The water use of two dominant vegetation communities in a semiarid riparian ecosystem

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Abstract

Consumptive water use from riparian evapotranspiration is a large
component of many semiarid basins' groundwater budgets – comparable in
magnitude to mountain front recharge and surface water discharge. In most
long-term groundwater studies the amount of water used by phreatophytes
is estimated by empirical formulae and extrapolation of measurements
taken elsewhere. These approaches are problematic due to the uncertainties
regarding the vegetation's water source (e.g., groundwater or recent
precipitation) and its magnitude. Using micrometeorological techniques in
this study, surface energy and water fluxes were measured for an annual
cycle over two dominant types of vegetation in the riparian floodplain of
the San Pedro River in southeastern Arizona. The vegetation communities
were a perennial, floodplain sacaton grassland (*Sporobolus wrightii*) and a
tree/shrub grouping composed largely of mesquite (*Prosopis velutina*).
These measurements are compared with estimates from previous studies.
Additionally, measurements of soil water content and water table levels are
used to infer the dominant sources of the evaporated water. The results
indicate that the grassland relied primarily on recent precipitation, while
the mesquite obtained water from deeper in the soil profile. Neither
appears to be strongly phreatophytic, which suggests that the dominant,
natural groundwater withdrawals in the Upper San Pedro Basin are mainly
confined to the narrow cottonwood/willow gallery that lines the river.

1 Introduction

For many of the human settlements in the semiarid Southwest, water from regional aquifers has become the largest single source of fresh water. Without this groundwater resource, the further development and perhaps even the sustainability of these communities would not be possible. This reliance has led to a significant effort to improve our understanding of the water balance of these regional groundwater systems.

In the basin and range physiographic province that characterizes much of the Southwest, the main natural inlet and outlet of the underlying groundwater systems are mountain front recharge and riparian zone recharge/discharge areas. Mountain front recharge is the infiltration of mountain precipitation into the "headwaters" of the aquifer. This typically occurs from streams that carry water out onto the highly permeable sediments of the mountain pediments. Water, having thus entered the regional groundwater aquifer, flows down gradient to the center of the basin. There, in areas such as southern Arizona, the groundwater table can intersect the ground surface and provide baseflow to streams and water for vegetation. This area where groundwater interacts (continuously or intermittently) with surface water and vegetation is called the riparian corridor. Odum (1971) defines a riparian region as an area of vegetation that exerts a direct biological, physical, and chemical influence on, and are influenced by, an adjacent stream, river, or lake ecosystem, through both above-and below-ground interactions.

The Upper San Pedro River Basin in southeastern Arizona and northern Sonora, Mexico (Figure 1a) is an ideal area in which to investigate these poorly understood processes of regional aquifer water balance. Unlike many riparian systems that have been disrupted due to the lowering of the groundwater table by

pumping, the basin has a lengthy reach of intact perennial flow, which sustains a relatively lush riparian corridor vegetation (Grantham, 1996). From previous observation and modeling studies, three dominant components of the basin's natural groundwater system have emerged. These three components–mountain front recharge, surface water discharge, and water uptake by riparian vegetation– are estimated to be of similar magnitude. (Corell et al., 1996; Vionett and Maddock, 1992)

It is widely believed that the presence of large-scale groundwater pumping in the nearby urban areas of Sierra Vista and Fort Huachuca has created a cone of depression which has, or will soon, diminish the baseflows in the river. The disruption of riparian corridor ecology due to groundwater depletion has been well documented throughout this region (Stromberg, 1993a, 1993b; Grantham, 1996). Numerous groundwater modeling and conceptual studies have been performed for various sub-basins of the San Pedro. All of them include the "Sierra Vista sub-basin" (See Figure 1a), the area of principal concern due to the larger amount of pumping therein (Kreager-Rovey, 1974; Freethey, 1982; Rovey, 1989; Vionnett and Maddock, 1992; Corell et al., 1996). The latest groundwater model of the Sierra Vista sub-basin was developed by the Arizona Department of Water Resources (Corell et al., 1996). This model estimates a pre-1940 steady-state mountain front recharge of 63,769 m^3 day^{-1} (18,870 ac-ft yr^{-1}) and an annual groundwater baseflow discharge to the stream of 32,206 m^3 day^{-1} (9,530 ac-ft yr^{-1}). With these major inputs and outputs they calculate an evapotranspiration rate of 26,697 m^3 day^{-1} (7,900 ac-ft yr^{-1}) by matching observed baseflows and well hydrographs. Riparian consumptive use in the model is assumed to be that portion of riparian vegetation water use withdrawn strictly from the saturated zone. For their 1940-1990 transient run water balance, Corell et al. (1996) report a mountain front recharge of 64,209 m^3 day^{-1} (19,000 ac-ft yr^{-1}), a base-flow

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discharge of 24,213 m^3 day^{-1} (7,165 ac-ft yr^{-1}), and an average well extraction of 30,317 m^3 day^{-1} (8,971 ac-ft yr^{-1}). This "post-development" simulation resulted in an evapotranspiration rate of 25,524 m^3 day^{-1} (7,553 ac-ft yr^{-1}). This value of 25,524m^3 day^{-1} (7,553 ac-ft yr^{-1}) matches well with an estimate of 26,021 m^3 day^{-1} (7,700 ac-ft yr^{-1}) based on an analysis of stream flow records, which estimated ET by using the difference between estimated baseflow in winter and summer.

These latest model simulations and conceptual estimates (Corell et al., 1996) of riparian vegetation water use from the water table compare well with the Vionnet and Maddock's (1992) previous modeling estimate of 26,690 m^3 day^{-1} (7,898 ac-ft yr^{-1}) but differ greatly from the Arizona Division of Water Resources observational estimate of 48,833 m^3 day^{-1} (14,450 ac-ft yr^{-1}) for the Sierra Vista sub-basin (ADWR, 1991). This observational study first mapped the species composition, extent and density of the San Pedro riparian corridor using a multi-spectral classification of a June, 1986 Landsat satellite image. The unsupervised classification was refined with large-scale color aerial photography interpretation and field verification. Table 1 reports the resulting categories of riparian vegetation and their associated areal coverage within the Sierra Vista sub-watershed– a delineation that includes the section of the river from the international border to the USGS Tombstone river gage (ADWR, 1991). This information along with species-dependent riparian vegetation water use rates from the lower Gila River valley in Arizona (Gatewood et al., 1950) and local meteorological information were used to derive Blaney-Criddle (Blaney and Criddle, 1950) estimates of riparian corridor evapotranspiration. Table 1 also reports the estimated consumptive rate for each species grouping along with a yearly flux rate on a per area basis. It is important to note that this estimate for total riparian corridor water use does not distinguish between vegetation water

use that is derived solely from groundwater and that which comes from other sources such as recent precipitation and river bank flooding. This points to an important distinction that we will try to address herein, namely, the importance of estimating both the quantity and the source for riparian evapotranspiration in order to delineate the transpired water which is a part of the groundwater budget.

In many areas within the Sierra Vista sub-basin, the riparian corridor is composed mainly of three natural vegetation groupings. A dense canopy of tall cottonwood and willow trees (*Populus fremontii, Salix gooddingii,* and *Baccaris glutinosa*) is crowded near the banks established by primary and secondary channels of the river. Beyond this forest canopy lies a broad floodplain (~100-500 m wide laterally) covered principally by a perennial floodplain bunchgrass called giant sacaton (*Sporobolus wrightii*). Finally, between the sacaton and the upper benches beyond the riparian area lies a community composed mainly of mesquite trees (*Prosopis velutina*), although the mesquites in this area are interspersed with several other woody shrubs and grasses. The objective of our study was to use micrometeorological techniques to quantify the water use of the sacaton and mesquite areas of the riparian corridor over the course of several seasons; this being the time scale relevant to groundwater models. By doing so, we hoped to better understand two of the three commonly encountered vegetation groupings in the San Pedro riparian corridor. Additionally, we monitored the status of the soil moisture and the water table elevation underneath these areas to help identify the source of the evaporated water. Numerous observations indicate that the sacaton and the mesquite are deep rooted; thus, they have been thought to rely mainly on water taken up from the nearsurface water table when they exist in riparian corridors. The cottonwood/willow gallery is the subject of other observational studies (e.g., Qi et al., 1998; Schaeffer et al., this issue; and Goodrich et al., this issue).

