

Vegetation-Hydrology Interactions

DYNAMICS OF RIPARIAN PLANT WATER USE

Introduction

Riparian vegetation intercepts surface and subsurface water flowing from drainage basins and forms a functionally important interface between terrestrial and aquatic ecosystems. The influence of riparian vegetation on hydrological processes (Malanson 1993, Tabacchi et al. 2000) and, conversely, the impact of hydrological processes on riparian vegetation (Rood and Mahoney 1990, Auble et al. 1994, Johnson 2000; and see chap. 1) have been the focus of considerable scientific investigation. Through such investigations, ecologists and hydrologists have formed productive, collaborative relationships and together have generated broad conceptual understanding of hydrological factors controlling riparian ecosystem structure and function and associated feedbacks with stream hydrology and geomorphology (Vannote et al. 1980, Minshall et al. 1985, Junk et al. 1989, Gregory et al. 1991, Stromberg et al. 1993).

Riparian vegetation influences hydrological processes through effects on runoff and through control of uptake, storage, and return of water to the atmosphere (Tabacchi et al. 2000). Interactions between riparian vegetation and hydrological processes are especially strong in arid and semi-arid basins where the quantity and spatio-temporal distribution of water clearly

determine the composition and structure of vegetation and associated biogeochemical processes. The stream catchment is commonly used as the fundamental unit for hydrological study, and it is within this unit that ecologists and hydrologists make measurements at a compatible scale.

This chapter describes the current state of knowledge of vegetation-hydrology interactions in riparian ecosystems of arid and semi-arid basins, focusing on studies conducted along the upper San Pedro River. We highlight some key concepts related to the influence of riparian plants on stream hydrology, describe patterns of water use by dominant vegetation communities along the San Pedro River, and evaluate some of the principal methodologies used to make these determinations. The upper portion of this river near the international border with Mexico has been the focus of numerous ecohydrological studies (D. Williams et al. 1998, Goodrich, Chehbouni et al. 2000, Goodrich, Scott et al. 2000, Schaeffer et al. 2000, R. Scott et al. 2000a, 2004, R. Scott, Goodrich et al. 2003, R. Scott, Goodrich et al. 2006, Snyder and Williams 2000, 2003, Yopez et al. 2003, Hultine et al. 2004). The principal goal of this research is to understand the impact of climate variability, land-cover variation and change, and hydrogeology on the water balance of riparian vegetation. These studies have focused particularly on evapotranspiration by riparian vegetation with special emphasis on groundwater use by velvet mesquite (*Prosopis velutina*) and sacaton (*Sporobolus* spp.) bunchgrass on terraces and Fremont cottonwood (*Populus fremontii*) on floodplains. These three, together with Goodding's willow (*Salix gooddingii*), and the shrubs seepwillow (*Baccharis salicifolia*) and saltcedar (*Tamarix* sp.), are the dominant vascular plants along primary and secondary channels, floodplains, and terraces of the river (see chap. 1).

The hydrogeomorphic, geologic, and climatic setting of the upper San Pedro River is complex (see chaps. 13 and 15). Variation in the type and depth of underlying bedrock, texture and composition of alluvial materials, and channel morphology produces substantial spatial heterogeneity in depth to groundwater, streamflow, and unsaturated zone hydraulic properties. Layered over this complex spatial geomorphology and hydrology is riparian vegetation characterized by heterogeneous patterns and agents of disturbance. Precipitation, an important driver of ecohydrologic patterns and processes, is seasonally and interannually variable in this semi-arid environment. The complexity of riparian vegetation structure, hydrogeomorphic setting, and climate in the upper San Pedro River basin creates significant challenges and opportunities for research aimed at understanding processes linking vegetation and hydrology and scaling these processes to the catchment level (Goodrich, Scott et al. 2000, R. Scott, Goodrich et al. 2006).

The need for better understanding and modeling of vegetation-hydrology interactions in riparian zones of arid and semi-arid basins is critical because

(1) a high level of regional biological diversity in dry landscapes occurs within riparian ecosystems, (2) riparian vegetation plays an important role in nutrient biogeochemistry affecting water quality (Peterjohn and Correll 1984; and see chap. 18), (3) riparian environments are valuable to humans for recreation and aesthetic appeal, and (4) abstraction of groundwater or diversion of streamflow for other human uses requires quantitative and objective evaluation of potential impacts on vegetation (Rood and Mahoney 1990, Hughes and Rood 2003).

Vegetation-Hydrology Interactions in Riparian Ecosystems

The role of riparian plants in stream hydrologic processes is best illustrated using the concept of a hydrologic balance (eq. 1).

$$Q_{in} + G_{net} + P - Q_{out} - ET - \Delta S = 0 \quad [\text{eq. 1}]$$

Here, Q_{in} and Q_{out} are streamflow into and out of the defined reach, G_{net} is net input of groundwater, P is precipitation occurring within the defined reach, ET is evapotranspiration from plants, soil and open water, and ΔS is the change in water storage in the alluvial floodplain deposits. Riparian plants can physically influence the hydraulic properties of the streambed and floodplain surface, thereby affecting transmission and storage of water in alluvium (Tabacchi et al. 2000). Further, the structural and physiological characteristics of dominant riparian plants control patterns, sources, and rates of ET at the landscape scale (Sala et al. 1996).

THROUGHFALL, STEMFLOW, AND INFILTRATION

Riparian plants influence the capture and cycling of precipitation. That fraction of precipitation falling on vegetation which does not quickly evaporate passes through the canopy as throughfall or is routed via stemflow to the plant base, where it can infiltrate the soil (Crockford and Richardson 2000). Living and dead plant roots and coarse debris at the ground surface create and alter infiltration flow paths, facilitating rapid transmission of direct precipitation, throughfall, and stemflow to deeper soil layers.

