APPENDIX F:
SUMMARY OF HYDROGEOLOGY

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Literature Review – Fort Huachuca Biological Assessment

The purpose of this review is to provide background information on recent hydrologic, geologic, and water resources studies cited in the main body of this Biological Assessment (BA). In general, since scientific studies tend to build on work by previous authors, this review does not cover documents published before 1982. 1982 was selected as the starting point for the review because of the ground-breaking groundwater modeling effort by Freethey during that year which formed the basis for virtually all subsequent modeling efforts of the Sierra Vista subwatershed. Policy studies more than 15 years old are likely to be out of date due to changing physical and political conditions in the basin, so they were also excluded from this review.

This review is limited to peer-reviewed, final documents or documents released by the author(s) as "in press." For the purposes of this BA, "peer-reviewed" is interpreted to include: a) state and federal government publications and documents containing research findings or basic data; b) university theses and other publications; c) journal articles and other formally published literature. In some cases, where consulting reports contain original data and analyses not available elsewhere, these reports may be referred to in the main body of the BA but are not reviewed here. Management plans are not considered to be peer-reviewed documents and do not provide any new research findings, so they are not included in this review.

The reports are discussed in chronological order. Quotes taken directly from the original report are shown as indented text.

USGS GROUNDWATER MODELING STUDY OF UPPER SAN PEDRO BASIN FROM MEXICO TO FAIRBANK, ARIZONA (FREETHEY , 1982)

The purpose of this US Geological Survey investigation was to develop a numerical groundwater model of alluvial basins in the Southwest. Existing information for the Upper San Pedro River basin, considered to be representative of such basins, was used to develop and test the model. The investigator determined that the three-dimensional model adequately simulated groundwater flow, the stream-aquifer connection, and evapotranspiration, but warned against using the model to simulate and analyze site-specific problems or to evaluate water-level changes throughout the model area. Water-level contour maps derived from existing data and data generated by transient simulations showed similar patterns of water level decline in the Fort Huachuca-Sierra Vista area and the expansion of the cone of depression. Freethey put the following caveat on the application of his model:

> The numerical model developed during this study was designed and calibrated only to a degree necessary to attain a reasonable definition of the hydrologic system and to support, if possible, prior conceptions of how these hydrologic mechanisms work and interact. This model is one viable representation of the system. It should not be regarded as an exact, unique duplication of the hydrologic processes taking place. The model can be used to gain a better understanding of the interrelations that may

> occur when significant natural or manmade phenomena change one or more hydrologic processes. The model provides a starting point for the development of more detailed models when additional data become available. Water-level monitoring and streamflow measurements need to be continued and expanded as development in this area progresses.

US ARMY CORPS OF ENGINEERS GROUNDWATER MODELING STUDY FOR FORT HUACHUCA (COE, 1987)

Previous studies indicated that groundwater pumping by communities near Fort Huachuca would lower the local water table and threaten the Fort's water supply. Consequently, the Corps of Engineers undertook a study to quantify the groundwater parameters of the basin, evaluate future water use scenarios, and propose rehabilitative measures to be further investigated. A USGS regional groundwater model was used to evaluate existing groundwater conditions and predict the basin response to future water use scenarios. The COE used existing data as input to the model; initial values for aquifer parameters were those of Freethey (1982). Although the investigators felt that their model adequately simulated the hydrology of the upper San Pedro basin, they stressed that the reliability of model results was dependent on the reliability of the available recharge and discharge data, aquifer parameters, and historical water level estimates. Some of their findings:

> Heavy pumping in the Fort Huachuca-Sierra Vista and Huachuca City areas has created cones of depression in the ground water table. The zone of influence around the Fort measures about 4 miles by 1-1/2 miles wide and is following new commercial development as it moves eastward. The cone in the Huachuca City area is about 3 miles by 1 mile wide and in this zone, the groundwater flow along the Babocomari River has reversed direction for some distance downstream. Ground water that previously flowed eastward, is now attracted to the pumping center.
>
> It is evident that even at the current rate of pumping, the Fort Huachuca water supply may be threatened at some time in the not too distant future. Proposed growth of Sierra Vista would speed up the process of declining water levels, and one or more of the Fort wells may dry out within 45 years. Though the decline in the regional aquifer may be relatively small (i.e., less than 1 foot per year), it is nonetheless evident that overall ground water withdrawals are exceeding the safe yield. Several areas where intensive pumping is occurring will experience noticeable declines in the water table. As stated in many of the previous studies of the water supply for the basin, there is a vast supply of water within the basin aquifers[.] The problem concerns the possibility of existing wells drying out from the declining water levels.
>
> It is becoming increasingly evident that definition of the aquifer's properties (i.e., the storage coefficient and the transmissivity) is very important in the modeling of the ground water system. Borehole and geophysical investigations would allow a clearer understanding of the anticipated drawdown of the water table. Wherever possible, pumping tests should be performed to supplement this analysis. Furthermore, the basin geology should be mapped in detail. This would help locate

> the boreholes, observation wells, and geophysical investigations. This report is limited by the available data for which a number of assumptions have been made and a complete definition of the substrata would help refine the model results.

The ACOE (1987) model explored eight potential future scenarios for groundwater development in the Fort Huachuca area. The first scenario projected 1985 pumping rates on the Fort out to 2000 and found that groundwater levels near the wells would decline at a rate of about 2.25 feet per year. The second scenario kept pumping at 1985 levels everywhere in the model area except in Sierra Vista, where annual pumping would increase from 750 acre-feet per year to 6,574 acre-feet per year in 2000. This scenario was predicted to increase the rate of groundwater decline in the Sierra Vista/Fort Huachuca cone of depression to 2.7 feet per year and to cause small declines elsewhere in the regional aquifer. The third and fourth scenarios examined potential pumping from a proposed utility company and Tenneco West Inc., but the utility company pumping was shown to have little effect on water levels at the Fort and the Tenneco plan was abandoned.

The fifth ACOE (1987) scenario proposed to move all Fort Huachuca pumping to the East Range as a potential solution to the possible drying out of one of the Fort's major wells. Under this scenario, average groundwater levels under the Fort were expected to initially rise 36 feet over the first five years and then decline at a rate of about 0.7 feet per year. Scenario six proposed to split the Fort's pumping between wells in the East Range and those between the main gate and the east gate. This scenario was predicted to result in a static water level rise of 13 feet over the first 5 years, followed by a decline of about 0.7 feet per year. Scenarios five and six were perceived to satisfy the Fort's need to preserve the integrity of the Fort's well #1 for more than 100 years.

Scenario seven combined scenarios six and two (i.e., moving half of the pumping to the East Range and significant growth in Sierra Vista). This scenario was predicted to result in an average water level decline of 0.7 feet per year, still ensuring the integrity of well #1 for more than 100 years. The eighth scenario examined a growth rate of 300 percent over 15 years at Huachuca City. This significant growth was predicted to only increase the water level decline by about 0.1 foot per year over the rate that was expected without growth (0.6 feet per year).

As a result of their modeling efforts, the COE investigators concluded that, despite the vast amount of groundwater stored in the regional aquifer, present and future withdrawals far exceed the perennial (safe) yield of the basin, thus threatening not only the Fort's water rights but the water supply of the entire basin. They recommended that the Army use wells on the East Range in order to reduce the stress on the established well field. They also recommended that groundwater levels at the Fort are closely monitored and studies conducted to better define model parameters.

ADWR STUDY OF WATER RESOURCES OF THE UPPER SAN PEDRO (ADWR, 1988)

The Arizona Department of Water Resources (ADWR) examined the hydrology and water use of the Upper San Pedro (USP) basin in order to assess the merits of designating the basin as an Active Management Area. The report summarized and interpreted data from previous hydrological studies of the basin (including those described above) and incorporated more-recent ADWR data. The ADWR investigators also employed a regional groundwater model, and Freethey's (1982) data, to update and project future hydrologic conditions in the Sierra Vista area.

Among the findings, the ADWR determined that water levels have declined in the USP regional aquifer an average of less than 1 foot per year outside the vicinity of Sierra Vista and Fort Huachuca; even in areas of little or no groundwater pumping. Although the reason for this was unclear, they speculated that the decline was due to a regional adjustment brought on by down cutting of the San Pedro River. Since the down cutting occurred prior to extensive groundwater pumping in the region, they postulated that the change resulted from overgrazing or climatic variation. The ADWR investigators also determined that, based on flow duration curves, the flow regime of the San Pedro River at Charleston was unchanged over the last 50 years. The ADWR reported the following conclusion to their study:

1. Groundwater withdrawals taking place in the regional aquifer around Sierra Vista result in an average groundwater decline rate of 1.4 feet per year between approximately 1968 and 1986. Decline rates rise to a maximum of 3.7 to 3.9 feet per year for several wells however. A cone of depression of about 7.5 square miles, within the enclosed 4,150-foot water elevation contour, probably occurs in the vicinity of Sierra Vista. This cone has grown from an area of about 5 square miles in 1968. The time at which the cone originally developed is not known.

2. Continued groundwater pumpage between 1986 and the year 2000 will mine an additional 208,000 ac-ft of groundwater from the regional aquifer around the Sierra Vista area, resulting in a maximum groundwater decline of about 80 feet at a maximum rate of about 6 feet per year.

3. Pumpage in the USP basin has not yet affected that portion of the regional aquifer adjacent to the San Pedro River except near Hereford. This conclusion is based on 1986 groundwater levels as estimated by an updated groundwater model of the area, and comparison of these water levels with 1968, 1978, and 1986 water level maps presented in this report. No significant change in groundwater levels has occurred near the San Pedro River at Lewis Springs or Charleston.

4. The groundwater model used to project water levels in the year 2000 showed that water levels in the regional aquifer several miles west of the San Pedro River would rise up to 20 feet at Hereford, would decline by about 10 feet west of Lewis Springs, and would decline by about 10 feet west of Charleston. This decline rate is about 0.7 feet per year. This model projection was based on estimated future pumpage.

5. The artesian heads present in some portions of the regional aquifer underlying the floodplain alluvium of the San Pedro River have decreased somewhat over time due to groundwater development in these areas.

6. The shallow floodplain aquifer which underlies the San Pedro River shows no long term declines in water level.

7. The retirement of agricultural lands acquired by the Bureau of Land Management will affect low flows in the San Pedro River, particularly in the Hereford area. The flow in the river will increase due to cessation of agricultural pumping, which will no longer draw water from the floodplain alluvium and San Pedro River. This will allow water levels in both the confined and unconfined regional aquifer to rise, enhancing groundwater discharge rates to the floodplain alluvium and river and increasing flow rates in the river. The increase in flow may eventually be offset somewhat if phreatophytes are allowed to invade previously fallow land.

8. No land subsidence has occurred in the USP basin to date.

9. There are no known regional water quality problems in the USP basin.

SAN PEDRO RIVER RIPARIAN MANAGEMENT PLAN AND EIS (BLM 1989)

The Bureau of Land Management (BLM) prepared a combined master plan-environmental impact statement for the proposed San Pedro Riparian Natural Conservation Area (SPRNCA). An analysis of the surface water and groundwater resources within the SPRNCA and adjacent lands was presented in Appendix 5 of the document. Although the BLM recognized the San Pedro River as an important and unique perennial desert stream, the agency was also aware that the river system is degraded both in terms of historic hydrologic condition and habitat diversity.

After reviewing the literature and conducting field surveys, the BLM scientists concluded that the San Pedro River has, and is continuing, to undergo an evolution to a new dynamic equilibrium condition that reflects current hydrologic and land use conditions. They were uncertain as to the cause of observed reductions in stream base flow but speculated that it could be caused by:

- reduced recharge of the floodplain aquifer by the regional aquifer;
- reduced recharge of the floodplain aquifer by surface runoff (high flows);
- increased use of the floodplain aquifer through pumping;
- increased use of the floodplain aquifer by phreatophytes; or
- increased loss of floodplain aquifer water to the regional aquifer.

The BLM team went on to state:

> It does not appear that the declines in base flows can be attributed to declines in overall runoff in the basin. Also, it is unlikely that changes in phreatophyte use or losses to the regional aquifer have significantly affected base flows. Thus, it can be deduced that either groundwater pumping in the floodplain aquifer, reduced recharge from the regional aquifer, or a combination of both have contributed to the lower base flows recorded at both [Charleston and Palominas] gauges.

HYDROLOGICAL RESOURCE ASSESSMENT OF LOWER BABOCOMARI WATERSHED (SCHWARTZMAN, 1990)

The Babocomari River is a principal tributary to the San Pedro River and flows near to the northern boundary of the Fort Huachuca military reservation. Schwartzman (1990) conducted an investigation of the lower Babocomari watershed in order to evaluate the effects of groundwater pumping on the river. The author summarized existing geological and hydrological information for the study area and monitored water level changes in local wells.

Schwartzman found that pumpage had affected flow patterns in the vicinity of northern Huachuca City and the Fort Huachuca East Range and that a minor cone of depression had formed in the area. Historic water-level declines in the study area had been low to moderate (4-12 inches). He concluded that continued groundwater level declines caused by pumping by local municipalities and Fort Huachuca would adversely affect the riparian habitat along the Babocomari River. The author recommended that water levels near the river be closely monitored in order to better manage the riparian resource.

ADWR HYDROGRAPHIC SURVEY REPORT FOR THE SAN PEDRO RIVER WATERSHED (ADWR, 1991)

The Arizona Department of Water Resources (ADWR) prepared this Hydrographic Survey Report (HSR) as part of the General Adjudication of the Gila River System and Source. The document serves as a compendium of ADWR information concerning the San Pedro River and has been used as a source of data in subsequent analyses and modeling studies. Volume 1 of the report, General Assessment, described the nature of the adjudication proceeding, water supply and water uses, investigation methods used by ADWR, and the results of the investigations for major water users and non-Indian federal law claims. A very useful summary of the water resources of Fort Huachuca was provided in Volume 1, Chapter 5, pages 382-430 and a description of the modeling methodology used to determine pumping effects was given in Volume 1, Appendix G. Volumes 2 through 9 presented additional information on individual water users and uses, well reports, well lists, and maps.

In Chapter 4 of Volume 1 (Hydrologic Analysis), the ADWR researchers listed several conclusions about the hydrology of the San Pedro River. Conclusions relevant to the Sierra Vista-Fort Huachuca situation are given below (with the original item numbers used in the HSR).

6. Cultural depletions impact the hydrologic system by lowering groundwater levels in the regional and floodplain aquifers and/or by directly reducing streamflow in the channels. The removal of groundwater may directly or indirectly interfere with streamflow. Direct interference occurs when the cone of depression of a pumped well(s) intercepts the streambed and induces surface water to move away from the stream. Indirect interference occurs when the cone of depression does not intercept the stream, but reduces the amount of groundwater discharged to the stream by intercepting groundwater flows.

8. The impacts of some cultural or groundwater withdrawals have not yet affected or reduced the surface water supply in the inner valleys, but are impacts in transit toward the younger alluvium that will eventually reach the younger alluvium. As more of these impacts arrive at the younger alluvium, their cumulative effect can be expected to further reduce the surface water quality.

24. A negative change in storage of -11,230 ac-ft is occurring in the Sierra Vista subwatershed as a result of municipal groundwater pumping in the Sierra Vista-Fort Huachuca area and pumpage to supply irrigation uses located near the San Pedro River.

As in previous studies, the ADWR researchers found a direct correlation between population growth and water usage as seen by the declining groundwater levels in the Sierra Vista area. They stated that the cone of depression that has formed under Fort Huachuca and Sierra Vista might cause a problem with the Fort’s water supply. The expansion and deepening of the cone would result in greater pump lifts and increased energy costs. In order to quantify the amount of diminishment of the water supply to Fort Huachuca, the ADWR investigators used the USGS MODFLOW model (Freethey 1982) to predict the effects of groundwater pumping by the Fort and surrounding communities. Two modeling scenarios were compared: the effect of past and future groundwater pumpage by the Fort alone on the water table, and, the combined effect of pumpage by the Fort and the surrounding municipal water companies on the water table. From this analysis the ADWR concluded:

> The results of the model runs demonstrate that the additional drawdown to Fort Huachuca’s wells because of the additional pumpage from the 8 surrounding water companies from 1940 through 1988 ranges from 13 feet at Fort Huachuca well No. 8 in the East Range, which is furthest from the pumping center, to 41 feet at wells No.1 and No. 2 nearest to the pumping center. The projected cost to the Fort over the 48 year period (1940-1988) could be between $75,000 to $125,000.

A pumpage scenario based on projected increases in population from 1989 through 2038 resulted in additional drawdown of 72 feet at well No. 8 to 223 feet at well No. 1 and No. 2. The projected cost from 1989-2038 could be between $500,000 and $1,880,000 over the next 50 years. [The ADWR stresses that this represents only a sample scenario; actual future growth rates and pumpage rates may be different.]

Fort Huachuca’s response to a lowering of water levels might also result in more pumpage being shifted away from the pumping center to the East Range well [COE 1987]. This would result in fewer well deepening costs, repair costs, and a reduction in lift costs.

WATER RESOURCES AND MANAGEMENT OPTIONS FOR THE SAN PEDRO BASIN (WWRC, 1991)

In 1990, a student-faculty team from the University of Arizona responded to a request by Upper San Pedro Basin Water Resources Council to examine the water resources situation of the basin and evaluate various management options. The university team developed or adapted 4 models to analyze the situation: a regional groundwater model (MODFLOW), a surface water-groundwater model used to evaluate institutional water use options (MODSIM), a spreadsheet-based, hydrology-economics-water resource allocation model called WATERBUD, and a plan evaluation model known as MATS. The investigators emphasized that the results of their modeling efforts were based upon a 20-year period of analysis during which time the long-term implications of increased pumping from the regional aquifer were not readily apparent.

From the analyses performed with the 4 analytical models the investigators concluded the following:

1. Pumping from the regional aquifer in the Sierra Vista area is depleting stored groundwater reserves there, and accelerated pumping in the future will accentuate this trend unless steps are taken to arrest.

2. Pumping from the regional aquifer is not the major factor imperiling streamflow in the San Pedro River. Drought-related reductions in surface runoff and irrigation-related pumping from the floodplain aquifer are much stronger influences, particularly in the short term. Management of minimum streamflows and maintenance of riparian ecosystems will require control of agricultural pumping and, possibly, the imposition of drought-coping policies.

3. Potential conflict over water management policies in the Upper San Pedro basin will be rooted in differing value judgments concerning economic and environmental impacts. However, the common desire to maintain local control over water management decisions provides a basis for successful negotiation and policy development.

The university team also made several recommendations for future policy development; including several that have a direct bearing on water policy for Fort Huachuca and the surrounding communities. The team recommended that the problem of groundwater overdraft be recognized and dealt with now rather than waiting for a future crisis. They also urged water conservation be encouraged through educational programs, replacement of water-wasting plumbing with water-saving plumbing, and reuse of effluent, either for irrigation or aquifer recharge.

MODELING OF GROUNDWATER FLOW AND SURFACE/ GROUNDWATER INTERACTION FOR THE SAN PEDRO RIVER BASIN (VIONNET AND MADDOCK, 1992)

The purpose of this study, conducted by university investigators and funded in part by the Cochise County Flood Control District, was to improve an existing ADWR groundwater model of the Upper San Pedro River basin by making the following modifications: 1) augmentation of the original MODFLOW module data set with newly acquired information; 2) replacement of river module with new stream-aquifer model; 3) addition of layer to represent bank storage; and 4) recalibration of model using river baseflow data. The model grid was based on that developed by Freethey (1982). A steady state simulation was used to reproduce the mean annual conditions existing in 1940. Information from the steady state simulation was used in the transient simulation which represented the period 1940 to 1988. General conclusions of investigators are given below.

The match between simulated water level contour maps and field data water level contour maps was acceptable. However, a less acceptable match between MODFLOW simulated streamflows and estimated baseflows from field data was obtained...The runoff component of the streamflows was not taken into account during the simulations. It is generally argued that, within the study area, runoff is exceedingly rapid, allowing little infiltration to the ground-water system. However, the runoff volumes provided some surface storage, a small quantity of local storage to the alluvial aquifer, that is usually consumed by riparian vegetation.

Prior to major development, losses to evapotranspiration and to streamflow constitute the majority of the discharge from the system for both cases. The ground-water outflow at Fairbank constituted 3.5% of the total discharge, a small amount compared to the other 2 components.

By the end of the transient simulation period (1988), 13,680 ac-ft/year of water were being extracted through pumping. However, the peak pumpage of 17,190 ac-ft/year (23.7 cfs) was reached during the early 1980's.
Over the 48-year simulation period, the evapotranspiration losses reduced around 20% with respect to predevelopment conditions. Streamflow gains were also reduced drastically over the 48 years. These reductions were due to the ground-water withdrawals to pumpage. Model results indicate that 48% of the pumpage was derived from aquifer storage...

Model results are dependent on the distribution of pumpage in time and space. The pumpage used to simulate transient conditions were provided by ADWR. Municipal pumping has been revised by the ADWR. The ADWR is presently revising pumping figures for agriculture. This process will redefine pumping rates estimates for irrigation wells drilled mainly in the alluvial aquifer. Depending on the scope of this redefinition, model results and conclusions could be affected to different degrees, particularly if the revised wells are located near the river system.

Before any attempt to use this groundwater model, it is essential that the user be aware of the model capabilities and limitations. Conclusions extracted from future simulations with this model will have to be based on the model assumptions and limitations. With these caveats in mind, 2 principal conclusions may be drawn.

1. The geologic formation in the vicinity of Charleston initially inhibits the effects of the Sierra Vista cone of depression on the San Pedro River. Simulation indicates that the cone will spread southward to perhaps intersect the river upstream of the formation.

