

Prepared in cooperation with the
BUREAU OF LAND MANAGEMENT

Hydrologic Requirements of and Evapotranspiration by Riparian Vegetation along the San Pedro River, Arizona

This report summarizes analyses of riparian system hydrologic requirements and ground-water use detailed in U.S. Geological Survey Scientific Investigations Report 2005-5163, "Hydrologic requirements of and consumptive ground-water use by riparian vegetation along the San Pedro River, Arizona," compiled by J.M. Leenhouts, J.C. Stromberg, and R.L. Scott.

In 1988, Congress designated portions of the San Pedro River in the Upper San Pedro Basin of Cochise County, Arizona, as the San Pedro Riparian National Conservation Area (SPRNCA; fig. 1). This conservation area is home to an ecologically diverse and important riparian system. The basin also hosts growing populations of residents in areas hydraulically upgradient from sensitive reaches of the riparian system. The largest communities are Sierra Vista, Bisbee, Tombstone, Huachuca City, and the U.S. Army's Fort Huachuca. The total population of these communities and surrounding rural developments is about 75,625 (Arizona Department of Economic Security, 2003). Residents of several local communities have responded to the need for water planning by forming the Upper San Pedro Partnership (USPP), a consortium of 21 agencies and organizations with a primary goal of ensuring long-term water needs are met, both for the area residents and for the riparian vegetation and wildlife along the river within the SPRNCA. As part of the overall planning strategy, the USPP assembled a multidisciplinary team of researchers and began a study to characterize the water needs of the SPRNCA's riparian system.

The characterization of riparian water needs was done by determining the (1) annual water-use rates for riparian species and open-water evaporation, (2) areal distribution of riparian species and, (3) relation between hydrologic factors, water-use rates, and the distribution of riparian species. These characterizations not only helped define the current water needs for the SPRNCA's riparian system, but also provided information about how the ecological structure of the system and its water needs could change under different hydrologic conditions. The study was a collaborative effort by the U.S. Geological Survey, Arizona State University, and the U.S. Department of Agriculture-Agricultural Research Service with assistance from the U.S. Army Corps of Engineers, the University of Wyoming, and the University of Arizona.

The San Pedro River within the SPRNCA was delineated into 14 reaches that were internally homogenous in terms of streamflow hydrology (spatial intermittence of streamflow) and geomorphology (channel sinuosity and flood-plain width). A total of 26 sites (fig. 1) within the SPRNCA were selected for collection of vegetation data from three primary streamflow regimes: perennial, intermittent-wet, and intermittent-dry (fig. 2). These regimes were defined by observed ranges of ground-water and streamflow conditions (table 1). Hydrologic data were collected at 16 of these sites (called biohydrology sites); water-use and water-source data were collected at a subset of 5 sites. Vegetation data were also collected at sites in the Lower San Pedro Basin. Data were collected from 2000 to 2003.

The term "riparian" refers to transitional areas between terrestrial and aquatic ecosystems that depend on the existence of surface or subsurface water flows. The riparian corridor in the SPRNCA is a band along the river that encompasses low-flow channel sandbars, streambanks, and post-entrenchment flood plains, as well as pre-