HYDRAULIC REDISTRIBUTION

Roots create macro-pores for infiltration and percolation and also modify water transport processes in riparian floodplains through "hydraulic redistribution" (Dawson and Pate 1996, S. Burgess et al. 2001, Hultine, Cable et al. 2003, Hultine, Williams et al. 2003, Hultine et al. 2004). When living root systems span soil layers with different moisture levels, water is passively redistributed along gradients from wet to dry soil layers through uptake and leakage by fine roots (Caldwell et al. 1998). Hydraulic redistribution, known as "hydraulic lift," when soil water is transported upward in the soil profile,

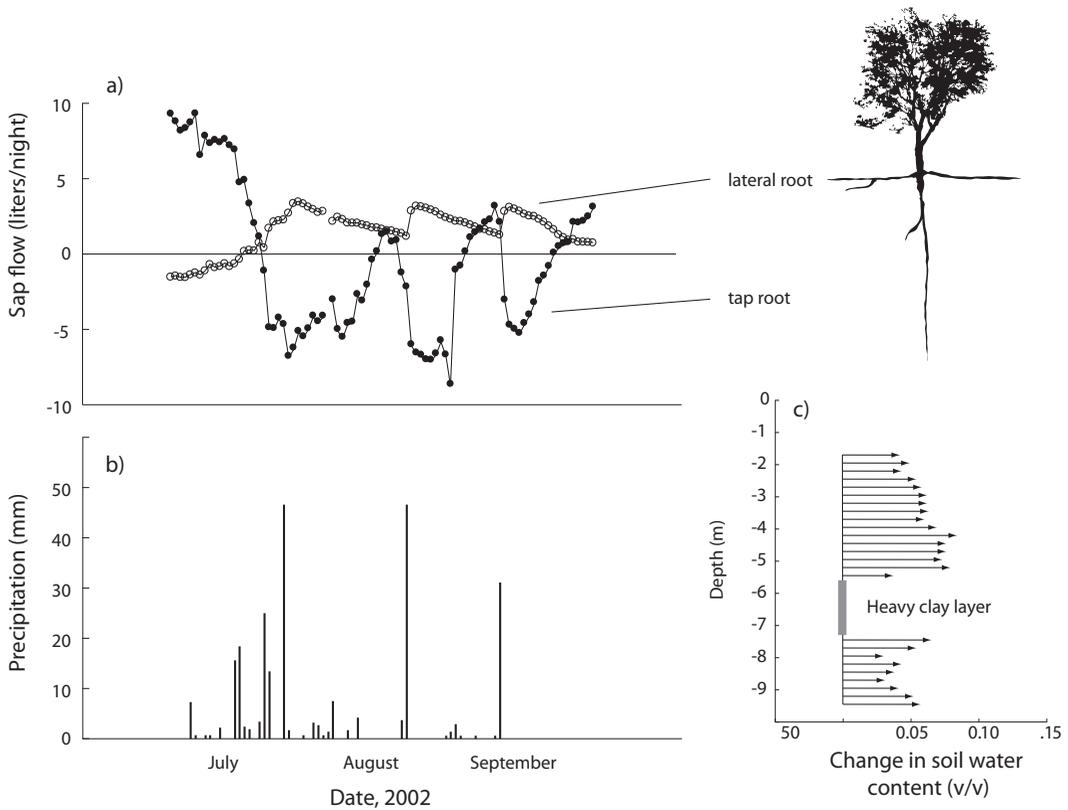


Fig. 2.1. (a) Total nocturnal sap flow of a tap root and lateral root of a large mesquite tree (*Prosopis velutina*) on a pre-entrenchment terrace along the San Pedro River in southeastern Arizona. Negative values indicate flow from tree to soil, and positive values represent flow from soil to tree. (b) Daily precipitation totals at this field site during the 2002 summer growing season. (c) Change in soil water content measured by cross-borehole ground penetrating radar (GPR) at the same field site in deep unsaturated soil layers (below layers directly wetted by precipitation and above the capillary fringe of the water table) from June 17, 2002, before the onset of the summer monsoon, to September 25 of the same year at the end of the monsoon. From Hultine et al. (2004). Used with permission.

typically occurs at night when root water potentials (the relative potential energy of water) rise as transpiration-induced tension on plant xylem water is reduced. The rise in energy of root water compared to water in the surrounding soil allows water to move passively from inside the root to the soil, in the opposite direction from daytime patterns. The wetted soil stimulates microbial activity, facilitating mineralization of important plant nutrients (Caldwell et al. 1998). Although the ecological significance of hydraulic redistribution may, to a large degree, be associated with effects on nutrient availability, the amount of water redistributed by plant root systems is not trivial (D. Smith et al. 1999, Hultine et al. 2004, Ryel et al. 2004).

It is still questionable whether hydraulic redistribution substantially alters landscape-level hydrologic balances. Hultine et al. (2004) revealed that sustained periods of downward hydraulic redistribution by velvet mesquite

on upper river terraces of the San Pedro during the summer monsoon corresponded to progressive accumulation of water deep in unsaturated alluvial substrates (fig. 2.1). If this accumulation at depth was strictly a function of hydraulic redistribution of groundwater and rainfall by mesquite roots, as the data suggest, and not rapid transmission of rainfall through soil macro-pores, then widespread conversion of sacaton grassland to mesquite-dominated communities may profoundly alter the relationships between precipitation, moisture storage in shallow and deep soil layers, and ET in riparian floodplain environments. Increased moisture storage in deep unsaturated layers resulting from hydraulic redistribution by mesquite would enhance the available water for this deep-rooted shrub during dry periods. Hydraulic redistribution by mesquite root systems takes place also during winter months when mesquite canopies are dormant and leafless; thus, mesquite presence potentially affects the spatial and temporal dynamics of both winter and summer precipitation storage (ΔS) and use within these ecosystems (Hultine et al. 2004).

EVAPOTRANSPIRATION OVERVIEW

Evapotranspiration is a dominant, but poorly characterized, component of the riparian corridor water balance. ET includes water taken up and transpired by plants to the atmosphere and direct evaporation of water from the stream, soil, and living and dead plant surfaces. Evaporation of precipitation intercepted by plant canopies is included within this term and can account for as much as 30 percent of the total ET, depending on microclimatic conditions, plant species composition, and rainfall intensity and duration (Shuttleworth 1988, Crockford and Richardson 2000). Evaporation from soil surfaces and interception constitutes a substantial fraction of ET release in upland ecosystems of arid and semi-arid environments; however, in riparian ecosystems of drylands, transpiration is by far the most important component of ET (Yepez et al. 2003).