2. Although a better calibration of baseflows can be achieved by reducing the maximum evapotranspiration rate to partially compensate the absence of runoff volumes, alternative ways to incorporate those volumes should be attempted in the future.

The investigators recommended that a Geographic Information System (GIS) be incorporated into the modeling process; the model grid be extended further east, north, and into Mexico; better field data be collected; water consumption by riparian vegetation be refined; the model time increment should be monthly instead of annual to accommodate seasonal variability; and recharge sources should be more accurately represented in the model.

ENTRENCHMENT AND WIDENING OF THE UPPER SAN PEDRO RIVER (HEREFORD, 1993)

This USGS- and BLM-funded study provided a comprehensive and detailed analysis of the geomorphic history and condition of the San Pedro River basin. The investigation included examination of pre- and post-entrenchment alluvium, riparian vegetation changes, channel morphology, and the association of climatic history with channel widening. A summary of the findings showed that:

> The river flowed in a shallow, narrow channel on the surface of the un-entrenched valley before 1890. A series of large floods, perhaps beginning as early as 1881, eventually led to entrenchment of the channel between 1890 and 1908. This deepening placed the channel 1 to 10 m below the former floodplain. The channel has widened substantially since entrenchment through lateral migration and expansion of entrenched meanders. The rate of channel expansion, however, has decreased since about 1955, coincident with a decrease of peak-flood discharge suggesting that the channel has stabilized and that further widening will probably be minor under present conditions of land use, discharge, and climate.
>
> The reduction in peak-flow rates was related partly to increased channel sinuosity and to development of floodplains and riparian woodlands. The increased sinuosity produced a reservoir effect that attenuated flood waves, and the development of floodplains enabled flood waters to spread laterally, thereby increasing transmission losses. In addition, flow rates were probably affected by improved land use and changes of rainfall intensity and short-term rainfall patterns, which reduced runoff and decreased the time necessary for channel stabilization. Livestock grazing decreased steadily after the turn of the century, and numerous stock ponds and small water-retention structures were constructed in tributaries. The cumulative effect of these structures probably reduced peak-flow rates. Short-term rainfall patterns of the wet season (June 15-October 15) have probably changed from annual alteration of above- and below-average rainfall to a biennial or longer pattern. Moreover, frequency of low-intensity rainfall (daily rainfall less than about 1.27 cm) was consistently above average for the decade 1957-1967. These factors probably improved conditions for growth and establishment of vegetation both in and outside the channel.
>
> The causes of the large floods that resulted in entrenchment are poorly understood, although climate and land use were key factors. Floods followed closely the rapid settlement of the area brought about by mining activity in the late 1870s; population rose from a few hundred to 6,000 in less than 5 yr. Extensive wood cutting for mine timber and fuel, suppression of wildfire, and reintroduction of large cattle herds

> undoubtedly exacerbated entrenchment. Flood-producing wet-season rainfall in the Southwest, however, was unusually heavy before, during, and shortly after entrenchment.

The investigator also made some observations regarding the implication of these results to channel and floodplain management of the San Pedro River:

> Future development of the San Pedro River channel is a highly speculative topic; a number of geomorphic uncertainties permit only broad generalizations to be made. Nonetheless, management of the resources requires general predictions regarding the stability of the channel system. Evidence indicates that the channel has or is close to a stable configuration. This new equilibrium was reached after at least 55 years of adjustment through widening. The implication for channel and floodplain management is that the system has largely adjusted to the post entrenchment conditions. Therefore, the system will probably not change significantly, if these conditions remain within existing limits.
>
> Impounding of sediment in reservoirs and upstream withdrawals of surface water for agriculture, mining, or domestic use will compromise the present flow regimen, degrading the recently developed riparian community. This community is closely linked with groundwater level; a drop in this level would probably have the same effect on the riparian community as upstream impoundments and withdrawals. The effect of lowering the water table is well illustrated by the extensive degradation of the riparian environment following the entrenchment of the San Pedro River channel between 1890 and 1908. In short, extensive development and exploitation of groundwater resources will almost surely lower the water table, with predictable consequences for the riparian forest.

A GROUNDWATER FLOW MODEL OF THE SIERRA VISTA SUBWATERSHED OF THE UPPER SAN PEDRO BASIN - SOUTHEASTERN ARIZONA (CORELL, *ET. AL.*, 1996)

This report describes the latest in a series of groundwater models developed for the Upper San Pedro Basin by the Arizona Department of Water Resources. The purposes of this model are to expand the model area from previous studies to incorporate new areas of concern and to develop an analytical tool capable of providing answers to questions concerning the effects on the San Pedro and Babocomari rivers, their associated riparian areas and floodplain alluvial aquifers, and on the regional groundwater system. The ADWR is interested in modeling the effects of municipal and non-agricultural growth at Sierra Vista and Fort Huachuca, retirement of agricultural lands or increased agricultural activities, municipal and agricultural conservation measures, recharge projects, future development adjacent to the San Pedro River on baseflow and seasonal variations in groundwater levels, river flows of a fully restored riparian system, long term drought, and increased Mexican groundwater use. The model is designed to provide a regional understanding of the interrelationships between the groundwater flow system and groundwater pumpage and recharge. It is not designed to address site-specific problems, seasonal variations in groundwater levels and river flow, and precise water levels and elevation changes.

The area of study includes the Sierra Vista, Huachuca City, Fort Huachuca, Palominas, Hereford, Charleston and Fairbank areas. The total model domain is 22 miles from east to west and 32 miles from north to south. Model cell sizes range from 40 to 160 acres. The model represents the Upper San Pedro Basin as consisting of a regional aquifer and a floodplain alluvial aquifer. The year 1940 was chosen to represent pre-development steady state conditions on the basis of limited groundwater development and the availability of water level and stream gage data. The Freethey (1982) and Vionnet and Maddock (1992) models also used 1940 to represent pre-development conditions. The years 1941 to 1990 were selected to represent the post-development period for the transient simulations. The model uses the MODFLOW code developed by the US Geological Survey. Three model layers were used to represent the hydrogeologic system.

Input data for the model were obtained from Freethey (1982), both specified and unspecified published data, map analysis and estimates by ADWR. Municipal and military pumping records were used in the simulations. (Note: Pumping by Fort Huachuca was significantly higher during the simulated period than at present.) Agricultural pumpage was estimated. Evapotranspiration estimates only include the groundwater-supplied portion of evapotranspiration. Therefore, these estimates are less than the total use by riparian vegetation. Also, due to the method used to estimate baseflow, near-stream pumpage was overestimated resulting in an overestimate of the effects of groundwater pumping on river inflows and outflows. The estimates of riparian, agricultural and evaporative losses may be smaller than previous estimates because they only include the portion of riparian, agricultural and evaporative uses derived from groundwater discharge to the San Pedro River and not the additional amount of evaporative losses supplied by flood flows, tributary inflows and rainfall.

According to the model report, the major change in the San Pedro River and the associated groundwater system over the past 50 years has been a decrease in groundwater discharge to the river between the years 1935 to 1940 and 1951 to 1956. The model report indicates that average baseflows have decreased through time from 1951 to 1980. However, the report also states that there may have been an increase in average baseflows for the period 1981 to 1990.

Based on a number of statistical comparisons of measured versus simulated conditions, the model appears to reasonably simulate measured water levels. Improvements in model-estimated streamflow could be made with improved estimates of evapotranspiration and recharge. In addition, the conceptual estimates of baseflow may include some component of runoff not accounted for in the model and may include some effects of near-stream pumping. The results of a sensitivity analysis indicate that the model is low to moderately sensitive to changes in streambed conductance, evapotranspiration depth and vertical conductance. The model is more sensitive to changes in evapotranspiration rates, especially in terms of fluxes and streamflows. The ADWR recommends that the model be updated as data become available to improve model calibration. Continuing acquisition of new field data is necessary for future improvements due to many unanswered questions about aquifer parameters, mountain front recharge, evapotranspiration and geology. The model could be improved by further analysis of the spatial and temporal distribution of pumpage, especially with respect to agricultural pumpage and the vertical distribution of pumpage within the aquifer. As the model is currently constructed, with stress periods are as long as 13 years, the model is not able to account for seasonal variations in pumpage, streamflow and evapotranspiration.

GROUNDWATER FLOW MODEL SCENARIOS OF FUTURE GROUNDWATER AND SURFACE WATER CONDITIONS: SIERRA VISTA SUBWATERSHED OF THE UPPER SAN PEDRO BASIN – SOUTHEASTERN ARIZONA (CORELL, 1996).

Corell (1996) issued a separate report containing simulations of future groundwater and surface water conditions based on the model described in Corell, et al (1996). He simulated the period 1990 to 2030 using scenarios developed by the Upper San Pedro Technical Committee and ADWR. The scenarios and model results are listed below:

Senario 0 (Baseline)

- Continued groundwater pumping at 1990 levels (population 51,400),
- Agricultural pumping near Palominas/Hereford phased out by 2000;

Results:

Groundwater: Water levels in Palominas/Hereford area increase 5 to 10 feet;; groundwater levels in Sierra Vista area decline up to 45 feet beyond 1990 levels; water levels in upper reaches of Babocomari decline up to 15 feet; 5 feet drawdown contour nearly intercepting northern half of San Pedro River by 2030.

Streamflow: Reductions in agricultural pumping resulted in increased flows at Palominas from 1.13 to 2.2 cfs and at Charleston from 4.81 to 5.74 cfs; flows decreased at Tomstone from 8.32 to 7.86 cfs as a result of pumping near Huachuca City and Sierra Vista; Babocomari River flows declined from 1.14 to 0.46 cfs at beginning of perennial reach

Scenario 1.1

- Population increase to 73,870 by 2020,
- Effluent recharge at the Sierra Vista Wastewater Treatment Plant (WWTP) of 2000 afa beginning in year 1999 and at the Fort Huachuca WWTP of 944 afa beginning in the year 2000,
- Agricultural pumping near Palominas/Hereford phased out by 2000;
- ET held constant at 1990 rate.

Results:

Groundwater: Levels increased by 5 to 10 feet in Palominas/Hereford area; decreased by up to 50 feet from 1990 levels in Sierra Vista area; continued decline near Huachuca City, decline of 20 feet near Naco; decline of up to 15 feet on upper reaches of Babocomari River; levels rise up to 45 feet under Sierra Vista WWTP resulting in increased groundwater levels along 3-mile reach of San Pedro nearest WWTP.

Streamflow: Increase at Palominas gage from 1.13 to 2.19 cfs and at Charleston from 4.81 to 6.25 cfs (higher than Scenario 0 because of Sierra Vista WWTP); increased at Tombstone from 8.32 to 8.46 (because of Sierra Vista WWTP); decreased from 1.14 to 0.47 on Babocomari River at entrance to canyon.

Other: 10% of pumping in conceptual model not simulated because model cells near Huachuca Mountain front go dry. Increased ET in Palominas/Hereford area.

Scenario 1.2

Same as Scenario 1.1 except agricultural pumping in Palominas/Hereford continues at 1990 levels.

Results:

Groundwater: same as Scenario 1.1 except levels remained mostly constant in Palominas/Hereford area.

Streamflow: Increased at Palominas from 1.13 to 1.63 cfs; decreased at Charleston from 4.81 to 4.74 cfs; decreased at Tombstone from 8.32 to 6.84 cfs as a result of agricultural pumping in Palominas/Hereford area; declined 1.14 to 0.47 cfs on Babocomari River at mouth of canyon.

Scenario 2

Same as Scenario 1.1 except slower population growth (68,330 in 2020) resulting in 5% lower pumping rate.

Results:

Groundwater: Same as Scenario 1.1 except that maximum water level declines in Sierra Vista/Fort Huachuca area was 45 feet.

Streamflow: same as Scenario 1.1.

Scenario 3

Same as Scenario 1.1 except higher population (77,724 in 2020) and no WWTP effluent recharge. No agricultural pumping in Palominas/Hereford area after 2000, and ET increased to 10,000 afa versus 7,553 afa in 1990.

Results:

Groundwater: Increased by 5 to 10 feet in Palominas/Hereford area; declined by up to 90 feet in Sierra Vista/Fort Huachuca area and higher declines than other model runs in Huachuca City area; decline of 30 feet in Naco area; decreased up to 20 feet in upper reaches of Babocomari and up to 5 feet along some portions of the San Pedro River.

Streamflow: Palominas flows increased from 1.13 to 1.81 cfs (limited by ET); decreased at Charleston from 4.81 to 4.56, decreased at Tombstone from 8.32 to 6.4 cfs (from regional water level declines and increased ET); decreased from 1.14 to 0.35 cfs in the Babocomari River at the mouth of the canyon.

Other: 5% of pumping not simulated due to model cells going dry, particularly along Huachuca Mountain front.

ANALYSIS OF HYDROLOGIC DATA COLLECTED BY THE US BUREAU OF LAND MANAGEMENT (1987-1995) AND RECOMMENDATIONS FOR FUTURE MONITORING PROGRAMS (SHARMA, *ET. AL.*, 1997)

This study analyzed stream flow and groundwater data collected by the US Bureau of Land Management on the San Pedro and Babocomari rivers. The purpose of the study was to establish a more efficient monitoring program for the SPRNCA. The report analyzed data on stream flow measurements taken at nine locations on the San Pedro River and one location on the Babocomari River, and groundwater levels in eighteen wells collected from 1987 to 1996. All of the stream discharge data and some of the groundwater level data were collected at non-systematic intervals, and the stream flow measurements may not have been collected at the same location at each site over time. The authors reached qualitative conclusions and suggested that the amount of groundwater entering certain stream reaches had diminished over the period of record (1987-1995) but indicated that their analysis was made difficult by inadequate documentation, inconsistent procedures and malfunctioning equipment. The report did not recommend future groundwater data collection efforts at the wells at these sites but did suggest that wells specifically designed to monitor the interactions of the regional and floodplain aquifers and the river should be instrumented to capture data on a daily basis, and that data from such stations can be used to verify model calibration in the future. The report concludes that existing groundwater models of the basin, and the expected improvements to them in the next few years, will make it possible to anticipate the effects of groundwater perturbations on the San Pedro River.

The authors made numerous suggestions to improve the surface water monitoring program. Suggestions included assuring that changes in the present relationships between the BLM sites and the Charleston gage can be identified and quantified, develop better relationships between the Palominas Gage and the International Boundary and Hereford Bridge site, maintain the Fairbank site and use it to generate flow data at Tombstone and Summers, obtain better flow data for the Babocomari, improve the utility of the streamflow data with groundwater data, and improve gaging station documentation. The study reports measurements on the Babocomari ranging from no flow to 1.5 cfs for intermittent gaging between 1990 and 1995. However, Sharma *et. al.* (1997) was not happy with their data and state that an accurate data set of generated surface flows at this site was not feasible.

PRELIMINARY INTERPRETATION OF THE 1997 AIRBORNE ELECTROMAGNETIC (EM) SURVEY OVER FORT HUACHUCA, ARIZONA, AND THE UPPER SAN PEDRO RIVER BASIN (WYNN AND GETTINGS, 1997)

In 1996 and 1997, Wynn and Gettings, under the supervision of the USGS, collected airborne electromagnetic data for subsurface structural investigations on Fort Huachuca and the Upper San Pedro River Basin. The study provides a preliminary interpretation of the March 1997 Upper San Pedro River basin airborne geophysical survey. Interpretations were based on limited data released to the USGS as of early May, 1997, comprising of (a) uncalibrated mathematical inversions of seven flight lines of the 60-channel airborne electromagnetic data, (b) a merged aeromagnetic map, (c) a graphic representation of the flight-lines, and (d) 6 grids representing x- and z-components of channels 2, 6, and 10 (early, middle, and late decay times corresponding to shallow, intermediate, and near maximum depths of penetration of the airborne EM system) (Wynn and Gettings 1997).

This study found preliminary evidence that suggests the existence of a shallow depth conductor and an intermediate depth conductor that underlies the shallow conductor. Wynn and Gettings (1997) report that based on drilling and ground geophysical surveys this intermediate conductor appears to be a clay body that may block the shallow aquifer between Fort Huachuca and the San Pedro River. While it remains unclear from these limited data how this structure affects water movement in the aquifer, isotopic evidence reported elsewhere, and the appearance of the intermediate conductor both suggest that there is at least some natural isolation between the recharge areas west of Fort Huachuca and much of the San Pedro River in the surveyed area (Wynn and Gettings 1997). The study also cites that if this natural isolation exists, then much if not most of the water in the SPRNCA must derive from the upper reaches of the San Pedro River drainage in Mexico (Wynn and Gettings 1997).

USGS HYDROGEOLOGIC INVESTIGATIONS OF THE SIERRA VISTA SUBWATERSHED OF THE UPPER SAN PEDRO BASIN (POOL AND COES, 1999)

The purpose of this hydrogeologic study was to "build a better understanding of the hydrogeologic framework, stream-aquifer interactions, and the rate and location of decreasing baseflow caused by ground-water withdrawals."

Improvements in the conceptual view of the Sierra Vista subwatershed include a better definition of silt and clay layers in the regional aquifer and a better definition of the source of base flow of the San Pedro River. Pool and Coes (1999) state that important changes have occurred that include geologic changes, changes in precipitation, changes in the distribution of ground-water withdrawals, and diminishment of summer base flow and annual runoff at the Charleston streamflow gaging station. Effects of these changes on the hydrologic system include variations in water levels, ground-water flow, recharge and discharge.

The authors note that variations in the seasonal distribution have had important effects such as decreased wet season (June through October) runoff after about 1960 and reduced rates of mountain front recharge during the winters (November through February) of the mid-1940's through mid-1970's. Annual runoff at the Charleston gaging station has decreased from more than 45,000 ac-ft before 1935 to less than 20,000 ac-ft during the mid-1990's. Wet season runoff volumes have varied from more than 40,000 ac-ft before 1935 to less than 10,000 ac-ft during the early and mid-1990's. Winter runoff has varied with precipitation.

The authors state in their summary section that even though wet season runoff volumes have decreased, there has not been a corresponding decrease in winter runoff volumes. An absence of a decline in the percentage of winter precipitation indicates that an increase in capture of precipitation and surface flow may have occurred during the wet season. Possible reasons for this include 1) direct capture through increased vegetation; 2) more frequent low-intensity rainfall events; 3) increased surface water diversions; and 4) increased recharge resulting from increased ground-water withdrawals by phreatophytes and by wells.

Additionally, declines in both winter and wet season base flows before 1951 could be related to several causes such as 1) growth and establishment of phreatophytes as the stream stabilized around 1955; 2) declining annual and seasonal precipitation; and 3) withdrawals for irrigation in the Palominas area. Infiltration of winter surface flows, especially during periods of low wet season precipitation and runoff, may be an important source of base flow. Ground-water withdrawals by wells and phreatophytes may have caused changes in winter and summer base flows after 1951 but the effects are probably masked by the effects of variation in infiltration of surface flow.

The authors also state that the entrenchment of the San Pedro River during the early 1900's resulted in hydrologic effects that were largely unrecorded. They go on to say that the hydraulic connection between the regional aquifer and the river improved because of the removal of pre-entrenchment alluvium. Silt and clay layers within the regional aquifer cause low storage capacity as well as separate the ground-water flow into deep and shallow flow systems while at the same time restricting the interaction between the regional aquifer and the river.

In general, the clay and silt layers occur west of the San Pedro River and north of Lewis Springs and underlie the river south of Lewis Springs resulting in a poor connection between the river and the regional aquifer in this area. In areas further to the south, clay and silt facies are not well known but confined conditions in the Palominas area are known to exist.

Between 1932 and 1982, below average precipitation resulted in water level declines of 0.2 to 0.5 ft/yr. in the regional aquifer with the greatest declines near the mountains. This indicates that mountain front recharge was insufficient to maintain ground-water levels. Between the mid-1960's and mid-1980's, declining water levels were mitigated by greater than average precipitation rates and recharge during associated wet periods.

Water levels have continued to decline where extensive ground-water withdrawals in the Sierra Vista – Fort Huachuca area have occurred. This has diverted ground water that would have normally flowed down gradient toward the Babocomari River and along the San Pedro River downstream of the Charleston gaging station.

Analysis of ground-water samples throughout the basin has identified three sources of groundwater in the San Pedro River. The sources are: 1) water recharged within the Holocene alluvium near the river; 2) recharge to the regional aquifer in Mexico and east of the river along the Mule Mountains; and 3) recharge to the regional aquifer west of the river near the Huachuca Mountains. The groundwater in the Holocene alluvium is distinguished on the basis of specific conductance values, which are greater than values from the regional aquifer. Groundwater recharged near the Huachuca Mountains is distinguished on the basis of stable isotope values, which are different than values from other areas within the basin. During the March 1996 and March 1997 monitoring period, it was found that ground water from the Holocene alluvium that infiltrated near the river during surface flows was the primary source of base flow at the Charleston gaging station. Groundwater discharge from the regional aquifer contributed a minor part of the base flow at the Charleston location during this same time period.

SIMULATION OF GROUNDWATER CONDITIONS IN THE UPPER SAN PEDRO BASIN FOR THE EVALUATION OF ALTERNATIVE FUTURES (GOODE AND MADDOCK, 2000)

This study presents the technical report on groundwater modeling associated with the Alternative Futures study by Steinitz, et al (2003). The stated purpose of the study was to "improve the knowledge of how the ground and surface water systems respond to past water demands by applying the most current information on geology, hydraulic properties, well locations and attributes, groundwater recharge and its distribution, streamflows and diversions, and riparian use." As with most modeling studies, development of a conceptual model preceded the numerical model simulations. One important difference between this modeling study and those before it is the incorporation of an extensive geographic information system (GIS) that included land surface, geology, hydraulic properties, mountain front recharge, riparian evapotranspiration, irrigated agriculture, well locations and the stream network. Improvements in modeling methodology facilitated by the GIS include:

- Distribution of estimated pumping rates (derived from State of Arizona well records) to known well locations rather than areas;
- Elevation-weighted mountain-front recharge distribution;
- Incorporation of recent evapotranspiration rate studies in riparian areas;
- Extension of model boundaries outward toward mountain fronts and to the entire Mexican portion of the Upper San Pedro Basin (USPB) as well as the headwaters of the Babocomari River watershed.