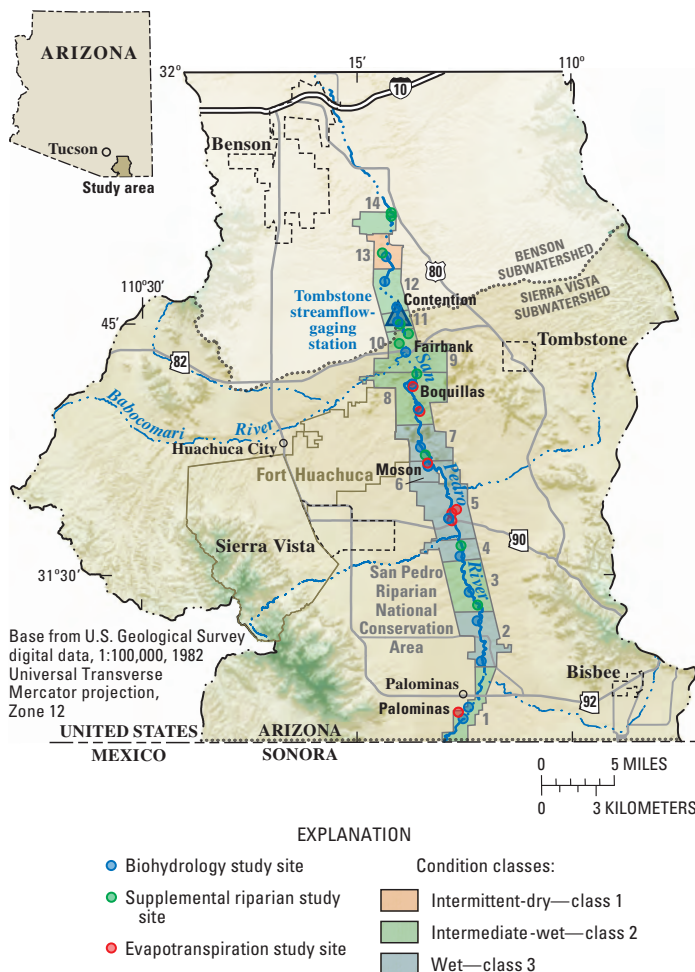


Figure 1. Boundaries of the Sierra Vista Subwatershed and locations of study sites and 14 reaches of the San Pedro River in the San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

Table 1. Observed hydrologic conditions of the three riparian condition classes

Condition class	Streamflow regime class	Streamflow permanence (percent)	Average flood-plain ground-water depth in dry season, in meters	Annual ground-water fluctuation, in meters
3	Perennial	100	Less than 2.5	Less than 0.5
2	Intermittent-wet	Between 100 and 60	Between 2.5 and 3.5	Between 0.5 and 1.0
1	Intermittent-dry	Less than 60	Greater than 3.5	Greater than 1.0



Figure 2. Active channel of the San Pedro River in summer. *A*, Perennial Moson site; *B*, Intermittent-wet Contention site.

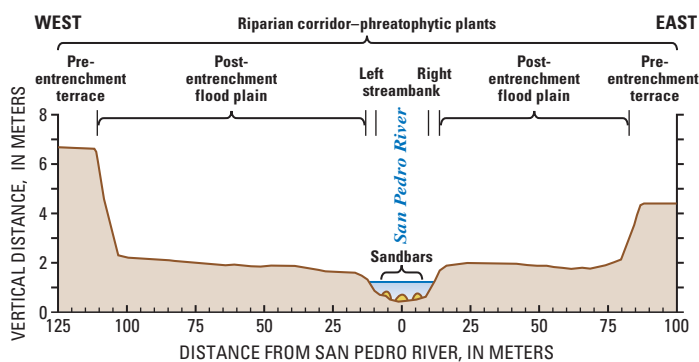


Figure 3. Cross section of stream-channel morphology, San Pedro Basin, Arizona.

entrenchment terraces at a higher altitude than the current flood plain (fig. 3) that are vegetated, in part, by phreatophytic plants that use ground water from the stream alluvium.

The hydrologic factors measured included ground-water depth and streamflow. Riparian vegetation measurements included biomass structure, abundance of common riparian plant species, and abundance of plants classified into functional groups. Riparian evapotranspiration (ET) and free-water evaporation were measured by using a combination of sap-flow, eddy-covariance, and meteorological techniques.