Riparian plants control transpiration rates by regulating stomatal pores on leaf surfaces. Excessively high rates of transpiration are avoided through closure of stomatal apertures to prevent tension-induced breakage (cavitation) of the continuous hydraulic connection that exists from soil, through roots and up to leaf surfaces (Sperry 1995, Sperry et al. 1998). The embolisms (i.e., the air-filled and dysfunctional xylem conduits) formed as a result of cavitation reduce the water-conducting capacity of the xylem, potentially exacerbating physiological stress in the plant. Indeed, tension-induced cavitation is likely the cause of branch dieback and tree mortality in riparian cottonwoods subjected to water table decline (Tyree et al. 1994). Riparian plant species such as mesquite, saltcedar, willow, and cottonwood differ in their vulnerability to tension-induced xylem cavitation (Pockman

and Sperry 2000) and regulate stomata to different degrees when subjected to soil or atmospheric drought (S.D. Smith et al. 1991, Horton et al. 2001a). Such species-specific stomatal behaviors and drought-stress vulnerabilities influence species' distributions and vegetation-hydrology interactions at a large scale.

In arid and semi-arid environments, ET of riparian vegetation greatly exceeds precipitation due to access to groundwater by deep-rooted plants (R. Scott et al. 2004, R. Scott, Goodrich et al. 2006). Potential ET in the San Pedro basin along the river corridor is ~1.8 m per year (R. Scott, Goodrich et al. 2006), and when the water table is shallow, actual ET in riparian vegetation approaches this maximum potential ET set by the available energy driving the vaporization of water (Gazal et al. 2006). Actual ET generally is less than potential ET due to stomatal limitation (Gazal et al. 2006, R. Scott, Goodrich et al. 2006), leaf phenology patterns of cold-deciduous species, and disequilibria between vegetation successional development and water availability (Gregory et al. 1991). Under conditions of high atmospheric evaporative demand or low soil-water availability, riparian vegetation transpires at rates well below potential ET (R. Scott, Watts et al. 2003, Gazal et al. 2006). As a result, simple models relying strictly on potential ET do not adequately predict uptake and release of water to the atmosphere by riparian vegetation.

Water Sources of Dominant Plant Species

The key vegetation process affecting riparian zone hydrology is uptake of water from the phreatic zone (groundwater) by deep-rooted plants followed by release of this water to the atmosphere. Unfortunately, groundwater uptake is one of the more difficult processes to characterize. Obligate phreatophytes (e.g., cottonwood and willow) are plant species that do not survive without access to groundwater. Facultative phreatophytes (e.g., mesquite and saltcedar) are plants that take up groundwater if it is available but are capable of using alternative water sources (e.g., rainfall) and can survive without access to groundwater.

Because of their structural dominance in riparian ecosystems of the American Southwest, the physiological ecology and water relations of willow, cottonwood, mesquite, and saltcedar have been intensively studied (S. D. Smith et al. 1991, Busch et al. 1992, Busch and Smith 1995, Sala et al. 1996, Cleverly et al. 1997, Devitt et al. 1997, Glenn et al. 1998, Snyder and Williams 2000, 2003, J. Horton et al. 2001a, Nagler et al. 2003, Hultine et al. 2004, Glenn and Nagler 2005, Gazal et al. 2006). Stable isotope tracer studies, which take advantage of variation in the abundance of deuterium (^2H) and ^{18}O in different source waters (Ehleringer et al. 2000), confirm that transpiration by willow and cottonwood originates predominantly from the phreatic

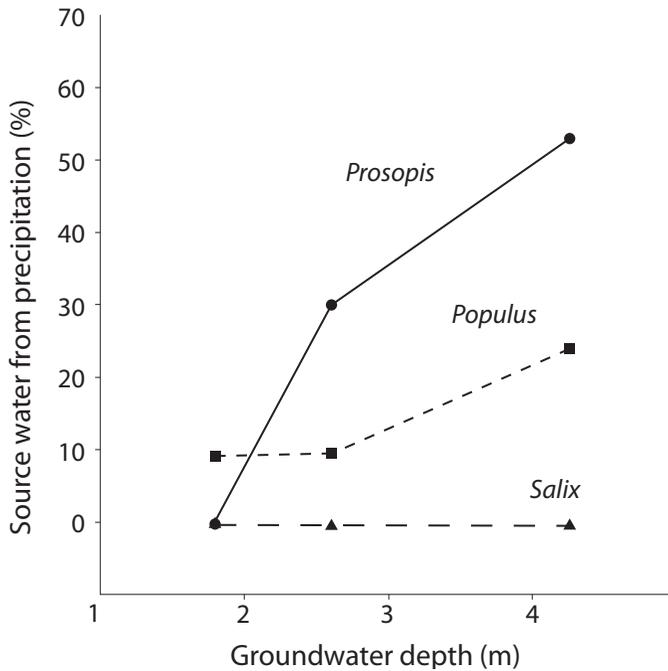


Fig. 2.2. Percentage of total plant transpiration in populations of mesquite (*Prosopis velutina*), cottonwood (*Populus fremontii*), and willow (*Salix gooddingii*) obtained from recent rainfall inputs at three sites along the San Pedro River in southeastern Arizona. The sites represented a gradient in depth to groundwater and reveal the heterogeneous nature of vegetation-water interactions in riparian ecosystems. From K. Snyder and Williams (2000). Used with permission.

zone (Busch et al. 1992, Snyder and Williams 2000). However, where water table depths for cottonwood exceeded 4 m, approaching the depth threshold for survival (see chap. 1), cottonwood obtained a significant proportion (>20 percent) of transpiration water from unsaturated soil layers wetted by rainfall (Snyder and Williams 2000) (fig. 2.2).

The facultative phreatophytes mesquite and saltcedar switch water sources more readily than cottonwood and willow, depending on depth to groundwater and availability of water in unsaturated alluvial soils (Busch et al. 1992, Snyder and Williams 2000, 2003). Across a gradient of water table depth from 1.8 to 4.2 m, Snyder and Williams (2000) observed shifts in the contribution of groundwater to mesquite transpiration from 100 to less than 50 percent (fig. 2.2). Saltcedar is similar to mesquite in its capacity to tolerate drought stress and its flexibility to use moisture either from groundwater or unsaturated soil layers (Busch and Smith 1995). Not fully resolved is whether uptake of rainfall by these riparian species replaces or adds to water taken from groundwater. This last point is important for understanding the influence of riparian phreatophytes on groundwater resources.

