Chapter D

Determining the Riparian Ground-Water use within the San Pedro Riparian National Conservation Area and the Sierra Vista Subwatershed, Arizona

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Introduction

Rationale and Background

The combined research team of the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS), the University of Wyoming, and the University of Arizona had the primary role in the San Pedro Riparian National Conservation Area (SPRNCA) water-needs study to improve estimates of the water use by the San Pedro River's riparian corridor and to identify the sources of that water. In order to do this, the main experimental objectives, developed in coordination with the Upper San Pedro Partnership were to:

1. Quantify the consumptive water use of riparian mesquite woodlands,
2. Quantify environmental factors that are likely to influence mesquite water use,
3. Quantify the consumptive water use of understory vegetation within the cottonwood-willow stands and the evaporation from the free water surface within the SPRNCA,
4. Identify the evaporation water source for the dominant vegetation communities, and
5. Quantify the total consumptive ground-water use from the regional aquifer by riparian vegetation within the SPRNCA.

These objectives followed from previous work done to estimate riparian ground-water use for portions of the Upper San Pedro Basin and were designed to refine knowledge of riparian vegetation functioning so that improved estimates can be made.

The work of Goodrich, Scott, and others (2000) is the most recent on this issue and was the foundation for this study. Their study synthesized the results of the interdisciplinary Semi-Arid Land-Surface-Atmosphere (SALSA) program in order to make the first field-measured, evapotranspiration (ET) data-based estimates of riparian ground-water use in a portion of the SPRNCA's riparian corridor. Most of the estimates made prior to Goodrich, Scott, and others (2000) were derived from ground-water modeling studies that indirectly infer or model riparian ground-water use in a simplified manner (Kreager-Rovey, 1974; Freethey, 1982; Vionnet and Maddock, 1992). Prior to Goodrich, Scott, and others (2000), Corell and others (1996) estimated riparian ground-water use by using the difference between river base flows in winter and summer at the U.S. Geological Survey (USGS) streamflow-gaging stations, San Pedro River at Palominas (09470500), at Charleston (09471000), and near Tombstone (09471550). Despite being derived from entirely different approaches, the estimates are surprisingly similar (table 38). The estimates of Corell and others (1996) also include potential losses caused by near-stream agricultural pumping.

This study's approach to determining riparian ground-water use was to refine previous water-use estimates for the open water surface and the key ecosystem types found within the SPRNCA using hydroecological measurements of ET and plant-water sources. Next, these revised estimates were combined with a new vegetation map developed for the SPRNCA in 2000 (U.S. Army Corps of Engineers, 2001) to determine riparian ground-water use. Following many of the recommendations of Goodrich, Scott, and others (2000), the ecosystems of interest were velvet mesquite (*Prosopis velutina*) woodlands and the Fremont cottonwood (*Populus fremontii*) forest, but a companion effort with the University of Arizona enabled an additional sacaton (*Sporobolus wrightii*) grassland and mesquite shrubland to be studied. Additionally, pioneer studies of open-water evaporation and the transpiration of a major understory plant species, seepwillow (*Baccharis salicifolia*) were carried out. Finally, meteorological variables collected from three meteorological sites were compared to determine how certain forcing variables relevant to the evaporation process and future modeling studies varied at different locations within the SPRNCA (appendix 8). An overall description of the vegetation, soils, streamflow, and climate of the upper San Pedro River is given in the introductory section of this report (see chapter A).

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Table 38. Previous estimates of ground-water use by the riparian system along the San Pedro River within the Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona

[m^3, cubic meter]

Source	Annual riparian ground-water use estimate m^3 (acre-feet)
Corell and others (1996)	[1]8,758,000 (7,100)
Goodrich, Scott, and others (2000)	[2]8,130,000 (6,590)

[1]From the start of the perennial reach upstream from the U.S. Geological Survey (USGS) streamflow-gaging station San Pedro River at Palominas (09470500) to the USGS streamflow-gaging station San Pedro River near Tombstone (09471550), and excluding 600 acre-feet per year from the Babocomari River, a major San Pedro River tributary.

[2]From the international border with Mexico to the USGS streamflow-gaging station near Tombstone.

Methods

ET was measured at three biohydrology study sites: Boquillas, Charleston mesquite, and Lewis Springs (fig. 43). ET was measured by using the eddy-covariance technique at the Charleston mesquite and Lewis Springs sites and by using the sap-flow method at the Lewis Springs and Boquillas sites (table 2). Among these sites, the dominant vegetation communities of sacaton (*Sporobolus wrightii*) grasslands, mesquite woodlands and shrublands, and cottonwood forests are all represented. ET from seepwillow, a major understory riparian shrub, and the evaporation from the open-water surface of the river were also measured. The method used to measure ET depended on the plant community being studied. The eddy-covariance technique requires a spatially extensive patch of similar vegetation and was used for the sacaton grassland (at the Lewis Springs site) and mesquite (at the Charleston mesquite and Lewis Springs sites) vegetation communities. The sap-flow method was used for the cottonwood and seepwillow vegetation communities (at the Lewis Springs and Boquillas sites) because these vegetation types do not occur in large, uniform stands along the San Pedro River. An extensive analysis of mesquite water sources using stable isotopes of water (at the Charleston mesquite and Moson sites) was also performed to better understand the partitioning of mesquite ET into ground-water and precipitation sources. Basic meteorological data were collected at the Palominas, Lewis Springs, and Charleston mesquite sites (table 2). See chapter A for additional information about the study sites.

Mesquite Woodland Evapotranspiration

Mesquite woodland evapotranspiration was measured at one location (Charleston mesquite; fig. 43) during the 2001, 2002, and 2003 growing seasons and supplemented by direct measurements of understory ET at two locations within the same site during 2001 and 2002. The growing season partitioning of mesquite ET into the component fluxes of mesquite transpiration, soil evaporation, and understory ET was estimated by a combination of micrometeorological and stable-isotope techniques.

Site Description

The Charleston mesquite study site is on the east side of the San Pedro River at an elevation of 1,200 m, about 16 km northeast of Sierra Vista, Arizona (fig. 43). The site is collocated with one of the biohydrology study sites (see chapters A–C) in a dense woodland dominated by mesquite. It has a typical fetch of about 300–1,000 m for most wind directions. The shortest fetch is limited to about 150 m southeast of the instrument tower. The understory is primarily sacaton grass with some shrubs and various annual herbaceous species. The average canopy cover, defined as the ratio of the projected canopy cover area to the total ground area, is about 75 percent. The measured Plant Area Index (PAI) ranges from an average (n=40) of about 1.0 prior to leaf-out to about 1.6 during most of the growing season. During the peak of the growing season, the PAI was equal to a one-time measurement of Leaf Area Index (LAI). The mean canopy height was about 7 m and the maximum canopy height was about 10 m.

The deepest observed rooting depths of the understory plants were 2 to 3 m, implying that the plants do not have access to ground water at a depth of about 10 m. Rooting patterns of nonriparian mesquite are quite varied and extensive (Heitschmidt and others, 1988) and have been described as "ubiquitous" (Gile and others, 1997). At the cutbanks along the river near the site, mesquite roots extending both laterally near the surface and vertically to the water table were observed. On the mesquite terrace, soils are sandy loams interspersed with layers of gravel and clayey material.

Meteorological Instrumentation

Evapotranspiration was measured using the eddy-covariance technique throughout most of the active mesquite growing season in 2001, 2002, and 2003. Basic meteorological, soil moisture, and water-table elevation data were also collected throughout most of each year.

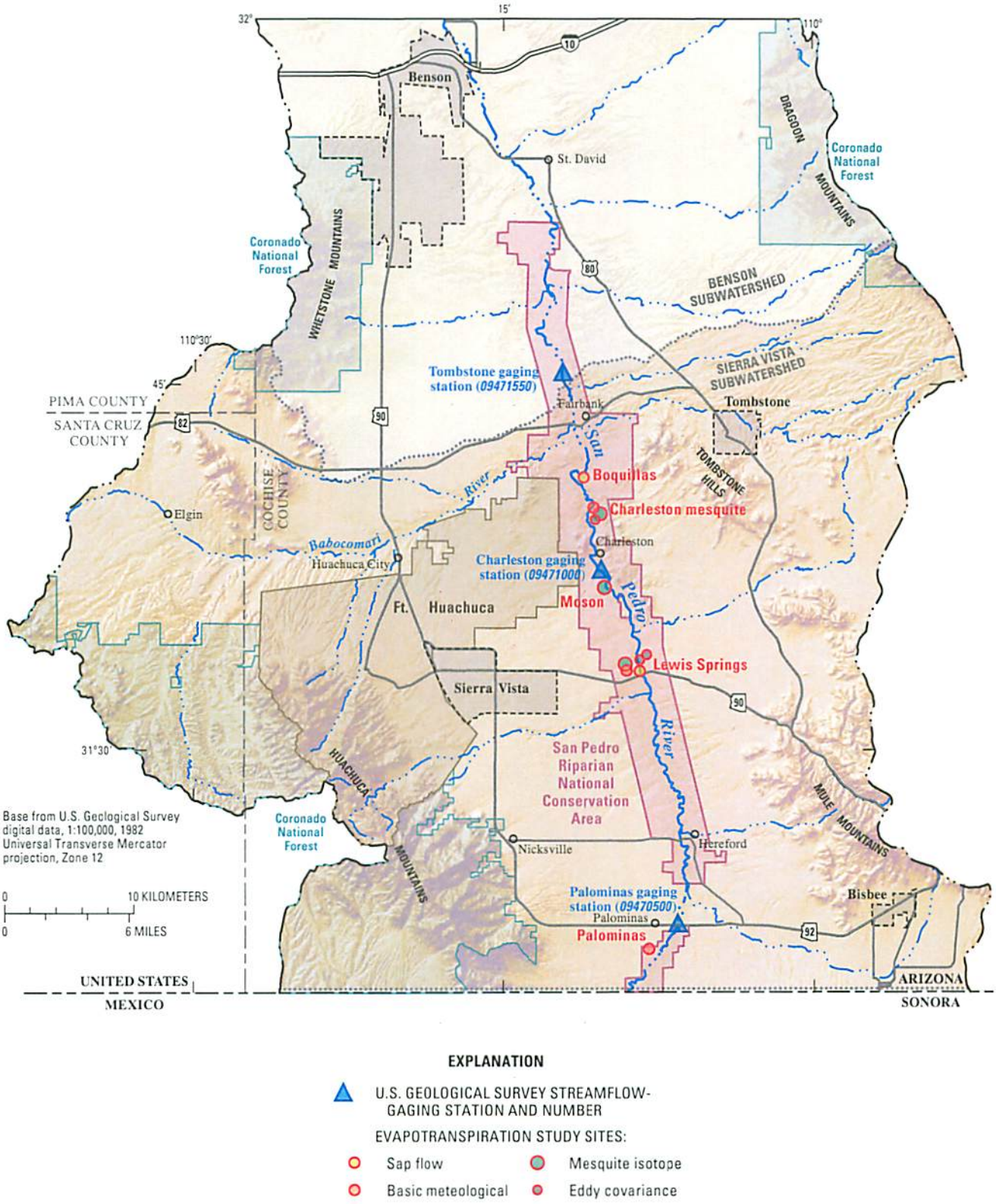


Figure 43. Location of study area showing the evapotranspiration study sites in the San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

A three-dimensional sonic anemometer and an open-path infrared gas analyzer (IRGA) mounted at the top of a 14-m-tall scaffolding tower measured the following: (1) components of the wind-velocity vector, (2) the sonic temperature, and (3) the densities of water vapor and carbon dioxide. These variables were sampled at 10 Hz by a datalogger. The datalogger also calculated the 30-minute covariances among the measured variables using block Reynolds averaging. Surface fluxes were later calculated off-line, after performing a two-dimensional coordinate rotation and accounting for density fluctuations (Webb and others, 1980). The sonic temperature was used to calculate sensible heat flux using the method suggested by Paw U and others (2000) that accounts for an otherwise missing energy-balance term associated with the expansion of air during evaporation under constant pressure. Fluxes measured when the wind direction was within 20° of directly behind the anemometer (about 6 percent of the data) were ignored owing to possible interference from the anemometer support and the IRGA mounted behind the anemometer.

Basic meteorological measurements were made with a wind-vane anemometer and a temperature/relative humidity probe at a height of 13.5 m, and above-canopy net radiation was measured at a height of 9 m by using a four-component radiometer attached to a horizontal boom extending 4 m from the tower. Ground heat flux was measured with eight soil heat plates installed 0.05 m below ground level. Measurements of the rate of change of soil temperature above the heat flux plates (at 0.02 and 0.04 m) allowed calculation of the soil heat flux at the surface using estimates of the specific heat of the 0.05-m-thick soil layer obtained with a thermal properties sensor.

Soil moisture was measured with 12 water-content reflectometers installed in vertical profiles at depths of 0.05, 0.10, 0.20, 0.30, 0.50, 0.70, and 1.0 m. Two probes were installed at each of the five upper depths, and the reported data for these depths are an average of the data from the two probes. A network of four piezometers was installed to measure fluctuations in the water table. These piezometers were installed in addition to the near-stream piezometers discussed in chapters A and B. Measurements of water-table elevation were taken manually until the installation of pressure transducers in late June 2001, and periodically afterward to confirm accuracy of the transducers. A tipping-bucket rain gage measured precipitation at the top of the tower. Data from all the sensors were recorded on dataloggers, which were downloaded every 7–10 days onto a personal laptop computer.

Studies using eddy-covariance instrumentation commonly use the standard of energy balance closure to evaluate the accuracy and efficacy of their measurements (Wilson and others, 2002). Neglecting the heat stored in the biomass and the air below the sensors, the one-dimensional energy balance for the mesquite woodland can be written as:

$$R_n - G + \lambda E + H, \qquad (3)$$

where (all units are W/m^2)

R_n = the net radiation,
G = the soil heat flux,
λE = the latent heat flux, (evapotranspiration multiplied by the latent heat of condensation), and
H = the sensible heat fluxes.

The results of a least squares regression of $(\lambda E+H) = R_n$ Slope $(R_n\text{-}G)$+Intercept for 30-minute fluxes and for daily total fluxes when data were available for more than 24 half-hour periods in the day provide a measure of how well the energy balance was closed in the observations (table 39). The ratio of the quantities in equations indicates that closure was moderate in this study; approximately 7 to 20 percent of the available energy was unaccounted for at the half-hourly time scale from year to year. Although not ideal, this result is consistent with numerous other studies made using eddy-covariance instruments (Wilson and others, 2002). Using daily average fluxes improves the slopes of the regressions, suggesting that there was a daily cycle in the (unmeasured) energy stored in the air and, particularly, the biomass below the sensors (Blanken and others, 1997; Gu and others, 1999) that equaled approximately 5 to 10 percent of the available energy.

One of the goals of this study was to quantify the magnitude and variability of the seasonal water use of the mesquite woodland. It was necessary to recognize the shortcomings in energy-balance closure when doing this, especially because the degree of closure was significantly different between the years that were compared. This study followed the advice of Twine and others (2000), who suggested that forcing closure was justified when available energy was known and errors in its measurement modest. Consequently, latent and sensible heat fluxes were scaled to force daily closure while conserving the measured Bowen ratio ($H/\lambda E$). Closing the daily energy balance, rather than the half-hour balance, was preferred because energy storage between the land surface and the eddy-covariance sensors was unmeasured and likely significant on a 30-minute basis but not on a daily basis.

In the following analysis, daily average ET values were calculated by first filling the gaps in the data that were caused by sensor malfunctions or bad measurements. Linear interpolation was used to fill short (0.5–3 hour) periods when data were missing. For times when more than 25 percent of the data were missing on an individual day, the daily total was estimated as being the average daily water use for the 3 days before and the 3 days after the day with missing records.

Table 39. Ordinary linear regression coefficients for energy-balance closure and mean quantities of the energy-balance components in equation 3 (R_n-G=λE+ H) for the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[n, sample size; r^2, goodness of fit; R_n, net radiation in watts per square meter; G, soil heat flux in watts per square meter; λE, latent heat flux in watts per square meter; H, sensible heat flux in watts per square meter; 30-minute ground-water levels were measured in a piezometer at the site.]

Year	n	Slope	Intercept	r^2	[1] R_n-G	[1] λE+H	[1] λE+H/R_n-G
	30-minute values						
2001	9,294	0.78	10.6	0.93	130.3	111.4	0.85
2002	9,818	.73	11.2	.92	145.4	116.9	.80
2003	10,510	.84	16.0	.93	161.5	150.9	.93
	Daily means[2]						
2001	225	0.87	-1.3	0.92			
2002	227	.80	1.0	.91			
2003	231	.99	-8.1	.90			

[1]Mean quantities computed only for 30-minute periods when all terms (R_n, G, λE, and H) were available.

[2]For days with at least 24 half-hourly values of all energy-balance components.

Evapotranspiration Partitioning

The partitioning of mesquite woodland ET into the component fluxes of mesquite transpiration, understory ET, soil evaporation, and understory transpiration was estimated for several days throughout the 2001 and 2002 growing seasons using micrometeorological techniques alone and a combination of micrometeorological and isotopic techniques. Using the results of the latter, daily partitioning amounts were extrapolated to determine growing season trends and totals.

Using Micrometeorological Techniques Alone

The first method used to separate total mesquite ecosystem ET into overstory transpiration and understory ET (ET derived from rainfall alone) involved a micrometeorological approach[1]. Two eddy-covariance systems were deployed 2 m above the ground to estimate the average understory flux sensed from the main tower. One site was located in a more closed patch near the tower, and the other was positioned in a more open patch farther away. The same method was used to measure ET at the understory eddy-covariance sites; the equipment was similar to that documented in the "Meteorological Instrumentation" section. Understory eddy-flux was measured during the periods June 13–15, July 27–August 1, and September 14–24, 2001; and June 13–19 and August 13–18, 2002, to capture ecosystem functioning before and after the summer monsoon rains and between 2 years having different antecedent conditions. Energy-balance closure was not forced as it was for the overstory eddy-covariance measurements, because accurate estimates of energy available in the understory were not feasible owing to a high degree of canopy heterogeneity. The average understory evaporation was computed by 0.7 E_{MC} + 0.3 E_{MO}, where E_{MC} and E_{MO} are the average daily ET values from the more closed and more open sites, respectively. This weighted average reflects the average canopy cover (about 70 percent) of the mesquite overstory; the source area of the tower measurement likely had a similar weighting of more closed and more open patches.

These estimates of mesquite transpiration were compared with those made by using White's (1932) method. The quantity of ground water withdrawn by mesquite transpiration during a 24-hour period can be determined by

$$T_{well} = S_y(24r \pm s), \tag{4}$$

where

T_{well} = the depth of water withdrawn (by tree transpiration)

S_y = the specific yield of the soil in which the daily fluctuation of the water table takes place,

r = hourly rate of rise of the water table from midnight to 4 a.m., and

s = the net fall or rise of the water table during the 24-hour period.

Using Isotopic and Micrometeorological Techniques

The second method to estimate water-use partitioning used the stable isotopes of water as a tracer of ET sources. By using this approach, the goals were to (1) develop methods

[1]See Scott and others, 2003, for detailed methods and the 2001 results of the study.

to partition ET into mesquite transpiration, understory transpiration, and soil evaporation using stable isotopes, and (2) determine the seasonal variation and totals of these ET sources. This approach will help to constrain estimates of ground-water use at the ecosystem scale for extrapolation to the riparian corridor.

The fraction of the ET flux corresponding to both understory and overstory transpiration (*FT*) was determined using an isotopic mass balance approach:

$$FT = (\delta_{ET} - \delta_E)/(\delta_T - \delta_E), \qquad (5)$$

where

δ_T = the isotopic value of water transpired by vegetation (from samples of stem xylem water),

δ_E = a modeled value for the isotopic value of water undergoing evaporation from soil (from soil samples), and

δ_{ET} = the isotopic value of water vapor collected within the vegetation boundary layer (Wang and Yakir, 2000).

Errors from this estimate were calculated by using the methods of Phillips and Gregg (2001). This approach was combined with the eddy-covariance measurements to obtain the component fluxes. A detailed description of the methods employed is described in Yepez and others (2003). In this chapter, estimates based only on the oxygen isotope ($\delta^{18}O$) variation were included.