This study also incorporated a portion of the Lower San Pedro Basin from "The Narrows" near Benson to the U.S. Geological Survey (USGS) streamgaging station at Redington.

The conceptual model was created by use of the GIS software known as ArcView, produced by Environmental Systems Research Institute, Inc. Geologic GIS coverages and Digital Elevation Models (DEMs) from the USGS were used to create the geologic boundary conditions. The geology determined the areal extent of the model domain which was limited to areas designated as "alluvial" on the ground surface. Bedrock outcrops within this area were excluded from the model domain.

This study also took a different approach to model layering. Although the same conceptual model used by previous authors was used as a basis for the model structure, the numerical model created a new Layer 1 to accommodate steep hydraulic gradients and perched conditions along mountain front areas. The DEMs were used to identify model areas with slopes greater than 3.0 degrees, and these areas were designated as Layer 1. This layer was assigned the same hydraulic properties of the regional aquifer system, with hydraulic conductivity ranging from 0.03 to nearly 4.0 meters per day. Vertical conductivities were held very low to reflect clay lenses and shallow bedrock which restrict vertical flow of water in these areas.

The model Layer 2 also diverges from traditional modeling methodology. In this study, Layer 2 includes both the upper basin fill of the regional aquifer and the floodplain aquifer. This approach was necessary to ensure that Layer 1 overlaid Layer 2 in all areas. Layer 2 was bounded by the ground surface everywhere except where overlain by Layer 1.

Layer 3 represents the lower basin fill aquifer, which is less extensive than the overlying Layer 2 due to bedrock boundaries on the perimeters of the basin area. Layer 4 corresponds to consolidated sediments of the Pantano formation deeper than roughly 305 meters (1000 feet) below ground surface, based on gravity surveys by Halverson (1984). Since the thickness of Layer 4 is unknown, its hydraulic properties were addressed as transmissivity rather than hydraulic conductivity. Layer 4 thickness ranges from 305 meters along the edges to nearly 2500 meters in the center of the basin near the Mexican border.

The authors used an initial value for mountain-front recharge that fell between the ranges computed by an empirical method from Anderson, et al (1992) and those developed by ADWR (1991 and Corell, et al, 1996).

Agricultural recharge was estimated at 30% of irrigation pumpage. The area for applying this recharge was determined by 1997 satellite imagery. The rate of agricultural pumping was determined from ADWR well data.

The areal extent of the San Pedro River riparian area was also determined from 1997 satellite imagery, with the assumption that this area was the same in 1940. Riparian evapotranspiration demand was based on vegetation type and values published by Scott (1999).

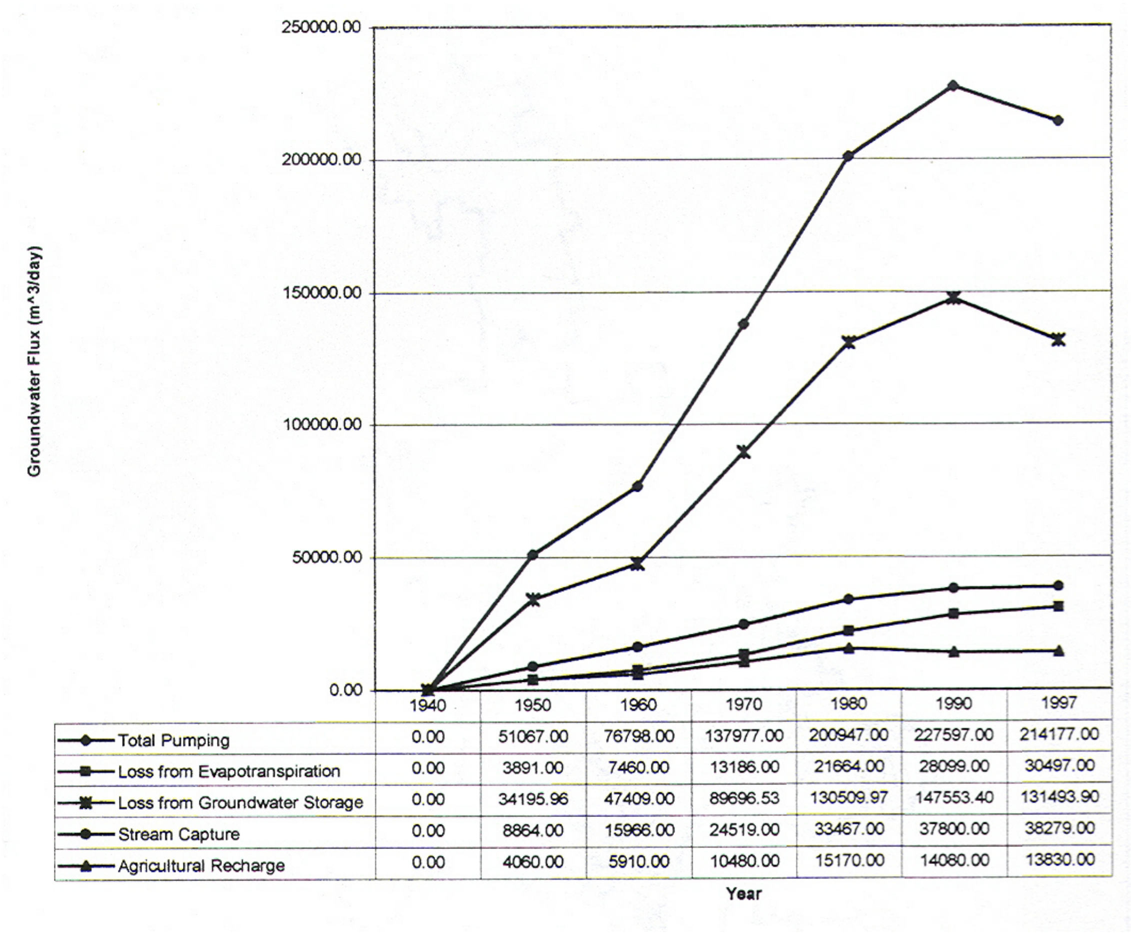
In contrast to previous modeling efforts, this study modeled groundwater pumping at individual well locations and rates derived from the ADWR's Well Registry and Groundwater Site Inventory. Wells with no associated pumping rates or water use type in the records were assigned pumping rates based on their well diameter and location (eg, large wells close within the floodplain were considered irrigation wells). Where actual pumping rates were unavailable, pumping estimates from previous studies were used to assign pumping rates to individual wells. In the case of agricultural wells, some previous studies reported pumping rates already reduced by 30% to account for agricultural recharge. Since this study used those rates, agricultural pumping rates are considered by the authors to be conservatively low. The authors note that records for wells prior to 1980 were essentially nonexistent, so some older irrigation wells may not be accounted for in this study. They also note that the elimination of irrigation pumping within the SPRNCA reduced basin-wide irrigation only slightly.

Pumping rates for domestic wells were assigned a rate of 0.5 acre-feet per year. Pumping rates for remaining non-domestic wells were estimated on the basis of casing area. Public water supply well pumping rates were obtained from water companies, municipalities, ADWR, and the Arizona Corporation Commission. Military wells were considered separately and were defined as those wells located on Fort Huachuca. Pumping rates for these wells were obtained directly from Fort Huachuca. Pumping rates for industrial, commercial, and institutional wells were either obtained from the individual organizations or estimated by casing area.

Pumping rates for wells in Mexico were assigned to domestic and industrial (mining) wells based on information from Lopez (1999) and ADWR (1991).

Like previous studies, this one used the USGS MODFLOW model to conduct simulations based on a finite-difference grid overlain on the model area. GIS polygon information was transferred to the model grid by use of a graphical user interface. Stream-aquifer interaction was modeled with the Prudic (1989) streamflow routing package. The model was calibrated to steady-state conditions based on stream baseflow at Charleston and Palominas (provided by Vionnet (1992)), and groundwater levels measured in wells prior to 1960. Transient-state calibration of the model was accomplished by comparison to recently measured groundwater levels and by baseflows at Palominas, Charleston, “The Narrows,” and Redington.

The transient model was run from 1940 to 1997. One of the most significant products of this study is the calculation and distribution of groundwater capture for the various pumping conditions. Figure 1 below illustrates the predicted distribution of capture from groundwater storage, streams, evapotranspiration, and agricultural recharge over the 58-year model period.



	1940	1950	1960	1970	1980	1990	1997
Total Pumping	0.00	51067.00	76798.00	137977.00	200947.00	227597.00	214177.00
Loss from Evapotranspiration	0.00	3891.00	7460.00	13186.00	21664.00	28099.00	30497.00
Loss from Groundwater Storage	0.00	34195.96	47409.00	89696.53	130509.97	147553.40	131493.90
Stream Capture	0.00	8864.00	15966.00	24519.00	33467.00	37800.00	38279.00
Agricultural Recharge	0.00	4060.00	5910.00	10480.00	15170.00	14060.00	13830.00

FIGURE 1. MASS BALANCE FLUX COMPONENTS OF THE TRANSIENT SIMULATION (SOURCE: FIGURE 8-1 IN GOODE AND MADDOCK, 2000).

The graphs in Figure 1 illustrate that, while the rate of capture from groundwater storage is expected to decrease as pumping decreases, capture from the rivers (Babocomari and San Pedro) and from evapotranspiration is expected to continue to increase over time. Simulated capture from individual stream reaches is displayed in a series of plates in the report. Major trends simulated from 1940 to 1997 include:

- Reduced streamflow in the San Pedro River (primarily downstream of Fairbank);
- Reduced riparian evapotranspiration along the San Pedro River;
- Formation of significant cones of depression (and associated large losses of groundwater storage) near many communities.

Details of the results of simulating various pumping and management scenarios associated with the selected alternative futures are described in the review of Steinitz, et al (2003).

ALTERNATIVE FUTURES FOR CHANGING LANDSCAPES, THE UPPER SAN PEDRO RIVER BASIN IN ARIZONA AND SONORA (STEINITZ, ET. AL., 2003)

Researchers from the Harvard University Graduate School of Design, the Desert Research Institute, the University of Arizona, Instituto del Medio Ambiente y el Desarrollo Sustentable del Estado de Sonora (IMADES), the U.S. Army Training and Doctrine command, and the U.S. Army Research and Development Center conducted a study on the entire Upper San Pedro River Basin, including the Benson and Sierra Vista subwatersheds, to analyze various possible futures for the natural and human-developed systems in the basin. The alternative "futures" were derived from a set of three major scenarios, each with three to four sub-scenarios, for a total of 10 possible alternative outcomes.

The scenarios compared various combinations of possible future populations, water management strategies, and land management strategies. The three primary categories of scenarios were: 1) "PLANS," 2) "CONSTRAINED," and 3) "OPEN." In a very general sense, these scenarios reflect roughly: 1) status quo growth (Fort Huachuca maintains current size) with some increase in land conservation and habitat protection; 2) much slower growth (Fort Huachuca population reduced significantly) and much more aggressive land conservation and habitat protection, including some in Mexico; and 3) much more rapid growth with most of that occurring in uncontrolled rural areas with some decrease in land conservation and habitat protection. Table 1 provides a comparison of the 3 primary scenarios and 7 variations on those scenarios.

While many different aspects of land use change were examined and reported, this review focuses on the water-related findings. Goode and Maddock (2000) provide a detailed description of the groundwater modeling done as part of this study. Simulations were conducted with the USGS MODFLOW finite-difference numerical simulation program using a baseline (pre-development) condition of 1940, in keeping with previous modeling efforts by Vionnet and Maddock (1992) and Corell (1996) and others. After calibrating the model to natural system inputs (recharge) and outputs (evapotranspiration, baseflow) and available data on aquifer characteristics, Goode and Maddock applied pumping stresses representative of actual well information for the entire Upper San Pedro Basin through the year 1997. Hydrologic conditions from the 1997 transient model run were then used as the starting point for the alternative futures simulations out to 2020.

Table 1. Comparison of Alternative Future Scenarios.

	PLANS	CONSTRAINED	OPEN
POPULATION			
Population in 2020	95,000	78500	111,500
% of new population in urban homes	80	90	15
% of new population in suburban homes	15	n/a	15
% of new population in rural homes	3		60
% of new population in exurban homes	2	10	10
Minimum size of new rural residential lot in USPRB (acres)	4	4	1
Minimum size of new rural residential lot within 1 mile of SPRNCA (acres)	4	40	1
Fort Huachuca	Maintains size in year 2000 (approx. 11,000 employees)	Reduces to 1500 personnel on post	Closes with land becoming available for economic growth in civilian sector
Kartchner Caverns - number of visitors per year	200,000	1,000,000	200,000
WATER MANAGEMENT			
Domestic per capita consumption from public and water company sources - change from 1995 level	20% decrease	20% decrease	none
Domestic per capita consumption from individually owned sources - change from 1995 level	40% decrease	20% decrease	none
Agricultural irrigation in USPRB	Existing irrigation rights within 1 mile of SPRNCA purchased and retired; no new irrigation within 1 mile of SPRNCA	None	Existing irrigation remains, but no new irrigation within 1 mile of SPRNCA
Removal of cottonwood and willow trees in riparian zone along San Pedro River	none	50%; cleared areas managed as grasslands	none
Upland mesquite tree removal	none	50%; cleared areas managed as grasslands	none
LAND MANAGEMENT			
Ranching in USPRB	eliminated on federal lands	eliminated on state-owned lands	no change
Leasing of state-owned lands in USPRB for conservation	allowed by competitive bidding	allowed by competitive bidding	not allowed
Prescribed fires in USPRB	Yes	Yes	No; all fires suppressed
Unprotected lands along SPR north of Mexican border	All purchased for conservation	All south of Cascabel purchased for inclusion in SPRNCA	All south of SPRNCA purchased for conservation
Protection of large (>5000 ac) natural patches and their connecting natural corridors	Yes	Yes	No
Potential habitat for endangered species	Protected	Protected	Protected
Potential habitat for threatened species	Protected	Protected	Not protected
Conservation/management for individual species	Yes	Yes	No
Protection of areas based on species diversity	No	Yes	No
Protection of basin scale GAPs	No	Yes	No
Protection of view of mountain ridge lines as seen from major roads	Yes	Yes	No
Protection of view of riparian vegetation corridor as seen from major roads	Yes	Yes	No
Scenario Variations			
PLANS1	AZ population increases at double forecasted rate		
PLANS2	Doubles population in Sonora		
PLANS3	Contrains AZ growth to urban areas		
CONSTRAINED1	Fort Huachuca on-post population is doubled		
CONSTRAINED2	Fort Huachuca is closed		
OPEN1	Increased controls on rural residential development		
OPEN2	Fort Huachuca on-post population is doubled; population in Sonora doubles with corresponding changes in mining activity but no change in conservatoin		

Table 2 summarizes the results of the 10 alternative future scenario model runs as they relate to impacts on groundwater and the San Pedro River. Unfortunately, the presentation of the results by the authors does not permit the distinction between impacts in the various parts of the Upper San Pedro Basin. The following general conclusions can be drawn from these results:

- PLANS scenarios reduce agricultural pumping by approximately 80%, while changes in industrial and municipal pumping vary from a slight decline to an increase of over 30%. These scenarios reduce losses to groundwater storage by roughly 20 to 40%, and decrease capture from the San Pedro by roughly 20 to 30%. Under these scenarios, the dry reaches of the San Pedro River would decline from 4.8 miles to 1.6 to 2.1 miles.

- CONSTRAINED scenarios almost eliminate agricultural pumping and keep industrial and municipal pumping to within 10% of its 2000 level. These scenarios reduce the groundwater storage deficit by 53 to 64% and reduce capture from the river by 45%. The resulting dry reaches of the San Pedro River would decrease from 4.8 to 1.6 miles.

- OPEN scenarios have the most severe groundwater impacts. Under these scenarios, agricultural pumping would decline less than 10%, while industrial and municipal pumping would increase by 16 to 53%. Groundwater storage would continue to decline with losses increasing from 8 to 37% over 2000 conditions. Finally, the San Pedro River would lose roughly 20 miles of perennial/intermittent flow under this scenario.

TABLE 2. GROUNDWATER IMPACTS (SOURCE: TABLE 9.1 IN STEINITZ, ET AL, 2003)

Alternative Future Scenario Impacts to Groundwater, 2000-2020

	Change in Agricultural Pumping over 20 Years			Change in Municipal and Industrial Pumping over 20 Years			Loss from Groundwater Storage over 20 Years			Capture from the San Pedro River System over 20 Years			Dry Length of San Pedro River		
	cu-m/d	ac-ft/yr	% of Baseline	cu-m/d	ac-ft/yr	% of Baseline	cu-m/d	ac-ft/yr	% diff from Baseline	cu-m/d	ac-ft/yr	% diff from Baseline	km	miles	% diff from Baseline
Baseline 2000	113,153	33,483		94,614	27,997		-131,494	-38,910		38,279	11,327		7.7	4.8	
PLANS	-92,190	-27,280	-81%	-2,759	-816	-3%	-76,133	-22,529	-42%	27,634	8,177	-28%	2.6	1.6	-66%
PLANS1	-92,190	-27,280	-81%	17,941	5,309	19%	-92,058	-27,241	-30%	30,087	8,903	-21%	2.6	1.6	-66%
PLANS2	-89,496	-26,483	-79%	30,737	9,095	32%	-106,991	-31,660	-19%	30,218	8,942	-21%	3.4	2.1	-56%
PLANS3	-92,533	-27,381	-82%	-816	-241	-1%	-78,735	-23,298	-40%	27,259	8,066	-29%	2.6	1.6	-66%
CONSTRAINED	-110,859	-32,804	-98%	-1,370	-405	-1%	-55,726	-16,490	-58%	20,901	6,185	-45%	2.6	1.6	-66%
CONSTRAINED1	-110,859	-32,804	-98%	5,140	1,521	5%	-61,493	-18,196	-53%	21,185	6,269	-45%	2.6	1.6	-66%
CONSTRAINED2	-110,859	-32,804	-98%	-9,000	-2,663	-10%	-47,515	-14,060	-64%	21,050	6,229	-45%	2.6	1.6	-66%
OPEN	-6,382	-1,888	-6%	15,083	4,463	16%	-142,102	-42,049	8%	38,096	11,273	0%	39.5	24.5	413%
OPEN1	-6,382	-1,888	-6%	19,213	5,685	20%	-147,114	-43,533	12%	37,523	11,103	-2%	38.0	23.6	394%
OPEN2	-3,294	-975	-3%	49,975	14,788	53%	-179,707	-53,177	37%	38,267	11,324	0%	40.8	25.4	430%

Notes: cu-m/d = cubic meters per day; ac-ft/yr = acre-feet per year; % diff = percent difference.

Figure 1 shows simulated baseflow in the San Pedro River starting at the headwaters in Mexico and continuing to the USGS Redington stream gage. The graph shows that the CONSTRAINED2 scenario comes closest to matching pre-development (1940) flow conditions. Upstream of the St. David Ditch, the PLANS and OPEN scenarios are relatively similar, both between 60 and 75% of baseflow at Fairbank under the CONTRAINED2 scenario, and bracket the actual conditions in 2000.

The study devotes two chapters to habitat impacts resulting from the various development scenarios. Some of the impacts are related to direct replacement or disturbance of habitat by development, while others result from depletions in streamflow as a result of groundwater pumping. Single species habitat impacts are explored for southwestern willow flycatcher, northern goshawk, gila monster, beaver, pronghorn, jaguar. Of these, the southwest willow flycatcher is the only species listed as threatened or endangered by the US Fish and Wildlife Service (USFWS).

For the southwestern willow flycatcher, depth to groundwater is a limiting factor in habitat. A high water table permits the growth of dense riparian vegetation essential for this species' success. The authors cite urban growth, expansion of agriculture, loss of groundwater, stream channelization, and livestock grazing as causes of habitat loss. The authors state that new habitat in the San Pedro River floodplain may be created by increasing the water table within the floodplain such that riparian vegetation replaces desert scrub communities. Conversely, lowering the water table in the floodplain reduces habitat.

Under the OPEN scenario, riparian vegetation decreases by 20% north of the SPRNCA, with an implied decline in southwestern willow flycatcher habitat. The proposed extension of the SPRNCA south of Palominas would increase habitat for the southwestern willow flycatcher. Under the PLANS scenarios, willow flycatcher habitat increases by 30 to 66%, primarily as a result of higher groundwater levels associated with removal of agricultural pumping and other wells within 1 mile of the San Pedro River. The PLANS scenario proposes to remove all livestock grazing from public lands and to extend the SPRNCA to the north and south, resulting in an increase in primary habitat for the willow flycatcher. The CONSTRAINED scenarios have the most positive impact on willow flycatcher habitat, with potential increases of more than 70%. Roughly half of this increase results from increased groundwater elevations in the floodplain.

Habitat for the Huachuca water umbel is addressed in the chapter on threatened and endangered species habitat. Other threatened and endangered species addressed in this group include Sonoran tiger salamander, desert pupfish, southwestern willow flycatcher, lesser long-nosed bat, Madrean ladies'-tresses, and the Mexican spotted owl. Southwestern willow flycatcher habitat (discussed above) and Mexican spotted owl habitat are treated separately from the other four [three aquatic] species. Potential habitat for the other four species is mapped as "potential and existing flat [cienega] or pond-forming areas…along the major watercourses and arroyos."