Unraveling the complex controls on actual ET and identifying sources of plant transpiration (groundwater, surface water, soil water, etc.) in the riparian floodplain are the two critical pieces of information needed to understand how riparian vegetation influences the groundwater hydrology of stream catchments. Identifying and partitioning plant water sources is fairly straightforward using stable isotope tracer methods (Ehleringer and

Dawson 1992, Ehleringer et al. 2000); however, measuring and predicting ET and its source across a complex landscape is somewhat more challenging.

Quantification of Evapotranspiration in Riparian Ecosystems

An accounting of ET across the riparian landscape requires fairly sophisticated measurement and modeling approaches. The techniques we review here have been employed in research on the upper San Pedro River. These include water budget, in situ measurement, modeling, and remote sensing approaches.

WATER BUDGET APPROACHES

Researchers use various forms of the water balance equation (eq. 1) to quantify riparian ET (Freethey 1982, Corell et al. 1996, Goodrich, Scott et al. 2000). To do this, ET is determined as the residual of the balance between inflow and outflow terms over a defined river reach and over a specified time interval. Because of the difficulty of estimating many of the equation's components over a river reach, a number of simplifying assumptions are often made to reduce the number of terms. For example, along the upper San Pedro River, researchers have used long-term streamflow data to compute an estimate of ET from groundwater by comparing the river baseflows (groundwater-derived streamflow) during winter months, when transpiration by the riparian vegetation is minimal, to those of summer, when the vegetation is active (e.g., Corell et al. 1996). On a smaller reach and for a shorter period, Goodrich, Scott et al. (2000) synthesized independent estimates for each term in eq. 1 for a 90-day, dry-season period and found that the water balance was within 5 percent of total inflows. However, such a detailed water balance is not feasible over larger reaches and longer time intervals due to the dynamics of precipitation, net groundwater inputs, and storage terms.

DIRECT MEASUREMENTS

Direct measurements of ET are necessary for validating and calibrating indirect measurement and for providing data input for modeling approaches (see next section). Direct approaches to measure riparian vegetation ET include sap flow and micrometeorological approaches.

Sap flow techniques. Sap flow techniques are used widely in riparian vegetation research because of their remote field portability, low cost, and capacity for high temporal and spatial resolution targeted to individual plants (Schaeffer et al. 2000, Nagler et al. 2003, Hultine et al. 2004, Gazal et al. 2006, R. Scott, Goodrich et al. 2006). This technique has advantages over other direct measurement techniques because it does not require a large, homogeneous patch of vegetation for application. It is well suited for strips of streamside vegeta-

tion (Schaeffer et al. 2000) where micrometeorological approaches present difficult challenges (Hipps et al. 1998).

The approach measures (1) the velocity of a heat pulse introduced to the flowing sap (Barret et al. 1995), and (2) the dissipation of heat applied continuously from heaters inserted into the wood (Granier 1987) or completely enveloping a branch (Baker and van Bavel 1987). When calibrated properly for variation in wood properties and damage from probe insertion, sap flow techniques provide highly reliable and accurate data. The difficulty with this approach lies in scaling the very localized point measurements on a tree to the stand and landscape levels. Compounded errors associated with spatial scaling can be significant (+/- ca. 10 to 20 percent), but not insurmountable (Schaeffer et al. 2000).

Micrometeorological techniques. Micrometeorological techniques, including the Bowen ratio and eddy covariance methods, monitor patch-scale ET in riparian areas (Devitt et al. 1997, Cleverly et al. 2002, Dahm et al. 2002, R. Scott et al. 2000a, 2004, R. Scott, Goodrich et al. 2006). These techniques involve measuring above-canopy meteorological conditions over a relatively homogeneous and extensive (>~200–500 m) patch of land (fig. 2.3), which limits their applicability in many riparian settings (Baldocchi et al. 1988, Schmid 1997). The advantages of micrometeorological data are their high temporal (often <1 hour) resolution, near-continuous sampling (data sets can be collected over months to years), and patch-scale spatial resolution, which is readily amenable to scaling up spatially. The disadvantages are its high cost (\$15,000–\$45,000) and low portability.

The Bowen ratio technique is simpler and less costly than eddy covariance measurement but requires complete measurements of the surface energy balance to determine ET. Over the last several years, the eddy covariance technique has become the predominant micrometeorological technique for measuring ecosystem ET. While the instruments are expensive and the data analysis sophisticated, it has the advantages of measuring ET directly and not requiring assumptions about energy balance. As a bonus, many eddy covariance setups can also estimate carbon dioxide exchange between the atmosphere and the land surface to understand the relationship between ecosystem productivity and water use (Baldocchi et al. 2001, R. Scott et al. 2004, R. Scott, Huxman et al. 2006).

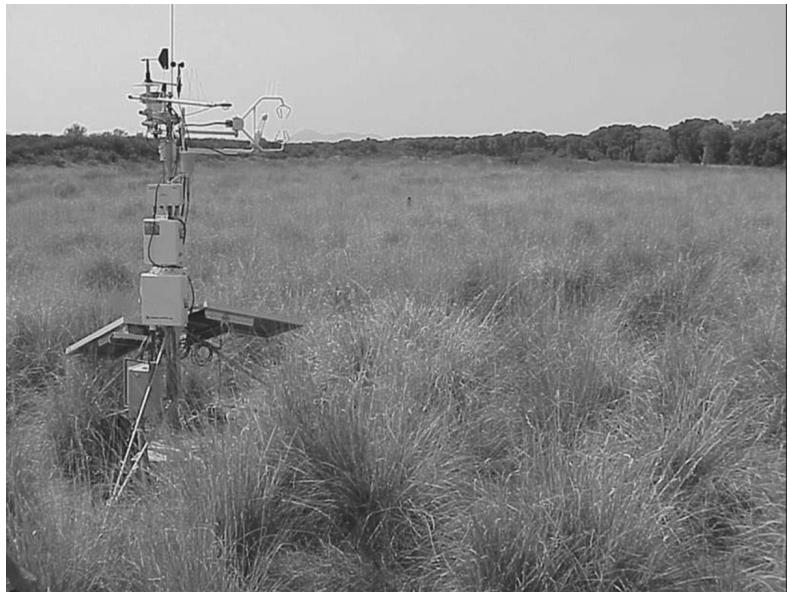
The accuracy of micrometeorological techniques for estimating ET depends on many site-specific factors and is generally difficult to ascertain. This is especially true for riparian ET measurements because one cannot rely on a simple surface water balance ($ET = P - \Delta S$) as a check since the contributions from the groundwater source are unknown. For eddy covariance measurements, a standard check is to evaluate how the surface energy



Fig. 2.3. (top; 2.3a):
A 14-m tall micro-
meteorological tower
measures evapo-
transpiration from
a riparian mesquite
woodland along the
San Pedro River.