ET partitioning was calculated by using stable-isotope techniques from data collected on September 22, 2001, and June 16, August 14, September 1 and 14, and October 9, 2002. In order to estimate the seasonal trend and totals for these component fluxes for 2001, 2002, and 2003, the following extrapolations were performed:

1. ***Soil evaporation***
   The conductance of the soil surface to evaporation is high when the soil moisture content at the surface is above a certain threshold value. Below this threshold soil-moisture value, conductance to evaporation is generally low. After rainfall, when the soil surface is wet during the first phase of soil drying, the evaporation rate is a function of available energy. During the second drying phase, soil evaporation is limited by available moisture and soil physical properties. A stable source analysis of ET source water was used to assign a threshold surface soil-moisture value of 0.1 cm^3/cm^3. Above this threshold, the evaporation rate was assumed to be 43 percent of the daily Penman potential evaporation (Shuttleworth, 1993). This value was calculated from isotope-partitioned estimates of midday average soil evaporation (mean = 6.3 mm/d) of two wet days relative to the average midday potential ET during the same period (mean =14.4 mm/d). For days on which soil moisture was below 0.1 cm^3/cm^3, evaporation estimated from stable isotopes was 3 percent of potential ET (again estimated from isotope partitioning of ET).

2. ***Understory Plant Transpiration***
   In order to account for the understory plant transpiration fraction of total ecosystem ET, the understory and overstory measurements of ET with the eddy-covariance technique and independent isotope-based estimates were used (Yepez and others, 2003). During the peak of the growing season when the understory vegetation was fully developed, understory transpiration contributed 14 percent of the potential ET. Late in the growing season when the vegetation started to senesce, understory transpiration was 8 percent of total potential ET.

3. ***Mesquite Transpiration***
   Weekly average tree transpiration was calculated by subtracting the weekly estimated understory transpiration and soil evaporation from the weekly averaged ET flux.

Mesquite Water Sources

Natural variation in the abundance of the stable isotopes of hydrogen and oxygen in water were used to partition mesquite transpiration sources into surface soil water (top 1 m of soil), deep vadose-zone water (unsaturated zone moisture below 1 m), and ground water. Efforts were focused on three mesquite sites in the SPRNCA, but the most intensive measurements were made at the Charleston mesquite site. Measurements were made during the growing seasons of 2000, 2001, and 2002.

Site Descriptions

Mesquite woodlands at three sites (Lewis Springs, Moson, and Charleston mesquite) were selected for study of water source in the SPRNCA (fig. 43). These sites spanned a water-table depth range of 6 to 10 m. Accessibility and the local availability of wells for stable-isotope sampling were important factors in site selection. The soil at the Lewis Springs site was a clay loam in the top 0.5 m that was underlain by sandy clay loam and loam layers. Soil at the Moson site was a loamy sand in the top 0.50 m that was underlain by sandy loam to clay loam soils with clay content ranging from 12 to 30 percent. Soil at the Charleston site was a sandy loam in the top 1 m that was underlain by sandy loam interspersed with clay and silt-clay layers.

Water Sampling Protocol for Isotopes

In 2000, stem and soil samples were collected monthly from June through September (premonsoon, early-monsoon, late-monsoon, and post-monsoon). During each collection period 1-2 year old stems from the canopy were taken from 10 trees to make one composite sample. Soil samples were collected from the top 0.5 m of the soil profile at 0.1-m increments. Each soil sample was a composite of three different cores that were combined by volume at each depth to make one sample per depth. Stem and soil samples were placed in glass vials and the vials were immediately stored in an ice chest to minimize evaporation. Ground-water samples were collected at all sites in August.

In 2001 and 2002, three trees from the Lewis Springs site and three trees from the Moson site were selected randomly from a cohort of trees in the area that were at least 6 m tall. The same trees were sampled for all collection periods. Seven trees, 3 to 15 m in height, were selected at the Charleston mesquite site. All were single-stemmed, except the two smallest trees. Soil cores were collected from underneath the canopy and in a gap near the canopy of three trees at each site. The top 0.5 m of soil was collected in 0.1-m increments. Thirty soil samples were collected at each of the three sites at every sampling period. Ground-water samples were collected from each of the sites during each collection period.

The protocol for stem and soil collection was slightly different in 2002. Each of three soil cores collected on two sample dates (June 16 and August 14) consisted of seven samples at depths of 0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.75, and 1 m. Ground water was sampled at each site during each collection period. Stems were collected from 10 trees at the Charleston mesquite site. At the Lewis Springs and Moson sites, the same three trees sampled in the summer of 2001 were sampled in 2002.

Deep soil cores were taken at the Lewis Springs, Moson, and Charleston mesquite sites in April 2001 using a truck-mounted percussion-driven soil corer. These cores sampled the entire soil profile from the surface through the capillary fringe and spanned as much as 10 m in depth. Deep soil cores were collected also in July 2002 using a hand auger at the Lewis Springs and Moson sites. Soil samples were collected in 0.3- to 0.5-m increments.

Isotope Analysis

Water was extracted from soil and plant samples using cryogenic vacuum distillation. Water samples were then analyzed for δ^2H and $\delta^{18}O$ on an isotope-ratio mass spectrometer at the Department of Geosciences Stable Isotope Facility at the UA. δ^2H and $\delta^{18}O$ from the mesquite stems, ground water, deep vadose zone, and the top 0.5–1.0 m of soil were used in the source partitioning models. A two-ended linear mixing model (Phillips and Gregg, 2001) was used for all the 2000 data and the 2001–2002 data from the Lewis Springs and Moson sites. A three-ended mixing model was used for the data collected at the Charleston mesquite site in 2001 and 2002. The three-ended mixing model was not used for the Lewis Springs and Moson sites because δ^2H values from the deep vadose zone and ground water were too similar to distinguish. The soil layer matric potential was used to weight isotopic values for the deep vadose zone and the shallow vadose zone. Data from any soil layer having a matric potential below -5 mPa were discarded because the water was assumed to be unavailable to mesquite. The fraction of ET drawn from each zone (that is, shallow or deep vadose zone at the Moson and Lewis Springs sites, and shallow vadose, deep vadose, or capillary fringe zone at the Charleston mesquite site) was computed for each set of environmental samples.

Mesquite Shrubland and Sacaton Grassland Evapotranspiration

ET was measured during 2002 and 2003 using eddy covariance at two locations near the Lewis Springs biohydrology study site in order to quantify the ground-water use of a sacaton grassland and a mesquite shrubland. The grassland was studied to determine if its water use could be a significant component of the SPRNCA water use, and the shrubland was studied to determine if mesquite water use at a site that has smaller and less dense tree cover was similar to that of a mesquite woodland like that at the Charleston mesquite site.

Site Description

Mesquite-shrubland and sacaton-grassland study sites were established in mid-2002 near the Lewis Springs biohydrology study site. The Lewis Springs site (fig. 43) is about 12 km east of Sierra Vista, Arizona, at an elevation of about 1,230 m. The instrument tower at the Lewis Springs sacaton study location lies in the center of a low alluvial terrace bordering the San Pedro River. The tower is surrounded by a lush growth of sacaton grass roughly 200 m to the east and west and 800–1,000 m to the north and south. The canopy height was about 1 m, and average canopy cover was about 65 percent. The mean depth to ground water in a collocated piezometer was about 2.6 m. The measured PAI averaged (n=40) about 1.0 prior to greenup, about 1.5 during the premonsoon season, and about 2.5 during and after the monsoon season. At the Lewis Springs site, the instrument tower for measuring mesquite shrubland ET lies immediately to the northeast of the sacaton grassland instrument tower. The mesquite shrubland sits on an upper alluvial terrace and surrounds the tower by roughly 500 m to the east and west, and by 500 m to the north and south. The mesquite canopy cover was estimated to be 55 percent, and the shrubland had an average tree height of 3–4 m. The depth to ground water was about 7 m, and the overstory PAI ranged from about 0.9 (prior to leaf flush) to 1.2 (during the monsoon).

Meteorological Instrumentation

The basic meteorological, soil-moisture, and eddy-covariance instrumentation and methods used at the Lewis Springs sacaton grassland and mesquite shrubland sites mirror those used at the Charleston mesquite site. The heights of the eddy-covariance instrumentation were 2.8 m at the sacaton grassland site and 6.5 m at the mesquite shrubland site. By using the rationale previously described, both latent and sensible heat fluxes were forced to close the daily energy balance (table 40) while conserving the measured Bowen ratio.

Both instrument towers lie in areas with more heterogeneous vegetation density and less extensive vegetation patches than at the Charleston mesquite site. This potentially complicates the interpretation of the measured fluxes. For this report, fluxes were not filtered with respect to wind speed and direction. Such filtering might have been needed to ensure that the measured fluxes were indeed representative of the vegetation type of interest. Thus, the measurements at these sites were, however, assumed to be representative of the ecosystems of interest. Likewise, for all three eddy-covariance sites, the issue regarding how to interpret the lack of closure has not been resolved within the scientific community. For this study, the guidance of Twine and others (2000; see the "Meteorological Instrumentation" section, "Mesquite Woodland ET" subsection) was followed, and closure was forced on the daily energy balance, thereby increasing the measured daily ET by as much as 23 percent. By doing this, it is implicitly assumed that the measured available energy was more accurate than the measured turbulent heat fluxes; however, this may or may not have been the case.

Cottonwood Transpiration

Along the San Pedro River, cottonwood trees generally grow in narrow, linear bands parallel to the stream channel, so micrometeorological techniques cannot be used owing to inadequate fetch. Instead, the velocity of rising sap was monitored in individual trees to measure the total water volume carried to the canopy and transpired.

Site Descriptions

The study locations used for cottonwood sap-flow measurements were at the Boquillas and Lewis Springs biohydrology sites (fig. 43). At each site, a cluster of trees with a distinct and clearly identifiable canopy area was selected, and within each cluster four cottonwood trees were monitored. The Boquillas location represents a cluster of trees that is on an intermittent reach of the river where the average depth to ground water is 3.3 m; the Lewis Springs location represents a cluster of trees on a perennial reach where the average depth to ground water is 1.6 m.

Site Instrumentation

Sap flow of each tree was measured using thermal dissipation probes (TDP-30 and TDP-80). Thermocouple needles 1.2 and 1.65 mm in diameter (TDP-30 and TDP-80, respectively) were installed as a vertically aligned pair 4 cm apart within the sapwood of each tree. The system measures the temperature difference between two needles inserted radially in the xylem, one constantly heated and the other unheated. The heating power is adjusted to 0.15 to 0.2 W for the TDP-30 and 0.4 to 0.5 W for the TDP-80 to achieve a maximum temperature difference of 8–10°C under conditions of zero flow. The temperature rise at the upper needle is inversely proportional to the velocity of sap flow, which carries away the heat. The TDP-30 probe monitors a single radial interval at 15 mm into the xylem, and the TDP-80 probe monitors two radial intervals at 15 and 70 mm. Sets of these Granier-type probes (Granier, 1987) were implanted on the north and south sides of each tree at 1.75 m above the ground.

Table 40. Ordinary linear regression coefficients for energy balance closure and mean quantities of the energy-balance components in equation 3 (R_n-G=λE+H) at the sacaton grassland and mesquite shrubland locations at the Lewis Springs site in 2003, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[n, sample size; r^2, goodness of fit; R_n, net radiation in watts per square meter; G, soil heat flux in watts per square meter; λE, latent heat flux in watts per square meter; H, sensible heat flux in watts per square meter; 30-minute ground-water levels were measured in a piezometer at the site.]

Site	n	Slope	Intercept	r^2	[1]R_n-G	[1]λE+H	[1]λE+H/R_n-G
	30-minute values						
Lewis Springs sacaton	12,369	0.95	-27.7	0.95	162.2	125.1	0.77
Lewis Springs mesquite	12,409	.82	-.9	.90	156.3	126.9	.81
	Daily means[2]						
Lewis Springs sacaton	276	0.77	-2.5	0.80			
Lewis Springs mesquite	278	.80	2.5	.85			

[1]Mean quantities computed only for 30-minute periods when all terms (R_n, G, λE, H) were available.

[2]For days with at least 24 half-hourly values of all energy balance components.

Sap flow was measured simultaneously on four trees per site from April to November 2003. Plastic putty was installed around the probe's heated and non-heated needles for water protection, and foam quarter-spheres were tightly secured on both sides of the probes to protect the wires from bending stress and to provide thermal insulation to the needles. Reflective bubble wrap was installed around the tree for additional insulation.

The Granier calibration method (Granier, 1985, 1987), valid for various tree species (cut-stem sections), was used to calculate a nondimensional variable (K) as

$$K = \frac{(\partial T_m - \partial T)}{\partial T}, \qquad (6)$$

where

∂T = the measured difference in temperature (°C) between the heated needle, referenced to the lower non-heated needle, and

∂T_m = the maximum temperature difference during each 24-hour period between the heated needle and the non-heated needle.

The maximum temperature difference typically occurred early in the morning or late at night, and it generally varied each day. A negligible or zero sap flow when ∂T was at a maximum was assumed. Average sap-flux density (V, cm³/cm²s) is calculated (Granier, 1987) as

$$V = (0.0119)K^{1.231}, \qquad (7)$$

Sap-flux density is then converted to a volumetric sap flow (J_s, cm³/h) as

$$J_o = (A_s)(V)(3{,}600), \qquad (8)$$

where

A_s = the sapwood horizontal area (cm²) of the instrumented trees, and 3,600 is the number of seconds in an hour.

Other environmental variables were measured in addition to the sap flow. LAI was measured in October 2003 using a plant canopy analyzer. LAI readings were taken from four cardinal directions around the base of each tree within the cluster. Meteorological data were measured at nearby meteorological towers at the Charleston mesquite and Lewis Springs sites. Air temperature, relative humidity, solar radiation, wind speed, air pressure, and precipitation were measured at these locations. Depth to ground water at the Boquillas site was measured manually on a weekly basis at a nearby piezometer. The USGS monitored ground-water levels with pressure transducers in nearby piezometers at the Lewis Springs site.

Scaling

Cottonwood-stand transpiration (T, mm/d) was calculated on the basis of information about individual tree sap flow, total sapwood area, and canopy area of the cluster (Wullschleger and others, 1998). Sapwood area (table 41) was determined from increment cores taken as close as possible to the probe insertions on each side of the tree. Sapwood was identified from heartwood by color change from light to dark. A sapwood area-to-diameter relation was used to estimate the total sapwood area of all the trees in the cluster (Schaeffer and others, 2000). The average tree diameter at breast height (at 1.5 m) of all the trees in the clusters was 49 cm at the Lewis Springs site and 61 cm at the Boquillas site.

For trees instrumented with TDP-80 probes, sap-flow rate per tree was scaled according to the sapwood area that covers the position of the two thermocouples per probe. The total half-hourly water use for the two thermocouple positions were summed and then divided by the total sapwood area of the tree to get J_s, the average sap-flow rate per unit sapwood area (g/cm²h), for each instrumented tree. For the trees instrumented with the TDP-30 probes, there was only one heater/thermocouple depth, and the velocity measured at this depth was assumed constant throughout the entire depth of the sapwood. Values for J_s from the north and south side of each tree were averaged to get $\hat{J}_s$. $\hat{J}_s$ from each tree was then averaged for all the instrumented trees in the cluster to get, $\bar{J}_s$, which was then multiplied with the total sapwood area of all the trees in the cluster to get the total water use (kg/d). Total water use of the entire cottonwood stand was divided by the canopy area (m²) to determine total water loss or transpiration of the entire stand, T (kg/m²d or mm/d). The projected canopy area of the tree clusters was estimated digitally by using aerial photographs.

Table 41. Structural characteristics of cottonwood clusters at the Lewis Springs and Boquillas sites, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[m², square meters; cm², square centimeters; A_L, total cluster canopy area; A_S, cluster sapwood area]

Site	Number of stems	Canopy area[1] (m²)	Sapwood area (cm²)	[2]A_L:A_S (m²/cm²)
Lewis Springs	9	421	7,175	0.31 ± 0.04
Boquillas	10	1,037	12,232	0.21 ± 0.02

[1]Canopy area refers to the planar area of the canopy as determined from aerial photographs.

[2]Mean +/- standard error of the canopy area/sapwood area ratio for measured trees within the cluster.

Seepwillow Transpiration and Open-Water Evaporation

Seepwillow transpiration and open-water evaporation were measured at the Lewis Springs study site (fig. 43). At this site, the river is divided into primary and secondary channels. The secondary channel conveys flow only when stream stage is elevated above base flow. Along the primary and secondary channels of the river, cottonwood and Goodding willow (*Salix gooddingii*) are the main overstory species and seepwillow is the dominant understory species. The broad flood plain between the primary and secondary channels is covered primarily with Johnson grass (*Sorghum halepense*), sacaton grass, and has sparse patches of cottonwood trees and seepwillow shrubs. During the 2002 and 2003 measurement periods, several flood events inundated the site. The depth to ground water in a nearby piezometer ranged from 1 to 1.6 m during the measurement periods.

Sapflow Study

Two patches of seepwillow shrubs were selected for this study. One patch was more sheltered by cottonwood canopy, and the other adjacent patch was in a more open area with no overstory vegetation directly overhead. Transpiration was estimated by using the stem heat-balance sap-flow technique (Sakuratani, 1981), which works better for the small stems of shrubs than the technique used for cottonwood. In this approach, stem sap flow is determined by application of a constant external heat source to the shrub stem while measuring the axial and radial heat losses from the stem. The amount of heat lost caused by convection, and transport of heat with the movement of sap, can be calculated.

The sap-flow sensor consists of three basic components (fig. 44): (1) heater wires wrapped around a section of the plant stem; (2) three differentially wired thermocouples, with the reference thermocouple at the center of the heat source, and the remaining thermocouples 15 mm upstream and downstream from the heat source to measure axial heat loss; and (3) a thermopile wrapped around the stem at the heat source to measure radial heat loss. Sensors were insulated with two layers of foam insulation material and one layer of insulating foam with reflective backing (not shown in figure 44) to reduce any influence of thermal perturbations from the surrounding climate conditions. All sap-flow sensors were monitored with a datalogger powered by a 12-volt battery. Data were logged every 30 minutes for all sensors and were collected every 7–10 days by using a laptop personal computer.

The following equations are applied to the raw data to separate the heat inputs and calculate stem sap flow:

$$Q_H = Q_f + Q_{up} + Q_{dn} + Q_{rad}, \qquad (9)$$

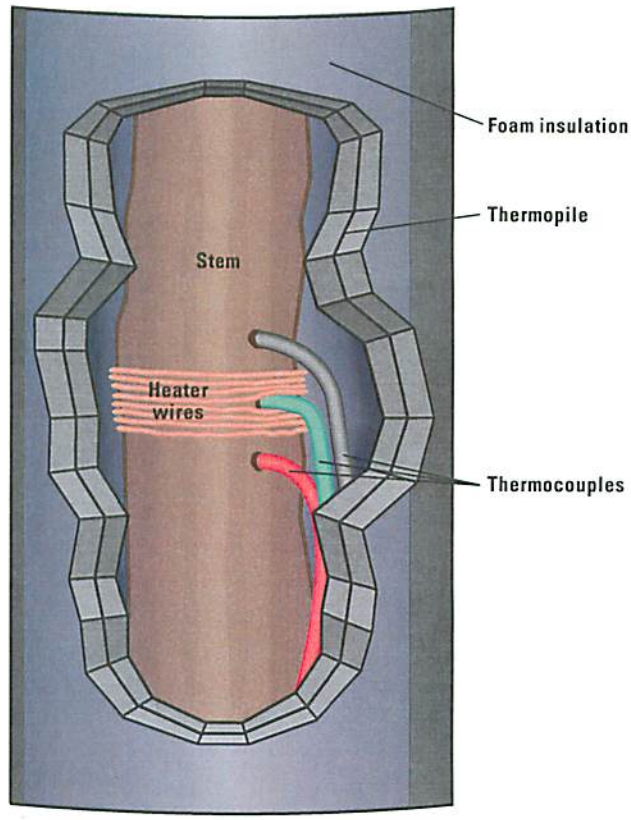


Figure 44. Sap-flow sensor unit used for the heat balance method, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

where

Q_H = heat input,

Q_f = the convective heat carried by sap flow,

Q_{up} and Q_{dn} = the heat conducted upstream and downstream through the plant stem, and

Q_{rad} = radial heat loss away from the stem and heat source. Units for all these components are J/s.