2 Background

2.1 Study Sites

Two vegetation study areas nearby Lewis Springs on the San Pedro River floodplain in southeastern Arizona, USA were chosen as the field sites for this study. A location map is given in Figure 1a. The study sites are located approximately 30 km southwest of Tombstone, Arizona and 20 km east of Sierra Vista, Arizona. The climate of the upper San Pedro valley is semi-arid with temperatures ranging from a mean maximum temperature of 24.8 °C to a mean minimum temperature of 9.9 °C (1960-1990 averages recorded in Tombstone). The precipitation distribution is bimodal with about 60% of the rainfall occurring during the summer monsoon months of July - September and 23% occurring in the winter months of December - March. The annual average precipitation is 343 mm at Tombstone though rainfall in this area has a high spatial and temporal variability.

One of the two study sites was established in the mesquite-dominated upper portion of the floodplain as seen in Figure 1b, a vegetation map for the site. This area was covered principally by ~3 to 6 m high mesquite but other species of grasses and shrubs were also found there. These include isolated clumps of sacaton grasses (*Sporobolus wrightii*) and shrubs such as whitethorn acacia (*Acacia constricta*), cat-claw acacia (*Acacia greggii*) and Mormon tea (*Ephedra spp.*). The other monitoring site was established in the sacaton grass-dominated lower portion of the floodplain, between the mesquite area and the cottonwood/willow tree gallery immediately adjacent to the river (Figure 1b). This site was mainly composed of ~1 m high sacaton bunchgrass, but a few smaller mesquite shrubs, tobosa grass (*Hilaria mutica*), and vine-mesquite grass

(*Panicum obtusum*) also existed within this vegetation area. The percent vegetation cover and species composition for the mesquite and sacaton areas were estimated from a 3 m thermal-IR image taken in 1997. The areal coverage within a 50 m radius of the sacaton tower was classified as about 80% sacaton, 10% shrub, and 10% bare soil. The coverage nearby the mesquite tower consisted of about 50% mesquite, 20% shrub, 20% grass, and 10% bare soil cover. While the mesquite area is not as dense or homogeneous as the typical mesquite bosque (or forest) found in other areas of the Southwest, it was representative of the other mesquite areas within the Upper San Pedro.

2.2 Methods

In 1996, we established one ten-meter-high meteorological tower at each of the two study sites. These towers were equipped with a set of standard meteorological instruments to measure the air temperature, relative humidity, incoming solar radiation, air pressure, wind speed, wind direction, and precipitation. The measurements were sampled every ten seconds and an average value recorded every twenty minutes. Additionally, the towers were equipped with instruments to measure the available energy (net radiation minus ground heat flux) and Bowen ratio, β, the ratio of sensible heat flux to latent heat flux. By measuring the difference in air temperature, ΔT (°C), and vapor pressure, Δe (kPa) under grass and the one under bare soil at two levels above the ground, the Bowen ratio was calculated from:

$$\beta = \gamma \frac{\Delta T}{\Delta e} \tag{1}$$

where γ is the psychrometric constant (kPa °C^{-1}). With this technique the amount of energy that is consumed at the land surface by the evaporation of water

can be determined. The total latent heat flux, λE, was then calculated from:

$$\lambda E = \frac{R_n - G}{1 + \beta} \tag{2}$$

where R_n is the net radiation at the land surface (W m^{-2}), and G is the ground heat flux (W m^{-2}).

Energy balance Bowen ratio (EBBR) systems (originally designed by Campbell Scientific Inc., Logan, Utah USA[1] were deployed over both sites. In the sacaton grassland, temperature and humidity were measured at 2.1 and 5.6 m above the ground, while over the Mesquite site, the height of the two levels were 5.9 and 10.0 m. Air was ducted continuously from the two heights into 2 liter, polyethylene buffer bottles; vapor pressure measurements were made every second from air that was sampled, alternating every two minutes, from these two bottles. These values were averaged and recorded every twenty minutes. Air temperature measurements were made every second with 75-μm diameter, chromel-constantan thermocouples located at each height and a twenty-minute average was recorded. Net radiation was measured with Q7.1 net radiometers (REBS Inc., WA USA) installed on separate tripods just south of the met towers at 4 m above a surface of grass and bare soil at the Sacaton site and at 4.7 m above a partial covering of mesquite, grass and bare soil at the Mesquite site. Soil heat flux at each site was obtained as an average of two measurements using soil heat flux plates (REBS Inc., WA USA) buried 0.08 m below grass and bare soil. The soil temperature above the heat flux plates was found by averaging soil thermocouple measurements made at 0.02 and 0.06 m above the heat flux plates. The soil heat flux at the surface was then calculated by adding the measured heat flux at 0.08 m to the change in energy stored in the layer above the heat flux plates ($0 - 0.08$ m), which is proportional to the rate of change of soil temperature measured by

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[1]The use of this and other commercial names in the paper is not intended as an endorsement of the product.

the soil thermocouples (Campbell Scientific, 1991).

Numerous difficulties have been reported (Nichols, 1992; Unland et al., 1996; Unland et al., 1998) when deploying this particular type of EBBR system in arid conditions. In this study, problems resulted from: 1) using the proprietary chilled-mirror, dew-point hygrometer to measure vapor pressure in arid environments; 2) leaks in the tubing, buffer bottles and connectors of the ducting system that is used to bring air from two different levels to the vapor pressure measuring device; and 3) condensation inside the tubing of the ducting system. To avoid difficulties with the dew-point hygrometer encountering conditions outside of its operating range and occasional ice formation on the mirror, we installed a more dependable HMP35D temperature/RH probe (Vaisala, Woburn, MA USA) to measure vapor pressure in the air ducted from the two different levels. Tests showed a good agreement between this probe and the hygrometer when both instruments were functioning within normal operating range. Cellier and Olioso (1993), who tested similar modifications for an EBBR system confirm our modifications. To insure that the ducting system was operating correctly, regular pressure tests were made at least every two months to check for leaks in the ducting. On numerous occasions, except for the warmest, driest months of the year, condensation occurred inside the tubing used for ducting the air to the humidity sensor. This problem resulted in a span of erroneous data (for about 1-4 hours, depending on its severity) after daybreak and was caused by the outside air temperature (and consequently, the dew point temperature) rising rapidly at dawn while the temperature rise inside the ducting lagged behind due to the thermal inertia of the ducting. Thus, air with a higher dew point was imported into a cooler environment and condensation could occur. This condensation happened almost daily, except for the driest months of April, May and June, and was detected during data processing by examining both the inside and outside

vapor pressure measurements. Condensation was indicated by a rapid rise and fall in the vapor pressure of the air ducted from one of the Bowen ratio intakes which was coincident with a difference between the vapor pressure measured with the Bowen ratio system and that measured with a separate humidity probe. Return to acceptable Bowen ratio measurements was diagnosed by the internal vapor pressure once again tracking the outside measurement. While this operation did not "solve" the condensation problem, it was extremely helpful in determining periods of erroneous data. Additionally, fluxes were not computed when the measured Bowen ratio was close to -1, specifically for the range $-0.4 > \beta > -1.6$. This condition occurs routinely for short morning or evening periods when the energy for evaporation is low, sensible and latent heat fluxes are in opposite directions and approximately equal, and the Bowen ratio method cannot determine the magnitude of the fluxes.

In order to compare the results of this study with a reference evaporation rate that can be computed with standard meteorological data alone, we computed the reference crop evaporation rate, E_{rc} (Shuttleworth, 1993). The reference crop evaporation is an estimate of the evaporation, which would occur from a short, well-watered grass with a fixed-height of 0.12 m, an albedo of 0.23 and a surface resistance of 69 s m^{-1}. It is calculated in units of mm day^{-1} by the following formula:

$$E_{rc} = \frac{\Delta(R_n - G)}{\Delta + \gamma^*} + \frac{900\gamma}{\Delta + \gamma^*(T + 275)}U_2 D \qquad (3)$$

where R_n is the net radiation exchange for the crop cover [mm day^{-1}], G is the soil heat flux [mm day^{-1}], T is the air temperature [°C], U_2 is the wind speed at 2 m [m s^{-1}], D is the vapor pressure deficit [kPa], Δ is the slope of the saturation vapor pressure versus temperature curve, γ is the psychrometric constant (kPa °C^{-1}), and γ^* is a modified psychrometric constant (kPa °C^{-1}).