(bottom; 2.3b):
Micrometeorological
instrumentation
to measure evapo-
transpiration from
a floodplain sacaton
grassland along the
San Pedro River.

Photo credits: Russell
Scott, USDA-ARS.



balance is closed. Along the San Pedro River, the eddy covariance sites have not demonstrated complete closure (R. Scott, Goodrich et al. 2006). Yet, this is a common occurrence for most sites around the world, and there has been no consensus as to whether this indicates the possibility that ET is underestimated using this approach (Wilson et al. 2002).

MODELING APPROACHES

There is a huge array of models that range from simple empirical relationships to very detailed ecohydrology land-surface models that estimate ET for specific vegetation types (Shuttleworth 1991). The simplest are based on derived empirical relationships between more easily measured atmospheric measurements—like air temperature, relative humidity, wind speed, and solar radiation—and ET measurements. However, it is often problematic to apply empirical relationships developed for a specific site and vegetation type elsewhere, and these models should be proven locally to validate their application. For example, the Arizona Department of Water Resources (ADWR 1991) modeled annual ET for several vegetation types over a large reach of the San Pedro River using a map of riparian vegetation and an empirical model (Blaney and Criddle 1950) driven by mean monthly air temperatures and the monthly percentage of daytime hours of the year (see R. Scott et al. 2000a for a summary of these model-based estimates). The vegetation-specific ET parameters for this model were derived from a study on the lower Gila River Valley in Arizona (Gatewood et al. 1950), and the results of this study were not validated due to the lack of data on the San Pedro. Numerous measurements of annual ET made later (table 2.1) are considerably less (500 mm yr^{-1} less for some vegetation types) and reveal the danger of using unsubstantiated model results.

The more complex models are physically based and try to represent the key physical mechanisms that control the ET process, yet applying these models is difficult due to the greater number of vegetation-specific parameter values required. Thus, it is often necessary to perform model calibration (again, requiring direct measurements for comparison) to determine the often unknown, or even unmeasurable, parameters to ensure the model's accuracy. For example, Goodrich, Scott et al. (2000) used sap flow estimates of cottonwood/willow ET (Schaeffer et al. 2000) to calibrate the stomatal resistance term in the well-known Penman-Monteith model (Monteith 1965). The calibrated model was then used with hourly air temperature, relative humidity, wind speed, and solar radiation to determine annual cottonwood/willow ET (fig. 2.4).

REMOTE SENSING

Remote sensing has the promise of making measurements of land-surface variables (e.g., surface temperature, solar radiation, soil moisture, absorbed photosynthetically active radiation, vegetation greenness) relevant to the ET process over large areas and at regular intervals (from sub-hourly to weeks). Researchers have developed many ways to utilize remote sensing measurements to drive ET models, ranging from empirical to physically based models. An example of an empirical approach is a regression relationship between

TABLE 2.1. Estimates of total growing season ET and ET from groundwater along the San Pedro River.

Cover type	Streamflow	Geomorphic surface	Vegetation notes	Date	Depth to GW [m]	ET [mm]	ET _{gw} [mm]	Canopy cover [%]	ET _{gw} [mm]
Cottonwood/ Willow	Perennial	Floodplain		1997	0.5-2	755	755	100	755
Cottonwood	Perennial	Floodplain	Mature stand	2003	1.6	966	966	100	966
	Intermittent	Floodplain	Mature stand	2003	3.3	484	410	100	410
Mesquite	Intermittent	Floodplain	Woodland	2001-2003	10	638-694	488-510	74	532-689
	Perennial	Floodplain	Dense shrubland	2003	6.5	565	380	55	691
Sacaton	Perennial	Floodplain	Sparse shrubland	1997	9.5	330	157	32	491
	Perennial	Floodplain		1997	>3.5	272	0	NA	0
Seepwillow	Perennial	Floodplain		2003	2.5	554	374	65	575
	Perennial	Floodplain	Cottonwood understory	2003	1-1.5	819	NA	100	NA
Open water	Perennial	Channel	Under mixed cottonwood canopy	2003	NA	1156	1156	NA	1156

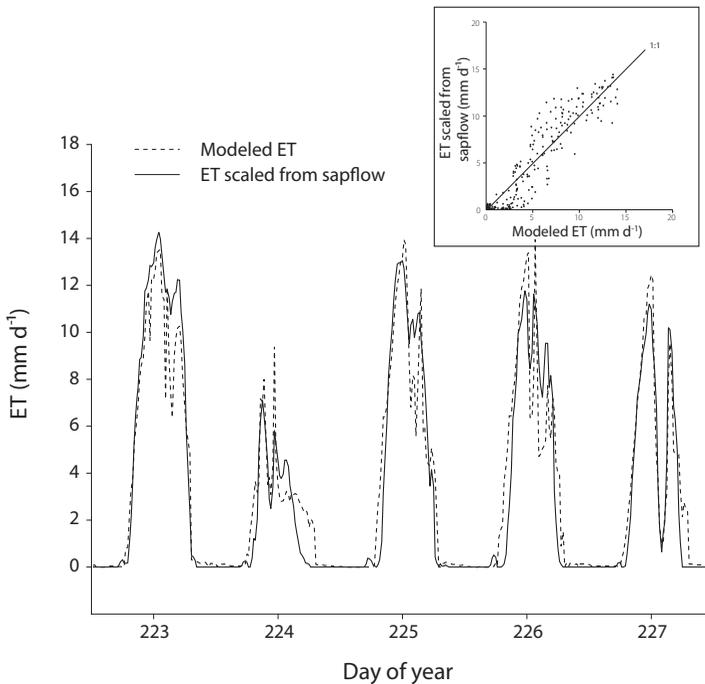


Fig. 2.4. Comparison of calibrated Penman-Monteith model for cottonwood/willow evapotranspiration versus scaled sap flow estimates for a five-day period during the monsoon in 1997. The study site was along a perennial section of the upper San Pedro River with a dense, but structurally heterogeneous, canopy of riparian trees. From Goodrich, Scott et al. (2000). Used with permission.

a vegetation index and ET, whereas a more physically based approach would use remote sensing to estimate light absorption or surface temperature as inputs in models that specifically represents the surface energy balance (Bastiaanssen et al. 1998, Davis and Roberts 2000, Kustas et al. 2003, Nagler, Cleverly et al. 2005).

