 1991). It is comprised of unconsolidated sands, gravels and boulders, usually of coarser grain than those found in the older alluvium (Schwalen and Shaw, 1957; ADWR, 1989). These stream channel and floodplain deposits have high hydraulic conductivities and, consequently, are the most productive and widely-used aquifer in the study area with some wells yielding over 1,000 gpm (Putman and others, 1983).

Occurrence and Movement of Groundwater

The inner valley of the southern portion of the study area has been described by Putman and others (1983) as a series of three sub-basins filled with water-bearing alluvium. A fourth sub-basin was described by Halpenny (1964). The sub-basins contain long, narrow, shallow "stringers" of alluvium in areas where more consolidated rocks encroach from inner valley margins. The sub-basins are analogous to four bathtubs arranged in a row. They contain water that enters at the upstream end and flows out on the downstream side. Water withdrawals from one "tub" will only cause declines in that basin, and not the others. The sub-basins possess limited water storage, and can be easily over-drafted. Generally, groundwater movement in this area converges on the river indicating the older alluvium, and possibly the Nogales Formation, drain into the younger alluvium (Putman and others, 1983).

The four sub-basins possess limited groundwater storage capacities. They include (1) the Buena Vista sub-basin, which extends from the International Border to the Buena Vista Narrows (D(24-15)6d), (2) the Kino Springs sub-basin, which extends from the Buena Vista Narrows to the Kino Springs Narrows (D(23-14)36dc), and (3) the Highway

82 sub-basin, which extends from the Kino Springs Narrows to the Guevavi Narrows (D(23-14)22cd) (Putman and others, 1983) (Figure 25). The fourth sub-basin, the Guevavi sub-basin, is located between the Guevavi and Eagan Narrows (D(23-14)8d). The younger and older alluvium and the Nogales Formation are present in the Kino Springs, Highway 82, and Guevavi sub-basins. Older alluvium is not present in the Buena Vista sub-basin (Putman and others, 1983). Figure 26 is a longitudinal profile of the study area illustrating the inter-relationship between groundwater and surface water.

Groundwater movement between adjacent sub-basins is limited by subsurface hardrock outcrops, particularly during times of low or no streamflow. This effectively limits available storage to water stored within an individual sub-basin. The depth to the water table in the younger alluvium is closely tied to the elevation of the streambed of the Santa Cruz River, because flow in the river serves as a principle source of recharge. Periods of above normal precipitation and runoff serve to maintain or replenish shallow groundwater reserves. During periods of low flow, however, not all sub-basins may be recharged. The Buena Vista sub-basin is the first to be recharged by river flow, with each succeeding downstream sub-basin recharged in turn.

Downstream of the Eagan Narrows, in the vicinity of the Sonoita Creek and Nogales Wash confluence with the Santa Cruz River, the inner valley widens considerably. Depth of both the younger and older alluvium increases significantly below this point. Increases become particularly significant in the vicinity of the Santa Cruz/Pima County line (Figure 26). Arizona Department of Water Resources (1989) determined that on average 5,600 ac-ft of water crosses the county line annually as underflow.

Most recharge occurs as storm water runoff infiltrates coarser alluvial channel sediments in the valley (Anderson, 1956; Cella Barr Associates, 1991). In Sonoita Creek valley, Bradbeer (1978) calculated the infiltration rate for the floodplain to be approximately 4

Figure 25

UPPER SANTA CRUZ RIVER SUBBASIN AND NARROWS LOCATIONS

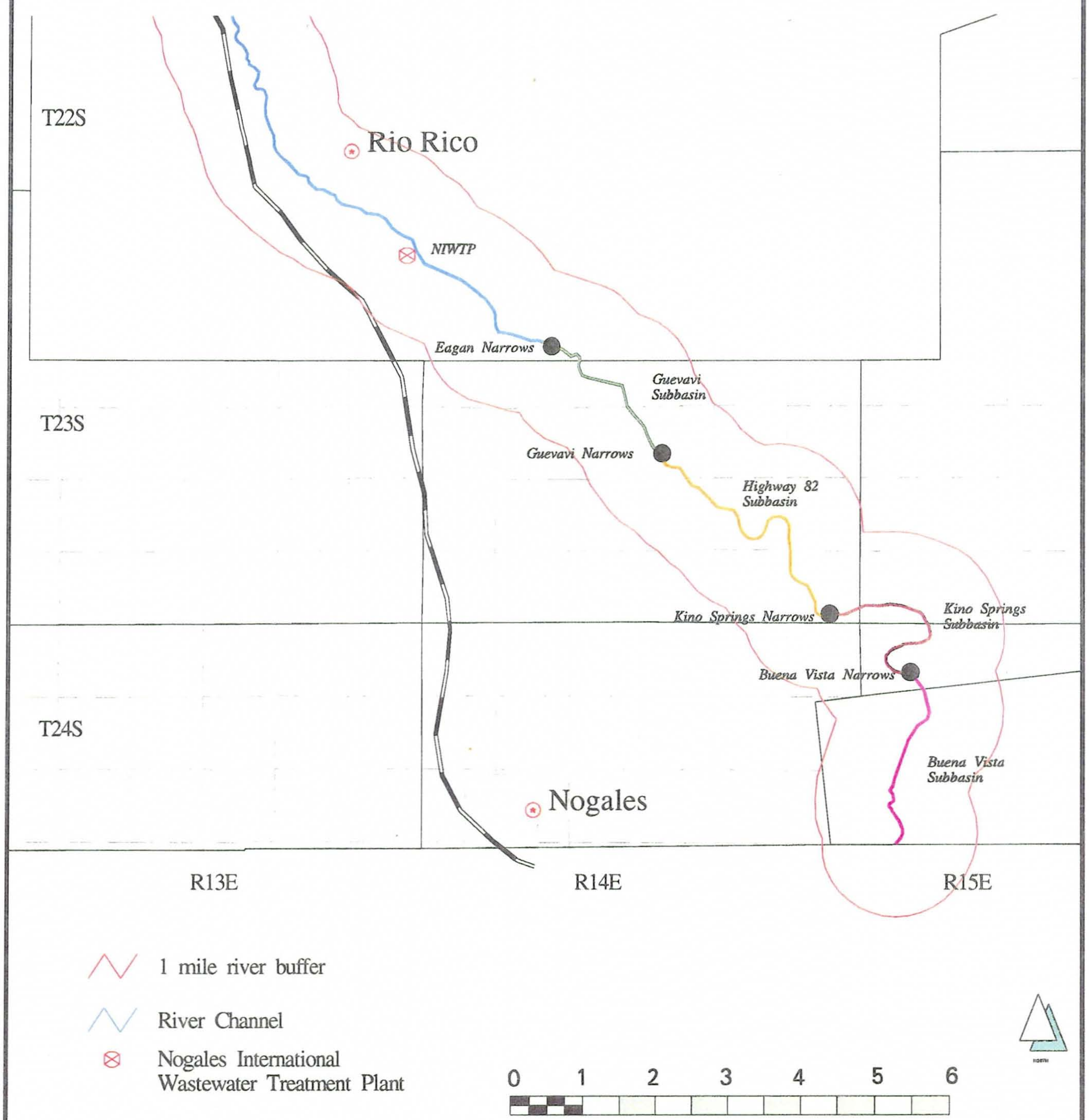
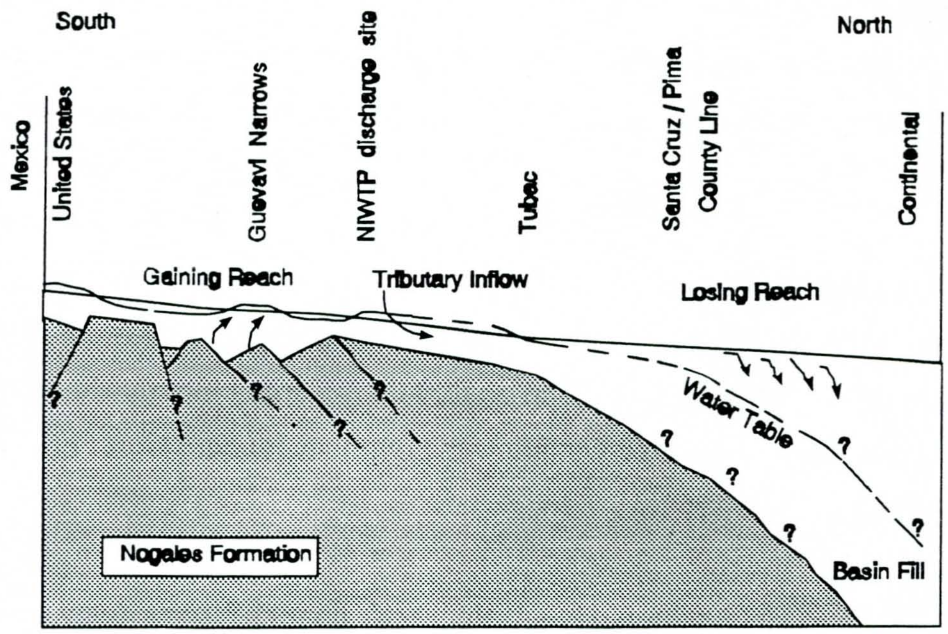


Figure 26. Generalized longitudinal geohydrologic profile of the study area



inches per hour, whereas, the coarser stream channel materials had a calculated infiltration rate of 30 inches per hour. Lesser forms of recharge include mountain front, irrigation seepage, sewage effluent and groundwater movement (Anderson, 1956; Schwalen and Shaw, 1957; Cella Barr Associates, 1991).

Groundwater Level Changes

Surface flow in the Santa Cruz River serves as the primary source of recharge for the younger alluvium. As long as streamflow is available, water levels in the younger alluvium remain constant. When groundwater withdrawals exceed recharge from surface flow in the river, water levels in the alluvium decline. According to Halpenny and Halpenny (1988) withdrawals from the younger alluvium began to increase in the late 1960s and continued to increase through about 1960 to 1970. By the 1980s, irrigation withdrawals began to decrease, in part because land became more valuable for municipal and industrial development (Halpenny and Halpenny, 1988), and because of water withdrawal limitations established by the Groundwater Management Act. In addition, the aquifer system downstream of the NIWTP discharge site was benefitting from effluent releases that began in 1951.

From the mid 1940s through the mid 1960s, due to the combined effects of groundwater withdrawals and drought, water levels in wells in the younger alluvium declined. Water levels were observed to decline as much as 20 feet in some inner valley areas south of the county line. In the mid 1960s a wetter cycle began and water levels began to recover (Halpenny and Halpenny, 1988).

Murphy and Hedley (1984) observed that water level changes in the study area from 1953 through 1982 ranged from an increase of 20 feet in the Calabasas area to a 120 feet decline near Continental and Green Valley. A groundwater decline of 20 feet was observed in an area immediately north of Arivaca Junction. From Nogales to the Amado-Tubac area, water levels had generally risen along the Santa Cruz River channel, except in the Nogales well field area (Plate 2, area surrounding index well D(23-14)36bcb1). Groundwater level contours (Murphy and Hedley, 1982) displayed on Plate 2, indicate that from the U.S./Mexico border north, groundwater flows northward, downgradient through the stream alluvium. Cones of depression caused by wells pumping in the stream alluvium cannot be discerned from the groundwater contour information because the 50 foot contour interval may exceed the saturated thickness of the aquifer in many locations. Near the county line the flow direction slightly angles away from the stream, due to a cone of depression located north of the study area near Sahuarita. Depth to groundwater also increases significantly at the county line, resulting in a disconnected groundwater-surface water system (Figure 25).

Groundwater levels have continued to rise within the study area, except in the Nogales well field area, and from Continental northward. Shallower groundwater levels in the stream alluvium have been associated with increased precipitation and decreased agricultural activities. Downstream of the NIWTP, effluent discharges have also played an important role in raising water levels. Eight index wells in the study area were selected for evaluation based on the length of their period of record and their location relative to established riparian vegetation transects. Depth to groundwater measurements were generally obtained from the index wells on an annual or biennial basis, however, for some wells periods of sporadic data collection occurred, with measurements taken once approximately every 5 - 6 years. The index wells selected for the evaluation are actively pumped. No monitor wells were available in the riparian zone of the study area. Data collected from the selected wells are presented as hydrographs on Plate 2.

The two southernmost wells D(24-15)18ab1 and D(23-14)36bcb1, are perforated in the younger alluvium in the Buena Vista and Highway 82 sub-basins, respectively. Since measurements began in 1939, depth to water in well D(24-15)18ab1, near Duquesne Road, has varied slightly. A maximum range of 10 feet is evident from the water level data. Water levels in this well were observed to decline for the period between 1939 and 1945, however, since that time water levels have recovered. In 1993, the groundwater level was 6 feet below land surface (bls). Well D(23-14)36bcb1 is located near Kino Bridge in the City of Nogales well field. The water level hydrograph generated for this well readily displays the rapid drawdown and refill capability of the stream alluvium in this sub-basin. Generally, water levels in the area drop each spring due to municipal withdrawals and recover in late summer due to higher streamflows. Since the early 1970s water levels in the well, although still displaying rapid drawdown and recharge capacity, have steadily declined. Rapidly fluctuating water levels have resulted in declined riparian abundance and regeneration. Most recent depth to water, measured in 1993, indicates the groundwater level is 28 feet bls.

Depth to groundwater in well D(23-14)17aca, located near Guevavi Ranch, declined from 1939, the beginning of the period of record, until 1953. After 1953, water levels began to rise and have continued to recover. In 1993, depth to water at the well site was measured at 13 feet bls. Shallower depth to water may be the result increased surface water flow in recent years, and/or reduced irrigation activity in the area.

The hydrograph developed for well D(22-13)34add, located in the Rio Rico area, displays the effects of effluent discharges to the river. Water level data collected from this well and effluent releases began in the same year, 1951. Data collection at this well has become sporadic, with only three measurements taken in the last 15 years. Data available for the well displays a continuous recovery averaging about 1 ft/yr. Depth to water measurements taken in 1993, indicate groundwater levels are about 10 feet bls.

Data collection for well D(21-13)19dbc, located near Clark Crossing, began in the early 1970s. Other than a slight decline during the mid 1970s, depth to water in the well has continued to recover, rising at a rate of 0.5 ft/yr. Groundwater levels, measured in 1993, were approximately 21 feet bls.

The Rex Ranch well, D(20-13)6cba, is located in the vicinity of the county line. In this location the inner valley begins to widen into the much broader Tucson basin. The alluvium, in this area, deepens significantly. The well at this location appears to go through recurring decline and recovery phases, probably in response to discharges from the treatment plant and storm events in the late 1960s and early 1980s. Current depth to water at the well site, measured in 1993, is approximately 26 feet bls.

The hydrograph developed for well D(19-13)09caa, located approximately 5 miles south of Green Valley, has since the late 1970's, displayed rising water levels. Recovery may be due to increased precipitation, effluent discharges, and reduced pumping for mining and irrigation. Most recent depth to water in this well, measured in 1993, was 69 feet bls, 56 feet above the 1978 depth to water measurement.

Well D(18-13)23bad, located between Green Valley and the USGS streamgage, Santa Cruz River at Continental, displays a continuous decline from initiation of data collection to present. Depth to water, measured in 1991, was approximately 195 feet bls.

Water Yielding Characteristics

According to ADWR the Groundwater Site Inventory (GWSI), 403 wells are located within the study area (Plate 2). They are dispersed throughout the floodplain with heaviest concentrations occurring in the vicinity of the City of Nogales well field and Tumacacori National Monument. Depending on sub-surface formations intercepted and well construction, the wells yield varying quantities of water. Transmissivity values obtained from aquifer tests performed on wells in the area range from 16,578 to 55,214 ft^2/d in the younger alluvium, and from 281 to 3,295 ft^2/day in the older alluvium and Nogales Formation (Table 13).

Table 13
Hydrologic properties of water bearing formations in Santa Cruz study area

Geologic Unit	Transmissivity (ft^2/d)	Well Location	Specific Yield	Reference
Younger Alluvium	55,214	D(23-14)22	17	Halpenny (1964)
	16,578	D(2415)16bd	17	Putman et. al. (1983)
	18,717		15	Halpenny (1982)
Older Alluvium/ Nogales Formation	281	D(24-15)18	10	Cella Bar Associates (1991)
	1,003	D(21-13)5abd	15	Halpenny (1982)
	508	D(21-13)5ddb	15	Halpenny (1982)
	2,941	D(21-13)7aba	15	Halpenny (1983)
	3,295	D(21-12)24aa	12	Halpenny (1984)

As indicated by the transmissivity values, the unconsolidated sand and gravel of the younger alluvium comprise the most productive aquifer in the study area south of the county line. The aquifer is unconfined, with depths to water ranging from less than 10 feet to approximately 35 feet (Putman and others, 1983; Halpenny, 1984). Even though the younger alluvium aquifer has limited storage, most of the water withdrawn in Santa Cruz County is derived from this aquifer (ADWR, 1989). Well yields as high as 1,000 gpm have been reported (Putman and others, 1983). The primary source of natural recharge for this aquifer is surface water from the Santa Cruz River. Given the aquifer's high transmissivity, recharge occurs quickly when surface flow is available (Putman and others, 1983; Cella Barr Associates, 1991). In addition to surface water flow, recharge is available from direct infiltration from precipitation, sewage effluent, inflow from the older alluvium and the Nogales Formation, and irrigation seepage. North of the county line the hydraulic character of the aquifer system changes.

Depth to water in wells penetrating the older alluvium and the Nogales Formation range from about 100 feet to more than 300 feet below the land surface (Putman and others, 1983; Halpenny, 1984). East of the Santa Cruz River, near Nogales, well yields are generally low (Cella Barr Associates, 1991). For example, well D(24-15)9acd, withdrawing water from the Nogales Formation and the older alluvium, produced 30 gpm (Putman and others, 1983). Well D(24-15)16bdd produced 100 gpm from the older alluvium. When deepened to the Nogales Formation, production from the well increased to 200 gpm as transmissivity improved. Immediately adjacent to the study area, Cella Barr Associates (1987) observed that wells in an area west of Nogales Wash, where the older alluvium exceeds 800 feet in depth, had produced over 1,000 gpm (Cella Barr Associates, 1987). However, within the study area the older alluvium, while it contains the majority of water and has the most available storage capacity, does not yield water as readily as the younger alluvium (ADWR, 1989).

Groundwater Withdrawals

Because this study area is located within the Tucson AMA, groundwater withdrawal and water use information is monitored and managed by ADWR. In 1992, 89,806 ac-ft of groundwater was withdrawn in the study area (Table 14). The primary use associated with groundwater withdrawals is irrigation, while mining consumes the second largest amount. Schwalen and Shaw (1957) estimated that 25% of the water used for irrigation in this area was recharged by deep percolation of excess applied irrigation water. Irrigation uses primarily occur during the growing season (April - October). Therefore, groundwater declines can be observed during months when major withdrawal activities occur. This is primarily observed in the months of May and June, prior to the onset of the monsoon season. During late fall through early spring, when irrigation uses cease and riparian vegetation is dormant, with adequate winter precipitation, water storage in the younger alluvium is generally replenished by streamflow.

Table 14
1992 groundwater withdrawals and use within Santa Cruz River study area

Groundwater Use	No. of Wells	Total Pumpage (Ac/Ft)
Domestic	70	3,473.49
Municipal	9	4,323.60
Industrial	16	7,400.60
Irrigation	152	45,416.79
Mining	16	22,487.48
Other	1,554	6,703.96
TOTALS	1,817	89,805.92

Source: ADWR, Registry of Groundwater Rights

Mining uses groundwater throughout the year for mineral extraction and processing, and dust control. Currently, no major mining operations are located within the study area, however, a mining operation located north of the study site withdraws large quantities of groundwater from wells located near the river within the study area and transports it by pipeline to the mine site. Similar to mining, water is withdrawn for municipal uses year around. According to ADWR data, between 1984 and 1992 the City of Nogales and Rio Rico Properties Inc. withdrew 58,985 acre-feet of groundwater for municipal and industrial uses, or approximately 10,000 af/yr. As growth in this area continues, the impact to and demand for water supplies along the Santa Cruz River will become more significant.

SURFACE WATER SYSTEM

Historically, the Santa Cruz River had perennial surface flow from its headwaters, located in the San Rafael Valley, to approximately 11 miles north of Tubac. Subsurface flow continued from that point to the mission San Xavier del Bac located south of Tucson (Betancourt and Turner, 1990). In wet years the river flowed perennially throughout this entire reach. Currently, the river from the U.S./Mexico border to the NIWTP is characterized as interrupted perennial. This is because "bedrock-controlled" perennial reaches, such as that located near the U.S./Mexico border, are interspersed among reaches with subsurface flow (Figure 25).

The surface flow of the Santa Cruz River is extremely variable (Putman and others, 1983). Most of the study area reach is ephemeral or intermittent, however, some segments with perennial or effluent dominated flow do exist. The stretches of perennial flow are due to sub-surface geologic barriers which force groundwater to the surface, while effluent dominated flows are the result of effluent discharge from the NIWTP. Currently, a total of approximately 14 miles of the river exhibits perennial or effluent dominated flow in the study area (Brown and others, 1981). Perennial flows occur from the international border to approximately Buena Vista Ranch, and at the Guevavi Narrows. Effluent dominated flow occurs for approximately 12 miles below the NIWTP effluent discharge site. Streamflow is measured by the USGS at two locations along the river within the study area, Nogales and Continental. The distance between the two stations is about 45 miles resulting in a stream gradient of approximately 19.2 feet per mile (Halpenny and Halpenny, 1988). Tables 15 and 16 provide a list of monthly flow volumes obtained from the Nogales and Continental gaging stations, respectively.

Perennial flow in the Santa Cruz River occur as a result of rainfall runoff. Historically, the highest annual flows occur in the July-September monsoon period in response to short duration, high intensity thunderstorms. Flows generated from these storms rise rapidly,

Table 15
Monthly streamflow statistics from USGS streamgage 09480500, Santa Cruz River near Nogales, 1970-1993

Month	CFS				% Annual Runoff
	Mean	Median	Maximum of Record	Minimum of Record	
October	66.8	13.6	904.0	0.0	13.7
November	14.5	9.0	120.0	0.0	3.0
December	49.5	15.1	542.0	0.0	10.2
January	70.9	31.5	492.0	0.0	14.6
February	55.0	31.1	370.0	0.0	11.3
March	51.6	28.8	318.0	0.0	10.6
April	15.5	12.7	50.0	0.0	3.2
May	4.5	3.9	17.0	0.0	0.9
June	2.0	0.4	24.0	0.0	0.4
July	46.4	8.1	254.0	0.0	9.5
August	77.9	30.0	745.0	1.5	16.0
September	31.3	10.8	159.0	0.0	6.4

Table 16
Monthly streamflow statistics USGS streamgage 09482000, Santa Cruz River at Continental, 1960-1985

Month	CFS				% Annual Runoff
	Mean	Median	Maximum of record	Minimum of Record	
October	93.7	3.1	755.0	0.0	23.0
November	5.7	0.1	133.0	0.0	1.4
December	81.6	2.4	658.0	0.0	20.0
January	44.1	7.5	565.0	0.0	10.8
February	29.5	7.8	207.0	0.0	7.2
March	19.5	0.9	132.0	0.0	4.8
April	0.0	0.0	0.1	0.0	0.0
May	0.0	0.0	0.0	0.0	0.0
June	0.3	0.0	6.2	0.0	0.1
July	30.3	1.1	227.0	0.1	7.4
August	74.1	16.8	753.0	0.0	18.2
September	28.5	0.3	285.0	0.0	7.0

produce high peak flow rates, and then rapidly decline back to baseflow conditions. A second, less intense, rainfall runoff period was observed during the winter months. However, over the last 30 year period, the climate regime has tended toward providing a greater volume of annual precipitation and wetter fall and winter runoff producing periods. According to streamflow data collected by the USGS from 1970-present, 47% of total annual runoff at the Nogales streamgage occurred from December through March (Table 15). The month of October accounted for 13.7% of total annual runoff, while August, the typical high runoff month, produced only 16 % of total annual runoff.

The period of record for USGS streamgage data collected at the Continental gage site spans 25 years, from 1960 through 1985. Runoff measured during this time period reflects the same wetter fall and winter seasons. Mean annual flow measured at this gage averaged 34 cfs, with 43% of the runoff occurring December through March. The month of October accounts for more runoff than the peak monsoon month of August. Figure 23 illustrates annual runoff for both streamgages for their respective period of record.

Mean annual discharge in the Santa Cruz River at the Nogales gage site has averaged about 28 cfs over the 64-year period of record. Since 1970, however, the mean annual discharge at this site has increased, averaging approximately 40 cfs. The Santa Cruz River at the Continental gage site exhibits no flow for much of the year, however, annual flows measured at this site are only about 8% lower than those measured at Nogales for the concurrent period of record (1970-1985). This is due primarily to the larger contributing watershed, and to some extent effluent discharge to the stream. The flashy character of streamflow at both gage sites is apparent, particularly for the Continental gage, when comparing mean and median flow values. The median value provides a more accurate determination of available streamflow at a given site, by removing the influence associated with infrequent high and low flow rates.

Annual mean daily flow duration curves developed for the Santa Cruz River at the Nogales and Continental streamgages further illustrate the flashy nature of the Santa Cruz River (Figure 27). Median daily flow values obtained from the curves are 3 cfs for Nogales and 0 cfs for Continental. The two gages also measure very dissimilar flows at low stage. At Continental, discharge is less than 1 cfs 88% of the time, while at Nogales the discharge is less than 1 cfs 35% of the time. However, the flow duration curves at and above 100 cfs are similar between the two gages, with Continental and Nogales experiencing flows greater than 100 cfs 5% and 7% of the time, respectively.

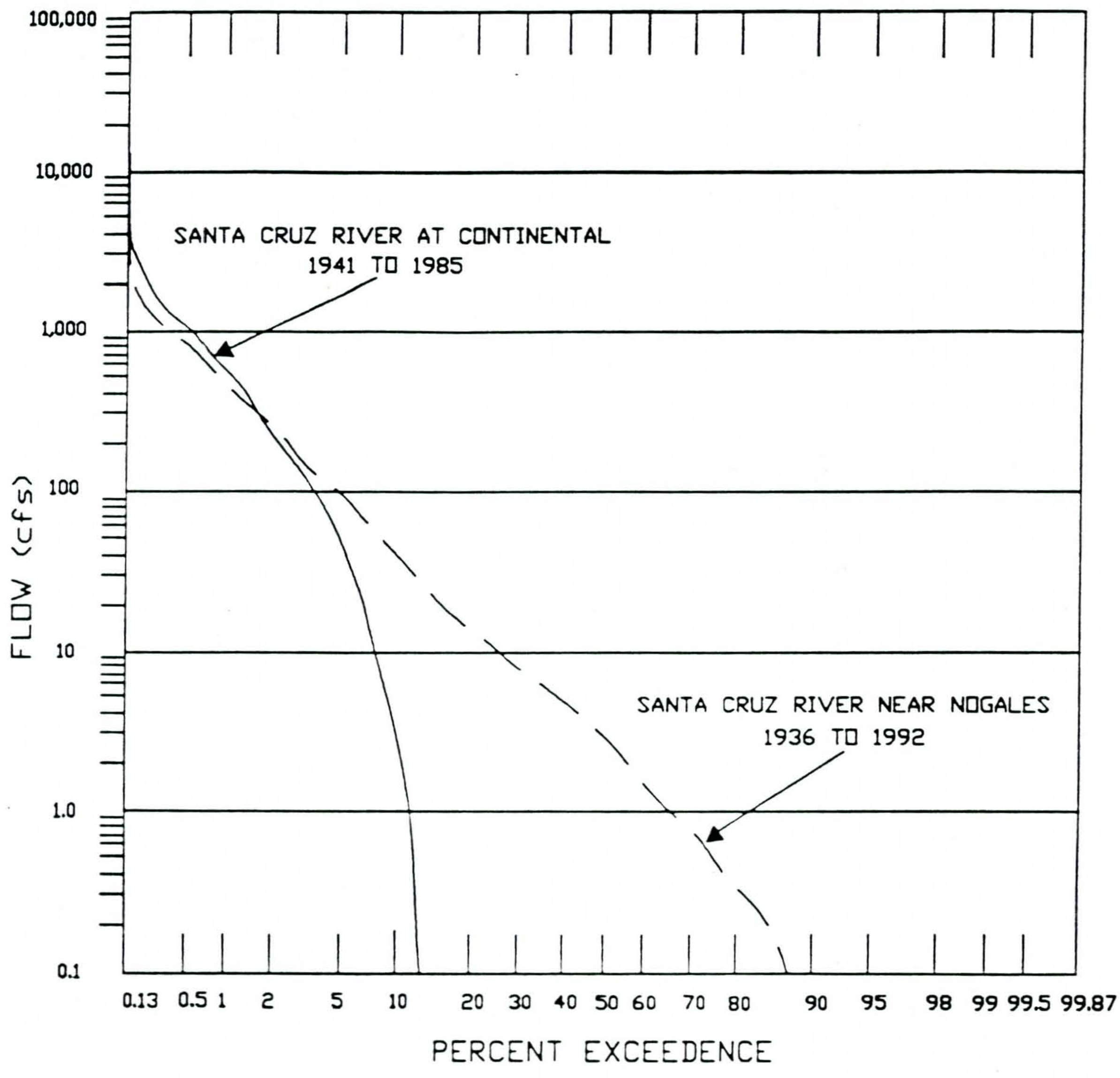
Analysis of the streamgage data indicates that Santa Cruz River baseflows disappear between Nogales and Continental. This primarily occurs because the Upper Santa Cruz River occupies a narrow valley with limited floodplain area. As the valley extends northward it gradually widens and, in the area of the Santa Cruz-Pima County line, opens into a wide alluvial floodplain. At this point valley fill sediments thicken greatly and any available surface flow infiltrates into the basin aquifer. Currently, perennial flows are present from the NIWTP effluent discharge site to the Tubac area. Therefore, any streamflow measured farther downstream at the Continental streamgage location is the result of intense, high volume precipitation events.

Because a streamgage is not located in the vicinity of the NIWTP discharge site, Nogales streamgage information was compared to effluent discharges from 1959 through 1992 (Figure 28). In addition to recharging the stream alluvium and extending the length of perennial flow in the river, the discharges may supply the only available surface water along some reaches during low flow years, such as 1980, 1982, and 1989.

Major Tributaries

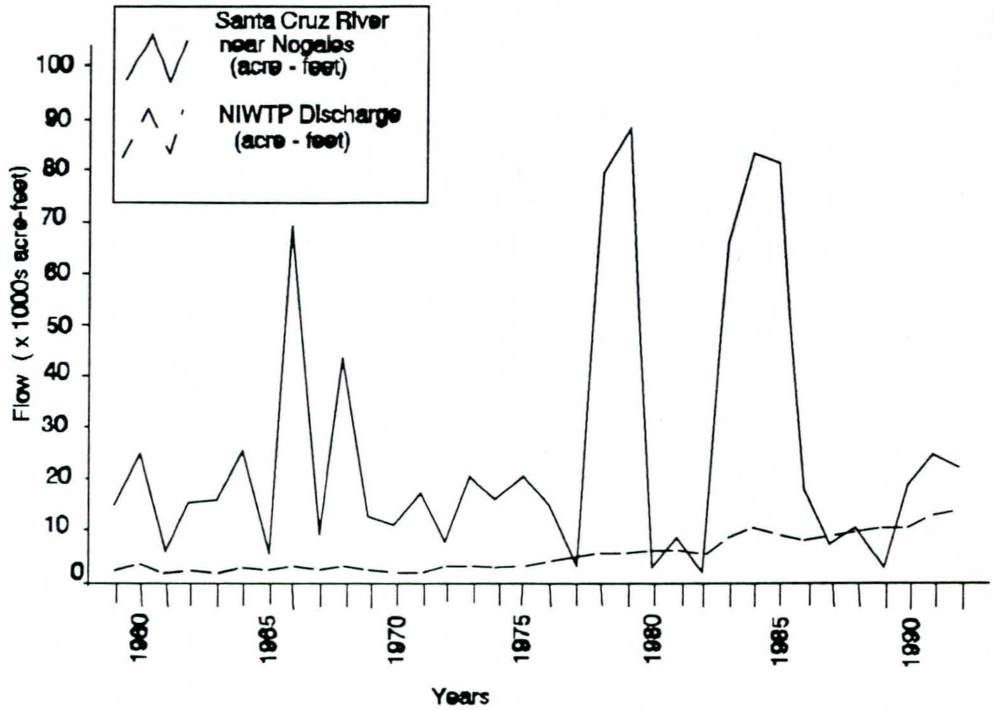
Major tributaries to the Santa Cruz River study area include Sonoita Creek and Nogales Wash (Plate 2). Although topographic maps show Nogales Wash converging with Potrero

Figure 27. Annual mean daily flow duration curves for the Santa Cruz River near Nogales and at Continental



Creek, the name "Nogales Wash" is applied locally and by other authors (Aldridge and Brown, 1971) to the main stream at the point where it enters the Santa Cruz River. Therefore, the tributary is referred to as "Nogales Wash" in this report.

Figure 28. Mean annual streamflow, Santa Cruz River at Nogales streamgage and NIWTP annual discharge



Streamflow from other tributaries is ephemeral, flowing only in direct response to rainfall or snowmelt. However, despite their ephemeral nature, they provide significant inflow to the river. Total tributary inflow to the Santa Cruz River system in the study area is approximately 21,100 af/yr. It occurs primarily as subflow in the stream alluvium of the larger tributaries (Harshbarger and Associates, 1970). Major tributaries are described below:

- Nogales Wash originates in Mexico and flows through Nogales, Arizona where it converges with Potrero Creek. This wash normally experiences ephemeral flows, however wastewater generated in Nogales, Sonora and discharged to the wash has resulted in 4 miles of perennial streamflow, flowing at a rate of a few gallons per minute. Nogales Wash converges with the Santa Cruz River adjacent to the NIWTP.
- Sonoita Creek serves as the primary tributary to the Santa Cruz River between the International Border and Tucson. The headwaters of Sonoita Creek are located near the town of Sonoita, Arizona. From the headwaters to Monkey Springs (located between Sonoita and Patagonia) short stretches of perennial flow are interspersed with ephemeral reaches. Flow from Monkey Springs results in perennial streamflow for approximately one mile. The stream becomes ephemeral again near Patagonia, where a fault cuts across the creek. From that point the streamflows perennially for approximately 6 miles and then becomes ephemeral again prior to converging with the Santa Cruz River (Halpenny, 1964).

Surface Water Diversions

Numbers of surface water diversions and total volume associated with those diversions were evaluated in the study area for claimed and certified water rights on file with ADWR. Sixty diversions occur along the Santa Cruz River, claiming a total volume of 41,321 af/yr. In addition, twenty-one diversions with claims to divert 1,645 acre-feet per year are associated with tributary reaches located within the study area. Some of these diversions, such as those by the City of Nogales at Guevavi, occur as subflow withdrawals. The accuracy of claimed and certified diversion figures are subject to verification, which is beyond the scope of this project. Claims and rights will not be thoroughly assessed until completion of the water rights adjudication process.

RIPARIAN VEGETATION ANALYSIS

Three subareas within the study area were selected to examine aerial photography and satellite imagery of riparian vegetation densities and locations of Fremont cottonwood-Goodding willow and mesquite communities, and land use. Subset 1 is located in the county line area, subset 2 is located south of Tubac, while subset 3 is in the vicinity of Duquesne Road and Kino Bridge (Figure 29). Different riparian vegetation densities and agricultural acreage generated from information for each subset area are presented in Figures 30 through 32. Figures 33 through 35 exhibit locations and densities of cottonwood-willow communities, and different land uses within each subarea.

The following riparian vegetation communities are described in order as they occur from the edge of the active channel to the upper floodplain terrace.

Cienegas

Cienegas (marshes) are a regional type of groundwater-dependent wetland vegetation association that were historically abundant along the upper Santa Cruz River (Hendrickson and Minckley, 1984). Historic changes in water table conditions have reduced these large expanses of cienega vegetation to tiny remnants. Two small cienegas persist in the Santa Cruz headwaters (San Rafael Valley) and have deep pools separated by braided channels flowing through sedges and other marsh vegetation (Meffe and others, 1983; Hendrickson and Minckley, 1984). Small cienega remnants also occur farther downstream along the Santa Cruz River near Calabasas (adjacent to Rio Rico) and along tributaries near Potrero Creek (Meadow Hill wetland). Several uncommon plant species grow in these cienegas.

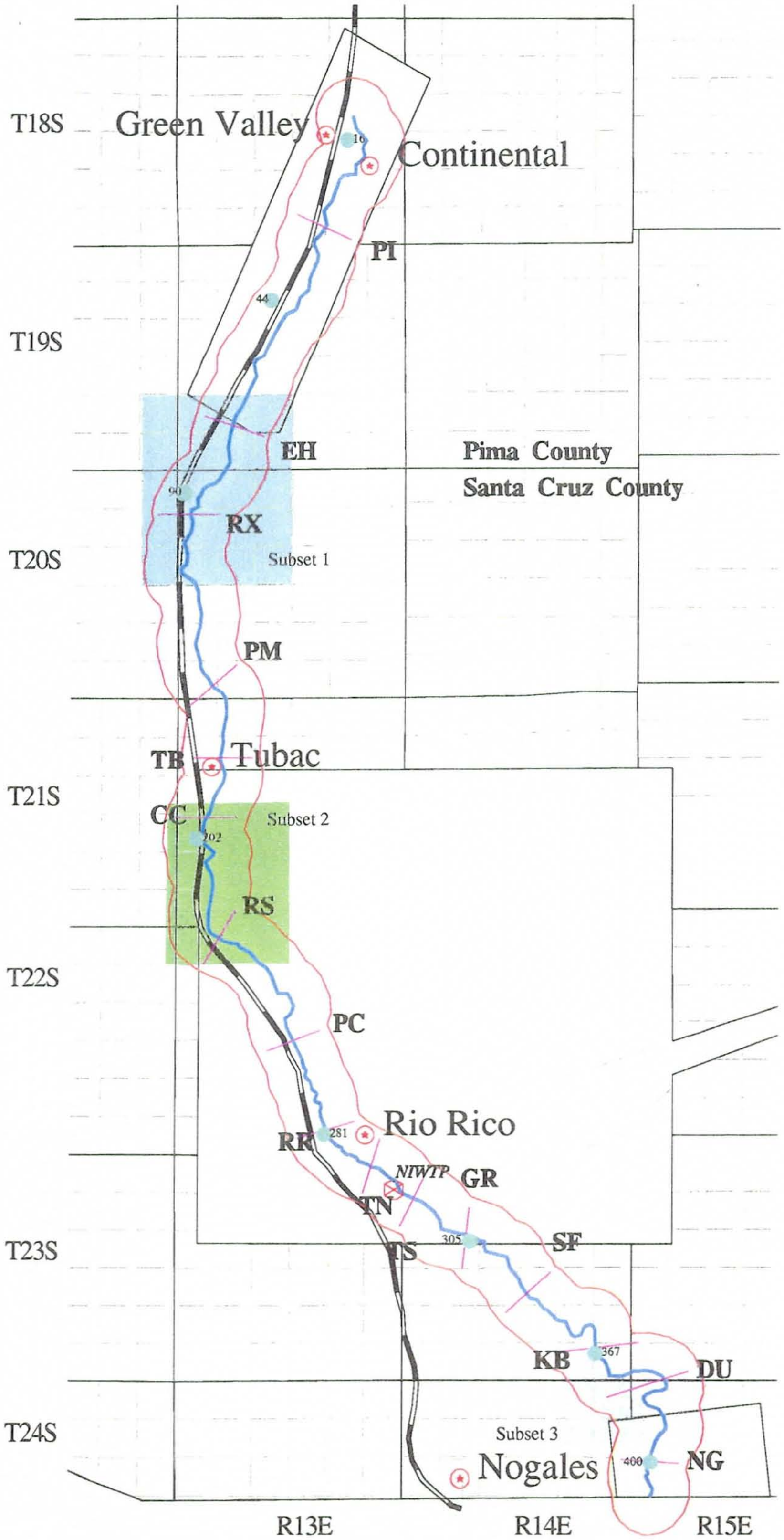
The herbaceous vegetation that comprise cienegas are more sensitive to groundwater or surface water supply changes than are other riparian species. Many cienega plants are obligate wetland species that require water slightly above the land surface or saturated soil only a few inches or feet below the surface (see San Pedro River case study).

Today, cienegas are rare along the Santa Cruz River largely due to the historical variation in water table levels (Bryan, 1928). During the period of arroyo cutting from about 1865-1915, human impacts interacting with climatic events (drought and floods) caused regional declines in water tables in the Southwest (Cooke and Reeves, 1976; Betancourt and Turner, 1990). On the lower Santa Cruz River, marshes near San Xavier were eliminated when arroyos dropped 3 m (10 ft) during turn-of-the-century arroyo cutting (Betancourt and Turner, 1993). On the upper Santa Cruz River, marshes that may have persisted beyond this time may have been eliminated by groundwater declines in the 1950s and 1960s. This was due to a combination of natural drought, surface water diversions, and groundwater withdrawals. In a river in which water tables are highly responsive to surface water changes, this combination produced sharp water table declines. During this same time period, the fish population in the Santa Cruz and nearby Sonoita Creek declined considerably (Miller, 1961).

Today, small patches of wetland vegetation are beginning to re-establish along the banks of the perennial reach of the Santa Cruz River downstream of the NIWTP. Streamside wetland vegetation also exists in localized areas of the Santa Cruz River upstream of the NIWTP where shallow bedrock results in stable water tables (e.g., Nogales gage site). Streamside areas in the effluent-dominated perennial reach of the Santa Cruz River support a higher percentage of obligate wetland, facultative wetland, and facultative plants (Reed, 1988) than do those located near groundwater pumping zones that are not being recharged by effluent. Table 17 displays herbaceous plant cover, by species-type, along the streambanks of the Santa Cruz River. Two sites were selected downstream of the NIWTP where perennial flow and high water tables are present (Tubac Bridge and PM Ranch), and upstream of the NIWTP near high groundwater pumpage areas (Kino Bridge and Duquesne Road).