The evaporation rate from a well-watered crop or vegetation community can differ from that of a reference crop of well-watered grass. Typical differences are $\pm$ 10-20% (Shuttleworth, 1993). We present this reference crop evaporation as a first order estimate of the evaporation that might have occurred from the cottonwood/willow riparian forest. Evaporation from the riparian forest would possibly differ from the reference crop due to differences in canopy architecture (e.g., roughness and height), available energy (e.g., lateral advection of energy, shading of canopy understory), water availability and boundary layer differences between the atmosphere and leaf surfaces, etc.

In order to understand possible controls on evaporation, we also monitored the state of the vadose zone soil moisture and the depth to groundwater. Soil thermocouples and water content reflectometers (WCRs - Campbell Scientific Inc., Logan, Utah USA) were installed in a vertical profile at 0.1, 0.25, 0.50, 1.0, and 2.0 m depth (0.1, 0.25, 0.50, 1.0, and 1.5 m under the sacaton) to measure the soil moisture under the each site. One 0.3 m probe was installed at each level. Hourly measurements were made of soil temperature and WCR probe frequency, this frequency being primarily sensitive to the amount of moisture in the soil. A piezometer was installed nearby each site to measure the fluctuations in the water table. Depth to groundwater and surface gravimetric soil moisture (0 – 0.05 m) were sampled manually approximately every two weeks, but hourly measurements were made on some days to quantify diurnal variations.

2.3 Measurement Accuracy and Representativeness

Energy Balance Bowen Ratio Measurements

EBBR measurements are prone to both random and systematic errors. Random errors are likely to be small when averaged in the cumulative flux values reported in this study. Systematic errors in the EBBR measurements can result from errors in the net radiation, soil heat flux, and in the measurement of the Bowen ratio.

Both the net radiometers used in this study were calibrated against a standard, four component Kipp and Zonen net radiometer (CNR 1, SCI-TEC Instruments Inc., Canada) to within an average root mean square error of 8 W m^{-2}. 80% of the upward contribution to net radiation comes from a circular region 18.8 m in diameter directly below the radiometer at the Mesquite site and from a 16 m diameter circle at the Sacaton site (L. Hipps, personal communication). We estimate that systematic errors in net radiation are pessimistically, 15%, and optimistically, 5%.

The soil heat flux is likely to be highly variable and is poorly sampled by a single heat flux plate under grass and a second under bare soil. However, sampling under grass and under bare soil will capture the extreme values of soil heat flux. These two measurements differed by as much as a factor of 2, depending on the time of day and season. Thus, we estimate errors in soil heat flux as pessimistically, 50%, and optimistically, 20%.

Errors in the Bowen ratio measurement vary, depending on the surface conditions. Temperature gradients are normally large and easily measured with the separation between measurement levels used in this study. When the daytime Bowen ratio is small, vapor pressure gradients are more pronounced and thus easily measured. However, when the vegetation is inactive and little water is being evaporated, the

vapor pressure gradient is very small, so small that the gradient can be less than the resolution of the temperature/RH probe. However, the computed latent heat flux is small under these conditions and contributes little to the cumulative latent heat flux. Given the uncertainties in the net radiation, the ground heat flux and the Bowen ratio, we estimate systematic errors in the computed latent and sensible heat fluxes to be pessimistically, $\pm$ 30%, and optimistically, $\pm$ 10%.

The micrometeorological approach used to measure evaporation in this study can only realistically provide measurements representative of a particular type of vegetation cover when there is a reasonably extensive, uniform area of that vegetation immediately upwind of the instruments. Thus, using micrometeorological techniques requires some knowledge of the flux footprint (i.e., the source area for the signal measured at the sensor). Horst (1999) points out that defining a flux footprint for the Bowen ratio technique is only possible in limited circumstances. Regardless, we used a simplified approach suggested by Schuepp et al. (1990, 1992) to estimate the source area for the measured fluxes. Assuming the roughness length, $z_o = 0.1 h_v$, and the zero plane displacement height, $d = 0.75 h_v$, where h_v is the average vegetation height equal to 3.4 m for mesquite and 0.75 m for sacaton. Assuming a typical daytime value for the sensible heat flux of 300 W m^{-2} and an air temperature of 30°C, for the mesquite tower, 80% of the measured (latent or sensible) heat flux is calculated to originate within 30, 84, 148, and 212 m of the tower for windspeeds of 1, 2, 3, and 4 m s^{-1}, respectively. Similarly, 80% of the flux measured at the sacaton tower is calculated to originate within 23, 64, 114, and 165 m of the tower for windspeeds of 1, 2, 3, and 4 m s^{-1}, respectively.

Both sites were located within an approximately rectangular region about 200 m wide (East/West) and several hundred meters long North/South (Figure 1b). Inspection of Figure 1b indicates that upwind sources of different land cover types

can lie within the footprint of the Bowen ratio measurements under certain circumstances. For example, under moderate to heavy westerly winds, the footprint at the mesquite tower includes contributions from the (presumably drier) upland desert scrub. Analysis showed that the winds were generally light across the site. The mean wind speed was 1.7 m s^{-1} and the median wind speed was 1.2 m s^{-1} at 10 m height over the Mesquite site, and the wind predominantly followed the south to north orientation of the river. In these typical conditions, the flux measurements primarily represent the land covers of interest, and in this paper, it is the average evapotranspiration that is of primary interest. The amount of time with poor fetch is fortunately only a small proportion of the time during which measurements were made. (Only 7% of the EBBR measurements were recorded when wind speeds at 10 m height were in excess of 3 m s^{-1} with wind direction between 225° and 315°.) In the following we therefore assume that the reported fluxes are in conditions with reasonably adequate fetch.

Soil Moisture Measurements

A combination of different techniques was used to calculate volumetric water content from the WCR frequency. First, an *in situ* calibration was made during installation where the probe period (inverse of frequency) was related to volumetric soil water content measured from gravimetric water content and bulk density samples taken at each probe depth. This information was used to modify Campbell Scientific's recommended calibration polynomial to best match data collected from the installation. Probe-computed water content was also corrected for temperature fluctuations in the soil following the recommended correction provided by the manufacturer. Periodic soil auger gravimetric water content measurements, along with the bulk density measurements made during the trench excavations, were made throughout the year to verify the probe calibration.

These subsequent auger measurements indicated that a simple, one-time adjustment (an offset of $\pm$ 0.02 - 0.07 m^3 m^{-3} added to the computed water content) was needed at most levels to minimize the difference between auger measurements and probe computed water content. It was difficult to get a good match using these methods, but a laboratory calibration using the site specific soils resulted in a calibration curve, which performed worse than the *in situ* technique reported here. We suspect that the calibration difficulties arose due to vertical soil heterogeneity in the profile (we used the same polynomial for each of the levels in the profile), probe-specific contact between the probe rods and the soil, and sampling errors in the bulk density and gravimetric measurements made from the auger. Given these difficulties, the WCR measurements reported later in this paper should be viewed more as an indicator of relative changes in water content rather than an absolute ones– keeping in mind that the measurement error might be as large as 0.03 to 0.10 m^3 m^{-3} for a given probe.

Due to cost limitations, only one 0.3 m probe was used to sample at each depth under each site, and this restricts the representativeness of the soil moisture measurements. Trench excavations revealed that the soil at each site was quite homogeneous in the horizontal plane, but significant layering of sand and gravel was observed at the Mesquite site. In spite of the uncertainty, the qualitative picture of the moisture redistribution process given by the probes under each site suggests that our soil moisture sampling is fairly accurate, and we assume this in the subsequent analysis.

We have collected data from both sites from 1996 to 1998. However in this paper, most of the data that we will present were collected from March 13, 1997 to March 13, 1998. We focus on this time period to present the water use characteristics of the two sites over the course of a full annual cycle when we had relatively complete Bowen ratio and vadose zone monitoring. Bowen ratio data

collected prior to this period were not used because they may have been prone to error due to leaks in the ducting system. In June, 1998, the sacaton site was completely burned due to a wildfire and monitoring was discontinued thereafter. For the Mesquite site, EBBR monitoring continued till November, 1998, but much of the data collected during the monsoon period was invalid due to equipment malfunctioning. We will, however, present additional soil moisture and precipitation data from the Mesquite site from March, 1997 to November, 1998 to demonstrate the vadose zone dynamics under the rainier conditions of 1998.