With the increased availability of remote sensing products from programs like NASA's Earth Observing System, there have been many recent attempts to use remote sensing to assess transpiration from riparian plant canopies. One approach is to determine ET indirectly from remotely sensed canopy temperature and in situ air temperature (Qi et al. 1998, Nagler et al. 2003). This approach is based on the cooling effect of transpiration on leaf surfaces and the remote measurement of canopy temperature (T_c) relative to surrounding air (T_a) (Jackson et al. 1981).

Another empirical approach is to use relationships between satellite-derived vegetation indices and ET. For example, Nagler, Cleverly et al. (2005) found strong correlations between MODIS-derived indices (Huete et al. 2002) and riparian ET along the Rio Grande and developed an empirical model using these indices and local air temperature to skillfully predict ET. This regression relationship has been updated (Nagler, Scott et al. 2005) with additional measurements of different cover types along the San Pedro and

lower Colorado Rivers. They found that one relationship could be used to predict ET from a range of riparian cover types from different Western rivers, and they used this relationship to predict ET for entire reaches.

In contrast to these empirical approaches, Bastiaanssen et al. (1998) developed a more physically based model that uses radiances recorded by satellite-based sensors, plus ordinary meteorological data, to solve the energy balance at the earth's surface. This model is currently being applied and tested over many different riparian vegetation types (<http://www.sebal.us>). One advantage of this more physical approach is that the model does not require that the vegetation be well watered, which might be the reason why the vegetation index approach of Nagler, Scott et al. (2005) has worked in its application so far but might not work for riparian vegetation along ephemeral flowing rivers that experience more seasonal water stress. One possible setback to the use of remote sensing for riparian ET is that the 0.25–1 km scale of many of the satellite measurements like surface temperature or some vegetation indices can be greater than the scale of homogeneous riparian vegetation patches of interest.

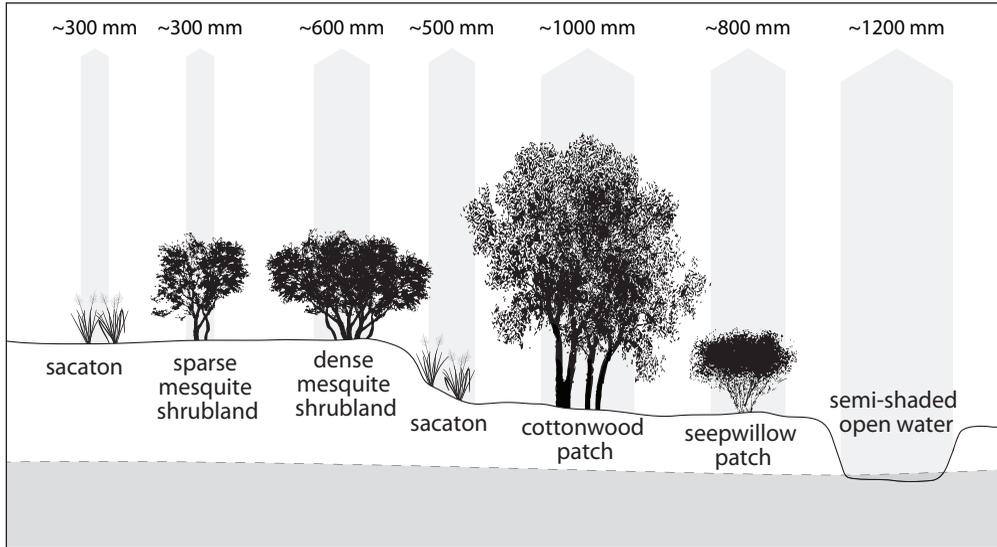
Patterns of Evapotranspiration in the Upper San Pedro Riparian Ecosystem

Many of the in situ estimates of riparian ET along the upper San Pedro River come from the Semi-arid Land-Surface-Atmosphere (SALSA) Program (Goodrich, Chehbouni et al. 2000), the National Science Foundation's Sustainability of Semi-arid Hydrology and Riparian Areas (SAHRA) center, and the Upper San Pedro Partnership (USPP) Water Needs Study (Leenhouts et al. 2006). For these studies, the amount of ET derived from groundwater was quantified so that the total groundwater use by phreatophytes in the basin, an important component of the basin's groundwater budget, could be determined. ET rates, summarized in table 2.1 and shown diagrammatically in figure 2.5, were quantified for various vegetation types in a range of hydrogeomorphic settings (Schaeffer et al. 2000, Goodrich, Scott et al. 2000, R. Scott et al. 2000a, 2004, R. Scott, Goodrich et al. 2006). In addition to seasonal ET, estimates were made for the amount of ET derived from groundwater (ET_{gw} , table 2.1) using a mass balance approach for the micrometeorological studies (R. Scott, Goodrich et al. 2006) or by isotopic identification of source water (Snyder and Williams 2000). Finally, ET_{gw} , normally given in units of water volume per land surface area per time, was divided by the fractional phreatophyte cover in order to provide an estimate of total riparian groundwater use for 100 percent land cover (ET'_{gw}) so that a total ET for a reach could be determined.

