Groundwater flow model of the Lower San Pedro River basin for the sustainability of riparian habitats

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Abstract Water issues in the Lower San Pedro River (SPR) basin are becoming increasingly contentious as human activity competes with sustainability of the riparian habitat. The SPR flows north from Sonora, Mexico to its confluence with the Gila River in Arizona, USA. In order to better understand the water demands in this basin, a new groundwater flow model was created simulating conditions prior to 1940 and changes from 1940 to 2000. The model results project potential impacts to the sustainability of groundwater within the basin. Natural indicators show downward trends involving declines in water table levels near the river due to pumping, underflow to the Gila River basin, water available for sustaining riparian vegetation, water available in storage, and flow from the aquifer to the river. In the future, the model will be used as an administrative tool to assess alternative land management scenarios and their abilities to sustain or improve the riparian habitat.

Key words Arizona; GIS; GMS; MODFLOW; natural indicators; phreatophyte, riparian habitat; San Pedro River; sustainability

INTRODUCTION

The San Pedro River flows north from the northern portion of the Mexican State of Sonora into southeastern Arizona, USA, draining an area of almost 13 500 km^2. The San Pedro basin is characterized as semiarid with temperatures ranging from below 0°C during the winter at higher elevations to over 40°C during the summer at lower elevations. Precipitation amounts vary from below 300 mm per year along much of the valley floor to over 600 mm atop the nearby high mountains, where much of the winter precipitation falls as snow (ADWR, 1991). The riparian habitat along the river is a major migratory corridor for many birds travelling to and from North and South America, as well as a permanent home for numerous animal and bird species.

The San Pedro basin is divided into Upper and Lower San Pedro basins separated by a geological constriction called "The Narrows" (Fig. 1). A model was developed to simulate groundwater flow in the Lower San Pedro River basin, with a focus on the impacts of groundwater withdrawal and surface water diversion on the river and the riparian habitat after 1940 when the widespread use of high-powered hydraulic lift pumps in farming and mining increased. Increased pumping has lowered water tables impacting the riparian habitat along the river and decreasing flows in the river itself, changing some sections from perennial to intermittent (ADWR, 1991). This model was developed to better understand the changes and as a tool to help sustain the riparian habitat with a balanced use of the water available in the basin.

CONCEPTUAL MODEL

A conceptual model was created using Geographic Information Systems (GIS) software based on current data on land surface elevation, geology, hydraulic properties, mountain front recharge, groundwater recharge, streamflows, riparian evapotranspiration (ET), well locations, well pumping rates, irrigated agricultural fields, and mine tailings ponds. The following sections describe the components of the conceptual model with details available in Whittier (2004).