Figure 29

UPPER SANTA CRUZ RIVER TRANSECT AND SUBSET LOCATIONS



HYDROGRAPHS

	LOCAL-ID	SITE-ID
16	D-18-13 23BAD	315110110591301
44	D-19-13 09CAA	314728111011101
90	D-20-13 06CBA	314303111032801
202	D-21-13 19DBC	313506111030701
281	D-22-13 34ADD	312818110594501
305	D-23-14 17ACA	312551110554701
367	D-23-14 36BCB1	312316110522701
400	D-24-15 18AB 1	312050110504501

TRANSECTS

REFERENCE-ID	SITE NAME
CC	Clark Crossing
DU	Duquesne Road
EH	Elephant Head
GR	Guevavi Ranch
KB	Keno Bridge
NG	Nogales Gage
PC	Pecks Canyon
PI	Pima County
PM	PM Ranch
RR	Rio Rico Bridge
RS	Rancho Santa Cruz
RX	Rex Ranch
SF	Santa Fe Ranch
TB	Tubac Ridge
TN	Treatment Plant North
TS	Treatment Plant South

DRAFT

Figure 30. Subset 1: Agricultural land and riparian vegetation densities of the upper Santa Cruz River

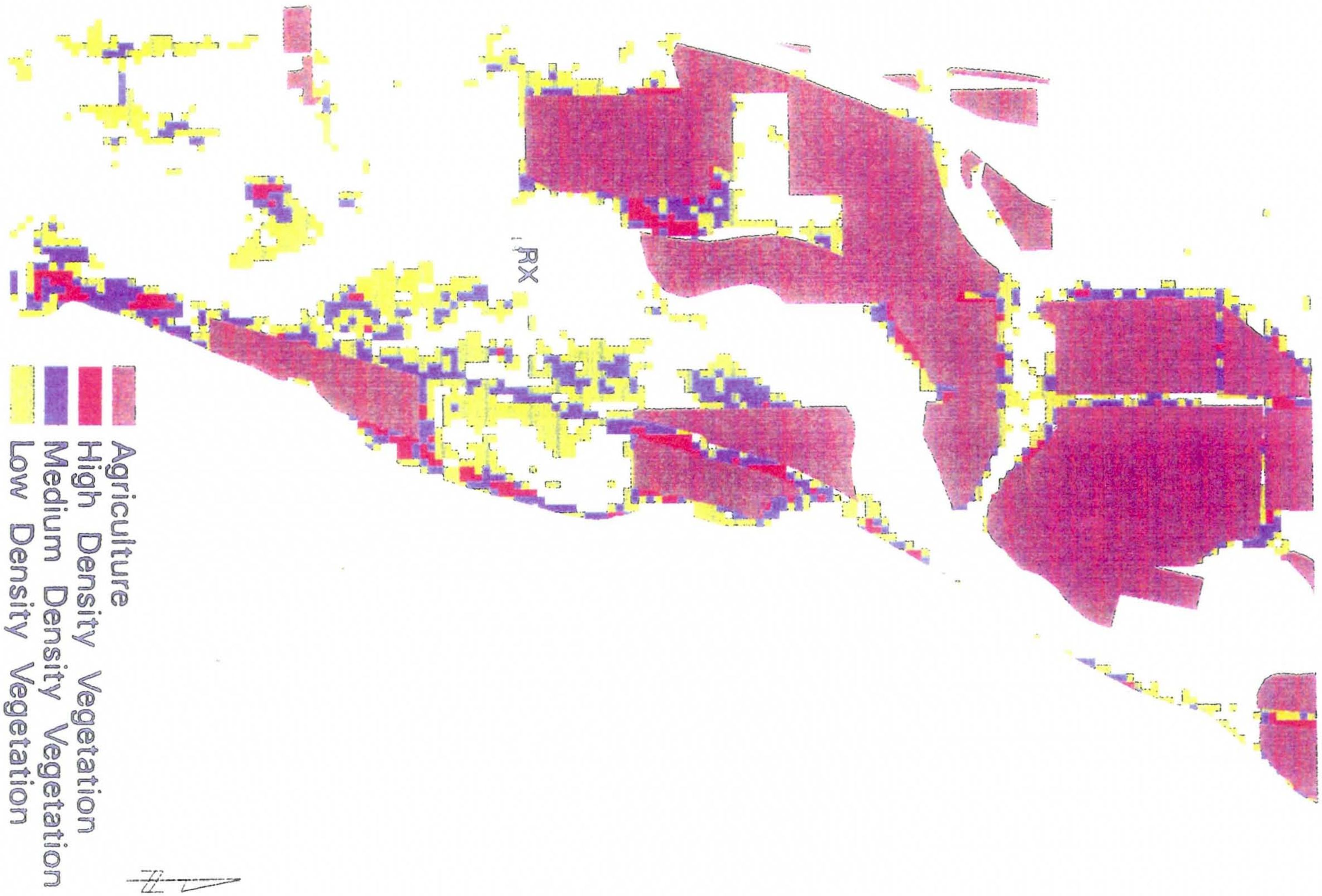


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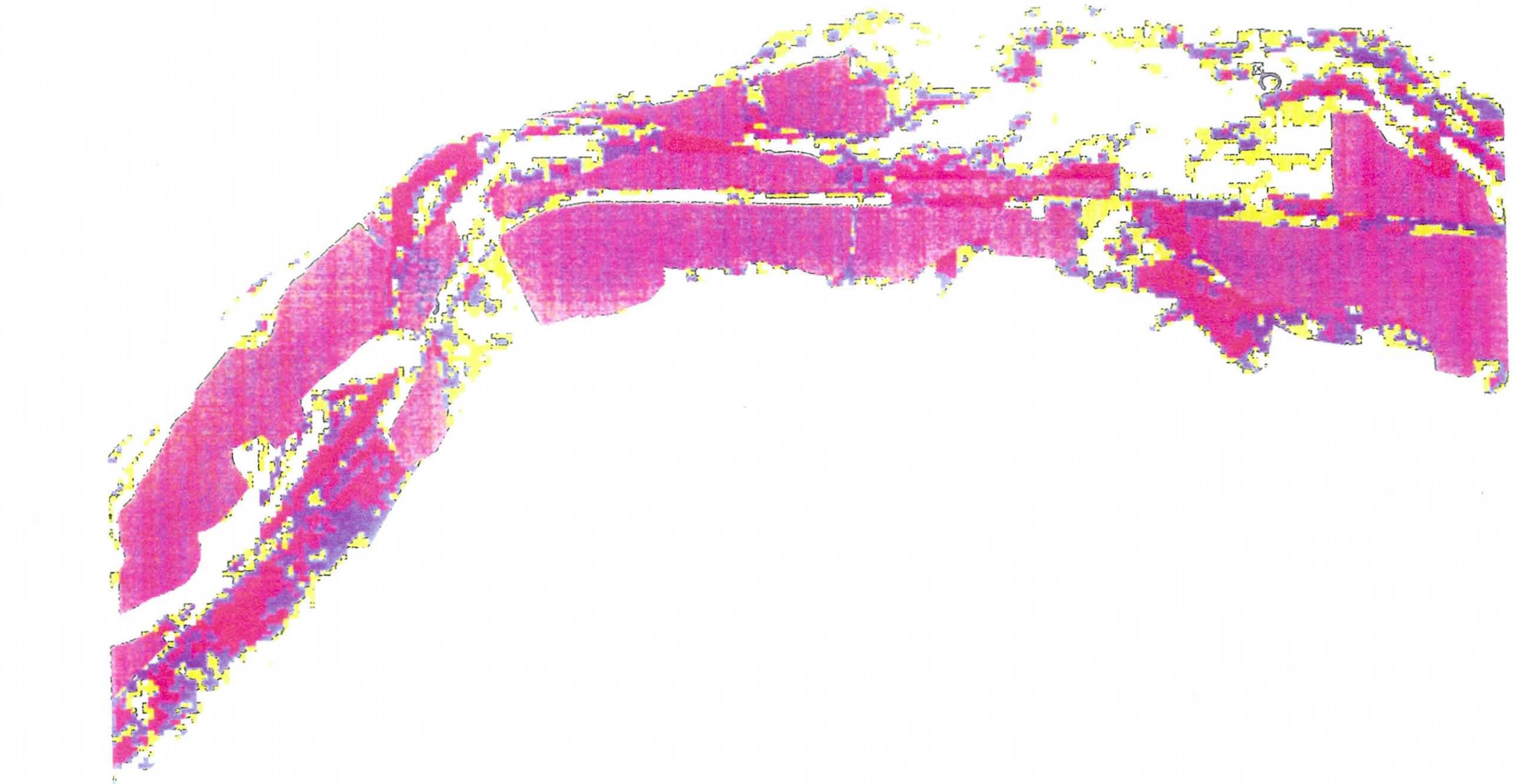
Figure 31. Subset 2: Agricultural land and riparian vegetation densities of the upper Santa Cruz River



D R A F T

Figure 32. Subset 3: Agricultural land and riparian vegetation densities of the upper Santa Cruz River

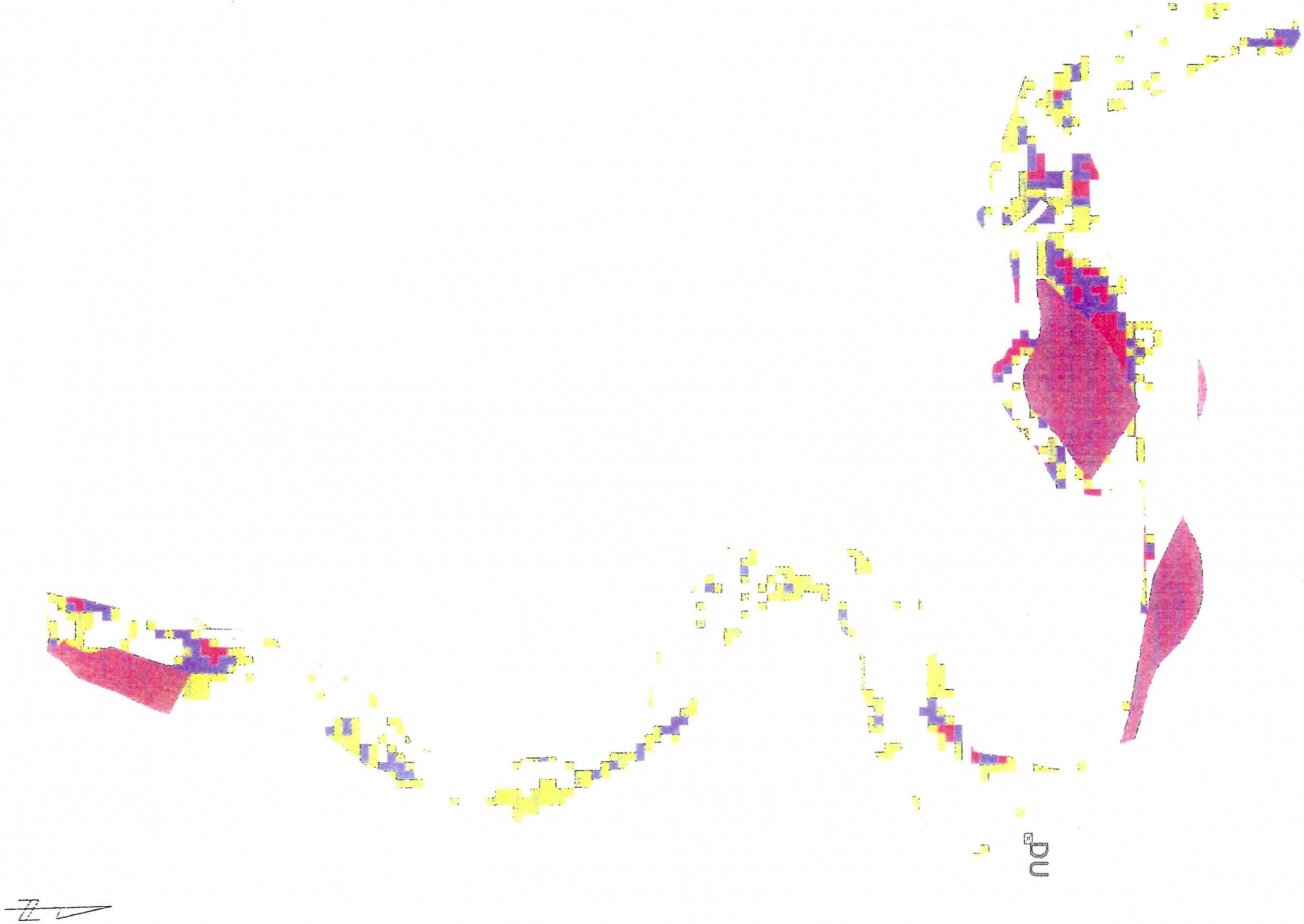


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Figure 33. Subset 1: Riparian land use and vegetation locations and densities of the upper Santa Cruz River

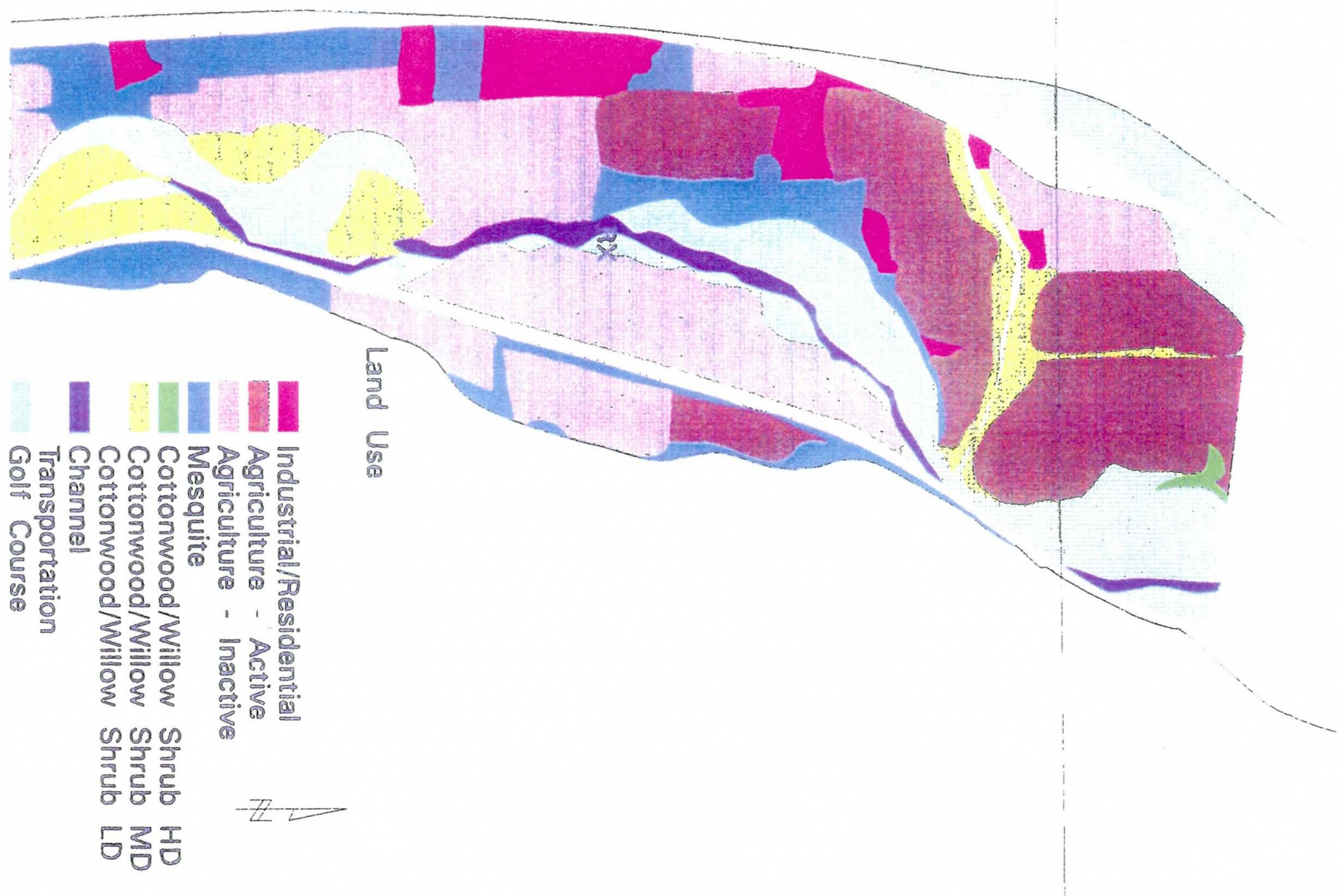

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Figure 34. Subset 2: Riparian land use and vegetation locations and densities of the upper Santa Cruz River

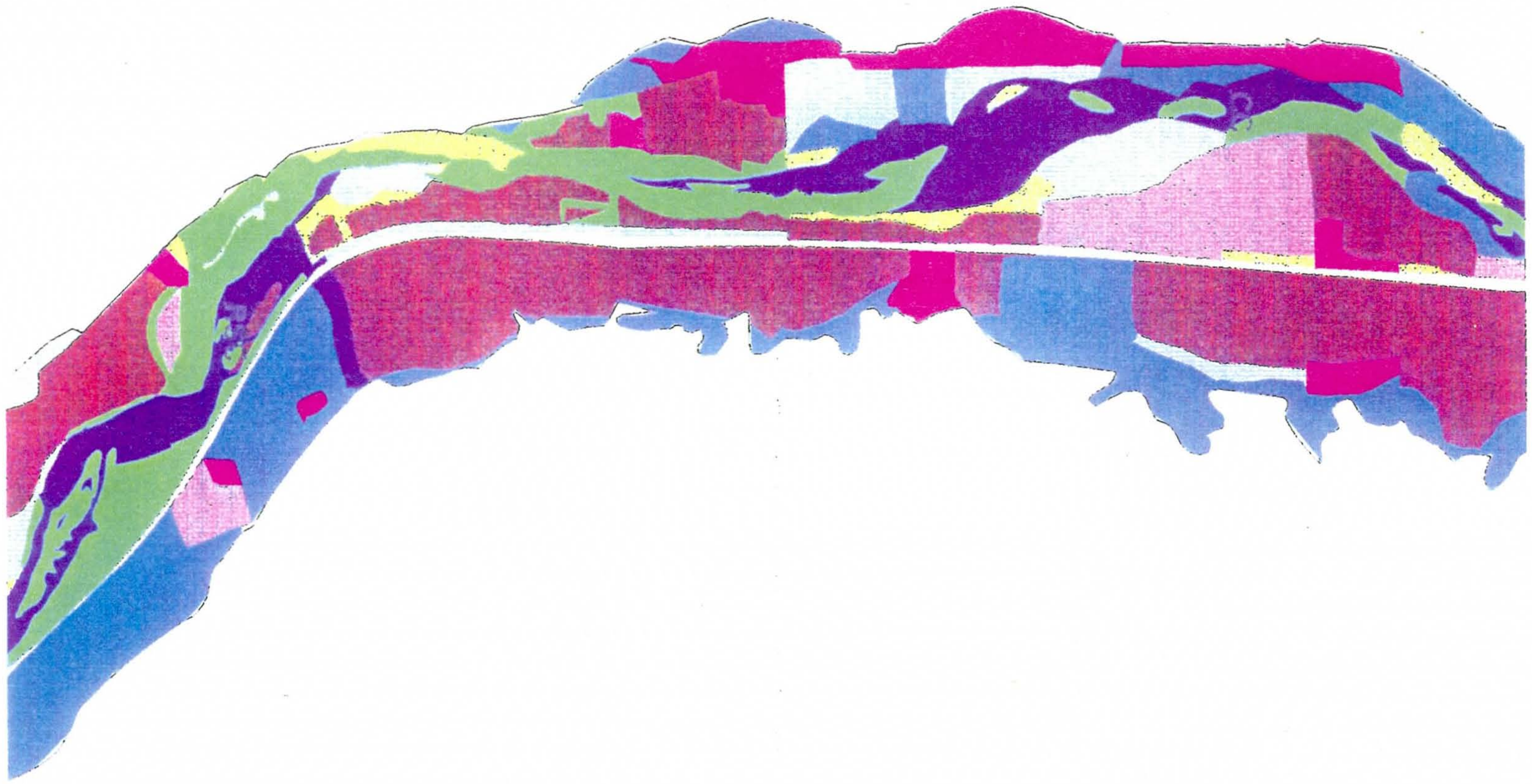

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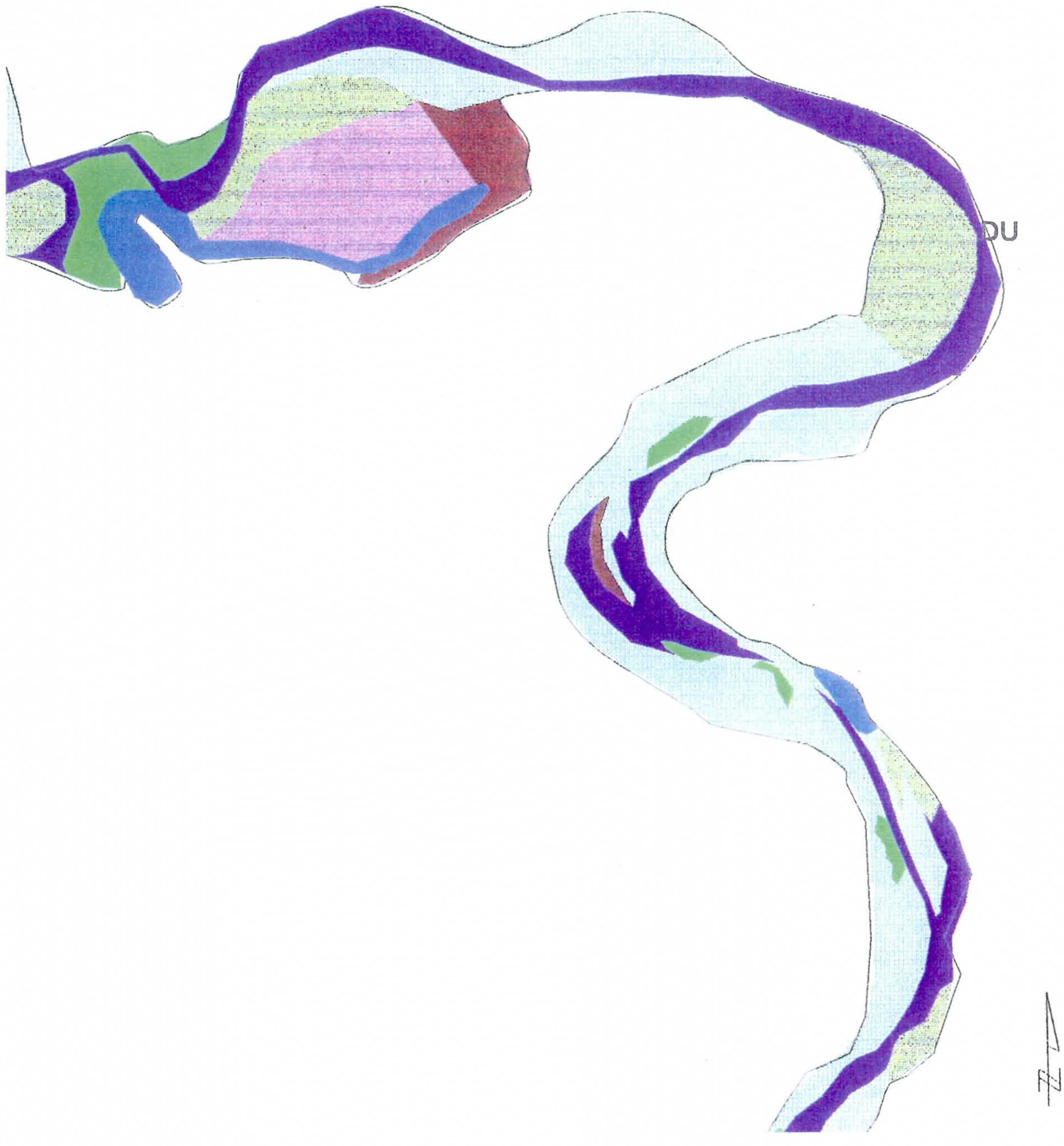
Figure 35. Subset 3: Riparian land use and vegetation locations and densities of the upper Santa Cruz River



The percent of all species-types was found to be greater at the effluent influenced sites than at the Kino Bridge and Duquesne Road sites, where virtually no obligate and facultative wetland or facultative species were present. The largest remnant cienega present in the Santa Cruz River study area is located on the extremities of the floodplain, near Rio Rico. Wetland plants in the cienega may be responding positively to raised water tables in this reach of the river, although no studies have been initiated to evaluate this issue. If groundwater levels continue to rise in the effluent-dominated reach of the Santa Cruz River, the potential for cienega expansion or re-establishment should be enhanced.

Table 17
Streamside herbaceous plant cover, by species-type (%)

	Tubac Bridge	PM Ranch	Kino Bridge	Duquesne Road
Obligate Wetland	5±5	4±5	0±0	0±0
Facultative Wetland	13±11	8±5	<1±<1	1±1
Facultative	2±3	18±17	0±0	<1±<1
Facultative Upland	9±13	4±4	4±3	3±3
Unclassified	2±2	1±2	6±6	5±5
TOTAL	31±21	35±27	10±6	9±7

Fremont Cottonwood-Goodding Willow Forests

Some historical reports in the mid 1800s described the extensive occurrence of marshes and mosquitos along the upper Santa Cruz River, while others described the streambanks of the Santa Cruz River as being "...lined with cottonwood trees of a gigantic size..." and as having "... deep pools shaded by willows and mesquite..." (Davis, 1982).

Fremont cottonwood-Goodding willow forests are presently the dominant riparian vegetation-type along the upper Santa Cruz River. Although these forests were a historical component of the river's ecosystem, they are the dominant type today, in a sense, by default. Water table decline has destroyed the marshes and sacaton grasslands, while agriculture has eliminated most of the mesquite bosques. Cottonwood-Willow forests persist because (1) they are rapidly growing pioneer species that can rapidly recolonize a floodplain once suitable environmental conditions (e.g., high water tables) return, (2) they establish and form young stands on relatively low floodplains that are frequently disturbed by floods, and therefore, less desirable for development, and (3) although they require shallow water tables, they are not as sensitive as cienega species to slight water table changes.

Before describing the status of the cottonwood-willow forests along the upper Santa Cruz River, a brief overview is presented of ecological factors associated with establishment and maintenance of this forest association, and techniques for evaluating the ecological condition of forests.

Establishment Process - General Role of Floods

Fremont cottonwood and Goodding willow trees establish episodically (i.e., many plants establish simultaneously in the same year) on low sediment bars, following flood flows (Brady and others, 1985; Rood and Mahoney, 1990; Stromberg and others, 1991). Large winter floods set the stage for recruitment by scouring vegetation from channel banks and floodplains and depositing fresh alluvium, temporarily reducing competition from herbaceous plants or overstory trees. Small flood surges in spring generally moisten floodplains at the appropriate time (i.e., during the limited period of spring seed dispersal), and at an appropriate place (moderately high surfaces above the zone of frequent summer flood scour which can kill young plants) (Stromberg and others, 1991; Stromberg, 1993).

Establishment Process- General Role of Water Tables

Floods stimulate germination of Fremont cottonwood and Goodding willow, while shallow, stable groundwater levels provide water essential to juvenile survivorship. Demographic studies indicate that one-year juveniles of both tree species experience greatest survivorship on floodplains where groundwater levels drop no lower than 0.5 to 1 m (1 to 3 ft) below the soil surface by summer's end. In this floodplain zone, seedling mortality, due to drought and late summer flood scour, is minimized (Stromberg and others, 1991). Seedling survivorship is greatest when the rate of water recession after the winter or spring flood is equivalent to the rate of seedling root elongation. Cottonwood seedlings have optimum growth and survival when the rate of water table decline is less than 3 cm (1 inch) per day (Mahoney and Rood, 1991; Segelquist and others, 1993). High groundwater levels that occur during flood years increase the probability of seedling survivorship.

In comparison to Fremont cottonwood, Goodding willows are less drought tolerant and require slightly shallower water tables, both as juveniles and as adults. Although willows and cottonwoods grow in close association along many rivers, close inspection reveals that the willows are often found in closer proximity to channels on slightly lower elevated floodplains. This is the partial consequence of an adaptive response in which willow seeds are dispersed slightly later in the season (and thus later during the process of spring water recession) than Fremont cottonwood seeds. This helps to ensure that willow seeds will germinate on slightly wetter sites than the Fremont cottonwood seeds, reducing competition between the two species.

Both species often consist of spatially separate, same-age cohorts that grow in linear bands parallel to primary or secondary channels (Stromberg and others, 1991). The youngest trees are closest to the channel, while older trees can be found on floodplains several hundreds of feet from the primary channel. These patterns have been described as arcuate bands, or "isochrones" of trees (Everitt, 1968; Bradley and Smith, 1986). Younger trees typically occur on shallow groundwater sites and the oldest trees (100 to 130 years) on higher floodplains. These patterns occur both because mature trees have greater rooting depth than juveniles, and because floodplains tend to aggrade with age (Brady and others, 1985). Although mature trees of both species can tolerate intermediate water table depths (up to about 3 m, or 10 ft, for willow and about 5 m, or 15 ft, for cottonwood; see Ecology Report, Chapter 3), continued reproduction by both species requires short periods in spring in which water tables are very near the floodplain surface, followed by a period in which water tables decline to a depth no greater than 1 m (3 ft) by summer's end. Variation in groundwater levels along different reaches of the Santa Cruz River have changed the ecological condition of cottonwood-willow riparian forests, as described below.

Ecological Condition: General Concepts

The ecological condition, or health, of cottonwood and willow populations can be measured in several ways. One aspect of ecological condition involves maintaining a "healthy" age structure. Populations with healthy age structure possess the following characteristics: (1) many age cohorts or age classes are present, including very old and very young individuals, and (2) young plants have higher stem densities than old plants. Presence of these attributes indicate that processes required for establishment have occurred uninterrupted over time, and that many young individuals will be available to replace older trees as they die. This is particularly important because, although older trees can survive in a stressed condition for several years before dying, the affected population will decline over time because new generations are unable to establish (Petts, 1985; Rood and Mahoney, 1990).

Forests in good ecological condition have high tree densities and canopy coverage. Cottonwood and willow stands often form long, relatively narrow stands. Stand width is determined by the width of the floodplain zone that possessed suitable surface water and groundwater conditions during the establishment process. Stands are often narrowed and thinned by subsequent flood mortality. Stands in the best ecological condition are those that cover a wide portion of a floodplain and have high within-stand tree and canopy foliage densities.

Another aspect of ecological condition involves tree growth rate and vigor. Fremont cottonwood trees are among the fastest growing trees in the world. They have evolved to grow quickly and reproduce before being killed during a flood event. High water tables, direct sunlight, and long growing seasons allow trees to attain stem diameter growth rates of 3 to 5 cm (1 to 1.5 inch) per year, and height growths (terminal growth) of greater than 1 m (3 ft) per year.

The ratio of cottonwood to willow trees also can indicate ecological condition, because willows are generally more sensitive to water stress than cottonwoods (McBride and others, 1988). Therefore, a high ratio of cottonwood to willow can indicate high water stress and that suitable environmental conditions are not available to allow both of members of this vegetation association to establish or persist.

Another indicator of ecological condition is the relative abundance of cottonwood-willow forests to facultative riparian shrub associations (e.g., rabbit brush and burro brush (also known as riparian scrub; Brown, 1982)). Similar to cottonwood-willow forests, riparian scrub grows on low, frequently inundated floodplains, but unlike cottonwood-willow has lower value to wildlife (see San Pedro River case study).

A final component of ecological condition is community health, or the extent riparian vegetation communities are affected by disease (e.g., bacterial 'slime flux' or fungal canker), parasites (e.g., mistletoe), or insects (e.g., caterpillar "bag worms"). Riparian stands that are weakened or degraded by hydrologic changes are more susceptible to infestation by these organisms.

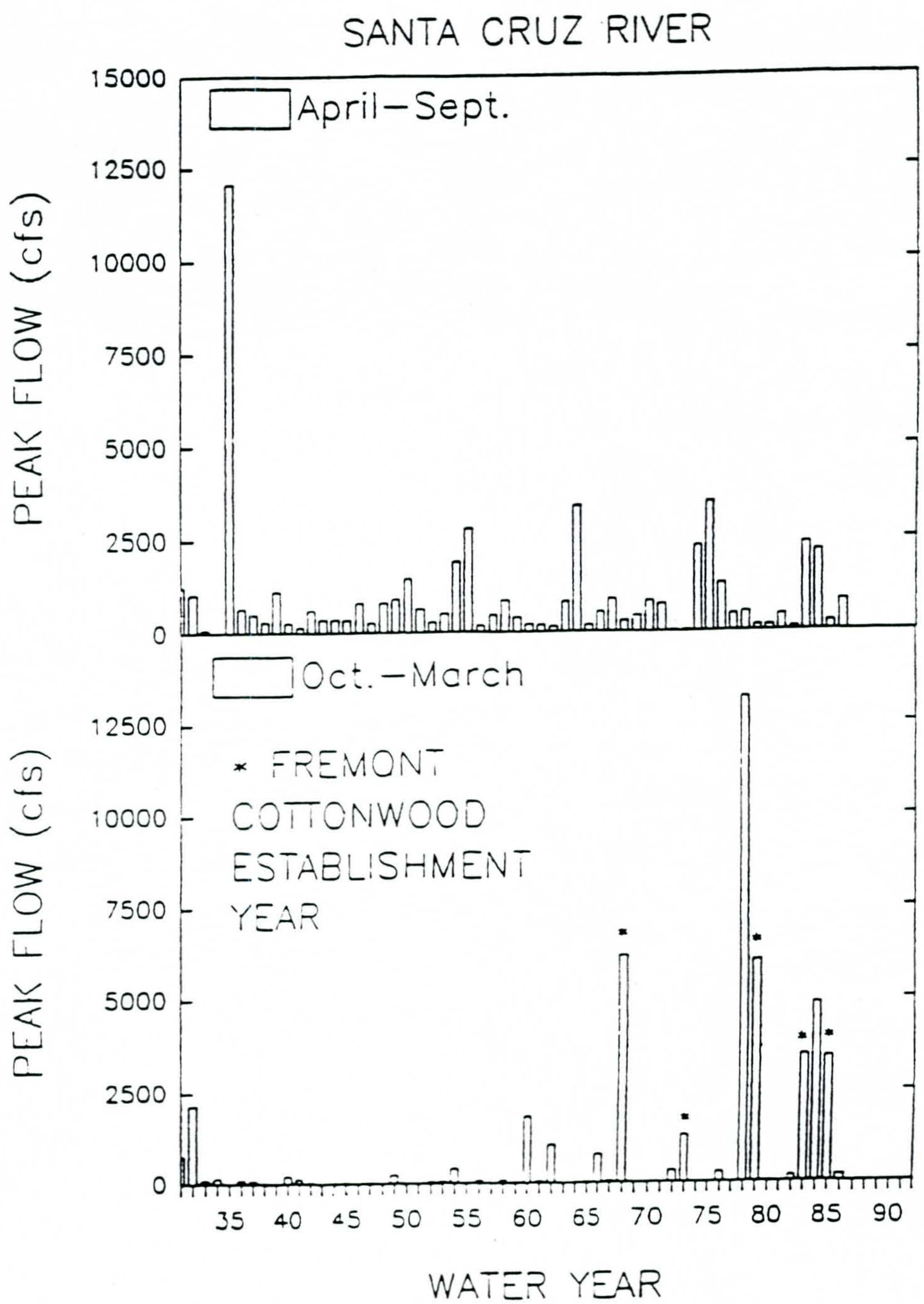
Ecological Condition of Upper Santa Cruz River Cottonwoods and Willows

This discussion is intended to provide an overview of trends occurring along the river in the study area, rather than provide an exhaustive summary of cottonwood-willow dynamics at every bend of the river. Groundwater levels and vegetative parameters of cottonwood and willow populations are evaluated over time. Parameters such as canopy foliage density, age class diversity, and the ratio of cottonwood to willow are used as general indicators of ecological condition and trend. In addition, predictions are presented, in terms of different management strategies, regarding the future status of cottonwood-willow forests located in various reaches of the river.

Flood Flows and Cottonwood-Willow Establishment

The ecological condition of Fremont cottonwood and Goodding willow populations along the Santa Cruz River differ greatly between river reaches due, not only to variations in land and water use, but to hydrologic conditions as well. Flood flow magnitudes and seasons of flood occurrence in the Santa Cruz River valley have fluctuated over time (Webb and Betancourt, 1992; and see Surface Flow discussion), affecting cottonwood and willow establishment along the entire river. Large winter floods were frequent prior to the early 1930s and following the early 1960s, but occurred infrequently between that general time period (1930-1960). As a partial result of this flooding pattern, during that time period, no large-scale episodes of Fremont cottonwood establishment occurred along the Santa Cruz River (Figure 36) and along Sonoita Creek, a major tributary to the Santa Cruz River (Stromberg, 1993). Extensive tree-coring along both rivers uncovered no areas supporting middle-aged trees that would have established between approximately 1930 to 1960. Increased frequency of large floods since the 1960s has stimulated establishment of Fremont cottonwood and Goodding willow along the Santa Cruz River and Sonoita Creek. Trees have established, for example, after floods in 1968, 1979, and 1983.

Figure 36. Fremont cottonwood recruitment years on the upper Santa Cruz River in relation to flood magnitude and season



Groundwater Impact Evaluations

Well impact analyses were conducted to determine the potential effect of groundwater withdrawals on riparian systems. Analytical methods developed by Theis (1935) were used to determine potential drawdown associated with single hypothetical wells located at different sites in the study area.

Site Selection

Three general areas were selected to conduct theoretical well impact determinations. The first two areas are located upstream of the NIWTP near Duquesne Road and Kino Bridge. The aquifer system in this area is composed of four sub-basins that are heavily pumped for municipal, domestic, stockwatering and irrigation uses. Available groundwater in storage can be rapidly depleted, particularly during drought periods. Fortunately, the system can be rapidly recharged when adequate surface water is available. However, as these areas are relied upon more heavily for groundwater supplies, in some locations, complete recharge may not occur. One such location is the Nogales well field area, where complete groundwater level recovery has not been observed in well D(23-14)36bcb1 since the early 1970s (Plate 2).

The third location is the area surrounding the Santa Cruz/Pima County line. In this zone, riparian vegetation has re-established over the last 10 year period due to increased groundwater levels and surface water flows, functions of effluent discharge and wetter climatic periods. This input to the Santa Cruz River system is gradually raising groundwater levels progressively farther downstream. However, continued development of this riparian area relies upon available streamflow and effluent discharge. Increased groundwater withdrawals or new diversions in or upstream of this area could effectively reduce further establishment and growth, or destroy the existing community.

Analytical Analyses

Hydrologic parameters used in the evaluation were obtained from existing pump test analyses. A transmissivity of 124,000 gpd/ft (16,578 ft^2/d), determined by Putman and others (1983) for the younger alluvium in the Buena Vista sub-basin, was used for the younger alluvium for the Duquesne Road (Buena Vista sub-basin) and Kino Bridge (Kino Springs sub-basin) area evaluations. Halpenny (1964) estimated a specific yield of 17% for the Guevavi (e.g. Highway 82) sub-basin.

A year-round, municipal well pumping at a rate of 750 gpm from the younger alluvium was assumed. Drawdown depth at the well, and resulting 1, 3 and 6 feet drawdown radii were determined. Year around, municipal groundwater pumpage from the younger alluvium was also evaluated for the county line area. However, the aquifer parameters and pumpage rate differed in accordance to aquifer characteristics present in this area. A transmissivity value of 140,000 gpd/ft (18,717 ft^2/d) and specific yield of 15% were used (Halpenny, 1982), and a pumpage rate of 1,000 gpm was assumed. Resulting drawdown radii, including groundwater depth at the well site, and corresponding areas of influence are presented in Table 18. Effects of potential drawdown to cottonwood-willow populations are described for the sites in the following sections.

Table 18
Theis analysis results: Predicted drawdown radii and acreage

Site	Drawdown Depth (ft)	Radius (ft)	Acreage	Hectare
Duquesne/Kino Bridge	1	4,621	1,542	624
	3	1,033	77	31
	6	14	0.01	0.006
	13	at well		
County Line	1	6,036	2,631	1,065
	3	1,653	197	80
	6	260	5	2
	101	at well		

Nogales Gage Site

The populations of cottonwood and willow near the Mexican Border at the Buena Vista narrows (Nogales gage site) are in relatively good ecological condition. The Fremont cottonwood population has a mixture of very old trees (>100 years) and young trees (<30 years). This population has relatively high growth rates and grows intermixed with Goodding willow trees.

These conditions are attributed to the presence of a shallow water table, about 2 to 3 m (7 to 10 ft) below the cottonwood vegetated floodplain surface. Figure 37, displaying a profile of the Santa Cruz River floodplain surface at the Nogales gage site, shows mean depth to groundwater as determined from index well D(24-15)bab1 for each decade from 1930 through 1980. In addition, location of riparian vegetation-types, and age and vigor of Fremont cottonwood are indicated. Groundwater levels have been sufficiently stable over time to prevent cottonwood death, and allow periodic recruitment of new generations of trees following flood events. Stable water tables at the Nogales gage site are a consequence, in part, of a shallow bedrock layer. This layer may serve to minimize changes in groundwater levels resulting from groundwater pumping in Mexico.

The Nogales gage population, however, did not "score" well on all points. Stand densities and average canopy foliage densities were lower at this site than in some other reaches of the river. Figure 38 displays average and maximum canopy foliage area values for Fremont cottonwood-Goodding willow in relation to distance from the international border. The lower densities for this site, located approximately one kilometer (km) from the border, are partially due to the loss of a relatively large population of trees during the 1993 winter flood. Although flood scour removed trees throughout the length of the Santa Cruz River, flood scour may have been particularly heavy at this site because of upstream land and water use practices in Mexico. South of the international border, cattle heavily graze the riparian zone, while the floodplain is extensively cultivated. All of these factors

Figure 37. Profile of Santa Cruz River floodplain at Nogales gage site.