FIGURE 1. SIMULATED STREAM FLOW OF THE UPPER SAN PEDRO RIVER, 1940-2020 (SOURCE: FIGURE 9.7 IN STENITZ, ET AL, 2003)

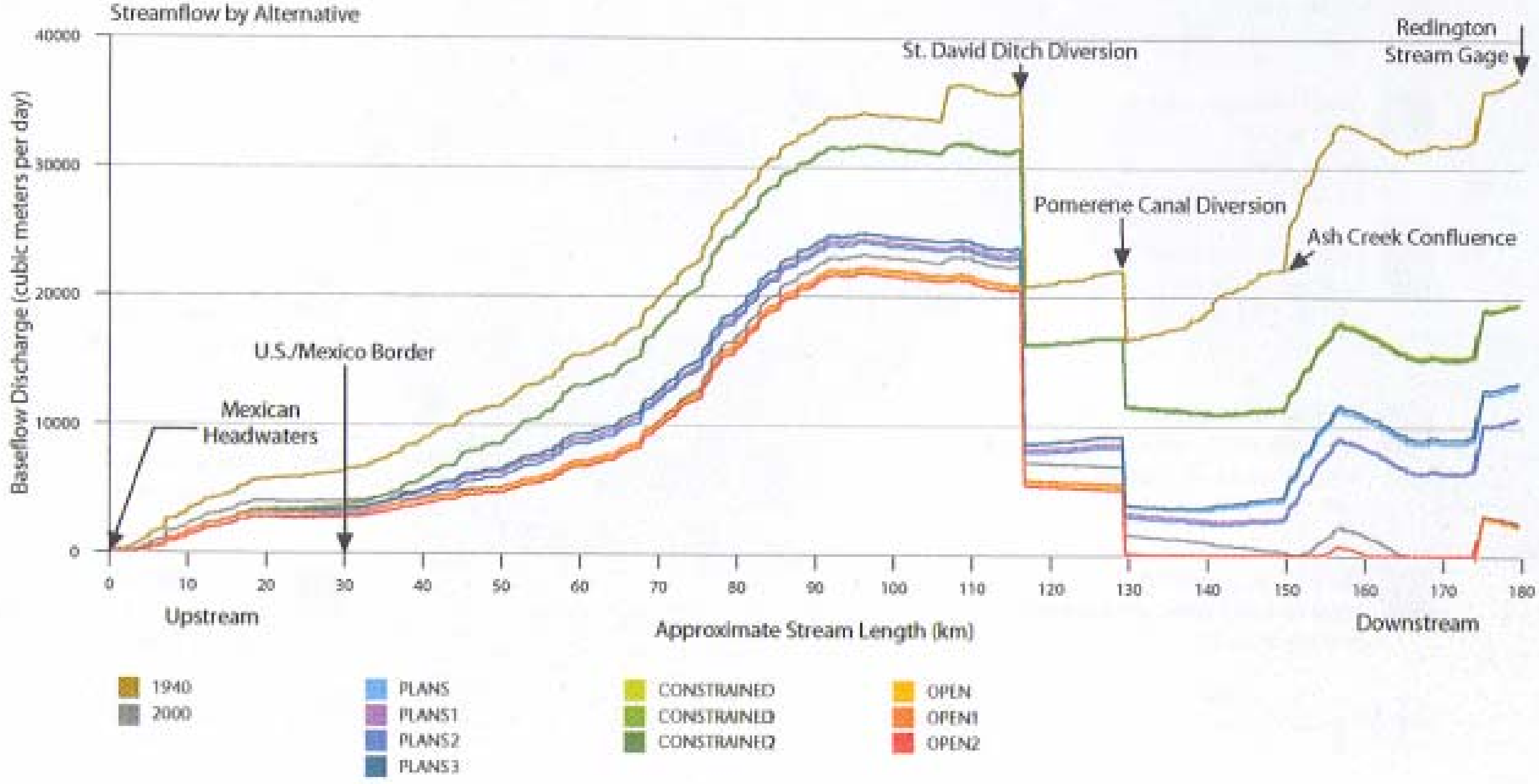


Figure 9.7 ■ Simulated stream flow of the Upper San Pedro River, 1940–2020

All scenarios in the Alternative Futures study incorporate a policy to protect endangered species, so little change should be expected from the simulations. Under the PLANS and CONSTRAINED scenarios, small gains of potential habitat occur in the northern part of the San Pedro River corridor as a direct consequence of higher groundwater levels. Small losses occur throughout the basin as a result of housing development. Under PLANS, habitat would increase by 993 to 1175 hectares (2450 to 2900 acres), and CONSTRAINED, habitat would increase by 1453 to 1464 hectares (3590 to 3620 acres). Under the OPEN scenario, continued declines in groundwater levels result in an expected loss of cienega/pond habitat along the San Pedro north of St. David and in various locations associated with housing development throughout the basin. These potential losses are estimated at 3185 to 3334 hectares (7860 to 8240 acres). Baseline habitat is estimated at 136,329 hectares (336,860 acres).

All of the alternative futures scenarios result in water table declines near Sierra Vista and Cananea. The decline near Sierra Vista is projected at 10 to 15 meters (33 to 49 feet) by 2020. Some water table gains could be achieved north of St. David by restricting agricultural irrigation, as in the CONSTRAINED alternatives. Under the PLANS and OPEN scenarios, the San Pedro River will continue to lose flow.

Agricultural irrigation policy has the single greatest potential impact on the future hydrology of the Upper San Pedro River Basin. The second most significant policy issue is development control. According to the authors, “population growth in Arizona, with its accompanying municipal and industrial water demands, is the second largest future consumer of water.” The authors note that the similarity between all of the OPEN scenarios, and the contrast between the OPEN and CONSTRAINED scenarios indicates that “the relaxation of development constraints has very powerful influences on potential negative environmental impacts.”

The third most significant policy issue is growth in Sonora, Mexico. Even though the high growth rates assumed for Sonora in PLANS2 and OPEN2 produce larger impacts than other scenarios, these effects are small relative to those of agricultural and development policies in Arizona. Similarly, the impacts of Fort Huachuca were tested by varying its population. The three options would either keep the population as 2000 levels, double it, or essentially eliminate it. Although local consequences of these alternatives may be large in the Sierra Vista area, they are small in comparison to potential effects of agriculture and urbanization in the Arizona portion of the study area.

USGS ANNUAL REPORT TO CONGRESS ON WATER MANAGEMENT OF THE REGIONAL AQUIFER IN THE SIERRA VISTA SUBWATERSHED (DOI, 2005)

Section 321 of the Defense Authorization Act of 2004, Public Law 108-136, requires the Secretary of the Interior, in cooperation with the Upper San Pedro Partnership (Partnership), the Secretary of Agriculture, and the Secretary of Defense, to submit annual reports to Congress on “water use management and conservation measures that have been implemented and are needed to restore and maintain the sustainable yield of the regional aquifer by and after September 30, 2011." The 2005 report, detailing water conservation measures taken in 2004, is the latest of the annual reports available at the time of this writing.

The initial goal of the Section 321 process was to "arrest storage depletion, with a management goal to accrete aquifer storage to achieve sustainable yield." Section 321 requires a plan that specifies "the quantity of overdraft of the regional aquifer to be reduced by the end of each of the fiscal years 2005 through 2011 to achieve sustainable yield." The report defines overdraft as "ground-water consumption in excess of sustainable yield," but then goes on to say that sustainable yield cannot be quantified at the present time. Therefore, the report "does not assign numerical values to overdraft but does present quantities of planned reductions in net groundwater withdrawals," with the understanding that "reductions in net ground-water withdrawals represent reductions in overdraft from the regional aquifer. The report stresses that correct computation of the groundwater storage deficit is less important than the aquifer's response over time to both human impacts and natural variability.

Even though the Partnership set a water conservation and augmentation target equal to annual storage depletion as their metric for evaluating progress toward sustainable yield, they acknowledged that "sustainable" groundwater use does not equate to zero impact to the aquifer system. The Section 321 report used a simple water-budget approach to assess sustainability, acknowledging that spatial water-use management impacts cannot be reflected in a water budget, nor can the water budget predict when certain conditions will occur or where they will occur. For this reason, the Partnership proposes to use a ground-water flow model in conjunction with a decision support system for future management planning purposes.

The Section 321 report adopted components from the ADWR's water budget from 2002 as its starting point and "minimum management target." The elements of the ADWR's 2002 water budget involving water-management measures and urban-enhanced recharge were moved out of the water budget and into the Section 321 reports "Plans" section. The baseline (2002) groundwater storage deficit assumed by the Partnership was 10,000 acre-feet per year.

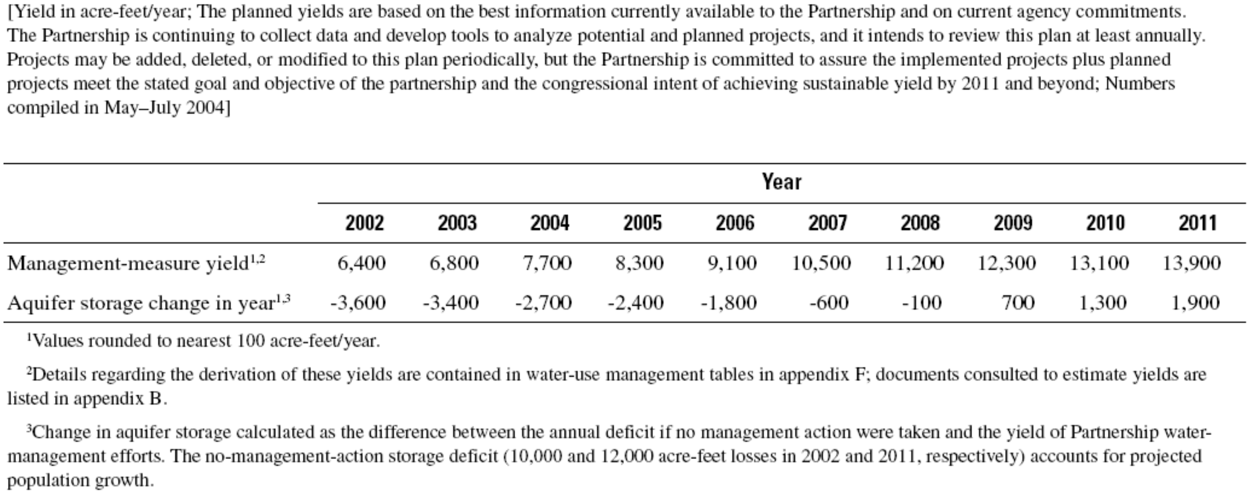
Using population estimates developed by Cochise County on the basis of Arizona Department of Economic Security population projections, the Section 321 authors assumed a 2011 population for the Sierra Vista subwatershed (SVS) of 83,150. From this population projection, the Partnership projects an annual storage deficit of 12,000 acre-feet per year by 2011 ignoring any yields from management measures and urban-enhanced recharge.

The water-management plan included in the Section 321 document includes "only existing water-management measures that have already been implemented by member agencies or potential future measures that have been evaluated for pros, cons, costs, and benefits by the Partnership." The management measures already enacted and those proposed for continuation and initiation were estimated to "eliminate annual storage depletion and begin accreting storage by 2009." By 2011, the predicted net change in groundwater storage (from 2002 baseline conditions) is + 2,000 acre-feet per year.

Based on the Partnership's estimated 6,400 acre-feet of "yield" from management measures in operation as of 2002, the authors estimate an aquifer-storage depletion of 3,600 acre-feet for

2002. Other estimated management-measure yields and associated aquifer-storage deficits are listed in Table 1.

TABLE 1. PROJECTED YIELD OF PARTNERSHIP WATER-MANAGEMENT PLAN MEASURES AND ESTIMATED ANNUAL CHANGE IN AQUIFER STORAGE—RESPONSE TO SECTION 321, PART 3(B) (SOURCE: TABLE 4 IN USGS, 2004)



[Yield in acre-feet/year; The planned yields are based on the best information currently available to the Partnership and on current agency commitments. The Partnership is continuing to collect data and develop tools to analyze potential and planned projects, and it intends to review this plan at least annually. Projects may be added, deleted, or modified to this plan periodically, but the Partnership is committed to assure the implemented projects plus planned projects meet the stated goal and objective of the partnership and the congressional intent of achieving sustainable yield by 2011 and beyond; Numbers compiled in May–July 2004]

	Year									
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Management-measure yield[1,2]	6,400	6,800	7,700	8,300	9,100	10,500	11,200	12,300	13,100	13,900
Aquifer storage change in year[1,3]	-3,600	-3,400	-2,700	-2,400	-1,800	-600	-100	700	1,300	1,900

[1] Values rounded to nearest 100 acre-feet/year.

[2] Details regarding the derivation of these yields are contained in water-use management tables in appendix F; documents consulted to estimate yields are listed in appendix B.

[3] Change in aquifer storage calculated as the difference between the annual deficit if no management action were taken and the yield of Partnership water-management efforts. The no-management-action storage deficit (10,000 and 12,000 acre-feet losses in 2002 and 2011, respectively) accounts for projected population growth.

In addition to presenting planned water yields for each "water-use controlling" member of the USPP, the Section 321 document lays out a rough budget for the cost of implementing the planned conservation and recharge/reuse measures. The two line items identified as requiring the largest federal contributions are for Sierra Vista municipal effluent recharge/reuse and/or stormwater recharge ($1.5 million federal funding needed) and the Huachuca effluent pipeline and recharge at Fort Huachuca ($5.6 million federal funding needed).

As required by Section 321, the report outlines legal impediments to accomplishing sustainable yield in the USPB. These impediments include the limited legal authority of local governments to implement code and zoning changes and control water prices, the lack of matching funds from State sources to implement conservation measures, and legal prohibitions on some types of water importation.

The Section 321 report also describes monitoring to be undertaken by the Partnership to "measure the reduction of the overdraft to the regional aquifer in the SVS," and provides a cost estimate of $1.7 million for this monitoring. Items specified for monitoring include: natural recharge, urban-enhanced recharge, stream baseflow and springs, riparian evapotranspiration within the SPRNCA, groundwater pumping, groundwater levels, stream and shallow groundwater system conditions within the SPRNCA, and riparian vegetation condition.

UPPER SAN PEDRO BASIN ACTIVE MANAGEMENT AREA REVIEW REPORT (ADWR, 2005)

The technical report to the Upper San Pedro Active Management Area (AMA) Review Report was published separately in February 2005 under the title, "Groundwater Resources of the Upper San Pedro Basin," and is wholly incorporated into the AMA Review Report, so the two documents are reviewed here simultaneously. Because the Upper San Pedro was not an AMA prior to the study (and still is not), the AMA review of the Upper San Pedro Basin was prompted by Arizona law and by considerable interest in the water resources of the subbasin by all levels of government:

> Under A.R.S § 45-412(C), the Arizona Department of Water Resources (Department or ADWR) must "periodically review all areas which are not included within an active management area to determine whether such areas meet any of the criteria for active management areas…" The criteria are specific. The director of ADWR may propose to designate a subsequent AMA if the director determines that any of the following criteria are met: 1) active management practices are necessary to preserve the existing supply of groundwater for future needs; 2) land subsidence or fissuring is endangering property or potential groundwater storage capacity; and 3) use of groundwater is resulting in actual or threatened water quality degradation.
>
> In 2001, ADWR undertook a review of the Upper San Pedro Basin (USP Basin or Basin) to determine if it met the statutory requirements for designation as an AMA. This report reviews the water supply and demand of the USP Basin in the context of the statutory criteria set forth in A.R.S. § 45-412(A), and includes a discussion of whether any of the criteria have been met.
>
> Previously, ADWR conducted a study of the USP Basin and issued a report in 1988 in which ADWR determined that the Basin did not meet the statutory criteria for AMA designation (Putman and others, ADWR 1988). ADWR indicated in the report that it would reassess conditions in the Basin in ten to fifteen years. Since 1988, there has been considerable local, state and federal interest in the water resources of the Sierra Vista area and the San Pedro Riparian National Conservation Area, which is located in the Basin. This interest has resulted in additional hydrologic studies and increased local water management activities.
>
> The study described in this report is an evaluation of whether the conditions of the USP Basin satisfy the statutory criteria of A.R.S. § 45-412. This report contains a description of the current and projected water resources and water demand in the Basin, incorporating new information since the previous review. The report examines historic water use trends, evaluates the groundwater resources of the Basin, and projects impacts of future water use on Basin groundwater supplies. The report includes an evaluation of the incidence of subsidence or fissuring, and of the potential for groundwater quality degradation due to groundwater use. The report further describes and evaluates the impact that AMA practices would have on water use, and includes a summary of findings, the director's determination of whether the Basin should be designated and recommendations. For purposes of

> this report, groundwater is defined as water withdrawn from a well or water located within an underground aquifer.

The report covers the entire Upper San Pedro Basin (USPB) from the international boundary with Mexico to the "Narrows" north of Benson. It distinguishes between the Sierra Vista Subbasin, which extends from Mexico to the Narrows, and the Allen Flat Subbasin, which extends north and east of the Narrows. The Sierra Vista and Benson subwatersheds, both part of the Sierra Vista Subbasin, are also distinguished in the report. The report provides an extensive review of basin geology, including recent bedrock mapping by Gettings and Houser (2000) and aquifer delineation by Pool and Coes (1999), Putman, et al (1988), Drewes (1980), and Burtell (1989). This review focuses on hydrology of the Sierra Vista subarea.

Historical and Current Conditions

Groundwater elevation maps for 1940, 1961, 1968, 1978, 1990, and 2001 are provided with data compiled from numerous published reports. Figure 1 below (from Figure 3-10 in the report) presents a generalized depth-to-groundwater map for the year 2001 in the basin. The groundwater elevation maps show a clear cone of depression under the Sierra Vista/Fort Huachuca area as early as 1966. From 1966 to 2001, groundwater elevations under the Sierra Vista pumping center had declined by at least 50 feet, according to the maps. As shown in Figure 1, depths to groundwater exceeded 500 feet under the Sierra Vista pumping center, with the cone of depression running roughly parallel to the Huachuca Mountains to the northwest and southeast from Sierra Vista. ADWR reports that most wells within the Sierra Vista cone of depression experienced water level declines of about 1 foot per year from 1990 to 2001. Wells between Sierra Vista and Huachuca City showed declines of 5 to 7 feet (0.4-0.6 feet per year) in the same 12-year period. Declines of 9.8 to 32.1 feet (0.8 to 2.7 feet per year) in the Naco area were the sharpest declines observed in the USPB from 1990-2001. ADWR speculates that a cone of depression is forming southwest of Bisbee along Greenbush Draw, close to a municipal well field. ADWR reports "no long-term declines in water level" for the floodplain aquifer along the San Pedro River. Recent "short-term" declines were attributed to drought conditions.

ADWR estimates total groundwater storage in the Sierra Vista subbasin[1] at between 19.8 million and 26.1 million acre-feet. This estimate includes water in the upper and lower basin fill units, the Pantano Formation, and the alluvial aquifer. This estimate is roughly 40 to 50% lower than previously published estimates by ADWR (1991) and Putman, et al (1988), largely because of a refinement in the bedrock depths (from Gettings and Houser (2000)) and lower specific yield values for the Pantano.

The report provides a detailed analysis of the water budget for the USPB, including a subdivision of the water budget components for the Sierra Vista sub-area and the remaining downstream portion of the Sierra Vista subbasin. The water budget analysis incorporated estimates from numerous publications, notably including Corell, et al (1996), ADWR (1991), Anderson and Freethey (1994), Putman, et al (1988), and Goode and Maddock (2000). One noteworthy change to previous authors' work is that ADWR reduced Corell, et al's (1996) estimate of recharge to the Sierra Vista sub-area by 1000 acre-feet per year based on recent information that mine

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[1] Note that the subbasin extends to the Narrows, while the northern extent of the sub-area is Fairbank.

discharge to evaporation ponds near Warren Ranch (near Naco), which was likely the source of recharge in Greenbush Draw, was discontinued in 1997. In addition to the 18,000 acre-feet of natural recharge to the sub-area adopted from Corell, et al (1996), ADWR added 1,500 acre-feet of effluent recharge and 2000 acre-feet of incidental municipal and industrial recharge for a total estimated recharge of 21,500 acre-feet annually.