The heat input is a function of the electrical characteristics of the heater. The radial and conductive losses can be calculated from the relevant temperature differences, thermal conductivities, and geometry (Sakuratani, 1981).

Convective heat carried by sap flow (Q_f) can then be determined by rearranging the elements of equation 9:

$$Q_f = Q_H - Q_{up} - Q_{dn} - Q_{rad}, \qquad (10)$$

The convective heat loss through sap flow (Q_f) is then converted into an equivalent mass flow (S, g/h):

$$S = 3{,}600 Q_f / 4.19 \delta T_{up-dn}, \qquad (11)$$

where 4.19 is the specific heat of liquid water (J/g °C), 3,600 is the number of seconds in 1 hour, and δT_{up-dn} refers to the difference in temperature between upstream and downstream thermocouples.

Eight stems were monitored in each patch. The diameters of all the shrub stems within each patch were measured, and stem areas were calculated. The total sap flow for each patch was calculated by taking the average sap flow of the instrumented stems divided by the cross-sectional area of the stems, and then multiplying this average by the total stem area of the patch. Finally, the transpiration rate was computed by dividing the total sap flow by the area of the seepwillow patch.

Pan-Evaporation Study

An open-water evaporation study was done to estimate the amount of evaporation that occurs directly from the river. Twelve 8-inch square aluminum pans and 12 standard rain gages were used in the open-water evaporation study. Both pans and gages were placed along the river edge, within primary and secondary channels and within the flood plain area in order to better quantify the variability and magnitude of evaporation. Each pan was filled with water and set into the soil so that the rim was level with the ground surface. Both the placement and the size of the pans were chosen so as to minimize "oasis-effects" that can occur with pan-evaporation studies. This study was done during a 6-day period (June 25 to July 2, 2003) during the premonsoon season. At the onset of the study, each pan was filled with 700 mL of water, forming a pool about 17 mm deep. The volume of water in each pan was measured every 24 hours by using a graduated cylinder. The pan was then refilled to 700 mL. Rain gages were monitored each day of the measurement period. The volume of water evaporated from each pan was divided by the surface area of the pan and the amount of time elapsed between measurements to compute an evaporation rate. The mean evaporation rate was compared to a standardized reference evaporation, ET_o, which was computed using the Arizona Meteorological Network (AZMET) standard (Brown, 1989; http://ag.arizona.edu/azmet/et2.htm) and meteorological data from the nearby Lewis Springs meteorological site (appendix 8).

Determining Total SPRNCA Water Use

Goodrich, Scott, and others (2000) calculated the most recent estimates of riparian ground-water use along the San Pedro River using estimates of vegetation area derived from a 1997 pixel-based vegetation classification (hereinafter referred to as VEG97). In the VEG97 map, each 3 x 3-m pixel is classified as a particular vegetation cover. From aerial photographs taken in 2000 and field data collected in 2001, the U.S. Army Corps of Engineers (2001) produced a new polygon-based, geographic information system (GIS) vegetation cover map (hereafter referred to as VEG00) for which continuous stands of vegetation were delineated and given various attributes, such as vegetation alliance, polygon area, total area of vegetation cover, and area of dominant vegetation cover. It includes 33 different vegetation communities, open water, and urban lands (see fig. 45 as an example).

Because of several differences between the two maps, various GIS manipulations were done so that the VEG00 map could be used for water-use analysis. The extent of the VEG00 map matched the boundaries of the SPRNCA, whereas the VEG97 map was created for the San Pedro River riparian corridor from Palominas to north of St. David (see Goodrich, Scott, and others, 2000). The VEG00 map was first clipped to the same extent as the VEG97 map. Since the VEG97 map did not cover the entire SPRNCA, the riparian corridor outline for the VEG00 map was extended with the use of a 1 x 1-m pixel digital elevation model (unpublished data) derived from Light Detection and Ranging (LiDAR) data collected in 2003, aerial photographs, and the vegetation classes in the map itself.

An additional vegetation analysis was conducted to delineate the riparian area that was within 3 m of the river bottom (thalweg) or stage, whichever was highest. Standard ArcInfo GIS functions were used with the 1-m digital elevation model to determine the minimum elevation of the river for each east-west row of grid cells along the entire river length within the SPRNCA. This information was then used to identify all grid cells within 3 m above the river bottom (or stages). The river trended east-west and intersected a row more than once. In those instances manual interpretation was used to identify cells within the 3 m of the river bottom or stage elevation.

The conversion from a pixel-based to a polygon-based coverage made the task of computing total vegetation areas for the relevant land-cover types more difficult. For the VEG00 map, both the polygon area and the percentage of area covered by the vegetation of interest were needed to estimate the total area of ground-water-using vegetation. The VEG00 map has five ranges for basic classification of the vegetation percent cover: 1–10, 11–25, 26–60, 61–80, and 81–100 percent. These ranges are quite coarse for calculating the total area covered by a specific vegetation type, and the use of these ranges adds uncertainty to the new estimates of vegetation ground-water use. The VEG00 map, however, provides the estimated vegetation cover to the nearest 5 percent for the mesquite or cottonwood-willow polygons, classified as woodland or forest. These woodland or forest polygons are defined as patches dominated by mesquite or cottonwood-willow polygons with greater than 60 percent cover.

Unfortunately, there are still many polygons not classified as woodland or forest that contain vegetation that uses ground water (for example, mesquite areas with less than 60 percent cover or sacaton grasslands). This uncertainty was incorporated into the new SPRNCA water-use estimates by computing a range (minimum to maximum amount) of area for each functional vegetation group. Then, the total vegetation area was calculated by summing up, over all polygons of a certain plant functional group, the product of the polygon area and the minimum, median, and maximum percent cover. If the more accurate cover data (to the nearest 5 percent) were available, then they were used instead.

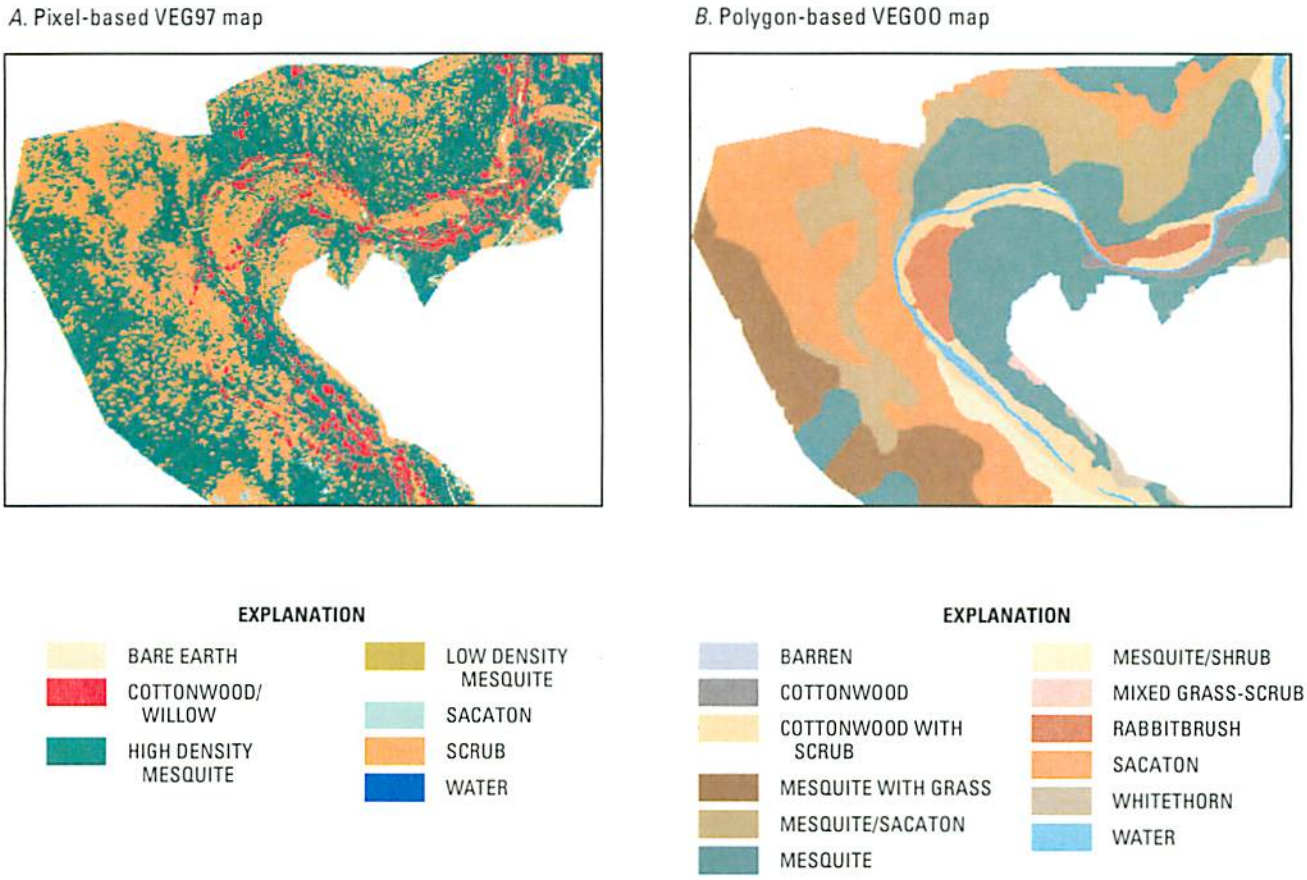


Figure 45. The vegetation distribution for an example reach of the San Pedro Riparian National Conservation Area near Boquillas, Upper San Pedro Basin, Arizona. *A*, Pixel-based VEG97 map; *B*, Polygon-based VEG00 map.

Ecosystem Water-Use Results

Mesquite Woodland

The USDA–ARS monitored ET fluxes at the Charleston mesquite site during the 2001, 2002 and 2003 growing seasons, along with precipitation, soil moisture, ground-water levels, and other variables. All three growing seasons were preceded by winters with little precipitation (fig. 46). The winter prior to the 2001 growing season was also quite dry, yet there was still a lot of carryover soil moisture from the large amount of rainfall in October 2000.

Mesquite Woodland Water Use

Continuous monitoring of the ground-water levels and the ecosystem ET indicated that the mesquites were using ground water. The spring 2002 greenup provides one of the many examples of evidence for this (fig. 47).

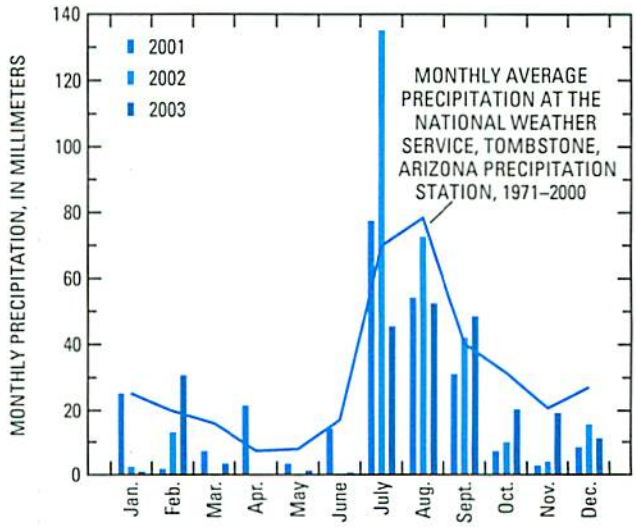


Figure 46. Total monthly precipitation during 2001–03 at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

Winter and spring of 2002 were dry; thus, surface soils were dry. Despite this drought, the trees leafed out and began to take up carbon dioxide [net ecosystem exchange of carbon dioxide (NEE)] and lose water vapor in mid-May (Scott and others, 2004). At the same time, ground-water levels began to drop and a regular pattern of diurnal ground-water fluctuation (ground water was closer to the surface in the early morning and farther from the surface at sundown) became established, providing clear evidence of a direct link between tree water use and ground-water fluctuations. This pattern of diurnal ground-water fluctuations caused by mesquite uptake continued throughout most of growing season, but the diurnal fluctuations ceased during brief monsoon periods when surface soils were wet (see next discussion). More information about the source of water for the trees is presented in the following sections.

Measured mid-canopy air temperature data indicates that the last freezes of spring occurred on May 6, 2001; May 22, 2002; and May 11, 2003. The first freezes of fall occurred on October 13, 2001; October 4, 2002; and October 27, 2003. These freeze events effectively constrained the mesquite growing season and, hence, much of vegetation water use in the riparian corridor. The mesquite trees leafed out in the spring around the time of the last spring freeze. Leaf-out was followed by a substantial increase in ET, beginning around mid-May of both years [day of year (DOY) 130–145; fig. 48]. Conversely, ET dropped quickly in the fall as the mesquite trees began to enter dormancy in late October (about DOY 290). The freeze intolerance of mesquite is consistent with a previous study of mesquite by Scott and others (2004). Temperatures in the riparian corridor were commonly quite different from those measured on the valley floor (appendix 8). Although maximum daytime temperatures were similar, minimum nightly temperatures generally were 5–10°C lower in the riparian corridor than on the valley floor, except in the more humid monsoon season when the difference was less. Because the water use of the mesquite trees (and likely other riparian tree species) was constrained to the frost-free period (typically about 150 days), models of riparian ET will require air-temperature data collected from within the riparian corridor, or at least estimates derived from a known relation between temperature in the riparian corridor and that measured elsewhere.

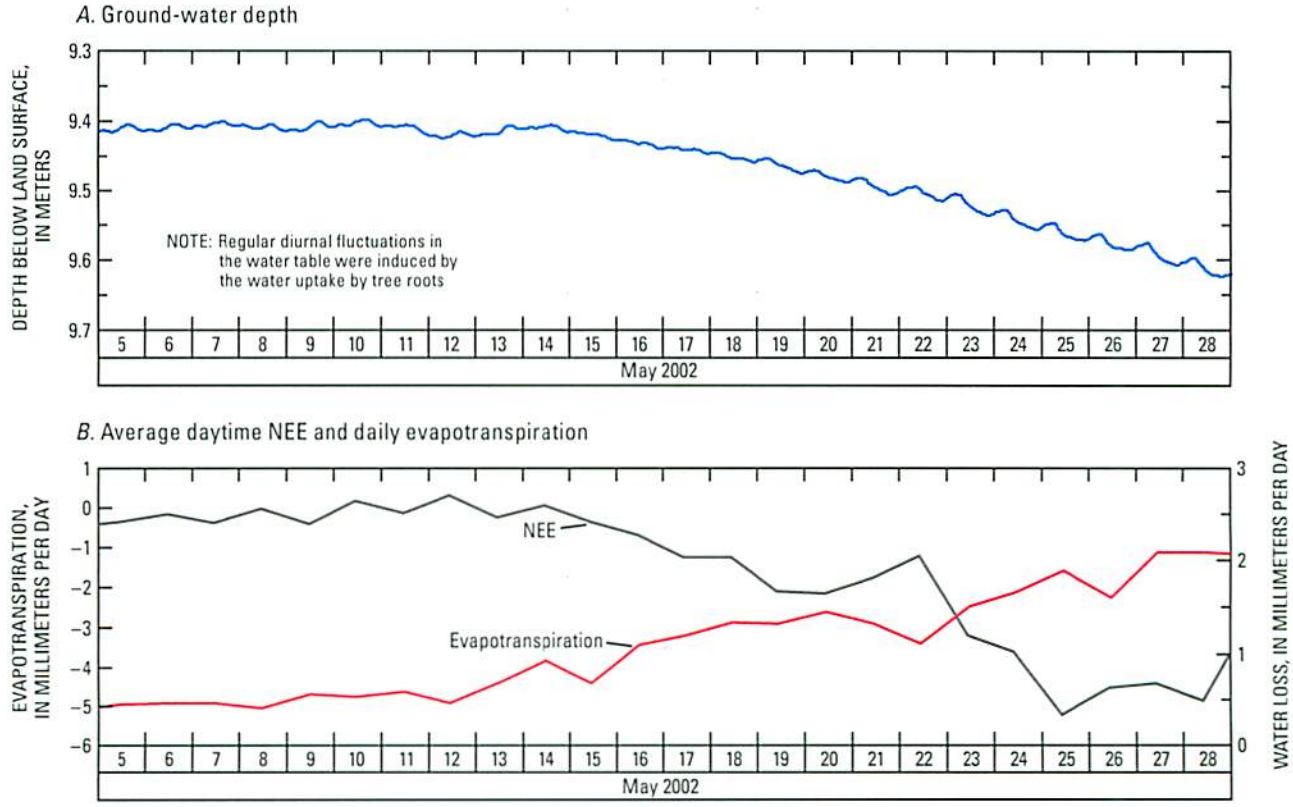
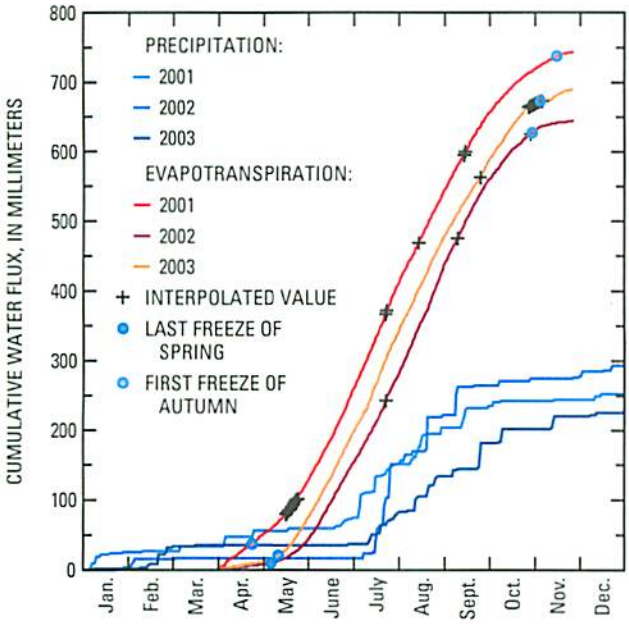


Figure 47. Data indicating ground-water use by mesquite at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona, May 2002. *A*, Ground-water depth below land surface; *B*, Average daytime net ecosystem exchange of carbon dioxide (NEE), and daily average evapotranspiration.



NOTE: Only evapotranspiration data from April 9 to October 28 of each year are shown, because 2001 data were limited to this time period

Figure 48. Cumulative fluxes of precipitation and evapotranspiration for 2001, 2002, and 2003 at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

In this semiarid environment, the availability of near-surface soil moisture for understory plants is closely linked with recent rainfall (fig. 49A). Not surprisingly, it takes longer for the near-surface soil profile to dry after winter rainfall owing to the lack of plant uptake and decreased evaporative demand. In 2001, the effect of precipitation was rarely seen at 50 cm depth, indicating that there was little deep infiltration during much of the year, and that most summer precipitation was either quickly evaporated or transpired. After the larger storms of the 2002 summer monsoon season, however, moisture moved farther down the soil profile, past 50 cm depth. Even then there was only a 2 percent increase in soil moisture at 100 cm depth (not shown on fig. 49). Infiltration in 2003 was similar to that in 2002 though the wetting of the near-surface soils was shallower owing to less intense monsoon rains. The entire root-zone profile was substantially wetter in the spring of 2001, probably because there were anomalous rains totaling 125 mm in October 2000. The origin of this soil moisture is not certain because soil-moisture probes were not installed until March 2001. Annual precipitation totals were 253 mm in 2001, 293 mm in 2002, and 232 mm in 2003, whereas the monsoon rainfall—the cumulative total between the mid-summer onset of precipitation and the end of September—was 177 mm in 2001, 248 mm in 2002, and 146 mm in 2003. All the study years had below-average precipitation, but the typical premonsoon "drought" was especially long and severe in 2002 (fig. 46 and chapter A).