3 Results

Figure 2 presents some basic meteorological information from the Mesquite site during the March, 1997 - 1998 period. In Figures 2-5, days of the year are plotted on the abscissa with a value of 365 added to days in 1998. Figure 2a presents average daily solar radiation and net radiation. Figure 2b plots the average daily dewpoint temperature (solid line) and the daily minimum/maximum air temperatures (dashed lines). Figure 2a shows that net radiation closely follows solar radiation in this most often dry and sunny climate. The nearly periodic dips in the radiation curves are evidence of the storm frequency for the region. Figure 2b shows that the hottest part of the year in this region occurred during the months of June and beginning of July prior to the onset of the monsoon season. The arrival of the rainier monsoon was around July 19, 1997 (DOY 200) where the increase in dewpoint temperature was evidence of the increase in moisture over the region. The riparian valley itself received cold air drainage from the uplands and was substantially colder than other areas in the valley at night. In 1997, nocturnal freezes occurred in the springtime till April 26 (DOY 116) and the first freeze of fall was October 12 (DOY 285). For reference, the first freeze of

autumn was October 23 in 1996 and October 6 in 1998. The last springtime freeze in 1998 was May 15. We will show later that these freeze dates seem to bound the transpiration activity of the mesquites.

Figure 3 shows cumulative evaporation and precipitation measured at both monitoring sites for the March 1997-1998 period. To calculate cumulative values, it was necessary to use (linear) interpolation when there were missing 20-minute records. Missing data occurred most days, usually in the early morning or late afternoon, when available energy is close to zero and the Bowen ratio is close to -1, and also during those hours when condensation occurred (see Section 2.2). A total of about 12% of the measurements or, on average, about 3 hours per day were estimated by interpolation. There were also occasional gaps in the record due to equipment malfunctions. These periods of missing record were filled by using the daily available energy from the alternate tower multiplied by the average evaporative fraction $(= \frac{\lambda E}{R_n - G})$ at the site of interest calculated a period of equal record length prior to equipment malfunction. In other words, we assumed that the evaporative fraction did not change significantly during these unmeasured times. For example, if two days of data were missing, we assumed that the evaporation rate for each day in the missing period was equal to the daily available energy (measured at the other site) multiplied by the average evaporative fraction from the the previous two days. Fortunately, these missing periods were often brief. They are indicated in Figure 3 by an "x" on the solid line.

Figure 3 shows that the yearly total precipitation at both sites was 247 mm, while the total evaporation loss measured at the mesquite site was 375 mm and that from the Sacaton site was 272 mm. The water use characteristics at the two adjacent sites were markedly different. For the sacaton, water use was strongly tied to recent precipitation and the seasonal cycle (the grass was senescent during

the wintertime). The grass did not green up during the dry spring of 1997 following an unusually dry winter of 1996-1997 with only a few green, basal shoots observed. Finally, when the more abundant rainfall of the monsoon season arrived, around DOY 200, the grassland ended senescence and began to take up water. This activity continued throughout late summer and then tapered off during the drier and colder months of October and November (DOY 270 - 330). For the mesquite site, total evaporation was less dependent on recent precipitation. The mesquite trees leafed out after the last nighttime freeze of spring on April 26, 1997 (DOY 116) and then transpired at a fairly constant rate throughout the growing season. The mesquite evaporation rate fell rapidly immediately following the first freeze of autumn on October 12 (DOY 285), thus providing indirect evidence that mesquite leaves cannot tolerate freezing conditions.

For the pre-monsoon period of May 15 to June 30 (DOY 135 – 181), the average evaporation rate for the Mesquite site was 1.6 mm day^{-1}, compared to 0.3 mm day^{-1} for the Sacaton site and 7.3 mm day^{-1} for the reference crop evaporation (not shown in Figure 3). For the monsoon period of August 1 to September 15 (DOY 213 – 258), the average evaporation rate for the Mesquite site rose to 2.4 mm day^{-1} (Sacaton = 1.6 mm day^{-1}; reference crop = 5.0 mm day^{-1}). At the Mesquite site, the 1.6 mm day^{-1} pre-monsoon rate is largely indicative of the mesquite transpiration alone, and the jump to 2.4 mm day^{-1} during the monsoon most likely reflects the added contribution of bare soil evaporation along with additional transpiration from the grasses and small shrubs, which greened up with the increased, near-surface soil moisture. The increase seen at the Sacaton site from the pre-monsoon to monsoon period is simply a matter of the grass becoming active. The wintertime evaporation is higher from the Sacaton site than at the mesquite site when the vegetation was senescent. This is arguably because

the sacaton area has more clayey, less well-drained soils relative to the mesquite area leading to higher soil evaporation. The reference crop evaporation rate far exceeds that of the mesquite and the grass; on a weekly average basis, it is about four times higher than the mesquite rate during the dry, pre-monsoon period and decreases to about twice the magnitude during the monsoon. This implies that the mesquites (or at least, some of them) are water-limited throughout the year, though never as much as the sacaton.

Figures 4a and 4b shows average daily volumetric soil moisture at depths of 0.10, 0.25, 0.50 and 1.0 m inferred by the water content reflectometers at the Sacaton (Fig. 4a) and Mesquite site (Fig. 4b). Figure 4c presents the daily precipitation for this same period of March, 1997 - 1998. The probes at 0.5 m and deeper under the sacaton failed to operate after DOY 260 due to electrical damage caused by a nearby lightning strike. For the entire monitoring period, no measurable changes were indicated at a depth of 2 m in the mesquite profile nor at the depth of 1.5 m under the sacaton . Two very different behaviors between the sites are apparent. For the sacaton profile, where the vadose zone is composed of a fairly homogeneous silty-clay to clay textured soil, there was a general increase in soil moisture with depth to the water table, located around 3 m below ground surface. The low permeability soil appears to prevent rainfall from penetrating to depth and almost all of the significant changes in soil moisture happened within the upper 0.25 m of the soil profile. For the mesquite profile, the vadose zone is composed of loamy/sandy-loam textured soils interspersed with thin gravel lenses. Consequently, rainfall penetrated farther into the soil column than at the Sacaton site. Moreover, the nearly uniform soil moisture with depth suggests that the profile was fairly well drained. At this site, the water table was at ~10 m depth. While the soil column shows very little change of soil moisture at 0.5 m and below during the summer rains, Figure 4b begins to show that soil

wetting penetrated to greater depth during the winter rains, and this may serve as a moisture source for mesquite transpiration during the subsequent dry season.

Figure 5a and 5b is an extension of the soil moisture and precipitation time series shown in Figures 4b and 4c, into the period of March to November, 1998 at the Mesquite site. We note that the scale for soil moisture and precipitation has been expanded in this figure to accommodate the higher values of soil moisture and daily precipitation observed during this time period. During this comparatively wetter year, recharge occurred at greater depths into the profile. The profile was wetter in the springtime and the decrease seen at 0.5 m around May 15, 1998 (DOY 500) coincides with the leafing out of the mesquite and the greening up of smaller shrubs and grasses that happened at this time. Also, Figure 5a shows the first and only time during our monitoring that we observed deeper, vadose zone recharge. Significant wetting down past 1.0 m occurred after receiving more than 58 mm of rain on August 12 (DOY 589), a day which was preceded by a 28 mm rainfall event.

4   Discussion

The measured, cumulative evaporation and precipitation shown in Figure 3 provides compelling evidence that the sacaton at the study site relied on recent precipitation as its principle source of water. Although sacaton roots were observed to extend to depths greater than 2 m during trench excavation, these deeper roots did not appear to extract water of any significant extent. Indeed, the grass became active only after water from monsoon rainfall had substantially moistened the surface soil layer. During the drier, hotter months of April, May, June, and the first half of July, 1997, most of the grass near the tower was almost

completely inactive, with only a few sparse green shoots interspersed in the large clumps of dry grass. Moreover, sacaton evaporation is seen to increase immediately after precipitation events and then decrease between the inter-storm periods of the monsoon (DOY 200 - 300, Figure 3). This behavior provides additional evidence that the sacaton responds to surface soil moisture, and does not access significant quantities of groundwater.

As a caveat to the hypothesis that the sacaton is non-phreatophytic in nature, we note that sacaton in the floodplain within about 10 - 20 m of the riverbank was noticeably greener during the dry season. Although the water table in this region might only be 0.5 - 1 m closer to the surface, it appeared that the sacaton located in this limited area were functioning as phreatophytes. One possible reason for this might be that the water table was slightly closer to the surface in this region. However, a second explanation is that the greener area was more for about 3 or 4 hours in the morning and that the air is perhaps more humid due to the presence of the nearby, tall forest gallery (see Figure 1b). Further evidence that the near-riverbank sacaton acts differently was apparent in June, 1998, when a fire burned the entire sacaton area. Within weeks of this event (and before any monsoon moisture had arrived), new green shoots were already sprouting vigorously from the sacaton located within about 20 m of the riverbank. Further away from the bank, re-growth was less noticeable.