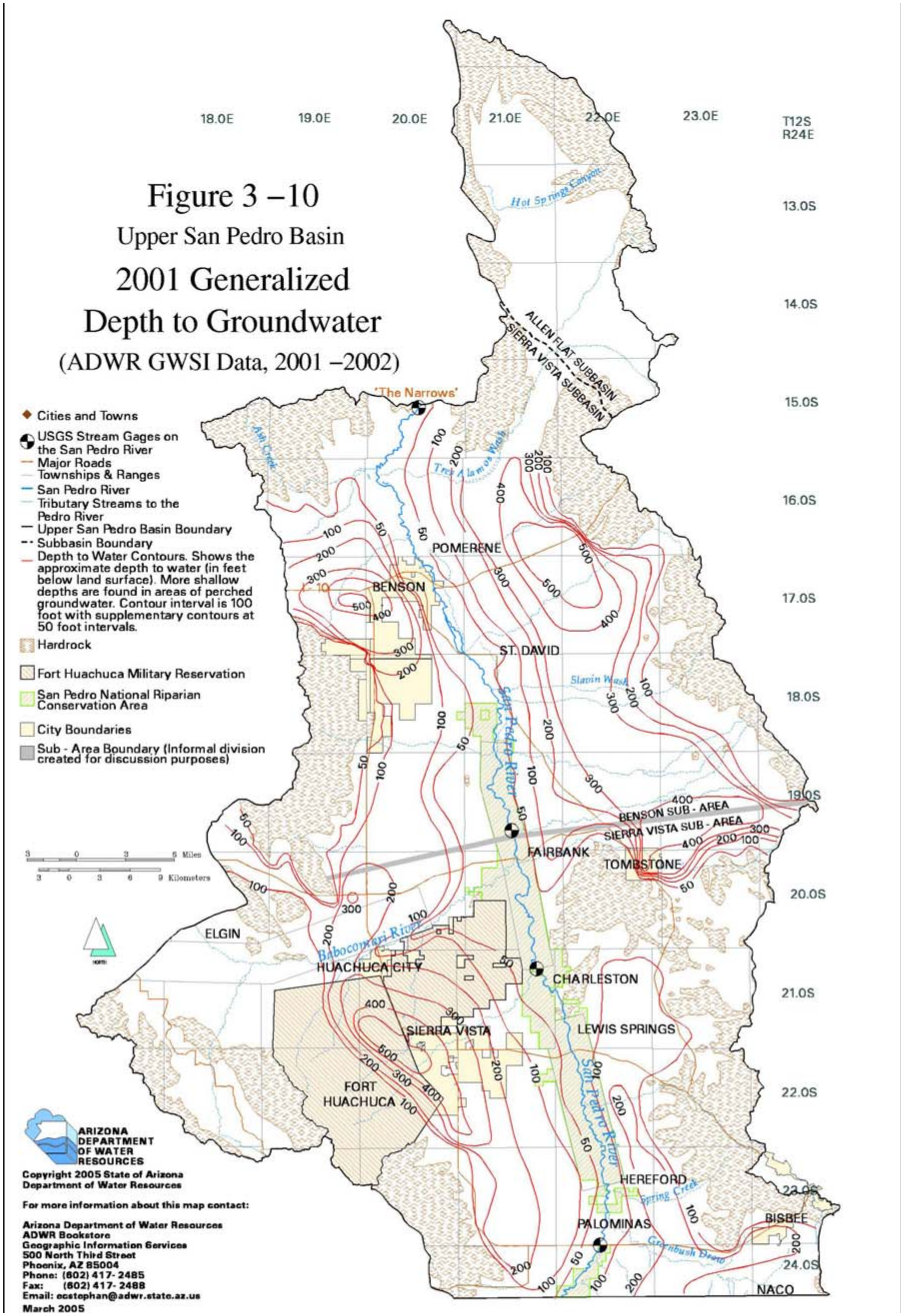


FIGURE 1. DEPTH TO GROUNDWATER (SOURCE: FIGURE 3-10 IN ADWR (2005B)).

TABLE 1. WATER BUDGET FOR SIERRA VISTA SUB-AREA (NOT INCLUDING MEXICO). (SOURCE: TABLE 3-2 IN ADWR 2005).

Inflows to Groundwater System	**Sierra Vista Sub-area**
Mountain Front, Ephemeral channel, Cross-border Flux	18,000
Artificial Recharge	1500
Incidental Recharge	2000
Total Inflow	**21500**
Outflows from Groundwater System	
Agricultural Demand	2500
Municipal Demand	14500
Industrial Demand	1300
Stock Demand	160
Riparian Use	7700
Underflow leaving sub-area	440
Baseflow leaving sub-area	3250
Total Outflows	**29850**
Change in Storage	-8350

ADWR estimated that 800 acres were under irrigation in the Sierra Vista sub-area in 2003. From this acreage, they estimated a consumptive agricultural water use of 2,500 acre-feet in 2002. ADWR estimates that 96% of all municipal water demand in the Sierra Vista sub-area (45,000 acre-feet) is met by groundwater, with the only surface water use coming from Miller Canyon in the Huachuca Mountains. Industrial water demand in the Sierra Vista sub-area derives from five sand and gravel facilities and two golf courses. This industrial demand was reported as 1,300 acre-feet in 2002.

ADWR used Corell, et al’s (1996) estimate of 7,700 acre-feet as annual riparian groundwater demand because that estimate incorporated a longer time period than the more recent estimate (7330 to 8970 acre-feet) by Scott and others based on a three-year study. At that time, Scott, et al’s values were unpublished and were considerably lower than the final values published by the USGS in 2005 (Scott, et al (2005) in USGS (2005)).

Baseflow at the USGS streamgaging station “San Pedro River near Tombstone” was estimated visually by ADWR from average daily flow data for the period 1997 to 2004. This period represented the most recent continous flow record after a 16-year hiatus in the record from 1981 to 1996. Baseflow was estimated as “an average non-flood related stream flow … of about 3,250 acre-feet per year,” with zero flows “generally recorded during late spring, summer and fall.” Winter baseflows (November through March) were estimated at 3,100 acre-feet per year. ADWR disregarded late spring and early fall baseflow (estimated at 150 acre-feet per year) because they considered it to be unavailable for groundwater recharge due to riparian consumptive use, and therefore not part of the water budget. Total groundwater storage depletion in the Sierra Vista sub-area was estimated at 8,350 acre-feet per year (see Table 1).

Groundwater extraction may lead to land subsidence in the USPB, but presently, there is no subsidence monitoring system in place. The ADWR concluded that “at this time, neither land subsidence nor fissuring is endangering property or potential groundwater storage.”

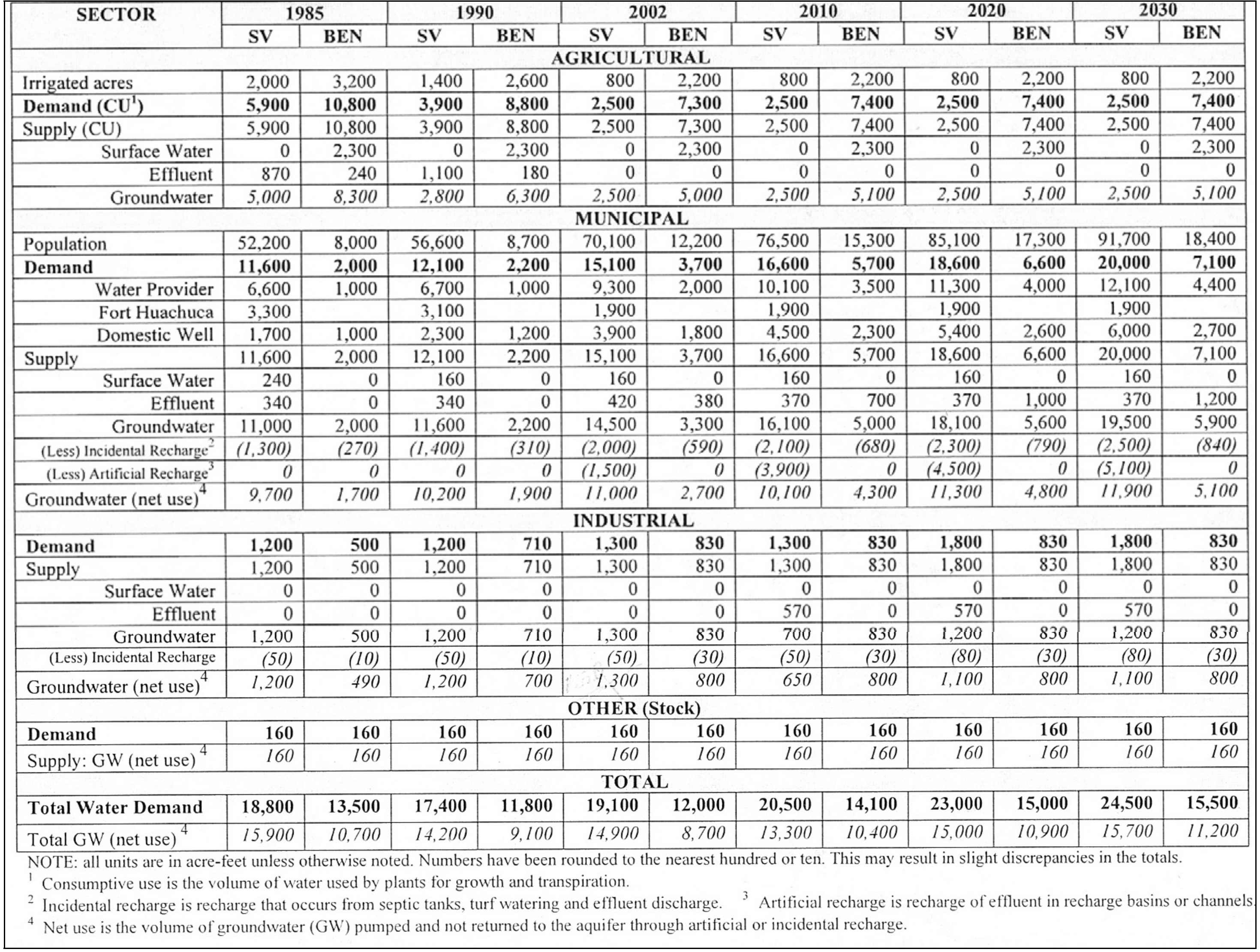
Water quality was assessed by ADWR through direct sampling and from data collected for other studies. Septic systems, faulty wastewater treatment systems, leaking underground storage tanks, naturally occurring arsenic, soil contamination at Fort Huachuca, and the Superfund site at Apache Powder (2.5 miles southwest of St. David) were all cited as potential sources of groundwater contamination. Ultimately, the report concludes that “the use of groundwater is not resulting in actual or threatened water quality degradation in the sub-basin.”

Water Use Projections

ADWR ran projections of water demand and supply for the USPB out to the year 2030 based on Arizona Department Economic Security population projections which apply a constant growth rate of 1.1% per year for a 2030 population of 110,000in the entire USPB, and 91,677 in the Sierra Vista sub-area. Applying the actual growth rate of 2.3% per year for the entire USPB between 1990 and 2000 yields a 2030 population of 160,000. Note that Arizona Department of Economic Security population figures for Bisbee, Fort Huachcua, Huachuca City, Sierra Vista, and Tombstone are only slightly lower than ADWR’s 2030 combined projected population for those same incorporated areas due largely to higher numbers for Fort Huachuca and Sierra Vista.

Current water demand distribution patterns were applied to the 2030 estimated population to predict future water demand. For example, ADWR found that 61.4% of total cultural water demand in the USPB was from the Sierra Vista sub-area. They also noted that 90% of the 5,300 acre-feet of effluent produced in the USPB was generated in the Sierra Vista sub-area, with just over 30% of that being recharged through constructed facilities in 2002. Table 2 shows ADWR’s projections for water supply and demand in the Benson and Sierra Vista sub-areas.

TABLE 2. USPB WATER DEMAND AND SUPPLY FOR SELECTED YEARS (SOURCE: TABLE 4-7 IN ADWR, 2005B).



SECTOR	1985		1990		2002		2010		2020		2030	
	SV	BEN	SV	BEN	SV	BEN	SV	BEN	SV	BEN	SV	BEN
AGRICULTURAL												
Irrigated acres	2,000	3,200	1,400	2,600	800	2,200	800	2,200	800	2,200	800	2,200
Demand (CU[1])	**5,900**	**10,800**	**3,900**	**8,800**	**2,500**	**7,300**	**2,500**	**7,400**	**2,500**	**7,400**	**2,500**	**7,400**
Supply (CU)	5,900	10,800	3,900	8,800	2,500	7,300	2,500	7,400	2,500	7,400	2,500	7,400
Surface Water	0	2,300	0	2,300	0	2,300	0	2,300	0	2,300	0	2,300
Effluent	870	240	1,100	180	0	0	0	0	0	0	0	0
Groundwater	*5,000*	*8,300*	*2,800*	*6,300*	*2,500*	*5,000*	*2,500*	*5,100*	*2,500*	*5,100*	*2,500*	*5,100*
MUNICIPAL												
Population	52,200	8,000	56,600	8,700	70,100	12,200	76,500	15,300	85,100	17,300	91,700	18,400
Demand	**11,600**	**2,000**	**12,100**	**2,200**	**15,100**	**3,700**	**16,600**	**5,700**	**18,600**	**6,600**	**20,000**	**7,100**
Water Provider	6,600	1,000	6,700	1,000	9,300	2,000	10,100	3,500	11,300	4,000	12,100	4,400
Fort Huachuca	3,300		3,100		1,900		1,900		1,900		1,900	
Domestic Well	1,700	1,000	2,300	1,200	3,900	1,800	4,500	2,300	5,400	2,600	6,000	2,700
Supply	11,600	2,000	12,100	2,200	15,100	3,700	16,600	5,700	18,600	6,600	20,000	7,100
Surface Water	240	0	160	0	160	0	160	0	160	0	160	0
Effluent	340	0	340	0	420	380	370	700	370	1,000	370	1,200
Groundwater	11,000	2,000	11,600	2,200	14,500	3,300	16,100	5,000	18,100	5,600	19,500	5,900
(Less) Incidental Recharge[2]	*(1,300)*	*(270)*	*(1,400)*	*(310)*	*(2,000)*	*(590)*	*(2,100)*	*(680)*	*(2,300)*	*(790)*	*(2,500)*	*(840)*
(Less) Artificial Recharge[3]	*0*	*0*	*0*	*0*	*(1,500)*	*0*	*(3,900)*	*0*	*(4,500)*	*0*	*(5,100)*	*0*
Groundwater (net use)[4]	*9,700*	*1,700*	*10,200*	*1,900*	*11,000*	*2,700*	*10,100*	*4,300*	*11,300*	*4,800*	*11,900*	*5,100*
INDUSTRIAL												
Demand	**1,200**	**500**	**1,200**	**710**	**1,300**	**830**	**1,300**	**830**	**1,800**	**830**	**1,800**	**830**
Supply	1,200	500	1,200	710	1,300	830	1,300	830	1,800	830	1,800	830
Surface Water	0	0	0	0	0	0	0	0	0	0	0	0
Effluent	0	0	0	0	0	0	570	0	570	0	570	0
Groundwater	1,200	500	1,200	710	1,300	830	700	830	1,200	830	1,200	830
(Less) Incidental Recharge	*(50)*	*(10)*	*(50)*	*(10)*	*(50)*	*(30)*	*(50)*	*(30)*	*(80)*	*(30)*	*(80)*	*(30)*
Groundwater (net use)[4]	*1,200*	*490*	*1,200*	*700*	*1,300*	*800*	*650*	*800*	*1,100*	*800*	*1,100*	*800*
OTHER (Stock)												
Demand	**160**	**160**	**160**	**160**	**160**	**160**	**160**	**160**	**160**	**160**	**160**	**160**
Supply: GW (net use)[4]	*160*	*160*	*160*	*160*	*160*	*160*	*160*	*160*	*160*	*160*	*160*	*160*
TOTAL												
Total Water Demand	**18,800**	**13,500**	**17,400**	**11,800**	**19,100**	**12,000**	**20,500**	**14,100**	**23,000**	**15,000**	**24,500**	**15,500**
Total GW (net use)[4]	*15,900*	*10,700*	*14,200*	*9,100*	*14,900*	*8,700*	*13,300*	*10,400*	*15,000*	*10,900*	*15,700*	*11,200*

NOTE: all units are in acre-feet unless otherwise noted. Numbers have been rounded to the nearest hundred or ten. This may result in slight discrepancies in the totals.

[1] Consumptive use is the volume of water used by plants for growth and transpiration.

[2] Incidental recharge is recharge that occurs from septic tanks, turf watering and effluent discharge. [3] Artificial recharge is recharge of effluent in recharge basins or channels.

[4] Net use is the volume of groundwater (GW) pumped and not returned to the aquifer through artificial or incidental recharge.

Much of the ADWR report is devoted to examining the potential effects of an AMA designation for the USPB on basin groundwater supply. In particular, they address the following components of AMA practice:

- Groundwater rights and permits including metering, reporting and fees.
- Well regulations.
- Agricultural land development restrictions.
- Groundwater management plans, which include agricultural, municipal and industrial water conservation programs, an augmentation program, groundwater quality assessment, and a water management assistance program.
- Assured water supply program requirements for new subdivisions to have long-term dependable water supplies consistent with the management goal.
- Transportation of groundwater between groundwater basins and sub-basins.

A qualitative summary of their findings on this issue is provided below:

> These practices include a groundwater rights system that restricts groundwater withdrawals, prohibits the development of new irrigated farmland, requires that new subdivisions have long-term dependable water supplies, requires that groundwater withdrawals be measured and reported, requires mandatory conservation for agricultural, municipal and industrial users, and develops management plans to achieve the management goal. AMA practices, however, would not affect all water users, would not prohibit growth, and would not significantly restrict current groundwater use. In the USP Basin approximately 27% of the current water demand would not be subject to AMA practices. Municipal per capita conservation requirements would apply to approximately 47% of the municipal water demand in the Basin. Total municipal water demand could increase as the population increased and new water service areas could be formed. Because water providers in AMAs are not required to demonstrate an assured water supply for their existing water service area, an assured water supply program would likely apply only to new subdivisions.

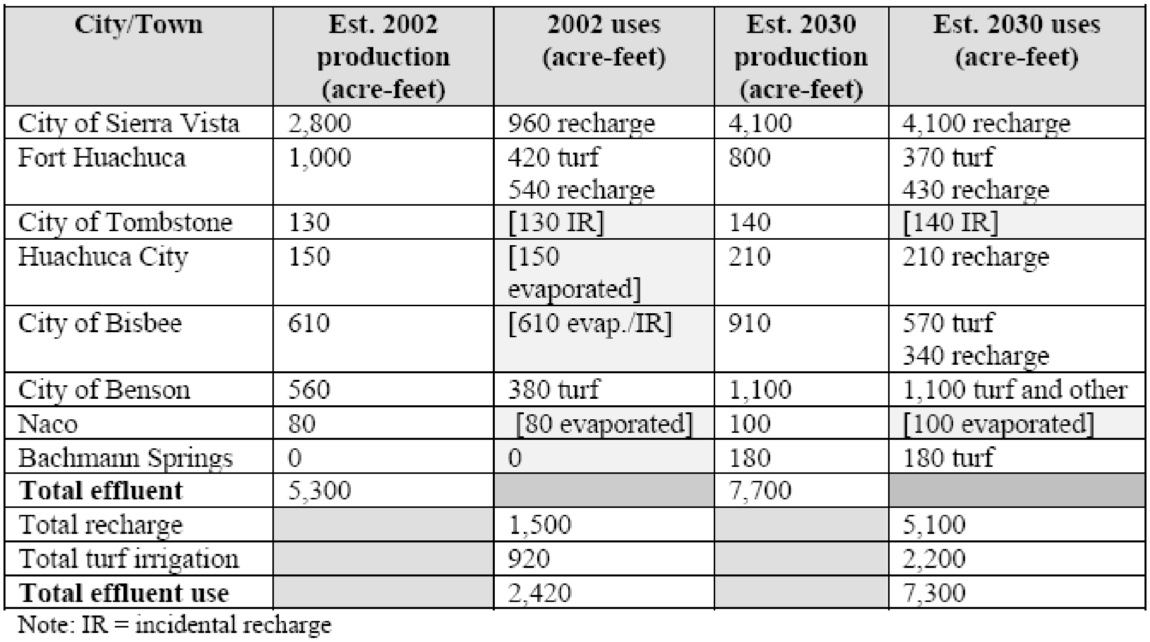
Two of the most significant tools for controlling groundwater use in AMA's are the groundwater rights system and the Assured Water Supply program (AWS). "In the absence of a groundwater rights system, there are no restrictions on future groundwater withdrawals by non-exempt wells. New non-exempt wells can be drilled without undergoing a well impact analysis." This system also caps agricultural groundwater use at historical levels. The AWS program "has been a major impetus to utilization of renewable supplies in the Pinal, Tucson, and Phoenix AMAs."

ADWR makes no predictions as to specific potential changes to the groundwater system as a consequence of AMA designation in the USPB. They do note that AMA practices are not required on federal lands.

Water Augmentation

Effluent, which is generated by only about 23% of the total cultural water demand, is noted as the only existing source of water in the basin available for artificial recharge. Table 3 shows ADWR's estimated effluent production and demand in 2002 and 2030.

TABLE 1. ESTIMATED EFFLUENT PRODUCTION AND USE IN THE USPB (SOURCE: TABLE 6-5 IN ADWR, 2005B).



City/Town	Est. 2002 production (acre-feet)	2002 uses (acre-feet)	Est. 2030 production (acre-feet)	Est. 2030 uses (acre-feet)
City of Sierra Vista	2,800	960 recharge	4,100	4,100 recharge
Fort Huachuca	1,000	420 turf 540 recharge	800	370 turf 430 recharge
City of Tombstone	130	[130 IR]	140	[140 IR]
Huachuca City	150	[150 evaporated]	210	210 recharge
City of Bisbee	610	[610 evap./IR]	910	570 turf 340 recharge
City of Benson	560	380 turf	1,100	1,100 turf and other
Naco	80	[80 evaporated]	100	[100 evaporated]
Bachmann Springs	0	0	180	180 turf
Total effluent	5,300		7,700	
Total recharge		1,500		5,100
Total turf irrigation		920		2,200
Total effluent use		2,420		7,300

Note: IR = incidental recharge

Little consideration is given by ADWR to other potential sources of water supply (i.e., imported water), on the basis that they are speculative. However, ADWR does cite an estimate by the Upper San Pedro Partnership of $121.7 million to construct a pipeline for importing Central Arizona Project water, and annual costs of $16.4 million. They also refer to two AMA's which do not have CAP allocations but do import water. These AMA's are the Prescott AMA, which has statutory authorization to import Big Chino Basin groundwater, and the Santa Cruz AMA which receives and treats effluent from Mexico. They note that "in general, groundwater cannot be transported between groundwater basins or from a groundwater basin outside an AMA into an AMA except for certain transfers specified in statute A.R.S. §§ 45-544 and 45-551 through 45-555. Groundwater may be transported between subbasins of the same basin, but it would be subject to payment of damages under certain conditions.