The depth to ground water fluctuated in response both to local and more regional forcing (fig. 49B). Data collected in all years showed the influence of mesquite activity on ground-water depth. Depths increased and regular diurnal fluctuations began in mid-May in response to mesquite leaf flush; water-levels recovered and diurnal fluctuations ceased after mesquite became dormant (about late October). The diurnal fluctuations were more muted in 2003 probably because a layer of film that developed on the pressure transducer reduced its sensitivity. The summer monsoon (about July–September) had a complex influence on the water levels. During this time, it is likely that water levels in site piezometers responded both to large floods in the nearby river channel and to the mesquite supplementing water uptake with lateral surface roots when and where surface water and nutrients were available.

Although much of the variability of total ET can be attributed to different starting and ending times for the growing season, monsoon rainfall and antecedent soil moisture conditions also appeared to influence ecosystem water use. In 2001, ET was substantially higher before mesquite leaf-out than after leaf-out owing to understory ET (mainly sacaton transpiration) that was fueled by higher, soil moisture at a 30 cm depth (figs. 50 and 49) The premonsoon dry period was considerably shorter owing to an early arrival of monsoon rains. Because of dry winters prior to 2002 and 2003, ET was low prior to mesquite leaf-out (DOY 130). After mesquite leaf-out, there was a considerably faster increase in ET and higher premonsoon ET in 2003 relative to 2002. The trees in 2002 appeared to be more drought stressed or possibly damaged by a late frost, resulting in the lowest seasonal ET of the study—despite the fact that the trees had access to ground water and the near-surface soil moisture was nearly identical to that in 2003.

The more stressed condition of the trees in 2002 was probably a result of drier meteorological conditions (higher vapor-pressure deficits and temperatures, little winter and spring precipitation). Scott and others (2004) have shown that the trees at this site regulate their stomata in response to the high vapor-pressure deficits found during the premonsoon period; the stomata regulation results in decreased ET. Additionally, the stressed condition could have been caused by unknown consequences of the mesquite trees' hydraulic redistribution of previous rainfall. Hultine and others (2004) discovered that mesquite at this site have the ability to redistribute near-surface soil moisture to the deeper vadose zone throughout the entire year (fig. 51). Measured sap flow in a mesquite tap root was upward before the monsoon onset even at night, and this water was distributed outward from the tree through lateral, surface roots. The situation was reversed when the surface soil was moist, and water in the lateral roots moved toward the stem and then downward in the tap root towards the water table.

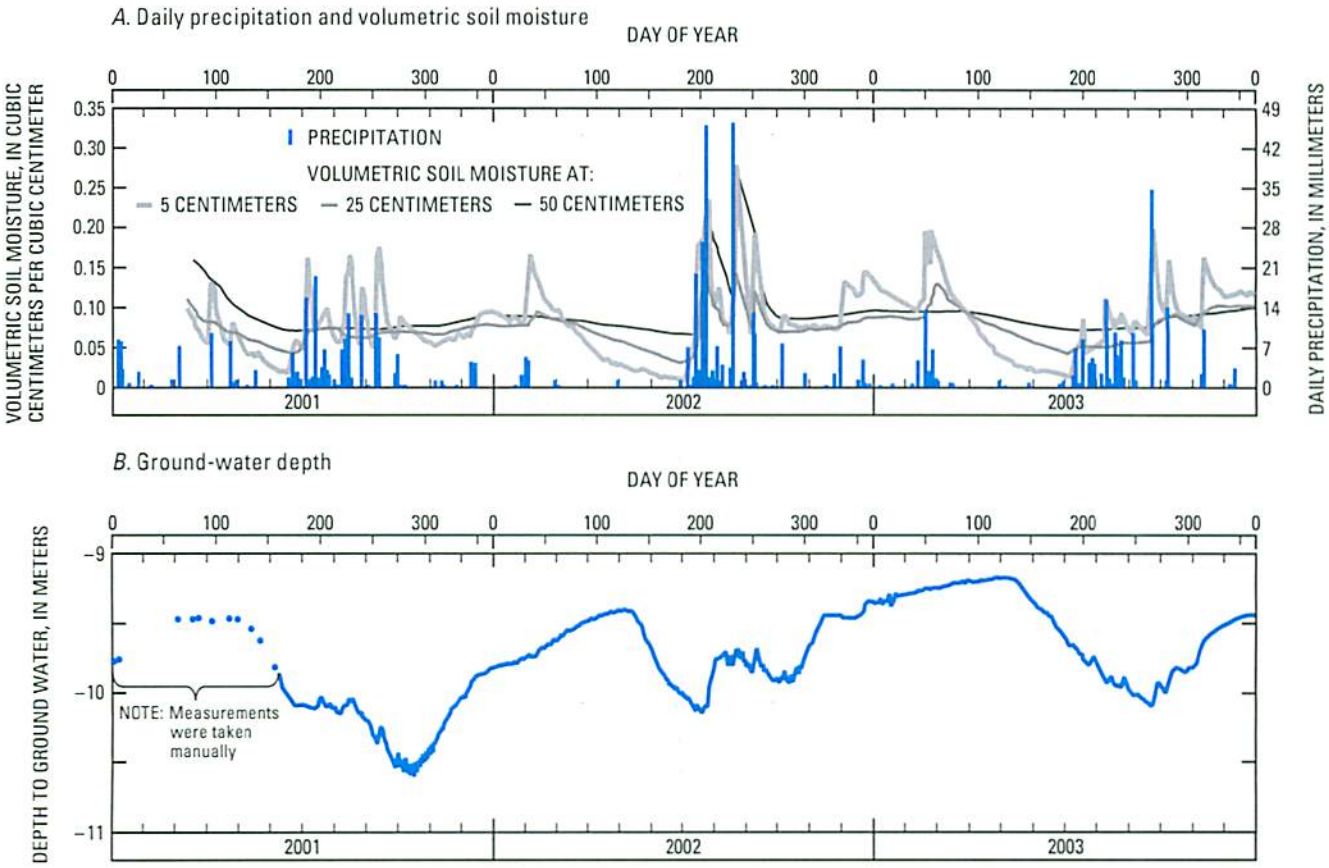


Figure 49. Availability of near-surface soil moisture at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona. *A*, Daily precipitation and volumetric soil moisture at 5 centimeters, 25 centimeters, and 50 centimeters below land surface; *B*, Ground-water depth below land surface.

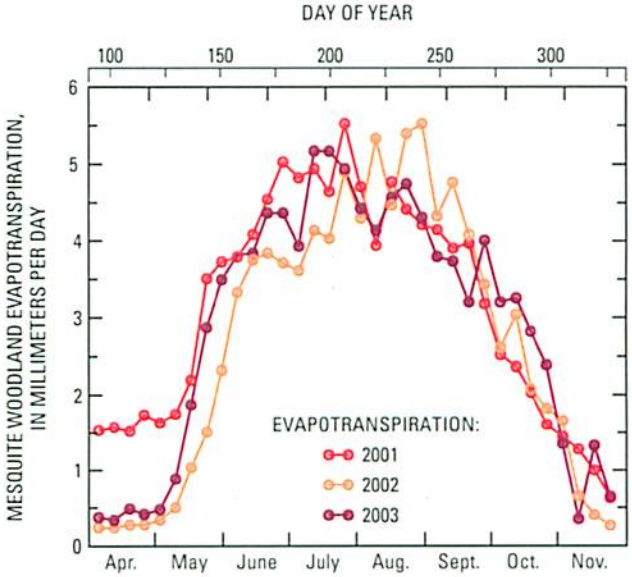


Figure 50. Average weekly woodland evapotranspiration for 2001, 2002, and 2003 at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

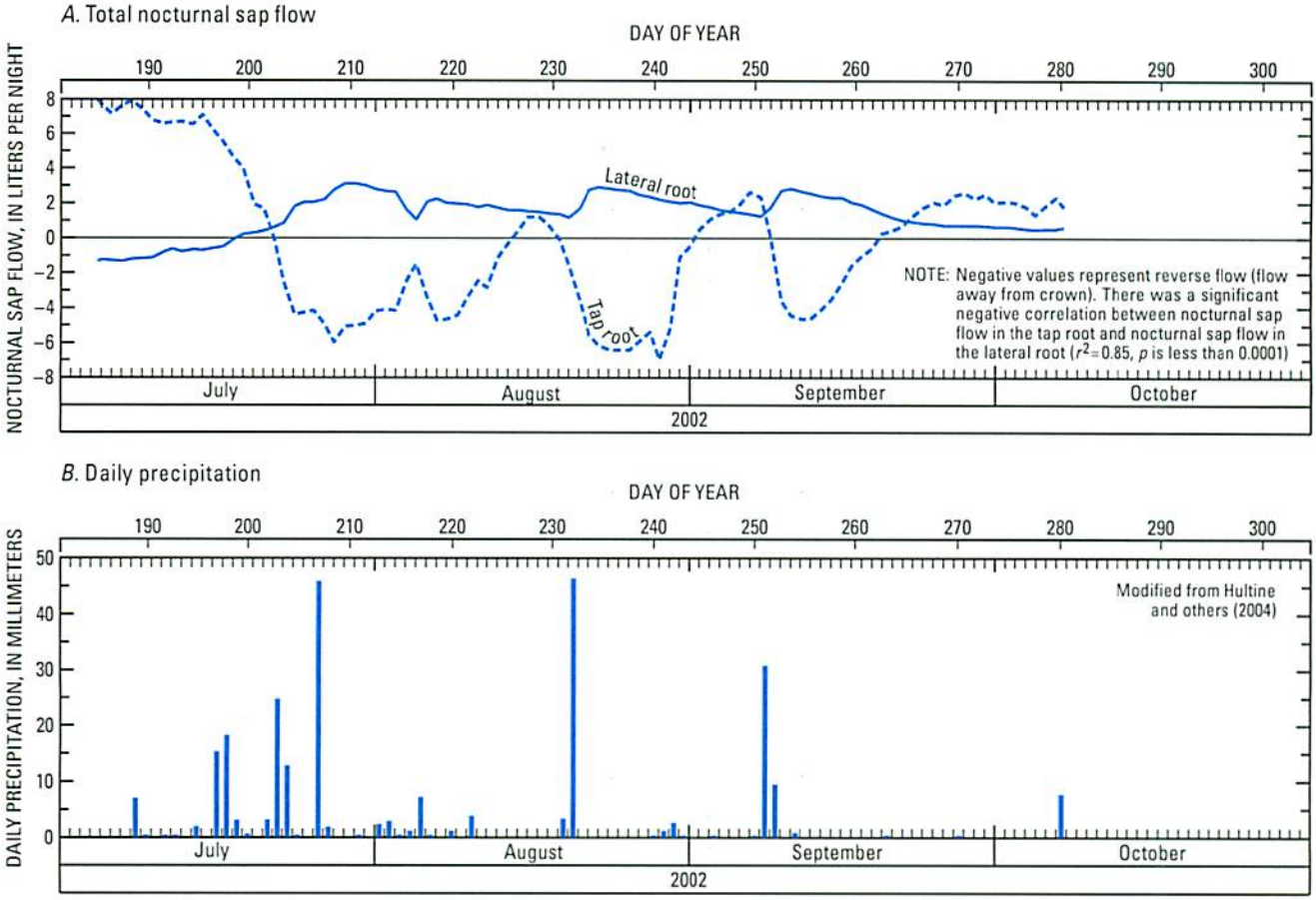


Figure 51. Evidence of the ability of mesquite roots to redistribute soil moisture at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona. *A*, Total nocturnal sap flow of the taproot and a lateral root of a mesquite tree at the Charleston mesquite site calculated from half-hourly measurements between 8 p.m. and 5:30 p.m.; *B*, Daily precipitation totals at the field site during the study.

Moisture redistribution followed the moisture-potential gradient with upward "lifting" of deep vadose-zone moisture or ground water during the dry season and downward descent of precipitation during times of abundant surface moisture. The antecedent monsoon and winter rains prior to the 2003 growing season were more abundant in 2002, indicating that more of this moisture can have been redistributed to deeper layers in the vadose zone, that later improved mesquite functioning during the premonsoon drought period.

The water-balance equation can be used to estimate the entire growing season ground-water use from ET measurements:

$$Q_t = ET - (P - \Delta S), \qquad (12)$$

where

Q_t = ground-water use,
ET = evapotranspiration,
P = precipitation, and
ΔS = the change of soil moisture in the top 1 m of soil.

At the Charleston mesquite site, runoff was negligible and only small changes were assumed to occur in soil moisture deeper than 1 m. Q_t, if positive, is the ET in excess of precipitation and change in soil-moisture storage. All of the excess moisture was assumed to be derived from ground water. The discovery of the ability of mesquite to redistribute water in the vadose zone (Hultine and others, 2004) makes this an overly simplistic view, but there were no methods for computing the change in storage in the deep (>1 m below the surface) vadose zone. The amount of ground water used per unit crown area of mesquite, Q_{veg}, rather than per unit ecosystem area, was computed by dividing Q_t by the percent cover of mesquite found at the site.

The water-balance components (table 42) calculated as part of this study for the Charleston mesquite site (for 2001, 2002, and 2003) by using the Bowen ratio energy-balance method for the Lewis Springs site (for 1997; Scott, Shuttleworth, and others, 2000) illustrate differences between the two sites. Goodrich, Scott, and others (2000) used the 1997 measurements for their consumptive-use estimates.

Table 42. Water balance for the mesquite growing season (May 1–November 27) at the Lewis Springs and Charleston mesquite sites, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[Values computed by using equation 12 (see text): $Q_t = ET - (P-\Delta S)$]

Water-use terms and site characteristics	Year				
	1997		2001	2002	2003
	Site name				
	Lewis Springs site		Charleston mesquite site		
Evapotranspiration (ET), in millimeters	330	330	694	638	676
Precipitation excess ($P-\Delta S$), in millimeters	173	173	206	244	166
Ground-water use per unit ground area (Q_t), in millimeters	157	157	488	394	510
Canopy cover fraction of dominant vegetation type	.50	.32	.74	.74	.74
Ground-water use per unit vegetation area (Q_{vrt}), in millimeters	314	491	659	532	689

The areal coverages of mesquite at the compared sites are estimated to be 50 percent (Scott, Shuttleworth, and others, 2000) and 74 percent for 1997 and 2001–03, respectively. Although the 1997 measurements were taken at a site that was considerably less dense (Lewis Springs), this difference was not sufficient to explain the much greater ground-water use at the woodland (Charleston mesquite) site in 2001–03. The site measured in 2001–03 had much larger and more mature trees. The trees at the 1997 site, being less developed, may have been less adept at tapping the deep ground-water source. The water-table depth at both sites was about 10 m. An alternative explanation of the difference in mesquite ground-water use between the 1997 (Lewis Springs) and 2001–03 (Charleston mesquite) sites is that the dense canopy area at the 1997 site was likely smaller in extent then the fetch of the measurements. As a result, the measurements may have been biased by zones of lower density mesquite cover. Overestimation of the canopy cover leads to a decreased Q_{vrt}. The mesquite canopy cover at the 1997 shrubland site was estimated to be 32 percent. This cover was calculated by using analysis of (previously unavailable) high-resolution aerial photography and the same methods used in this study for determining the canopy percentage within 100 m of the flux measurement towers at the other sites. This analysis yields a Q_{veg} of 491 mm, a quantity, considering year-to-year variability, more in line with the current study. The value also is consistent with the results for a similar, nearby mesquite shrubland (see the "Mesquite Shrubland and Sacaton Grassland" section).

The new 2001–03 mesquite measurements indicate that the mesquite ground-water use varied considerably from year to year. In 2002, the first two months of the growing season, prior to the onset of the monsoon rains, were drier and hotter than in 2001 and 2003. The trees showed considerably more stress (Scott and others, 2004), and used less ground-water. The monsoon rainfall in 2002 was greater than that in 2001 and 2003, and likely offset some of the mesquite ground-water use.

In the "Mesquite Shrubland and Sacaton Grassland" section, the functioning of this mature mesquite woodland site is compared with a less-dense and smaller mesquite shrubland site to determine how representative these measurements might be of other mesquite ecosystems along the San Pedro River.

Mesquite-Woodland Evapotranspiration Partitioning

The nearly continuous overstory eddy-covariance measurements (see results in the previous section) were supplemented periodically throughout the 2001 and 2002 growing seasons with understory eddy-covariance measurements and isotope sampling to partition total ET into understory ET, soil evaporation, and understory transpiration. From these measurements, relations were developed to partition ET for 2001 through 2003.

Using Micrometeorological Techniques

The understory/overstory ET data collected in 2001 and 2002 reveal that overstory water use was nearly constant during the premonsoon to monsoon periods (fig. 52; see Scott and others, 2003, for details). The overstory ET can be interpreted as being mainly tree transpiration throughout most of the days of the study; however, rainfall did occur on DOY 208, 257, and 258 of 2001 that would have resulted in a significant amount of evaporation from the tree canopy surface. The difference in total ecosystem water use throughout the growing season was principally caused by changes in the understory ET, whereas the overstory water use did not appear to increase despite the changes in near-surface soil moisture (fig. 49). The trees certainly had access to a source of deeper vadose-zone water during the 2001–03 premonsoon periods, and the tree transpiration did not increase when near-surface soil moisture increased in the monsoon season (fig. 49). The eddy-covariance estimates of tree transpiration compared favorably with estimates of tree transpiration calculated by using diurnal water-table fluctuations (T_{well}), except for during the monsoon season of 2002 when river floodflows may have invalidated the assumptions of the water-table fluctuation techniques. The aquifer-storage coefficient to compute T_{well} was estimated by dividing the average of the diurnal water-table fluctuation [the quantity ($24r \pm s$) in equation 4] by the tree transpiration estimated from the eddy-covariance approach. The agreement between the two transpiration estimates changed little from the premonsoon to the monsoon periods; thus, the main water source for the mesquites likely remained ground water.

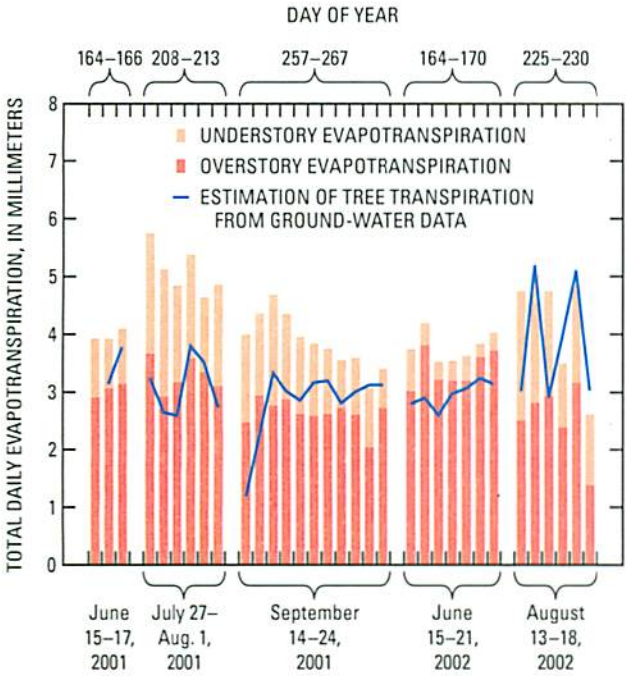


Figure 52. Total daily evapotranspiration (ET) from the Charleston mesquite site and ET partitioning into overstory/understory sources, and an estimate of tree transpiration calculated by using ground-water fluctuations and the method of White (1932) with a storage coefficient of 0.04, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

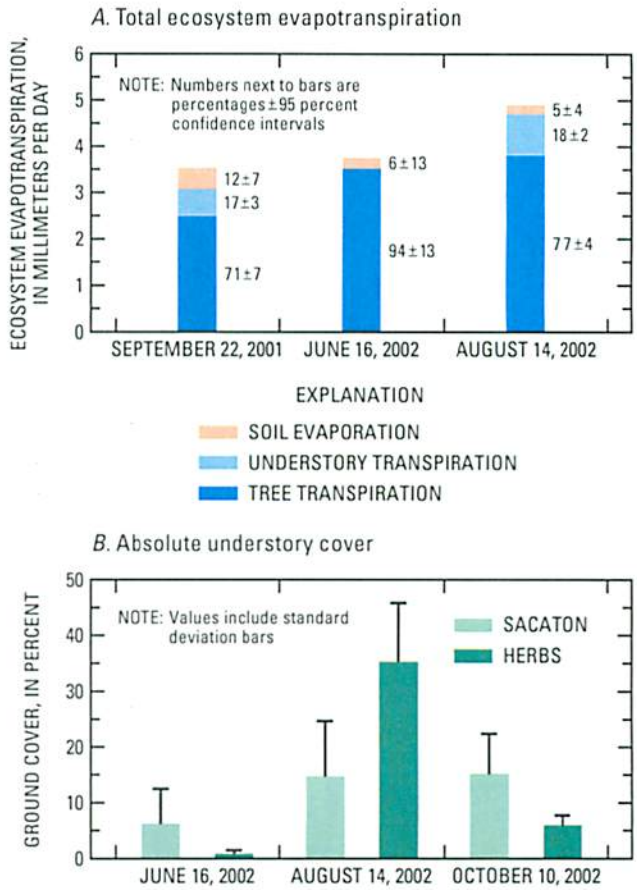


Figure 53. Charleston mesquite site evapotranspiration, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona. *A*, Total evapotranspiration partitioned into tree transpiration, understory transpiration and soil evaporation during three dates of contrasting phenologies and environmental conditions; *B*, Absolute understory cover during the summer of 2002.