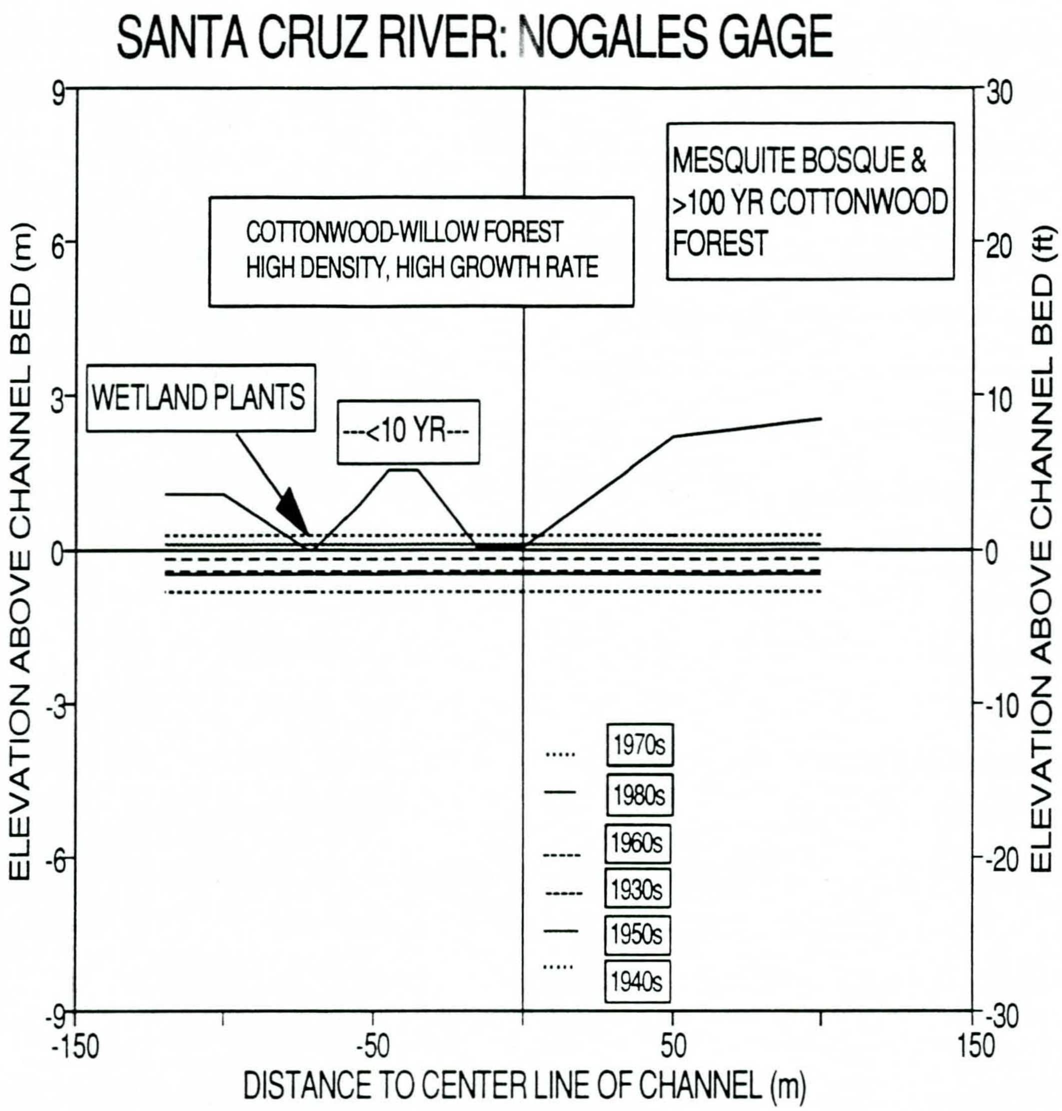
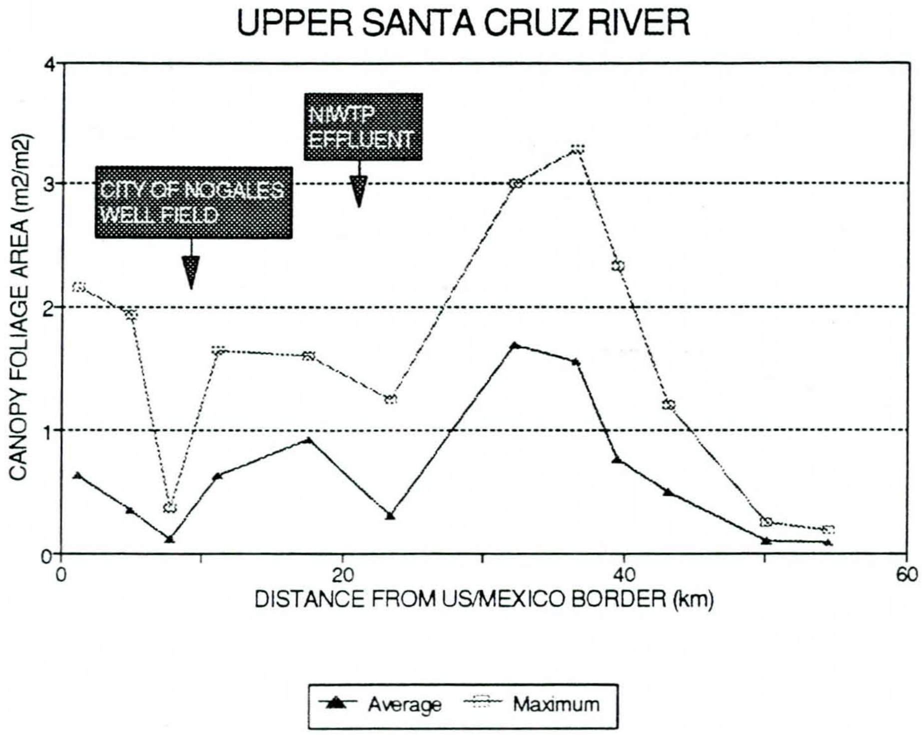


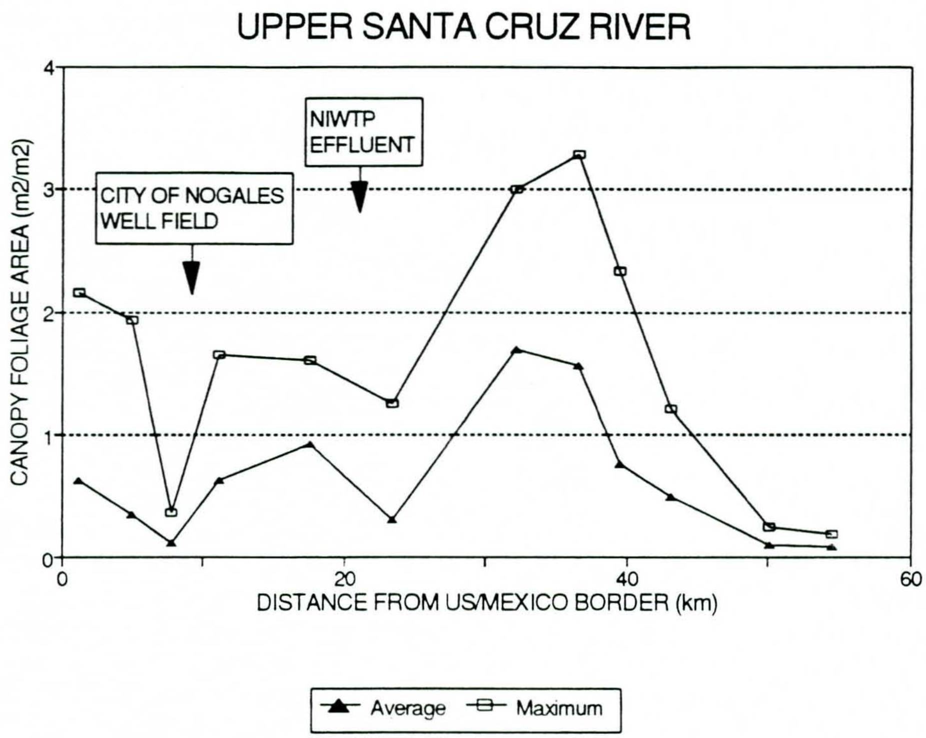
Figure 38. Cottonwood-willow canopy foliage area in relation to distance from U.S./Mexico border



reduce the ability of the riparian zone to slow flood waters, and therefore, increase downstream flood flow velocities and tree scour.

Although Nogales gage site vegetation is in relatively good ecological condition, increased groundwater pumpage could cause conditions to deteriorate. For example, simulations of well pumping impacts indicate that a single well pumping 750 gpm from the younger alluvium, would after 1 yr cause a 1 m (3 ft) decline in the water table in a 31 ha (77 acres) area (Table 18). On the higher floodplain terraces that presently support the >100-yr Fremont cottonwood trees, the depth to groundwater is about 2.8 m (11 ft). Figure 39 displays the canopy foliage area of Fremont cottonwood-Goodding willow stands in relationship to groundwater depth. Groundwater declines to 3.8 m (12 ft) would cause substantial reductions in factors such as canopy cover (foliage area) of the stand. A decline to 2.8 m would result in a canopy foliage area value of less than 0.5 m^2/m^2 for the affected area. Declines to approximately 6.5 m would result in loss of this old, established community.

Figure 39. Canopy foliage area of Fremont cottonwood-Goodding willow in relationship to depth to groundwater



Duquesne Road and Kino Bridge Sites

The populations of cottonwoods near the City of Nogales Highway 82 well field and the Kino Springs well field areas (Duquesne Road and Kino Bridge sites) are in poor ecological condition. Trees at both sites have radial growth rates of less than 1 cm/yr (0.4 inch), compared to 1 to 3 cm (0.4 to 1.2 inch) for all other sites. They also exhibit low canopy foliage densities (Figure 38, Duquesne Road and Kino Bridge sites are located 5 and 8 km from the border, respectively), and low within-stand tree densities. Only 1% of the floodplain in this general reach of the river supports high density cottonwood forests (Figures 32 and 35). Table 19 presents land use categories and vegetation density classes for three reaches of the Santa Cruz River study area.

Table 19
Floodplain acreage by land use category and vegetation density class for three reaches of the upper Santa Cruz River*

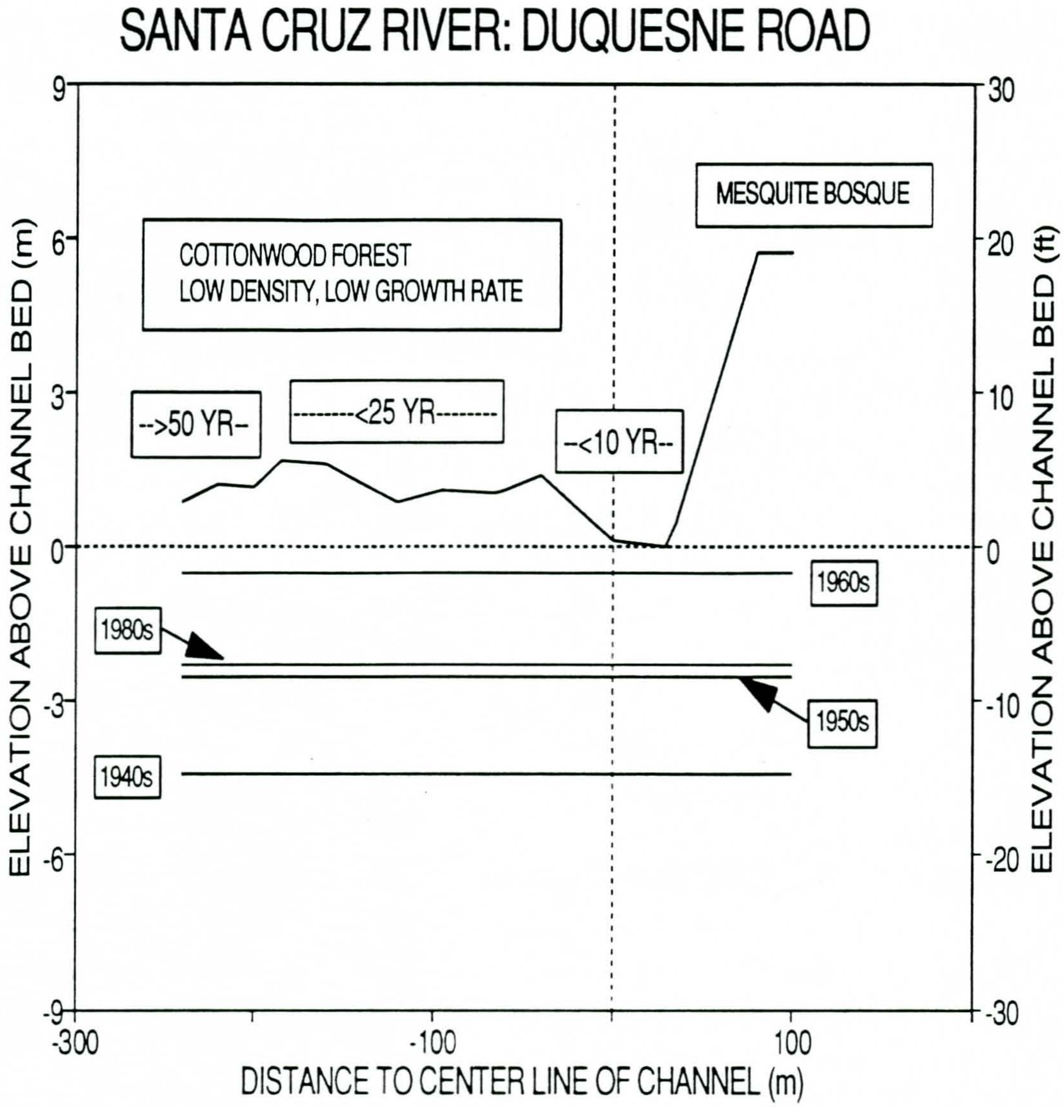
	Reach 1 (Pima County line to Tubac Bridge)			Reach 2 (Tubac to NIWTP)			Reach 3 (NIWTP to US/Mexico border)		
Land Use Class	Hectare	Acre	%	Hectare	Acre	%	Hectare	Acre	%
Residential/Industrial	106	262	6	84	208	3	116	287	12
Agriculture (active)	286	706	15	645	1593	26	96	237	10
Agriculture (inactive)	433	1070	24	326	805	13	38	94	4
Transportation	135	333	7	96	237	4	0	0	0
Golf course	25	62	1	0	0	0	0	0	0
Developed Subtotal	**985**	**2433**	**53**	**1151**	**2843**	**46**	**250**	**618**	**26**
Mesquite (HD[1])	232	573	13	466	1151	19	94	232	10
Mesquite (LD)	144	356	8	45	111	2	99	245	10
Cottonwood[2] (HD)	26	64	1	191	472	8	26	64	3
Cottonwood (MD)	106	262	6	51	126	2	130	320	13
Cottonwood (LD)	297	734	16	326	805	13	181	447	19
Riparian Subtotal	**805**	**1988**	**44**	**1079**	**2665**	**44**	**530**	**1309**	**55**
Channel	47	116	2	245	605	10	178	440	18
TOTAL	**1834**	**4530**		**2475**	**6113**		**958**	**2369**	

* see Figure 29 for reach locations

[1] HD = High density; MD = Mid density; LD = Low density
[2] Cottonwood category also includes willows and riparian shrubs

The Duquesne Road site supports a mixture of cottonwood age classes, but the age structure is unhealthy in that very few young trees are present. Most of the trees at this site established due to relatively high water tables resulting from storm events that occurred during the period between the early 1960s and 1980 (Figure 40). Few trees established in the 1980s, despite the occurrence of several large winter floods. The

Figure 40. Profile of Santa Cruz River floodplain at Duquesne Road



scarcity of young trees presumably is a consequence of recent water table declines. Groundwater levels in the late 1980s were lower than levels observed in the 1960s. In addition, few old trees are present in this location, implying that water tables dropped sufficiently low in the past (e.g., to about 6 m [20 ft] below the floodplain in the 1940s) to cause cottonwood stress and death. The few trees greater than 50 years of age that are present are located on abandoned stream meanders adjacent to agricultural fields. Irrigation seepage may have sustained these trees during the period of mid-century groundwater depression.

At the Kino Bridge site, which is located in the same alluvial sub-basin as the Duquesne Road site, water tables similarly rose from the 1940s through 1960s but have steadily declined since that time (Figure 41). The age structure at the Kino Bridge site is unhealthy in that no cottonwood trees older than 10 years were found at the site. All trees currently present established after the 1983 flood, which set up widespread recruitment conditions throughout several areas within the Santa Cruz River floodplain. However, even this cohort is sparsely represented. Tree density and growth rate are very low, and the population is on the verge of being lost. High surface flows in recent decades have no doubt contributed to the survivorship of the few cottonwoods that currently persist in this reach of the river. The sensitivity of Fremont cottonwood to changes in surface flow (and thus to changes in groundwater depth) is apparent in Figure 42, which shows the correlation between surface water flow (measured at the Nogales gage) and annual radial growth of cottonwood located at the Nogales gage, Duquesne Road, and Kino Bridge sites.

Another indication of past subjection to stress and the resulting poor ecological condition at both sites is a relatively high abundance of riparian scrub and a very low abundance of Goodding willows. Apparently, water tables dropped sufficiently low to either preclude willow establishment or cause willow mortality, resulting in a high ratio of Fremont

Figure 41. Profile of Santa Cruz River floodplain at Kino Bridge

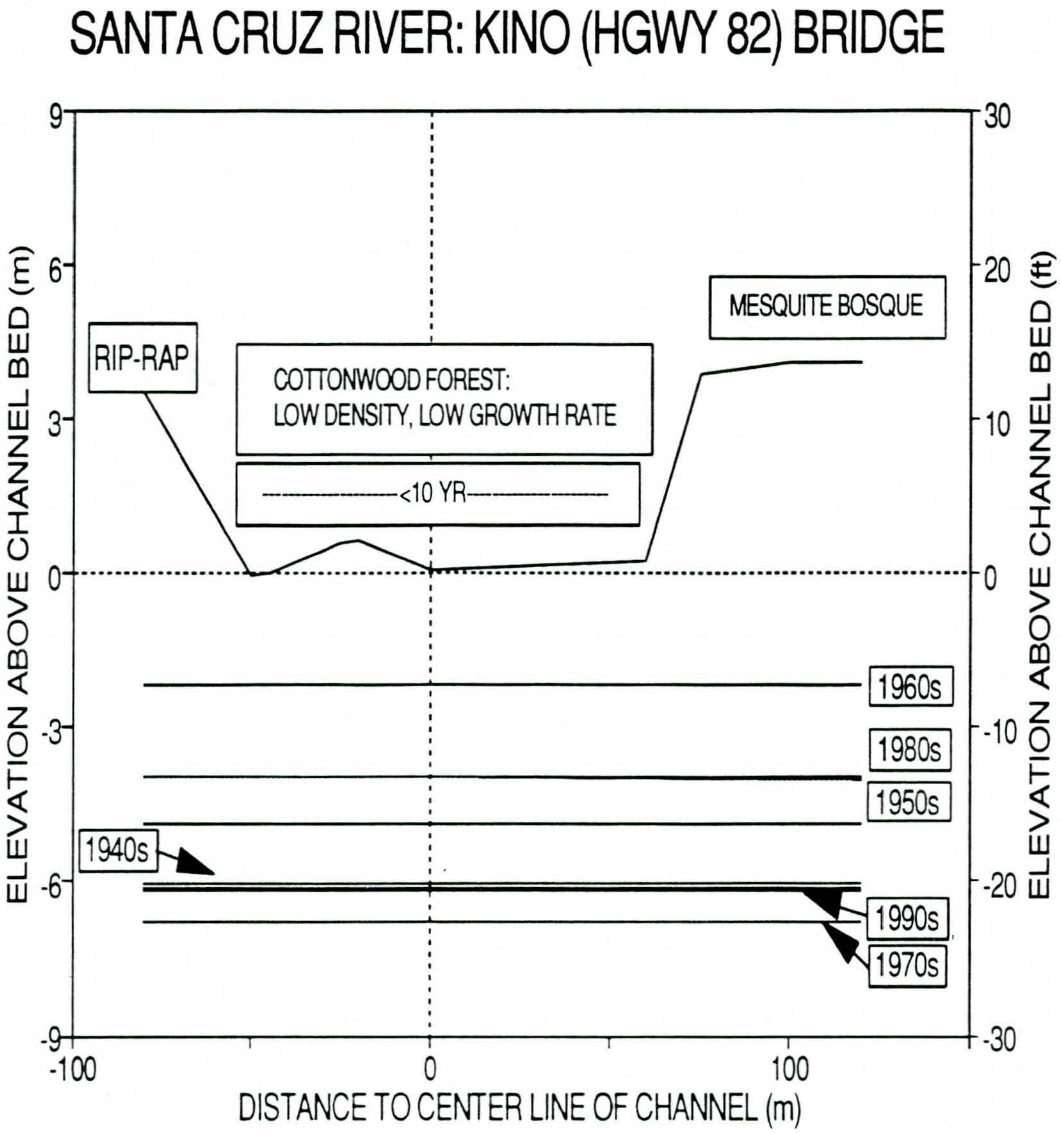
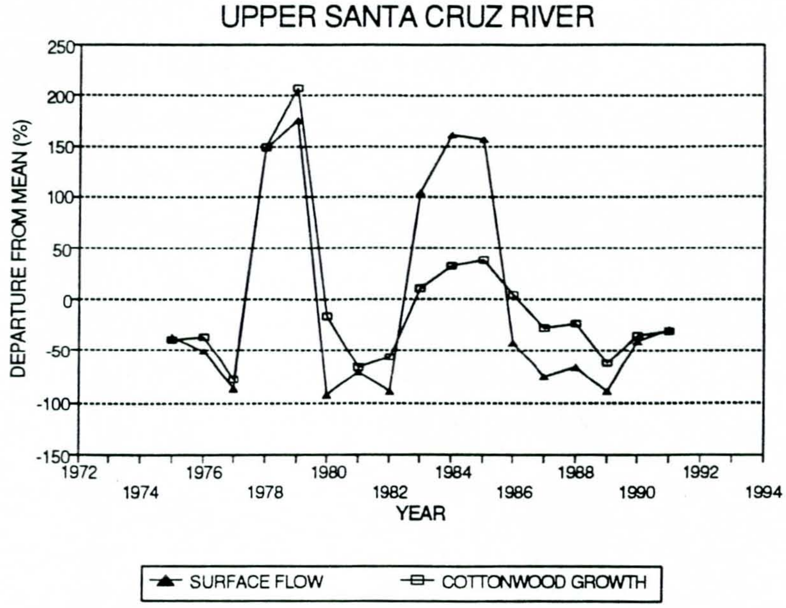


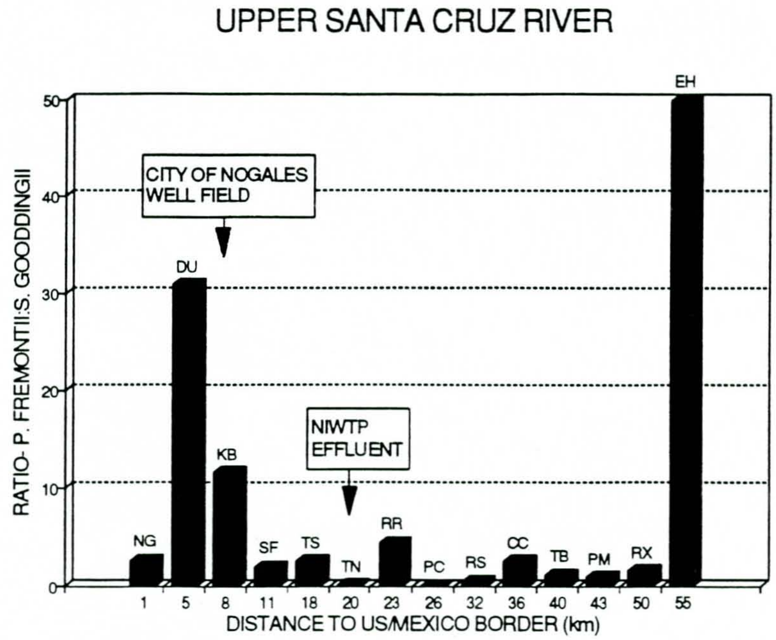
Figure 42. Annual radial growth of Fremont cottonwood in relation to surface flow volume



cottonwood to Goodding willow basal areas (a measure of the amount of the forest floor covered by plant stems of each species)(Figure 43). At the Duquesne site, there is a population of a different species of willow, the yew leaf willow (*Salix taxifolia*). This willow is apparently more drought tolerant than Goodding willow, as implied by the small, needle-like structure of its leaves. Because of its rarity in Arizona and ongoing threats to riparian habitat, it is a species of concern to the U. S. Fish and Wildlife Service (Sue Rutledge, personal communication).

The poor condition of these forest stands in this area is due to high rates of groundwater pumping from alluvial sub-basins near Kino Bridge. More than 8,000 ac-ft of water has been pumped from this area over the past 7 years. Figure 44 displays groundwater volume pumpage zones (as total ac-ft pumped from 1984-1991 per 1 mi^2 section of land), riparian vegetation densities, and locations of narrows or hardrock constrictions where subflow is forced up to or near the ground surface. Groundwater pumpage has caused

Figure 43. Ratio of Freemont cottonwood basal area to Goodding willow basal area



groundwater levels to fluctuate extensively over time (Plate 2, well D(23-14)36bcb1 hydrograph), dropping water tables to threshold levels for Fremont cottonwood-Goodding willow survivorship (5-6 m, or 15-20 ft and more below the floodplain surface). Groundwater level contours, presented in Figure 45, were generated from GWSI data collected in the Kino Bridge area, located immediately downstream of the City of Nogales Highway 82 well field. In areas where groundwater depths are greater than 7 m (25 ft), cottonwoods and willows have been lost.

The future condition of Fremont cottonwood and yew-leaf willow stands in this reach of the river will likely decline with continued, intensive groundwater pumping. In the City of Nogales well field and Kino Springs areas cottonwood-willow forests would continue to decline, while a locally rare species of willow could be lost.

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Figure 44. Groundwater pumpage zones and riparian vegetation densities in Santa Cruz River study area

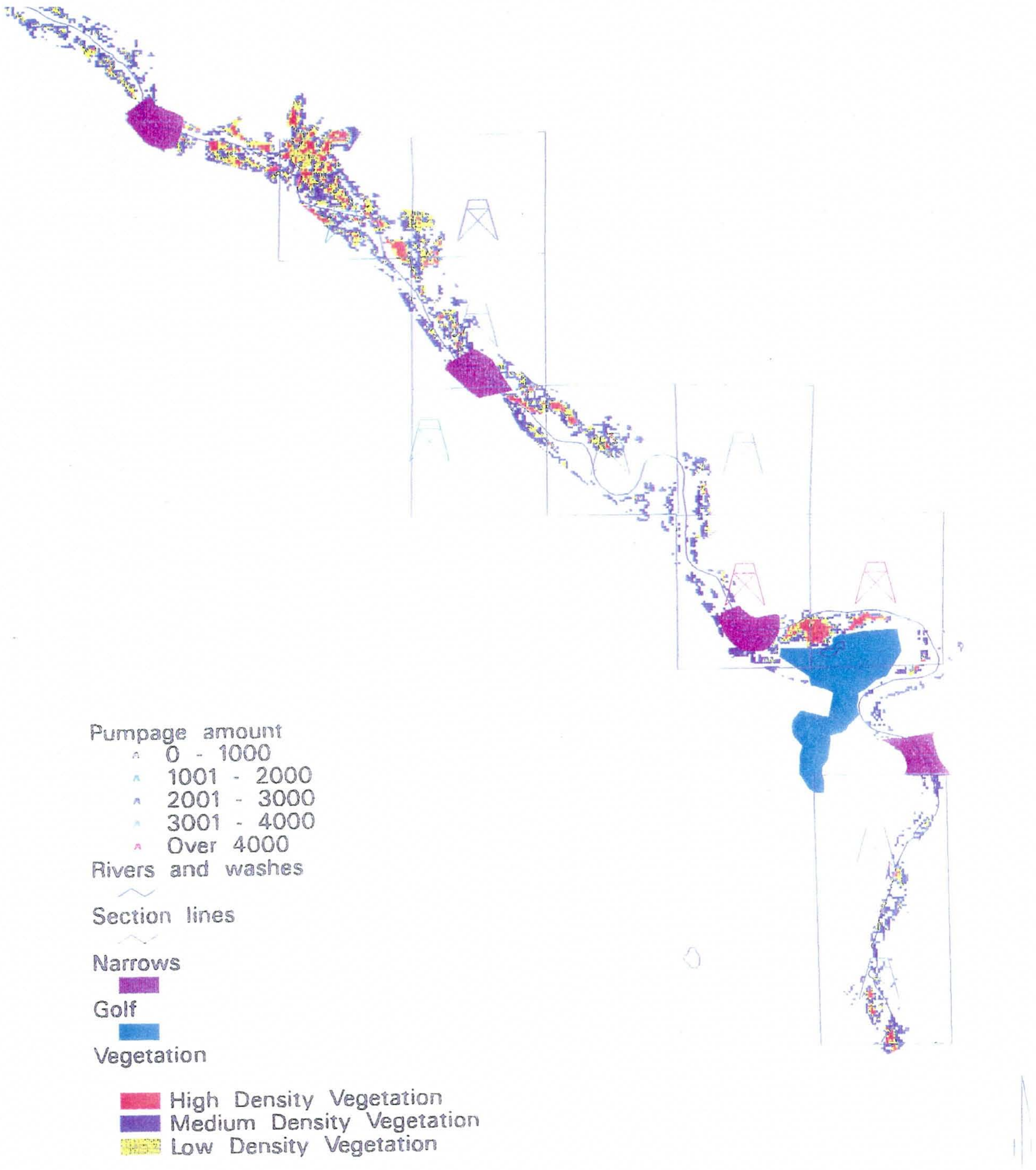

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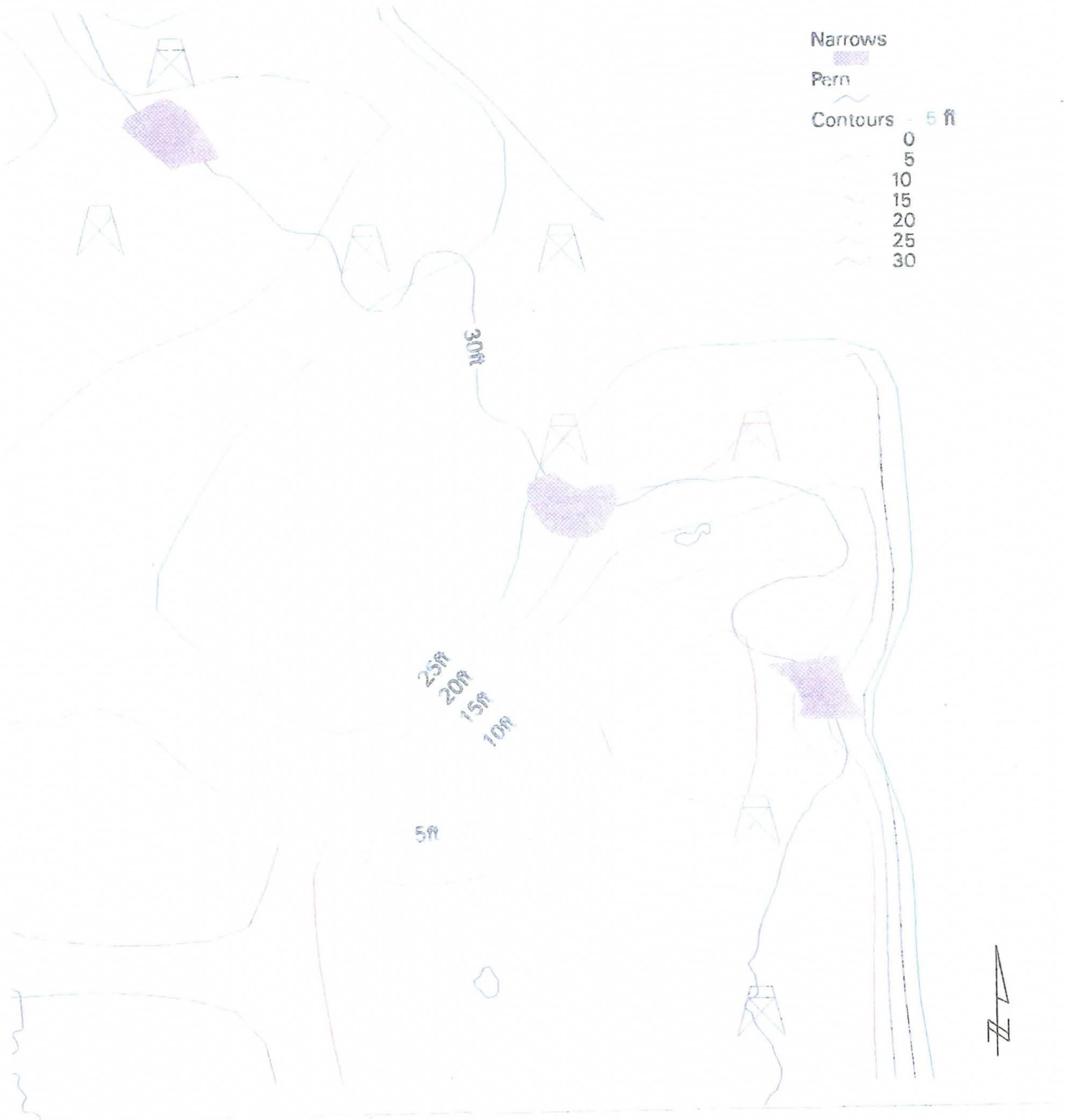
Figure 45. Groundwater contours in the Kino Springs area of the upper Santa Cruz River



Although it is the cumulative effect of multiple wells pumping from the stream alluvium that have caused extensive riparian forest deterioration along this reach, single pumping wells can also inflict impacts. Well pumping simulations, for example, indicate that a single well pumping 750 gpm from the younger alluvium would, after 1 year, cause a 0.3 m (1 ft) decline in the water table in an area 624 ha (1,542 acres) in size, with greater declines in sequentially smaller areas (Table 18). At the Duquesne Road site, where depth to groundwater is presently about 4 m (13 ft), such a well would cause groundwater to drop by another 3 ft (1 m) over an area the size of 31 ha (77 acres). This would cause further declines in forest condition. Parameters, such as canopy foliage area, would decline below its present low value (Figure 38, located approximately 5 km from border). At the Kino Bridge site, a 3 ft (1 m) decline could potentially result in the total loss of cottonwoods on 31 ha. The combination of groundwater pumping and natural declines in available surface water would accelerate the loss of cottonwoods and willow in this reach.

Guevavi Ranch Site

Farther downstream of the City of Nogales Highway 82 well field lies the Guevavi Narrows. This hydrologic constriction, similar to that at the Nogales gage area, forces groundwater to the surface and minimizes groundwater level variability. As a consequence, Fremont cottonwood and Goodding willow stands in this area are in generally good ecological condition (Figure 46). This reach also supports perhaps the greatest abundance of large, old cottonwoods of any reach along the river (Figure 47, area RU). These trees have been maintained by relatively stable groundwater levels. However, although riparian forest density is high in the downstream end of this alluvial sub-basin, areas closer to the Highway 82 pumpage areas support more limited riparian development (Figure 44).

Figure 46. Profile of the Santa Cruz River floodplain near Guevavi Narrows

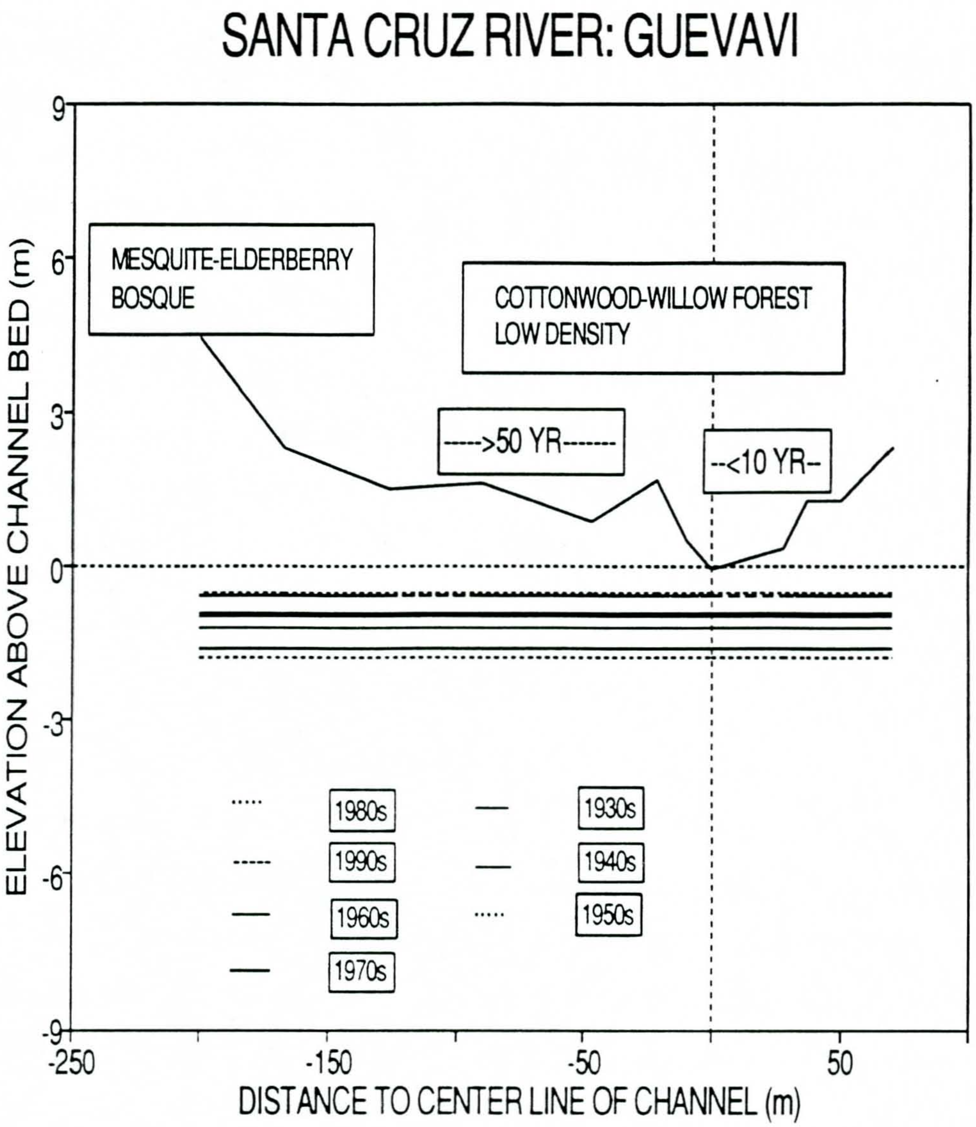


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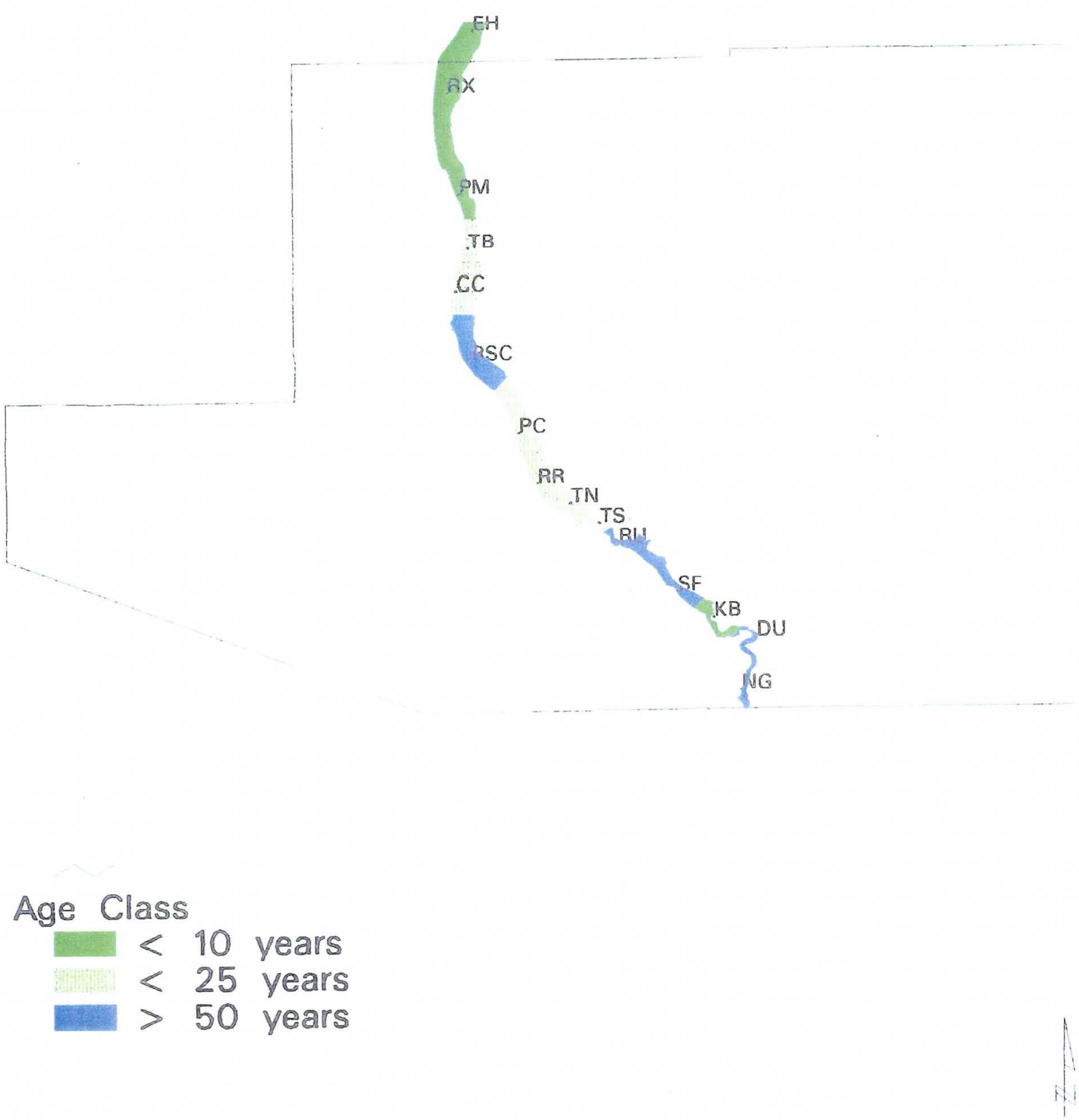
Figure 47. Maximum age of Fremont cottonwood populations within the Santa Cruz River study area



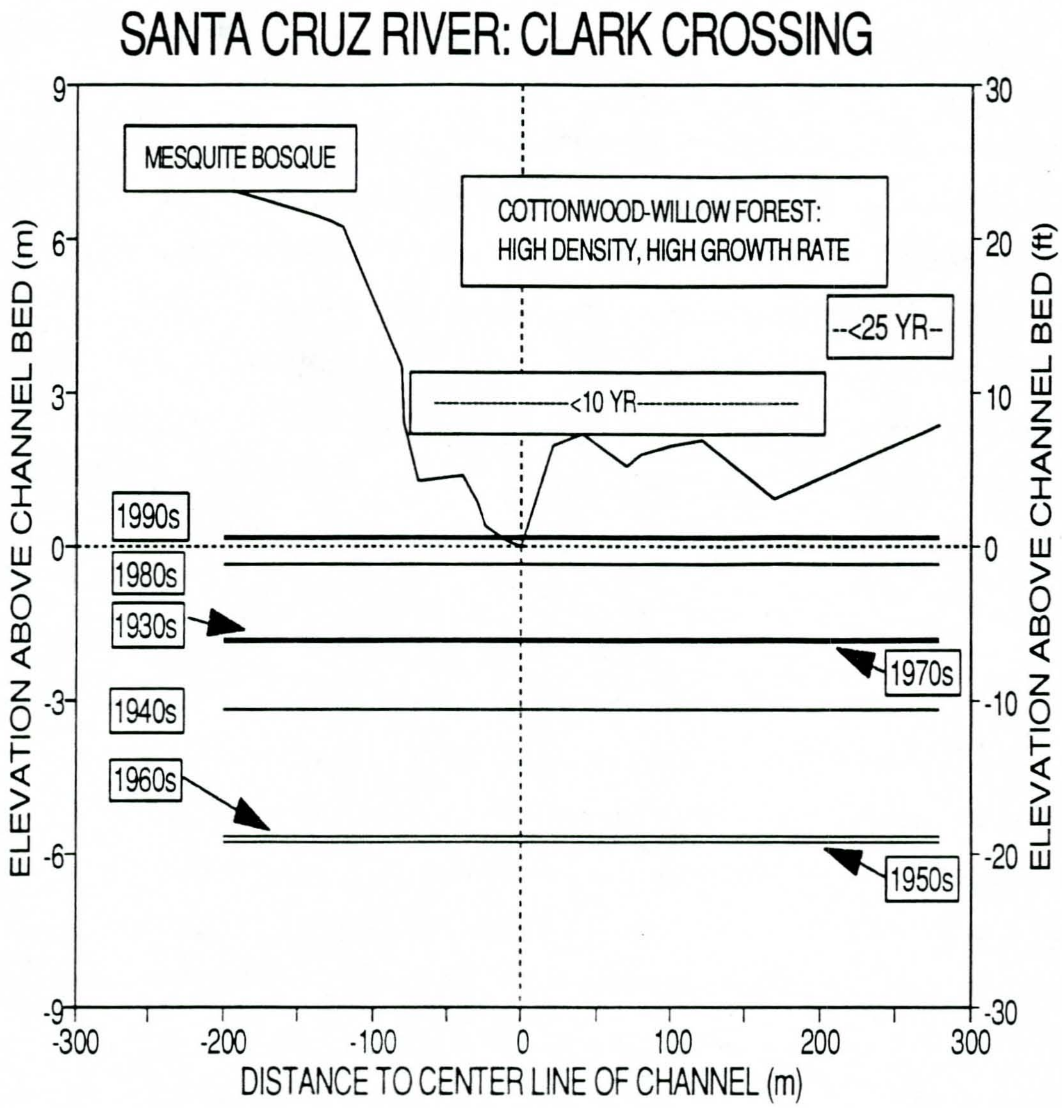
Effluent Dominated Sites

Effluent, together with naturally higher streamflows in recent years, has played a major role in raising water tables and developing extensive, young cottonwood-willow riparian forests downstream of the NIWTP. The reach of the river immediately downstream of the NIWTP supports the largest areas of high-density cottonwood stands (8% of the floodplain) than any other reach of the river (Table 19; and Figures 31 and 34). Most sites downstream of the NIWTP are in relatively good ecological condition, although there are exceptions. The Fremont cottonwood-Goodding willow population near the Rio Rico Bridge, which is the riparian study site located closest to the NIWTP, is in somewhat poor ecological condition as indicated by the low canopy foliage density of the cottonwood-willow stand (Figure 38, approximately 22 km from border). At this site, extensive cattle grazing is prohibiting young stands of cottonwood and willow from growing above browse-height and preventing development of dense tree canopies.