Given that the evaporation data and our observations suggest that the majority of sacaton evaporation was solely reliant on recent precipitation, it is arguably possible to estimate the accuracy of the EBBR measurements from a simple water balance calculation. Assuming negligible runoff from this level site, the sum of the evaporation and the change in soil moisture storage should equal the total precipitation. The total sacaton evaporation during the study period was 272 mm, and the change in soil moisture storage was +30 mm based on before- and

after-study soil auger gravimetric measurements multiplied by a depth-dependent bulk density (sampled during trench excavations) and an effective depth. The basic error in the water balance is therefore 22%. However, precipitation gages are prone to under-catch due to local wind field effects, and tipping bucket gages may have difficulty in measuring all the precipitation in high intensity storms. Making a conservative 5% correction to the total precipitation, the water balance error is around 16%, consistent with our error estimate in Section 2.3.

The Mesquite site had a markedly different water use than the sacaton. In this case, the cumulative total evaporation shown in Figure 3 suggests a water use that is more closely tied to available energy than recent rainfall in frost-free periods. Thus, it appeared that mesquites obtain water from deeper in the soil column. For some days in the middle of the growing season, water table levels below the mesquite were measured on an hourly basis. If mesquites obtain water from the saturated zone, cyclical, diurnal fluctuations should occur in the water table elevation: numerous studies have reported such a phenomenon under phreatophytes (e.g., Todd, 1959; Gatewood et al., 1950; Tromble, 1972). However, we did not detect diurnal changes in water level of the piezometer at the Mesquite site. This suggests that either the trees were obtaining water from the deeper (2 - 10 m) vadose zone rather than from the saturated zone, or, alternatively, that the mesquites' water uptake from the saturated zone might not have been large enough to affect the water levels at the piezometer. We can assume that the pre-monsoon evaporation rate for the Mesquite site was primarily representative of the more mature, deep-rooted mesquite trees alone since they were the only visibly active plants at the site. With this assumption, an average rate of about 1.6 mm day^{-1} is a conservative estimate of mesquite water use from deeper in the vadose zone and/or from the capillary fringe at our site.

The fact that the cumulative total mesquite evaporation loss of 374 mm is close

to the 343 mm annual-average precipitation at nearby Tombstone, Arizona might be further evidence that the mesquite community as a whole does not withdraw much water from the water table. Arguably, if the mesquites relied solely upon the deep vadose zone soil moisture, the average-annual mesquite water use is expected to be equivalent to the long term average precipitation (but not necessarily the precipitation total in any one year). Moreover, the evaporation rate for the Mesquite site in this study is, for instance, vastly different from that measured at a mesquite thicket located along the upper Santa Cruz River of Arizona (Unland et al., 1998). Unland et al. (1998) report a consumptive water use of 848 mm/year in 1995, which is more than twice that measured at our site. While both measurements were made over vegetation composed primarily of mesquite trees, the Santa Cruz site had taller and denser canopy. Additionally, the water table was closer to the surface (1 - 2 m) at the Santa Cruz site , and occasionally the site was flooded.

Finally, we compare our summer, monthly average ET from the mesquite community with several average values reported in the literature. Table 2 shows the average total evaporation between May and September in comparison with values from previous studies of the water use of mesquite in southern Arizona. Specifically, the three other studies were:

1. a study of mesquite (100% cover) growing in large tanks (Gatewood et al., 1950),

2. a water balance study for a mesquite bosque (80% cover) growing over a small confined aquifer (Tromble, 1972), and

3. a micrometeorological study using an EBBR system over a mesquite bosque (~80% cover) (Unland et al., 1998).

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The average depth to groundwater for these studies was about 1.5, 3 and 3 m, respectively. Table 2 shows that the average evaporation at the Upper San Pedro site is 2 - 3 times less than those observed in previous studies. The reference crop rate is about 1 to 4 times higher for the months of June to September and seems to be an approximate upper bound for the mesquite transpiration with the notable exception of Tromble's (1992) June value, which was probably due to a large amount of lateral advection into their site from the neighboring desert. Differences between our study site and the others reported in Table 2 are likely due to differences of the studies' mesquite tree areal density. The areal density of the mesquites is most likely determined by the depth to groundwater, which at our Mesquite site was much deeper (around 10 m). For example, the mesquite canopy cover at the Santa Cruz site (Unland et al., 1998) had an areal density of around 80%, whereas our Mesquite site was estimated to be 50%, the difference between the sites being a factor of 1.6. During the dry months of May and June when it was likely that only the deeper-rooted mesquite trees were active, Table 2 shows that our site differs from the Santa Cruz site by a factor of 2.2 (May) and 1.8 (June). However, we would not expect the transformation of an evaporation rate from an area with 50% cover to one with 80% cover to be linear since significant in-canopy feedbacks exist that would tend to reduce the evaporation per unit leaf area as the density increased.

At this stage in our study, we are not yet able to quantify the groundwater use of the riparian vegetation as a whole. Such an estimate will largely depend on an adequate estimation of the water use for the cottonwood/willow gallery. Also, it will be important to delineate the depth to groundwater of the different mesquite stands in the Upper San Pedro (or the density of the stand, which is a likely consequence of the water table depth), since our comparison suggests that the amount of groundwater they use varies accordingly. The vegetation classification

and associated water use given by ADWR, 1991 in Table 1 estimates a water use of 1271 mm/year for the cottonwood. For 1997, the transpiration activity of the riparian cottonwood and willow trees lasted approximately from mid-April to mid-October (DOY 110 – 285). Our reference crop estimate for this period is 982 mm. The ADWR classification did not delineate sacaton areas explicitly. For their "medium-dense mesquite" classification they applied a rate of 486 mm/year, while our measured yearly total was 374 mm/year. Our results suggest that much of this total is not derived from the saturated zone; thus, it might be appropriate to omit this category from a tally of total riparian vegetation groundwater use. If total water use were revised accordingly, the total evaporation would be 33,332 m^3 day^{-1}, which is closer to the model estimates of about 26,000 m^3 day^{-1} (Corell et al., 1996; Vionett and Maddock, 1992). Yet, it is important to re-emphasize that the ADWR estimates of dense-mesquite and cottonwood/willow evaporation need to be confirmed by future studies.

5 Conclusions

This research begins to address the question of how much groundwater is being used by vegetation located within a riparian corridor along the Upper San Pedro River, a perennial stream in southeastern Arizona, USA and northern Sonora, Mexico. This study quantifies the yearly water use of two common riparian biomes: a perennial, floodplain bunchgrass community and a moderately-dense mesquite area. Our results suggest that the strength of the vegetation water demand for the sacaton grassland closely followed the available precipitation. Within experimental error, the total evaporation from the Sacaton site was nearly equal to incoming precipitation. The floodplain grasses beyond the riverbank edges showed little ability to access water from the phreatic zone. For the

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Mesquite site, evaporation exceeded precipitation by a factor of about 1.5. In the mesquite area, there was likely a combination of different water acquisition strategies shown by the plants therein. The grasses and shallower-rooted shrubs seemed to rely on near-surface soil water, which was recharged by recent precipitation. The mesquite trees likely relied on water from deeper in the soil profile, which is probably a combination of both deeper vadose zone water (2 − 10 m depth) and water from the capillary fringe. These results based on the evolution of cumulative precipitation, cumulative evapotranspiration and soil moisture measurements indicate that much of the vegetation in these two areas of the riparian corridor are not using groundwater. Consequently, the two areas together used less groundwater than previously assumed. The results of this study suggest that, in order to estimate the groundwater use from riparian vegetation from the total riparian corridor in the Upper San Pedro, efforts should be concentrated principally on estimating the water use from obligate phreatophytes. The obligate phreatophytes are likely confined to the narrow, gallery forest immediately adjacent to the river, which is dominated by the cottonwood and willow trees, and to areas of dense mesquite stands.

6   References

ADWR, 1991. Hydrographic Survey Report for the San Pedro River Watershed. Vol. 1: General Assessment. Arizona Department of Water Resources. Filed with the court, Nov. 20, 1991. 604 p.