INTER-ANNUAL VARIABILITY

For vegetation types with multi-year ET estimates (the cottonwoods along a perennial reach and the mesquite woodland), there was considerable inter-

Perennial Reach



Intermittent Reach

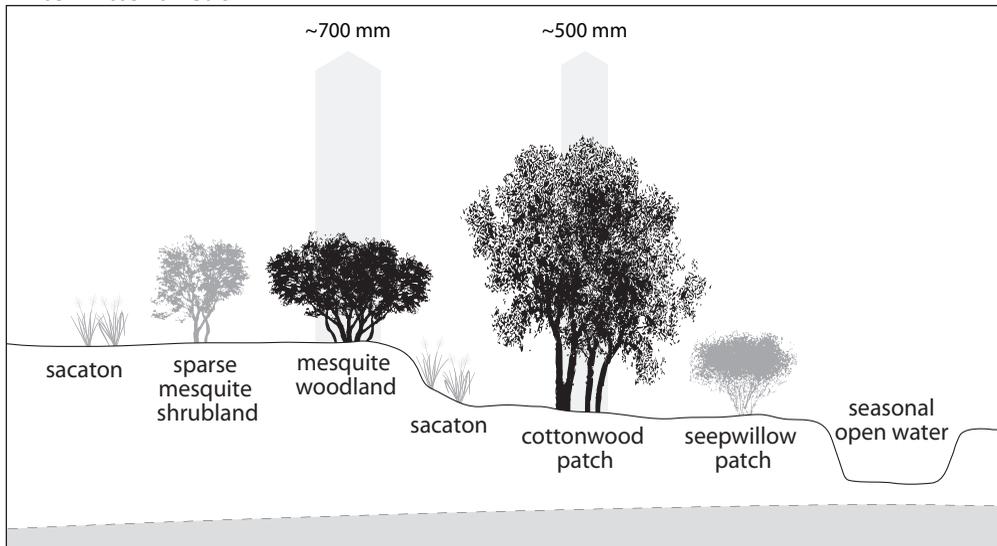


Fig. 2.5. Stylized representation of growing season evapotranspiration (ET) rates for riparian vegetation types (and open water) on different fluvial surfaces (flood-plains and terraces) and in perennial and intermittent reaches of the San Pedro River riparian corridor (values are based on measurements given in table 2.1). ET values are not available for vegetation patches shown in gray. Illustration credit: Mike Buffington.

annual variability (table 2.1). We speculate that most of this variability is controlled by climate, namely, spring and fall temperatures (frost events) and precipitation. The spring and fall temperatures determine the length of the transpirational growing season and are quite variable from year to year (R. Scott, Goodrich et al. 2006). The amount of precipitation within the growing season also impacts total ET due to use of shallow soil water

by plants such as mesquite. Wintertime precipitation also appears to play a role in the functioning of mesquite later in the year, likely through storage of water by hydraulic redistribution (Hultine et al. 2004, R. Scott et al. 2004).

VARIATION IN ET WITHIN AND AMONG PLANT COMMUNITIES

In general, the highest rates of ET along the upper San Pedro River are for open water surfaces followed by cottonwood, seepwillow, mesquite, and sacaton (table 2.1). For cottonwoods, ET and ET_{gw} were higher along a perennial reach with shallow groundwater but markedly reduced along an intermittent reach with a greater depth to, and fluctuation in, groundwater. ET was highly variable among mesquite communities, but ET_{gw} was less variable, indicating that the groundwater use by mesquite trees was similar across sites with different depths to groundwater (R. Scott, Goodrich et al. 2006). Sacaton had high ET and used groundwater at one site but had low ET and did not use groundwater at another site with a greater depth to groundwater; a depth to groundwater of 3 m is a likely cutoff that determines whether this grass does or does not use substantial quantities of groundwater. Finally, seepwillow ET was large, despite the reduced atmospheric demand present in the cottonwood understory occupied by these shrubs. Apparently, the cottonwood canopy structure allows sufficient (radiative and/or advected) energy to reach the understory shrubs, allowing them to transpire at high rates.

Evapotranspiration in Stands of Saltcedar (*Tamarix* spp.)

Reported estimates of saltcedar ET vary widely. Variable environmental conditions and differing structural characteristics observed among saltcedar stands may explain these differences. Evapotranspiration in any riparian vegetation type is spatially and temporally variable due to differences in vegetation density, groundwater depth, seasonal plant phenology, and available energy. Collectively, studies reporting ET in saltcedar reveal magnitudes and levels of temporal and spatial variability comparable to those reported for stands of native riparian woody vegetation (Robinson 1970, Weeks et al. 1987, Sala et al. 1996, Devitt et al. 1998, Cleverly et al. 2002, Dahm et al. 2002). On a per leaf area or plant basis, saltcedar has transpiration rates similar to native riparian taxa (Busch and Smith 1995, Sala et al. 1996, Cleverly et al. 2002, Dahm et al. 2002). Where saltcedar occurs at very high densities and has a high leaf area index, its ET may be greater than for other riparian vegetation (Sala et al. 1996, Nagler et al. 2004).

However, several recent studies employing eddy covariance methods show that saltcedar ET is not greater than riparian stands dominated by native woody taxa (Weeks et al. 1987, Cleverly et al. 2002, Dahm et al. 2002). Total annual ET of saltcedar stands ranged from 74 cm in an unflooded stand to 122 cm in a flooded stand (Cleverly et al. 2002). For comparison, total grow-

ing season ET was 48 to 97 cm in unflooded stands of cottonwood and 33 to 69 cm in unflooded stands of mesquite along the San Pedro River (table 2.1). Clearly, saltcedar is not an extraordinary water user in all situations. Indeed, leaf area index, a measure of the evaporative surface area of leaves per unit of ground area, which is highly correlated to actual ET in riparian vegetation (Sala et al. 1996, Schaeffer et al. 2000, Cleverly et al. 2002), was, on average, lower in stands of saltcedar than in stands of cottonwood and willow along the lower Colorado River (Nagler et al. 2004).

Scaling Evapotranspiration up to the Catchment Level

Riparian ET at the stream reach or catchment level can be a major component of the surface water and groundwater budgets of watersheds in arid and semi-arid environments, and ET at these scales is often the most relevant for watershed stakeholders. Often the surface water and groundwater budgets are determined independently, so it is important to identify the riparian ET source water so that ET can be partitioned into surface water (ET_{sw}) and groundwater (ET_{gw}) sources. In the Sierra Vista subbasin of the upper San Pedro River basin, the focus has been on determining groundwater use by riparian vegetation because perennial flow in the river, the condition of the riparian vegetation, and people living in the basin all depend on water from this aquifer source.