Rancho Santa Cruz and Clark Crossing, located several miles downstream of the NIWTP, are typical of sites in this area, in that groundwater declined between 1940 and 1960 but has been recovering since that period. Currently, groundwater levels at Clark Crossing are within about 2 m (7 ft) of the lower floodplain terrace (Figure 48). As a consequence, Clark Crossing's cottonwood and willow stands are in good ecological condition. Stands in this area are dense, with individual trees displaying high growth rates and substantial canopy foliage areas and lateral widths. Willows and cottonwoods are about equally abundant at this site, while riparian scrub is sparse.

All trees at Clark Crossing are less than 25 years old (Figure 47, area CC). Some trees at this site established after floods in the 1970s, a period when groundwater levels recovered to elevations conducive to cottonwood establishment. The bulk of the trees at this site, however, are less than 10 years old (having established after the 1983 flood). This 10-yr cohort forms a stand that has a lateral width of several hundred feet.

Figure 48. Profile of the Santa Cruz River floodplain near Clark Crossing



Water tables in the 1950s and 1960s were too deep to support cottonwood and willow populations at Clark Crossing (Figure 48). The combination of drought stress (which would severely thin the riparian stand) and subsequent flooding eliminated any mature cottonwoods that may have been present at this time (Applegate, 1981).

A site upstream of Clark Crossing, Rancho Santa Cruz supports similar extensive stands of young (<10-yr) cottonwoods, and trees that are relatively old (>50 yrs) (Figure 47, area RSC). The few older trees at this site may have been maintained during the groundwater decline by agricultural return flows, similar to patterns seen at some other sites. Many trees near Rancho Santa Cruz, however, are infested with a species of wood-boring beetle and other insectivorous herbivores which are causing the decline and death of some cottonwood and willow stands. It is unknown if these outbreaks are related to effluent release as it influences water quality (nutrient availability, salinity, etc.) and/or water quantity and seasonal flow patterns. Outbreaks of this beetle have occurred in the past, but little is known about the ecology of the beetle or its interaction with cottonwood populations.

The long-term trend for this reach of the river should be positive, despite any short-term decline resulting from the current infestation. Naturally occurring tree/herbivorous insect interactions, and potential interaction changes due to effluent releases to the system, need further study. Effluent release allows for increased riparian vegetation abundance, however, ecosystem response to these releases (e.g., reduction of seasonal streamflow variation, increase in nutrient concentrations) should be closely monitored.

County Line Sites

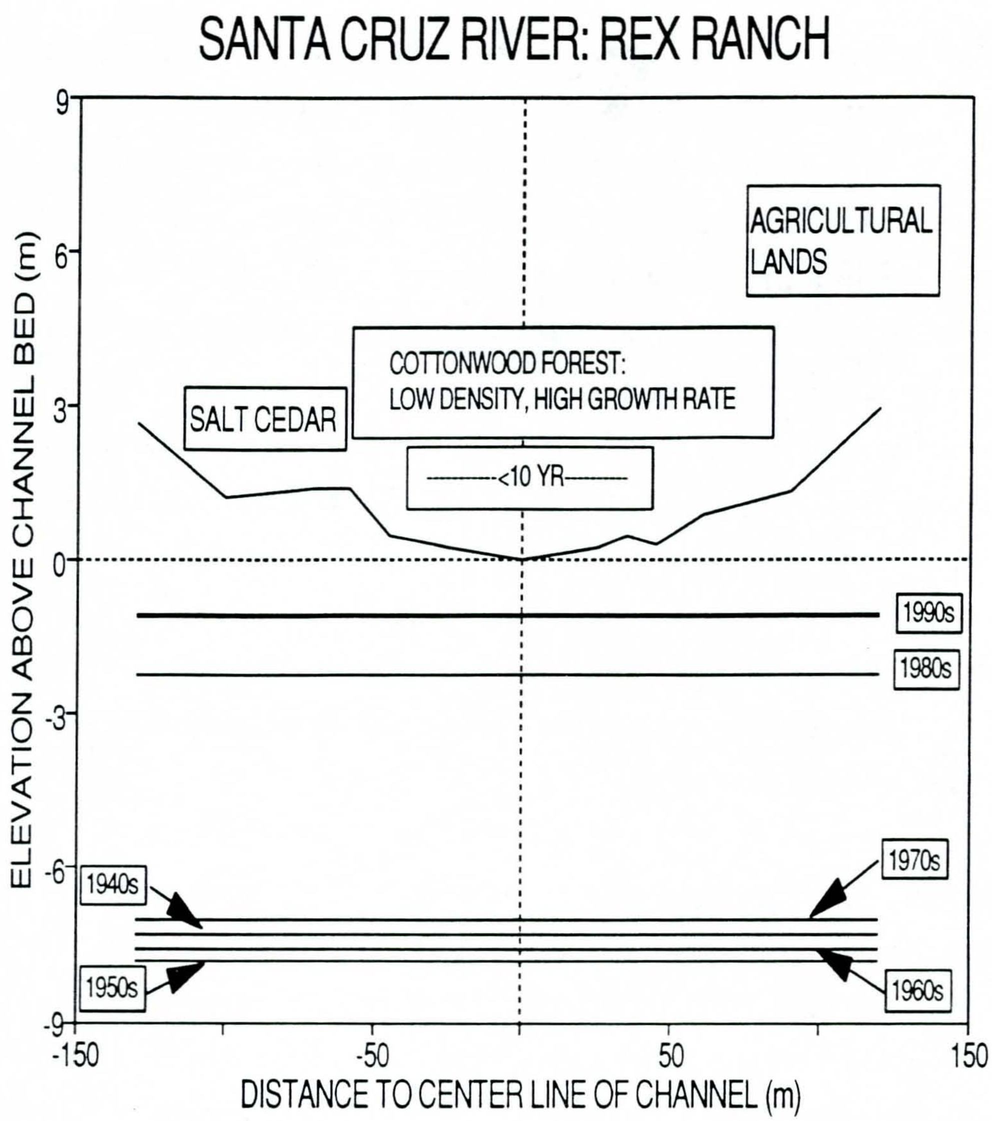
The three sites include the PM Ranch, Rex Ranch, and Elephant Head (Figure 29). Riparian vegetation becomes less dense with increasing distance downstream from the NIWTP (Figures 30 and 33). Riparian basal area peaks in abundance about 15 km (9 mi) downstream of the NIWTP, declines rapidly as perennial base flows cease, and falls nearly to zero at the Pima County line where groundwater levels are deep (Stromberg and others, 1993).

The ecological condition of the cottonwood populations in these areas scores low by some measures but high by others. For example, at the Rex Ranch site, cottonwood growth rates are very high but canopy density and stand density are low (Figure 49). Occurrence of Goodding willow is relatively infrequent at this site in comparison to Fremont cottonwood (Figure 43, column RX). The exotic tree salt cedar (*Tamarix chinensis*), although having relatively low abundance on the upper Santa Cruz River, attains its greatest abundance in these County line sites where flows are not perennial. All cottonwood trees that were aged in this part of the river were less than 10 years old (Figure 47, areas PM, RX, and EH).

Changes in groundwater levels over time explain these phenomena. Groundwater levels in the 1950s through the 1970s were deeper than 7 m (23 ft) below the floodplain surface, depths that are beyond the range needed for establishment or survivorship of cottonwood populations. Not until the 1980s did water tables rise to levels conducive for cottonwood survivorship. Although streamflow is not perennial along this reach, groundwater is sufficiently shallow to allow for cottonwood establishment and high growth rates.

The trend for riparian vegetation in this reach of this river is positive. If effluent release continues and groundwater levels continue to rise, conditions should remain good for riparian forest regeneration. Effluent release, in combination with above average (climatically-driven) river flows, has raised groundwater levels and allowed the cottonwood-willow forest to expand farther downstream. These cottonwood forests are expanding into an area that historically (i.e., in the mid 1800s) supported mesquite

Figure 49. Profile of Santa Cruz River floodplain surface at Rex Ranch site



bosques interspersed with small cottonwood stands (Davis, 1982; Betancourt and Turner, 1993).

River flows fluctuate over time, therefore groundwater levels could stabilize or decline in these northern study area reaches with the return of drought conditions. Positive trends could be impacted by future recharge projects which would permit the "recapture" of recharge credits by an applicant. Other negative impacts could occur if effluent was directly re-used or a decrease in effluent releases occurs. Although groundwater levels are currently high, groundwater pumping still has potential ecological impacts. Simulation of well pumping impacts indicates that a single well pumping 1,000 gpm from the younger alluvium would, after 1 year, result in a 1 m (3 ft) decline in the water table in an area the size of 80 ha (197 acres) (Table 18). At the Rex Ranch site (Figure 49), this would cause groundwater underlying the higher floodplains, vegetated by a mixture of salt cedar, Fremont cottonwood, and very sparse Goodding willow, to decline from about 2.8 m (9 ft) to 3.8 m (12 ft). This would have the potential to cause the few Goodding willow present in the area to lose vigor, making the area more susceptible to invasion by salt cedar, disease, and/or parasites.

Gains made by riparian vegetation in the young, open stands located near the Santa Cruz/Pima County line, however, are occurring at the expense of older stands upstream of the NIWTP. Water extracted from well fields in the alluvium along the upper reaches of the Santa Cruz River is used, treated, and then returned to the river downstream as effluent, routing water from the groundwater/surface water system for about 6-8 miles between the point of groundwater withdrawals and the effluent discharge site.

Southern Pima County

Cottonwood populations, as well as other obligate riparian species, are nonexistent in southern Pima County, due to excessively deep groundwater tables that preclude any obligate riparian vegetation. Water tables in the Green Valley area declined, primarily during the middle part of this century, due to groundwater pumping for mining and agriculture. Both of these activities are ongoing. Historically, cottonwoods were not abundant in this reach, although cienegas and cottonwood-willow forests were found in localized areas where groundwater flowed above the ground surface (e.g., at San Xavier). Today, most of the floodplain supports pecan groves or land sparsely vegetated with desert broom (*Baccharis sarothroides*), burro weed (*Isocoma tenuisecta*), burro brush (*Hymenoclea* spp.), and other types of limited value riparian scrub.

Sacaton Grasslands

Giant sacaton grasslands were historically abundant along the higher elevation floodplains of the upper Santa Cruz River and other streams in southern Arizona (Humphrey, 1958). Today, these riparian grasslands are essentially nonexistent within the Santa Cruz River floodplain (with the exception of a few scattered plants). Loss of sacaton is also due, in large part, to floodplain clearing for agriculture. Past groundwater declines, that extended below sacaton's tolerance range, may have provided an additional factor.

Similar to velvet mesquite, giant sacaton produces shallow lateral roots as well as deep roots that proliferate in the fine textured soil of the high floodplain terraces. These roots absorb water located immediately above the water table and surface water obtained from rain and occasional overbank flooding. Unlike velvet mesquite, however, giant sacaton does not tolerate deeper groundwater levels. Meinzer (1927) indicated that extensive stands of a second species of sacaton, alkali sacaton, grew where groundwater was up to 8 m (25 ft) below the surface, but stated that most luxuriant growth occurred at water table depths of 2 to 5 m (5 to 15 ft). On the nearby San Pedro river, sacaton currently forms extensive stands where depth to groundwater is about 3 to 5 m (10 to 15 ft) (see San Pedro River case study).

Groundwater tables declined to very low levels along the upper Santa Cruz River during the 1940s and 1950s. During this period depth to water underlying many floodplain terraces was greater than 10 m (33 ft), beyond the normal range for sacaton and on the low end of the tolerance range for riparian mesquite (Figures 37, 40, 41, 46, 48, and 49). This may have caused the loss of any sacaton that persisted along the floodplain at this time. Sacaton grasslands could also have succumbed during an earlier period of water table decline that occurred near the turn of the century. Farther downstream along the Santa Cruz River, for example, Bryan (1928) noted that the sacaton grass covering the Santa Cruz valley near Tucson disappeared when arroyo cutting began in the 1800s causing the channel to drop more than 5 m (15 ft) below the floodplain surface.

Today, effluent elevated groundwater levels in the stream alluvium, located downstream of the NIWTP discharge site, have created conditions that could potentially allow sacaton grass restoration. However, conditions required for natural sacaton establishment are poorly understood. There is some indication that sacaton may establish in the understory of mature cottonwood forests, as a result of floodplain habitat modification by cottonwoods (e.g., improved soil structure, and increased moisture holding capacity). The current lack of significant sacaton re-establishment along the river may be a reflection of the young age of most cottonwood forests along many areas of the Santa Cruz River (see next section).

Mesquite Bosques

In contrast to cienegas, which grow in perennially wet soils and are highly sensitive to groundwater decline, mesquite bosques grow on higher elevation floodplains in the riparian zone and are least sensitive to groundwater decline. The high floodplain forests of the Santa Cruz River, although dominated by velvet mesquite, also contain significant pockets of netleaf hackberry and Mexican elder (a species which is absent from the nearby San Pedro River drainage). Old, mature Fremont cottonwoods that are occasionally present in these bosques, testifies to the fact that this vegetation-type occurs on relatively old, stabilized floodplains. Cottonwood-willow forests, in contrast, grow in abundance on dynamic, lower floodplain areas (see Fremont cottonwood-Goodding willow forest section).

Historically, mesquite bosques probably occupied the greatest area of any riparian forest type along the Santa Cruz River, as was the case for most southern Arizona rivers that flowed through wide, low gradient, alluvial valleys (Lacey and others, 1975). This is because mesquite has a wide tolerance for depth-to-groundwater (e.g., about 3 to 15 m, or 10 to 50 ft) and, therefore, can extend laterally away from the river for great distances. As floodplain terraces gradually slope higher above the water table, the height, foliage density, and density of mesquite communities declines. In areas of the Santa Cruz River where flow was perennial and water tables were shallow, mesquite bosques co-dominated with cottonwood and willow in the floodplain. With increasing distance downstream along the Santa Cruz River, mesquite bosques and sacaton grasslands replaced the Fremont cottonwood-Goodding willow associations on the low floodplains, as perennial flows and shallow water tables gave way to ephemeral flows and declining water tables.

Today, Mesquite-hackberry-elderberry bosques are generally restricted to narrow areas at the perimeter of the Santa Cruz River floodplain, although a few places support moderately large mesquite stands (e.g., the City of Nogales' newly developed Calabasas Park). Loss of mesquite bosques along the upper Santa Cruz River is due primarily to clearing high floodplain terraces for agriculture. Because mesquite fertilize the soil by adding nitrogen and trapping sediment from occasional flood waters, the soil associated with bosques is well suited for agriculture. Shallow water tables and the relatively low risk of flooding adds to their desirability as agricultural sites.

Much of the mesquite bosque to agricultural land conversions occurred along the river downstream of the NIWTP discharge site, where the floodplain widens and the channel gradient is low (Figures 30, 31, 33, and 34; Figure 29 displays subset locations). From the NIWTP to the Santa Cruz/Pima County line, about 40% of the floodplain area is in agriculture, while another 5% is used for residential or industrial purposes. A relatively large percentage of the agricultural acreage presented in Table 19 is now fallow or abandoned. In 1973 less than 1% of land in agricultural use was inactive, either fallow or retired, while in 1990, 44% of agricultural lands were inactive or fallow. In some cases riparian vegetation, primarily young mesquite stands, are re-establishing these fields.

On the lower reaches of the Santa Cruz River (i.e., in Pima County), water table decline has been a major cause of destruction of mesquite bosques (Betancourt and Turner, 1993). Riparian mesquite and sacaton grasslands historically supported by subflows that extended from north of Tubac to Tucson are, for the most part, no longer present (Humphrey, 1958). Farther downstream, bosques along the Santa Cruz River near Tucson described by Swarth (1905) as covering " ... miles in extent, with a thick growth of giant mesquite trees, ... many of them sixty feet high and over..." were lost to groundwater decline associated with arroyo cutting. Until a few decades ago, an extensive mesquite bosque, locally known as the New York Thicket, persisted near the confluence of the Santa Cruz and Gila Rivers and three major washes (Vekol, Green, and Santa Rosa). In the late 1930s this bosque was described as being up to 10 km (6 miles) wide with mesquite and screwbean mesquite (*Prosopis pubescens*) reaching heights of up to about 12 m (40 ft) (Neff, 1940). Rea (1983) reported about 90% mortality of the mesquite in the late 1970s when the groundwater table had fallen to about 33 m (100 ft) as a result of groundwater pumping. Mesquite have deep roots and tolerate some water stress, but lowering of water tables below about 15 m (50 ft) results in death of riparian mesquite trees or in conversion of mesquite from a dense tree-form community to a sparse shrub-form community (Cannon, 1913).

Groundwater declines along the upper Santa Cruz River in the 1950s and 1960s contributed to declines in mesquite vigor and death of mesquite located along the floodplain fringes, however floodplain clearing has also assisted in the wholesale loss of mesquite bosques. Presently, lowered water tables in groundwater-depleted reaches upstream of the NIWTP may also be reducing mesquite vigor. Conversely, raised water tables in the NIWTP-influenced reach may be enhancing growth of mesquite and hastening riparian recovery in fallow fields.

DISCUSSION

Effluent Discharge

Municipal water is increasingly being treated and discharged to river systems as effluent. Reuse of effluent, which is being considered by many municipalities as an alternative to meeting more stringent federal water quality standards, can result in decline or elimination of riparian vegetation (Jones and Snyder, 1984). Potential impacts would be great because of the large number of riparian systems either partially or totally dependent upon this source of water (Tellman, 1992).

Although riparian vegetation along many of the state's effluent-dominated river reaches owes its existence to availability of these discharges, there are unanswered questions regarding the impacts of effluent release to riparian ecosystems (Stromberg, Sommerfeld and others, 1993; Tellman, 1992). For example, although effluent can restore streamflows, raise water tables, and minimize impacts of groundwater pumpage or flow diversion, it can also dampen natural fluctuations in flow volume and modify water quality by increasing nutrient content, salinity, or concentrations of pollutants (e.g., heavy metals). This raises several questions, such as, are there pollutant loading rates above which biotic community structure and function are degraded? What is the role of biota in reducing downstream nutrient and pollutant concentrations to levels in accordance with Federal Clean Water Act standards? How do the potential ecological consequences of pollutant or nutrient loading compare to the consequences of water reduction caused by removing effluent from the streambed? What role does riparian vegetation play in enhancing percolation of effluent into an aquifer? It is known that fast-growing trees, such as Fremont cottonwood, have a high capacity for nutrient uptake (Karpiscak and others, 1993) and may be playing a substantial role in assisting to reduce nutrient loads to ambient water level concentrations in the upper Santa Cruz River (Stromberg, Sommerfeld and others, 1993). Heavy metals present in effluent are also taken up by riparian vegetation (Sullivan, 1991). Ecological effects of added nutrient or pollutant load, however, needs further study. The greatest concern may lie with species (e.g., birds) that feed higher on the food chain and could suffer adverse effects from biomagnification of toxic materials.

Effluent release essentially involves the recycling of river water. In the case of the upper Santa Cruz River, water is removed from the stream alluvium upstream of the effluent discharge site, and returned to the river farther downstream as effluent. While effluent presents positive for riparian ecosystems downstream of the discharge site, the initial removal of water from the aquifer poses negative consequences for the upstream riparian ecosystem.

Remote Sensing and Ground-Based Ecological Studies

Several important tools can be used to detect riparian stress and assess changes resulting from groundwater decline or surface flow alteration. Remotely sensed data, such as satellite imagery or aerial photographs, is useful for detecting riparian vegetation changes over large geographic areas. Several meteorological satellites provide data that are useful for natural resource applications. The National Oceanic and Atmospheric Administration (NOAA) series of satellites contains an Advanced Very High Resolution Radiometer (AVHRR). The AVHRR data has been very useful for monitoring large areas of vegetation. Two vegetation indices, the simple vegetation index (VI) and the normalized vegetation index (NVI), have been calculated from AVHRR data. The indices utilize a visible band and a near-infrared band to determine the presence of green vegetation (Lillesand and Kiefer, 1987). Remotely sensed images allow detection of areas of low riparian vegetation density or, when refined properly, detection of declines or increases in specific plant species, such as salt cedar (Everitt and DeLoach, 1990). These images also provide an important tool that can be used to track changes over time and detect upward or downward trends in riparian vegetation abundance or composition.

Infrared aerial photographs, another type of remotely sensed data, can provide information relating to stress detection in plants and can detect "hot spots" or areas that are undergoing riparian decline. This method has traditionally been used for agricultural crop applications, for example, cornleaf blight, potato wilt, sugarbeet leaf spot, and steam rust of wheat and oats, have been detected using aerial photograph interpretation. Insect damage caused by aphids, red mites, fire ants, harvester ants, army worms, and grasshoppers as well as moisture stress, iron deficiency, nitrogen deficiency, excessive soil salinity, wind and water erosion, rodent activity, road salts, air pollution, and cultivator damage have also been detected using this method.

Remote sensing, to examine riparian vegetation plant stress, can also be performed using laboratory spectrophotometry. This technique provides a method for measuring vegetation spectral reflectance under controlled conditions (Jackson and Ball, 1993). Spectrophotometry can also be used to measure spectral reflectance in the field, with the advent of hand-held field instruments. Plant stress may manifest itself in many ways including changes in water potential, leaf water content, stomatal conductance, transpiration, photosynthesis, or chlorophyll/pigment changes. Spectral reflectance for riparian plant canopies and leaves are determined by their geometry, chlorophyll content, and pigments. Spectral reflectance data received from satellite remote sensing, in theory, could be used to detect stress in riparian vegetation.

Ground-based studies of ecological response to groundwater or surface water changes is an important adjunct to remotely sensed data. These studies allow examination of impacts to riparian vegetation with greater detail, and determination of species requirements and tolerances to hydrologic conditions. Ecological field studies of plant populations and their water requirements can be used to determine hydrologic conditions that must be met to restore degraded areas or to maintain healthy ones in good ecological condition.

SUMMARY AND CONCLUSIONS

Hydrologic Systems

Groundwater levels in the study area declined during the mid 1940s through the early 1960s, and have been recovering in most areas since that time. In the mid 1960s a wet cycle began initiating water level recovery, despite increased groundwater pumping from approximately 1960 to 1970. Since 1980 groundwater withdrawals, particularly those associated with irrigation use, began to decrease, further assisting groundwater level recovery. Effluent discharge from the NIWTP has been primarily responsible for raising groundwater levels located downstream of its discharge site to approximately the county line. Locations within the study area, continuing to display declining groundwater levels, are located in the City of Nogales well field area near the Kino Springs (Highway 82) Bridge, and in the Continental area, where significant agricultural withdrawals continue to occur.

The reach of the Santa Cruz River, located upstream of the NIWTP, is composed of four sub-basin areas separated by geologic constrictions. Groundwater storage, and consequently pumpage, in these sub-basins is limited. These areas experience rapid drawdown and rapid refill when adequate surface flow is available and groundwater pumpage does not exceed individual sub-basin storage and refill capabilities. Surface water flow in this reach is primarily limited to the geologically constricted channel areas where natural rock barriers force water to the surface.

Downstream of the NIWTP the upper Santa Cruz River valley widens and the basin fill deepens. Along this reach of the river groundwater levels and surface water flows are augmented by effluent releases. In the Santa Cruz/Pima County line area the basin widens and deepens significantly and surface water flows become ephemeral. At this point, the surface water/groundwater system disconnects and groundwater flow slightly angles away from the river channel toward a cone of depression located near Sahuarita.

The Santa Cruz River study area is located within the Tucson AMA. Therefore, substantial groundwater withdrawal information was available for the project. However, because the Santa Cruz River watershed has not been adjudicated, the accuracy of claimed and certified water rights have not been verified. In addition, adequate surface water flow and groundwater level information was not available for some river reaches. This occurred because long-term surface water flow data is not collected between the Nogales and Continental streamgage sites and along major tributaries, and monitor wells, specifically designed to evaluate riparian area groundwater levels, are not present in the study area.

Riparian Vegetation

The riparian forests of the upper Santa Cruz River differ in ecological condition due to differences in water and land use practices throughout the river. Groundwater declines of the 1950s and 1960s caused loss of riparian forests along much of the Santa Cruz River. Effluent discharge, together with above average streamflows and flood flows in recent decades, has allowed for re-establishment of a large, young Fremont cottonwood-Goodding willow forest that has been extending farther downstream as water tables continue to rise. These riparian gains, however, are at the expense of older cottonwood-willow forests located upstream of the NIWTP. Groundwater withdrawals upstream of the

NIWTP, water which serves as a primary source for the effluent, are degrading existing mature cottonwood and willow stands. Degradation is apparent in the low growth rates, canopy covers, total stand densities, and densities of young trees and the greater relative abundance of cottonwoods vs. willows in the stands. All of these changes have consequences for wildlife. For example, although expansion of riparian forests with dense canopies is beneficial to bird species, loss of mature cottonwood trees has negative consequences for species that require large, old trees with hollow nesting cavities. Loss of willows affects species that may nest in cottonwood, but require willow stands for foraging.

Most of the cienegas along the Santa Cruz River were lost due to groundwater declines that occurred at the turn of the century and again in the 1940s to 1960s. There is much potential for their recovery, however, driven by effluent-related groundwater level recovery downstream of the NIWTP. Currently, some wetland plant redevelopment is occurring downstream of the NIWTP. Wetland vegetation also occurs upstream of the NIWTP but is limited to areas where shallow bedrock maintains high, stable water tables.

Riparian forests of the high floodplain terrace, composed of mesquite, hackberry, and elderberry, have been significantly reduced due to extensive floodplain clearing for agriculture. Mesquite is recovering as agricultural lands are abandoned, but the potential for such land to remain fallow for the 200 plus years required for young mesquite to develop into a mature forest is unknown.

Sacaton grasslands have been essentially eliminated from the Santa Cruz River floodplain as a result of groundwater decline and floodplain clearing. Their recovery potential has been enhanced by effluent release and water table recovery, but recovery may not occur until existing, young cottonwood-willow stands have matured.

If groundwater pumpage from the floodplain aquifer continues at equal or higher rates upstream of the NIWTP, riparian forests in that location will continue to deteriorate. Loss would be accelerated during drought periods. If effluent release continues at equal to or higher than current discharge rates, cottonwood-willow forests downstream of the NIWTP will continue to expand farther downstream, fallow fields will continue to recover to mesquite bosque, and wetland vegetation will be enhanced. If effluent releases are discontinued, or if groundwater pumpage is increased to recapture effluent recharge credits, riparian gains in this reach will be lost.

CONSIDERATIONS FOR RIPARIAN PROTECTION

To maintain and improve the ecological condition of the riparian ecosystems along the upper Santa Cruz River, several actions should be considered. The following list is not intended to be comprehensive. Rather, it should provide a starting point for further discussion and evaluations.

- Depth-to-groundwater monitoring programs should be initiated at several sites along the river supporting riparian vegetation-types of concern. These programs should include installation of monitoring wells equipped with continuous water level recording devices in riparian zones.
- Surface water diversions should be quantified and actively managed so that permitted diversion volumes are not exceeded.
- The streamflow monitoring network should be upgraded and additional gages installed; upstream of Continental, on Nogales Wash, and re-installed on Sonoita Creek (above and below the dam).
- A quantitative scoring system should be developed that would assess the ecological condition of cottonwood-willow populations based on such attributes as canopy foliage density, age class diversity, and the relative abundance of cottonwood to willow trees.

- To prevent deterioration of Fremont cottonwood-Goodding willow stands, groundwater depths should not fall below the optimum for this forest type (about 2 to 3 m, or 7 to 10 ft below the floodplain), and particularly to depths that approach threshold ranges for Fremont cottonwood-Goodding willow forest survivorship (5 to 6 m, or 15 to 20 ft and more below the floodplain surface).
- To prevent deterioration and loss of wetland vegetation groundwater levels should not decline below the channel surface (i.e., when perennial flows cease).
- To minimize adverse impacts to the riparian zone, groundwater pumping could be: transferred from the floodplain aquifer to the regional basin-fill aquifer; reduced or eliminated from the portion of the floodplain aquifer not being recharged by effluent; and could be eliminated from river reaches that presently do not flow perennially or where associated groundwater tables are presently declining.
- Effluent should continue to be released, with investigation of the possibility of releasing wastewater in a manner that simulates natural seasonal flow patterns (high spring flows followed by lower mid-summer flows). In addition, the effluent release site should ideally be located closer to the area where its groundwater source is withdrawn.
- Surface water and groundwater quality should continue to be monitored.

VERDE RIVER CASE STUDY

INTRODUCTION

The Verde River is one of the major perennial rivers in central Arizona. It is a 170-mile ribbon of green marshes, canyons, and water-dependent woodlands that joins the Salt River upstream of Phoenix. The upper Verde River area is located about 100 miles north of Phoenix near the communities of Camp Verde and Cottonwood. It is within the Central Highlands physiographic province, a mountainous region that marks the transition between the Basin and Range Lowlands to the southwest and the uplifted Plateau Uplands to the northeast. The area of primary interest to this study is located within the Verde Valley basin which occupies approximately 2,600 square miles of the upper Verde River valley, and is bounded by the Mogollon Rim to the north and the Black Hills to the southwest (see Figure 1 in Chapter II; Plate 3 in map pocket). The portion of the Verde Valley within the study area is approximately 10 miles wide and 50 miles long and trends northwest along the southern edge of the Colorado Plateau. Elevations in the area range from 9,256 feet above sea level at Bill Williams Mountain to 2,976 feet at Beasley Flat south of Camp Verde.

The lower reaches of the Verde River are regulated by dams (e.g., Bartlett and Horseshoe Dams), and riparian vegetation in this reach is in poor ecological condition. The vegetation in these areas, dominated by Fremont cottonwood, Goodding willow, mesquite, and riparian shrublands, has been stressed by periodic low flow releases from these dams as well as by altered flood flow patterns and sediment content resulting from river damming. Groundwater pumping also poses a potential threat to the lower Verde River in areas such as the rapidly urbanizing Rio Verde area and farther downstream near the City of Phoenix's well fields. Floodplain clearing for agriculture also is a continuing threat. Mesquite bosques on the Fort McDowell Indian Reservation, for example, are being converted to irrigated agricultural fields due to recent Federal water rights settlements which increased the quantity of water available to the Reservation.

In the Verde Valley, activities which are of greatest concern include "sand and gravel mining, residential and commercial development, flood control, bank stabilization and agricultural diversions" (US Fish and Wildlife Service, 1991:13). Much of the floodplain has been converted to agricultural fields, a typical pattern for most of Arizona's larger perennial rivers. Floodplain agriculture consumes much water, as does the increasing urban population along the river. In addition to the numerous existing surface water diversions, some water use models project a streamflow reduction of several thousand additional acre-feet per year in the near future (Moore, 1989; Arizona Dept. of Water Resources, 1993). Existing and new diversions of surface water and groundwater pumpage from alluvial aquifers poses a threat to the Verde River riparian zone.

The upper Verde River was selected as a case study area because of the extent the river is presently affected by surface water diversions, and the potential for future groundwater withdrawals to supply increasing development. The population of the Verde Valley nearly doubled during the 1980's, from 16,865 people in 1980 to 31,805 by the end of the decade. During the same period, the towns of Camp Verde, Clarkdale, and Cottonwood exhibited population increases of 63, 42, and 30 percent respectively (Arizona State Parks, 1991; Arizona Department of Economic Security, 1991). Additionally, the Verde Valley area provides an example of an intermontaine alluvial valley that differs from large alluvial basins in the Basin and Range lowlands of southern Arizona (e.g., San Pedro and Santa Cruz River study areas). The Verde River has been widely acknowledged as an ecologically critical area and is in the initial stages of study and planning by State and Federal natural resources agencies and local citizens groups.

The objectives of the Verde River case study were to: (1) characterize the hydrogeology of the upper Verde River area, (2) present instream flow models that show relationships between riparian vegetation abundance (e.g., canopy foliage density, woody plant cover, and abundance of particular plant species) and surface flow rate, (3) compare instream flow models between the Verde River watershed and other Arizona watersheds (San

Pedro and Santa Cruz) to determine to what extent the models are transferable between regions, and (4) apply the instream flow models to predict changes in riparian vegetation abundance resulting from increased surface flow diversion or groundwater pumping.

DESCRIPTION OF THE AREA

Local Climate

The Verde Valley has a mild, semiarid climate, an attribute that is largely responsible for the rapidly increasing population of the area. Elevations along the river in the study area range from 3,500 feet at Clarkdale to 3,300 feet at Camp Verde. Average annual temperature is 62 degrees at Cottonwood. The frost free period typically occurs between March and November when the minimum monthly temperatures are above 32 degrees. The growing season for irrigated crops and riparian vegetation typically lasts from April to September. Table 20 summarizes climatic data for Cottonwood, Arizona and provides a general indication of annual precipitation and temperature ranges for the Verde Valley area.

The Mogollon Rim and surrounding mountain ranges rise from 4,000 to 6,000 feet above the valley floor and strongly influence the local climate. Moist air forced to rise over these topographic features cools and condenses, forming precipitation. Total annual precipitation is variable, ranging from approximately 12 inches in the central valley to 27 inches at the highest elevations of the watershed along the Mogollon Rim (National Climate Data Center, 1993). Distinct seasonal precipitation patterns representative of the Verde Valley area are evident in Figure 50, showing average monthly precipitation at Cottonwood for 1948-1974. The summer months of July and August contribute about 35% of total annual rainfall. Summer precipitation results from short duration, high intensity storms originating in the Gulf of Mexico. A second, less apparent season of high precipitation occurs from September through December. The lowest precipitation occurs in spring and early summer with approximately 12% of the annual total occurring between April and June.

Table 20 Summary of Climatological Data for Cottonwood, Arizona.			
Month	Average Monthly Precipitation (Inches)	Degrees Fahrenheit Maximum Temperature	Degrees Fahrenheit Minimum Temperature
JAN	0.77	58.1	28.1
FEB	0.78	63.3	31.7
MAR	0.83	68.4	35.6
APR	0.54	76.3	41.8
MAY	0.38	84.8	49.2
JUNE	0.50	94.7	57.7
JULY	1.89	98.5	65.9
AUG	2.23	95.5	63.8
SEP	1.08	91.3	57.4
OCT	1.04	81.2	46.4
NOV	0.73	68.1	35.6
DEC	1.05	58.6	28.7
ANNUAL	11.8	78.3	45.2

Source: National Climatic Data Center, 1993

Winter precipitation results from cyclonic storms of moderate intensity originating in the Pacific Ocean. Annual runoff of the Verde River shown in Figure 51 does not correspond to the annual cycle of precipitation. Peak runoff occurs during the months of February through April and is due to snowmelt. Monthly runoff is at an annual low from May through July, and is relatively low throughout the summer and fall growing season.

Geologic Setting

The study area contains rocks that range in age from Precambrian to Recent that exhibit complex structural and stratigraphic relationships. Rocks of Precambrian age within the area consist of metamorphosed volcanic and sedimentary rocks (Twenter and Metzger, 1963). Precambrian rocks are unconformably overlain by an extensive

Figure 50. Average Monthly Precipitation at Cottonwood, Arizona

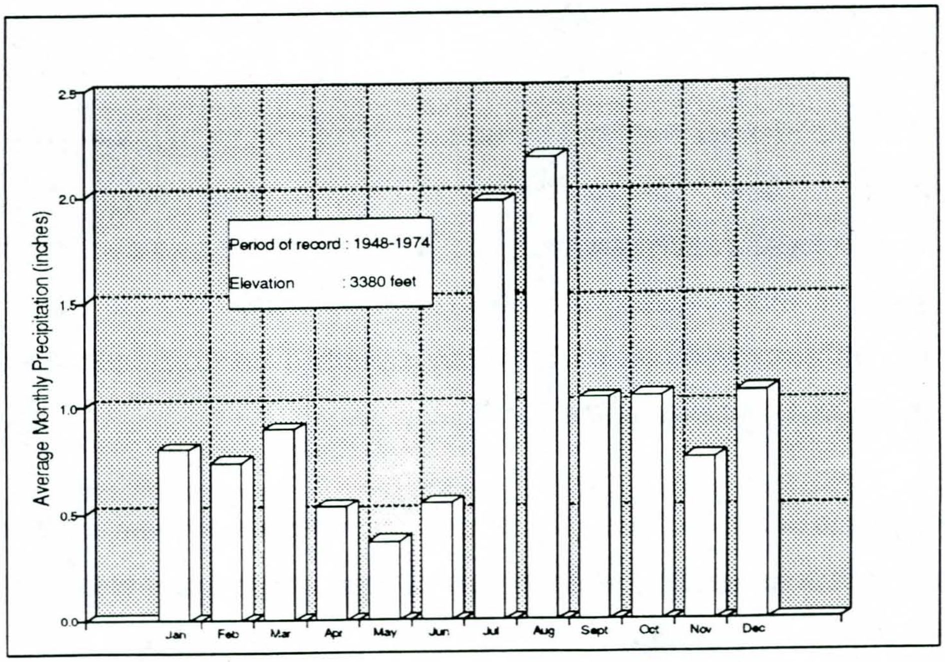
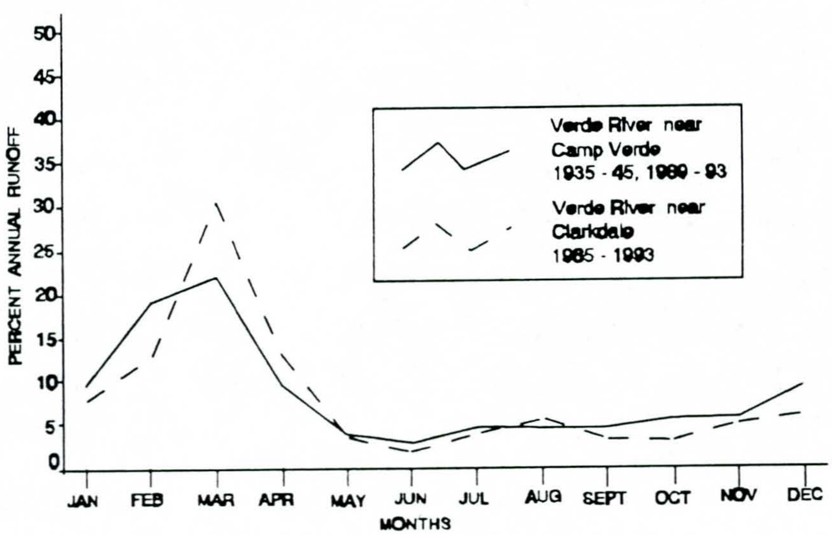


Figure 51. Mean Monthly Runoff as a Percent of Annual Runoff for the Verde River near Camp Verde and near Clarkdale.



Paleozoic sequence which includes the Tapeats Sandstone, Martin Limestone, Redwall Limestone, Naco Formation, Supai Formation, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983). Paleozoic rocks are exposed in the northern portion of the Verde Valley and form much of the Mogollon Rim escarpment. Cenozoic rock units lie unconformably on Paleozoic rocks and consist primarily of Tertiary volcanic and sedimentary rocks and Quaternary alluvium. Most of the Paleozoic and Mesozoic rocks were removed by erosion from the central part of the valley prior to Cenozoic sedimentation and volcanism (Twenter and Metzger, 1963).

Of primary concern to this study are formations occurring within the main valley of the Verde River that are capable of producing economic quantities of water. The Tertiary Verde Formation and Quaternary stream alluvium are the primary water bearing units within the Verde Valley groundwater basin. The Verde Formation was formed when Tertiary volcanism blocked and impounded the water of the ancestral Verde River resulting in the deposition of lacustrine (lake) sediments and associated fluvial (river) sediments (Twenter and Metzger, 1963). These sediments combined with local interbedded basalt flows constitute the Verde Formation.

Unconformably overlying the Verde Formation along the Verde River and the larger streams is Quaternary alluvium. The Quaternary alluvium is comprised of channel, floodplain, and terrace deposits found near the stream channels and extending in an almost continuous strip 4 to 5 miles wide along the Verde River (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983). The stream alluvium is usually less than 50 feet thick in the study area, but may exceed 100 feet near Camp Verde.

METHODS

Instream Flow Models

The general research approach for this case study involved quantifying changes in riparian vegetation abundance across natural gradients of surface water flow rate, so that these relationships could be used as a basis for predicting ecological response to streamflow depletion and for determining flow requirements of the riparian vegetation. This approach can be referred to as a space-for-time substitution approach, in which changes observed across natural spatial gradients are assumed to be representative of changes that would occur over time in response to surface water reduction.

To develop the instream flow models, riparian vegetation characteristics were sampled along 10 streams of varying size in the Verde River watershed of Arizona between about 2,900 and 4,800 feet in elevation. These characteristics were also sampled along 13 streams of varying size within the Santa Cruz and San Pedro watersheds of southern Arizona, between about 2,400 and 4,600 feet in elevation (Table 21).