Using Isotope Techniques

Late in the growing season of 2001 (September 22) total ET was 71 percent from mesquite transpiration, 17 percent from transpiration by the understory plants, and 12 percent from soil evaporation. Combining these data with estimates of ET from eddy covariance revealed that of the 3.5 mm/d total ET, 2.5 mm/d was from transpiration by mesquite, 0.6 mm/d was from transpiration by the understory plants, and 0.4 mm/d was from soil-surface evaporation (fig. 53A; Yepez and others, 2003). Yepez and others (2003) found that partitioning estimates from the micrometeorological and isotope techniques during 2001 compared favorably.

The fraction of total ET attributed to transpiration in 2002 varied from nearly 100 percent during dry periods to about 35 percent following large precipitation events when soil evaporation was high. During the dry period of 2002 (June 16), ET was partitioned as 3.5 mm/d (94 percent) from mesquite transpiration and 0.2 mm/d (6 percent) from soil evaporation. On August 14, the ET was 3.8 mm/d (77 percent) from tree transpiration, 0.9 mm/d (18 percent) from understory vegetation, and 0.2 mm/d from soil evaporation (5 percent).

During these contrasting periods, the percent cover of the green understory vegetation varied from 0 to 32 percent for the herbaceous dicots, and from 6 to 14 percent for the sacaton, suggesting that an important source of the understory transpiration was from the herbaceous dicot cover (fig. 53B).

Evaporation was significant only immediately after rainfall, when volumetric water content exceeded 0.1 cm^3/cm^3 in the top 5 cm of soil (fig. 54). Following two significant rainstorms, on September 1 and September 14, 2002, the combined tree and understory transpiration accounted for only 2.1 mm/d (38 percent of ET) and 1.4 mm/d (33 percent of ET), whereas soil evaporation represented 3.3 mm/d and 2.8 mm/d, respectively (fig. 54).

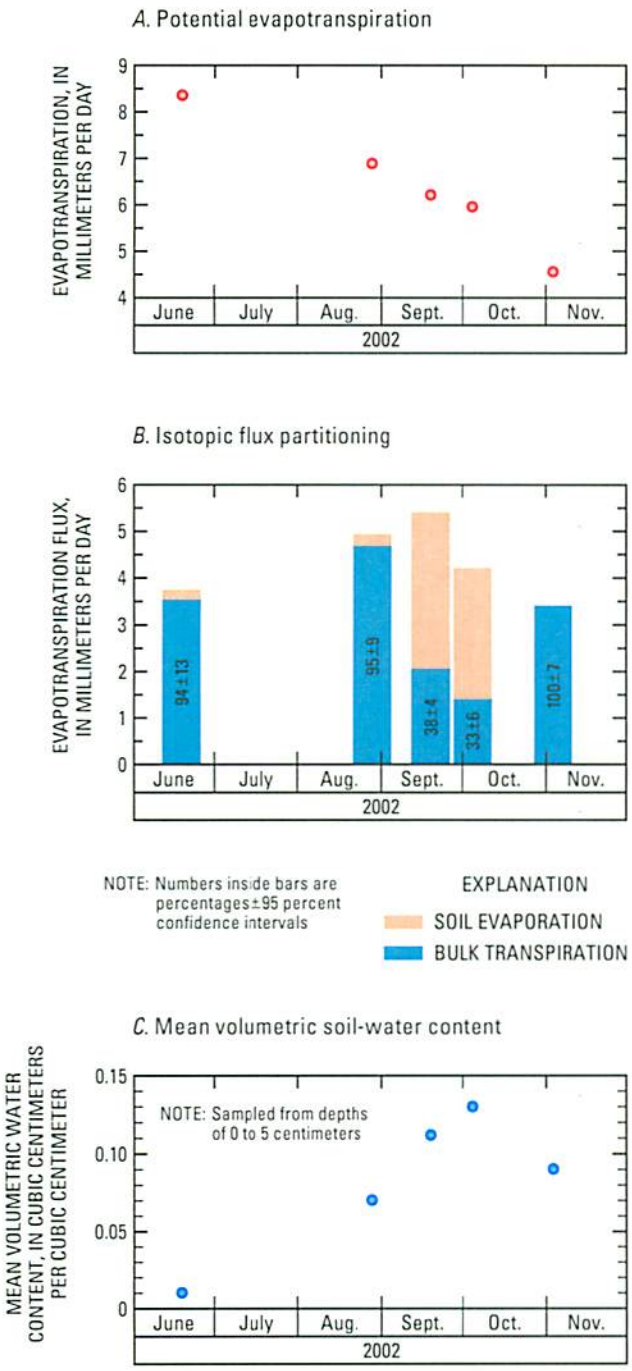


Figure 54. Isotopic evapotranspiration partitioning in relation to seasonal precipitation at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona. *A*, Potential evapotranspiration; *B*, Isotopic flux partitioning calculated by using the isotopic composition of plants, soil, and vapor samples and measurements of evapotranspiration with the eddy-covariance technique; *C*, Mean volumetric soil-water content.

The seasonal trends of ET flux components were estimated by using the relations between the isotopic partitioning, total ET fluxes from the eddy-covariance technique, and environmental conditions (potential ET and soil moisture) observed during the growing seasons of 2001, 2002, and 2003. The growing season was assumed to be from DOY 121 to DOY 321 for all 3 years (fig. 55). From seasonal trends, the total growing-season water balance was determined (table 43).

Mesquite Water Sources

The objective of this portion of the project was to determine the seasonal and interannual patterns of water source use by mesquite. Mesquite had access to water in three different zones of the soil during the growing season: deep water in the saturated zone/capillary fringe (ground surface); water in the deep unsaturated zone (>1 m below the soil), which probably was a mixture of both ground water and precipitation; and water from growing season precipitation (<1 m below the surface). Mesquite, a deeply rooted phreatophyte, was predicted to obtain the majority, if not all of its water, from the deep saturated zone or capillary fringe—essentially the ground water. The work discussed in the "Mesquite Woodland Water Use" section indicates that mesquite did indeed have access to the ground water throughout the growing season, and that the regular diurnal patterns of ground-water drawdown because of mesquite-root uptake occurred throughout most of the season, except for limited periods during the monsoon when water was abundant in the shallow soil. The data in the previous section indicates that the majority of the water used by the mesquite was ground water; this was largely confirmed by using stable isotopes. Significant uptake of ground water for a limited number of sampling days was observed; but uptake from the deep unsaturated zone and from growing season precipitation also occurred. Apparently, mesquite is very opportunistic and uses water when and where it is available.

Precipitation was a significant transpiration source for mesquite during the monsoon period in July, August, and September at the Charleston mesquite, Moson, and Lewis Springs sites in 2000, 2001, and 2002 (figs. 56, 57, 58 and table 42). In 2000, the use of monsoon precipitation (from shallow soil water) as a proportion of transpiration for mesquite was greater at the Charleston mesquite site than at the Moson and Lewis Springs sites (fig. 56). This may reflect differences in soil properties, the amount of rainfall preceding measurements, or the access to ground water among the three sites (depth to ground water was greatest at the Charleston mesquite site). Mesquite relied principally on deep water (ground water plus deep vadose-zone water) and had little shallow soil-water uptake during the dry premonsoon periods.

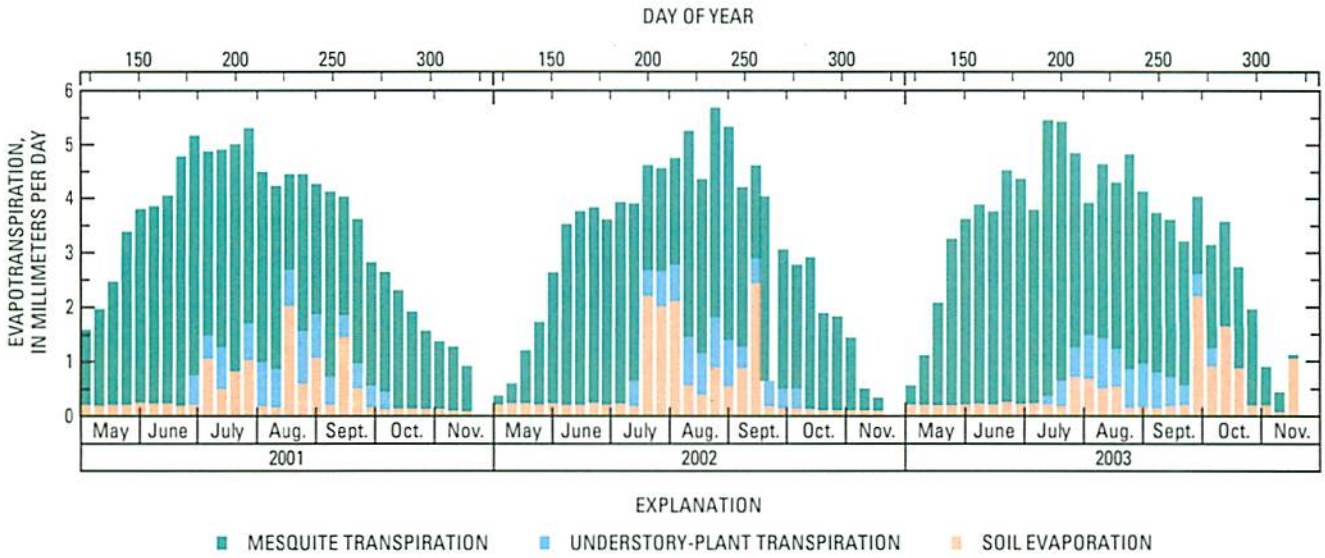


Figure 55. Seasonal trends of average weekly evapotranspiration-flux components calculated by using the isotopic-flux partitioning and the eddy-covariance derived distributed measurements of evapotranspiration at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona (May 1 to November 17, 2001, 2002, and 2003).

Table 43. Water balance at the Charleston mesquite site during the growing season (May 1–November 27), San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

Year	Total evapo-transpiration (millimeters)	Soil evaporation (millimeters)	Understory-plant transpiration (millimeters)	Mesquite transpiration (millimeters)
2001	694	82	64	548
2002	638	110	54	474
2003	676	91	52	534

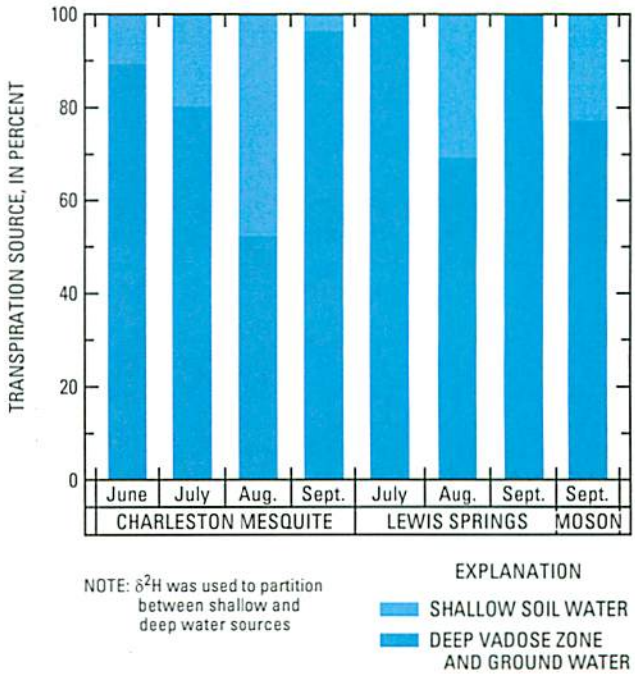


Figure 56. Mesquite transpiration-source partitioning for the Charleston mesquite, Lewis Springs, and Moson sites for the 2000 growing season, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

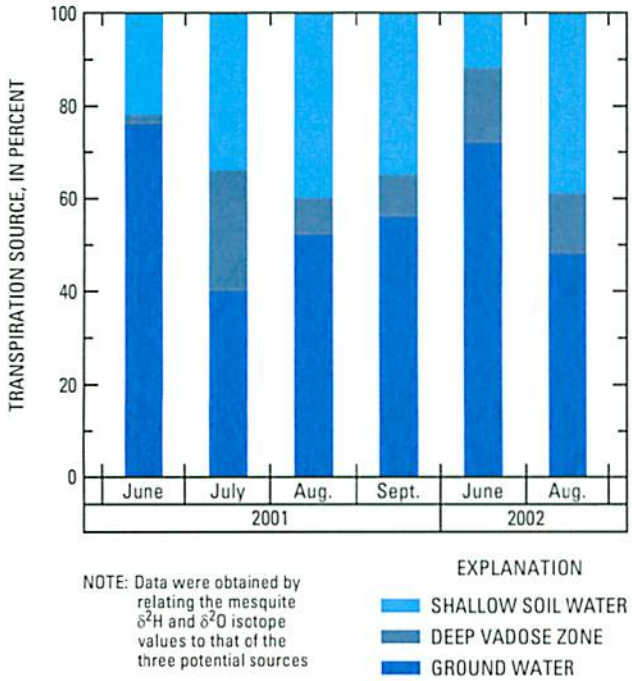


Figure 57. Mesquite transpiration sources at the Charleston mesquite site, 2001 and 2002 growing seasons, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

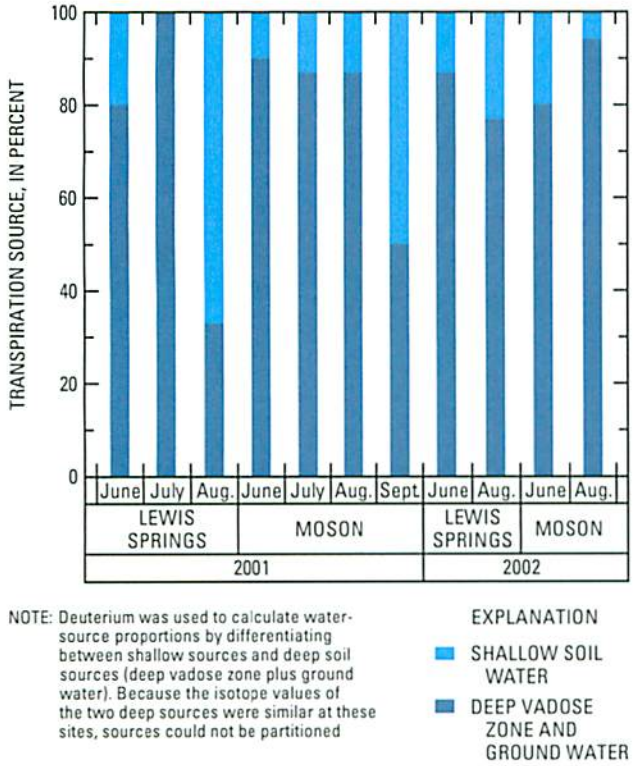


Figure 58. Water-source partitioning for the Lewis Springs and Moson sites, 2001 and 2002 growing seasons, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

Deep vadose-zone water contributed 2 to 26 percent of the total transpiration by mesquite at the Charleston mesquite site in 2001 and 13 to 16 percent in 2002 (table 44). Ground water was the most important source of water at this site; June ground water source fractions were 76 and 72 percent in 2001 and 2002, respectively.

Mesquite transpiration rates from ET partitioning at the Charleston mesquite site (see the "Mesquite Evapotranspiration Partitioning" section) were used to partition the transpired water into three sources: (1) ground water, (2) the shallow vadose zone, and (3) the deep vadose zone. The fraction of tree transpiration from recent precipitation (during prior weeks and months) was highly dependent on soil-moisture content within the 0.2–1.0 m depth increment. The linear relation between volumetric soil-moisture content within the 0.2–1.0 m depth increment and the fraction of moisture uptake from this layer determined by isotope methods was highly significant (fraction from surface soil = 14.8 × (soil-moisture content) -0.68; r^2=0.93, $p < 0.001$, n=6).

The regression relation between volumetric soil-moisture content and the fraction of moisture uptake was used to estimate the precipitation use for each week from May 1 to October 21 (DOY 121–323) of 2001, 2002, and 2003. ET derived from ground water and the deep vadose zone was calculated by using the proportions from the three-ended isotope mixing model. The remaining water use was divided between ground water and deep vadose-zone water by using calculated proportions from ET-source isotope measurements. Deep vadose-zone and ground-water proportions were calculated for premonsoon (DOY 121–211), monsoon (DOY 212–260), and post-monsoon (DOY 261–323) periods. These calculated proportions were held constant for each period. Estimates of weekly and annual growing-season transpiration from ground water by the mesquite ecosystem at the Charleston mesquite site were then calculated.

Cumulative mesquite transpiration at the stand level during entire growing seasons was 474 to 548 mm at the Charleston mesquite site (table 43 and fig. 59). Ground water accounted for the majority of mesquite transpiration, and precipitation held in the shallow soil zone accounted for the second largest source (table 45). Deep vadose-zone water accounted for a minor yet important source of mesquite transpiration. Proportionally, 58 to 62 percent of the total transpiration flux from mesquite was from ground water, 29 to 31 percent was from shallow soil water, and 13 to 14 percent was from deep vadose-zone water.

Possible Inconsistency in Mesquite Woodland Evapotranspiration Partitioning and Ground-Water Use

The calculations above assume that growing-season precipitation and depletion of shallow soil water were sufficient to provide all the water needed for bare-soil evaporation and understory transpiration (table 43) as well as part of the mesquite transpiration (table 45). The total of these estimates, however, was greater than the measured available precipitation excess in each year (table 46).