Blaney, H. F., and W. D. Criddle, 1950. Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data. USDA (SCS) TP-96, 48 p.

Campbell Scientific, 1991. Bowen Ratio Instrumentation Instruction Manual. Campbell Scientific, Inc., Logan, Utah, p. 4-3.

Cellier, P. and A. Olioso, 1993. A simple system for automated long-term Bowen ratio measurement. *Agric. For. Meteorol., 66*, 81-92.

Corell, S. W., F. Corkhill, D. Lovvik, and F. Putnam, 1996. A Groundwater Flow Model of the Sierra Vista Subwatershed of the Upper San Pedro Basin – Southeastern Arizona. Arizona Department of Water Resources, Hydrology Division. Modeling Report No. 10. Phoenix, Arizona. 107 p.

Freethey, G. W., 1982. Hydrologic Analysis of the Upper San Pedro Basin from the Mexico U.S. Boundary to Fairbank, Arizona. U.S. Geological Survey Open-file Report 82-752.

Gatewood, J. S., T. W. Robinson, B. R. Colby, J. D. Hem, L. C. Halpenny, 1950. Use of water by bottom-land vegetation in the lower Safford Valley, Arizona. United States Geological Survey Water Supply Paper 1103.

Goodrich, D.C., Scott, R., Qi., J., Goff, B., Unkrich, C.L., Moran, M.S., Williams, D., Schaeffer, S., Snyder, K., Mac Nish, R., Maddock, T., Pool, D., Chehbouni,

A., Cooper, D.I., Eichinger, W.E., Shuttleworth, W.J., Kerr, Y., Marsett, R. and Ni, W., 2000. Seasonal estimates of riparian evapotranspiration using remote and in-situ measurements. *Agric. For. Meteorol.*, this issue.

Grantham, C., 1996. An Assessment of the Ecological Impacts of Ground Water Overdraft on Wetlands and Riparian Areas in the United States. United States Environmental Protection Agency. EPA 813-S-96-001. 103 p.

Horst, T. W., 1999. The footprint for estimation of atmosphere-surface exchange fluxes by profile techniques. *Boundary-Layer Meteorol., 90*, 171-188.

Kreager-Rovey, C., 1974. Numerical Model of Flow in a Stream-aquifer System. Hydrology Paper No. 74, Colorado State University.

Nichols, W. D. 1992. Energy budgets and resistances to energy transport in sparsely vegetated rangeland. *Agric. For. Meteorol.*, 60. 221-247.

Odum, E. P. 1971. *Fundamentals of Ecology, third ed.* W.B. Saunders Co., Philadelphia, Pennsylvania. 574 p.

Qi, J., M. S. Moran, D. C. Goodrich, R. Marsett, R. Scott, A. Chehbouni, S. Schaeffer, J. Schieldge, D. Williams, T. Keefer, D. Cooper, L. Hipps, W. Eichinger, and W. Ni, 1998. Estimation of evapotranspiration over the San Pedro riparian area with remote and in situ measurements. American Meteorological Society, Special Symposium on Hydrology, Phoenix, Arizona, 11-16 Jan 1998. Session 1: Integrated Observations of Semi-Arid Land-Surface-Atmosphere Interactions, Paper-P1.13.

Rovey, C., 1989. Hydrologic Investigation of the Upper San Pedro Basin, Southeastern Arizona, Preliminary Report.

Schaeffer, S.M., Williams, D.G., and Goodrich, D.C. 2000, Transpiration of

cottonwood/willow forest estimated from sap flux, *Agric. For. Meteorol.*, this issue.

Schuepp, P. H., Leclerc, M. Y., MacPherson, J. I., and Desjardins, R. L., 1990. Footprint prediction of scaler fluxes from analytical solutions of the diffusion equation. *Boundary-Layer Meteorol., 50*, 355-373.

Schuepp, P. H., MacPherson, J. I., and Desjardins, R. L., 1992. Adjustment of footprint correction for airborne flux mapping over the FIFE site. *J. Geophys. Res., 97*, 18455-18466.

Shuttleworth, W. J., 1993. 'Evaporation' in Maidment, D. R. (Ed.), *Handbook of Hydrology.* McGraw-Hill, Inc., pp. 4.1-4.53.

Stromberg, J. C., 1993a. Riparian mesquite forests: a review of their ecology, threats, and recovery potential. Journal of the Arizona – Nevada Academy of Science 27. 111-124.

Stromberg, J. 1993b. Fremont cottonwood-Goodding willow riparian forests: a review of their ecology, threats, and recovery potential. Journal of the Arizona – Nevada Academy of Science 26. 97-110.

Todd, D. K. 1959. Groundwater Hydrology. John Wiley and Sons, Inc., New York.

Tromble, J. M., 1972. Use of water by a riparian mesquite community. National Symposium on Watersheds in Transition. American Water Resources Association and Colorado State University. 267-270.

Unland, H. E., P. R. Houser, W. J. Shuttleworth, and Z. L. Yang, 1996. Surface flux measurement and modeling at a semi-arid Sonoran Desert site. *Agric. For. Meteorol., 82*, 119-153.

Unland, H. E., A. M. Arain, C. Harlow, P. R. Houser, J. Garatuza-Payan, P. Scott, O. L. Sen, and W. J. Shuttleworth, 1998. Evaporation from a riparian system in a semi-arid environment. *Hydrological Processes, 12*, 527-542.

Vionnet, L. B. and T. Maddock, 1992. Modeling of Groundwater Flow and Surface Water/Groundwater Interactions in the San Pedro River Basin- Part I – Cananea, Mexico to Fairbank, Arizona; University of Arizona, Department of Hydrology and Water Resources, HWR No. 92-010.

Category	Areal Coverage [hectares] & (acres)	Evapotranspiration [m^3 day^{-1}] & (ac-ft yr^{-1})	Evapotranspiration per unit area [mm/year]
Cottonwood	541 (1337 acres)	18,840 (5575 ac-ft yr^{-1})	1,271
Dense Mesquite	630 (1556)	13,045 (3860)	756
Medium-dense Mesquite	1,164 (2875)	15,495 (4585)	486
Willow	17 (42)	558 (165)	1198
Cienega/Dense Grass	34 (84)	889 (263)	954
TOTAL	**2,386 (5894)**	**48,827 (14448)**	747

Table 1: Riparian vegetation categories and associated water use in the Sierra Vista sub-watershed of the San Pedro River Basin reported by ADWR, 1991.

	May	*June*	*July*	*August*	*September*
Gatewood et al., 1950	2.5	6.5	7.2	3.4	3.4
Tromble, 1972	4.5	11.8	NA	NA	NA
Unland et al., 1998	2.2	3.2	4.1	4.2	3.1
San Pedro Mesquite *This study*	1.0	1.8	2.0	2.4	2.3
Reference Crop *This study*	6.0	6.9	5.9	4.7	4.8