ADWR notes that "attempting to change the law to allow importation of groundwater could face political challenges, as well as present physical, economic, environmental, and legal obstacles."

The ADWR director's determination relative to the USPB's consideration for AMA status is summarized below:

> Based on an evaluation of water quality data, the director has determined that the use of groundwater is not resulting in actual or threatened water quality degradation in the USP Basin.

> Because the director has determined that none of the statutory criteria have been satisfied, the director does not propose to designate the USP Basin as an active management area at this time.

QUANTIFYING BASEFLOW INPUTS TO THE SAN PEDRO RIVER: A GEOCHEMICAL APPROACH (BAILLIE, 2005)

This study used a suite of natural and anthropogenic geochemical tracers to try to identify and quantify the sources of water that support riparian groundwater (i.e., groundwater within the alluvial aquifer) and baseflow in the San Pedro River between the USGS streamgaging stations at Palominas and Charleston. The study area was bound on the west by the Huachuca Mountains and on the east by the San Pedro River. The geochemical tracers used in the study included stable isotopes of oxygen (^{18}O) and hydrogen (^{2}H), radioactive isotopes of hydrogen (^{3}H) and carbon (^{14}C), and the ratio of sulfate (SO_4) and chloride (Cl) ions.

The ^{18}O and ^{2}H tracers were used to differentiate between groundwater derived from winter frontal and summer convective precipitation. In precipitation, these isotopes vary with temperature, humidity, and moisture in the source area. Precipitation isotope composition also varies with elevation and evaporation. The radioactive isotopes ^{3}H and ^{14}C were used to determine mean groundwater residence times in the aquifer. Tritium (^{3}H) has a short half-life and provides information on residence times of short-flowpath and recently recharged groundwater, while ^{14}C, with its much longer half-life, was used to date older groundwater. Corrections were made to the ^{14}C activity-based groundwater ages to account for post-recharge processes such as mixing and carbonate dissolution along the flowpath. The SO_4/Cl ratio was used to help identify source areas for groundwater and baseflow.

The author identifies five possible sources of riparian groundwater and baseflow in the study area: 1) lateral inflow of basin groundwater from the Huachuca Mountains (G1) to the west, 2) lateral inflow of basin groundwater from the Mule Mountains to the east (G3), 3) lateral inflow of basin groundwater from Mexico to the south (G1), 4) local recharge of monsoon precipitation, and 5) local recharge of winter precipitation during flooding events.

In examining the chemical signatures of each of these types of waters, the author found no correlation between distance from the mountains and groundwater chemistry. He interpreted this to indicate that ephemeral streamflow does not provide a significant contribution to basin groundwater over the long term across the basin as a whole. He did acknowledge the possibility of localized areas of high ephemeral recharge rates and cited Goodrich, et al's (2004) estimate that ephemeral channel recharge made up 15 to 40% of basin-wide aquifer recharge during a relatively wet year.

A mixing model was used to evaluate the seasonality of basin recharge, with summer and winter precipitation, corrected for elevation, being the two end members. This model predicted that basin groundwater from the Huachuca Mountains is between 65 and 80% winter precipitation. Although few data points exist for groundwater coming from Mexico or the Mule Mountains, these two groundwater sources were found to be similar to each other and chemically distinct from Huachuca Mountain groundwater. The author suggests that this chemical signature of groundwater from Mexico and the east side of the Upper San Pedro reflects a lower recharge elevation (relative to the Huachucas) and possibly a greater proportion of recharge from summer precipitation versus winter.

By using SO_4/CL ratios and $\ast^{18}O$, the author found that “almost all of the riparian wells and baseflow samples can be explained by a mixing line between G2 [Huachuca Mountain groundwater] and R1 [summer precipitation].” Furthermore, he states that, “there is nothing to indicate that winter floodwater (R2) constitutes a significant recharge input to the riparian area.” In fact, he found that age tracer data suggest that riparian groundwater is quite old, and therefore likely derives from basin groundwater. Groundwater from Mexico (G1) was also ruled out as a major contributor to riparian groundwater because of the lack of correlation of riparian well chemistry with distance from Mexico.

Groundwater contributions from the Mule Mountains (G3) were judged by the author to be highly uncertain due to a lack of data and any other suggestive evidence of a significant impact from G3 chemistry on riparian groundwater samples. Ultimately, the author makes “a qualitative assertion that G3 must represent some input to the riparian aquifer, as groundwater discharging on the east side of the river at Lewis Springs is very similar to G3.

Another simple two end-member mixing model based on stable isotopes and SO_4/Cl ratios, with monsoon floodwater and basin groundwater being the two end members, was used to calculate the relative proportion of each source of water in riparian groundwater and baseflow. The results of the mixing model yielded an estimate of 10-90% basin groundwater in riparian groundwater and 0 to 55% basin groundwater in baseflow. This variability is explained, in part, by the fact that source water in the riparian aquifer is “clustered with some areas dominated by monsoon floodwater,…[and] other areas…dominated by basin groundwater.” This spatial distribution was compared with gaining and losing reaches identified by Stromberg, et al (2006). The author found that all riparian wells dominated by (i.e., more than 60%) basin groundwater were located in gaining reaches. He also found that groundwater in all riparian wells in losing reaches contained 70% or more monsoon recharge, and that there appears to be some increase in the basin groundwater fraction with increased well depth. In other words, gaining reaches are dominated by basin groundwater, and losing reaches are dominated by monsoon recharge.

Groundwater fractions of baseflow at four river study sites were quantified based on end-member isotope values and supported by SO_4/Cl ratios, for G2 (Huachuca Mountain groundwater) and R1 (monsoon precipitation). The Palominas site (losing reach) was found to be dominated by monsoon precipitation, with 0 to 60% basin groundwater, but an average of 20%. The Highway 90 and Hereford sites (both gaining reaches) averaged 29 and 40% basin groundwater, respectively. Basin groundwater contributed 21 to 60% of baseflow at Charleston, and averaged 45%. In general, basin groundwater fraction increases as the river passes through gaining reaches, but baseflow in all areas was found to have a larger monsoon component than co-located riparian wells, suggesting that shallow groundwater discharge supports baseflow, even in gaining reaches.

Several findings in this study support the concept of a relatively impermeable layer of silt and clay beneath the shallow aquifer in the vicinity of Palominas and Hereford. The author found that wells in this area “are hydrologically separated from the river” and are not receiving monsoon recharge, but rather, are significantly affected by groundwater underflow from Mexico. Likewise, the chemical spatial variability in baseflow was found to mimic the variability in riparian groundwater, suggesting a good hydrologic connection between the two water bodies above the silt and clay layer in the southern part of the study area.

The most significant conclusion of the study is that monsoon floodwater is the dominant source of baseflow year round, to both gaining and losing reaches of the river, from the international border with Mexico to Charleston. Monsoon recharge constitutes 45 to 100% of baseflow in these reaches. The implication is, therefore, that monsoon floodwater must remain available to the river in order to maintain baseflows. The author also points out that basin groundwater is the foundation for maintaining baseflows. It constitutes between 10 and 90% of riparian groundwater and up to 55% of baseflow. Based on Pool and Coes (1999), baseflow and riparian evapotranspiration equal about 13,400 acre-feet per year. If 50% of this amount is comprised by monsoon recharge, then monsoon flooding contributes roughly 6,700 acre-feet per year.

QUANTIFYTING MOUNTAIN SYSTEM RECHARGE IN THE UPPER SAN PEDRO BASIN, ARIZONA, USING GEOCHEMICAL TRACERS (WAHI, 2005)

This is a companion paper to Baillie (2005). Rather than focusing on the source of water in the river, however, this study used geochemical tracers to examine mountain system recharge (MSR) directly. The study area includes the Huachuca Mountains and the adjacent portion of the San Pedro River basin bounded on the east by the river. Isotopic, major anion, and noble gas tracers were used to resolve “the location, rate, and seasonality of recharge as well as groundwater flowpaths and residence times.” MSR is defined as “mountain runoff that infiltrates at the mountain front (mountain-front recharge, hereafter MFR), and percolation through the mountain bedrock that reaches the basin via the movement of deep groundwater (mountain-block recharge, hereafter MBR).” Traditionally, both processes have been referred to as MFR collectively, possibly reflecting the general assumption that MBR is small relative to MFR.

The author argues that traditional methods for estimating MSR using numerical models based on Darcy’s Law incorporates large uncertainties because of their dependence on hydraulic conductivity values which are often highly uncertain and variable in nature. He states that rates obtained by radioactive tracers avoid the uncertainty associated with the use of conductivity as a parameter. The tracer method uses saturated thickness and aquifer porosity to calculate a net volumetric flux in a basin from tracer-derived residence times, and this flux is related to MSR by mass balance.

The tracers used in this study include radio carbon (^{14}C), and tritium (^{3}H). Noble gases neon and helium provide corrections to the tritium data. Stable isotopes of hydrogen and oxygen are used to evaluate location and seasonality of recharge. Common anions help identify sources of water and chemical exchange processes along the groundwater flow path. Stable carbon (∗^{13}C) and sulfur ($*^{14}S$) isotope ratios were used to help “constrain groundwater flowpaths by tracking different sources of solutes.”

One of the most significant findings of the study is that, except in the riparian area, uncorrected[2] (maximum possible) ^{14}C groundwater ages increase (from modern at the mountain front) with distance from the mountain front, indicating that MSR is the dominant input to the basin and that groundwater flow is approximately perpendicular to the mountain front. With corrections to the ^{14}C ages, the total residence time of groundwater in the Upper San Pedro Basin is estimated at greater than 10,000 years.

Uncorrected 14C ages in the riparian area indicate various degrees of mixing between (old) basin groundwater and younger groundwater recharged from losing reaches of the San Pedro River. This finding supports work described in Baillie (2005).

Another significant finding is that residence times, and thus groundwater fluxes, decrease from the northwest to the southeast portions of the study area. The author explains this trend with “a large structural low in the bedrock” in the southeast quadrant of the study area, north of Palominas and west of the San Pedro River (see Gettings and Houser, 2000), and by higher recharge fluxes from the deepest channels in the mountains. Overall, flux rates range from 1.0 to 4.0 meters per year (3.3 to 13 feet per year).

The average saturated thickness used for the flux calculations (250 ±100 m; 650 ± 300 feet) was based on bedrock mapping by Gettings and Houser (2000) and water-table mapping by Anderson and Freethey (1995). Porosity was determined from density logs from gamma ray measurements in 6 test wells. “Assuming a grain density of 2.67 g/cm^3**,** porosity values were obtained from bulk densities, then averaged vertically and between wells for [porosity] of 0.3 ± 0.1.”

Using these values of saturated thickness and porosity, uncorrected radiocarbon ages, and calculating flux through a surface roughly parallel to the Huachuca Mountains, the author estimated minimum and maximum MSR rates from the Huachuca Mountains of 2 to 9 million cubic meters per year (1500-7300 acre-feet per year). The author notes that these numbers are “recommended not on a standalone basis but rather as a means to improve other estimates by synthesis of many types of data.” He also states that this range of values likely brackets the true value because the assumed uncertainties in aquifer parameters were conservatively large. He continues,

> “The fact that the geochemical estimates and water budget estimates [of Anderson, et al (1992) and Pool and Coes (1999)] are within an order of magnitude, have a similar range, and are entirely independent supports the idea that both sets realistically captured at least some aspects of the true behavior of MSR in the basin.”

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[2] Various processes during recharge such as mixing with other waters, dissolution of carbonates, and fractionation during deposition of carbonate minerals can change the ^{14}C activity in groundwater. Once corrected for these processes, the activity of ^{14}C can reveal the mean residence time of a groundwater.

In terms of water management implications, the author points out that the long residence time (10,000 years or more) of groundwater in the basin emphasizes how small the amount of recharge across the basin floor (except in riparian areas) must be. From chloride concentrations, he estimates that roughly 90% of all precipitation (minus runoff) is lost to transpiration, with only 10% actually going to groundwater recharge. Most of that 10% occurs as MSR along the Huachucas, with a smaller fraction derived from the Mule Mountains. From the stable isotope data, the author found that 40 to 90% of MSR occurs in winter, with an apparent average of about 75% winter composition. Likewise, 10 to 60% of groundwater is recharged during the summer months.

The fraction of MSR occurring as MBR is still uncertain, but the fact that some deeper wells near the mountain front appear to tap groundwater from deep MBR flowpaths suggests that only slow-moving groundwater is locally important. This issue may become important in evaluating potential artificial recharge projects. Also, the MSR rates estimated in this study integrate the impacts of prior droughts, but individual drought signals are “attenuated over the timescale of fluxes below the mountain front.” The author cautions that short-term droughts could have a noticeable impact on MBR, but that some data suggested residence times on the order of up to 50 years within the bedrock of the mountain block. Irrespective of this point, groundwater residence times between the mountain front and the population centers are considerably longer than a few decades, so long-term conservation measures are advised.

HYDROLOGIC REQUIREMENTS OF AND CONSUMPTIVE GROUND-WATER USE BY RIPARIAN VEGETATION ALONG THE SAN PEDRO RIVER, ARIZONA (USGS, 2006)

The USGS, US Department of Agriculture-Agricultural Research Service (USDA-ARS), and Arizona State University, with assistance from the US Army Corps of Engineers, the University of Wyoming, and the University of Arizona, undertook a joint study with the following objectives:

1. “To determine the water needs of riparian vegetation through the riparian growing season and throughout the SPRNCA to ensure its long-term ecological integrity;”
2. “To quantify the total water use of riparian vegetation within the SPRNCA;” and
3. “To determine the source of water used by key riparian plant species within the SPRNCA.”

The following text is excerpted directly from the Executive Summary of the document:

> To meet these objectives, the study was divided into three elements: (1) a characterization of the status and variability of hydrologic factors within the riparian system (USGS), (2) a riparian biohydrology study to relate spatial and temporal aspects of riparian changes and condition to the hydrologic variables (Arizona State University), and (3) a water-use evapotranspiration (ET) study to quantify annual consumptive ground-water use by riparian transpiration and direct evaporation from the stream channel (USDA–ARS) in cooperation with the U.S.

> Army Corps of Engineers, the University of Wyoming, and the University of Arizona.
>
> Twenty-six sites within the SPRNCA were selected for collection of vegetation data from three primary streamflow regimes (perennial, intermittent-wet, intermittent-dry), which include the principal vegetation communities. Detailed hydrologic-condition data were collected at a subset of 16 of these sites, called the SPRNCA biohydrology sites. Water-use and water-source data were collected at a subset of 5 of the 16 biohydrology sites. Vegetation data also were collected at supplemental sites within the SPRNCA boundary in the Upper San Pedro Basin and in the Lower San Pedro Basin. In addition to information about vegetation and geomorphic conditions, hydrologic data collected at the 16 biohydrology sites were used to delineate 14 reaches that were internally homogenous in terms of streamflow hydrology (spatial intermittence of streamflow) and geomorphology (channel sinuosity and flood-plain width).
>
> Although this overall study consisted of three elements, the elements were closely coordinated to derive integrated results. Specifically, the connection between water demand, water availability, and riparian functioning represents a synthesis of the study elements. The effects of intra- and inter-annual as well as spatial variability of hydrologic and riparian factors were observed in each of the three study elements."

Hydrology (Leenhouts, et al, 2006)

The first chapter of this paper is devoted to a general overview of the hydroclimatic and hydrogeologic setting and descriptions of the biohydrology study sites. The second chapter presents results of the detailed hyrologic analyses conducted at the 16 biohydrology sites. The following paragraphs from the Executive Summary provide a good overview of the hydrology section:

> The hydrologic factors studied at the 16 SPRNCA biohydrology sites included: (1) depth to ground water beneath the riparian vegetation; (2) percentage of time surface flow existed in the channel (streamflow permanence); (3) monthly mean stream discharge; and (4) inundation elevations corresponding to various flood recurrence intervals (2, 5, 10, 25, and 50 years). Hydrologic monitoring began in summer 2000 and concluded in October 2003.
>
> Ground-water depths were measured in piezometers installed at each site and extrapolated to cross sections perpendicular to the stream channel. Streamflow permanence was estimated by using a combination of stream-stage recorders, temperature recorders, electrical-resistance recorders, and visual observations during site visits. Monthly mean discharge was estimated by correlating discharge measurements at the sites to long-term records from the three permanent streamflow-gaging stations within the SPRNCA. Inundation elevations were estimated through modeling and measurements of high-water

> marks left by a flood in October 2000. Gaging-station records were used to evaluate the streamflow permanence observed at the sites in the context of long-term conditions.

Vegetation-Hydrology Relationships (Stromberg, et al, 2006)

The vegetation-hydrology relationships study is presented in the third chapter (Chapter C) of the report. This section of the report examines relationships between riparian functional groups (rather than specific species) and the hydrologic settings that occur in the SPRNCA. The authors classified the 608 known vascular plant species in the SPRNCA into 12 functional groups, as explained below:

> Relations of vegetation with streamflow permanance, ground-water depth and fluctuation, and average flood intensity at a site were determined using correlation analysis, for each functional group, for several of the most common plant species, and for various measures of vegetation biomass structure. Effects on vegetation of site elevation and recent fire also were analyzed. Short-term response of riparian vegetation to rain and flooding was determined by making intra- and inter-annual comparisons of herbaceous cover and composition. To assess longer-term vegetation trends, changes in the relative abundance of three pioneer woody species (Fremont cottonwood, Goodding willow, and tamarisk) within age classes were assessed for the reaches. Branch growth rate of willow, a drought-sensitive tree, was measured within each reach, and values were related to streamflow and ground-water variables.

The authors also developed a "Riparian Condition Index" (RCI) to diagnose ecosystem conditions caused by changes in surface- and ground-water conditions. The RCI was developed from a suite of field-measured vegetation traits which are sensitive to changes in streamflow permanence and/or ground-water levels along the San Pedro River. The entire SPRNCA was categorized into one of three riparian condition classes based on riparian condition scores. Class 1 represents reduced water availability (or stressor resulting in effects similar to reduced water availability), roughly described as "dry." Class 2 corresponds to intermediate conditions, while class 3 indicates conditions of no water stress (i.e., wet). In general, these classes roughly correspond to hydrologic conditions as follows: class 1 – ephemeral losing reach with maximum depth to ground-water of 3.5 meters (11.5 feet); class 2- intermittent losing reach with maximum depth to ground-water of 2.1 to 3.9 meters (5.4 to12.8 feet), and class 3 – perennial reach with maximum depth to groundwater of 1.2 to 2.1 meters (3.9 to 6.9 feet).

Figure 1 illustrates the distribution of the three condition classes over the length of the study area from just south of St. David to the Mexican border. The only class 1 reach occurs in a reach east of the Whetstone Mountains, downstream of the Sierra Vista subwatershed. Most of the riparian zone south of Charleston is rated as class 3, while everything north of Charleston up to 3 miles north of Fairbank is rated as class 2. Thirty-nine percent of the SPRNCA riparian corridor was classified as class 3, fifty-five percent fell into class 2, and six percent was categorized as class 1. The authors report major changes in the herbaceous vegetation between class 3 and class 2 reaches.

From class 3 to class 2, "streamside cover of hydric plants is reduced, owing to loss of perennial streamflow. Many of the hydric perennial herbs have been replaced by mesic perennials, such as bermuda grass." From class 2 to class 1, major changes occur in woody vegetation structure and composition in the floodplain. Cottonwood and willows are generally replaced by deep-rooted phreatophytes like tamarisk.

In conjunction with the RCI, the authors developed a riparian assessment, as described below:

> A riparian assessment model was developed by using data collected during 2000–2002 at 17 San Pedro River study sites (6 of the SPRNCA biohydrology study sites and 11 of the supplemental lower basin sites) and validated at 10 additional upper basin sites. There were five steps in developing the assessment model: (1) determine distinct hydrologic classes relative to threshold values for plant community change, (select potential bioindicators, (determine bioindicator scoring ranges, (4) iteratively select the final set of bioindicators and site scoring ranges, and (5) validate the model.

The assessment model allows the diagnosis of riparian ecosystem change from dewatering via measurement of hydrologically sensitive vegetation traits. The authors report that the model functions well over the normal range of variability in the riverine system (i.e., after fires, during drought, after normal flooding, etc.), but is not robust enough to handle the changes associated with the first few years after "large, infrequent, channel-moving floods" that "reset successional processes, and change vegetation attributes, such as percent open area, relative abundance of marshland versus forested area, and tree-age structure." The authors advise that the model be reassessed every 5 to 10 years to determine whether revision is required.

The condition scores that determine which class a particular reach falls into can be used to monitor the impacts of water-conservation and management measures. For example, upward changes in the condition scores would indicate that the riparian system is responding favorably to management measures, while downward changes might suggest the need for additional intervention to prevent further degradation. However, the authors caution that changes in water availability, which directly affect condition scores, will result from both natural and anthropogenic effects. They advise that drought will likely "cause short-term [downward] shifts in the condition-class scores."

Water Use and Water Needs by Vegetation Type (Scott, et al, 2006)

The fourth chapter (D) in the study describes a three-year study (2001-2003) that used water balance and isotope methods to estimate overall ET demand by vegetation type as well as to partition that demand by water source. Distribution patterns of the various vegetation types were also reported.

The authors considered six primary sources of riparian groundwater demand: 1) mesquite woodland; 2) cottonwood-willow forest at perennial streamflow sites; 3) cottonwood-willow forest at intermittent streamflow sites; 4) sacaton grassland (where groundwater is less than 3 m

(10 ft) deep; 5) tamarisk; and 6) open water sites in the floodplain area that are supported by shallow groundwater. Seep willow transpiration was measured by sap-flow methods and found to be relatively large (comparable to cottonwoods) on a per canopy unit basis. Unfortunately, the total amount of seep willow could not be estimated from the vegetation map used in the study due to its understory position which is often obscured in the aerial imagery used to make the map. Transects revealed that seep willow overall abundance is fairly low, and its total ground-water use was considered to be small relative to water use by other major cover types, so it was omitted from the ground-water use budgets. The authors note that if the consumptive use of seepwillow and other flood-plain understory plants that consume groundwater were included, the overall SPRNCA consumptive groundwater use rates would increase.