Distribution Patterns, Effects of Hydrologic Conditions, and Water Use by Riparian Vegetation

Fremont Cottonwood (*Populus fremontii*)-Goodding Willow (*Salix gooddingii*) Forest

Cottonwood-willow forests are present mainly in the active flood plain; a few old cottonwood trees are present on the pre-entrenchment terraces. The forests were dense and multi-aged where maximum ground-water depths averaged less than about 3 meters, streamflow permanence was greater than about 60 percent, and intra-annual

ground-water fluctuation was less than about 1 meter (Lite and Stromberg, 2005), but declined in abundance and age-class diversity where water availability was less (fig. 4). Cottonwood-willow forests gave way to tamarisk stands as site-average ground-water depths across the flood plain exceeded 3 meters. Conditions were too dry at intermittent-dry streamflow regime sites to allow for establishment of cottonwood and willow seedlings.

Cottonwood sap flow was measured during most of the 2003 growing season to estimate transpiration along a perennial and an intermittent-wet reach (table 2). Cottonwood transpiration at the perennial reach was about 20 percent greater on a per canopy area basis than previous estimates (Goodrich and others, 2000). Cottonwood transpired considerably less at the intermittent-wet reach than at the perennial reach, and had greatly reduced rates of transpiration as ground-water levels declined in the premonsoon season. Reduced transpiration likely was a result of physiological stress. Roughly 40 percent of the cottonwood forests in the SPRNCA were classified as being on intermittent reaches. Work by Snyder and Williams (2000) suggests that cottonwood transpiration was fully derived from ground water at perennial reaches and about 85 percent derived from ground water at intermittent reaches.

Table 2. Total growing-season evapotranspiration of specific vegetation types and annual evaporation from open-water surfaces per unit land area

[---, indicates no data; ET, evapotranspiration; ET is reported per unit land area occupied by each vegetation type; ET is the total water use by the vegetation, including ground- and surface-water sources]

Vegetation type	Water use, in millimeters		
	2001	2002	2003
Mesquite woodland	694	638	670
Mesquite shrubland	---	---	565
Cottonwood – perennial reach	---	---	966
Cottonwood – intermittent-wet reach	---	---	484
Sacaton	---	---	554
Open-water evaporation	---	---	1,156
Seepwillow	---	---	819

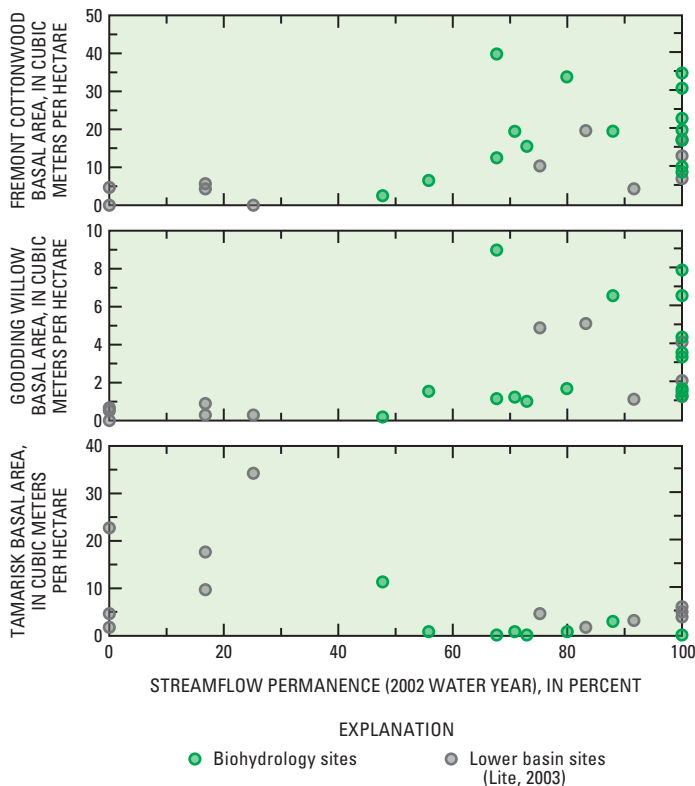


Figure 4. Basal area of Fremont cottonwood, Goodding willow, and tamarisk in relation to streamflow permanence of San Pedro River sites, Arizona. Each data point represents a site. Data shown for the 16 biohydrology study sites in the San Pedro Riparian National Conservation Area, and for 12 sites in the Lower San Pedro Basin, Arizona (Lite, 2003).