Table 44. Estimated distribution of water sources for mesquite transpiration at the Charleston mesquite, Lewis Springs, and Moson sites, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona, 2000–2002

[*f*, proportion of water derived from the listed source; *SE*, standard error; total proportions may not add to 1.00 owing to independent rounding; ---, no data; <, less than; +, plus; deep vadose zone, 1–8.5 meters]

Site	Sources	June		July		August		September	
		f	*SE*	*f*	*SE*	*f*	*SE*	*f*	*SE*
					2000				
Charleston mesquite	Shallow (<1 meter)	0.11	0.08	0.20	0.05	0.52	0.04	0.04	0.06
	Deep vadose zone + ground water	.89	.08	.80	.05	.48	.04	.96	.06
Lewis Springs	Shallow (<1 meter)	---	---	0	.32	.31	.03	0	.03
	Deep vadose zone + ground water	---	---	1	.32	.69	.03	1	.03
Moson	Shallow (<1 meter)	---	---	---	---	.23	.03	---	---
	Deep vadose zone + ground water	---	---	---	---	.77	.03	---	---
					2001				
Charleston mesquite	Shallow (< 1 meter)	0.23	0.07	0.34	0.10	0.40	0.10	0.07	0.35
	Deep vadose zone	.02	.07	.26	.17	.09	.18	.09	.09
	Ground water	.76	.06	.40	.27	.52	.28	.56	.14
Lewis Springs	Shallow (< 1 meter)	.19	.36	0	.10	.67	.10	---	---
	Deep vadose zone + ground water	.81	.36	1	.10	.33	.10	---	---
Moson	Shallow (< 1 meter)	.10	.14	.13	.04	.13	.04	.50	.23
	Deep vadose zone + ground water	.90	.14	.87	.04	.87	.04	.50	.23
					2002				
Charleston mesquite	Shallow (< 1 meter)	0.12	0.07	---	---	0.39	0.09	---	---
	Deep vadose zone	.16	.07	---	---	.13	.09	---	---
	Ground water	.72	.13	---	---	.48	.18	---	---
Lewis Springs	Shallow (< 1 meter)	.13	.12	---	---	.23	.08	---	---
	Deep vadose zone + ground water	.87	.12	---	---	.77	.08	---	---
Moson	Shallow (< 1 meter)	.20	.05	---	---	.06	.05	---	---
	Deep vadose zone + ground water	.80	.05	---	---	.94	.05	---	---

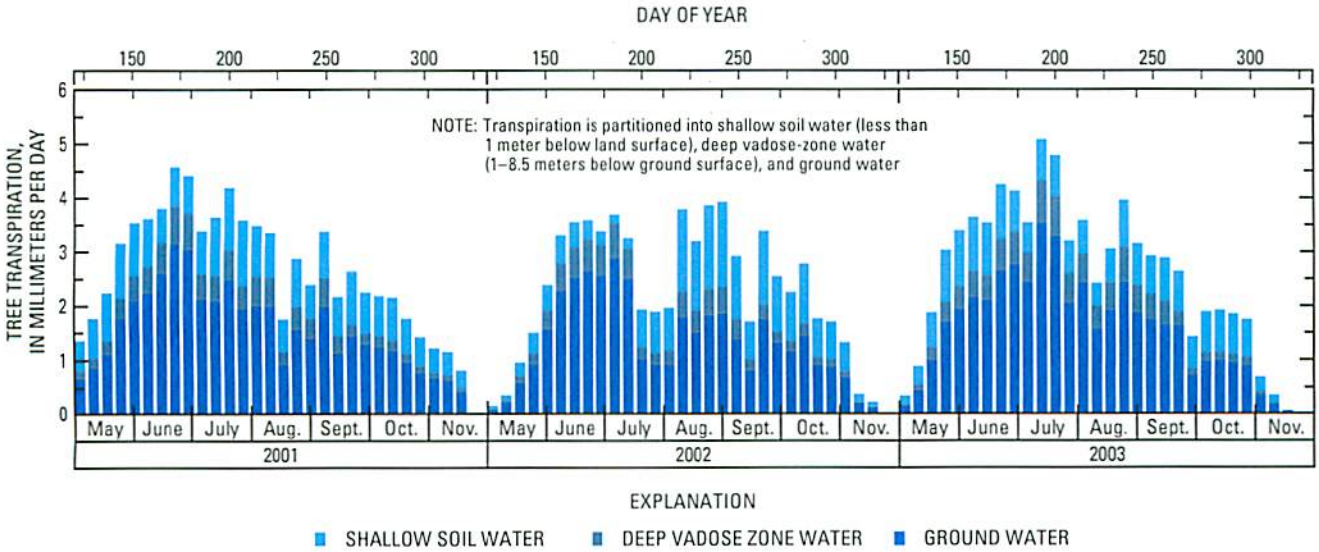


Figure 59. Total tree-transpiration flux from May 1 to November 17 for 2001, 2002, and 2003 at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

Table 45. Mesquite transpiration flux by source and total flux for the 2001–03 for the growing seasons at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[Transpiration is partitioned into shallow soil water (less than 1 meter below land surface), deep vadose-zone water (1 to 8.5 meters below land surface), and ground water]

	Transpiration flux (millimeters)			
Year	Ground water	Deep vadose zone	Shallow soil	Total
2001	321	71	156	548
2002	275	61	138	474
2003	333	75	126	534

Table 46. Seasonal water-balance totals of measured and derived water fluxes at the Charleston mesquite site, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[Values given in millimeters]

Year	Total evapotrans-piration[1]	Precip-itation excess[1]	Understory evapotrans-piration[2]	Mesquite shallow soil-water use[3]	Rainfall deficiency[4]
2001	694	206	146	156	96
2002	638	244	164	138	58
2003	676	166	143	126	103

[1]From table 42, measured value.

[2]From table 43, derived value.

[3]From table 45, derived value.

[4](understory ET) + (mesquite shallow soil-water use) – (precipitation excess).

The excess demand on shallow soil water was 58 to 103 mm, or 23 to 62 percent of the precipitation excess. Several factors may have led to this discrepancy. First, understory ET, especially during the dry period before the onset of the monsoon, may have come from water sources greater than 1 m below land surface. The portion of the soil profile used in the water-budget calculations was 0–1 m (table 42). Sacaton has roots penetrating to at least 3 m beneath the flood-plain terraces and may be transpiring water from these deeper layers. Second, mesquite redistributes water from deep soil layers (>1 m) to the near-surface soil during the dry periods (Hultine and others, 2004), and this water may be subject to evaporation or uptake and transpiration by sacaton, leading to higher than expected understory ET. Finally, any one or all of the estimates of component fluxes and water balance can include measurement or scaling errors. These errors may have led to the inconsistency between precipitation excess and the amount of ET from the upper 1 m of soil.

Mesquite Shrubland and Sacaton Grassland

The seasonal water uses by the adjacent mesquite shrubland and sacaton grassland study at the Lewis Springs site followed a similar pattern to that seen at the mesquite woodland at the Charleston mesquite site (figs. 60 and 61). The grassland greened up and started to transpire about a month earlier in the year than the frost sensitive mesquites. After mesquite leaf flush, however, the cumulative shrubland ET caught up to the grassland, perhaps owing to an enhanced ability of the deeper rooted trees to acquire ground water more effectively. From the start of the monsoon until the end of the growing season, the two sites had essentially the same amount of ET.

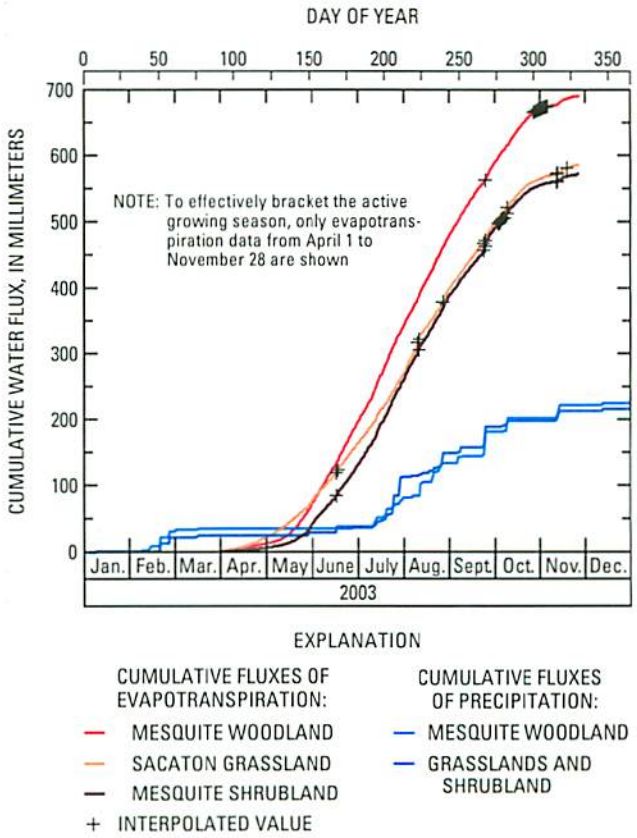


Figure 60. Cumulative fluxes of precipitation and evapotranspiration at all eddy-covariance sites for 2003: mesquite woodland (Charleston mesquite site) and sacaton grassland and mesquite shrubland (Lewis Springs site), San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

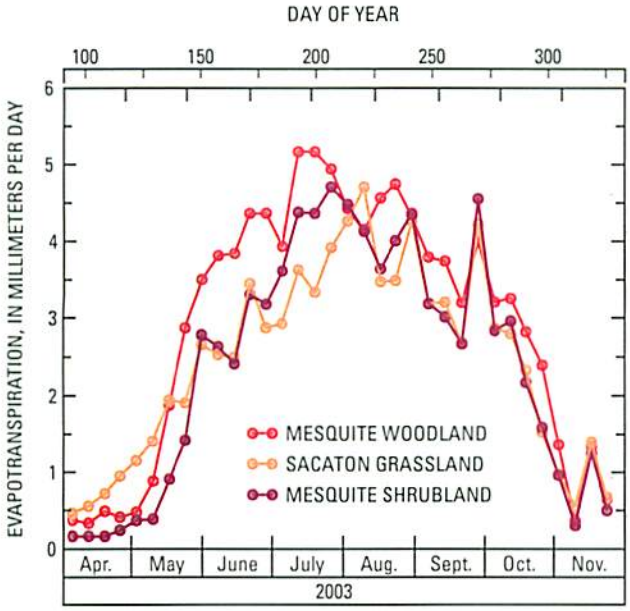


Figure 61. Weekly average evapotranspiration for all eddy-covariance sites for 2003: mesquite woodland (Charleston mesquite site), sacaton grassland and mesquite shrubland (Lewis Springs site), San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

The water-use pattern by the sacaton grassland at the Lewis Springs site differed considerably from that at the similar Lewis Springs site across the river that was monitored in 1997 using the Bowen ratio technique (Scott, Shuttleworth, and others, 2000). The 1997 sacaton site was shown to have a tight coupling between precipitation and ET from which Scott, Shuttleworth, and others (2000) concluded that sacaton used little ground water. The cumulative water use measured at the sacaton grassland location in this study indicates that ET was significantly in excess of precipitation; this implies ground-water use by the grassland. Regular diurnal fluctuations during the growing season in a piezometer at the site provided confirmation. The likely explanation for the disparity between the water-use patterns at the two sites is that ground-water depth at the earlier sacaton grassland site was greater than 3.5 m, whereas ground-water depth was commonly less than 3 m at the sacaton grassland location in this study. Thus, sacaton does not appear where ground-water depths are greater than about 3 m. This conclusion is supported by Scott, Shuttleworth, and others (2000), who mentioned that sacaton closer to the river bank (and closer to the water table) appeared greener in the dry season, and by a stable-isotope analysis of the sacaton source water (Tiller, 2004) that indicated that sacaton did not appear to use ground water at sites at which depth to ground water was greater than about 3 m.

The water use by the mesquite shrubland at the Lewis Springs site in this study also differed from water use at a Lewis Springs mesquite shrubland site that was measured in 1997 (Scott, Shuttleworth, and others, 2000) by using the Bowen ratio method. The 1997 and present study stands have similar characteristics, but the depth to ground water is about 3 m less at the present Lewis Springs mesquite shrubland site. Although annual ET at the 1997 site was in excess of precipitation, the source of ET in excess of precipitation was uncertain. Scott, Shuttleworth, and others (2000) speculated that the source of ET in excess of evapotranspiration might have been derived from deeper vadose-zone moisture, because the fluctuations in a site piezometer did not indicate phreatophytic fluctuations. More trees at the mesquite shrubland at the Lewis Springs site were probably able to access the ground water, because the age distribution of the trees and because ground water is closer to the surface. Alternatively, the 1997 mesquite site probably had a lower density of mesquite, which would result in a lower ET (see the "Mesquite Woodland Water Use" section).

By using the growing season water balance given in equation 12, the ground-water use of the mesquite shrubland and sacaton grassland at the Lewis Springs site on a per unit canopy-area basis were computed and compared to the mature mesquite woodland at the Charleston mesquite (Q_{veg}, table 47). Although evaporation excess (Q_t) at the sacaton grassland at the Lewis Springs site was the same as that at the adjacent mesquite shrubland at the Lewis Springs site, the sacaton ground-water use per unit canopy area was less owing to its denser canopy area. Nevertheless, the sacaton ground-water use was significant at this site and represents a revision in of the understanding of consumptive use in the SPRNCA.

Table 47. Water balance for the growing season (May 1–November 27) at the Lewis Springs and Charleston mesquite sites for 2003, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[mm, millimeters; values computed by using equation 12 (see text)]

Water use terms	Site		
	Lewis Springs sacaton	Lewis Springs mesquite	Charleston mesquite
Evapotranspiration (ET), in mm	554	565	676
Precipitation excess ($P - \Delta S$), in mm	180	185	166
Ground-water use per unit ground area (Q_t), in mm	374	380	510
Canopy cover fraction of dominant vegetation type	.65	.55	.74
Ground-water use per unit vegetation area (Q_{veg}), in mm	575	691	689

It is encouraging that the Q_{veg} measured for the mesquite shrubland at the Lewis Springs site was nearly equal to that measured at the mesquite woodland at the Charleston mesquite site as it indicates that mesquite seem to function similarly from site to site. This result proved helpful for scaling up these ET measurements to the entire SPRNCA; the vegetation map did not distinguish how coupled the mesquites were to the ground water at any particular riparian site. Although it was encouraging that the Q_{veg} of the shrubland and woodland were equivalent, the calculations were highly sensitive to the canopy cover percentage—the near equality between the sites probably is by chance.

Cottonwood Forests

During the peak dry period of the premonsoon season, mean daily maximum vapor-pressure deficit (VPD) was 6 kPa at the Boquillas (intermittent streamflow) and Lewis Springs (perennial streamflow) flood-plain sites (fig. 62).

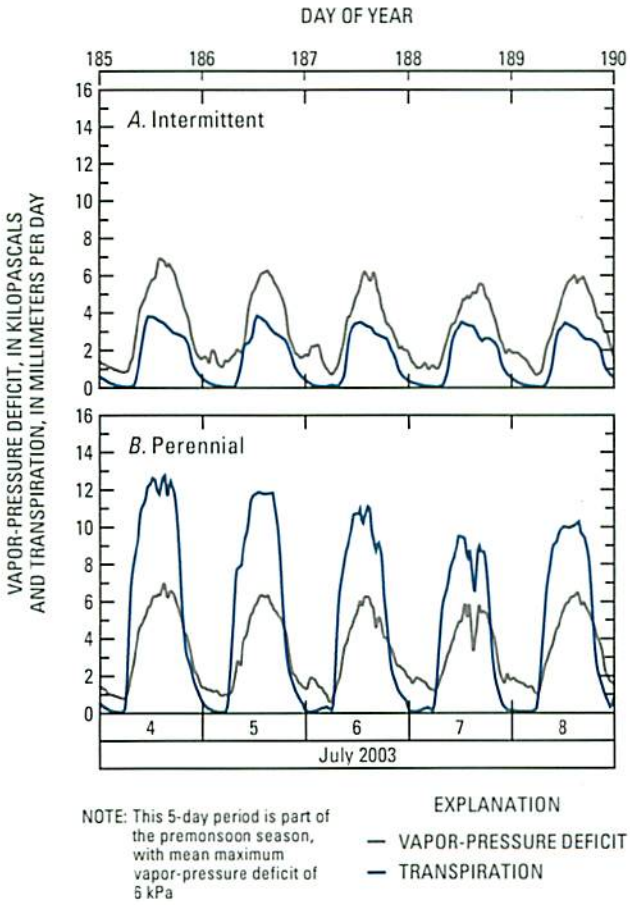


Figure 62. Vapor-pressure deficit and measured cottonwood transpiration for July 4–9, 2003 (day of year 185–190), San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona. *A,* Boquillas (intermittent streamflow) site; *B,* Lewis Springs (perennial streamflow) site.

VPD and cottonwood tree transpiration (T) followed similar patterns throughout the day. The cottonwood stand at the Boquillas site exhibited midday-afternoon depression in T probably in response to high VPD (fig. 62), implying that the trees were regulating their stoma to prevent water loss (O'Grady and others, 1999; Horton and others, 2001c). During a relatively rain-free period (August 8–13) in the monsoon season, mean maximum VPD was similar to that in the premonsoon season (July); the peak VPD during the monsoon season was about 5 kPa (fig. 63). In contrast to the premonsoon pattern, T increased with no apparent stomatal closure at midday after significant monsoon rains and runoff events had recharged the soil moisture and ground water at both sites.

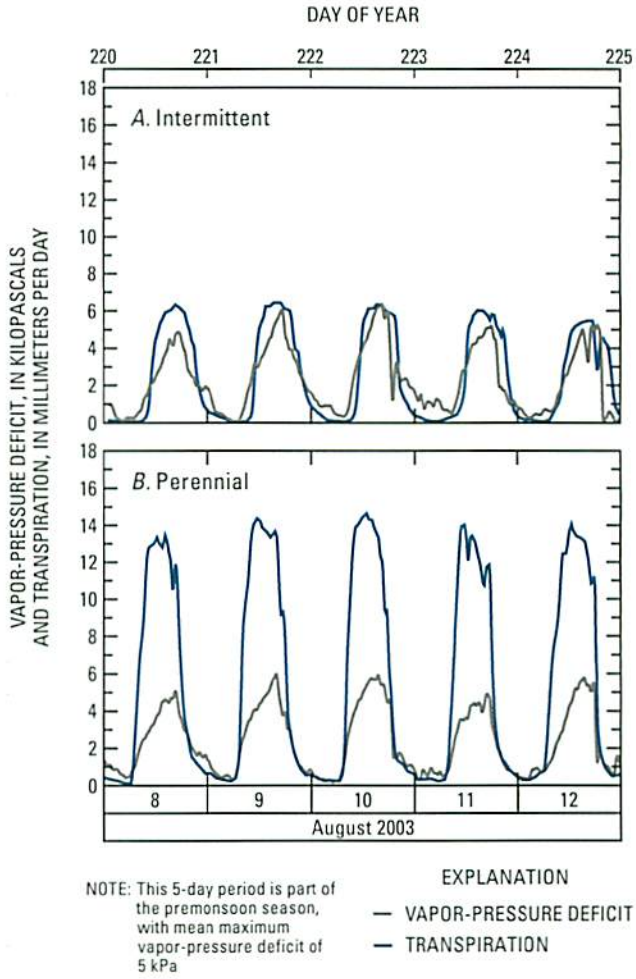


Figure 63. Vapor-pressure deficit and measured cottonwood transpiration for August 8–13, 2003 (day of year 220–225), San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona. *A,* Boquillas (intermittent streamflow) site; *B,* Lewis Springs (perennial streamflow) site.

There was no dependence of *T* on VPD at the Boquillas site, which again confirms that stomatal regulation or leaf area reduction reduced water loss during periods of high atmospheric demand. A significant positive linear relation of *T* and VPD at the Lewis Springs site indicates low resistance to water demand (fig. 64A; Oren and others, 1996). *T* appeared to be controlled by water-transport capacity and amount of foliage in the cottonwood trees at the Lewis Springs site (Cinnirella and others, 2002).

Daily transpiration of the cottonwood stand at the Lewis Springs site was higher than at the Boquillas site throughout the growing season (fig. 65). A marked decline in *T* at the Boquillas site was observed during the peak of the early summer drought or premonsoon period. The leaves of cottonwood trees fully leafed out at DOY 91 and completely senesced at DOY 309. Total annual stand *T* was 484 mm at the Boquillas site and 966 mm at the Lewis Springs site.