Prior to the SALSA Program (Goodrich, Chehbouni et al. 2000), numerous estimates of upper San Pedro River riparian corridor groundwater usage were derived indirectly using conceptual and numerical models (e.g., Freethy 1982, Vionnet and Maddock 1992, Corell et al. 1996). More recently, Goodrich, Chehbouni et al. (2000) and R. Scott, Goodrich et al. (2006) have quantified riparian corridor groundwater use from direct measurements of ET (see Quantification of Evapotranspiration in Riparian Ecosystems, p.44). These estimates of ET_{gw} (table 2.1) for each vegetation type were multiplied by the area within the riparian corridor covered by that vegetation and then totaled to determine riparian groundwater use. A major advantage to this approach is that it is based on actual measurements rather than on model outputs, which have considerable uncertainty at large scales. A major disadvantage stems from the implicit assumption that ET of a particular vegetation type can be accurately represented from measurements at a few locations. Site-to-site heterogeneity in vegetation age, density, and environmental conditions is the rule along most rivers, and the effects of this heterogeneity on ET are often unknown. Instrumentation networks need to be expanded to sample the range of conditions occupied by each particular vegetation type, but the costs and feasibility of such sampling can be prohibitive.

Table 2.2 presents a detailed riparian groundwater-use budget for the San Pedro River from the international border to the Tombstone gage during

TABLE 2.2. Riparian groundwater use in 2003 along the main stem of the San Pedro River from the international border to the Tombstone gaging station (from R. Scott, Goodrich et al. 2006).

Cover type	Minimum amount ^d [ha]	Maximum amount ^d [ha]	2003 ET _{gw} [mm yr ⁻¹]	Min. GW Use [1000 m ³ yr ⁻¹]	Max. GW Use [1000 m ³ yr ⁻¹]
Mesquite	723	973	689	4983	6706
Cottonwood/Willow (perennial flow)	253	253	966	2444	2444
Cottonwood/Willow (intermittent flow)	118	118	410	484	484
Sacaton (<3 m to groundwater)	113	167	575	650	961
Open water	43	43	1156	497	497
Saltcedar ^a	1	3	689	7	21
Total				9065	11112
Total from Corell et al. (1996) ^b					8758
Total from Goodrich, Scott et al. (2000) ^c					8130

^aSaltcedar *ET* was not measured and assumed the same as mesquite.

^bUsing baseflow information from the Palominas, Charleston, and Tombstone gages and subtracting their estimate of 600 ac-ft/yr for the Babocomari River.

^cFrom the international border to the Tombstone Gage.

^dVegetation amounts vary due to the polygon-based map, which did not specify exact percentages of vegetation cover for some of the sacaton and mesquite polygons.

2003 (R. Scott, Goodrich et al. 2006). The median estimate of 2003 groundwater withdrawal by riparian vegetation along the San Pedro and within the Sierra Vista subwatershed is 10,089,000 m³ yr⁻¹ (table 2.2), and the natural groundwater recharge estimated to have occurred in 2002 within this basin is 22,203,000 m³ yr⁻¹ (ADWR 2005a). This reveals the importance of riparian ET in the water budget.

The estimates of riparian groundwater use from R. Scott, Goodrich et al. (2006) and Goodrich, Scott et al. (2000), the two most recent studies that used a similar approach, differ by nearly 3,000,000 m³ yr⁻¹ or 27 percent of the larger amount. The difference between these two studies can be explained by revisions and improvements made by R. Scott, Goodrich et al. (2006) to the approach of Goodrich, Scott et al. (2000) including (1) revised estimates of water use of different cover types, based on improved measurement methodology and sampling of a greater number of sites and a greater range of hydrologic conditions, and (2) use of a more detailed vegetation map. The difference in vegetation areas between the two vegetation maps

is alarming. This type of scaling depends on an accurate vegetation map, and differences between the two maps highlight the difficulty in vegetation classification.

Uncertainty in the estimates of R. Scott, Goodrich et al. (2006) is difficult to quantify and arises from measurement errors, the application of site-specific measurements across the reach, and uncertainty in vegetation amounts. Given these complications, uncertainty will always be a part of these and future reach-scale estimates even while we hope that their accuracy improves with each successive iteration.

Conclusions and Challenges for Future Research

Due to spatial and temporal heterogeneity in water availability and a high-frequency pulse-disturbance flood regime, the structure and hydrologic function of riparian plant communities in arid and semi-arid environments are extremely dynamic. Understanding the effects and feedbacks associated with spatio-temporal heterogeneity and scaling these responses to the catchment level represent great challenges to researchers focused on ecohydrological interactions in riparian ecosystems. Riparian vegetation influences the hydrologic cycle directly through controls on interception, soil water redistribution, and evapotranspiration, and indirectly through effects on stream geomorphology and accumulation of coarse woody debris. Evapotranspiration is particularly difficult to quantify and model in riparian ecosystems. However, the combined application of sap flow, eddy covariance, isotope, and remote sensing techniques has greatly reduced the uncertainty in estimates of ET and clarified our understanding of vegetation-groundwater relationships.

We still have limited understanding of how riparian vegetation water use responds to discrete pulses of rainfall, flood events, and rapid groundwater fluctuations. A more complete integration of plant ecophysiological properties and vegetation dynamics within a hydrological context will lead to models of vegetation-hydrology interactions that include pulsed resource and disturbance processes. Such models, when calibrated with landscape characteristics and vegetation parameterizations, offer researchers a valuable scientific tool for synthesizing information on key processes and identifying limitations to conceptual understanding. For stakeholders who wish to negotiate the most prudent policies for managing riparian vegetation and groundwater resources, such models could form the basis for identifying risks and potential outcomes of management activities.

An accurate accounting of riparian ET is required to properly apportion water for both human and environmental needs, especially along rivers in dryland regions like the southwestern United States. Accordingly, efforts to estimate riparian ET similar to those used for the San Pedro have been, or

are being employed in the middle Rio Grande and lower Colorado basins (Brower 2004, USBOR 2002). A common approach of using state-of-the-art direct measurements of ET over representative vegetation types to calibrate and improve models driven with local meteorological and/or remote sensing measurements has emerged in these efforts. As these efforts progress, a more general understanding of the riparian ET process and how to quantify this process will emerge.