The sample sites in the Verde River watershed included sites along the Verde River and along perennial (e.g., Wet Beaver Creek, Oak Creek, West Clear Creek) and intermittent and ephemeral tributaries (e.g., Red Tank Draw, Rattlesnake Canyon, Williamson Valley Wash, and Dry Beaver Creek). Riparian study sites in southern Arizona included perennial sites along the San Pedro River, Santa Cruz River, and Sonoita Creek, as well as along ephemeral and intermittent tributaries. Mean annual flow rate at the Verde River watershed sites ranged from 7 to >300 cfs per year, and mean annual flow rate at the San Pedro/Santa Cruz watershed sites ranged from <1 to about 50 cfs .

Each riparian study site was located within 4 miles of an established United States Geological Survey (USGS) streamgaging station, in areas least affected by human disturbance and where the floodplains were least constrained by canyon walls. Nevertheless, most of the riparian areas were disturbed by various land uses and, thus were not necessarily representative of pristine riparian systems. Stream channel substrates ranged from sand and gravel to boulders. Valley types ranged from wide alluvial valleys to somewhat narrower V-shaped valleys.

Table 21 USGS Streamgaging Stations within the Verde, San Pedro, and Santa Cruz River Watersheds		
Site Name	**Elevation (ft. above MSL)**	**USGS Gage Number**
VERDE RIVER WATERSHED		
Red Tank Draw	3920	9505250
Rattlesnake Canyon	4870	9505300
Williamson Valley Wash	4455	9502800
Verde River- Paulden	4115	9503700
Wet Beaver Creek	4020	9505200
Dry Beaver Creek	3695	9505350
West Clear Creek	3630	9505800
Oak Creek- Cornville	3470	9504500
Verde River- Clarkdale	3520	9504000
Verde River- Camp Verde	2875	9506000
SAN PEDRO-SANTA CRUZ WATERSHED		
Airport Wash	2490	9482400
Atterbury Wash	2680	9485390
Peck Canyon Tributary	2850	9472100
Canado del Oro Tucson	2380	9486300
Altar Wash	2980	9486800
Arivaca Creek	3480	9486600
Santa Cruz River- Lochiel	4620	9480000
Pantano Creek	3150	9484600
Santa Cruz River- Continental	2400	9482000
Sonoita Creek	3818	9481500
San Pedro River- Palominas	4188	9470500
Santa Cruz River- Nogales	3703	9480500
San Pedro River- Charleston	3954	9471000

Streamflow rate at each riparian study site was quantified from USGS streamgage records for: (1) mean and median annual flow rate; (2) mean and median flow rate during the April-September growing season; (3) mean and median flow rate in the May-June dry season; and (4) mean daily flow rate equalled or exceeded for at least 90% of the time. The streamgages had different record lengths for streamflow measurements because of differences in dates of installation or inactivation of the gage stations. Flow rates used in the models were thus based on different periods.

Data were collected on several measures of riparian vegetation abundance. Measured riparian abundance traits included: (1) width of the riparian stand measured at five random points, (2) canopy foliage area measured with a LICOR canopy meter at a minimum of 20 random points, (3) woody plant basal area measured, by species, in 10 randomly located 1000 ft^2 (100 m^2) quadrants (study plots). Canopy height was measured with a clinometer in the same 10 quadrants, for the southern Arizona sites only. Also, for the southern Arizona sites, herbaceous species cover was measured in August and September, 1993 within 10, 3.3 ft^2 (1 m^2) plots in the streamside vegetation zone and 10, 3.3 ft^2 (1 m^2) plots randomly located throughout the entire floodplain. Foliage area and stand basal area were converted to values per unit (ft) of river length. Relationships between the vegetation and hydrologic data sets were quantified with univariate regression analysis. Models with the highest degree of significance were used to predict the response of a hypothetical Verde River riparian zone to decreased flow rate.

Both the surface water and groundwater hydrology of the area was assessed from existing hydrologic data. Daily, monthly and annual streamflow rates were quantified for the Verde River from USGS streamgage data to better characterize the present flow regime within the Verde Valley area. The instream flow models were used in conjunction with the calculated flow rates to predict changes in riparian abundance resulting from hypothetical stream diversion scenarios.

Assessment of the groundwater system included analysis of the occurrence and movement of groundwater, water yielding characteristics of the aquifer, and the interaction between groundwater and surface water systems. Based on the results of the hydrologic investigation, a conceptualized model of the stream-aquifer system within the Verde Valley was developed. Analytical methods of Jenkins (1968) were used to predict the amount of streamflow depletion that could occur from wells pumping near the Verde River. Groundwater withdrawal scenarios were developed and used to predict impacts to Verde River riparian abundance resulting from streamflow depletions.

RESULTS: VERDE RIVER HYDROLOGY

Groundwater System

Water bearing rock units in the upper Verde River area are grouped into a regional aquifer that includes: Tapeats Sandstone, Martin Formation, Redwall Limestone, Naco Formation, Supai Formation, Coconino Sandstone, Verde Formation, and stream alluvium (Twenter and Metzger, 1963). Within the regional aquifer all units are hydraulically connected. In the Verde Valley, the regional aquifer is comprised of Redwall Limestone, Supai Formation, Verde Formation and stream alluvium (Owen-Joyce and Bell, 1983). In the central valley, from north of Clarkdale to south of Camp Verde, the Verde Formation and stream alluvium comprise the main water bearing units near the river. For ease of discussion, the alluvium and the Verde Formation are referred to in this report as the Verde aquifer.

Currently, groundwater use in the Verde Valley is mainly for domestic, municipal, and industrial purposes. Approximately 10,000 acre-feet of groundwater is withdrawn annually by wells in the Verde Valley basin (Konieczki and others, 1992). As population in the study area increases, groundwater withdrawals will most likely provide the additional municipal water supply as surface water in the watershed is fully appropriated. This is due to the presence of senior surface water rights that divert Verde River water downstream for use in the Salt River Valley. Most wells are concentrated near the Verde River or the major tributaries. Water applied to irrigate crops is mostly surface water diverted by the more than 30 irrigation diversions in the area (Sullivan and Richardson, 1993). Groundwater may be used to supplement irrigation during periods of less than normal flow. Paleozoic sedimentary rocks also contain water, however these formations generally underlie the valley fill sediments at depth in the central valley. The Verde Formation and stream alluvium contain large quantities of groundwater in storage compared to the consolidated sedimentary and crystalline rocks that bound and underlie the basin. The emphasis of this section, therefore, is on the Verde aquifer.

Aquifer Description

The Verde Formation forms the primary aquifer in the study area. The Verde Formation is composed of sandstone, siltstone, mudstone, limestone, evaporites and interbedded volcanic rocks deposited as lenticular discontinuous strata. Deposition of the Verde Formation occurred in ancient Lake Verde, thus, limestone, claystone and mudstone characteristic of lacustrine depositional environments are widespread throughout the basin. Twenter and Metzger (1963), in their study on the Verde Valley, divided the Verde Formation into six facies including the thick limestone facies; the upper, middle, and lower limestone facies; the mudstone facies; and the sandstone facies. Within the formation the limestone beds are the major aquifers. The lower and middle limestone facies are interbedded with fine grained clastic and evaporite units of the nearly impermeable mudstone facies that act as aquitards. These aquitards usually cause the lower and middle limestones to be confined.

The Verde Formation is at least 1,800 feet thick and covers about 325 square miles of the Verde Valley (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983). It underlies the stream alluvium and terrace gravels and covers an area extending from north of Clarkdale to Cottonwood basin, south of Camp Verde. The Verde Fault forms the western boundary where the Verde Formation is brought into contact with upthrown Precambrian and Paleozoic rocks. To the north and east the Verde Formation onlaps Paleozoic rocks.

Unconsolidated Quaternary alluvium forms the channel, floodplain, and terrace deposits along the Verde River and its major tributaries. Gravel terrace deposits cover larger areas bordering the Verde River but are generally found above the water table (Twenter and Metzger, 1963). Stream channel and floodplain deposits consisting of unconsolidated gravel, sand, silt, and clay are collectively referred to as the alluvium.

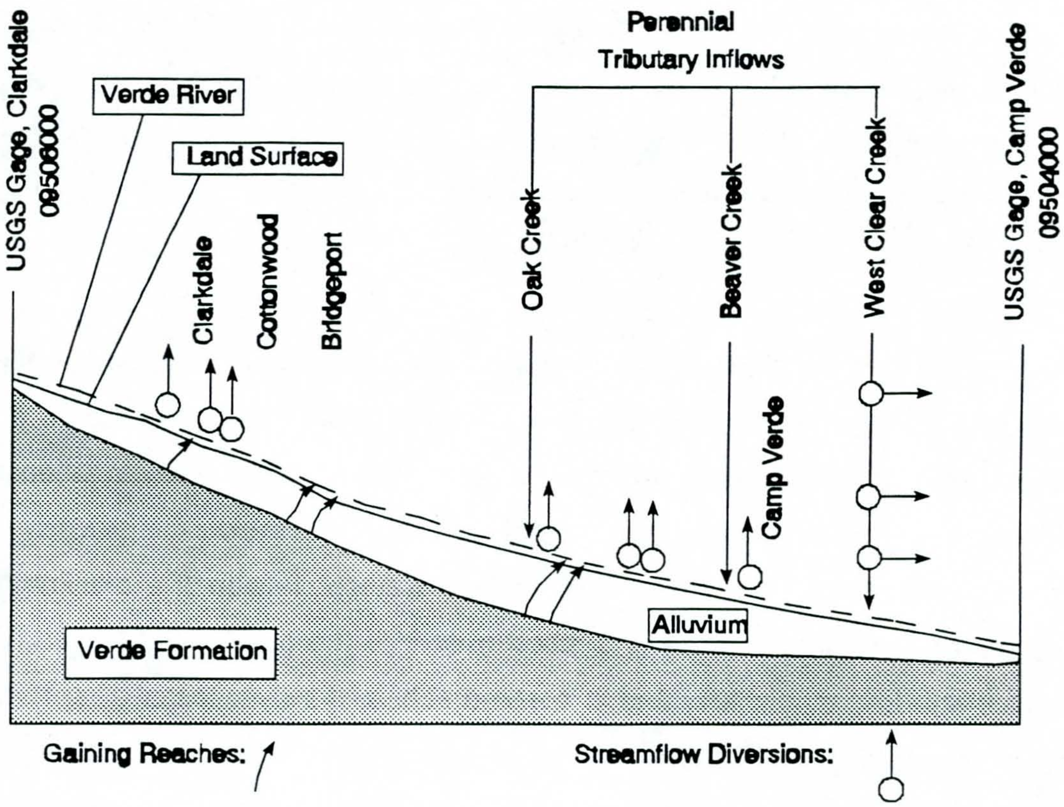
Stream alluvium forms an aquifer where saturated along the Verde River, Oak Creek, Beaver Creek, and West Clear Creek. The stream alluvium exceeds 1 mile in width through much of the Verde Valley but narrows dramatically where the river passes over consolidated rocks at the upstream and downstream study area boundaries. The alluvium is typically about 60 feet thick, but exceeds 100 feet in the Camp Verde area (Owen-Joyce, 1984).

Occurrence and Movement of Groundwater

Groundwater is unconfined in most of the area, however local confined (artesian) conditions occur in the Verde Formation throughout the area from Cottonwood to south of Camp Verde (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983; Glotfelty, 1985). Depth to water in wells that penetrate the Verde Formation ranges from flowing at the land surface to 489 feet below land surface (Owen-Joyce and Bell, 1983). Regionally, groundwater moves downgradient from areas of high hydraulic head (basin margins and northern Verde Valley), to areas of low hydraulic head (Verde River and southern Verde Valley). The altitude of the water table in the alluvium and the potentiometric surface of the Verde Formation was mapped by Owen-Joyce (1984) for an area along the Verde River from south of Camp Verde to Cottonwood Basin (see inset, Plate 3). Water level contours indicate that groundwater flows southwest toward the Verde Fault. Additionally, groundwater flows downgradient through the permeable stream alluvium of the Verde River, in a southeast direction. Groundwater level contours "V" upstream, indicating that in this area groundwater is flowing from the alluvium to the river.

The hydrogeologic section drawn longitudinally through the upper Verde River study area (Figure 52), illustrates general relationships between the groundwater and surface water systems. Groundwater discharge from the Verde Aquifer provides baseflow to the river. In addition to groundwater contributions to the flow of the Verde, runoff comprises a major portion of the overall streamflow. Surface water entering the Verde

Figure 52. Longitudinal hydrogeologic section representing groundwater-surface water relationships within the upper Verde River study area.



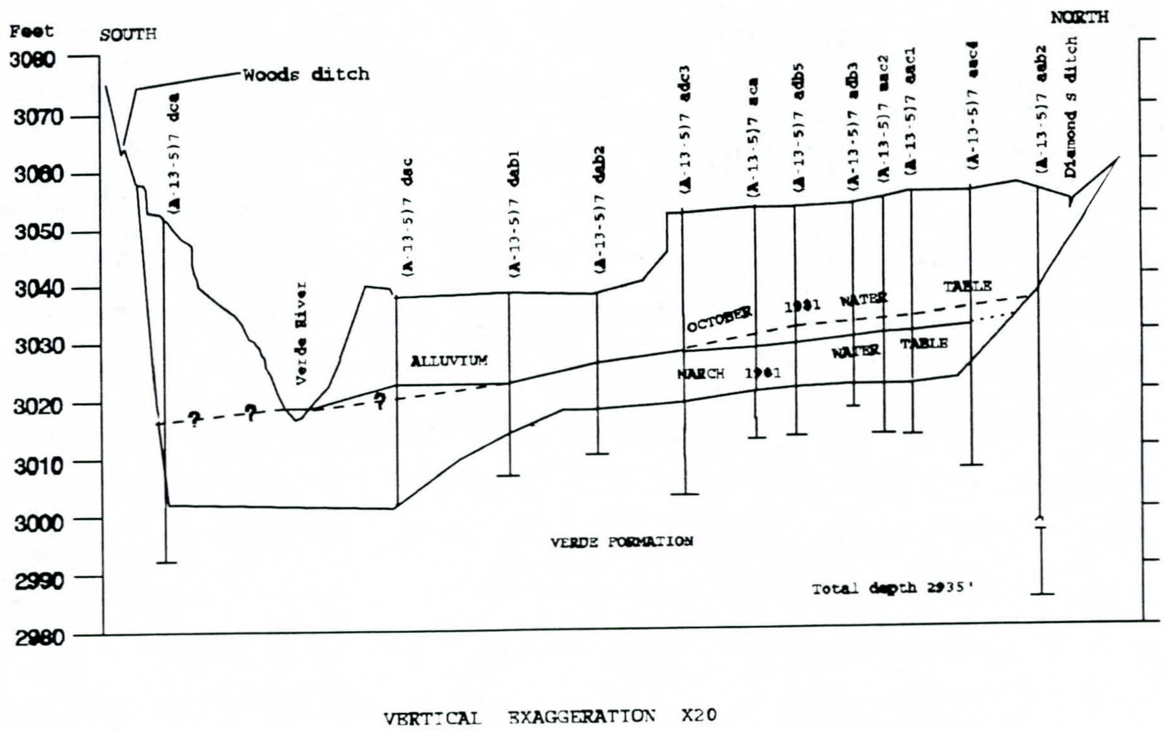
Valley is supplemented by perennial tributary inflows from Oak, Beaver, and West Clear Creeks. Streamflow diversions for irrigation deplete the streamflow of the mainstem of the Verde as well as its tributaries as indicated in Figure 52 and Plate 3.

Infiltration of precipitation through permeable rocks of the Colorado Plateau and infiltration through stream channels provides the majority of the recharge to the Verde aquifer (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983). Recharge to the alluvium is mainly from streamflow, irrigation return flow, septic tank effluent, and inflow from the Verde Formation (Owen-Joyce, 1984). Most recharge to the alluvium occurs during high streamflow events when the increased river stage causes groundwater levels in the alluvium to rise. Streamflows are high in the winter and spring due to snowmelt and runoff from winter storms. Water levels in the stream alluvium increase in response to these high flow events. The magnitude of water level changes varies with distance from the river, water table gradient, and aquifer characteristics. Owen-Joyce (1984) observed water levels in wells 2,500 feet from the river rise as much as 2.0 feet then quickly return to pre-rise levels.

Recharge to the alluvium from irrigation return flows also occurs seasonally. Surface water is diverted from the Verde River from multiple irrigation ditches in the Verde Valley and used to irrigate agricultural fields overlying the alluvium, adjacent to the Verde River. Much of the diverted water applied to the land during the growing season infiltrates into the permeable soils and raises water levels in the alluvium. It is estimated that during the growing season over half the flow of the Verde River is diverted into irrigation ditches, and in some reaches, the river loses all surface flow (Sullivan and Richardson, 1993). Figure 53, from Owen-Joyce (1984), shows a cross section through the alluvium near Camp Verde. Water levels farthest from the river rose nearly 5 feet above spring levels by the end of the growing season in October. However, water levels close to the river were higher in the spring due to increased river stage.

Vertical and lateral lithologic changes and inter-fingering beds impede groundwater flow in the Verde Formation. Interbedded basalt flows and clay layers confine groundwater creating local artesian conditions. Faulting affects the hydrology of the stream-aquifer systems by off-setting geologic formations, fracturing and folding rocks, and otherwise altering aquifer storage and flow properties. Major faults in the area (e.g., Verde Fault) appear to act as barriers to the movement of groundwater, however permeable fault

Figure 53. Hydrogeologic section through the alluvial aquifer near Camp Verde (From: Owen-Joyce, 1984)



breccia may act as conduits for groundwater flow. Groundwater in the basin flows southwest toward the Verde Fault zone, however once reaching the fault zone groundwater flows southeast in the fractures and joints parallel to the fault (Twenter and Metzger, 1963).

Groundwater is discharged to springs and seeps and maintains the baseflow of the Verde River. Discharge also occurs from wells and from evapotranspiration. Water levels in wells fluctuate in response to variations in recharge and discharge. Twenter and Metzger (1963) recorded water levels in well A(15-03)12adb1 and found fluctuations of 4 feet over a year, with highest water levels observed between December and March and lowest levels occurring June through August. Beginning in 1966, water levels have declined in this well by approximately 1 foot per year (Plate 3). Water levels were observed to fluctuate about 1 foot over the course of a year in well A(13-5)7aba2, located about 3,500 feet from the river and tapping the Verde Formation (Owen-Joyce, 1984).

Owen-Joyce (1984) observed that seasonal fluctuations of alluvial water levels (up to 5 feet in 1981) were caused by changes in river stage and mounding of the water table from application of irrigation water on agricultural fields on the alluvium. Water level fluctuations due to deep percolation of irrigation water were most noticeable farthest from the river, away from the influences of river stage. Areal distribution of irrigation, amount of water applied, crop water use, and infiltration rates all influence the amount and location of irrigation return flows. The water table elevation appears to respond less to irrigation return flows than to changes in river stage, this is due to the river being at its lowest stage during the irrigation season (Owen-Joyce, 1984). Thus, because the river stage is low, groundwater drains from the alluvium to the stream more rapidly, even though recharge of irrigation to the alluvium creates mounding of the water table. The saturated thickness of the alluvium increases during irrigation season and then returns to pre-irrigation levels by about January.

Water levels in the alluvium range from 5 to 50 feet below land surface and fluctuate seasonally. Wells in the alluvium are from 12 to 120 feet deep, with the deeper wells bottoming in the lower permeability clay units of the Verde Formation (Owen-Joyce, 1984). The maximum saturated thickness of the alluvium is about 30 feet, but also varies seasonally. Well yields range from 3 to 300 gallons per minute with highest yields occurring where sediments consist mainly of sand and gravel with little cementation.

Water levels fluctuate over the coarse of the year, but recharge from streamflow and irrigation return flows keeps the alluvium saturated. Wells A(13-5)5bdc and A(14-5)32bbb1 (Plate 3) are completed in alluvium. Fluctuations of about 7 feet are evident in well A(13-5)5bdc, however no net long-term declines have occurred. The second well fluctuated only about 2-3 feet prior to 1982, then water levels dropped over 30 feet by 1991 but have since recovered to pre-1982 levels. It is not known whether this drastic decline represents a significant decline in the water table or if it is the result of measurements taken during well pumping.

Water Yielding Characteristics

The transmissivity (T) of an aquifer is a measure of the rate of groundwater movement and is used in assessing the effect of groundwater withdrawals on the aquifer. Values of T are determined by conducting aquifer tests on wells, however aquifer test data are sparse in the study area. Transmissivity values range from 20 to 8,700 feet squared per day (Table 22). The variation in T is caused by areal and vertical changes in lithology and effects of faulting, fractures, and solution channels (Owen-Joyce and Bell, 1983).

The amount of water capable of being produced by a pumping well depends on the lithology, saturated thickness, and transmissivity of the aquifer penetrated by the well, in addition to the pump size and well design. Well yields in the Verde Formation are reported by Owen-Joyce and Bell (1983) to range from less than 10 to over 1,600 gallons per minute (gpm) with a median of approximately 30 gpm. However, these amounts may represent maximum pump capacity and not necessarily the maximum yields achievable. The highest yields are in sandstone and limestone with solution channels and fractures (Owen-Joyce, 1984). The Verde Valley groundwater basin contains over 1,200 wells at present. Approximately 550 wells are located within a one mile buffer of the Verde River within the study area (Plate 3). The USGS (1992) estimated groundwater pumpage at 10,000 acre-feet during 1986, the most recent year pumpage is estimated. Groundwater use in the Verde Valley is primarily for domestic and municipal supply.

Table 22 Hydraulic Properties of Water Bearing Formations In Verde River Study Area				
Geologic Unit	**Transmissivity (ft2/d)**	**Well Location**	**Storage Coefficient**	**Reference**
Stream Alluvium	3000		.15	ADWR estimate, 1993
Verde Fm.	880	A(14-5)17aac		Owen-Joyce & Bell, 1983
	20	A(16-4)27dcc		Owen-Joyce & Bell, 1983
	200	A(16-4)34abb		Owen-Joyce & Bell, 1983
	8690	A(14-5)32cbb	.0005	Glotfelty, 1985
	1560	A(16-3)17dab	.0002	ADWR Files, 1991

Surface Water System

The Verde River is one of the larger perennial rivers in Arizona, draining an area of approximately 6,600 square miles at its confluence with the Salt River near Scottsdale (USGS, 1989). It flows in a southeast direction for 170 miles from its headwaters near Paulden to the confluence with the Salt River northeast of Scottsdale. The upper 125 miles of the river is free flowing, however, the lower Verde River is impounded by two dams operated by the Salt River Project that form Horseshoe and Bartlett Reservoirs.

Major perennial tributaries to the Verde River in the study area include Sycamore Creek, Oak Creek, Beaver Creek, West Clear Creek, and Fossil Creek. West Clear Creek is often dry at its mouth during the growing season due to at least three major upstream diversions (Plate 3). These tributaries drain the area to the north and east of the river and flow south or southwest toward the river. The Mogollon Rim to the north receives large amounts of precipitation which infiltrates into permeable rock formations. As a result, some of the larger south-flowing streams are perennial.

Streams entering the Verde River from the south and west are ephemeral, and flow only in direct response to rainfall.

The upper reaches of the Verde River upstream of the Verde Valley occupy a narrow canyon carved into the consolidated Paleozoic rocks of the mountains. In this area canyon walls constrict the channel, resulting in a minimal development of floodplain area. Between Cottonwood and Beasley Flat, the valley opens up into a broad valley over which the river meanders and has formed a significant floodplain. It is within the Verde Valley that most demand for water has occurred.

Streamflow has been measured by the USGS at various times and locations within the Verde River watershed. Two USGS gaging stations are of primary interest to the study area. Streamflow entering the Verde Valley is measured at the gaging station, Verde River near Clarkdale, located 5.6 miles north of Clarkdale. The gaging station, Verde River near Camp Verde, is located 9 miles southeast of Camp Verde and measures streamflow exiting the Verde Valley. The location of streamgages are shown on Plate 3. Comparison of streamflow data from these two gaging stations provides information on impacts to water resources occurring within the Verde Valley area.

Streamflow Characteristics

The Verde River is perennial throughout the study area, however the availability of streamflow is limited by natural low flows, upstream diversions for irrigation, and evapotranspiration (Owen-Joyce and Bell, 1983). Runoff of the Verde is bimodally distributed, with highest flows occurring in the winter months of February through April, and lowest flows in the summer months of May through July (Tables 23, 24). Historically, June flows are the lowest on the Verde River, with March having the highest mean monthly flow. The summer growing season is the critical period of water use because the need for surface water to irrigate agricultural fields occurs concurrently with the growing season for riparian vegetation. Increased water demands during the summer season corresponds with the lowest monthly streamflows of the year. Thus, groundwater pumping and surface water diversions occurring in the summer months have the greatest potential for impacts to the riparian ecosystem.

Streamflow is composed of direct runoff and baseflow. The streamflow component derived from direct runoff of precipitation and snowmelt drains rapidly through the stream system and increased flows are not sustained for long periods. Baseflow is the component of streamflow derived from groundwater discharged from the regional aquifer. It is the primary dependable surface water supply of the Verde River. Baseflow is relatively constant with time at the Clarkdale gage due to the large recharge area, the buffering affect of the aquifer as groundwater slowly and continuously moves toward the river, and the relatively small amount of upstream diversion and evapotranspiration. Within the Verde Valley, baseflow varies with location and through time. Changes in baseflow are due to seasonal changes in the amount of water diverted from the river to irrigate crops and the amount returned to the river from deep percolation of excess irrigation water. During the summer irrigation season, gains to streamflow are greatest near irrigated fields adjacent to the river. In winter gains are smaller owing to the lack of irrigation returns (Owen-Joyce, 1984). In general, the Verde River gains flow from groundwater discharge throughout the Verde Valley (i.e., a gaining river).

Owen-Joyce and Bell (1983) found that baseflow is at a maximum in January and February, and at a minimum during July and August. The Clarkdale gage showed a small yearly variation in baseflow entering the valley between 1966 and 1978, indicating minimal upstream use by riparian vegetation and cultural diversions. In addition, baseflow had not changed between 1921 and 1978, indicating that the system is in equilibrium upstream of Clarkdale. The Verde River near Camp Verde gage showed significant seasonal variation for the baseflow leaving the valley. Comparison of gage records from 1935-1945 with those from 1976-1979 showed no changes in winter baseflow, however summer baseflow had declined, indicating that evapotranspiration or irrigation uses may have increased in the valley. Baseflow in the area between the upstream and downstream gages is not defined, due to unmeasured irrigation diversions and return flows which occur throughout the area.

Streamflow Availability

Streamflow varies with time and location in the upper Verde Valley primarily because of surface water diversions for irrigation, but is also because of seasonal variations in runoff and evapotranspiration. Statistical descriptors of streamflow availability were calculated from mean daily flow data at two USGS streamgage sites: the Verde River near Clarkdale and the Verde River near Camp Verde. Calculated streamflow statistics include mean and median annual flow, mean and median monthly flow, and the percent of time a given mean daily flow was equalled or exceeded. Streamflow values are valid only for the streamgage site. Flow can vary considerably from place to place on the river, especially during the growing season, due to an undetermined amount of surface water diversions, groundwater pumping, and irrigation return flows that occur in the 50 mile reach between the gages.

Mean annual discharge averaged 313 cfs at the Camp Verde gage and 202 cfs at the Clarkdale gage. These values represent the arithmetic average of mean daily flows during the respective periods of record. Mean flows may overestimate streamflow because the arithmetic average can be heavily influenced by the occurrence of infrequent flood flows. Median annual flows, however, are more representative of the "typical" flow in the Verde River. The median is the middle value when flows are arranged in order of magnitude, and is the flow value which half of all recorded flows are greater and half are less. Median annual flows at the Camp Verde and Clarkdale streamgages are 225 cfs and 133 cfs, respectively.

Monthly analysis of mean daily flows indicates flow distribution throughout the year, and when the highest and lowest monthly flows are likely to occur. Tables 23 and 24 provide monthly mean, median, maximum, and minimum flows and the percent of annual runoff for the two gages. Similar to annual mean flows, monthly mean flows are skewed upward. Median monthly flow is the flow most likely to occur at the streamgage site during a given month. Table 24 shows that the highest monthly median flows can be expected to occur between January and April at the Clarkdale gage. March has the highest flow (365 cfs) and the lowest monthly flow has historically been in June with 76 cfs.

The distribution of monthly flows at the Camp Verde streamgage is similar to that at Clarkdale. March again is the high flow month with a median flow of 813 cfs, and June has the lowest monthly flow of 72 cfs (Table 23). June median flow is lower at Camp Verde than at Clarkdale even though the Camp Verde gage has a much larger contributing watershed, including inflows from perennial tributaries such as Oak Creek, Beaver Creek and West Clear Creek. Lower June flows at the downstream gage indicate that consumptive use of water is large in the Verde Valley during the summer season. During March when irrigation diversions and ET are greatly reduced, flow at Camp Verde is over twice that of Clarkdale.

Table 23
Monthly Streamflow Statistics USGS Streamgage 09506000, Verde River near Camp Verde, 1935-1945, 1989-1993

Month	Mean (cfs)	Median (cfs)	Maximum of Record (cfs)	Minimum of Record (cfs)	Percent of Annual Runoff
October	137	131	551	1383	3.6
November	192	191	339	169	5.1
December	217	212	1350	199	5.8
January	291	231	819	198	7.7
February	492	359	4400	221	13.1
March	1185	813	4030	280	31.6
April	520	208	3050	126	13.8
May	110	103	337	85	2.9
June	84	72	114	61	2.2
July	122	104	209	65	3.2
August	259	144	416	114	6.9
September	146	130	1150	83	3.9

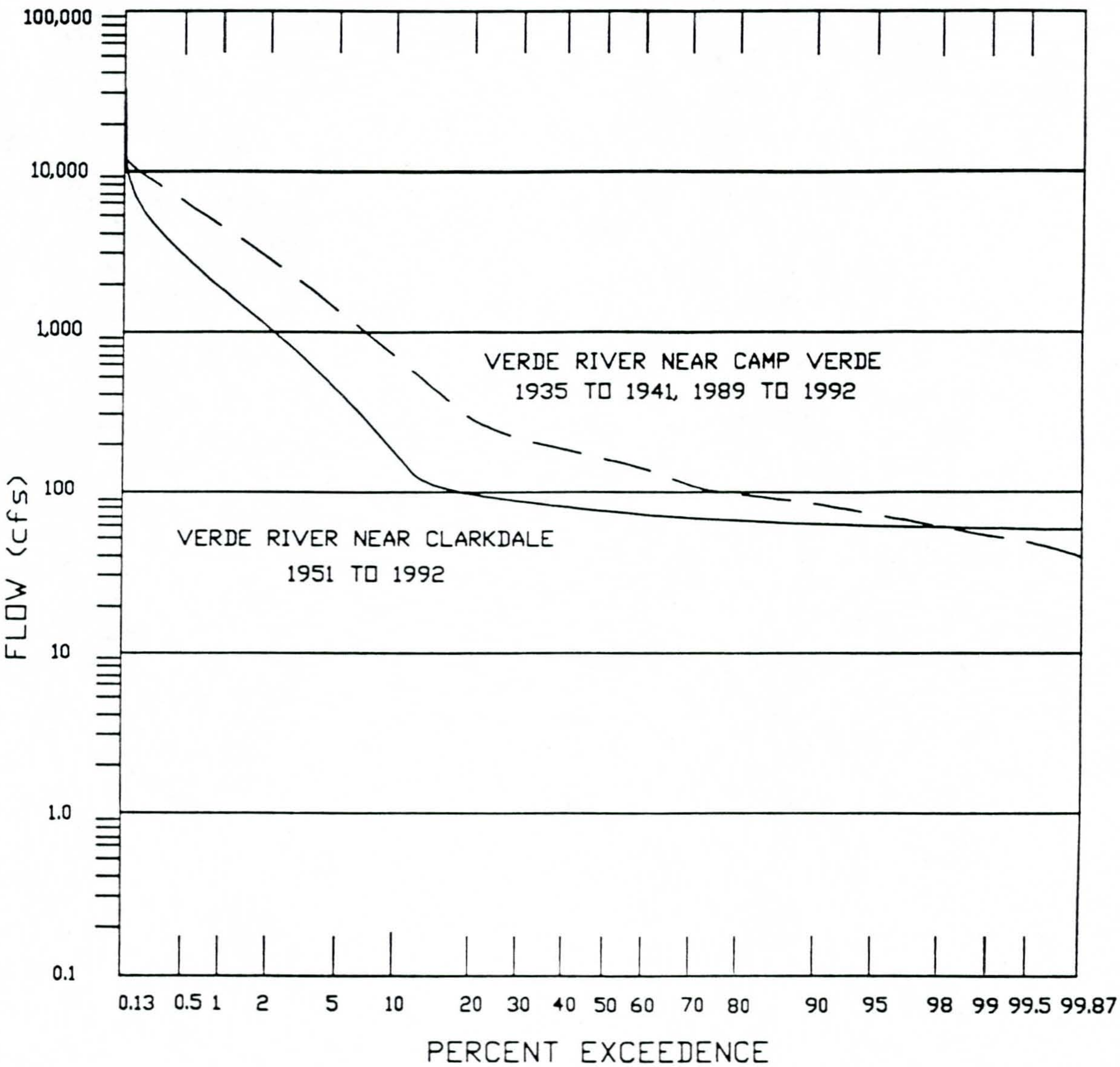
Table 24 Monthly Streamflow Statistics USGS Streamgage 09504000, Verde River near Clarkdale, 1965-1993					
Month	Mean (cfs)	Median (cfs)	Maximum of Record (cfs)	Minimum of Record (cfs)	Percent of Annual Runoff
October	123	82	1080	68	5.1
November	133	83	736	70	5.5
December	212	93	1030	75	8.7
January	224	133	578	73	9.3
February	471	249	3490	74	19.5
March	535	365	2760	73	22.1
April	236	159	1520	69	9.7
May	89	85	355	69	3.7
June	77	76	91	62	3.2
July	108	105	670	64	4.5
August	106	89	201	74	4.4
September	106	80	670	66	4.4

Annual flow duration curves were developed for the Verde River from mean daily flow data at the Clarkdale and Camp Verde streamgages (Figure 54, Table 25). Flow duration curves are cumulative frequency curves and indicate the percent of time that a specified discharge is equalled or exceeded. The curves indicate that streamflow is perennial (at the two streamgages) and flows exceed 70 cfs about 95 percent of the time. Both curves have a steep slope in the high flow, low exceedence range, indicating high flows occur infrequently. For example, flows are less than 1,000 cfs about 95 percent of the time. The curve for the Clarkdale gage has a gentle slope over the low flow, high exceedence range. It shows little variability of baseflow and fairly consistent flows about 85 percent of the time. This low variability of flow may be due to minimal impacts from diversions and ET upstream of the gage. The slope of the duration curve for the streamgage at Camp Verde is steeper and baseflow is more variable than that at the Clarkdale gage. Higher flow variability at Camp Verde is probably due to ET and the seasonal use of surface water for irrigation within the Verde Valley and along the major perennial tributaries. However, neither surface water diversions or ET have been quantified.

Table 25 Flow Duration Table for Verde River Streamgaging Stations		
% of time value equalled or exceeded	Verde River near Camp Verde (cfs)	Verde River near Clarkdale (cfs)
95	71.2	70.0
90	82.3	71.4
85	92.3	72.8
80	102.2	74.2
75	112.8	75.6
70	128.0	77.0
65	143.5	78.4
60	159.1	79.8
55	173.2	81.2
50	186.1	82.6
45	199.0	85.0
40	212.2	87.7
35	225.6	90.4
30	238.9	93.1
25	258.8	95.8
20	314.0	98.6
15	456.3	117.1
10	802.4	195.9
5	1552.4	513.4

The quantity of water diverted from the Verde River annually in not accurately known. The watershed has not been adjudicated, nor have present water uses been investigated for the pending adjudication. Surface water rights on file with the ADWR indicate claimed diversions of approximately 91,000 acre-feet (125 cfs) annually for the upper Verde Valley. The diversion totals include both subflow withdrawals from wells and infiltration galleries, and direct diversions from instream diversion structures. The accuracy of claimed diversions tabulated from the ADWR registry of water rights is not certain; future adjudication of the watershed will provide more accurate estimates. Sullivan and Richardson (1993) estimated that 7 main diversion works in the Verde Valley have the capacity to divert about 158 cfs (115,000 af/yr) to irrigate 7,781 acres

Figure 54. **Flow Duration curves for USGS gages: Verde River near Clarkdale and Verde River near Camp Verde.**



of agricultural lands. Owen-Joyce and Bell (1983) estimated that 31,000 af/yr (43 cfs) is consumptively used by irrigated crops in the valley. The difference between the amount of surface water diverted and the amount consumed by crops is returned to the river through canal returns, drainage systems, or deep percolation through the alluvium. The locations of 10 major irrigation diversions (7 on the Verde River and 3 on West Clear Creek) are shown on Plate 3.

RESULTS: RIPARIAN VEGETATION

Riparian Vegetation Overview

The upper and middle reaches of the Verde River, which were the focus of this study, are vegetated by the Cottonwood-Willow Series of the Warm-Temperate Interior Riparian Deciduous Forest (Brown, 1982). The headwaters and tributaries support a diverse mixed broadleaf riparian forest containing Fremont cottonwood and Goodding willow on lowest floodplains, and velvet ash, box elder, desert willow, netleaf hackberry, velvet mesquite, and Utah juniper on higher floodplains (Table 26). Shrubs Shrubs growing near the stream include coyote willow (*Salix exigua*) and seepwillow (*Baccharis salicifolia*), while graythorn (*Zizyphus obtusifolia*) is common on higher terraces. Farther downstream along the Verde River, the forests shift to a more pure cottonwood-willow-mesquite type, with mixed broadleaf trees such as box elder, Arizona sycamore, Arizona walnut and others forming a smaller component of the forest overstory. Large cottonwood stands occur within Dead Horse State Park and the Verde River Greenway near Cottonwood, and extensive mesquite forests are located near Tuzigoot National Monument. The exotic saltcedar is locally abundant along the river, as is tree-of-heaven (*Ailanthus altissima*), which most likely "escaped" from nearby settlements. Cattail, bulrush and other wetland plants are locally abundant along the river channel, and form extensive stands within Peck's Lake and Tavasci Marsh.

The width of the riparian vegetation zone in the Verde River watershed varied from less than 30 feet for the smallest ephemeral streams to greater than 1,000 feet for the

Table 26 Obligate and facultative riparian tree species present at Verde River watershed and San Pedro/Santa Cruz watershed study sites.		
Scientific Name	**Common Name**	FAMILY
Species Sampled in Verde River and San Pedro/Santa Cruz Watersheds		
Acacia greggii var. arizonica	Catclaw acacia	Leguminosae
Celtis reticulata	Netleaf hackberry	Ulmaceae
Chilopsis linearis	Desert willow	Bignoniaceae
Fraxinus velutina	Velvet ash	Oleaceae
Juglans major	Arizona walnut	Juglandaceae
Platanus wrightii	Arizona sycamore	Platanaceae
Populus fremontii	Fremont cottonwood	Salicaceae
Prosopis velutina	Velvet mesquite	Leguminosae
Salix bonplandiana	Bonplands willow	Salicaceae
Salix gooddingii	Goodding willow	Salicaceae
Sapindus sapondaria var. drummondii	Western soapberry	Sapindaceae
Tamarix chinensis	Salt cedar	Tamaricaceae
Species Sampled Only in Verde River Watershed		
Acer negundo	Box elder	Aceraceae
Alnus oblongifolia	Arizona alder	Betulaceae
Juniperus deppeana	Alligator juniper	Cupressaceae
Quercus spp.	Oak	Fagaceae
Species Sampled Only in San Pedro/Santa Cruz Watershed		
Cercidium floridum	Blue palo verde	Caesalpinioideae
Cercidium microphyllum	Foothill palo verde	Caesalpinioideae
Morus microphylla	Texas mulberry	Moraceae
Parkinsonia aculeata	Mexican palo verde	Caesalpinioideae
Rhus lancea	African sumac	Anacardiaceae
Rhus microphylla	Desert sumac	Anacardiaceae
Sambucus mexicana	Mexican elder	Caprifoliaceae

largest perennial streams. Many of the floodplains support two distinct floodplain zones- an interior zone of cottonwood, willow and mixed broadleaf trees- and an outer zone dominated by mesquite. The mesquite zone in many areas has been extensively modified by land use and riparian clearing and thus it is sometimes difficult to determine the exact width of the riparian zone. For example, on the Verde River mainstem, much of the riparian floodplain acreage has been replaced by agricultural fields or urban areas. Arizona Game and Fish riparian maps thus indicate a much narrower riparian zone than potentially exists (Plate 3).

Instream Flow Models

All descriptors of riparian vegetation abundance varied with high significance as functions of flow rate. Relationships between the riparian descriptors and the flow variables were curvilinear. Riparian strip width, canopy foliage area per unit of stream length, and basal area per unit stream length all increased significantly with flow rate (i.e., all regression equations were significant at $P<0.05$). Vegetation increased most sharply with flow over the low range of flow rates and then tapered somewhat at higher flow rates. All variables showed relatively strong correlations with annual flow rate, but correlations overall were higher with growing season flows. Watershed area and elevation explained less of the variance in riparian response than did flow parameters.

One riparian vegetation parameter, riparian zone width, was separated into two variables- width of the entire riparian zone and width of the broadleaf component of the riparian zone, exclusive of the mesquite component. Both measures of riparian zone width were highly correlated with mean growing season flow rate. Width of the broadleaf zone was very similar for a given rate of water flow in the Verde watershed and in the San Pedro/Santa Cruz watersheds (Figure 55). However, width of the total riparian zone, inclusive of the mesquite component, was much greater per unit of water in the southern Arizona watersheds (data not shown). The mesquite zone encompassed about 1/2 to 2/3 of the total riparian zone width.

Canopy foliage area and woody stem basal area (as measured within the broadleaf zone) were more highly correlated with median growing season flow rate than with mean flow rate (Figures 56 and 57). Canopy foliage area and woody stem basal area were slightly higher per unit of flow within the San Pedro/Santa Cruz watershed than in the Verde River watershed. Average canopy height and maximum canopy were measured only for the San Pedro and Santa Cruz River watersheds. Canopy height showed strongest correlations with the May-June median flow (Figure 58). This relationship occurred because tall riparian trees (e.g., Fremont cottonwood) grew in abundance only where flows were perennial during the dry season of the year. It is not known if relationship between canopy height and dry season flows for southern Arizona streams is valid for the Verde River watershed.

Abundance of Fremont cottonwood (measured as basal area per unit of stream length) increased most significantly with mean growing season flow rate (Figure 59). Fremont cottonwood abundance per unit of flow did not differ between the watersheds. Results are still being analyzed for other riparian plant species, including herbaceous plants which often are highly sensitive indicators of change in water availability.