Mesquite was found to utilize water from three distinct sources: 1) surface water (recent precipitation), 2) groundwater, and 3) deep (1 to10 meters; 3.3 to 33 feet) vadose-zone water at the capillary fringe just above the water table. The use of these sources varied according to water availability, such that as monsoon rains and runoff became available, the percentage of ET attributable to groundwater diminished. Overall, 58 to 62 percent of total mesquite transpiration was estimated to derive from groundwater, 29 to 31 percent from shallow soil water, and 13 to 14 percent from deep vadose-zone water. Two

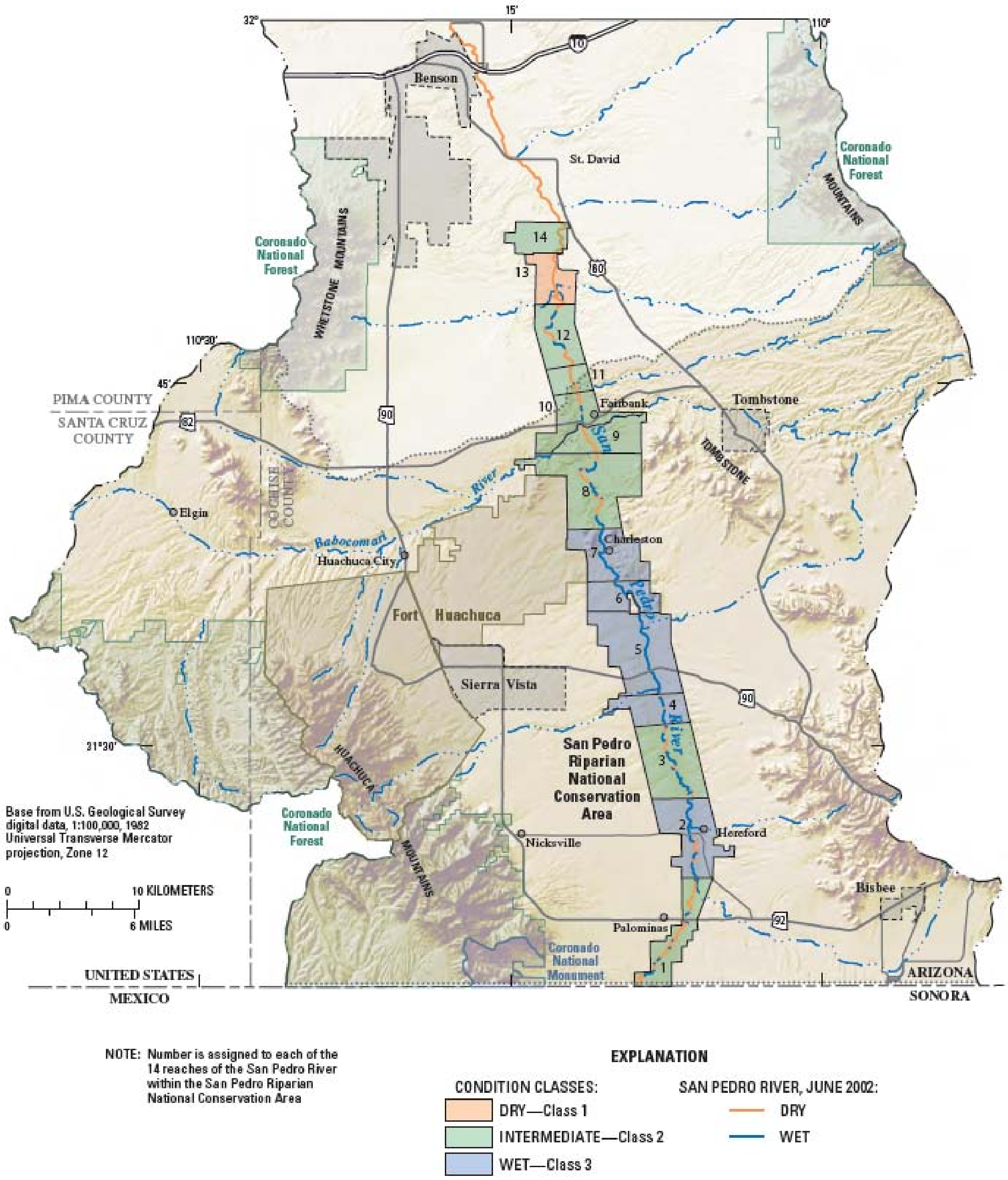


Figure 1. Riparian ecological condition classes for 14 reaches and streamflow present for June 2002 within the San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona (source: Figure 42 in USGS, 2006).

methods were used to estimate mesquite ground-water use: a water-balance method and an isotope-partitioning method. Results from the water-balance method were approximately 50% higher than those for the isotope method, but the authors chose to use them because they involved fewer assumptions and less extrapolation of data. The authors acknowledged that these values are likely conservatively high because the mesquite's ability to redistribute antecedent moisture between deep and shallow soil zones is ignored in the water-balance approach. The authors also note an inconsistency between precipitation excess and the amount of mesquite ET estimated for the upper 1 meter of soil which results in an over-allocation of shallow soil water in their water budgets.

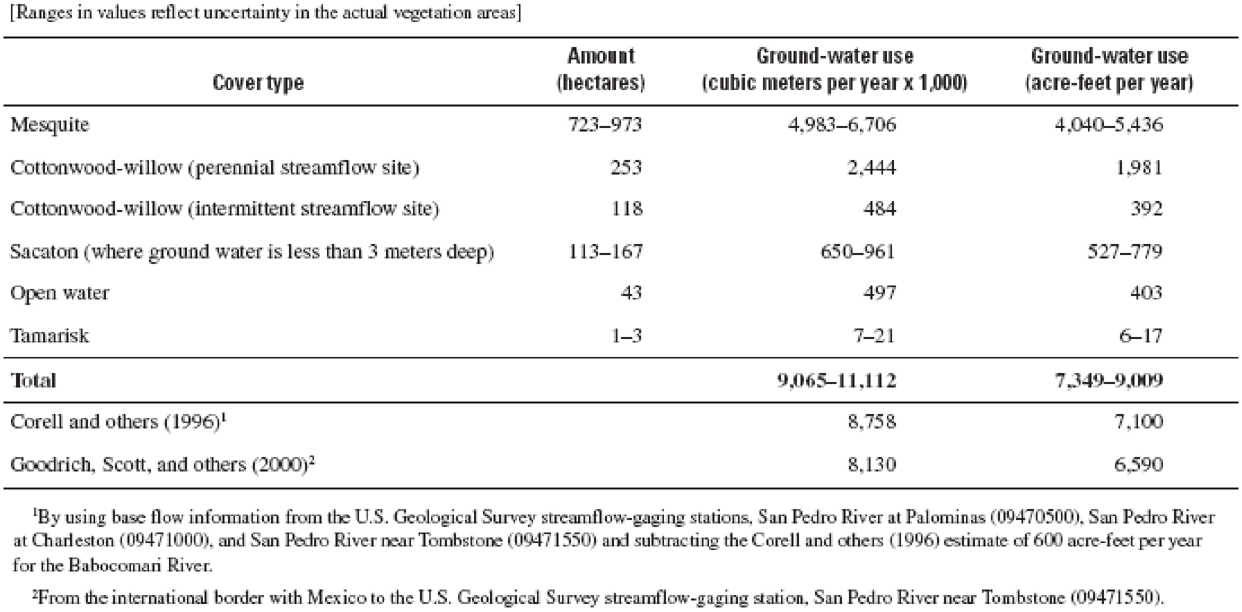
The authors report confirmed earlier studies that concluded that sacaton grass uses groundwater only when groundwater is less than about 3 meters (10 feet) below ground surface. At sites where sacaton occurs over deeper groundwater, its water use is restricted to shallow soil zone water and precipitation.

The cottonwood study sites confirmed that cottonwoods at sites with an abundant water supply (eg, perennial stream flow) transpired more than twice as much as those in water-stressed environments. Comparison of transpiration rates at the Boquillas and Lewis Springs study sites revealed that transpiration in trees at the Boquillas (drier) site decreased during the peak of the early summer drought or premonsoon period while transpiration increased in response to atmospheric demand at the Lewis Springs site where water was abundantly available.

Small evaporation pans were used to measure evaporation from standing [ground] water in the flood-plains. The authors found that measured evaporation averaged 65% of reference evapotranspiration (ETo). Although evaporation rates are highly dependent on local site conditions (shading, etc.), the authors used the 65% ETo value for estimating all open-water evaporation from the floodplain in the study area since the overall area of this water is small compared with the vegetation communities.

While tamarisk transpiration was not measured directly, it was assumed to consume groundwater at roughly the same rate as mesquite because of its deep root structure. Table 1 summarizes total groundwater consumption from the six major riparian categories considered in the study along the main stem of the San Pedro River from the international border with Mexico to the USGS streamgaging station near Tombstone. Table 2 presents the same totals for the Babocomari River. Combining the totals from Tables 1 and 2 gives a total riparian ground-water consumption rate of 9,600 to 12,055 acre-feet per year.

TABLE 1. ESTIMATED RIPARIAN CANOPY AREA, OPEN-WATER AREA, AND GROUND-WATER USE FOR 2003 ALONG THE MAIN STEM OF THE SAN PEDRO RIVER FROM THE INTERNATIONAL BORDER WITH MEXICO TO THE U.S. GEOLOGICAL SURVEY STREAMFLOW-GAGING STATION, SAN PEDRO RIVER NEAR TOMBSTONE (09471550), UPPER SAN PEDRO BASIN (SOURCE: TABLE 52 IN USGS, 2006).



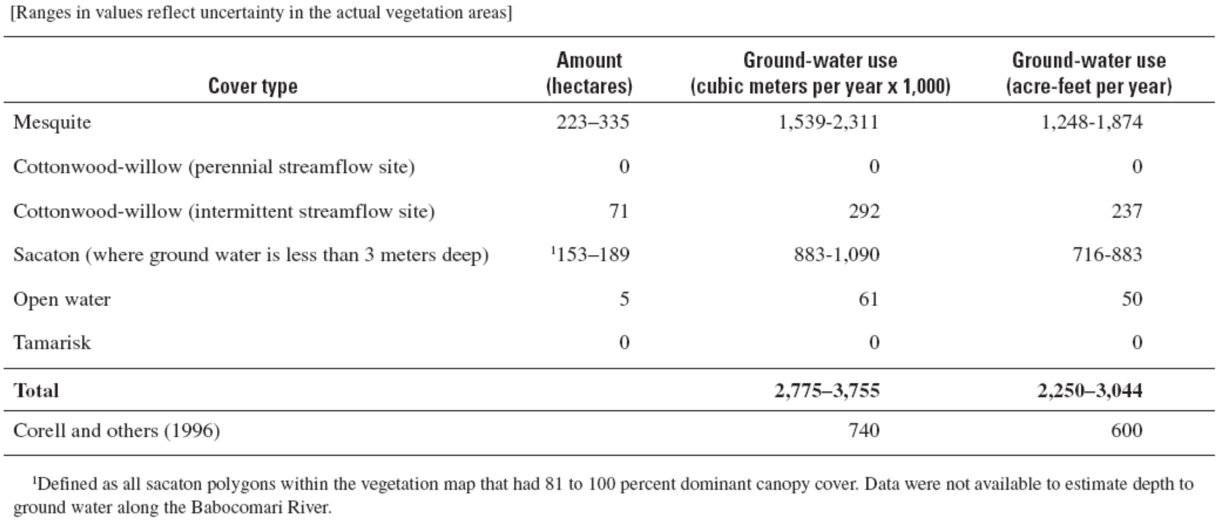
[Ranges in values reflect uncertainty in the actual vegetation areas]

Cover type	Amount (hectares)	Ground-water use (cubic meters per year x 1,000)	Ground-water use (acre-feet per year)
Mesquite	723–973	4,983–6,706	4,040–5,436
Cottonwood-willow (perennial streamflow site)	253	2,444	1,981
Cottonwood-willow (intermittent streamflow site)	118	484	392
Sacaton (where ground water is less than 3 meters deep)	113–167	650–961	527–779
Open water	43	497	403
Tamarisk	1–3	7–21	6–17
Total		**9,065–11,112**	**7,349–9,009**
Corell and others (1996)[1]		8,758	7,100
Goodrich, Scott, and others (2000)[2]		8,130	6,590

[1] By using base flow information from the U.S. Geological Survey streamflow-gaging stations, San Pedro River at Palominas (09470500), San Pedro River at Charleston (09471000), and San Pedro River near Tombstone (09471550) and subtracting the Corell and others (1996) estimate of 600 acre-feet per year for the Babocomari River.

[2] From the international border with Mexico to the U.S. Geological Survey streamflow-gaging station, San Pedro River near Tombstone (09471550).

TABLE 2. ESTIMATED BABOCOMARI RIPARIAN CANOPY AREA, OPEN-WATER AREA, AND GROUND-WATER USE FOR 2003, UPPER SAN PEDRO BASIN, ARIZONA (SOURCE: TABLE 53 IN USGS, 2006).



[Ranges in values reflect uncertainty in the actual vegetation areas]

Cover type	Amount (hectares)	Ground-water use (cubic meters per year x 1,000)	Ground-water use (acre-feet per year)
Mesquite	223–335	1,539-2,311	1,248-1,874
Cottonwood-willow (perennial streamflow site)	0	0	0
Cottonwood-willow (intermittent streamflow site)	71	292	237
Sacaton (where ground water is less than 3 meters deep)	[1]153–189	883-1,090	716-883
Open water	5	61	50
Tamarisk	0	0	0
Total		**2,775–3,755**	**2,250–3,044**
Corell and others (1996)		740	600

[1] Defined as all sacaton polygons within the vegetation map that had 81 to 100 percent dominant canopy cover. Data were not available to estimate depth to ground water along the Babocomari River.

From Table 1, the following relative contributions of riparian cover types to ground-water consumption can be derived:

- Mequite: 55-61%
- Cottonwood-willow (perennial streamflow site): 16%
- Cottonwood-willow (intermittent streamflow site): 6%
- Sacaton grass (where groundwater is less than 3 meters deep): 11-14%
- Open water: 4%
- Tamarisk: 0.1%

The authors report that their use of the latest polygon-based GIS coverage of riparian vegetation, VEG00 (U.S. Army Corps of Engineers, 2001) resulted in large changes in interpreted vegetation and open-water areas from those based on the previous pixel-based vegetation map, VEG97. In general, total vegetation amounts declined from VEG97 to VEG00 by about 40% while total open water area increased by 800%. Consequently, the authors concede that the magnitude of the change associated with the new cover map is as large as any change resulting from the study's refined plant ground-water use estimates. They also note that the changes between VEG97 and VEG00 coverage maps likely do not reflect actual changes in the SPRNCA environment.

Comparison of this study's totals with those from previous studies (see Tables 1 and 2) reveals that the current study's predictions for riparian vegetation ground-water use are 4 to 37% higher along the main stem of the San Pedro River than Corell, et al (1996) and Goodrich, et al (2000). A much larger discrepancy (375 to 507%) in estimates for Babocomari River riparian evapotranspiration exists between this study and Corell, et al (1996)[3] (see Table 2). The authors recommend further study to determine whether extrapolation of vegetation water use rates along the San Pedro River can be extrapolated to the Babocomari River.

The water-use calculations in this study are based on 2003 measurements. The authors found that mesquite water use varied by as much as 30 percent from year to year during the study period (2001-2003), and speculate that such variability is probable in other vegetation communities. The authors state that "ground-water use for 2003 probably was higher than what might be expected for 2001 and 2002 owing to the longer growing season…and the smaller amount of winter and monsoon precipitation."

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[3] Corell, et al (1996) base their estimate of Babocomari evapotranspiration on data in Schwartzman (1990).

TRENDS IN STREAMFLOW OF THE SAN PEDRO RIVER, SOUTHEASTERN ARIZONA, AND REGIONAL TRENDS IN PRECIPITATION AND STREAMFLOW IN SOUTHEASTERN ARIZONA AND SOUTHWESTERN NEW MEXICO (THOMAS AND POOL, 2006)

This study evaluated trends in streamflow and precipitation in the San Pedro River in an attempt to improve understanding of the underlying causes of observed declines of more than 50% in annual flows at the USGS gaging station on the San Pedro River at Charleston during the 20th century. The analyses involved numerous statistical tests of monotonic (continuous in one direction) trends and step changes over time.

As a means of comparing observed trends in the upper San Pedro Valley with those in surrounding areas in the region, trends in precipitation were analyzed from 38 sites and streamflow data from 21 sites within a 7000 square mile study area (Figure 1). Streamflow from San Pedro at Charleston gaging station and precipitation from the Tombstone weather station were chosen to represent the San Pedro basin because of their long and relatively complete records.

The San Pedro River was included in the southwest portion of the study area, along with the Santa Cruz River near Tucson to the west and Whitewater Draw to the east. In general, the authors found that the southwest portion of the study area was generally similar to the other portions of the study area except that larger percentages of annual precipitation and streamflow occur in the summer in the southwest portion, makingwater resources there inherently more vulnerable to changes in summer precipitation.

Figure 2 illustrates average monthly precipitation at Tombstone and historical streamflows at the Charleston gaging station for 1913-2002. Together, the two graphs show a clear relationship between precipitation and streamflow, with summer monsoons typically producing the largest streamflows of the year.

Monotonic trends in precipitation were determined using a nonparametric Kendall tau test. This test was considered more appropriate than parametric tests (such as linear regression) for precipitation and streamflow data because these data usually have many outliers and are not normally distributed. In order to avoid bias related to natural cycles of precipitation, trends were analyzed for 11 time periods starting every 5 years from 1930 to 1980, and ending in 2002 (eg, 1930-2002, 1935-2002, and 1940-2002). Monotonic trends in monthly and seasonal precipitation were evaluated over the entire period of record were examined, and monotonic trends over shorter periods were evaluated to identify possible changes in trends over time. To evaluate step trends or cycles in seasonal precipitation and streamflow, the years of data were grouped in to six successive time periods and measures of the central tendency (mean) and variability (difference between the 75th percentile and 25th percentile) of the data.

Following trend analyses on individual sets of precipitation and streamflow data, the authors partitioned the variation in streamflow and tested for trends in streamflow

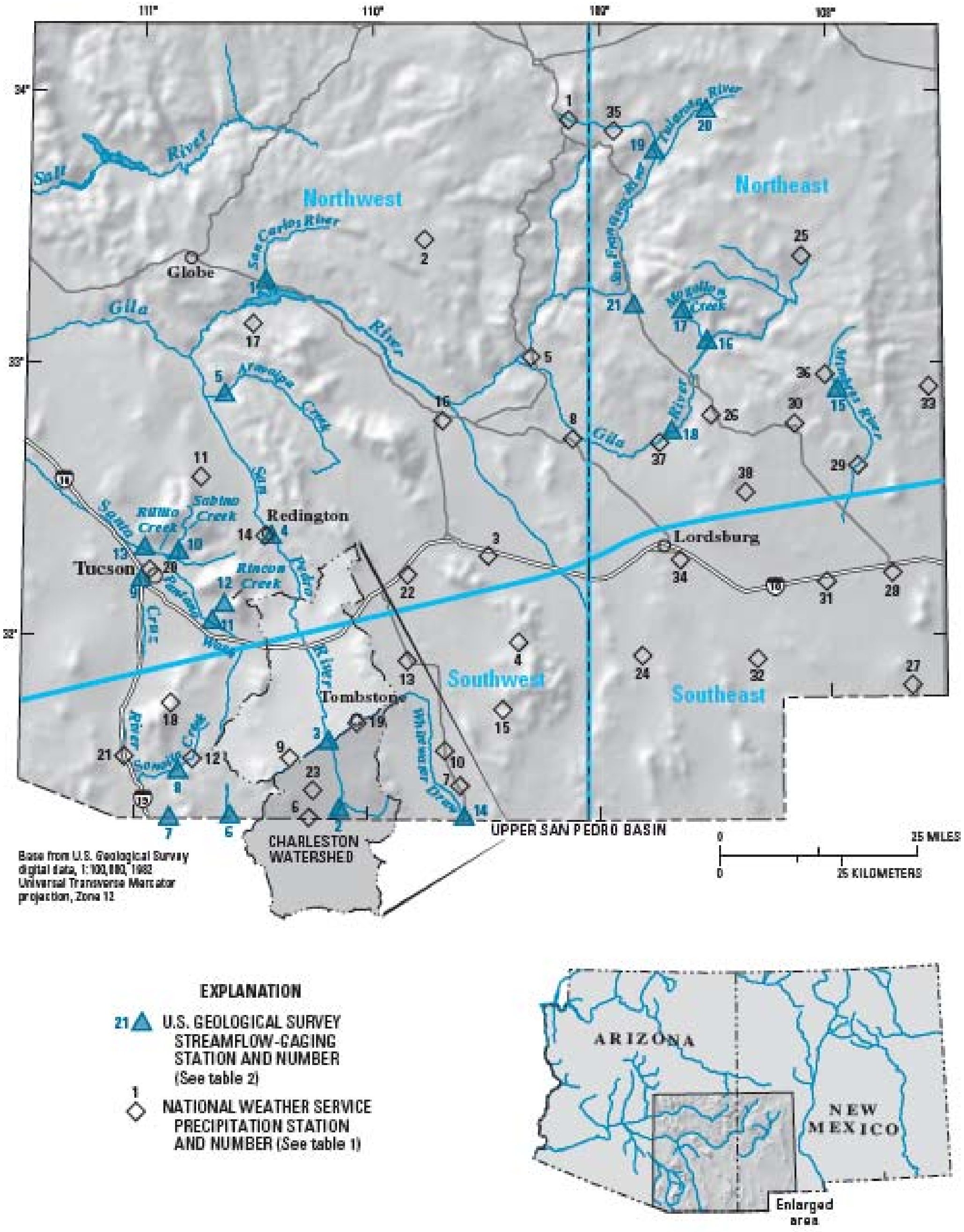


FIGURE 1. LOCATION OF REGIONAL STUDY AREA AND DATA-COLLECTION SITES (SOURCE: FIGURE 2 IN THOMAS AND POOL, 2006).