Mesquite (*Prosopis velutina*) Woodland and Shrubland

Velvet mesquite is deep-rooted and can survive in areas where it does not access ground water, but forms denser stands when in riparian settings. It was widely distributed in the SPRNCA, being abundant at dry and wet sites and on flood plains and terraces. Growth form and abundance of velvet mesquite was related to site elevation (with trees larger and more abundant at downstream sites) and to average flood intensity but not to site water-availability factors.

Mesquite is the most abundant vegetation type within the SPRNCA. Multiyear ET observations from a mature mesquite woodland and a mesquite shrubland indicate that (1) both used substantially more water than previously estimated, and (2) their water use was nearly equal on a per unit canopy area basis (table 2). Stable-isotope measurements ($\delta^{18}\text{O}$) revealed considerable seasonal variation in the proportion of mesquite transpiration derived from ground water between sites. Mesquite used a combination of surface (recent precipitation), ground-water, and deep (1 to 10 meters) vadose-zone sources depending on the availability of each source through the season. There was a tendency toward proportionally less ground-water use in mesquite stands that had comparatively less access to ground water (deeper water table). Nevertheless, mesquite at all isotope sample sites used substantial quantities of ground water.

Sacaton (*Sporobolus wrightii*) and Other Herbaceous Vegetation

The perennial grass sacaton occupies more area on the Upper San Pedro River flood plain than any other herbaceous plant species and is also abundant on terraces. Bermuda grass and johnson grass also have high cover on flood plains. These common flood-plain plants show some seasonal variance in cover and likely use a variety of water sources, including ground water, precipitation, and flood

water, depending in part on seasonal availability. Some plant groups, including wetland annuals, upland annuals, and xerophytic perennials, increased sharply in abundance following the summer monsoonal rains and floods; this relation likely indicates primary reliance on monsoon water sources.

The ET of sacaton in this study (table 2) was substantial and was partially derived from ground water; this result differs from a previous study that reported that sacaton did not use ground water (Scott and others, 2000). The likely reason for this discrepancy was shallower ground water depths (less than 3 meters) at sacaton sites in the current study. High-resolution topographic measurements suggest that about 30 percent of the total sacaton within the SPRNCA likely grows where depth to ground water is less than 3 meters.

Tamarisk (*Tamarix ramosissima*)

Currently, there is a relatively small amount of tamarisk in the SPRNCA, mainly restricted to areas north of Fairbank. In contrast to the patterns of cottonwood and willow, tamarisk abundance increased at dry sites, likely due, in part, to reduced competitive interactions with cottonwood and willow trees (Sher and Marshall, 2003). This study also found that the relative abundance of tamarisk to that of cottonwood-willow along the San Pedro River has been stable at many sites but has increased over time at other sites, including those in the Palominas and Boquillas-Fairbank areas and north of Fairbank. Recent increases in tamarisk abundance may be indicative of decreasing site water availability.

For the water-use estimates, ET rates and ground-water use patterns of tamarisk were assumed to be similar to those of mesquite, in part, because mesquite and tamarisk have a similar stand structure and are able to acquire ground water at deeper depths than cottonwoods.

Seepwillow (*Baccharis salicifolia*) Shrublands

Seepwillow is an evergreen shrub that forms thickets on low-lying flood plains adjacent to the stream channel. Seepwillow was most abundant on surfaces where the annual maximum (2002 data) ground-water depth was less than about 2 meters. Seepwillow had very sparse cover at the intermittent-dry sites.