Table 2: This study's San Pedro average monthly values for mesquite evapotranspiration and reference crop evaporation versus other studies [mm day^{-1}].
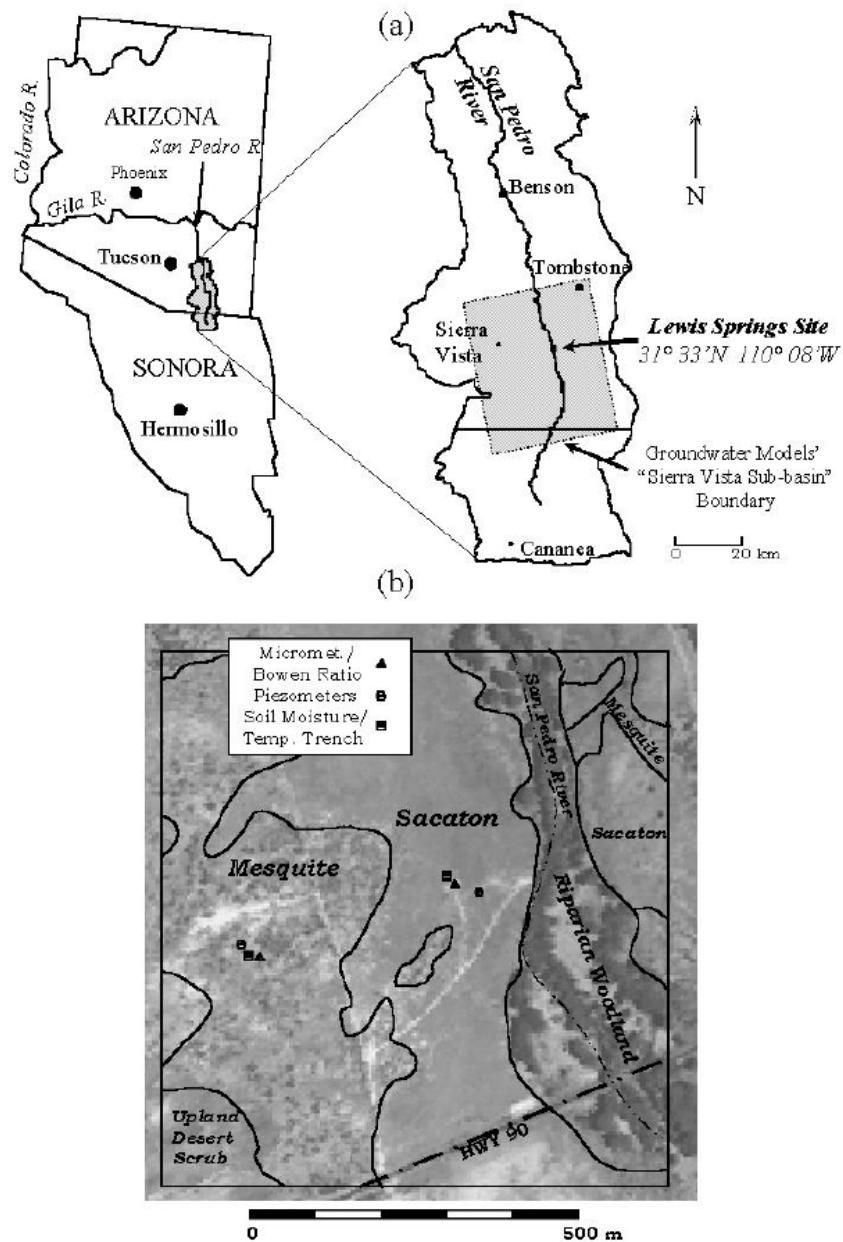
Figure 1: (a) Location map for the Upper San Pedro Basin in Northern Sonora, Mexico and Southern Arizona, USA. Study area for this report was in the riparian corridor of the San Pedro River, nearby Lewis Springs. The shaded area indicates the approximate boundary of the "Sierra Vista groundwater sub-basin" – an area of interest for many of the previous basin groundwater studies. (b) Greyscale, infrared image over Lewis Springs study site with locations of the sacaton and mesquite monitoring sites and approximate boundaries of the different vegetation groupings of mesquite, sacaton, and riparian woodland commonly found in the San Pedro riparian corridor
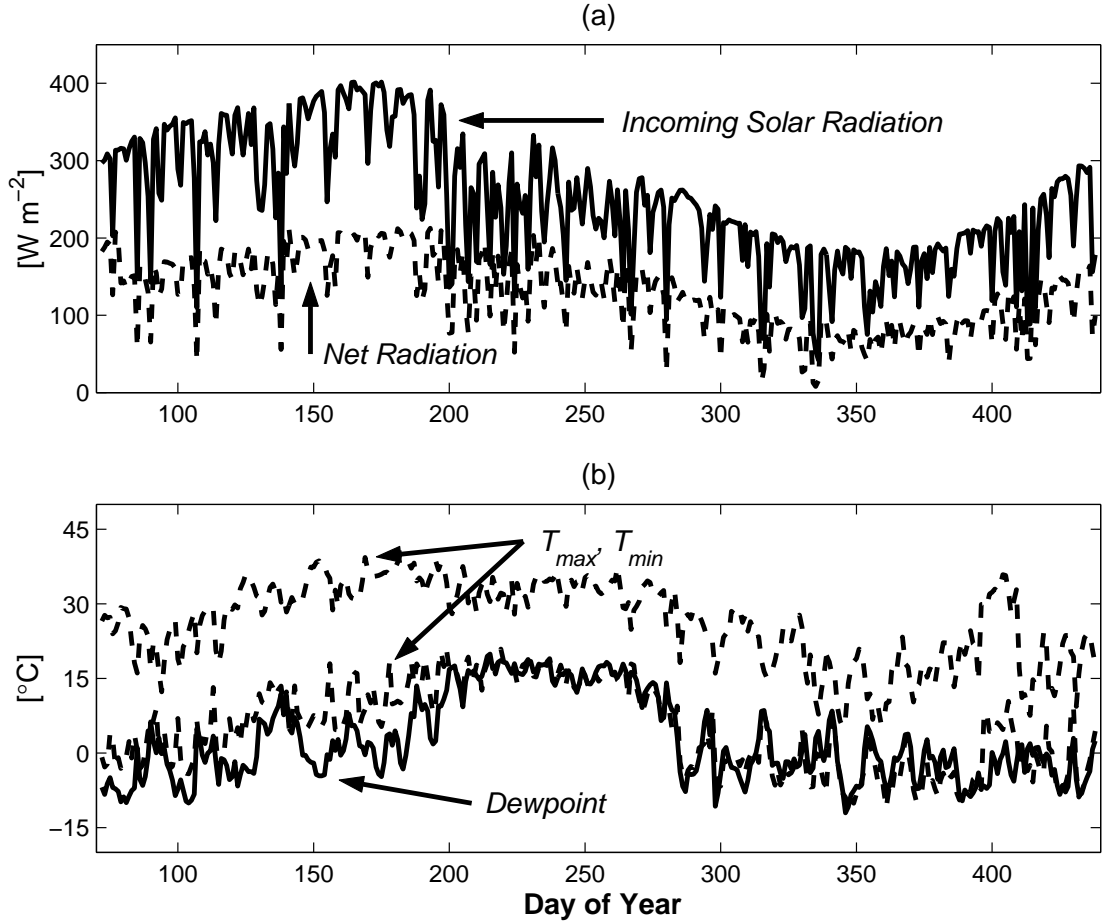
35