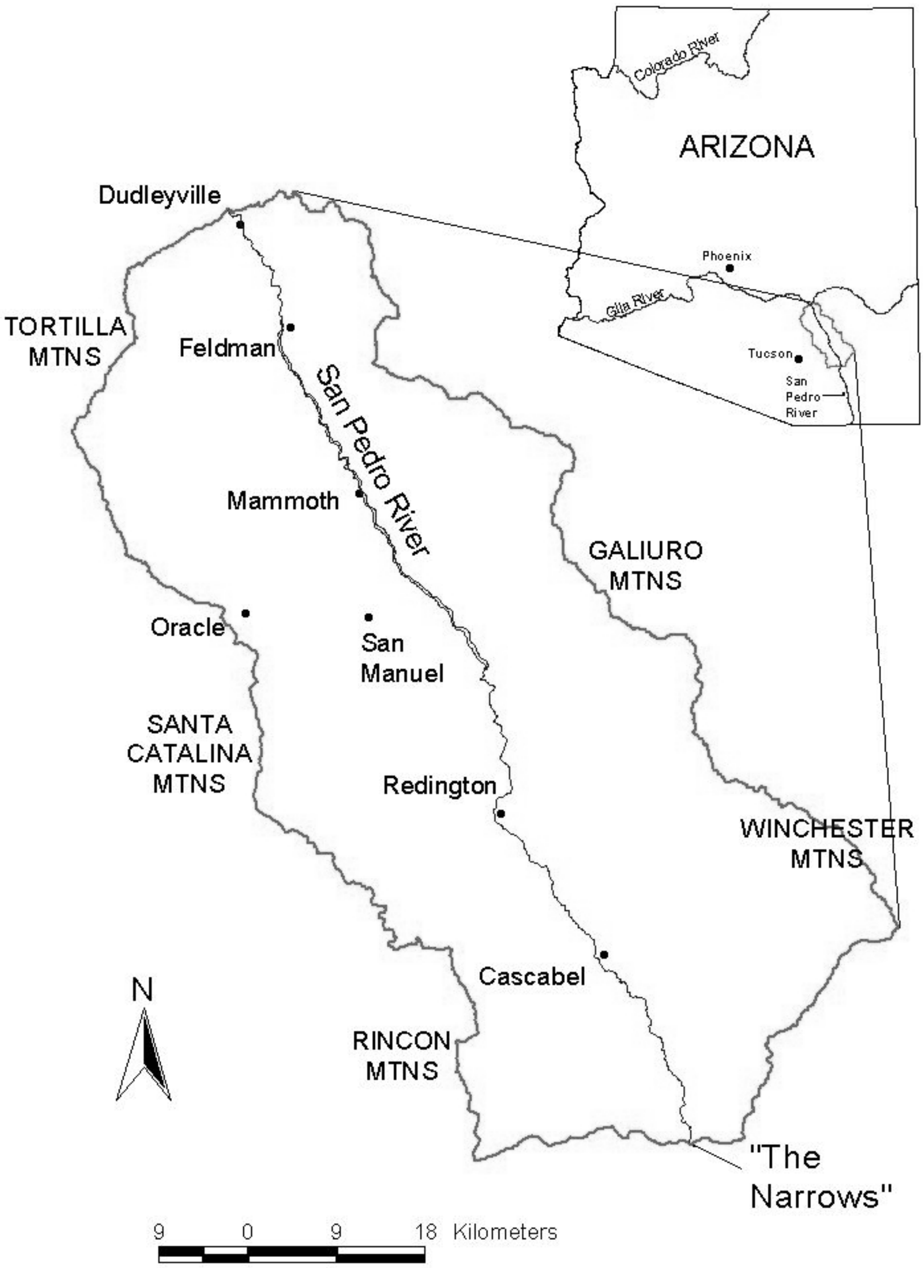


Fig. 1 Location of the San Pedro River basin within the state of Arizona (ALRIS, 1999; ADWR, 1999a).

Hydrogeology

The San Pedro basin is part of the Basin and Range Physiographic Province bounded to the east and west by mountain ranges that rise to almost 2800 m from the basin floor, which varies in elevation from approximately 1000 m near "The Narrows" to approximately 580 m near the confluence with the Gila River. Three major hydrogeological units exist in the basin: San Manuel Formation, Quiburis Formation, and Quaternary alluvium. The San Manuel Formation is a semi-consolidated conglomerate deposited prior to the Basin and Range deformation (Dickinson, 1991), now primarily found at depth below 300 m (Roeske & Werrell, 1973), forming Layer 3 of the model. The Quiburis represents the basin fill deposited from the mid-Miocene to the mid-Pliocene in a lacustrine environment (Dickinson, 2003), forming Layer 2 and most of Layer 1 of the model. Incised within the Quiburis are 25–75 m of gravel-rich Quaternary deposits laid down by Holocene stream activity (Dickinson, 1991), forming a narrow corridor of highly permeable material in Layer 1.

Hydraulic properties

The deposition of the Quiburis formed three distinct facies: conglomeritic, sand-flat, and lacustrine. The facies grade from coarse-grained to fine-grained with increasing distance from the mountain front and downgradient within the basin (Dickinson, 2003). Testing of the hydraulic properties in the basin has primarily been limited to the coarse-grained stream alluvium with little or no data existing for the basin fill. The different facies formed zones of similar hydraulic conductivity and storage terms, but final numbers were assigned during calibration.

Mountain front recharge

An ArcView preprocessor, CRWR-PrePro, delineated the drainage basins within the watershed (Maidment, 1998). These drainage basins each contribute a fraction of mountain front recharge proportional to the respective annual precipitation received. The Precipitation-elevation Regression Independent Slopes Model (PRISM) provided the estimates of precipitation for the region (Daly & Taylor, 1998). The amount of recharge roughly corresponds to the amount of precipitation minus water removed through ET. To estimate the recharge for the San Pedro basin, Anderson and others developed the following equation:

$$\log Q_{rech} = -1.40 + 0.98 \log P \quad (1)$$

where Q_{rech} represents recharge rate (inches year^{-1}) and P represents average amount of precipitation in excess of 8 inches year^{-1} (Anderson *et al.*, 1992). The recharge volume was then distributed to each contributing drainage basin based on the basin's precipitation.