Seepwillow transpiration was measured using sap-flow methods as a preliminary step toward quantification. Because available cover data indicate that total seepwillow area is small in the SPRNCA, ground-water use by seepwillow was likely small and was omitted from the water-use budgets.

Streamside Wetland Vegetation and Open Channels

Among all herbaceous plant groups analyzed, the wetland perennials showed the strongest correlation with surface-water availability. Rushes, bulrush, and other wetland perennial herbs depend on shallow, inflowing ground water and had high abundance only at sites with perennial or near-perennial streamflow; abundance declined sharply as flows became intermittent. The channel-bar vegetation became sparser and less diverse, and species composition shifted towards more mesic species such as bermuda grass (*Cynodon dactylon*) as sites became increasingly intermittent (along spatial gradients and through time). Wetland herbaceous plants (perennials and annuals) varied in abundance between years; they were particularly abundant in 2001 in response to a large flood in October that increased streamflow in the SPRNCA for several months.

Wetland vegetation ET was not quantified owing to the relatively small area that the vegetation occupies. The evaporation from the river surface (table 2) was determined using potential evaporation and a reduction factor to account for the effect of shading and entrenchment that would reduce this rate relative to the rate for unsheltered open water.

Riparian Condition Class

A riparian condition index was developed, on the basis of field-measured vegetation traits, to diagnose and monitor riparian vegetation condition change as related to changes in streamflow and ground-water conditions. Site index scores allow for categorization into condition classes 1 through 3, each associated with particular ranges for site hydrology, vegetation structure, and ecosystem functional capacity. Condition class 3 indicates ecological conditions reflecting the highest water availability, class 2 indicates intermediate availability, and class 1 indicates the lowest water availability presently occurring within the SPRNCA (table 1). Overall, 39 percent of the SPRNCA riparian corridor fell within class 3, 55 percent in class 2, and 6 percent in class 1 (fig. 1).

At class 3 sites (and reaches), flood-plain vegetation is characterized by tall, dense, multi-aged cottonwood-willow forests and woodlands with intermixed areas of other vegetation types. Drought-tolerant, deep-rooted pioneer species such as tamarisk are subdominant in the forests. The stream channel is lined by dense and diverse herbaceous cover. At class 2 sites, cottonwood and willow are the dominant pioneer trees in the flood plain, but tamarisk presence is increased, and cottonwoods and willow trees undergo dry-season declines in water use and productivity. Major changes in the herbaceous vegetation occur between classes 2 and 3. Streamside cover of wetland plants is reduced, owing to loss of perennial streamflow. Many of the wetland perennial herbs have been replaced by perennials that are more drought tolerant, such as bermuda grass.

In the transition from class 2 to class 1, major changes occur in woody vegetation composition and structure in the flood plain. Hydrologic thresholds for cottonwood and willow survivorship have largely been exceeded and only a few age classes of these species persist in favorable locations. Deep-rooted phreatophytes, typically tamarisk, have replaced shallower-rooted species. Structurally, the flood plain is dominated by shrublands with little upper canopy cover. Streamside herbaceous cover is sparse in the summer dry season.

The vegetation characteristics of the three condition classes provide some measure of the changes in vegetation structure and composition that might occur in response to future changes in base flow and ground-water availability. For example, if streamflow became more intermittent and depth to the alluvial ground-water table increased, herbaceous species such as bulrush and rushes would decline in abundance, and streamside-zone species composition would shift towards species such as bermuda grass. Across the flood plain, cottonwood-willow recruitment rates would decrease and mortality rates would increase; cottonwood-willow forests could give way to tamarisk shrublands. A reverse scenario would occur if streamflows became more permanent and ground water in the alluvium became shallower and more stable.

In all three condition classes, periodic floods of varying size and timing increase diversity by providing the physical disturbance that allows for establishment of a wide range of disturbance-adopted and pioneer plant species.