DISCUSSION

Instream Flow Models

Instream flow needs of riparian vegetation can differ from instream flow needs of aquatic organisms (e.g., fish) or other riparian ecosystem components (e.g., channel maintenance) (Hill and others, 1991). Some of the approaches that have been taken to identify instream flow needs for riparian vegetation include site-specific studies that relate growth or vigor of key riparian trees to surface flow volume, using dendroecological techniques (Stromberg and Patten, 1990, 1991). Evapotranspiration models also have been used to estimate water needs of riparian vegetation stands of varying size (O'Keefe and Davies, 1991). The instream flow approach described in this study is similar to that described by Taylor (1982) who showed that riparian stand width and other community characteristics could be modeled as functions of stream discharge within watersheds.

Empirical instream flow models described in this study indicate that riparian vegetation abundance varied in a continual fashion as a function of streamflow rate and, in particular, with growing season flow rate. Several indicators of riparian abundance -

Figure 55. **Width of the broadleaf riparian zone (exclusive of the mesquite zone) as a function of mean seasonal (April-September) streamflow rate for stream sites in the Verde River watershed of central Arizona and the San Pedro/Santa Cruz watersheds of southern Arizona.**

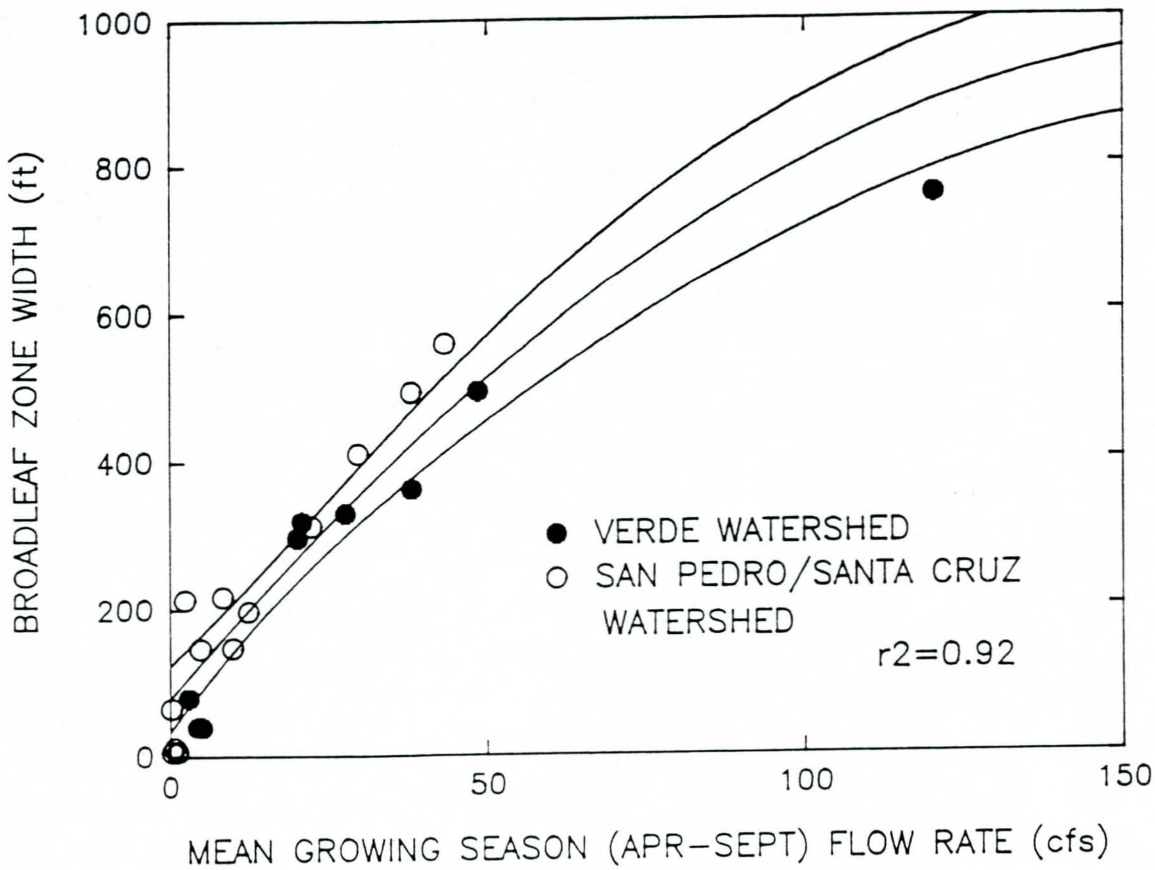


Figure 56. **Canopy foliage area per unit of stream length as a function of median seasonal (April-September) streamflow rate for stream sites in the Verde River watershed of central Arizona and the San Pedro/Santa Cruz watersheds of southern Arizona.**

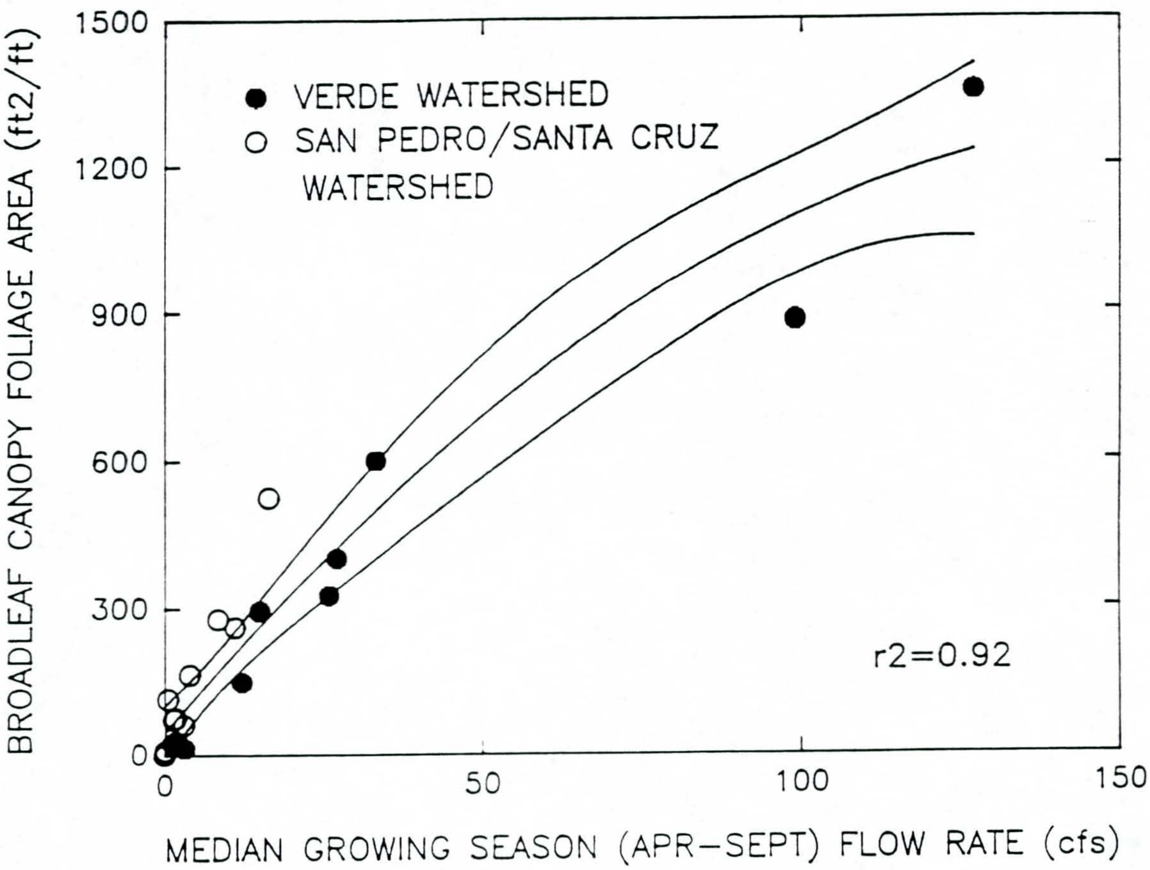
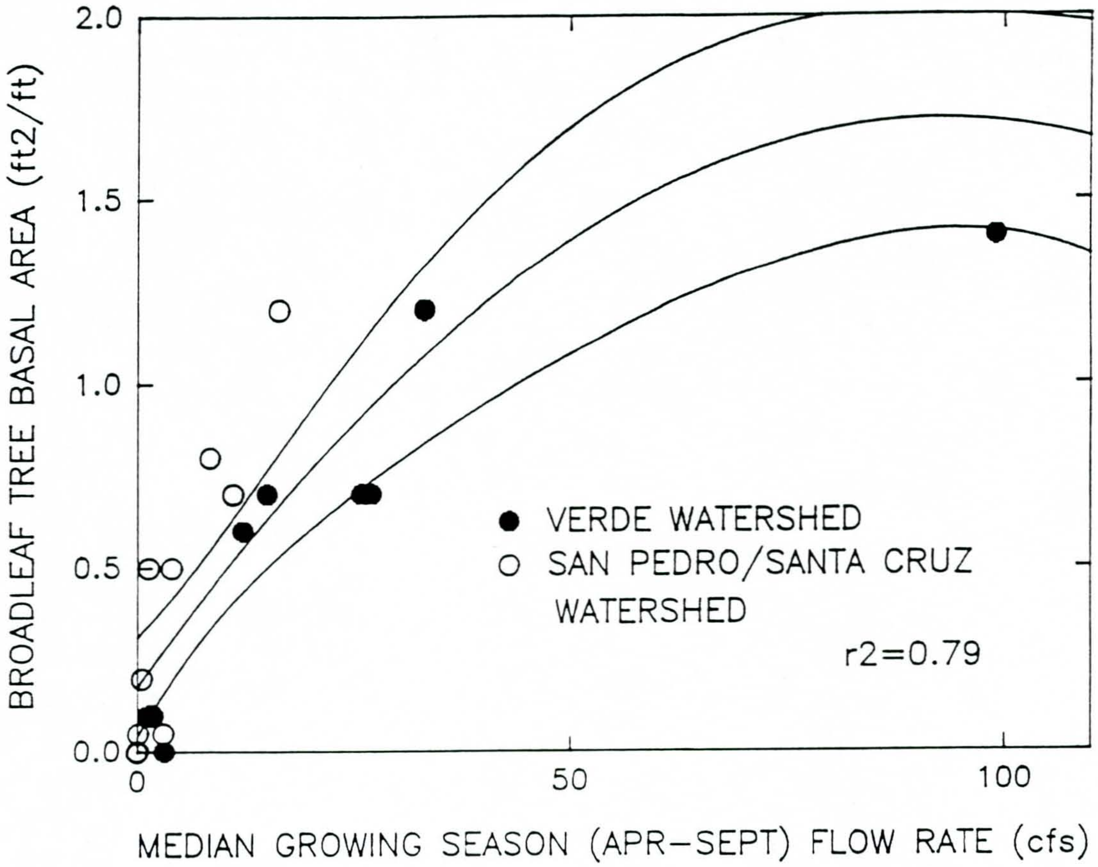


Figure 57. **Woody plant basal area per unit of stream length as a function of median seasonal (April-September) streamflow rate for stream sites in the Verde River watershed of central Arizona and the San Pedro/Santa Cruz watersheds of southern Arizona.**



foliage area, stem basal area, riparian stand width, and abundance of particular tree species (i.e., cottonwood)- increased continuously with flow rate within the Verde River watershed and San Pedro/Santa Cruz watersheds. These models indicate as growing season surface flow increases, the abundance of the riparian forest increases in turn.

In these instream flow models, surface flow is functioning as a surrogate indicator of water available in the riparian zone. Riparian plants can obtain water from a variety of sources including directly from the stream, bank-stored surface water or from flood water; from groundwater (either in the saturated zone or in the overlying vadose zone); and from direct precipitation or overland run-off (Figure 60). For example, root profiles indicate that some riparian trees and shrubs extend roots vertically to the water table and laterally to stream banks (Gary, 1963). Isotope studies indicate that trees on floodplains and stream banks often use groundwater, whereas seedlings of some species often directly use surface water (Dawson and Ehleringer, 1991; Flanagan and others, 1992; Busch and others, 1992). Periodic flood inundation also serves as an important water source for some riparian species (Reily and Johnson, 1982). Thus, the relationships expressed in the instream flow models are a reflection of the role that surface water plays in directly sustaining streamside vegetation and in recharging the floodplain aquifer. Although growing season flows were of greatest significance in the models, annual flow also was related to the riparian abundance measures, because aquifer recharge continues year-round. Higher relationships of some riparian variables with mean flows, as opposed to median flows, were significant perhaps for the same general reason. However, median flows were important determinants of some measures of riparian abundance, because median conditions are a more accurate measure of conditions that are most frequently present. To protect riparian vegetation, it is important to protect all sources of riparian water table recharge, including surface water which recharges floodplain aquifers during higher flow periods, as well as regional aquifers that may recharge floodplain aquifers during lowflow conditions (i.e., baseflow discharge to the stream).

Given that the relationships between surface flow and riparian vegetation abundance had high significance, the models can be used as a tool to determine instream flows necessary to maintain existing amounts of riparian vegetation or to predict riparian response to flow reduction. For example, water in the Verde River and its floodplain aquifer is diminished by the cumulative effects of at least 30 separate surface flow diversions and many more groundwater wells. This has reduced the growing season flow volume to below its historic norm, before the onset of agriculture in the Verde Valley. The precise amount of flow that is diverted is unknown (although estimates have been made) because surface flow diversions are not presently measured. If such values were known, instream models such as those presented in this paper could be used to indicate the extent to which existing diversions have reduced riparian vegetation or riparian potential on the Verde River. The models also can provide an approximation of riparian loss expected from additional future stream diversions or groundwater pumpage. Applications of the instream flow models to two such scenarios are described below.

Increased water demand of 6,000 af/yr (8 cfs) for municipal and industrial use is projected for the Verde Valley by 2015 (ADWR, 1993). Assuming that increased demand will be met through instream diversion structures or subflow infiltration galleries, the reduction in riparian abundance resulting from reduced streamflows can be predicted using the models developed for this study. Figure 61 indicates the predicted reduction in riparian vegetation abundance (measured as woody plant basal area per unit of stream length) in response to new diversions of 4, 8, 12, and 16 cfs. Riparian abundance declines continuously as the amount of diversion increases. Diversion of 8 cfs would reduce riparian abundance by about 10%, based on regression equations derived from the relationship depicted in Figure 56. Other measures of riparian abundance (e.g., riparian zone width, canopy foliage area, cottonwood basal area) would show similar declines (data not shown). The previous example is based on continuous, year-long diversions of surface water for municipal supply, and does not take into account return flows to the Verde River from effluent

Figure 58. **Average canopy height in the riparian zone as a function of median dry season (May-June) streamflow rate for stream sites in the San Pedro/Santa Cruz watersheds of southern Arizona.**

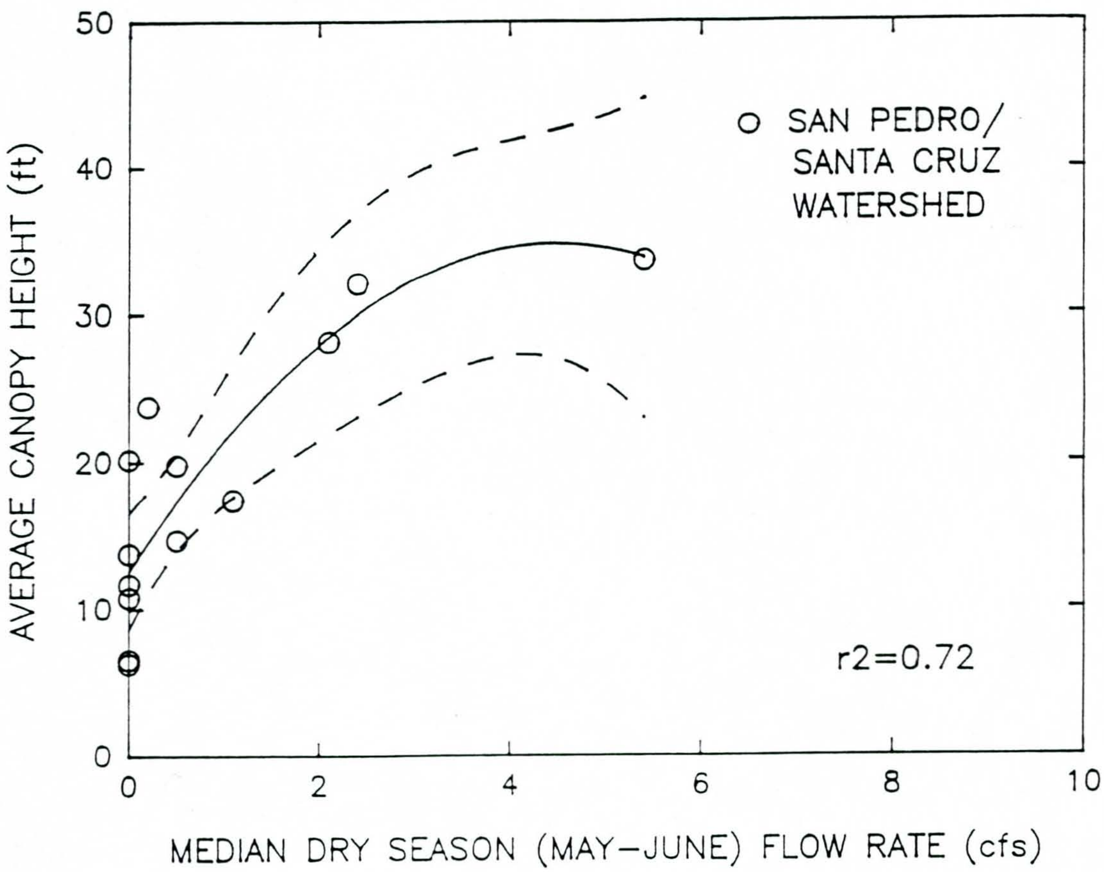


Figure 59. **Fremont cottonwood basal area per unit of stream length as a function of mean seasonal (April-September) streamflow for stream sites in the Verde River watershed and the San Pedro/ Santa Cruz River watersheds of southern Arizona.**

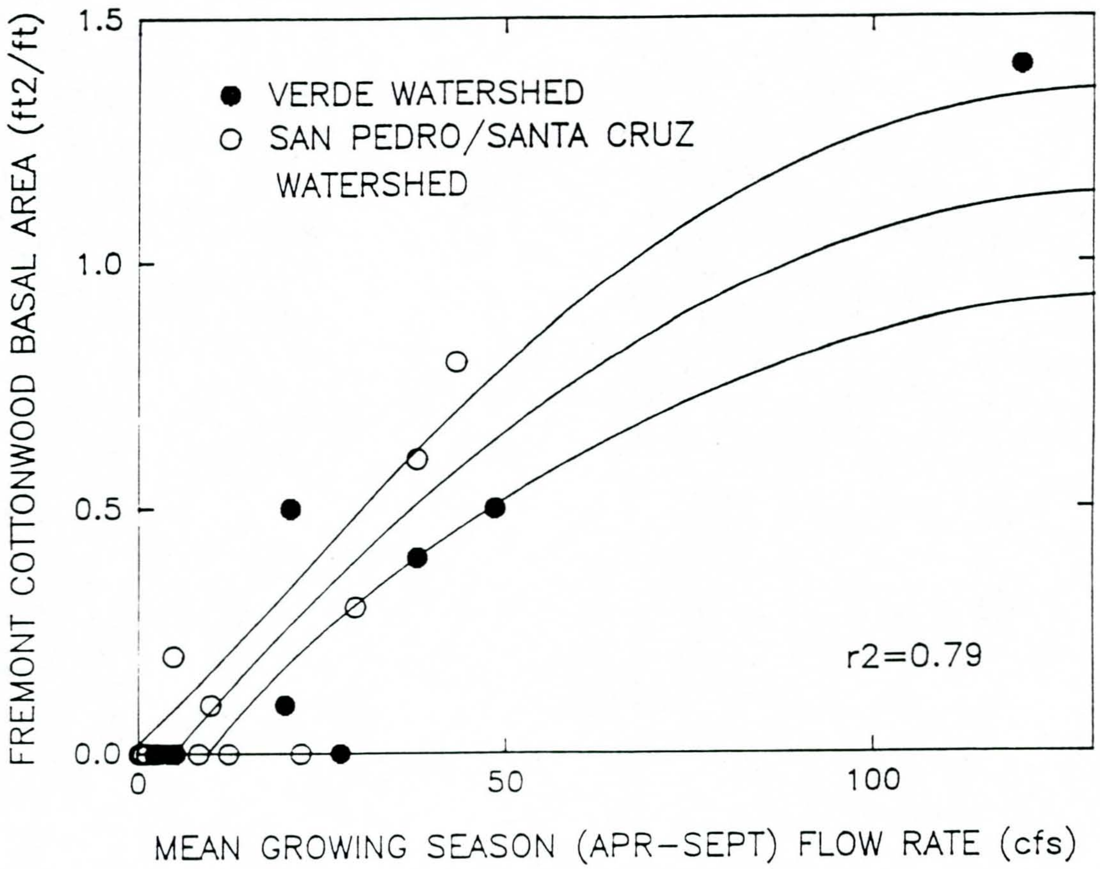
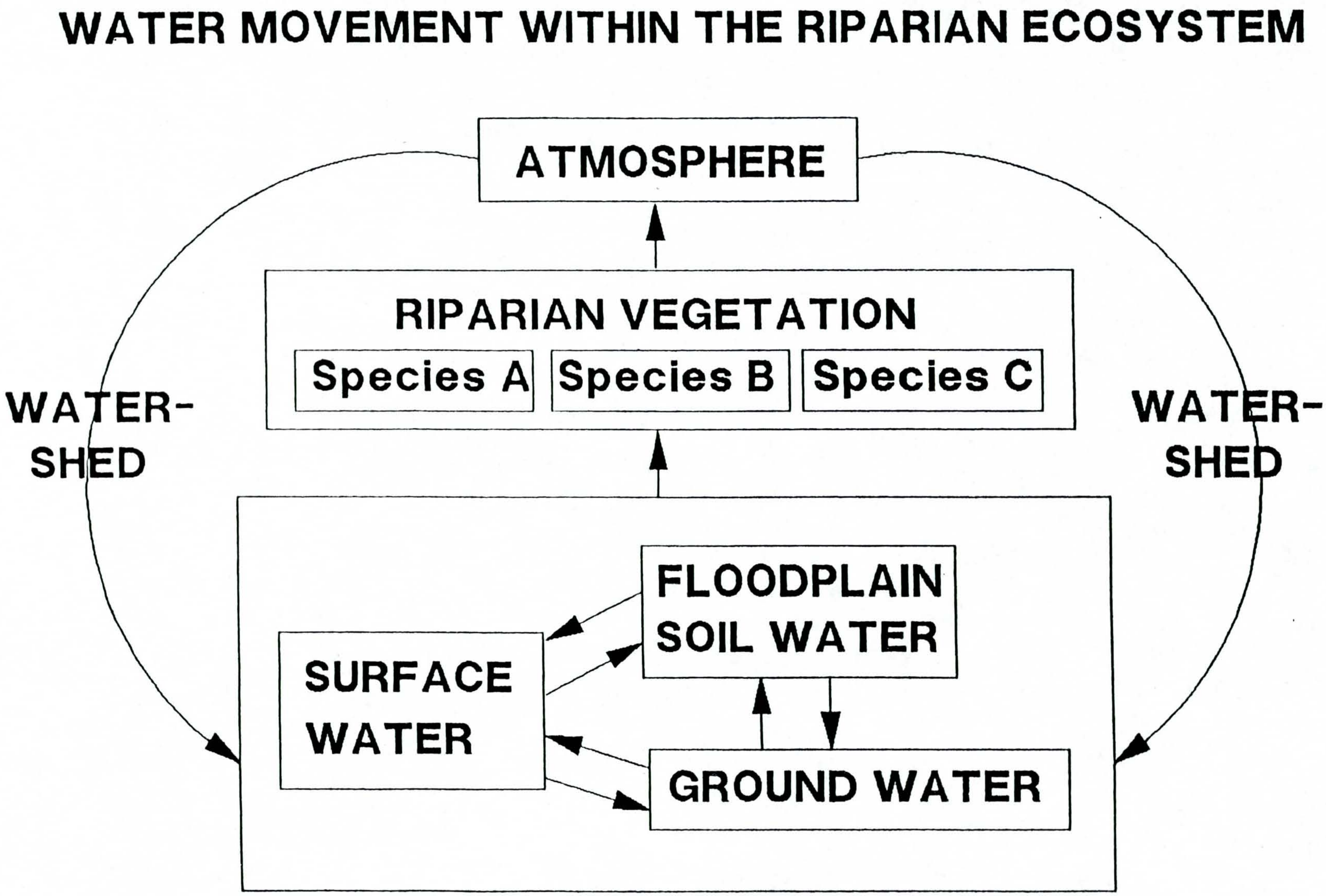


Figure 60. Generalized diagram indicating the interconnection between groundwater, surface water, and riparian zone soil water.



discharges. Impacts to the riparian ecosystem would obviously be greatest immediately downstream of the point of diversion. Impacts may be less severe with distance below the diversion point as the Verde River gains streamflow, that is baseflow discharge, from the Verde aquifer.

Figure 62 presents riparian vegetation reduction under another scenario, where surface flows are reduced by groundwater pumping. This scenario assumes that a single well located in the stream alluvium, 200 feet from the river, is pumping at a rate of 1,000 gpm. Based on analytical methods of Jenkins (1968), described in Chapter 2, the cone of depression created by the well will intercept the stream and directly divert surface water. The well pumping at 1,000 gpm withdraws 4.4 ac-ft/day (2.2 cfs). After 6 months, approximately 96% of the water pumped by the well is derived from the stream (and 4% is from aquifer storage). Figure 62 shows the projected decline area caused by 1, 2, 4, 8, and 16 wells pumping at the rate described above. The instream models indicate that one well would cause small percentage declines in riparian abundance, while multiple wells would cause substantial declines (e.g., about 15% decline in riparian abundance for 8 wells). This vegetation decline would in turn lead to declines in densities of birds and other animals whose abundance is correlated with riparian biomass (Mills and others, 1991). As with any models, there are several assumptions that must be met to insure high accuracy of the predictions (see Chapter 2, Hydrology). If field conditions approximate the idealized assumptions (i.e., simple aquifer system with a single well pumping) the method will provide accurate predication. If, however, the aquifer is complex, or multiple interfering wells are concentrated near the stream, the cumulative impacts compromise the results. In this situation, a numerical groundwater model would be the preferred alternative. Even after the pumping well is discontinued, the stream will continue to lose water, and eventually the amount of streamflow depletion will equal the amount pumped.

Increasingly sophisticated models are being developed that show the interaction between surface flow and groundwater. Such models can predict surface water declines from groundwater pumping, or conversely, predict groundwater decline expected from surface water diversion. Riparian vegetation models, in turn, can predict riparian vegetation change from surface water decline (as described here) or from ground water decline (see San Pedro River Case Study).

Transferability of Instream Flow Models

There are numerous rivers in the State that have irrigation or municipal diversions that deplete surface flow. The cumulative impact of many small diversions can be high. Aravaipa Creek and the San Pedro River, for example, although free-flowing, have numerous diversion ditches. The potential application of instream flow models for assessing riparian loss expected from existing or additional flow diversions is thus high.

The instream flow relationships for the Verde River watershed were similar in some respects to those for the San Pedro/Santa Cruz watersheds. For example, abundance of Fremont cottonwood varied in similar fashion with flow rate in the central and southern Arizona watersheds. However, canopy foliage area and woody plant basal in vegetation foliage area were somewhat higher per unit of flow at the southern Arizona sites. The width of the mesquite-dominated fringe of the floodplain (and thus total riparian width) was much greater per flow unit in southern Arizona. This may be due to the summer-dominated precipitation and streamflow pattern of southern Arizona, which is more favorable for mesquite (because of its subtropical origin). Also, width of the alluvial aquifer, and thus the width of the zone suitable for deep-rooted riparian trees, may differ between the watersheds.

Empirical instream flow models also have been developed for streams in the semiarid eastern Sierra Nevada of California (Taylor, 1982). These models indicated that riparian strip width and riparian plant diversity increased with surface flow volume. Discharge, together with elevation, stream gradient, and an index of channel incision, explained 67% of the variation in strip width. The instream flow models developed for the Arizona watersheds differed in some ways from those developed by Taylor (1982).

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Figure 61. **Predicted reduction in woody plant basal area in the Verde River riparian zone (Clarkdale area) in response to stream depletion by surface water diversion.**

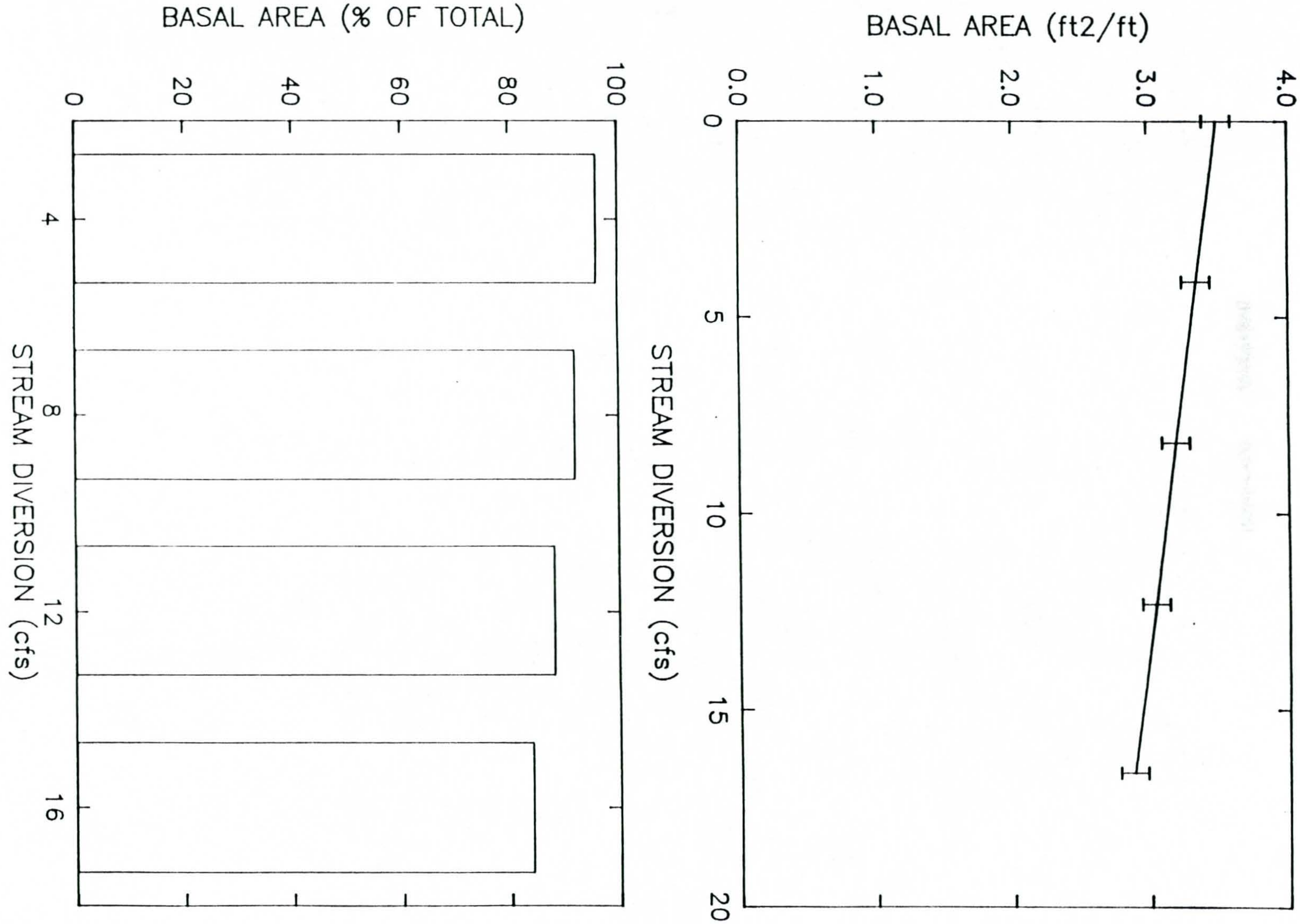

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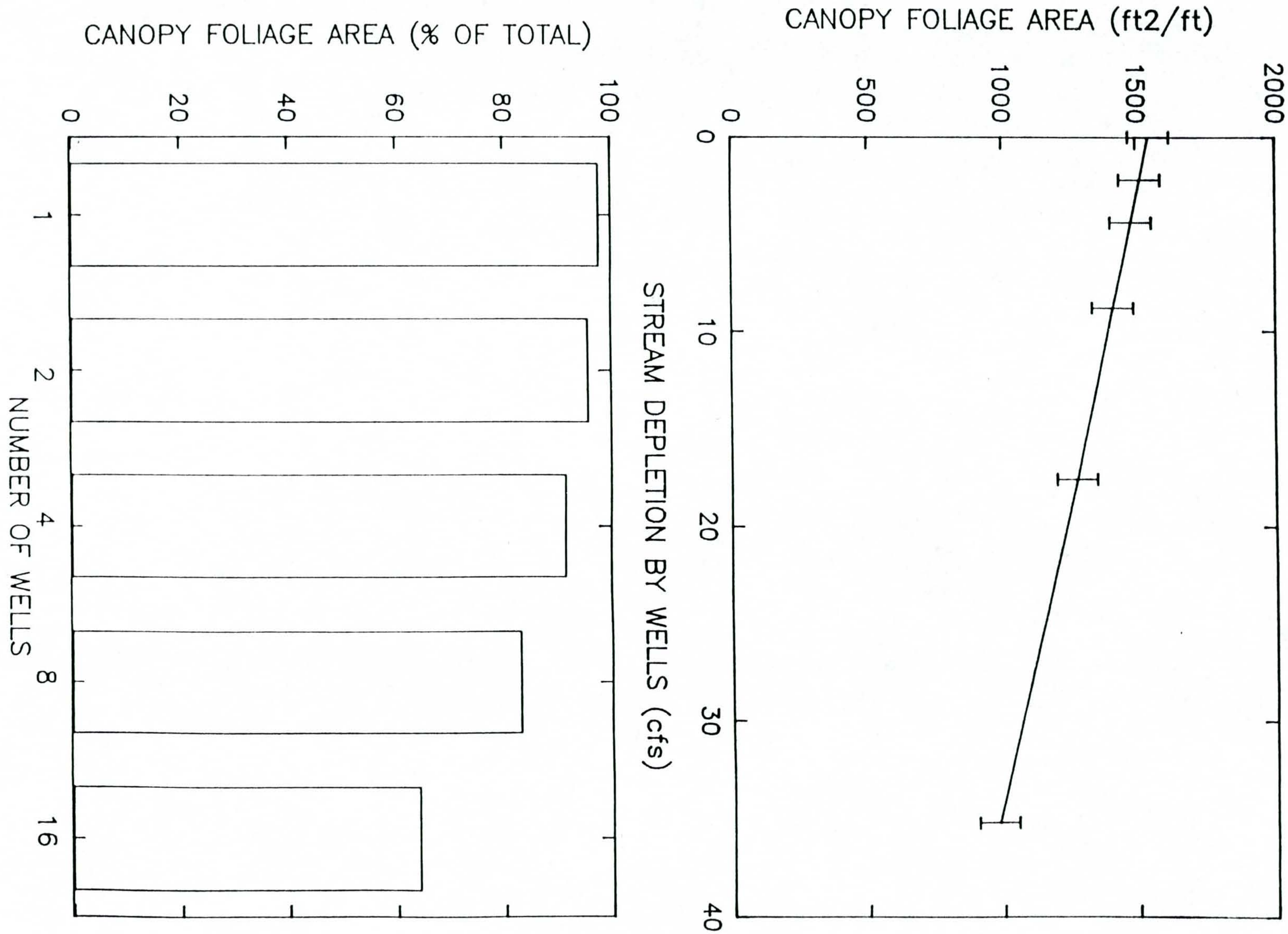
Figure 62. **Predicted reduction in canopy foliage area for the Verde River riparian zone (Clarkdale area) in response to stream depletion by groundwater pumping.**



For example, flow rate explained a much higher percentage of the variance in stand width within the Verde River watershed (>90%) than in the eastern Sierra Nevada (44%). This may be because the Sierra Nevada study sites encompassed a wider geographic area as well as greater geomorphic diversity.

Overall, these results suggest that instream flow models are to some degree transferable between watersheds of generally similar elevation and morphology. However, most accurate prediction will come from development of watershed-specific models, because individual watersheds have different physical characteristics as well as different assemblages of riparian plant species, each with unique environmental requirements and tolerances.

The ability of the instream flow models to predict riparian loss is based on the assumption that "space-for-time" substitutions are valid. Validation of the models would require a time-series approach of monitoring riparian abundance on streams undergoing flow reduction. Taylor (1982), for example, calibrated (developed) his instream flow models on undiverted streams and validated them on dewatered streams. On the dewatered streams, Taylor (1982) found that riparian vegetation abundance was lower than that expected based on historical flows.

It must be borne in mind, however, that vegetation response to dewatering may not occur immediately. Time-lags on the order of years to decades may occur as the riparian ecosystem adjusts to a new set of flow conditions. This is because tree mortality on partially dewatered streams often occurs episodically during periodic low-flow years. Also, young plants often are less tolerant of water stress and stream dewatering than are older plants (Smith and others, 1991). Whereas older plants may survive in a stressed condition for many years, the species may decline over time because new generations are not establishing to replace the old plants (Petts, 1985; Rood and Mahoney, 1990).

Flood Flows, Seasonal Flow Patterns, and Riparian Vegetation

Riparian Establishment

The instream flow models described in this study identify average flows needed to sustain riparian areas of varying abundance. They do not, however, address relationships between surface flows and specific ecological processes, such as seedling establishment. Whereas median and mean seasonal flow rates are important for the maintenance of riparian vegetation, periodic flood flows, accompanied by high flows in spring and summer, are necessary for riparian establishment. For example, a study of riparian recruitment dynamics along the Hassayampa River in central Arizona (elevation of about 2,000 ft) indicated that Fremont cottonwood established after winter or spring floods of a magnitude equal or greater than the seven-year return flow (Stromberg and Patten and others, 1991). Large winter floods set the stage for recruitment by scouring vegetation from channel banks and floodplains, and depositing fresh alluvium (thereby reducing herbaceous and overstory competition, at least temporarily). Small flood surges in spring served to moisten floodplains at an appropriate time (during the limited period of spring seed dispersal) and appropriate place (moderately high surfaces above the zone of frequent summer flood scour which can kill young plants).

High water tables produced by the receding flood waters were essential for high rates of seedling survivorship of both species. Along the Hassayampa River, Fremont cottonwood and Goodding willow seedlings had best survivorship on floodplains where water tables were between about 1 to 3 ft below the floodplain surface by summers end, and where water tables in early summer were within several inches of the floodplain surface. On sites where groundwater was deeper than these values, seedlings had high mortality from drought (because of limitations on maximum root growth attainable in one year), while those growing immediately along the stream banks (where groundwater was shallowest) died from summer flood scour. Studies in other regions show that rate of water table decline also influences seedling survivorship, with cottonwood seedlings having greatest survival in years in which floodwaters recede slowly during the growing season (e.g., no more than about 1 inch per day) (Mahoney and Rood, 1991). Water tables in alluvial rivers such as the Hassayampa and Verde fluctuate directly with river stage, and thus high flows during the seedling establishment period are essential to maintain the high water tables periodically needed for seedling survivorship.

On the lower Verde River, the ecological health of the riparian ecosystems is directly related to the management of Horseshoe and Bartlett Dams. Dams modify many attributes of the downstream ecosystem, and as a result, dam construction has contributed to the decline of riparian cottonwood and willow forests throughout the western United States (Rood and Mahoney, 1990). This decline is due, in part, to reduced flow releases and to reduced frequency of winter and spring floods needed for establishment of new generations of spring-germinating tree species (Bradley and Smith, 1986; Rood and Mahoney, 1990; Johnson, 1993). Loss or reduction in sediment and nutrients, and reduced frequency of river meandering and channel realignment also reduce establishment frequency by preventing formation of "nursery" bars for seed germination. On the lower Verde River, reduced flood frequency and reduced flows in March and April appear to be related to reduced cottonwood recruitment between Bartlett and Horseshoe Dams (McNatt and others, 1980). Similar phenomena are believed to be occurring in the riparian forests along the Salt River above its confluence with the Verde River, in a reach influenced by a flow-regulating dam (Stewart Mountain Dam). Fenner and others (1985) described how loss of spring flow peaks in this reach has reduced the frequency of Fremont cottonwood germination and produced a "decadent" population.

The upper Verde is not dammed and still follows a normal hydrograph with respect to flood frequency and magnitude. However, although the flood hydrograph remains intact, the effects of flooding on the riparian zone have been modified both because floodplain clearing has intensified flow velocities (thereby reducing ecosystem resistance to flooding) and because flow reduction has reduced the ability of the vegetation to recover (reducing its resilience). In a healthy riparian ecosystem, an abundance of water allows a dense vegetation cover to develop that stabilizes the floodplain soil and minimizes plant and soil loss from flood scour. Abundant water availability after the flood allows the plants to rapidly recover. Factors that stress the ecosystem before or after the flood, however, increase the damage caused by the flood. As a general rule, there are few plants that tolerate the combination of chronic stress and frequent disturbance or perturbation.

The Verde River, like many rivers in Arizona, experienced very large floods in early 1993. On the upper Verde, the combined effects of floodplain clearing and diversion-related water stress most likely exacerbated the destructive effects of floods in the riparian zone and decreased the recovery ability of the ecosystem. Many rivers in the state are recovering from this recent flood disturbance as evidenced by the abundance of a new generations of cottonwoods and other tree seedlings. On the upper Verde River, however, seasonal flow patterns are modified by agricultural diversions which typically divert most water in the growing season. The resultant low flows during the critical spring and summer seedling establishment period can reduce the ability of the riparian ecosystem to recover after floods. For example, large irrigation diversion ditches in the Verde Valley divert 90% of the Verde River summer flows between Clarkdale and Camp Verde (Plate 3). These diversions, and possibly groundwater pumping, are believed to be preventing new cottonwood recruitment and producing decadent (unhealthy, or over-mature) cottonwood age structures on the middle Verde (Design Workshop, 1992).

On the lower Verde River, there is evidence that drought-related vegetation reduction may have exacerbated riparian flood mortality (McNatt and others, 1980). As of 1983, the city of Phoenix had an infiltration gallery and 14 groundwater wells in a section of the Verde River located in the Fort McDowell Indian Reservation, to supply about 20,000 ac-ft/yr of water for municipal use (Water Resources Associates, 1983). In 1977, very low flows were released to this section of the Verde River due to operation needs of Bartlett Dam by SRP (McNatt, 1980). McNatt and others (1980) reported that a combination of natural drought, low flow release from Bartlett Dam, and groundwater pumping from the City of Phoenix's Verde River Infiltration Gallery and Well Facility resulted in death of 46% to 84% of the Fremont cottonwoods along a stretch of the Verde River in the Fort McDowell Indian Reservation during the late 1970's. Water Resources Associates (1983) further investigated this issue and concluded that floods, rather than drought, were the main cause of the mortality. Mortality of cottonwood was greater below the dam than above the dam. Few new generations of trees have established to replace the dead trees, and age-class diversity is low. The 1993 floods also caused mortality from which there is little recovery evident (personal observation of author).