Surface water

The San Pedro River is the primary drainage feature in the basin with five major tributaries and one surface water diversion also included in the model. Only the baseflow component of streamflow was included in this model for it was assumed that surface runoff quickly flows out of the system having little or no impact on the basin aquifer (Goode & Maddock, 2000). Stream gauges located on the model boundary provided the data for estimating the baseflow entering the basin in the San Pedro River and Aravaipa Creek, the largest of the five tributaries with its confluence between Mammoth and Feldman. Annual baseflow was estimated from the 7-day low flow, which was calculated for each year and then averaged over the years of gauge records (USGS, 2002). Baseflow estimates from the other gauges within the basin were used as part of the calibration process.

Annual baseflow estimates for the other tributaries were calculated using the Drainage Area Ratio Method (Stedinger *et al*., 1992). This method estimates the baseflow for an ungauged stream based on a comparison of the contributing drainage areas of the gauged and ungauged streams. Estimates for the four ungauged tributaries were calculated based on comparisons with Aravaipa Creek and one other gauged tributary in the Upper basin (USGS, 2002). The estimates proved to be similar so the average was used as the annual baseflow estimate for each of the four tributaries. The estimate for the water diverted through the Bayless Ditch came from the Hydrographic Survey Report (HSR) (ADWR, 1991).

Riparian vegetation

Riparian vegetation in the basin forms a narrow corridor along the San Pedro River where the water table is shallow. The areal extent of the riparian communities was determined from aerial photographs taken primarily in December 2001 as part of the San Pedro River, Arizona Wetland/Riparian Mapping Project (Dall, 2002), assuming no change through time. Cottonwood (*Populus fremontii*), goodding willow (*Salix gooddingii*), and mesquite (*Prosopis velutina*) were the three phreatophytes included in this model using ET rates based on vegetation type (Scott, 1999).

Well pumping

The Groundwater Site Inventory (GWSI) and the Well Registry databases provided the location, depth, diameter, and primary water use of individual pumping wells in the basin (ADWR, 1999a and 1999b). The HSR provided estimates for the volume of water pumped within the basin based on the primary water use (ADWR, 1991). This estimate was distributed to the individual wells based on the cross-sectional area of the well assuming that the larger wells were drilled to pump more water.

Anthropogenic areal recharge

Agriculture activity in the basin is concentrated primarily along the flood plain, where water is used for irrigation. The recharge rate for each set of fields was calculated as 30% of the total volume of water pumped from nearby irrigation wells distributed over the area of the fields (Goode & Maddock, 2000). The other major water user in the basin is mining with an estimated 16% of water pumped returning to the aquifer (ADWR, 1991), simulated as recharge over the tailings ponds. Locations of the agricultural fields and the tailings ponds were determined from 1991 satellite images and 1991–1992 airborne video imagery to map Arizona's natural vegetation (Graham, 1995).

NUMERICAL MODEL

A groundwater flow model was then created to simulate the movement of groundwater within the basin prior to 1940 and assess the impacts of withdrawals and diversions on the ground and surface water systems between 1940 and the present (2000) (Whittier, 2004). The numerical model was created from the conceptual model through the use of Groundwater Modelling System (GMS) (GMS, 1999), a graphical user interface for several hydrological computer models including MODFLOW, a Modular three-dimensional Finite-Difference Groundwater Flow Model (MODFLOW) (McDonald & Harbaugh, 1988). In GMS, the various GIS shapefiles of the conceptual model were imported and converted into the necessary MODFLOW input files. Further manipulation of the MODFLOW packages, creation of the grid, creation of the numerical model, and calibration were conducted in GMS.

Steady-state model

The steady-state model simulated the period of time prior to development when the natural recharge into the basin was equal to the natural discharge out of the basin with no change in storage. Development did occur in the basin prior to 1940, but the use of water at that time was limited to surface or shallow well water. After 1940, rural electrification allowed for larger pumps and the removal of more water and from greater depths (Goode & Maddock, 2000). Recorded pre-1947 water levels supplied calibration levels for the steady-state computed head conditions, with 1947 being the installation year for the first large pumping well for mining. The calibration process involved adjusting various hydraulic parameters, mainly hydraulic conductivity and streambed conductivity, to match predevelopment water levels and streamflows.

Transient model

The transient model simulated the time period from October 1939 until September 2000. Over 400 wells had water level measurements taken from 1940 to 2000. These water level measurements were used in the calibration of the transient model and matched primarily through the adjustment of the storage terms.