Scaling-up Water Use Estimates to the System Scale

Vegetation cover maps were used to scale species-specific ET measurements to the system scale. Mesquite ground-water use was the dominant component of the riparian water use, owing to high abundance, followed by cottonwood-willow, open water, sacaton, and tamarisk. Riparian ground-water use in 2003 along the San Pedro River from the international boundary to the USGS streamflow-gaging station near Tombstone, 09471550, (within the Sierra Vista Subwatershed) was calculated to be 9,065,000 to 11,112,000 cubic meters per year (7,350 to 9,010 acre-feet per year), 12 to 37 percent higher than the total that Goodrich and others (2000) estimated for 1997. Combining totals for the Babocomari River and the San Pedro

River, 11,840,000 to 14,867,000 cubic meters per year (9,600 to 12,050 acre-feet per year) of ground water was consumptively used within the riparian corridors of the Sierra Vista Subwatershed for 2003. This is 25 to 57 percent greater than the 9,498,000 cubic meters per year (7,700 acre-feet per year) estimate of Corell and others (1996) owing in part to a large disparity between the two studies' estimates for the Babocomari River. It is important to recognize that interannual climatic variability will result in different water-use values year to year (as much as 30 percent for mesquite).

—James M. Leenhouts (U.S. Geological Survey), Julie C. Stromberg (School of Life Sciences, Arizona State University), and Russell L. Scott (Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture)

References

- Arizona Department of Economic Security, 2003, July 1, 2003, population estimates for Arizona's counties, incorporated places and balance of county areas, accessed November 17, 2005, at http://www.workforce.az.gov/admin/uploadedPublications/1003_EEC-03.pdf
- Corell, S.W., Corkhill, F., Lovvik, D., and Putnam, F., 1996, A groundwater flow model of the Sierra Vista Subwatershed of the Upper San Pedro Basin, southeastern Arizona, in Modeling Report No. 10: Phoenix, Arizona Department of Water Resources, Hydrology Division, 107 p.
- Goodrich, D.C., Scott, R.L., and 17 others, 2000, Seasonal estimates of riparian evapotranspiration using remote and in-situ measurements: *Agricultural and Forest Meteorology*, v. 105, p. 281–309.
- Leenhouts, J.M., Stromberg, J.C., and Scott, R.L., 2006, Hydrologic requirements of and consumptive ground-water use by riparian vegetation along the San Pedro River, Arizona: U.S. Geological Survey Scientific Investigations Report, 2005–5163, 154 p.
- Lite, S.J., 2003, San Pedro River riparian vegetation across water availability and flood disturbance gradients: Tempe, Arizona State University, Ph.D. dissertation, 166 p.
- Lite, S.J., and Stromberg, J.C., 2005, Surface water and ground-water thresholds for maintaining *Populus* - *Salix* forests, San Pedro River, Arizona: *Biological Conservation*, v. 125, no. 2, p. 153–167.
- Scott, R.L., Shuttleworth, W.J., Goodrich, D.C., and Maddock, T., 2000, The water use of two dominant vegetation communities in a semiarid riparian ecosystem: *Agricultural and Forest Meteorology*, v. 105, no. 1–3, p. 241–256.
- Sher, A.A., and Marshall, D.L., 2003, Seedling competition between native *Populus deltoides* (Salicaceae) and exotic *Tamarix ramosissima* (Tamaricaceae) across water regimes and substrate types: *American Journal of Botany*, v. 90, no. 3, p. 413–422.
- Snyder, K.A., and Williams, D.G., 2000, Water sources used by riparian trees varies among stream types on the San Pedro River: *Journal of Agricultural and Forest Meteorology*, v. 105, no. 1–3, p. 227–240.

For further information, contact:

James M. Leenhouts
U.S. Geological Survey
Arizona Water Science Center
520 North Park Avenue, Suite 221
Tucson, Arizona, 85719-5035
Email: leenhout@usgs.gov or visit home page
<http://az.water.usgs.gov>