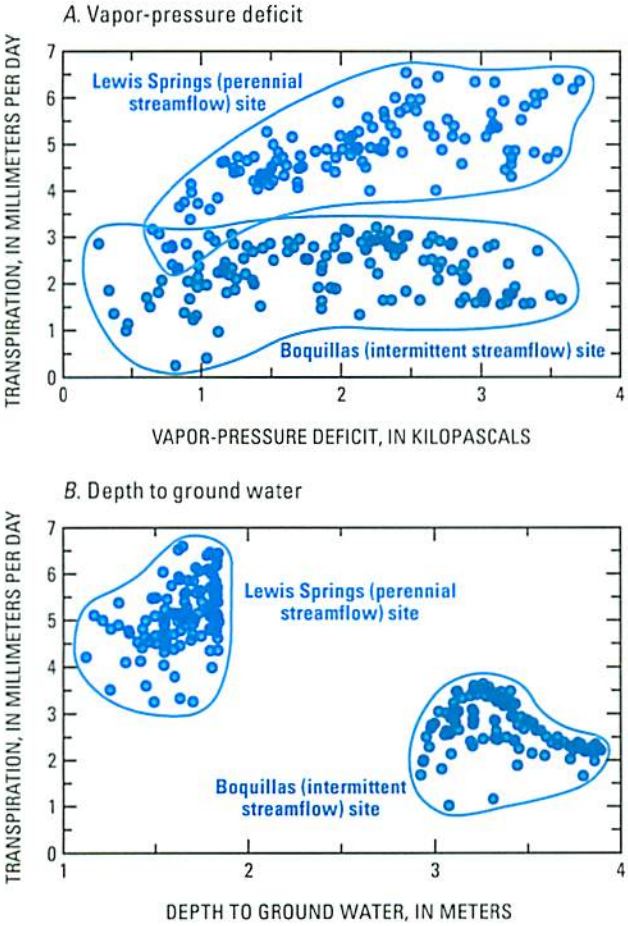
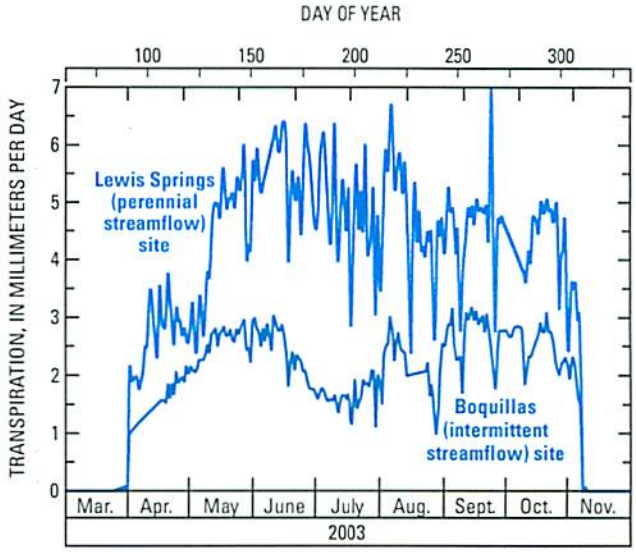


Figure 64. Relation of measured cottonwood transpiration to vapor-pressure deficit and depth to ground water at the Boquillas (intermittent streamflow) and Lewis Springs (perennial streamflow) sites, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona. *A*, Vapor-pressure deficit; *B*, Depth to ground water.



NOTE: Transpiration at the beginning of the season was interpolated from a value of zero at the time of observed leaf flush to the measured value at the beginning of the measurement period

Figure 65. Seasonal cottonwood transpiration at the Boquillas (intermittent streamflow) and Lewis Springs (perennial streamflow) sites, 2003, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

A previous study conducted at the Lewis Springs site revealed that cottonwood trees in the primary channel had higher *T* than trees in the secondary channel (Schaeffer and others, 2000). On a daily basis, cottonwood trees at the Lewis Springs site transpired at higher rates than trees at the Boquillas site, indicating low resistance to the transpiration flux at the Lewis Springs site (little drought stress). The higher *T* rate at the Lewis Springs site suggests that, because of an abundant supply of water, atmospheric demand is the driving force for *T* (Oren and others, 1996). Hence, *T* at the Lewis Springs site approached predicted potential evaporation levels at the onset of the monsoon season because of the high VPD and readily accessible ground water (fig. 66). At the Boquillas site, however, *T* did not increase with atmospheric demand because of increased resistance to water uptake (soil-root interface) or to transpiration (stem resistance, stomatal resistance, or reduced LAI) during drought (Oren and others, 1996; Leffler and Evans, 2001).

During the early part of the growing season, a localized infestation of leaf-eating caterpillars occurred at the Boquillas site. A decline in *T* started at the onset of the herbivory at DOY 113 and continued until DOY 120 when the cottonwood trees were almost entirely defoliated (fig. 65). A reduced *T* was observed throughout the duration of infestation. Cottonwood trees fully recovered from herbivory at DOY 130 when new leaves flushed out and *T* started to increase. The reduced flow observed during

herbivory may have been due to water used in bud swell for the production of new photosynthetic tissues. Evidence of sap flow before bud break in some species in southern deciduous forests indicated that loss of water to the atmosphere occurred through the bark, young branches, and expanding buds (Oren and Pataki, 2001).

Ground-water depth below land surface at the Boquillas site was greater than at the Lewis Springs site (fig. 67). At the Boquillas site, ground-water depth increased from 3.1 m during the early part of the spring season to 3.9 m during the peak of the premonsoon drought period (fig. 67A). At the Lewis Springs site, ground-water depth varied less throughout the premonsoon drought period than at the Boquillas site, but depth to ground water declined gradually and steadily. Ground-water depth decreased from 1.5 m at the beginning of the spring season to 1.1 m during the monsoon season. At the peak of the premonsoon drought period, ground-water depth dropped to 1.8 m. Ground-water levels at both sites peaked during the monsoon season in response to rises in stream stage (fig. 67).

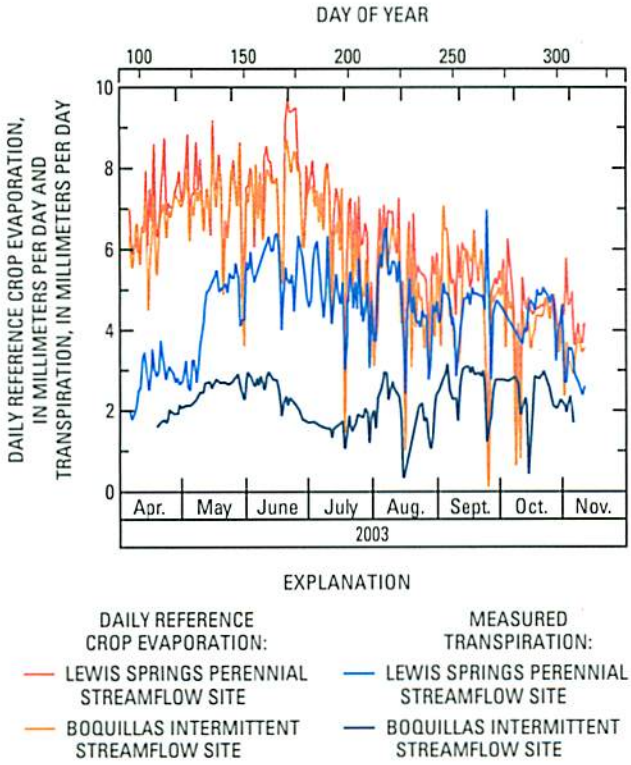


Figure 66. Daily reference crop evapotranspiration and measured transpiration of cottonwood trees at the Boquillas (intermittent streamflow) and Lewis Springs (perennial streamflow) sites, 2003, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

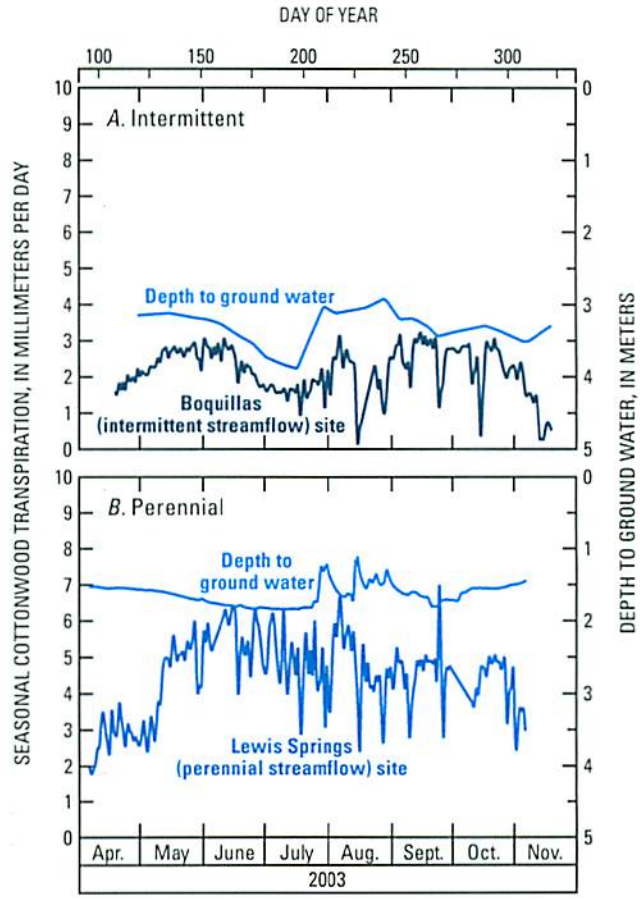


Figure 67. Seasonal cottonwood transpiration, 2003, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona. *A*, Boquillas (intermittent streamflow) site; *B*, Lewis Springs (perennial streamflow) site.

Seasonal fluctuation in the water use of cottonwood trees at the Boquillas site was closely related to the fluctuations of the ground-water table (fig. 67A). Cottonwood trees at the Boquillas site likely were dependent on shallow ground-water sources. The significant decline in the water table in the premonsoon season period probably caused increased water stress on the cottonwood trees (Cooper and others, 2003; Rood and others, 2003; Tyree and others, 1994). *T* at the Lewis Springs site showed little evidence of water stress probably because the water table was high and water-level declines were small (Oren and Pataki, 2001). At the Boquillas site, however, larger and deeper declines in the water table caused large reductions in *T* that may be associated with a loss of hydraulic conductivity that facilitated a reduction in stomatal conductance (Cooper and others, 2003). At the onset of the monsoon rains, *T* at the Boquillas site rebounded in response to increases in soil moisture and (or) water-table rise (fig. 67A).

According to previous studies, the LAI of cottonwood trees at the Boquillas site was consistently lower than at the Lewis Springs site and was relatively constant throughout the growing season (Sean Schaeffer, University of Arkansas, and David Williams, University of Wyoming, unpublished data; Schaeffer and others, 2000). In October 2003, the LAI at the Boquillas and Lewis Springs sites was 1.75 and 2.75, respectively. This difference in LAI corresponds well with the difference in transpiration magnitudes under unstressed conditions between the two sites (fig. 65). The leaf area to sapwood area ratio was significantly higher at the Lewis Springs site than at the Boquillas site (table 41).

Seepwillow Transpiration and Open-Water Evaporation

A seepwillow transpiration and open-water evaporation study was conducted in 2002 and 2003 to make transpiration measurements from a dominant understory species and from an open-water surface in the flood-plain zone at the Lewis Springs site. These are the first ET measurements made from these two cover types along the San Pedro River. Previous estimates of open-water evaporation from the riparian corridor have been calculated by using empirical formulae and commonly available meteorological data. Ground-water use by obligate phreatophytic understory plants has previously been completely ignored owing to measurement difficulties. Further, the total area covered by such plants is thought to be insignificant compared with the cover of other vegetation elements in the riparian corridor.

A discussion of major understory species is presented in chapter C of this report, and visual surveys of active, green understory plants were made in June 2002 prior to the monsoon. Green understory plants in the premonsoon period were an indicator that the species did rely upon ground water. These surveys showed that seepwillow and sacaton are the dominant understory vegetation types that are probable ground-water users.

Understory Seepwillow Water Use

Floods during the monsoon season destroyed sap-flow instrumentation in 2002, and as a consequence, most of the transpiration measurements were not reliable for the 2002 study period. In 2003, seepwillow sap flow was measured at both open- and closed-canopy sites at Lewis Springs from May 30 to November 6 (DOY 150–310). This time period represented seasonal sap-flow values of the premonsoon, monsoon, and post-monsoon periods. Transpiration measurements from the open- and closed-canopy sites were compared with the AZMET reference ET (ET_o; fig. 68). ET_o was calculated by using data from the Lewis Springs meteorological tower, which is in a more open environment than the open- and closed-seepwillow sap flow sites. The ET_o in the understory flood-plain environment is expected to be somewhat less than in an open area owing to the sheltering effect of the cottonwood overstory. During the premonsoon period, transpiration rates for seepwillow were fairly consistent and not responsive to daily fluctuations in atmospheric demand, indicating that ET_o was not a limiting factor of seepwillow sap flux during this period. Both open- and closed-canopy sites had similar and fairly constant transpiration rates; stand transpiration averaged about 5 mm/d in June and early July. After the monsoon began about DOY 200, atmospheric demand was lower and the seepwillow transpiration was more responsive to fluctuations in the demand, indicating more atmospheric-demand limitations during this time.

Seepwillow and the cottonwood forest had comparable water-use rates (fig. 69). Mean differences in transpiration rates between cottonwood and seepwillow were 1.0 mm/d during the premonsoon period, 1.9 mm/d during the monsoon season, and 1.6 mm/d during the post-monsoon period.

A linear regression between mean seepwillow transpiration and ET_o indicated a high level of correlation (r^2=0.79, p<0.0001). Seepwillow growing-season totals were estimated by applying the regression equation ($1.1406233 + 0.427397\ ET_o$) to 2003 ET_o data from the Lewis Springs site meteorological tower. The extent of the seepwillow growing season was assumed to be the same as that for the cottonwoods (DOY 91 to 309) at the site. Comparison of the estimated seepwillow ET (819 mm) with that of the cottonwood (966 mm) indicates that the shrubs had little difficulty accessing ground water.

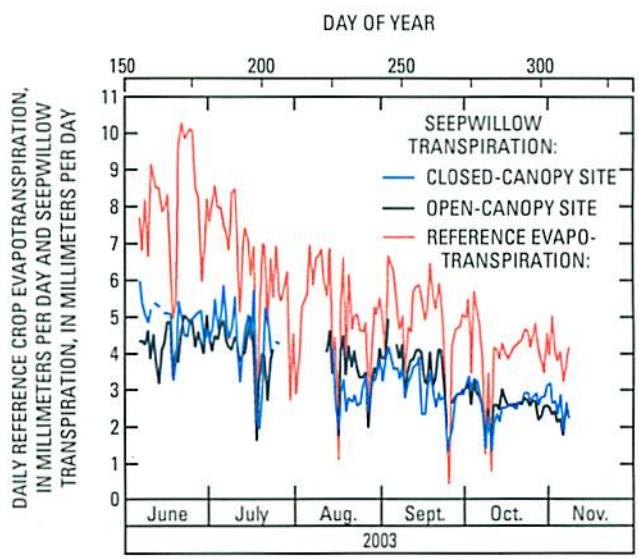


Figure 68. Comparison of seepwillow transpiration with reference crop evapotranspiration at the Lewis Springs site, 2003, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

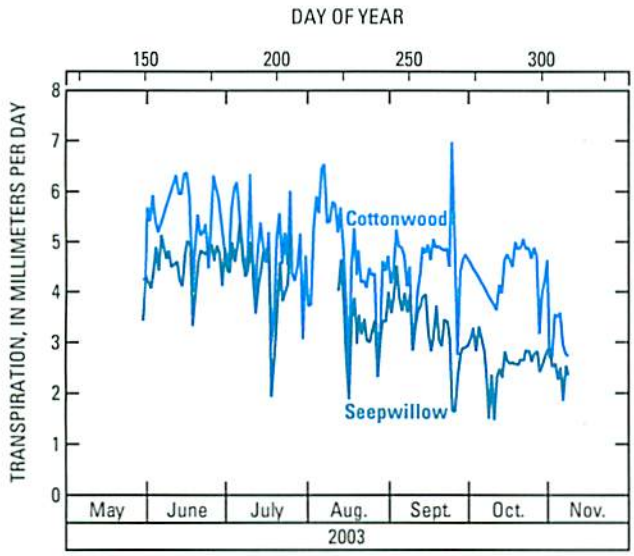


Figure 69. Comparison of seepwillow with cottonwood transpiration at the Lewis Springs site, 2003, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

The total amount of understory vegetation consisting of major ground-water-using species like seepwillow and sacaton could not be computed from the VEG00 map in this study. Nonetheless, biohydrology transect vegetation surveys and reach information can be used to compute a rough estimate of seepwillow prevalence within the SPRNCA (chapter C and table 48). This preliminary work shows that the amount of seepwillow within the SPRNCA was small in comparison with the other major cover types (tables 48 and 49). Seepwillows were not included in the total consumptive-use calculations owing to the small amount of area that they covered. Nonetheless, if one considers the consumptive use of seepwillow along with the additional flood-plain understory plants like sacaton that probably were using ground water, the overall SPRNCA consumptive-use estimates would increase. Unfortunately, seepwillow, along with these other understory ground-water-using plants, were not accounted for in the VEG00 map of dominant vegetation communities (U.S. Army Corps of Engineers, 2001) because the understory plants were often obscured by the overstory canopy in the aerial imagery used to construct the map. Thus, an accurate quantification of this component of the SPRNCA water use was not possible in this study.

Table 48. Reach length, average flood-plain width, seepwillow percent cover, and estimated total seepwillow amount for each reach, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[Derived from data in chapter C and appendix 7, table 7-G]

Reach number	Reach length (kilometers)	Flood-plain width (meters)	Seepwillow cover (percent)	Seepwillow amount (hectares)
1	8.1	203	2.05	3.4
2	7.6	155.5	2.1	2.5
3	6.1	185	3.4	3.8
4	2.3	305	1.7	1.2
5	6.5	175	1.8	2.0
6	3	269	2.1	1.7
7	4.1	64	1.3	.3
8	5.8	112.5	3.9	2.5
9	3.1	83	4.75	1.2
10	1.9	140	1.8	.5
11	2.1	63	4.7	.6
12	4.7	350	4.7	7.7
13	3.9	306	1.2	1.4
14	2.5	143	2.7	1.0
TOTAL				**30.0**

Table 49. Estimated riparian canopy area, open-water area, and ground-water use for 2003 along the main stem of the San Pedro River, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

[m^3/yr, cubic meters per year; ranges in values reflect uncertainty in the actual vegetation areas; <, less than]

Cover type	Cover amount (hectares)	Ground-water use (m^3/yr x 1,000)	Ground-water use (acre-feet per year)
Mesquite	1,154–1,456	7,953–10,035	6,448–8,135
Cottonwood-willow (perennial streamflow site)	253	2,444	1,981
Cottonwood-willow (intermittent streamflow site)	177	726	588
Sacaton (where ground water is < 3 m deep)	113–168	650–967	527–784
Open water	73	844	684
Tamarisk	72–108	496–744	402–603
TOTAL		**13,113–15,759**	**10,630–12,775**

Channel Evaporation

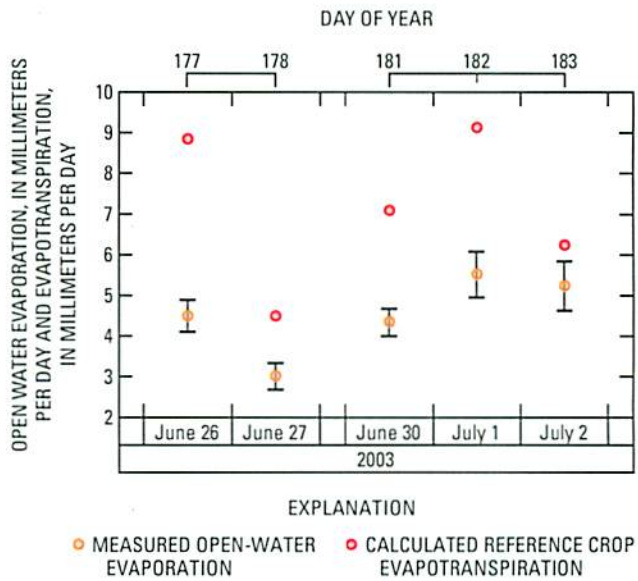
The daily variation in the mean small-pan evaporation rates and ET_o correlated well (fig. 70). Previously, Goodrich, Scott, and others (2000) estimated open-water evaporation as a constant fraction (0.6) of the Penman open-water evaporation amount to account for the more shaded streamside environment:

$$E_{ow} = \alpha E_p, \tag{13}$$

where

E_{ow} = the open water evaporation (mm/d),
α = is the reduction factor, and
E_p = the Penman potential evaporation (mm/d).

This study reveals that the average ratio between ET_o and the measured evaporation was 0.65. The total amount of water lost to evaporation from the open-water surface in 2003 was computed to be 1,156 mm; the sum of the yearly ET_o was 1,781 mm. By using this site-specific relation for the entire open-water surface within the SPRNCA is a gross simplification as site-specific conditions that would affect the evaporation rate (for example, the degree of canopy shading or amount of entrenchment) are highly heterogeneous. Fortunately, the amount of open-water surface is small (table 49) compared to the vegetation community amounts, so additional refinements in the open-water evaporation estimate were not warranted.