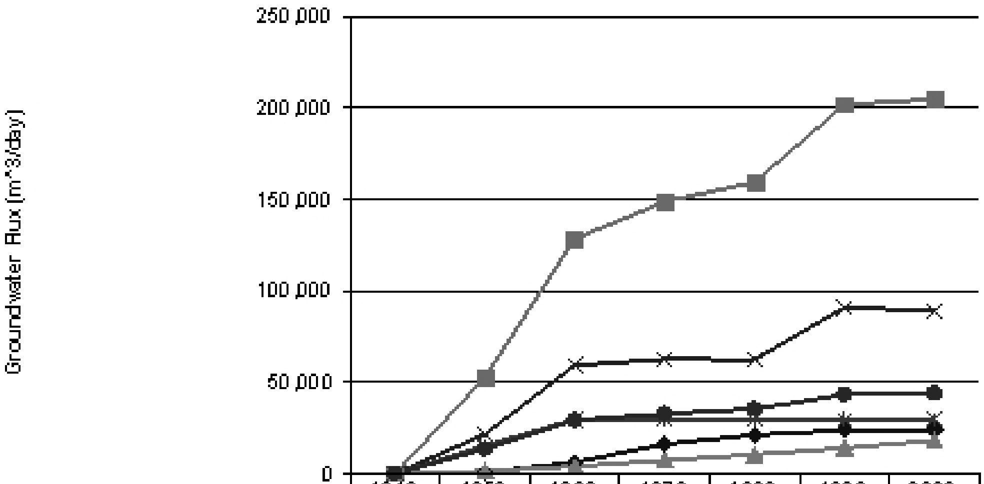
RESULTS AND ANALYSIS

Two methods were used to study the effects of groundwater pumping in the Lower San Pedro basin: capture and water table decline. Capture is a measure of the effect of groundwater pumping on surface water and ET. In 1941, it was recognized that three possibilities could occur whenever groundwater was pumped: the recharge to the system (ΔR) may increase, the discharge from the system (ΔD) may decrease, and water may be removed from storage over time ($\Delta S/\Delta t$). This can be represented in equation form as the following:

$$\left(R+\Delta R\right)-\left(D+\Delta D\right)-Q=\frac{\Delta S}{\Delta t} \tag{2}$$

where R is the natural recharge, D is the natural discharge, and Q is the pumping rate. During the predevelopment period, no groundwater pumping is occurring and the natural recharge was assumed to equal the natural discharge: $R = D$. Therefore, $\Delta S/\Delta t = (\Delta R + \Delta D) - Q$, where the $(\Delta R + \Delta D)$ term represents the "capture". Sources of capture in the basin include ET, stream discharge, and loss of flow to the Gila River basin. The changes in key components of the hydrological system over time are shown in Fig. 2.

With the increase in groundwater pumping from 1940 to 2000, several natural indicators show an overall downward trend. First, the flow out of the Lower San Pedro River basin to the Gila River basin decreased (Fig. 2), shown as an increase in the loss of flow to the Gila River basin. Second, as water levels declined the overall ET rate decreased, shown as an increase in the loss of flow to ET. Third, the loss of water out of groundwater storage increased, leaving less water available in storage and lowering the water table level. And fourth, leakage to the stream decreased over time causing an increase in the rate of stream capture. Artificial recharge was included as it is a



	1940	1950	1960	1970	1980	1990	2000
Loss of Flow to Gila Basin	0	800	6,200	16,300	21,200	23,800	24,100
Total Pumping	0	52,800	128,500	148,800	159,400	201,900	204,900
Loss from Evapotranspiration	0	1,500	4,000	7,300	10,500	14,100	18,100
Loss from Groundwater Storage	0	21,600	59,300	62,600	62,500	91,000	89,000
Stream Capture	0	15,300	29,700	29,700	29,700	29,700	29,700
Artificial Recharge	0	13,500	29,200	32,900	35,500	43,300	44,000

Year

Fig. 2 Changes in the key flux components of the hydrologic system through time (Whittier, 2004).

percentage of the groundwater pumping for mining and agriculture that is returned to the system and increases with increased groundwater pumping. The regions of significant drawdown were near the town of Mammoth due to the mining operations and between the Narrows and the town of Cascabel from irrigation practices.

CONCLUSIONS

The mathematical approximations needed to model groundwater flow and the geographic model scale led to simplification of the complex hydrological system within the Lower San Pedro River basin. This simplification process leads to a loss in accuracy but overall trends in the natural indicators are still apparent, especially in response to groundwater pumping. These trends include a reduction in streamflow in the San Pedro River, a reduction of ET by the riparian vegetation along the river corridor, and the formation of several cones of depression along the river. The reduction of streamflow is most apparent near the town of Mammoth, an area that also experienced the largest decline in water table level. By 1990, no streamflow occurs in the San Pedro near Mammoth. Other smaller cones of depression exist around the larger irrigation wells along the river corridor with the largest impact on the water table between “The Narrows” and Cascabel.