Several studies have demonstrated the role that riparian loss from water diversion, groundwater pumping, cattle grazing, or wood cutting can play in decreasing the natural resistance and resilience of riparian ecosystems to flood disturbance. Platts and others (1985), for example, showed that large storm events of 1983 and 1984 had major impacts on heavily grazed riparian reaches. The effects were less pronounced in ungrazed watersheds in the Great Basin Desert region of Nevada (which is similar to the Basin and Range Province of Arizona). In the Sonoran Desert of central Arizona, poor riparian management and low plant cover contributed to high scour of Tonto Creek by the 1993 winter floods (Meyers, 1993). In California, as well, stream dewatering for hydropower production decreased the resistance of the ecosystem to flood impacts (Stromberg and Patten, 1992). Conversely, high flood survivorship on densely vegetated portions of Date Creek indicates the buffering effect and natural resilience of riparian zones (Knight, 1993). Extensive floodplain clearing for agriculture also decreases the ability of the riparian zone to buffer itself from flood effects (Ohmart and others, 1988).

Exotic Species

Changes in flood patterns and seasonal flow patterns also can affect spread of exotic species which are adapted to the altered flow conditions. The timing of seed dispersal and seed germination for native riparian trees closely tracks the timing of naturally high flow peaks. For example, Fremont cottonwood and Goodding willow germinate during spring, a period of naturally high flows, while mesquite germinates in abundance after the high summer monsoon flows. The exotic tree saltcedar, however, is an opportunistic plant that has more flexible germination and establishment requirements. Salt cedar disperses seeds throughout most of the growing season, although it begins to disperse seeds somewhat later in the year than do cottonwood and willow (e.g., June vs. April and May). In healthy riparian zones where conditions for native tree reproduction are present, dense thickets of cottonwood and willow seedlings develop that preclude germination of the later-germinating salt cedar. If flows are highest in summer or fall rather than spring or early summer (such as can occur if diversions are relatively greater in April, May or June than they are later in summer) conditions will favor the opportunistic tree saltcedar. For example, on the upper Verde, irrigation diversions reduce flows in spring and early summer, and may tip the balance in favor of salt cedar establishment. Increased salinity of irrigation tail water also favors salt cedar, which is much more salt tolerant than cottonwood or willow. Increased drought and lowered riparian water tables associated with diversions also favor salt cedar, because of its greater inherent drought tolerance. All of these factors may be contributing to the presence of salt cedar on the Verde River (see maps in AGFD, 1993). Once present, saltcedar excludes native species from its understory by pumping salt from the groundwater to the surface soil and by increasing riparian fire frequency (Busch and Smith, 1993).

Irrigation for agriculture during the summer months also typically results in greatest flow reduction during prime growth seasons for established riparian plants. The importance of high flows during the growing season has been demonstrated by Reily and Johnson (1982) in a study of the effects of Garrison Dam on the downstream Missouri River riparian ecosystem. They reported that several riparian tree species had reduced growth rates, due to a combination of shifts in the peak flow pattern from spring and summer to winter, as well as from reduced frequency of flood inundation. Growth reduction was attributed, in part, to the fact that seasonally high flows and water tables were no longer in phase with the vernal growth pattern typical of some floodplain trees. Many of the species studied by Reily and Johnson (1982) have closely-related Southwest riparian counterparts.

Consequences of Riparian Decline for Wildlife

Bird Species

Among the animals potentially impacted by loss or degradation of Verde River riparian forests are the 200 or so species of birds that nest in the Verde Valley, and the hundreds of waterfowl that use the river corridor as migratory nesting areas (Brown, 1985; VRCPSC, 1991). One species in particular, the Southwest willow flycatcher (*Empidonax traillii extimus*), has been proposed for listing as an endangered species by the U.S. Fish and Wildlife Service. Proposed critical habitat for this species along the Verde River includes that portion between about Cottonwood and Horseshoe Dam. Other species dependent on the riparian forests include the federally listed endangered Bald eagle (*Haliaeetus leucocephalus*) and peregrine falcon (*Falco peregrinus*), both of which nest in the cliffs and tall Fremont cottonwood trees along the river. Other rare raptors of the Verde River riparian zone include the common black hawk (*Buteogallus anthracinus*) and zone-tailed hawk (*Buteo albonotatus*) (both Forest Service sensitive species). Among passerine birds, the threatened yellow billed cuckoo (*Coccyzus americanus*) (Arizona Game and Fish listing), blue-throated hummingbird (*Lampornis clemenciae*), and summer tanager (*Piranga rubra*) are "obligate" riparian species that survive no where but cottonwood-willow forests (Anderson and Ohmart, 1986; Hunter and others, 1987). As an upper canopy dweller, the yellow billed cuckoo depends upon the tall-statured cottonwoods and willows for foraging and nesting (Reiner and Griggs, 1989). Several low-canopy specialists (e.g., Bewick's Wren, *Thyromanes bewickii*, and Common Yellowthroat, *Geothlypis trichas*) also depend upon riparian habitat. Many of these species are Neotropical migrants, a group for which the U. S.

Fish and Wildlife Service has documented severe population declines. Loss of riparian habitat increases the risk of extirpation for these species.

Fish Species

Native fish are among the most endangered of any animal group in the southwest (Minckley and Deacon, 1993). The Verde River is unique in supporting a strong native fish community in its headwaters, with more native fish species than any Arizona river except for Aravaipa Creek (VRCPSC, 1991). The Verde River fish fauna include the federally listed threatened spikedace (*Meda fulgida*) and other natives: longfin dace (*Agosia chrysogaster*), Gila Mountain sucker (*Pantosteus clarki*), Gila sucker (*Catostomus insignis*), roundtail chub (*Gila robusta*), and speckled dace (*Rhinichthys osculus*). Another federally listed species, the Gila trout (*Oncorhynchus gilae*), lives in a tributary to the Verde. All of these fish species depend upon healthy functional riparian ecosystems, and are adversely affected by changes in water temperature, sediment loads, and other factors resulting from riparian degradation.

Other Animals

The Verde River has been designated as a "Wildlife Resource Category 1" by the Arizona Game and Fish Department, signifying that it supports habitats that are of "the highest value to Arizona wildlife species, and are unique and/or irreplaceable on a statewide or ecoregion basis" (AGFD, 1991). Among these species are the red bat (*Lasiurus borealis*) (a Forest Service sensitive species), and many sensitive reptiles and amphibians, including federal candidates for listing (e.g., the Yavapai leopard frog, *Rana yavapaiensis*, and the narrow-headed garter snake, *Thamnophis rufipunctatus*). Many of these amphibians are highly sensitive to changes in water quality and are impacted by loss of riparian functions including toxin filtering.

CONCLUSIONS

The upper Verde River within the Verde Valley was selected as case study site to test instream flow models for the following reasons: (1) it presently supports a sensitive riparian forest with important ecologic functions and values, (2) a large amount of the Verde River streamflow is presently diverted for agricultural irrigation, (3) it is one of the most rapidly developing areas of the state and future impacts are highly probable, and (4) the stream-aquifer system is in direct hydraulic connection and the area generally meets the assumptions necessary for application of analytical hydrologic models. Based on projected future water demands for the Verde River area, models predict that some measures of riparian abundance may decline 10-15% within 20 years. This is assuming no changes in use occur such as converting agricultural water uses to municipal or industrial.

Riparian vegetation abundance in the Verde River watershed and other watersheds in Arizona varies significantly with flow rate of a stream, and is highly sensitive to changes (increases or decreases) in growing season flow rates. Because these relationships are significant, instream flow models were developed that related streamflow rate to general measures of riparian community abundance (e.g., stand foliage area) and to abundance of particular species (e.g., Fremont cottonwood).

In the instream flow models, surface flow is functioning as a surrogate indicator of water available to the riparian vegetation. The relationships between surface flow and riparian abundance exist not only because of the role that surface water plays in directly sustaining riparian vegetation but also because of the role that surface water plays in recharging groundwater (i.e., bank storage in floodplain aquifers).

The instream flow models are to some degree transferable between watersheds of similar elevation and geomorphic type. Surface flow-riparian abundance relationships developed for the Santa Cruz and San Pedro watersheds of southern Arizona were similar but not identical to relationships developed for the Verde River watershed.

The instream flow models can be used as tools to determine instream flows necessary to maintain existing amounts of riparian vegetation or to predict riparian response to flow reduction. When used in conjunction with hydrological methods, the models can project riparian response to flow reduction resulting from either surface water diversions or groundwater pumping. Such scenarios are described in this report, and indicate the percentage decline in riparian vegetation expected from different diversion rates or groundwater pumpage rates.

The Verde River riparian zones have been substantially reduced by the cumulative effects of many factors, including surface water diversions and groundwater pumping, as well as floodplain clearing for agriculture and urban development, sand and gravel mining, cattle grazing, and flooding on devegetated floodplains. However, because of time constraints, this case study was not intended as an exhaustive summary of the status and condition of the Verde River riparian ecosystems.

CONSIDERATIONS FOR RIPARIAN PROTECTION

Recommendations resulting from this case study are as follows:

- A hydrologic survey of the watershed should be undertaken immediately to accurately quantify existing diversions and water uses. Effects of proposed new diversions should be assessed with the instream flow models described in this report, to allow for consideration of effects of new diversions on riparian vegetation.

- Surface flow diversions should be minimized in the growing season, and in key seasons for riparian plant establishment (spring and early summer), to minimize riparian decline. This could be accomplished through retirement of agricultural lands, or by conversion of agricultural water rights to non-consumptive instream flow water rights.

- Studies should be undertaken to document and monitor changes in groundwater levels in the Verde River riparian zone and in the regional Verde aquifer. Based on this data, site-specific hydrologic models should be developed that incorporate the interrelationships between surface flow and groundwater along the Verde River.

- Groundwater pumping should be minimized in floodplain zones in which groundwater has declined below required levels for riparian tree seedling establishment or adult survivorship. These levels could be determined by applying groundwater relationships described for other rivers in the state (see Santa Cruz and San Pedro Case Studies).

- Site-specific ecological studies should be conducted that identify groundwater needs for seedling establishment and adult survivorship along the Verde River. These studies should identify groundwater and surface flow conditions associated with past successful establishment years.

- Thorough studies should be undertaken on the status of the Verde River riparian zone, using a combination of remote sensing and ground based field studies (see Santa Cruz Case Study). For example, remote sensing data can provide detailed high-resolution information on the locations and density of remaining riparian vegetation and on the locations of other land uses in the floodplain.

- Additional streamflow gaging stations should be constructed on the Verde River and its perennial tributaries. A network of riparian monitoring wells should be installed and monitored continuously to better characterize the hydrologic relationship within the Verde Valley area.

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APPENDICES

APPENDIX E. GROUNDWATER FLOW MODEL OF THE UPPER SAN PEDRO BASIN--T23S R21E, R22E

INTRODUCTION

The Arizona Department of Water Resources (ADWR) has developed a groundwater flow model of the Upper San Pedro River Basin (USP) for Township 23 S Range 21E and 22 E. This report documents the development and calibration of the numerical computer model, riparian case study scenarios, as well as recommendations for future improvement and uses of the model.

GOALS AND SCOPE

The goal of the Upper San Pedro Riparian Model (USP Riparian Model) is to provide an analytical tool capable of determining the hydrologic effect of groundwater pumping on streamflows and on the USP riparian areas.

PURPOSE

The purpose of this report is to document the development and calibration of the numerical computer model, the USP riparian case study scenarios, and recommendations for future improvement and uses of the model.

MODEL AREA

The USP basin is located in southeastern Arizona and northern Mexico. The USP basin extends from Mexico to "The Narrows" north of Benson. The Sierra Vista sub-basin extends approximately 23 miles south of the international boundary to approximately 27 miles north of the international boundary to Fairbank, Arizona. This area covers approximately 1,650 mi^2 and trends to the northwest. The area modeled in this study covers approximately 72 mi^2 and is located in T23S R21E, R22E (Figure 1).

The climate of the model area is semi-arid with hot summers and mild winters. Annual precipitation averages range from 25 to 30 inches per year in the Huachuca Mountains to approximately 12 inches along the San Pedro River (Putman and others, 1988). Most of the precipitation occurs during the winter months and during the summer monsoons. The model area is drained by the San Pedro River, which is generally perennial within the study area.

CONCEPTUAL MODEL

The USP basin is composed of an elongated north to south trending structural trough filled with basin-fill sediments from the adjacent mountains. The modeled area is bound to the west by the Huachuca Mountains and to the east by the Mule Mountains. Groundwater is stored within the basin-fill sediments. Water enters the model area as underflow from the south, infiltration along stream channels, and infiltration of surface water along mountain fronts.

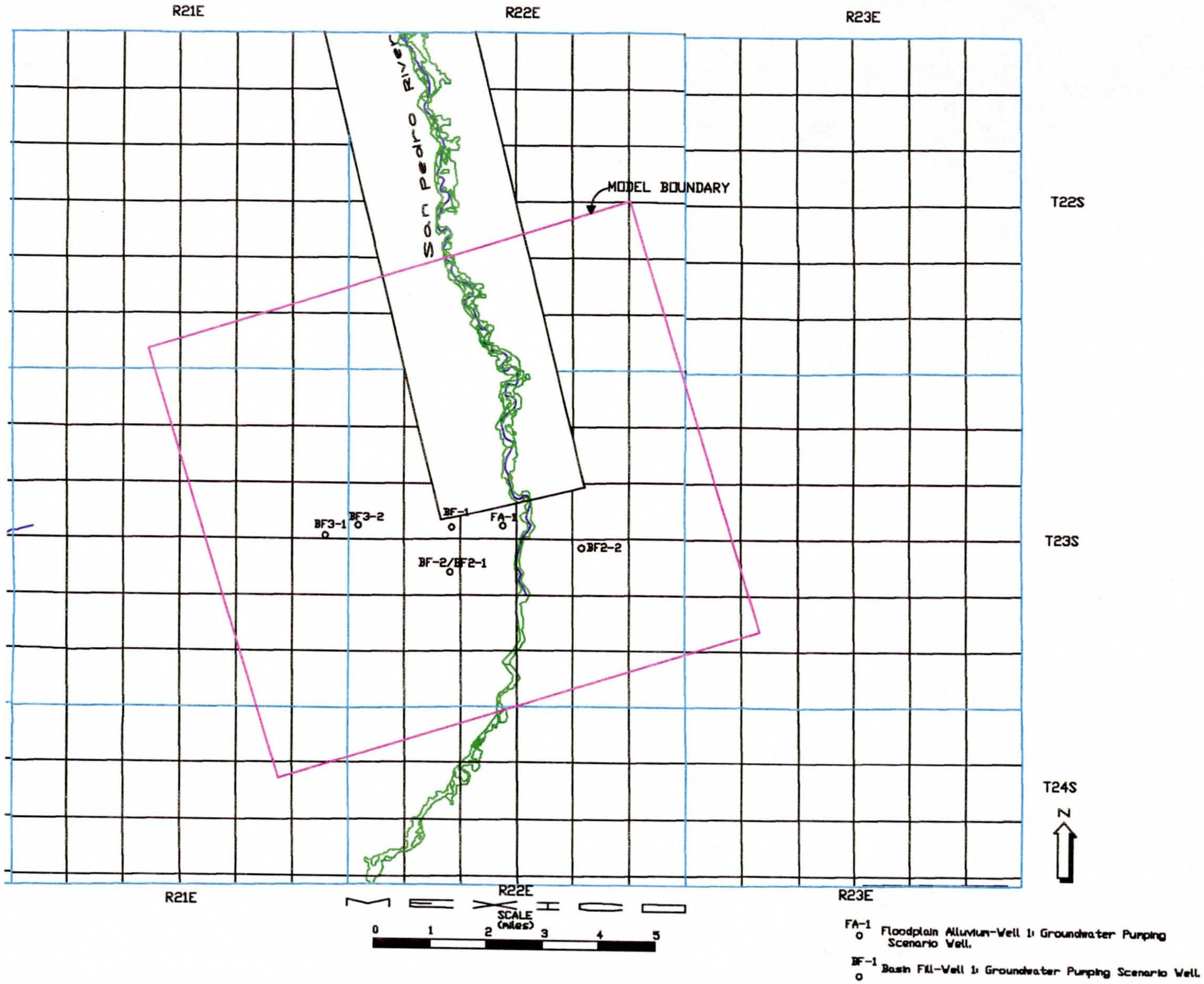
Mountain front recharge is the primary source of groundwater inflow to the model area along the Huachuca and Mule Mountains.

HYDROGEOLOGIC FRAMEWORK AND HYDRAULIC PROPERTIES

The majority of the data used to construct this model was obtained from a model of the San Pedro Basin developed by the USGS (Freethey, 1982). The following is a brief discussion of the hydrogeology obtained from this source.

The upper boundary of the aquifer is the water table, the lower boundary is the consolidated rock which forms the base of the structural trough and may be as deep as 5,000 feet (Oppenheimer and Sumner, 1980).

FIGURE 1
LOCATION OF UPPER SAN PEDRO BASIN--
RIPARIAN MODEL



The rocks and sediments that form the upper part of the main aquifer of the USP basin consist of Tertiary conglomerate, lower basin-fill, upper basin-fill, and floodplain alluvium associated with the floodplain of the San Pedro River. Hydrologically the lower and upper basin fill can be considered as one unit.

The floodplain alluvium is generally coarser grained than the basin-fill sediments and generally higher in hydraulic conductivity.

Transimissivity of the basin fill is as low as 100 ft^2/d near mountain fronts to as high as 15,000 ft^2/d in central areas of the basin.

Confined groundwater conditions occur in local areas where lenses of silt and clay occur. A few wells in the Palominas - Hereford area have water levels above land surface, this is a local condition and regionally the aquifer is unconfined.

Estimated values of storage coefficient from aquifer tests and analysis of driller's logs range from 0.03 to 0.25.

MOUNTAIN FRONT RECHARGE

Mountain front recharge within the model area occurs along the Huachuca and Mule Mountains. The Huachuca Mountains due to higher elevations receive approximately 25 inches per year with recharge ranging from 5.5 ft^3/s to 6.9 ft^3/s. The Mule Mountains are much lower in elevation and recharge is approximately 2.8 ft^3/s.

UNDERFLOW

Groundwater underflow moves from the upper reaches of the USP basin across the international boundary and into the study area. The quantity of this underflow has been estimated at 3,500 acre-feet/year (Harshbarger and Associates, 1974).

STREAM AQUIFER CONNECTION

The San Pedro River is in hydraulic connection with the aquifer. Seepage investigations by the USGS in 1969 and 1970 indicate an average streamflow increase of 8.5 ft^3/s from Palominas to Charleston. Groundwater flow is discharged to the stream in this reach (gaining conditions).

EVAPOTRANSPIRATION

Evapotranspiration occurs along the San Pedro River where groundwater is near land surface and groundwater is transpired by riparian vegetation. Factors affecting the rate of evapotranspiration include soil type, soil moisture, groundwater levels, vegetation type, elevation, and seasonal variations. Evapotranspiration rates within the study area range from 3.0 acre-feet per acre near Charleston to 2.0 acre-feet/acre near Hereford (Stromberg, 1993).

NUMERICAL MODEL

The objective in developing a numerical groundwater flow model of the USP basin T23S R21E, 22E was to determine the areal extent of the effects of groundwater pumpage on streamflow and on riparian vegetation. Table 1 provides a description of the general characteristics of the USP Riparian model.

MODEL CODE

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 USP Riparian Model also incorporated the Streamflow Routing Package (Prudic, 1989). This package allows the model to account for the amount of flow in streams and to simulate the interaction between surface streams and groundwater.

Table 1 GENERAL CHARACTERISTICS OF THE USP RIPARIAN MODEL		
MODEL CHARACTERISTIC	DESCRIPTION	MODEL UNIT
Steady-State Calibration	circa 1940 (Predevelopment)	
Model Grid	38 rows X 28 columns	Length = Feet
Layer 1 (FA)	Unconfined Aquifer	Length = Feet
Layer 2 (BFU)	Confined/Unconfined Aquifer	
Layer 3 (BFL)	Confined/Unconfined Aquifer	
Horizontal Hydraulic Conductivity	No Horizontal Anisotropy	Feet/Day
Vertical Hydraulic Leakance	Provided using VCONT	1/Day
Specific Yield	Volume of water yielded per unit area per unit change water table elevation	Dimensionless
Storage Coefficient	Volume of water yielded per unit area per unit change in confined aquifer potentiometric surface elevation	
Recharge	Applied to uppermost active cell	Feet/Day
Pumpage	Distributed to cells in USP riparian case studies	$Feet^3/Day$
Model Cell Types	No-Flow, Constant and Variable Head	
Boundary Conditions	Constant Head, Constant Flux	
Numerical Solution Technique	Strongly Implicit Procedure	0.01 Feet Closure Criteria

FA = Floodplain Alluvium
BFU = Basin-Fill Upper
BFL = Basin-Fill Lower

MODEL SIMULATION PERIODS

The model has been used to simulate the steady-state groundwater flow conditions of the predevelopment era (circa 1940). The model was also used to simulate transient-state groundwater flow conditions between 1940 and 1990. However, limited time did not allow for calibration of the transient-state model.

GENERAL MODEL CHARACTERISTICS

The model was constructed using six packages offered by MODFLOW. The packages utilized include: (1) the BASIC package, (2) the Block Centered Flow (BCF) package, (3) the WELL package, (4) the Stream Flow Routing (SRP) package, (5) the Evapotranspiration (EVT) package, and (6) the Strongly Implicit Procedure (SIP) package. A brief description of each MODFLOW package and how they relate to the modeling of the hydrogeologic system follows. The model unit of length was feet and of time was days.

The BASIC package established the orientation of the active model area, boundary conditions, initial water levels, and the discretization of time.

The BCF package simulated the hydrogeologic framework of the model area. This package contains the basic geologic inputs to the model and computed the conductance components of the finite-difference equation which determine flow between adjacent cells. It also computed the terms that determine the rate of movement of water to and from storage.

The WELL package simulated groundwater pumpage from the aquifer at specified rates for the riparian case studies which will be discussed later in the report.

The Recharge package simulated the areal distribution of mountain front recharge.

The SRP package was used to simulate the amount of flow in streams and to simulate the interaction between surface streams and groundwater.

The EVT package simulated the effects of plant transpiration and direct evaporation in removing water from the saturated groundwater system.

The SIP package was used to implement the Strongly Implicit Procedure, 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).

MODEL GRID

The USP Riparian model is 38 rows by 28 columns, with 3 layers and is aligned 15 degrees west of due north. A variable size grid was used to obtain better resolution in the primary area of interest, model cells in the area of the San Pedro River and within the floodplain alluvium are 1320 feet by 660 feet. Each model layer corresponds to a single hydrogeologic unit. The active model domain encompasses approximately 72 square miles and is primarily located in T23S and R21E, 22E.

MODEL LAYERS AND AQUIFER CONDITIONS

Three model layers were used in the model to represent the three hydrogeologic units modeled. The uppermost layer, Layer 1, corresponds to the floodplain alluvium (FA). The FA is modeled as an unconfined aquifer. The middle layer, Layer 2, corresponds to that part of the basin-fill for which data were available (Freethey Model Layer 1). Layer 2 is modeled as a confined/unconfined aquifer, confined when the overlying FA is saturated and unconfined when the FA is unsaturated. The bottom layer, Layer 3, corresponds to basin-fill greater than 1,000 feet in depth (Freethey Model Layer 2).

There are two types of active cells used in the model, (1) variable head, and (2) constant head. Variable head cells permit the water level elevation to vary with time. Variable head cells comprise the active simulated region within the model. Constant head cells fix the water level elevation at a constant specified elevation.

Constant head cells are specified at locations along the model boundary where groundwater underflow enters or leaves the model domain. The cells permit groundwater fluxes to change at the boundaries in response to changing hydraulic gradients within the model domain. Constant head cells are located at the north and south boundaries of the USP Riparian model.

WATER LEVELS

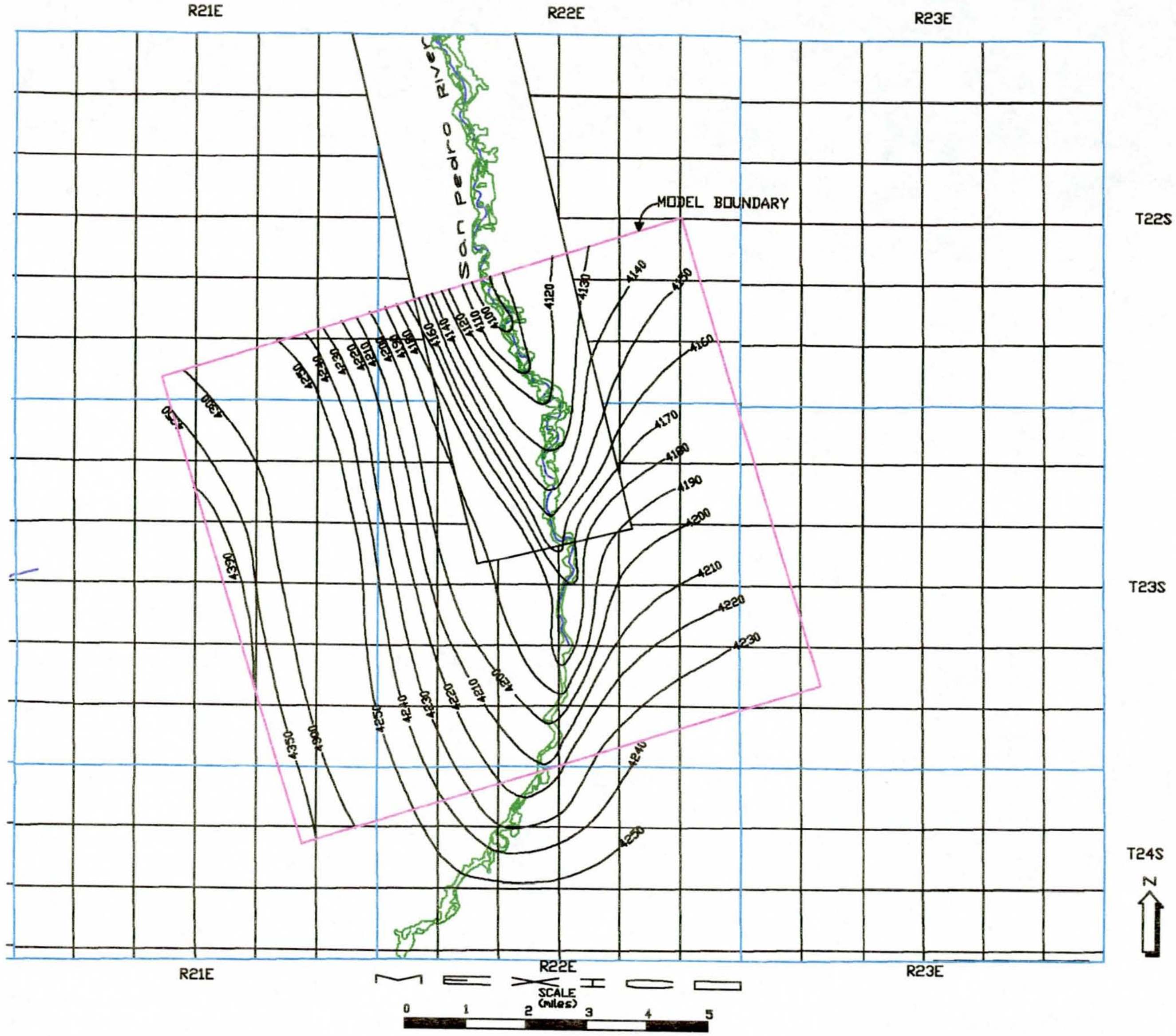
The water level data for the steady-state model simulation was constructed from data obtained from GWSI (Groundwater Site Inventory, an ADWR database) and is representative of the predevelopment groundwater system, circa 1940. The configuration of the water table circa 1940 is presented in Figure 2. This map is assumed to be representative of the predevelopment groundwater levels. The same water level elevation was used for all three model layers as it was assumed there was little vertical hydraulic gradient in the predevelopment era.

The transient model simulation (1940 - 1990) used heads generated by the final calibrated steady state model run as initial heads. A map was constructed from GWSI water level data for 1990. The 1990 water level map serves as a guide for the calibration of the ending transient model heads. However, due to time limitations the model has not been calibrated for transient-state.

MODEL CALIBRATION--STEADY STATE

The USP Riparian model was initially calibrated to the steady-state conditions that characterized the predevelopment era (circa 1940). The primary purpose of the steady-state calibration was to refine the original estimates of river bed conductance, vertical conductance (VCONT) between layers, and to obtain model calibrated heads for use in the transient-state model. The estimates of mountain front recharge and hydraulic conductivity are unchanged from those estimates of the USGS model of the USP basin (Freethey, 1982).

FIGURE 2
Upper San Pedro Riparian Model
Predevelopment Water Levels
(Circa--1940)



Initial estimates of river conductances for the San Pedro River were calculated for each active river cell. The initial estimates of river conductance per river cell were equal to the product of the reach length, width, estimated vertical hydraulic conductivity divided by the estimated river bed thickness.

All steady-state boundary fluxes were represented by constant-head cells. These fluxes included groundwater underflow in from the south, and groundwater underflow out to the north. Identical steady-state water level arrays were used as initial heads for all layers as it was assumed there was little vertical hydraulic gradient between the layers. Figure 2 illustrates the water levels circa 1940 used as initial heads for the steady-state calibration.

The steady-state calibration process involved making adjustments to VCONT and river conductances until an acceptable match between model simulated water levels and measured water levels was obtained. Figures 3, 4, and 5 show the final model simulated steady-state water levels, in comparison to Figure 2 it can be seen that a reasonable head match was obtained.

In addition, water budget fluxes were compared to the independent estimates to assure that inflows and outflows were maintained within an acceptable range.

STEADY-STATE WATER BUDGETS

The volumetric water budget 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). Acceptable steady-state model solutions should have small differences between total inflows and outflows. Table 2 presents a comparison of the conceptual water budget for the predevelopment era (circa 1940) to the final calibrated steady-state model run--SS56. The two water budgets compare favorably indicating that the model reasonably simulated the steady-state groundwater flow conditions of the predevelopment era.

Table 2
Steady-State Water Budget Comparison
Conceptual Water Budget vs. Model Run SS-56
(acre-feet)

INFLOW	CONCEPTUAL	MODEL RUN SS-56
Underflow	3500	3680
Recharge	2280	2280
Stream Leakage	0	40
TOTAL IN	**5780**	**6000**
OUTFLOW		
Underflow	1500	1740
Evapotranspiration	1550	1550
Stream Leakage	2730	2720
TOTAL OUT	**5780**	**6010**

UPPER SAN PEDRO BASIN RIPARIAN MODEL CASE STUDIES

To determine the hydrologic effect of groundwater pumping on riparian areas several USP Riparian Model case study scenarios were run, the results of these model runs follow. Model runs were simulated under transient conditions with constant head boundaries at the north and south model boundaries. The final calibrated water levels of steady-state model run SS56 are used as initial heads for the case study scenarios. Each scenario simulated pumpage in either the floodplain alluvium (FA), or in the basin-fill aquifer (BF), and was run for time periods of 6 months, 1 year, 10 years, and 20 years. Each model run was then analyzed to determine the areal extent of drawdown greater than 1 feet, 3 feet, and 6 feet for the floodplain alluvium (Layer 1). Also tabulated are maximum drawdown for Layer 1 and Layer 2, and changes in San Pedro River leakage as compared to a base case in which no pumpage is simulated.

FIGURE 3
Final Steady-State Model Simulated
Water Levels--Layer 1 (Floodplain Alluvium)

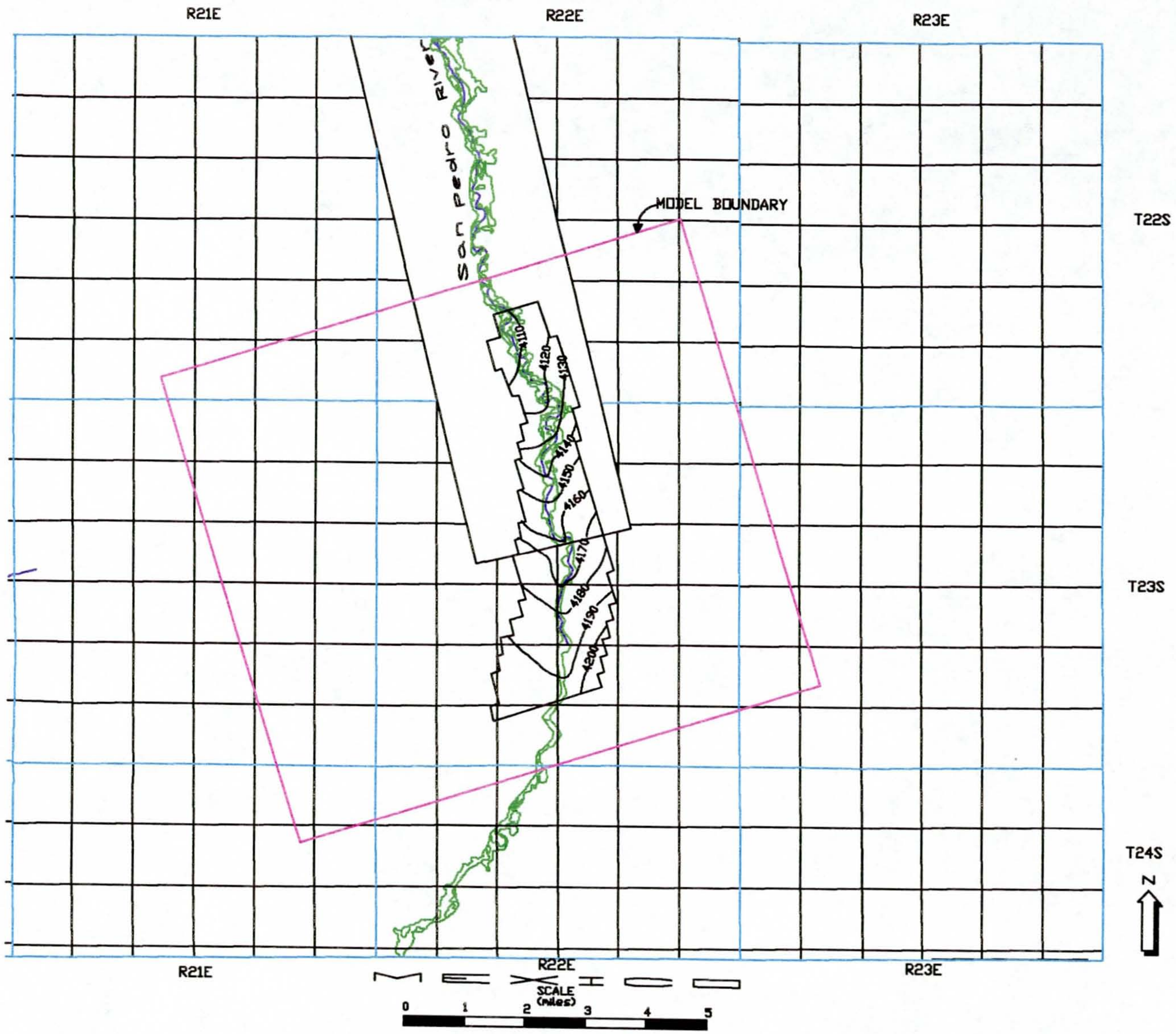
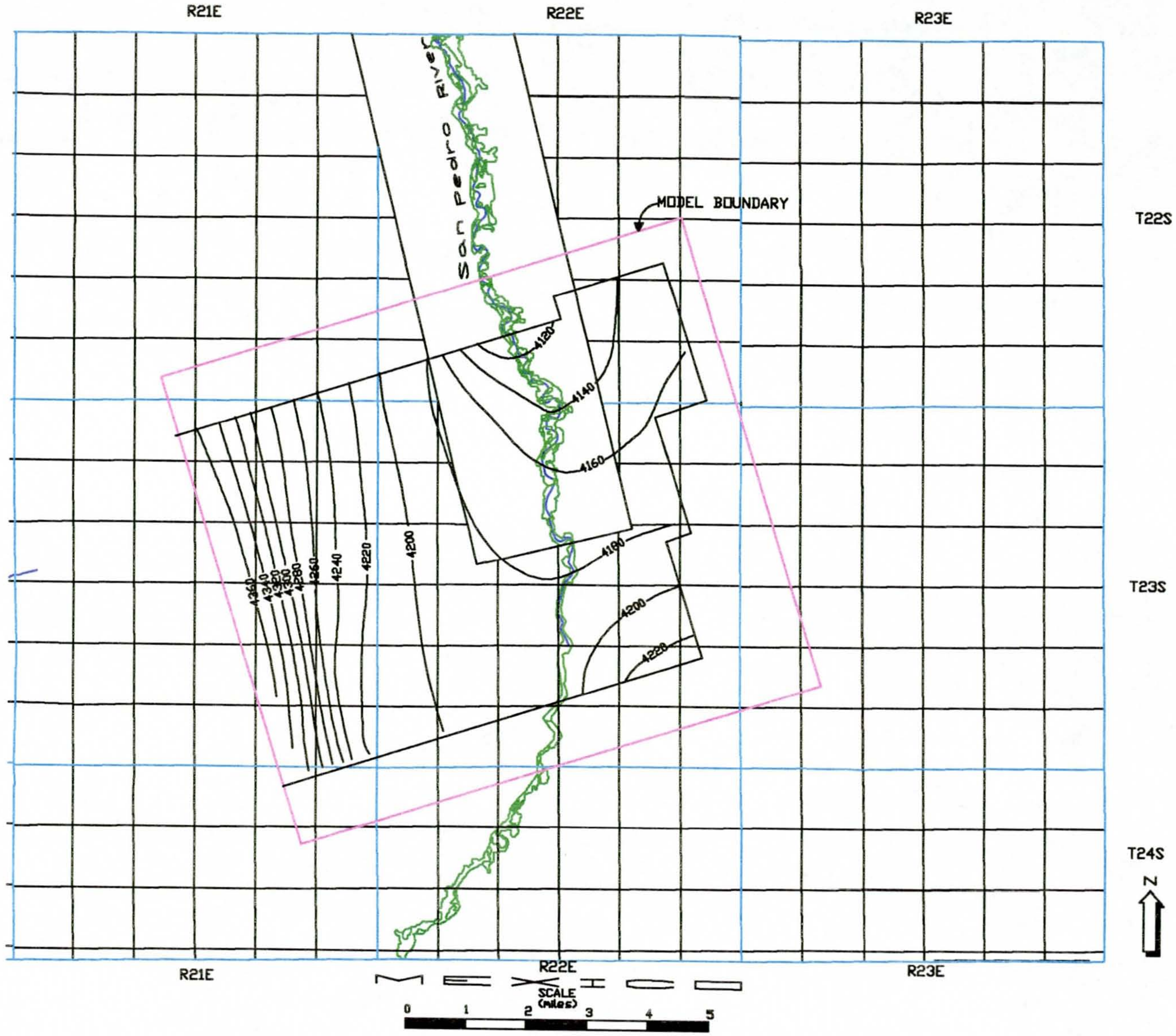


FIGURE 4
Final Steady-State Model Simulated
Water Levels--Layer 2 (Basin-Fill Upper)

FIGURE 5
Final Steady-State Model Simulated
Water Levels Layer 3--(Basin-Fill Lower)



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USP RIPARIAN MODEL CASE STUDY--Scenario 1

Scenario 1: A well in the floodplain alluvium located in T23S R22E Sec 16D. This corresponds to USP Riparian model row 18 col 11. Set Q = 500 gpm or 2.21 acre-feet/day. Determine what is the impact on water levels due to this pumpage in areal extent (@ 1', 3', and 6' drawdown) for Layer 1, for time periods of 6 months, 1 year, 10 years, and 20 years.

Model Run FA1-1 = 6 months
Model Run FA1-2 = 1 year
Model Run FA1-3 = 10 years
Model Run FA1-4 = 20 years

Tabulate results;

TABLE 3: RESULTS OF SCENARIO 1								LAYER 1 DRAWDOWN AREA > 1 Ft, 3 Ft, 6 Ft (Acres)			Layer 1
MODEL RUN	TIME	SAN PEDRO RIVER LEAKAGE				EVT	% CHANGE	@ >1 Ft DDN	@ >3 Ft DDN	@ >6 Ft DDN	MAX DDN (Feet)
		GAIN	% CHANGE	LOSE	% CHANGE						
FA1-1	6 mo	1188	-6%	25	0	777	0	473	211	139	40.8
FA1-2	1 yr	2267	-9%	62	+16%	1550	0	666	253	167	47.7
FA1-3[1]	10 yr										
FA1-4[1]	20 yr										

[1] Model Run FA1-3: Model cell 1 18 11 (layer,row,col) went dry at iteration 11 of time step 1. This is 3.7 years into the simulation and corresponds to the cell where well FA1 is located. Therefore model run FA1-4 was not simulated.

Note: GAIN = San Pedro River Leakage gaining in the case study scenario
LOSE = San Pedro River Leakage losing in the case study scenario.
% Change = the % change in leakage from a base case model run in which no pumpage was simulated.

USP RIPARIAN MODEL CASE STUDY--Scenario 2

Scenario 2: Two wells in the basin-fill alluvium located in T23S R22E Sec 17d and 20d. Determine what is the impact on water levels due to this pumpage in areal extent (@ 1', 3', and 6' drawdown) in Layer 1, for time periods of 6 months, 1 year, 10 years, and 20 years.

Well BF#1 row 11 col 12 Q = 500 gpm (2.21 ac-ft/d)
Well BF#2 row 9 col 9 Q = 500 gpm (2.21 ac_ft/d)

Model Run BF-1 = 6 months
Model Run BF-2 = 1 year
Model Run BF-3 = 10 years
Model Run BF-4 = 20 years

Tabulate results;

TABLE 4: RESULTS OF SCENARIO 2								LAYER 1 DRAWDOWN AREA >1 Ft, 3 Ft, 6 Ft (Acres)			LAYER 1	LAYER 2
MODEL RUN	TIME	SAN PEDRO RIVER LEAKAGE				EVT	% CHANGE					
		GAIN	% CHANGE	LOSE	% CHANGE			@ >1 Ft DDN	@ >3 Ft DDN	@ >6 Ft DDN	MAX DDN (Feet)	MAX DDN (Feet)
BF-1	6 mo	1230	-3%	25	0	777	0	535	0	0	2.48	17
BF-2	1 yr	2361	-6%	54	+4%	1549	0	1017	<1	0	3.5	18.9
BF-3	10 yr	20533	-18%	700	+23%	15499	0	2382	677	0	6.72	23.6
BF-4	20 yr	39848	-20%	1473	+26%	30998	0	2431	729	<2	7.13	24.1

* % CHANGE: From model run with no pumpage in the simulation

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USP RIPARIAN MODEL CASE STUDY--Scenario 3

Scenario 3: Two wells in the basin-fill alluvium located on both sides of the floodplain alluvium (Layer 1) in T23S R22E Sec 20d and 23b. Determine what is the impact on water levels due to this pumpage in areal extent (@ 1', 3', and 6' drawdown) for Layer 1, for time periods of 6 months, 1 year, 10 years, and 20 years.