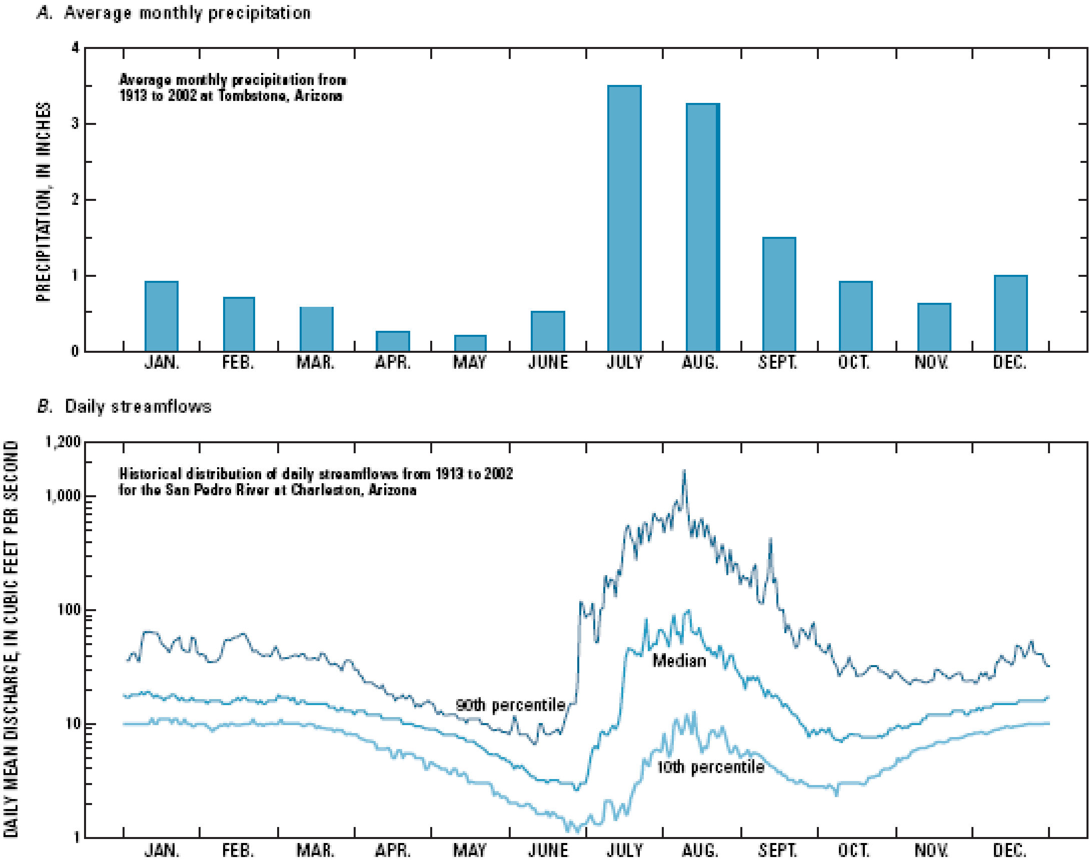


Figure 2. A. Average monthly total precipitation at Tombstone, Arizona and B. Historical distribution of daily streamflows for the San Pedro River at Charleston, Arizona (source: Figure 5 in Thomas and Pool, 2006).

variation caused by factors other than precipitation. This process was accomplished with two methods:

> (1) regression analysis between precipitation and streamflow for all years in the record and evaluation of time trends in regression residuals, and (2) development of regression equations between precipitation and streamflow for three time periods (early, middle, and late parts of the record) and testing to determine if the three regression equations are significantly different. Method 1 is an evaluation of monotonic change for the entire record, and method 2 is an evaluation of step changes during three time periods in the record.

Most of the precipitation records analyzed revealed no significant trends. The trends that were detected were mostly seasonal and focused on certain time periods. Winter and spring precipitation trends were for time periods starting during the 1945-1960 drought. Most significant summer trends were found in time periods starting between 1930 and 1965. Ninety-five percent of the trends in precipitation were positive, with most of the negative trends occurring in summer. Annual precipitation trends for the other portions of the study area were much more positive than those for the southwest portion.

For the entire study area, seasonal and annual streamflow had no trends for most of the 11 time periods. Most significant trends in winter, spring, fall, and annual flows were positive, and most of those in summer flows were negative. The San Pedro and Santa Cruz rivers had consistent negative summer trends, while other streams had no summer trends. The San Pedro River was the only river that had a negative trend in annual flows. The authors note that major precipitation cycles have affected the entire study area, particularly in winter: “[w]inter and spring precipitation were generally high in the 1930’s low in the 1950’s and 1960’s, high in the 1980’s, and low in the late 1990’s and early 2000’s.” Although streamflows in the northwest and northeast portions of the study area apparently responded to these major cycles, the San Pedro streamflows just decreased steadily.

The authors present a pre-development water budget for the San Pedro River at Charleston, where evapotranspiration from all sources except directly from groundwater constitutes 94% of total (precipitation) input to the watershed. Runoff and groundwater flow and discharge comprise 4.5, and 1.5 percent of the budget, respectively. Total inflow to groundwater (recharge) was estimated at 14,000 acre-feet per year in pre-development conditions. Using 3-day low flows for the period 1931 to 1945, they estimate pre-development baseflow at Charleston to be 7,900 acre-feet annually (afa), or 56% of the groundwater budget. Evapotranspiration (estimated at 5,700 afa), and underflow north past the Charleston gaging station (estimated at 400 afa) make up 41 and 3 percent of the groundwater budget, respectively.

Trends in the San Pedro

Total volume, intensity, frequency, and volume per storm were all analyzed for the precipitation record at Tombstone. The only significant decreasing trend was for July and summer season for the period 1913-2002. November precipitation had significant decreasing trends for 1913-50 and 1913-60, while summer showed a significant decreasing trend for 1951-2002.

Annual total streamflow at Charleston decreased by 62 percent from 57,700 afa prior to 1940 to 22,000 afa in 1991-2002. Approximately 70% of the decrease in annual flow was attributable to decline in summer flow. Annual low flow decreased by 46 percent from 7,900 to 4,300 afa, with about 60 percent of this decrease occurring in fall and early winter.

Seasonal trends in total streamflow at Charleston were compared with those at Redington (downstream) and Palominas (upstream), revealed decreasing summer flows at all three sites. There were no trends in winter flows at the three sites from 1951, 1961, and 1971 to 2002 (the three time periods examined). Spring and fall flow trends were mixed at all three sites. From these results, the authors conclude that the same factors influenced streamflow trends at all three sites.

Figure 3 illustrates the differences between precipitation trends at Tombstone and streamflow trends at Charleston. The authors' interpretation is provided below:

> Streamflow had larger changes over time in median values and variability than did precipitation (fig. [3]). For median total and maximum streamflows, there is a step change at about 1943; before 1943 all seasonal flows were high, and after 1942 all seasonal flows were generally low. The behavior of the median seasonal flows after 1942 is different; summer median flows decreased continuously, and fall and winter median flows were mostly steady except for higher values during 1977–89.
>
> The interannual variability of seasonal streamflows also had patterns. The variability of winter maximum flow had two distinct step changes; the variability was high during 1913–42, low during 1943–76, and high again during 1977–2002. Variability of summer total flow decreased monotonically during the entire record, and variability of summer maximum flow had a step change from high to low values at 1960. Variability of fall total and maximum flow was generally similar for the entire record except for a high period during 1977–89.

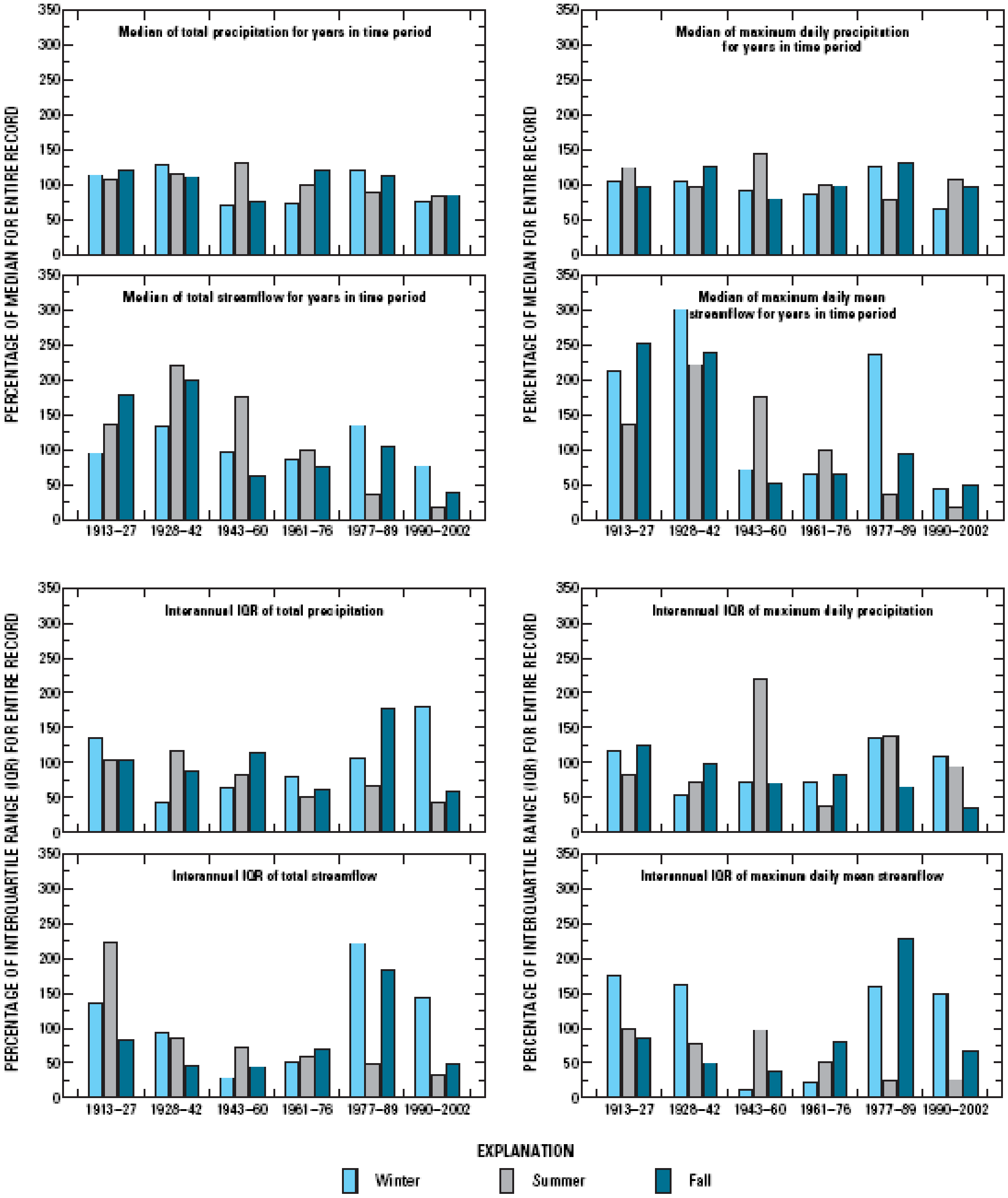


Figure 3. Step trends in central tendency and variability of precipitation at Tombstone, Arizona, and streamflow of the San Pedro River at Charleston, Arizona. IQR is the interquartile range; 75th percentile minus the 25th percentile (source: Figure 11 in Thomas and Pool, 2006).

Once variations in streamflow attributable to precipitation were removed, the remaining streamflow variation was analyzed for trends over time by the same monotonic and step-testing methods described above. These residuals in streamflow variation were referred to as "precipitation adjusted" or simply "adjusted" values. The authors concluded that "factors other than precipitation caused significant decreasing trends in streamflow." They further observed that, "[a]djusted total flows and low flows had similar seasonal trends; summer, fall, and early winter flows (June-December) significantly decreased, and late winter and early spring flows (January – March) had no significant trends."

Because bank storage strongly controls fall and early winter streamflows, the authors concluded that declining summer flows would have resulted in declining flows in fall and early winter. By contrast, late winter and early spring flows were depend primarily on precipitation in the winter months, and are largely independent of summer flows.

The authors identify five possible causes for decreasing trends in seasonal streamflow on the San Pedro River:

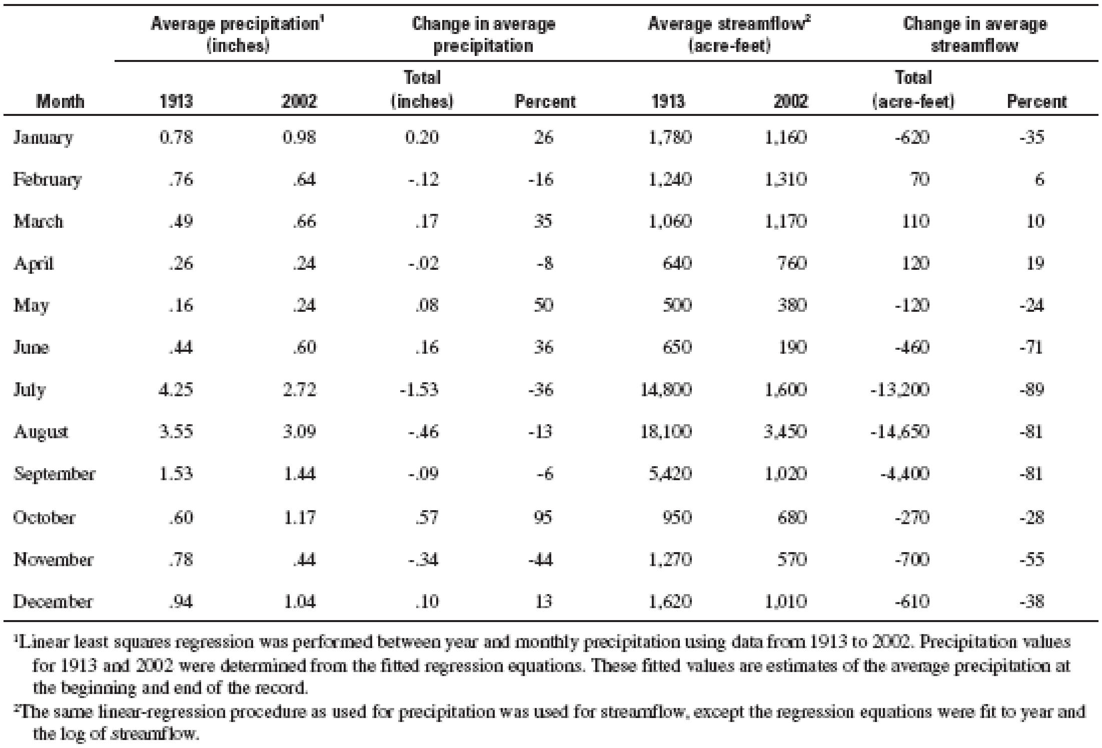
> (1) fluctuations in precipitation; (2) fluctuations in air temperature; (3) changes in watershed characteristics, such as changes in riparian vegetation, upland vegetation, and stream-channel morphology; (4) human activities such as ground-water pumping, urbanization, construction of runoff-detention structures, and cattle ranching (grazing); and (5) changes in seasonal distribution of flow between the San Pedro River and storage in the stream bank and alluvial aquifer.

The portion of decrease in streamflow attributable to fluctuations in precipitation could not be determined, but Table 1 provides a summary of changes in monthly precipitation and streamflow at Tombstone and Charleston, respectively. The authors note that fluctuations in precipitation are clearly not consistently reflected in streamflow changes. For example, July precipitation decreased by 36 percent, but July streamflow decreased by 89 percent over the period 1913-2002.

Because the summer and fall streamflows on the San Pedro decline signficiantly, and winter/spring flows do not, the authors suggest that changes in riparian and upland vegetation are largely responsible for the declining streamflows observed. They reason that if pumping from the regional aquifer were a major factor, then declines would be observed in all seasons. They do acknowledge, however, that agricultural pumping near the river has the same general impact as increase riparian vegetation in that it extracts water near the river during the growing season.

Air temperature is listed as a possible cause of declining summer streamflows because increased temperatures could cause changes in vegetation and could increase the length of the growing season, thereby resulting in a greater total volume of annual evapotranspiration. A two-degree Farenheit increase in average temperature has been recorded at the Tombstone weather station over the past century.

TABLE 1. CHANGES FROM 1913 TO 2002 IN MONTHLY AVERAGE PRECIPITATION AT TOMBSTONE, ARIZONA AND MONTHLY AVERAGE STREAMFLOW FOR SAN PEDRO RIVER AT CHARLESTON, ARIZONA. (SOURCE: TABLE 24 IN THOMAS AND POOL, 2006).



	Average precipitation[1] (inches)		Change in average precipitation		Average streamflow[2] (acre-feet)		Change in average streamflow	
Month	1913	2002	Total (inches)	Percent	1913	2002	Total (acre-feet)	Percent
January	0.78	0.98	0.20	26	1,780	1,160	-620	-35
February	.76	.64	-.12	-16	1,240	1,310	70	6
March	.49	.66	.17	35	1,060	1,170	110	10
April	.26	.24	-.02	-8	640	760	120	19
May	.16	.24	.08	50	500	380	-120	-24
June	.44	.60	.16	36	650	190	-460	-71
July	4.25	2.72	-1.53	-36	14,800	1,600	-13,200	-89
August	3.55	3.09	-.46	-13	18,100	3,450	-14,650	-81
September	1.53	1.44	-.09	-6	5,420	1,020	-4,400	-81
October	.60	1.17	.57	95	950	680	-270	-28
November	.78	.44	-.34	-44	1,270	570	-700	-55
December	.94	1.04	.10	13	1,620	1,010	-610	-38

[1] Linear least squares regression was performed between year and monthly precipitation using data from 1913 to 2002. Precipitation values for 1913 and 2002 were determined from the fitted regression equations. These fitted values are estimates of the average precipitation at the beginning and end of the record.

[2] The same linear-regression procedure as used for precipitation was used for streamflow, except the regression equations were fit to year and the log of streamflow.

Changes in seasonal distribution of flow between the San Pedro River and stream bank storage and the alluvial aquifer may have also affected streamflows in the San Pedro, but the authors reason that since summer flows are correlated only to summer precipitation (and not precipitation in earlier months), bank storage should have little or no influence on summer flow trends. By contrast, fall and early winter flows correlate to precipitation in summer months and reflect water draining from bank storage. Spring flows also reflect water draining from bank storage accumulated from winter precipitation. For this reason, changes in bank storage would be reflected in fall/early winter and spring streamflows but not summer.

In addition to the finding that trends streamflows were different in summer and winter, the authors cite documented changes in riparian and upland vegetation during the 20th century and the fact that evapotranspiration is such a large part (more than 90 percent) of the water budget as justification for their conclusion that vegetation changes are largely responsibly for declines in streamflows in the San Pedro River. Kepner and Edmonds (2002) found that, from 1973 to 1997, grasslands area decreased by 16 percent, desert scrub area decreased by 22 percent, and the area of mesquite woodland increased by 400 percent in the San Pedro basin above Redington. The authors list several mechanisms by which changes in vegetation can influence streamflow, but of particular interest is the finding by Scott, et al (2000) that grasslands use approximately 30 percent less water than mesquite woodlands.

Riparian vegetation near the San Pedro generally increased in the 20th century, with the most rapid increase occurring between the 1930's and 1960's. Because evapotranspiration is such a large component of the watershed budget, the authors argue that even small changes in ET could have major impacts on streamflows.

Groundwater pumping from the regional basin-fill aquifer and alluvial aquifer was examined by statistical methods for its potential impact on streamflows. They estimated that groundwater pumping was responsible for a 3600 acre-foot (5 cubic-feet per second) decline in baseflows at Charleston. This value is within the range of estimates from modeling studies by Vionnet and Maddock (1992), Corell and others (1996), and Goode and Maddock (2000), and represents a 46 percent change in flow. The authors conclude that "seasonal pumping from wells near the river was a major factor in the decrease in low flows (base flows) at Charleston, but year-round regional pumping was not a major factor." They suggest that modeling studies, which generally simulate all groundwater pumping on an annual basis, do not reflect the seasonality of groundwater impacts on the river, and thus, have not distinguished between impacts from seasonal pumping near the river and year-round pumping from the regional aquifer far away from the river (i.e., Sierra Vista/Fort Huachuca area).

As a test of this hypothesis, the authors examined the potential "balancing" effect of urbanization and constructed detention basins. The authors surmised that if urbanization increases recharge and detention basins increase recharge and possibly prolong streamflow, then they could possibly balance out the negative impacts of pumping on streamflows, thereby obscuring pumping-related declines in streamflow in winter months. Ultimately, this theory was dismissed because: a) urbanization in Sierra Vista was relatively insignificant prior to the 1970's, and b) many detention structures were built in the first half of the 20th century making their impact uniform over the period of study. The authors acknowledge that pumping from the regional aquifer may yet have a significant impact on river flows because the impacts of groundwater storage depletions on streamflows are often significantly delayed.