FUTURE

The model will be used by The Nature Conservancy to study the effects of groundwater pumping on the hydrological system of the Lower San Pedro basin. The sustainability of the riparian habitat within the basin depends on a balanced use of the groundwater for all uses: mining, farming, domestic, and riparian.

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REFERENCES

ADWR (Arizona Department of Water Resources) (1991) *Hydrographic Survey for the San Pedro River Watershed, General Assessment*, vol. 1. Arizona Dept of Water Resources, Phoenix, Arizona, USA.

ADWR (1999a) *Arizona Well Registry Distribution Database CD-ROM*, 3rd edn. Arizona Dept of Water Resources, Phoenix, Arizona, USA.

ADWR (1999b) *Groundwater Site Inventory*. Arizona Dept of Water Resources, Phoenix, Arizona, USA.

ALRIS (Arizona Land Resource Information System) (1999) Data Set: AZTOWNS. Phoenix, Arizona. http://www.land.state.az.us/alris/alrishome.html.

Anderson, T. W., Freethey, G. W. & Tucci, P. (1992) Geohydrology and water resources of alluvial basins in South-Central Arizona and parts of adjacent states. *US Geol. Survey Professional Paper 1406-B*.

Dall, D. (2002) San Pedro River, Arizona Wetland/Riparian Mapping Project. National Wetlands Inventory. USFWS Region 2, Albuquerque, New Mexico, USA.

Daly, C. & Taylor, G. (1998) *Arizona Average Monthly or Annual Precipitation, 1961–1990*. Water and Climate Center of the Natural Resources Conservation Service, Portland, Oregon, USA.

Dickinson, W. R. (1991) Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona. *Geol. Soc. Am. Special Paper 264*.

Dickinson, W. R. (2003) Depositional facies of the Quiburis Formation, basin fill of the San Pedro Trough, southeastern Arizona basin and Range Province. In: *Cenozoic Systems of the Rocky Mountain Region* (ed. by R. G. Raynolds & R. M. Flores), 157–181. Society for Sedimentary Geology (SEPM), Rocky Mountain Section, Denver, USA.

GMS (1999) GMS v. 3.0 Reference Manual. Brigham Young University, Environmental Modeling Research Laboratory, USA.

Goode, T. C. & Maddock III, T. (2000) Simulation of groundwater conditions in the Upper San Pedro basin for the evaluation of alternative futures. *HWR No. 00-030*. Department of Hydrology and Water Resources and University of Arizona Research Laboratory for Riparian Studies, University of Arizona, Tucson, Arizona, USA.

Graham, L. A. (1995) Arizona natural vegetation, as mapped for the Arizona GAP Analysis Program. Digital GIS File. School of Renewable Natural Resources, University of Arizona, Tucson, Arizona, USA.

Maidment, D. (1998) Delineating the Watershed and Stream Network of the Guadalupe basin. Developed for the CE-394 K3 GIS in Water Resources class at the University of Texas, Texas, USA. http://www.ce.utexas.edu/prof/olivera-/prepro/ExerciseDelineate/delinex.htm.

McDonald, M. G., & Harbaugh, A. W. (1988) A modular three-dimensional finite-difference groundwater flow model. *US Geol. Survey TWI 6-A1*.

Roeske, R. H. & Werrell, W. H. (1973) Hydrologic conditions in the San Pedro River Valley, Arizona, 1971. *Arizona Water Commission Bulletin 4*.

Scott, R. L. (1999) Riparian and rangeland soil-vegetation-atmosphere interactions in southeastern Arizona. PhD Dissertation, University of Arizona, Tucson, Arizona, USA.

Stedinger, J. R., Vogel, R. M. & Foufoula-Georgiou, E. (1992) Frequency analysis of extreme events. In: *Handbook of Hydrology* (ed. by D. R. Maidment), 18.54–18.55. McGraw-Hill Inc., San Francisco, California, USA.

United States Geological Survey (USGS). (2002) Daily Streamflow for the Nation. http://nwis.waterdata.usgs.gov-/usa/nwis/discharge.

Whittier, J. D. (2004) Groundwater flow model of the lower San Pedro River basin for the conservation of riparian habitats. MSc Thesis, University of Arizona, Tucson, Arizona, USA.