Well BF2#1 row 9 col 9 Q = 500 gpm (2.21 ac-ft/d)
Well BF2#2 row 28 col 8 Q = 500 gpm (2.21 ac_ft/d)

Model Run BF2-1 = 6 months
Model Run BF2-2 = 1 year
Model Run BF2-3 = 10 years
Model Run BF2-4 = 20 years

Tabulate results;

TABLE 6: RESULTS OF SCENARIO 3								LAYER 1 DRAWDOWN AREA >1 Ft, 3 Ft, 6 Ft (Acres)			LAYER 1	LAYER 2
MODEL RUN	TIME	SAN PEDRO RIVER LEAKAGE				EVT	% CHANGE					
		GAIN	% CHANGE	LOSE	% CHANGE			@ >1 Ft DDN	@ >3 Ft DDN	@ >6 Ft DDN	MAX DDN (Feet)	MAX DDN (Feet)
BF2-1	6 mo	1230	-3%	25	0	777	0	402	0	0	2.42	9.5
BF2-2	1 yr	2363	-6%	53	0	1549	0	1233	0	0	3.07	10.6
BF2-3	10 yr	21001	-16%	670	+19%	15499	0	2343	323	0	4.87	13.6
BF2-4	20 yr	41163	-17%	1388	+22%	30998	0	2377	383	0	5.1	13.9

* % CHANGE: From model run with no pumpage in the simulation

USP RIPARIAN MODEL CASE STUDY--Scenario 4

Scenario 4: Two wells in the basin-fill alluvium located on the same side of the floodplain alluvium (Layer 1) in T23S R21E Sec 13d and T23S R22E Sec 18c. Determine what is the impact on water levels due to this pumpage in areal extent (@ 1', 3', and 6' drawdown) for Layer 1, for time periods of 6 months, 1 year, 10 years, and 20 years.

Well BF3#1 row 3 col 14 Q = 500 gpm (2.21 ac-ft/d)
Well BF3#2 row 4 col 14 Q = 500 gpm (2.21 ac_ft/d)

Model Run BF3-1 = 6 months
Model Run BF3-2 = 1 year
Model Run BF3-3 = 10 years
Model Run BF3-4 = 20 years

Tabulate results;

TABLE 7: RESULTS OF SCENARIO 4								LAYER 1 DRAWDOWN AREA > 1 Ft, 3 Ft, 6 Ft (ACRES)			LAYER 1	LAYER 2
MODEL RUN	TIME	SAN PEDRO RIVER LEAKAGE				EVT	% CHANGE					
		GAIN	% CHANGE	LOSE	% CHANGE			@ >1 Ft DDN	@ >3 Ft DDN	@ >6 Ft DDN	MAX DDN (Feet)	MAX DDN (Feet)
BF3-1	6 mo	1265	0	25	0	777	0	0	0	0	1.18	24.17
BF3-2	1 yr	2500	0	52	0	1549	0	0	0	0	1.19	32.83
BF3-3	10 yr	23762	-5%	575	+6%	15499	0	1262	0	0	2.97	73.79
BF3-4	20 yr	45817	-8%	1280	+16%	30998	0	1986	137	0	4.52	83.61

* % CHANGE: From model run with no pumpage in the simulation

Table 8 illustrates the change in streamflow out due to pumpage in Scenarios 1 to 4 as compared to a base case, the final calibrated steady-state model run--SS 56.

Table 8
Summary of Streamflow Changes--Scenarios 1 to 4

MODEL RUN	Streamflow In (cfs)	Streamflow Out (cfs)			
		6 months	1 year	10 years	20 years
SS 56 (base case)	32	36	36	36	36
Scenario 1	32	35.1	34.9	n/a	n/a
Scenario 2	32	35.2	35.1	34.6	34.5
Scenario 3	32	35.2	35.1	34.7	34.7
Scenario 4	32	35.4	35.3	35.1	34.8

RECOMMENDATIONS

Recommendations are provided to improve future data collection and analysis efforts. The recommendations include the following:

1. Complete the transient-state (1940 - 1990) calibration to bring the model up to date to current groundwater conditions. Upon completion of transient-state calibration, rerun USP Riparian Model case study scenarios 1 to 4.

2. Extend the western model boundary further west to the hardrock boundary of the Huachuca Mountains. The western boundary of the Freethey model (USGS, 1982) is located approximately 3 to 4 miles from hardrock. Recent pumpage appears to be intercepting the mountain front recharge before reaching the current boundary.

3. Incorporate the General Head Boundary (GHB) package for transient-state. The GHB package provides a convenient way to change boundary head values during the simulation. The southern model boundary is currently configured with constant heads which may be allowing to much water to enter the model domain during transient conditions.

4. The accuracy of the transient model could be improved by seasonalizing (dividing) the pumpage and evapotranspiration into winter and summer stresses, or two stress periods per year.

5. Add another model layer to simulate the silt and clay lenses underlying the floodplain alluvium in the Palominas-Hereford area.

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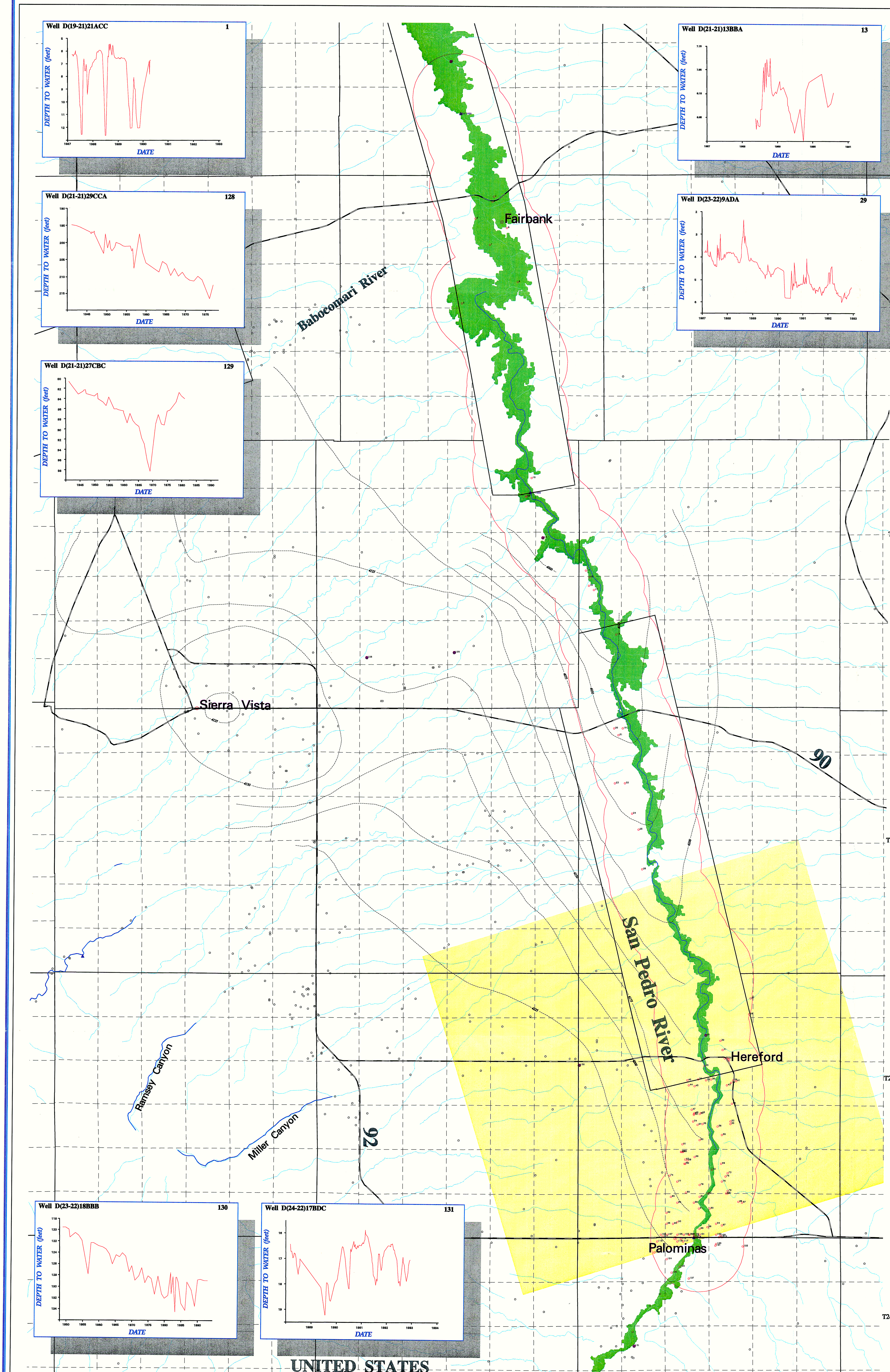
PLATES

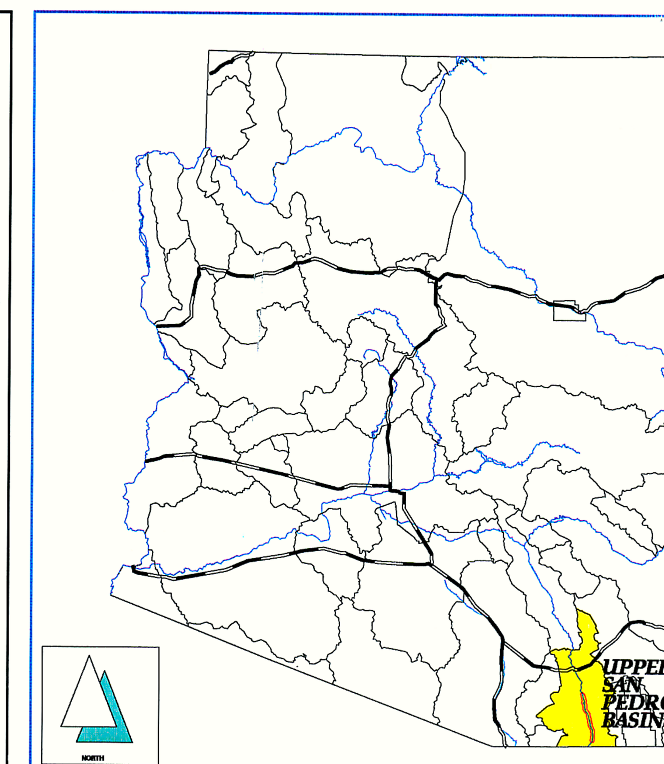
UPPER SAN PEDRO RIVER

PLATE 1

UPPER SAN PEDRO RIVER



This map is preliminary and subject to review (printed on 11/93).



WELL INFORMATION

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2	D-20-21 03BDD	314324110111601
3	D-20-21 03CAA	314318110111801
4	D-20-21 03DDC	314300110105701
5	D-20-21 03CD	314258110114201
6	D-20-21 10AAC	314247110105801
7	D-20-21 10CAA	314227110112201
8	D-20-21 14BCC	314143110104301
9	D-20-21 16DDC	314117110120101
10	D-21-21 02D	313750110102401
11	D-21-21 11AAC	313728110103101
12	D-21-21 11AA	313728110103201
13	D-21-21 13BBA	
14	D-21-22 18CCA	313600110090801
15	D-21-22 19BAB	313552110090301
16	D-21-22 19BAC	313542110090401
17	D-21-22 19BDB	313537110085701
18	D-21-22 30ADA	313444110082601
19	D-22-22 05BC	313252110081701
20	D-22-22 06ADC	313252110082901
21	D-22-22 06DAC	313250110082301
22	D-22-22 08CBC	313155110081501
23	D-22-22 07DAD	313147110082801
24	D-22-22 17CBA	313110110080701
25	D-22-22 17CDB	313052110075501
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31	D-23-22 10CDB	312630110055801
32	D-23-22 10CDD	312620110055101
33	D-23-22 10CDC	312620110055501
34	D-23-22 09DDD	312630110062401
35	D-23-22 16AAA	312611110062301
36	D-23-22 15BCC	312555110061401
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46	D-23-22 15DCC	312526110054501
47	D-23-22 21ABB	312519110064101
48	D-23-22 21AAC1	312515110062801
49	D-23-22 21ABD3	312515110063701
50	D-23-22 21AAC2	312514110063001
51	D-23-22 21ABD1	312514110063801
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53	D-23-22 22BDA	312508110055301
54	D-23-22 21ACD	312505110063901
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59	D-23-22 22CAC	312449110055901
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74	D-23-22 28CBB	312401110071201
75	D-23-22 27CAA1	312400110055401
76	D-23-22 27CAC	312357110055901
77	D-23-22 28CAC	312354110070101
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88	D-23-22 33ABD	312329110063801
89	D-23-22 33BAC	312329110070101
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92	D-23-22 33BCC	312317110071601
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HYDROGRAPHS

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129	D-21-21 27CBD	313421110121401
130	D-23-22 18BBB	312614110091901
131	D-24-22 17BDC	312039110080101

STREAM GAGE INFORMAT

USGS ID	NAME	PERIOD OF RECOR
9471550	SAN PEDRO RIVER NEAR TOMBSTONE, ARIZ.	1967-1986
9471000	SAN PEDRO RIVER AT CHARLESTON, ARIZ.	1912-PRESENT
9470500	SAN PEDRO RIVER AT PALOMINAS, ARIZ.	1951-PRESENT

Township and Range lines

Section lines

One mile well selection buffer

Perennial Stream/River
Source: Arizona Game and Fish Department

Non-Perennial Stream/River
Source: Arizona Game and Fish Department

Riparian Vegetation
Source: AG&FD preliminary vegetation mapping contracted through UofA Advanced Resources Tech. Lab

Water table elevation contour
Source: ADWR, 1991

Sub-regional model boundary

Well location within the well selection buffer zone

Well location outside of the well selection buffer zone

Well with a referenced hydrograph

Stream Gage Location

City/Town

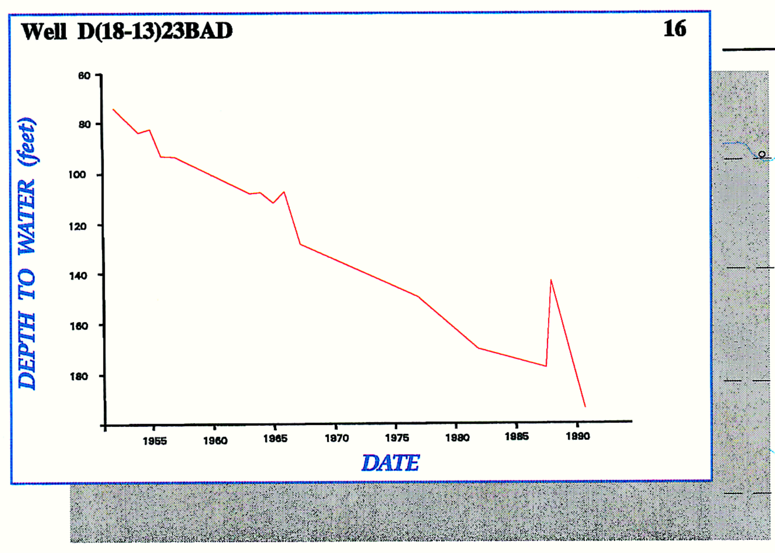
ARIZ
DEPA
OF W
RESO

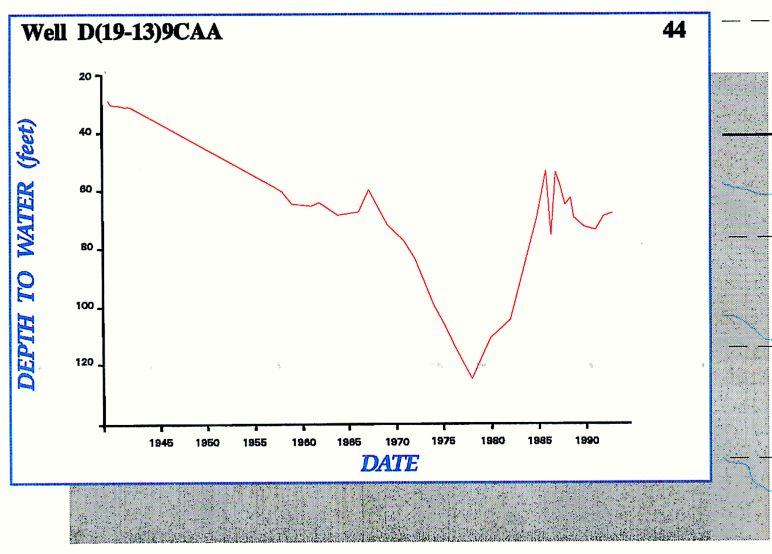
0 1 2 3

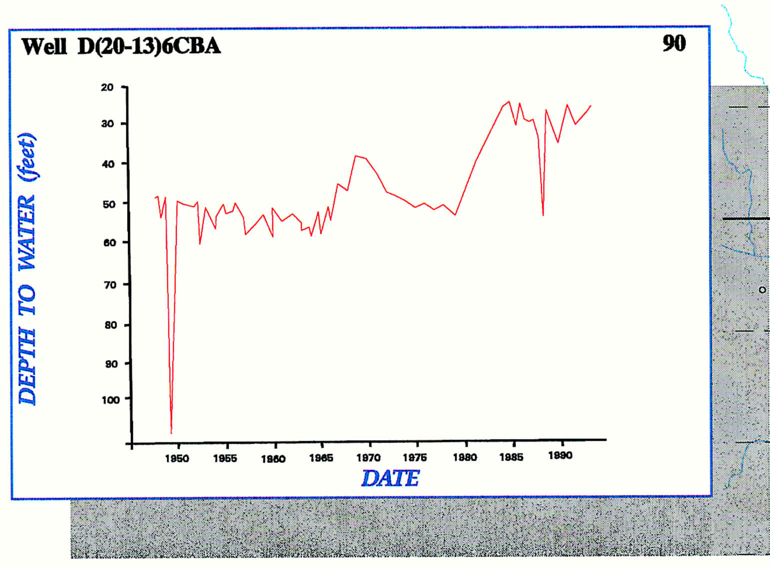
MILES

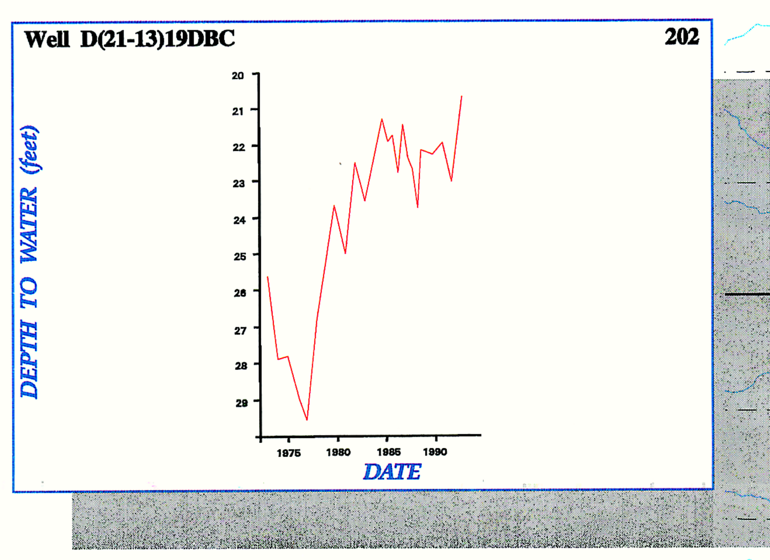
Scale 1:48941

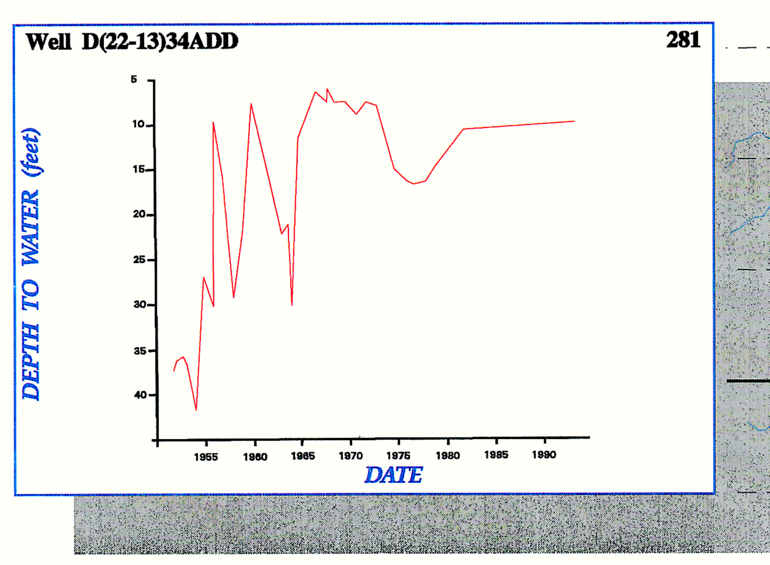
UPPER SANTA CRUZ RIVER

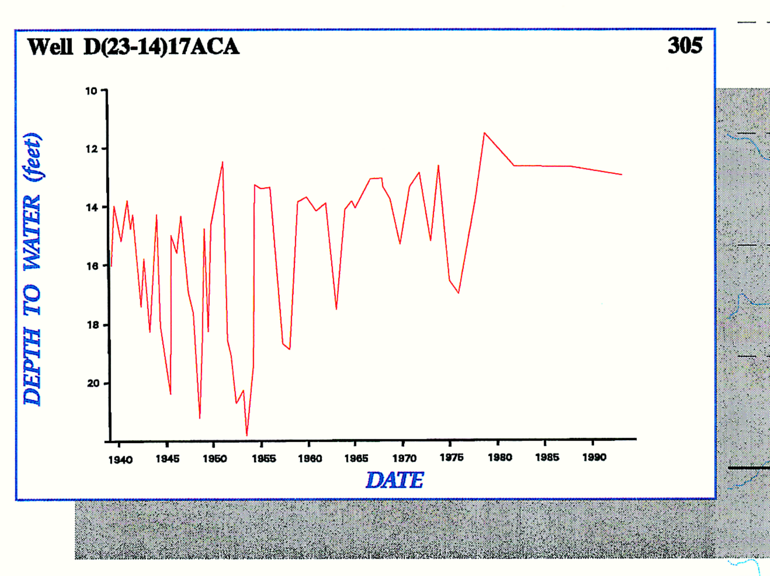


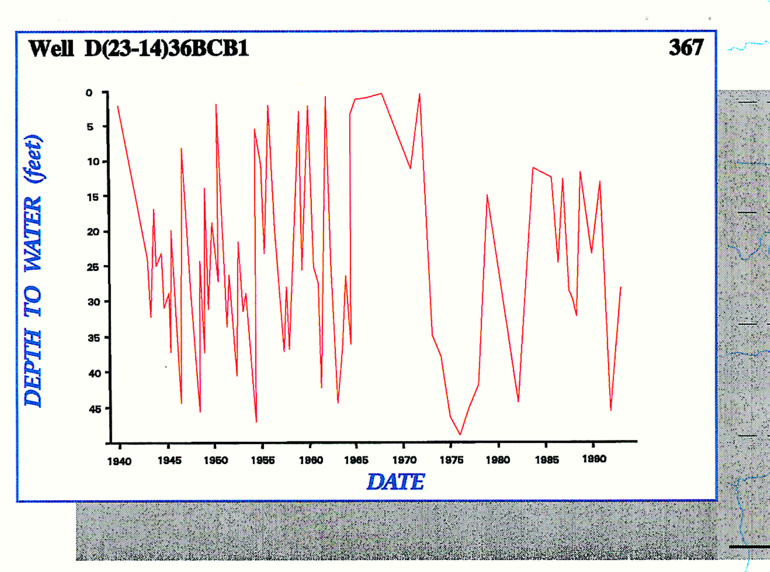


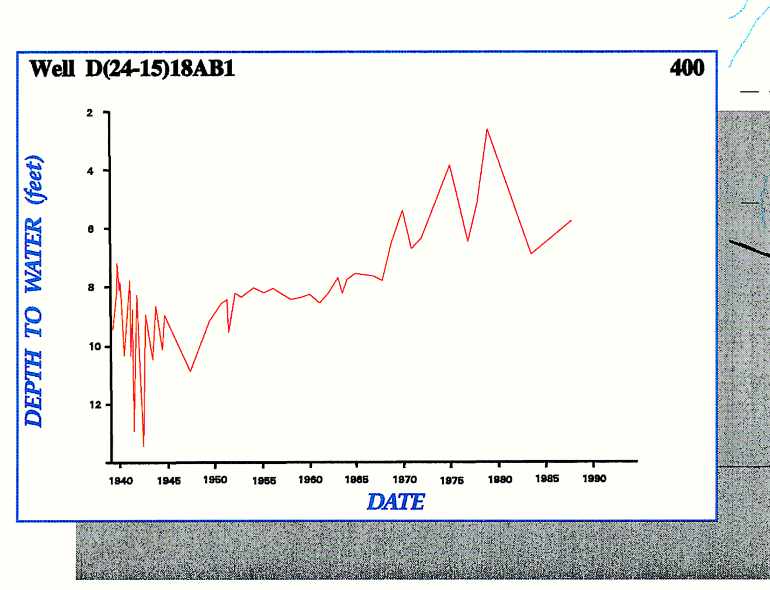


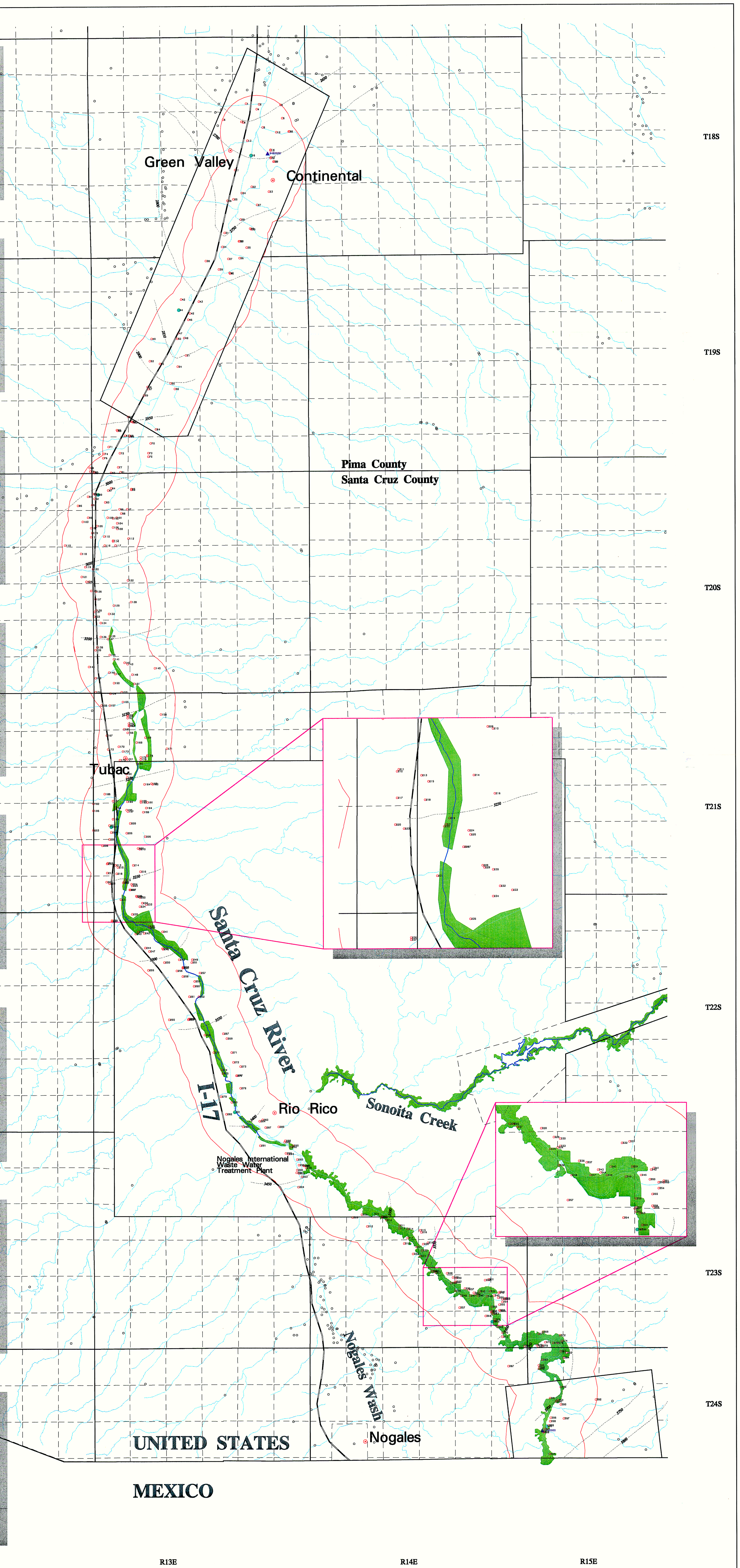




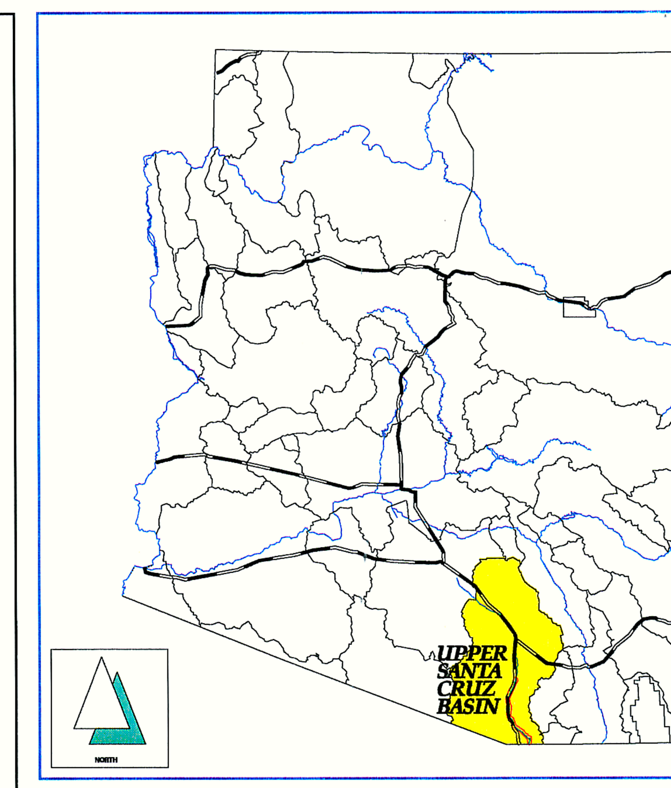








This map is preliminary and subject to revision (printed on 11/93).



WELL INFORMATION

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3	D-18-13 12CDB	315221110581801	205	D-21-13 19DDA	31345711
4	D-18-13 11DCD	315217110585801	206	D-21-13 20CDD	31345211
5	D-18-13 13BAC	315202110581501	207	D-21-13 19CDD	31344811
6	D-18-13 15ACA	315200110595501	208	D-21-13 30BAC	31343911
7	D-18-13 14BDB2	315157110592401	209	D-21-13 29BCCU	31343511
8	D-18-13 14BDB	315156110592101	210	D-21-13 29BD	31343411
9	D-18-13 14ADC	315149110584801	211	D-21-13 30CA 2	31341411
10	D-18-13 13DBB	315143110580401	212	D-21-13 30CA 1	31341311
11	D-18-13 13DB	315143110580301	213	D-21-13 30DBCU	31341111
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13	D-18-13 14CDA	315130110591401	215	D-21-13 30DC U	31340611
14	D-18-13 24BBB2	315117110583501	216	D-21-13 29CD U	31340211
15	D-18-13 24BBB1	315116110583501	217	D-21-13 30CD	31340011
16	D-18-13 23BAD	315110110591301	218	D-21-13 30DC	31335911
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21	D-18-13 23CBB	315048110593501	223	D-21-13 31B	31334511
22	D-18-13 26BA	315018110590301	224	D-21-13 32BB 2	31334411
23	D-18-13 26AAD	315017110583801	225	D-21-13 32BCB	31334211
24	D-18-13 26BBD	315011110591701	226	D-21-13 32BC 2	31333611
25	D-18-13 27ADA2	314958110593801	227	D-21-13 32BC 1	31333611
26	D-18-13 27ADC1	314957110594801	228	D-21-13 32CB 1	31332711
27	D-18-13 26DBA	314958110585801	229	D-21-13 32CB 2	31332611
28	D-18-13 26CCD	314934110591901	230	D-21-13 32CAB	31332511
29	D-18-13 35BAD	314924110591001	231	D-21-13 31DA U	31332211
30	D-18-13 35BA	314923110590801	232	D-21-13 32CD	31331711
31	D-18-13 34AC	314918110595301	233	D-21-13 32CD U	31331511
32	D-18-13 35CBB1	314906110592901	234	D-21-13 32CDB	31331211
33	D-18-13 35CBB2	314859111003601	235	D-22-13 05BBB	31330111
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35	D-18-13 35CDB	314857110591601	237	D-22-13 06AC1	31325111
36	D-18-13 35CC	314842110592801	238	D-22-13 05AC	31324411
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38	D-19-13 03BBA	314838111002501	240	D-22-13 05CB 1	31323611
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43	D-19-13 10BCB	314740111003701	245	D-22-13 05DD	31321711
44	D-19-13 09CAA	314728111011101	246	D-22-13 05DD 2	31321111
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HYDROGRAPHS

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16	D-18-13 23BAD	315110110591301
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202	D-21-13 19DBC	313506111030701
281	D-22-13 34ADD	312818110594501
305	D-23-14 17ACA	312551110554701
367	D-23-14 36BCB1	312316110522701
400	D-24-15 18AB 1	312050110504501

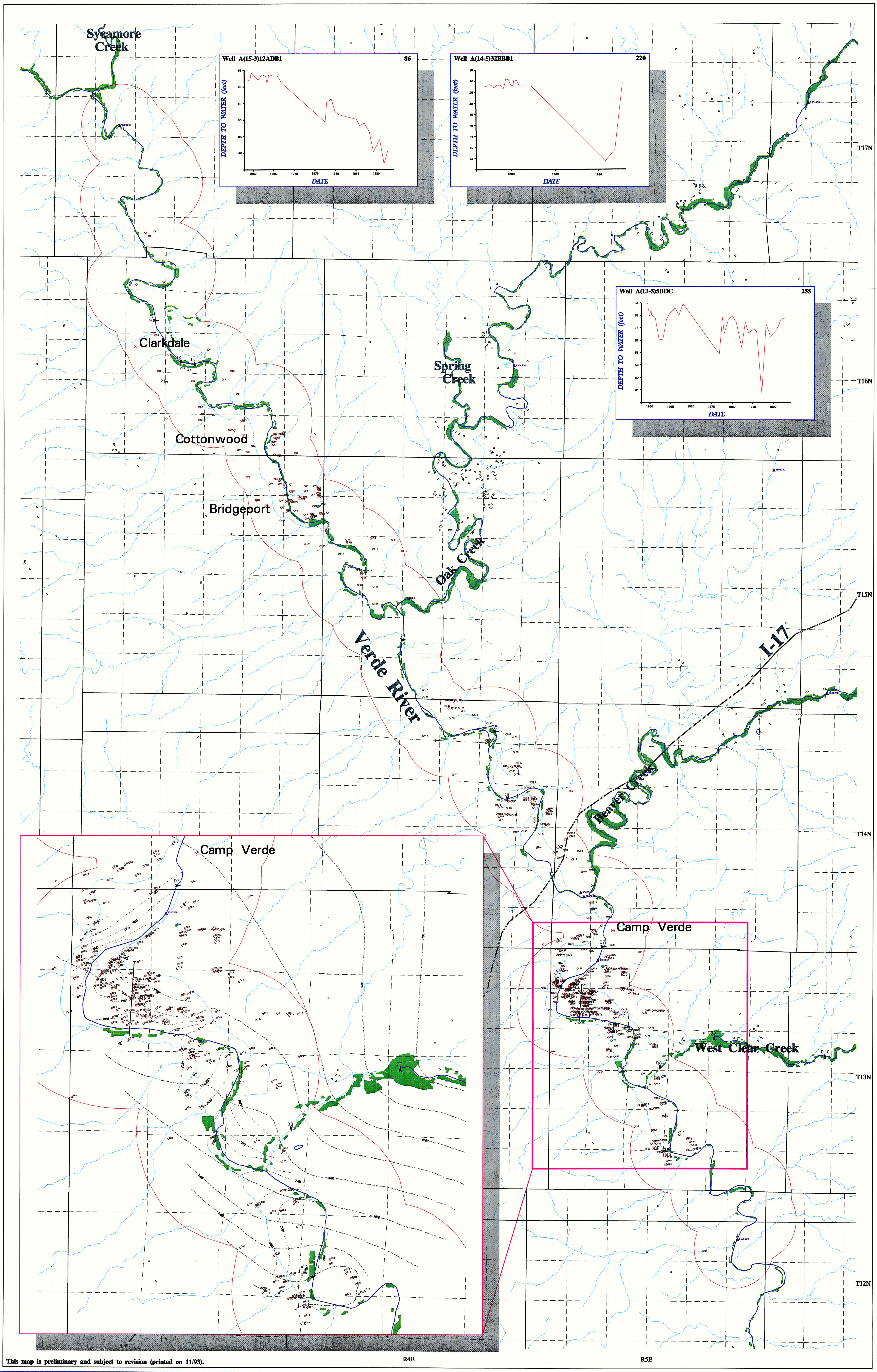
STREAM GAGE INFORMA

USGS ID	NAME	PERIOD OF REC
9482000	SANTA CRUZ RIVER AT CONTINENTAL, ARIZ.	1940-47, 1952-PRESENT
9480500	SANTA CRUZ RIVER NR. NOGALES, ARIZ.	1914, 1917-19, 1931-33, 1936-

- Township and Range lines
- Section lines
- one mile well selection buffer
- Perennial Stream/River
  Source: Arizona Game and Fish Department
- Non-Perennial Stream/River
- Riparian Vegetation
  Source: AG&FD preliminary vegetation mapping contracted through UofA Advanced Resources Tech. Lab
- Water table elevation contour (50ft intervals)
  Source: B. A. MURPHY AND J. D. HEDLEY, 1982
- Well location within the well selection buffer zone
- Well location outside of the well selection buffer zone
- Well with a referenced hydrograph
- Stream Gage Location
- City/Town

0 1 2 3 4
MILES
Scale 1:66858

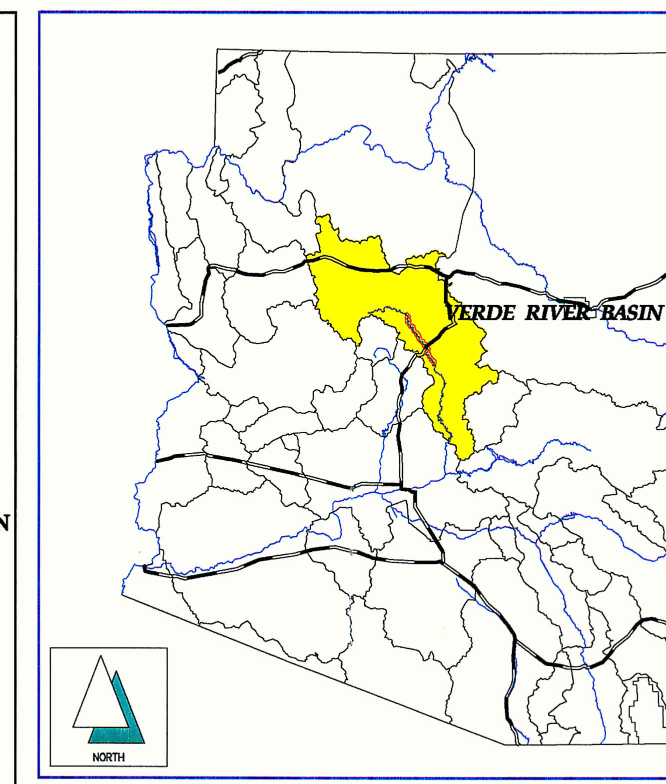
UPPER VERDE RIVER



This map is preliminary and subject to revision (printed on 11/93).

PLATE 3

UPPER VERDE RIVER



WELL INFORMATION

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6	A-16-03	08CDB	344737112032601
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39	A-16-03	35DAB2	344418111594101
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541	A-13-05	33AAB2	[illegible]
542	A-13-05	34BBB	[illegible]
543	A-13-05	34BBC3	[illegible]
544	A-13-05	34BBC2	[illegible]
545	A-13-05	34BBC1	[illegible]
546	A-13-05	34BCB3	[illegible]
547	A-13-05	34BCB1	[illegible]
548	A-13-05	34BCB2	[illegible]
549	A-12-05	02C UN	[illegible]

HYDROGRAPHS

REFERENCE-ID	LOCAL-ID	SITE-ID
86	A-15-03 12ADB1	3442501111583
220	A-14-05 32BBB1	3434091115111
255	A-13-05 05BDC	3432541111505

STREAMFLOW DIVERSIO

REFERENCE-ID	DIVERSION NAME
D1	PECK'S LAKE DIVERSION
D2	HICKEY DIVERSION
D3	COTTONWOOD DIVERSION
D4	OK DIVERSION
D5	EUREKA DIVERSION
D6	WOOD'S DIVERSION
D7	DIAMOND S DIVERSION
D8	UNNAMED DIVERSION ON W. CLEAR
D9	UNNAMED DIVERSION ON W. CLEAR
D10	UNNAMED DIVERSION ON W. CLEAR

STREAM GAGE INFORMA

USGS ID	NAME	PERIOD OF RECO
9504000	VERDE RIVER NEAR CLARKDALE, ARIZ.	1915-21, 1965-PRESENT
9506000	VERDE RIVER NEAR CAMP VERDE, ARIZ.	1934-45, 1988-PRESENT

Geohydrologic Section (Source: Owen-Joyce, 1984)
Township and Range lines
Section lines
one mile well selection buffer
Perennial Stream/River
Source: Arizona Game and Fish Department
Non-Perennial Stream/River
Riparian Vegetation
Source: AG&FD preliminary vegetation mapping contracted through UofA Advanced Resources Tech. Lab
Potentiometric elevation contour (20ft intervals)
Source: Owen-Joyce, 1984
Water table elevation contour (5ft intervals)
Source: Owen-Joyce, 1984
Well location within the well selection buffer zone
Well location outside of the well selection buffer zone
Well with a referenced hydrograph
Stream Gage Location
City/Town
Surface water diversion point (arrow indicates the direction of diversion)

0 1 2 3

MILES

Scale 1:52628