NOTE: The measurements were made using a network of 12 small pans distributed throughout the understory environment of the cottonwood gallery forest, and the calculated reference crop evapotranspiration was computed by using data from a nearby meterorological tower outside of the forest by using AZMETstandards. The average ratio between the measured and the calculated values is 0.65

Figure 70. Measured (with plus or minus one standard error) open-water evaporation compared to calculated open-water evaporation at the Lewis Springs site, 2003, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona.

Riparian Corridor Ground-Water Use

The preceding sections provide detailed results of the site-specific water-use measurements that were carried out for this study. The following information documents how these results were scaled up to estimate total ground-water use for various portions of the Upper San Pedro Basin.

Ground-Water Use Rates

Consumptive ground-water use was determined for 2003 because simultaneous measurements of the cottonwood forest, sacaton grassland, and mesquite shrubland were available only during that year. Only the 2003 measurements from the mesquite woodland were used in this exercise so that all the revised estimates came from the same growing season. An alternative to choosing one year to estimate water use would be to use these measurements to build and calibrate component models of each vegetation functional group (for example, cottonwoods along intermittent reaches), that could be used to model water use in any given year that meteorological data and amount of each cover type were available to drive the models. This alternative was not selected because (1) not enough data were collected (with the possible exception of data for the mesquite woodland site) to capture interannual variability, and (2) the incorporation of modeling would only lead to more uncertainty in the results. Future data collection and analysis may lead to a point where the factors that determine the water-use rates can be understood accurately, and then this understanding can be incorporated into in a model environment

The following list summarizes how the component ground-water use estimates in this study (table 50) were derived.

1. **Mesquite**. All mesquite within the riparian corridor of the SPRNCA were assumed to have the same ground-water use in 2003 as that of mesquite at the Charleston mesquite site ("Mesquite Woodland" section). The ground-water use rate per unit mesquite canopy area was derived from the growing-season water budget (table 47) and was equivalent to that of the mesquite shrubland site. The 2003 ground-water use derived from the water-balance calculation was used because (1) all other vegetation ET measurements were only available in 2003, (2) the isotope-partitioning method results were based on regression models using data collected only in 2001 and 2002, and (3) the water-balance method involved fewer assumptions. Using the water-balance calculation will probably result in a 2003 estimate that is conservatively high given the possible effects of hydraulic redistribution by the mesquite throughout the deeper vadose zone. Additionally, there are younger, smaller mesquite trees within SPRNCA (but outside the study sites) that are of insufficient size to tap into the ground water but nevertheless are part of the total mesquite area.

2. **Cottonwood-willow** (at perennial-streamflow locations). All cottonwood-willow stands along mostly perennial reaches where the maximum depth to ground water was estimated not to exceed 3 m (chapter C, table 15) were assigned the growing-season total water use estimated by the 2003 sap-flow studies at the Lewis Springs site ("Cottonwood Water Use" section). The portions of the SPRNCA that met these qualifications were delineated by the biohydrology reaches 2–7 (fig. 19). Isotopic data (Snyder and Williams, 2000) suggest that the cottonwoods at the Lewis Springs site derived most of their water from ground water. Thus, it was assumed that the seasonal total water use of the cottonwoods along reaches 2–7 was derived completely from ground water.

3. **Cottonwood-willow** (at intermittent-streamflow locations). All cottonwood-willow stands along intermittent reaches where the maximum depth to ground water exceeded 3 m were assigned the growing-season total water use estimated by the 2003 sap-flow studies at the Boquillas site ("Cottonwood Forests" section). The reach definitions and information in chapter C were used to assign this category to trees in reaches 1, and 8–14 (fig. 19). All the water used by these trees prior to the start of the monsoon was assumed to be derived from ground water and that 70 percent of the daily total transpiration between the start of the monsoon and leaf senescence was derived from ground water. Isotopic data collected by Snyder and Williams (2000) from a cottonwood site with similar ground-water depths supports this ground-water source apportionment. In 2003, multiple sapwood-tissue samples for isotopic source-water analysis were collected; these results, when available, should help to refine the fraction of total cottonwood water use supplied by ground water at both sites. The estimated total ground-water use of cottonwood-willow was about 410 mm (table 50), which is 84 percent of the total season transpiration of 484 mm.

4. **Sacaton** (located where depth to ground water was 3 m or less). The total canopy area of sacaton grasslands where the estimated depth to ground water was 3 m or less was assumed to have the 2003 ground-water use (Q_{veg}) of the sacaton grassland at the Lewis Springs site (see the "Mesquite Shrubland and Sacaton Grassland" section). The region where the estimated depth to ground water was less than 3 m was delineated by using LiDAR measurements and GIS analysis (see the "Determining Total SPRNCA Water Use" section) to determine the area that fell within the 3 m contour height above the cross-section low point—assuming that the water table perpendicular to the thalweg had the same elevation as the biohydrology transect low point. The amount of sacaton within this area was estimated by intersecting this delineated region with the vegetation (VEG00) map. LiDAR data were not available for the Babocomari River, the major tributary of the San Pedro River within the SPRNCA. For the Babocomari River, only the sacaton within the vegetation map that had 81 to 100 percent canopy cover was included—assuming that these dense sacaton areas probably

had access to ground water. The ground-water-use rate per unit sacaton canopy area was derived from the growing season water budget (table 47).

5. **Tamarisk.** Because tamarisk was not measured in this study, it was assumed that these trees had a water use equal to that of the mesquite. Reasons for this assumption are that both types of tree have a similar stand structures and both are able to acquire ground water from deeper sources than cottonwoods. Dahm and others (2002) reported a total ET of 740–760 mm per year for a medium-density stand of tamarisk along the Middle Rio Grande, New Mexico, though they did not estimate how ET was partitioned between surface-water and ground-water sources. The Dahm and others (2002) ET estimate was about 300 mm less than that for a dense stand of tamarisk and a mature cottonwood stand growing along the same reach. Measurements of mesquite ET and cottonwood ET along a perennial reach differed by a similar amount.

6. **Open Water.** Open-water evaporation estimates were derived from the total 2003 reference crop evapotranspiration, ET_o, calculated by using data from the meteorological tower at Lewis Springs (appendix 8). These estimates were multiplied by a factor of 0.65, which represents the ratio of average small-pan evaporation rate near or within the streambank to the calculated ET_o (see the "Seepwillow and Open Water Evaporation" section). Since measurements were only made during one part of the year, the ratio of reference-crop ET to open-water evaporation was assumed to be constant throughout the year.

Table 50. Ground-water use rates by vegetation type per unit vegetation area for 2003, Upper San Pedro Basin, Arizona

[Amounts represent yearly total ground-water use per unit vegetation area]

Cover type	Annual ground-water use during 2003 (millimeters)
Mesquite	689
Cottonwood-willow (perennial-streamflow site)	966
Cottonwood-willow (intermittent-streamflow site)	410
Sacaton (where ground water is less than 3 meters deep)	575
Open water	1,156

Vegetated and Open Water Areas

The change from the pixel-based vegetation map, VEG97, used by Goodrich, Scott, and others (2000), to the polygon-based GIS coverage, VEG00 (U.S. Army Corps of Engineers, 2001), used in this study, resulted in large changes in interpreted vegetation and open-water areas. As an example of this shift, there was a distinct change in the total amount of area covered by each of four ground-water-using groups along the San Pedro River between the USGS gaging stations at Palominas and near Tombstone (table 51). The ranges specified in the VEG00 map represent the minimum and maximum percents of vegetation cover. The amount of riparian vegetation was calculated as the product of total polygon area and percent cover (single value or range). The open-water area used in calculations is the entire open-water polygon area on the VEG00 map. For the areas listed in table 51, all cottonwood-willow polygons had an exact area assigned to them, which was not the case for the sacaton and mesquite polygons.

Table 51. Total canopy or open-water area covered by the ground-water-using groups along the San Pedro River between the U.S. Geological Survey streamflow-gaging stations San Pedro River at Palominas (09470500) and San Pedro River near Tombstone (09471550) using the maps of Goodrich, Scott, and others (2000) and this study, Upper San Pedro Basin, Arizona

Cover type	Vegetation map: VEG97	Vegetation map: VEG00
	Aerial coverage (hectares)	
Mesquite	1,166	718–964
Cottonwood-willow	526	308
Sacaton (where ground water is less than 3 meters deep)	382	362–512
Open-water	5	41

In this chapter, the uncertainty in the vegetation amounts was accounted for by computing a range of water use for each plant functional type. This range was computed by multiplying the minimum and maximum vegetation areas by the appropriate water-use amounts. The change in amount of vegetation between the VEG97 and VEG00 maps will result in a large change in the water-use amounts from those previously estimated by Goodrich, Scott, and others (2000). The magnitude of this change (about 40 percent for some vegetation types and 800 percent for open water) was as large as that for any change resulting from this study's refinement of plant ground-water use. Although there have been some

natural vegetation cover changes from 1997 to 2000, mainly due to fires, it is unlikely that vegetation cover differences between the VEG97 and VEG00 maps truly reflects change in the SPRNCA environment.

Riparian Corridor Ground-Water Use

The total amount of riparian cover for (1) the San Pedro River's riparian corridor from the southernmost boundary of the SPRNCA to the northernmost boundary (table 49), (2) the San Pedro River's riparian corridor from the United States' international border with Mexico to the USGS gaging station near Tombstone (table 52), and (3) the Babocomari River's riparian corridor (table 53) were multiplied by their respective ground-water consumptive-use rates (table 50) to determine total ground-water use (tables 49, 52, and 53). The amount of riparian vegetation within the private land inholdings just south of the Charleston Bridge site is included in the vegetation totals for the San Pedro River reaches (tables 49 and 52), but the amount of ground-water-using vegetation within these lands was only 7.7 ha because most of the riparian corridor fell outside of the property boundaries. It is important to include the Babocomari River's riparian vegetation water use within the water budget of the Sierra Vista watershed (even though a large part of the Babocomari River lies outside the SPRNCA) because the water use is significant.

Overall, mesquite ground-water use was the dominant component of the water budget with cottonwood-willow, open water, sacaton, and tamarisk ground-water use, respectively, being of decreasing importance. For ground-water use in the entire SPRNCA no previous estimates were available for comparison. This study's 2003 estimate for ground-water use along the San Pedro River from the United States' international border with Mexico to the streamflow-gaging station near Tombstone (table 49) was 4 to 27 percent higher than that of Corell and others (1996) and 12 to 37 percent higher than that of Goodrich, Scott, and others (2000).

The estimate of Corell and others (1996) for 1985–91 was derived from a base-flow analysis. This study's estimate of annual ground-water use along the Babocomari River (table 53) was larger than Corell and others' (1996). The estimates of Goodrich, Scott, and others (2000) were based on data collected in 1997; estimates for this study are higher owing to the new vegetation map and new water-use estimates. The total annual riparian ground-water use for the Sierra Vista Subwatershed was 11,840,000–14,867,000 m^3/yr (9,600–12,055 acre-ft/yr; tables 52 and 53), which is 25 to 57 percent greater than the 9,498,000 m^3/yr (7,700 acre-ft/yr) estimated by Corell and others (1996). Given the disparity between results calculated in this study and the results of Corell and others (1996), a beneficial element of future studies would be to examine whether ground-water-use rates determined for the major San Pedro River vegetation types can be extrapolated to the Babocomari River, as this study assumed, and further investigate and validate the two vegetation maps.

Table 52. 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, Arizona

[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 53. Estimated Babocomari riparian canopy area, open-water area, and ground-water use for 2003, Upper San Pedro Basin, Arizona

[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.

The study's water-use calculations are based on 2003 measurements; it is important to keep in mind that the mesquite water use varied from year to year (as much as 30 percent less, relative to 2003) during the 3 years mesquite-ET data were collected for this study. Seasonal variability were the climatic drivers that determine the length of the growing season, the amount of rainfall, and the atmospheric-evaporation demand. It is reasonable to expect that consumptive use by other vegetation communities would have similar variability. Interpretation of the limited period of record collected for this study indicates that ground-water use for 2003 probably was higher than what might be expected for 2001 and 2002 owing to the longer growing season (see appendix 8, table 8-B) and the smaller amount of winter and monsoon precipitation.

Summary

The purpose of this portion of the Upper San Pedro Partnership water-needs study was to provide improved estimates of ground-water use by the riparian vegetation and open water surface within the SPRNCA and within the Sierra Vista Subwatershed (see chapter A). Improved knowledge will enhance understanding of the riparian ET and the role of riparian vegetation ground-water use in the Upper San Pedro Basin's water budget. The approach used in this study was to make new, direct measurements of ET from dominant ecosystem types within the SPRNCA that are the principal components of the riparian ground-water demand. Estimates of ET partitioning between surface-water or ground-water sources were coupled with measurements of ET. Then, these revised and refined estimates of ecosystem ground-water use were combined with a new vegetation map of the SPRNCA and of the Babocomari River, the major tributary of the Upper San Pedro River, to extrapolate the local ET measurements across the basin to estimate total riparian ground-water use. The following improvements were made to the most recent estimates (Goodrich, Scott and others, 2000) of ground-water use along the San Pedro River:

Mesquite Woodland and Shrubland.— Mesquite is the most spatially extensive vegetation type within the San Pedro River's riparian corridor, yet its water use was identified as the most uncertain. The current study made multiyear ET observations from a mature mesquite woodland (Charleston mesquite site) and a mesquite shrubland (Lewis Springs site) and found 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 between sites. Stable-isotope measurements revealed considerable seasonal variation in the proportion of mesquite transpiration derived from ground water at several sites. Mesquite used a combination of surface–water (recent precipitation) and ground-water sources. A third source of water for mesquites was the deep (1–10 m below surface) vadose zone, where water likely was contributed both from surface-water and ground-water sources. The use of surface-water, ground-water, and deep vadose-zone sources depended on the availability of the sources 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, all mesquite used substantial quantities of ground water. Total annual ground-water use by a mesquite woodland at the Charleston mesquite site was determined by using two

methods (water-budget method and isotope-partitioning method), and the values were not in agreement. Recent studies at this site reveal that mesquite can redistribute significant amounts of water between deep and shallow soil layers during winter and summer months through its extensive root system (Hultine and others, 2004). This redistribution process likely was a reason for the disagreement in the water-use values. At this time, a way to quantify how much water was redistributed by the mesquite or whether the source of deep vadose-zone moisture was from precipitation or ground-water sources was not available. The water-balance approach did not account for the redistribution effects and resulted in seasonal ground-water use amounts for the mesquite woodlands of 488 mm in 2001, 394 mm in 2002, and 510 mm in 2003 (per unit ground area, table 42), which were about 50 percent higher than the estimates based on isotopic analyses (table 45). The value calculated by using the water-balance approach was used in the subsequent estimates of riparian corridor ground-water use because the water balance approach involved fewer assumptions and less extrapolation of the data collected. This water-use value likely was conservatively high because the possible redistribution of antecedent rainfall was ignored by using this approach.

Cottonwood Forest.— The current study measured sap flow during most of the 2003 growing season to estimate transpiration at perennial streamflow (Lewis Springs) and intermittent streamflow (Boquillas) sites. A cottonwood stand at the perennial reach transpired 966 mm, about 20 percent more water on a per canopy area basis than previous estimates. A cottonwood stand at the intermittent site transpired 484 mm in 2003, considerably less water than at the perennial site, and had greatly reduced rates of transpiration as the water table declined in the premonsoon period. Low rates of cottonwood forest transpiration at the intermittent site were a result of: (1) physiological stress acting on stomatal conductance of leaves, and (2) the sparse density of leaves at the stand level. Roughly 40 percent of the cottonwood forests in the SPRNCA were classified as being on intermittent reaches. Cottonwood source water sampling results (Snyder and Williams, 2000) indicate that all of the 966 mm of perennial site cottonwood transpiration was derived from ground water. Cottonwood ET at the intermittent site used 410 mm of ground water.

Sacaton.— The current study revealed that a sacaton grassland used 374 mm of ground water in 2003. The ground-water use of sacaton contradicted previous understanding. The depth to ground water at the Lewis Springs sacaton study site was less than about 3 m, and this likely was the reason for the discrepancy with the previous findings. The area where the land-surface elevation was within 3 m of the river stage was used as an estimate of the area where the depth to ground water was less than 3 m. The amount of sacaton within this area was determined by intersecting this delineated region with the vegetation map. About 30 percent of the total sacaton grassland area within the SPRNCA fell within this region. The sacaton within the 3 m depth to ground-water boundary was assumed to have the ground-water use of the sacaton measured in the current study.

Open-Channel Evaporation.— Open-water evaporation on the San Pedro River was estimated by multiplying a potential evaporation rate (derived from meteorological data) by a factor to account for reduction in evaporation caused by entrenchment of the river and shading by riparian vegetation. The current study made measurements of small-pan evaporation distributed throughout the near-stream environment at one site to compute a reduction factor. By using these measurements, open-water evaporation in 2003 was computed to be 1,156 mm.

Understory Species.— Seepwillow transpiration was measured by using sap-flow methods as a preliminary step toward quantifying seepwillow ground-water use, which had been ignored in previous studies. Vegetation measurements from the riparian biohydrology study (see chapter C) were used to estimate the amount of seepwillow within the SPRNCA. Measurements indicated that seepwillow transpiration on a per unit canopy area basis was nearly as large in magnitude as that for any of the major ground-water-using vegetation types studied in this report. Because total seepwillow cover along the SPRNCA was estimated to be low compared to other vegetation types, however, total consumptive use by seepwillow was small compared to the other components of the SPRNCA's ground-water use and was neglected from the ground-water use budgets.

Vegetation Mapping.— The use of a new vegetation map produced by the U.S. Army Corps of Engineers (2001) resulted in large changes in the computed amounts of vegetation within the SPRNCA. The new map provided a range for percent cover of the dominant vegetation type in each polygon; therefore, the exact amount of vegetation could not be calculated. The new map was clipped to the approximate extent of the riparian corridor. Reach-level information from the riparian biohydrology study (see chapter C) was used to enumerate the amount of cottonwood-willow forest that occurred along perennial or intermittent reaches. An additional calculation delineated the sacaton grasslands that occurred in regions having elevations equal to or less than 3 m of the river stage in order to delineate sacaton that used ground water.

Total Riparian Vegetation Ground-Water Use for the SPRNCA and the Sierra Vista Subwatershed.— Total vegetation and open-water areas were multiplied by their respective ground-water-use rates as determined by measurements made in 2003 to determine riparian ground-water use. For 2003, the total ground-water use by riparian vegetation within the SPRNCA was 13,113,000–15,759,000 m^3 (10,630–12,775 acre-ft). Mesquite ground-water use was the dominant component of the water budget followed by cottonwood-willow, open water, sacaton, and tamarisk ground-water use, in that order. This study's estimate of the riparian ground-water use along the San Pedro River from the

United States' international border with Mexico to the gaging station near Tombstone (within the Sierra Vista Subwatershed) for 2003 was 9,065,000–11,112,000 m^3 (7,350–9,010 acre-ft). This estimate is 12 to 37 percent higher than the estimate of Goodrich, Scott, and others (2000) for 1997 owing to the combination of using the new vegetation map and the new water-use estimates. Corell and others (1996) estimated an average of 8,758,000 m^3/yr (7,100 acre-ft/yr) for this reach for 1985–91. Combining results for the Babocomari River and the San Pedro River, this study estimated that 11,840,000–14,867,000 m^3 (9,600–12,055 acre-ft) of ground water was consumptively used by the riparian corridor within the Sierra Vista Subwatershed in 2003. This was 25 to 57 percent greater than the 9,498,000 m^3/yr (7,700 acre-ft/yr) of Corell and others (1996) owing in part to a large disparity between the estimates for the Babocomari River. It is important to recognize the influence of interannual climatic variability on these estimates. For example, interpretation of only 3 years of data, show that the annual mesquite ground-water use varied by as much as 30 percent (relative to 2003). It is reasonable to expect that the functioning of other vegetation communities are similarly affected by climate variability and that the riparian water use fluctuates to a similar degree.

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