Figure 2: (a) Average daily incoming solar (solid line) and net (dashed line) radiation [W m^{-2}]. (b) Average daily dewpoint (solid line) along with daily minimum and maximum air temperature (dashed lines) [^{o}C] at 5 m height for the period of March, 1997 to March, 1998 at the Mesquite site. For Figures 2 - 5 a value of 365 was added to the days of the year in 1998
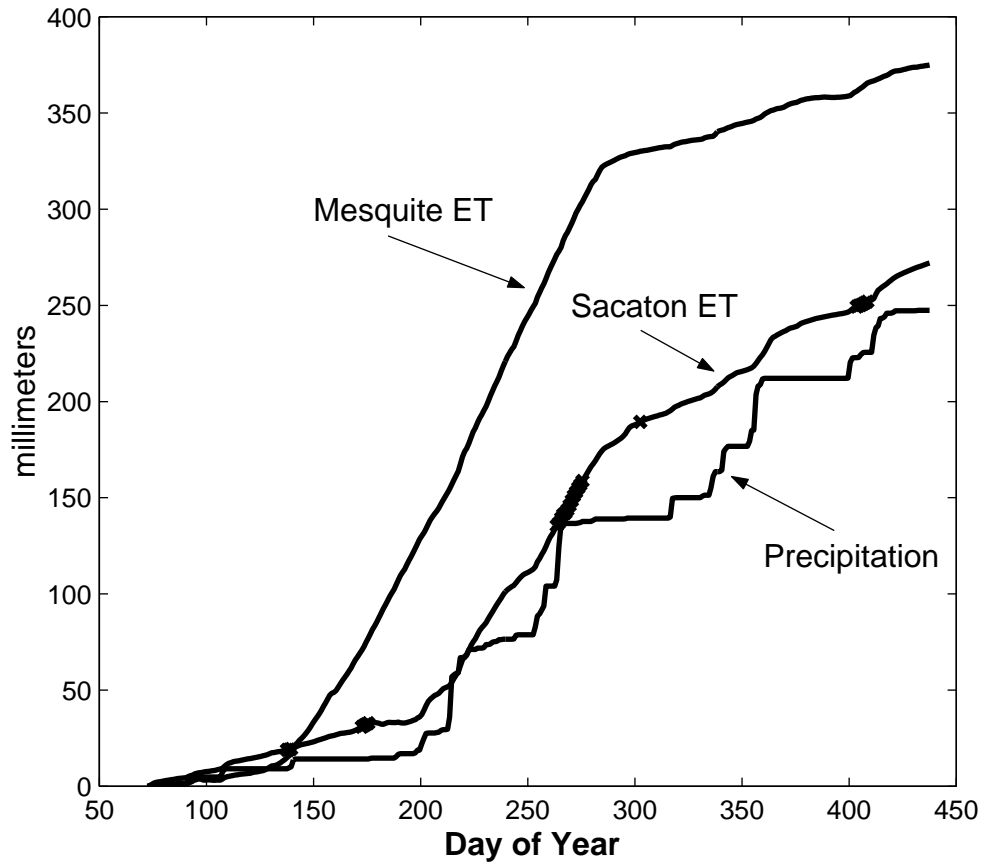
Figure 3: Cumulative precipitation and evapotranspiration from the sacaton and Mesquite sites for the period of March, 1997 to March, 1998. Periods of missing data, where the cumulative water use was extrapolated, are indicated by an "x".
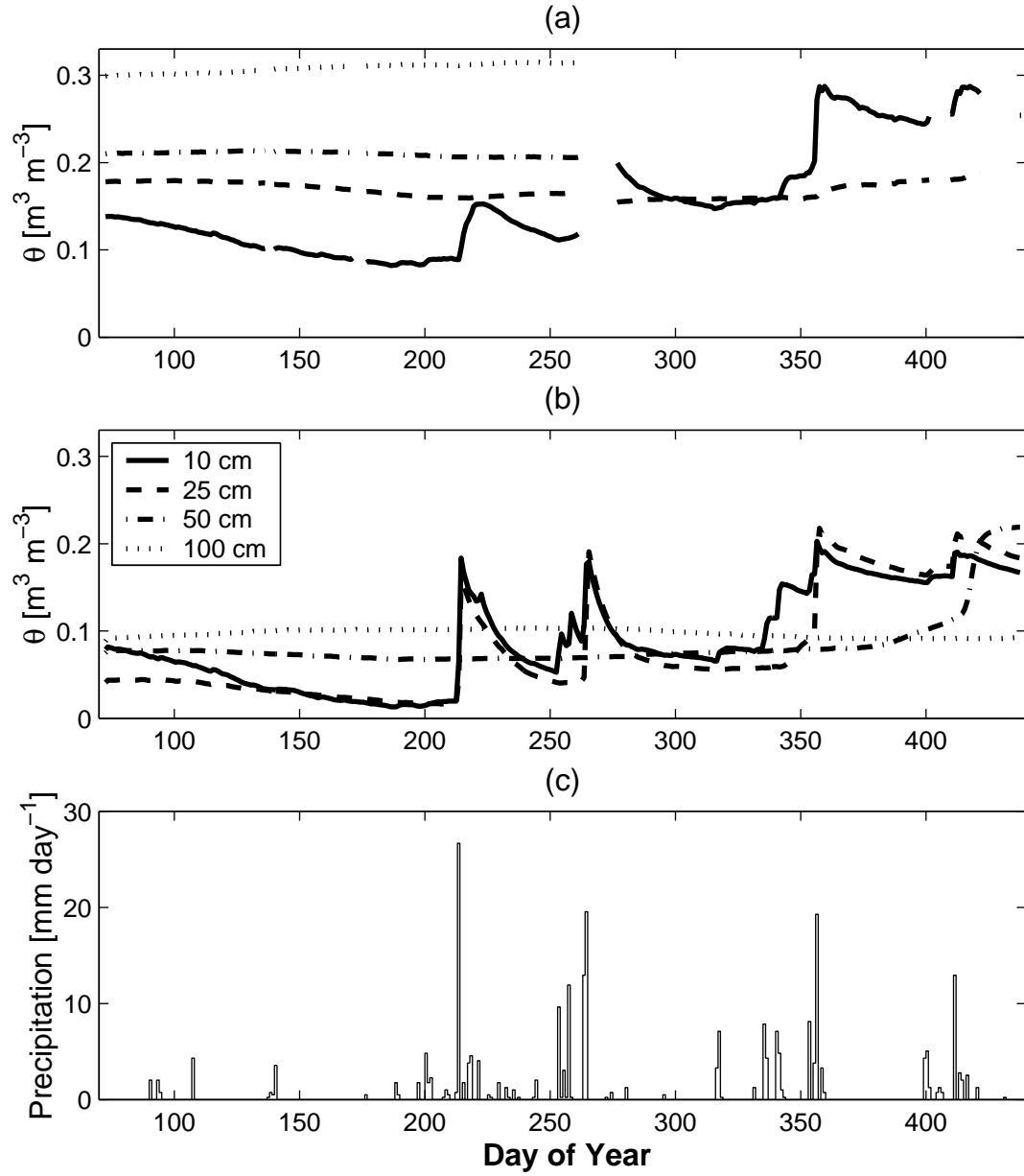
Figure 4: Volumetric soil moisture under the (a) Sacaton and (b) Mesquite sites measured at 0.1, 0.25, 0.5 and 1.0 m depth along with the (c) daily precipitation for the period of March, 1997 to March, 1998. In Fig. 4a, the probes at 0.5 and 1.0 m no longer functioned after DOY 260 and no data was recorded after DOY 421.
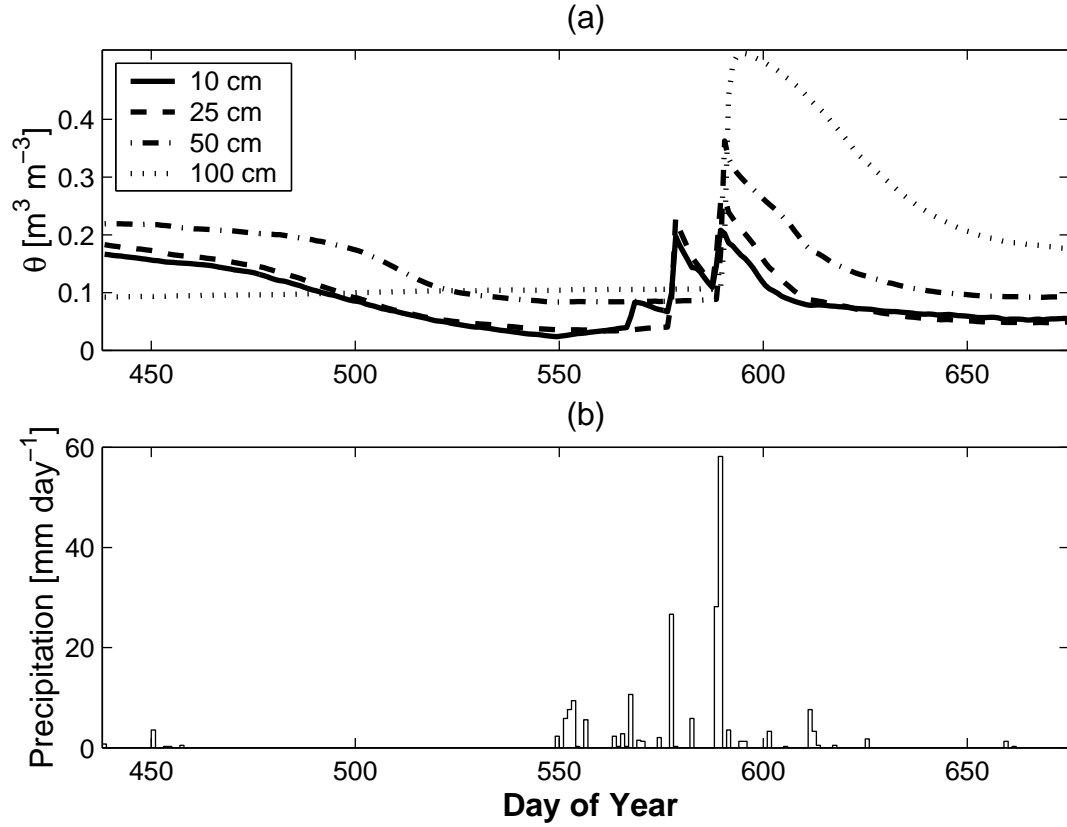
Figure 5: (a) Average daily volumetric soil moisture, θ, [m^3 m^{-3}] at 0.1, 0.25, 0.50 and 1.0 m depth under the Mesquite site for the extended period of March, 1998 to November, 1998. (b) Total daily precipitation [mm] at the site during this same period. The wetter winter and summer rainfall of 1998 (as compared to 1997) led to considerably deeper vadose zone recharge under this site.