

Groundwater, Vegetation, and Atmosphere: Comparative Riparian Evapotranspiration, Restoration, and Water Salvage

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Abstract—As water shortages persist throughout the Western U.S., a great deal of money and effort is directed toward decreasing riparian water loss, thereby enabling continued water use by irrigators, industry, and municipalities. This study focuses upon long-term measurement of evapotranspiration (ET) by native and non-native riparian species along the Middle Rio Grande (MRG) in New Mexico where riparian ET has been estimated to be 20 to 50 percent of water budget depletions. Leaf area index (LAI) was most strongly related to average ET rates, irrespective of species composition. Decreased LAI caused by crown dieback in native cottonwood was found at sites where the drought has also resulted in groundwater decline. Saltcedar ET, on the other hand, increased from 6 to 9 mm/day during groundwater declines of up to 7.5 cm/day. Atmospheric conditions that influence ET rates include vapor pressure deficit, net radiation, precipitation, friction coefficient, and the relative contribution of winds that are tangential and transverse to the riparian corridor. Some of these conditions interact to affect ET rates. For example, precipitation events are associated with lower net radiation, vapor pressure deficit, and ET. Potential water salvage following removal of non-native vegetation was predicted by comparing ET and LAI rates in various vegetation types. Lowest LAI and ET are found in a saltcedar/saltgrass non-overlapping mixed stand. In contrast, a dense monospecific saltcedar stand frequently consumes up to 11.5 mm/day, especially when flooded. ET from other vegetation types along the Middle Rio Grande seldom spikes so high. Conversion from dense monospecific saltcedar to sparse saltcedar/saltgrass woodland is predicted to save 0.2 m per year, based upon both ET and LAI changes in such a conversion. Previous studies of water salvage place this value between positive or negative, for unsuccessful removal of saltcedar may result in increased ET.

The Middle Rio Grande: A Case Study

The Middle Rio Grande (MRG) passes through semi-arid and arid landscapes as it descends from Otowi to Elephant Butte, New Mexico (fig. 1). With average annual precipitation declining over these 372 km, most of the water resources available to riparian vegetation is supplied from upstream through the shallow alluvial aquifer that surrounds the Rio Grande. Historically, the MRG floodplain hosted small Rio Grande cottonwood (*Populus deltoides* ssp. *wislizenii*) copses, riverbank cottonwood and Goodding willow (*Salix gooddingii*) individuals, riverbank coyote willow (*S. exigua*) thickets,

and wide expanses of grasses such as saltgrass (*Distichlis spicata*) (Scurlock 1998). These riparian areas have become dense with native and non-native vegetation, where monospecific and mixed xeroriparian saltcedar (*Tamarix chinensis*) thickets dominate the bosque to the south of the Rio Puerco confluence and dense cottonwood, saltcedar, and Russian olive (*Elaeagnus angustifolia*) forests dominate in the northern MRG. In either case, this dense vegetation presents a fire hazard and is potentially responsible for a great deal of water loss to the atmosphere.

The Rio Grande Compact dictates how much water may be legally lost between official river discharge gauges. In the MRG, the upstream and downstream gauges of record were changed to Otowi and Elephant

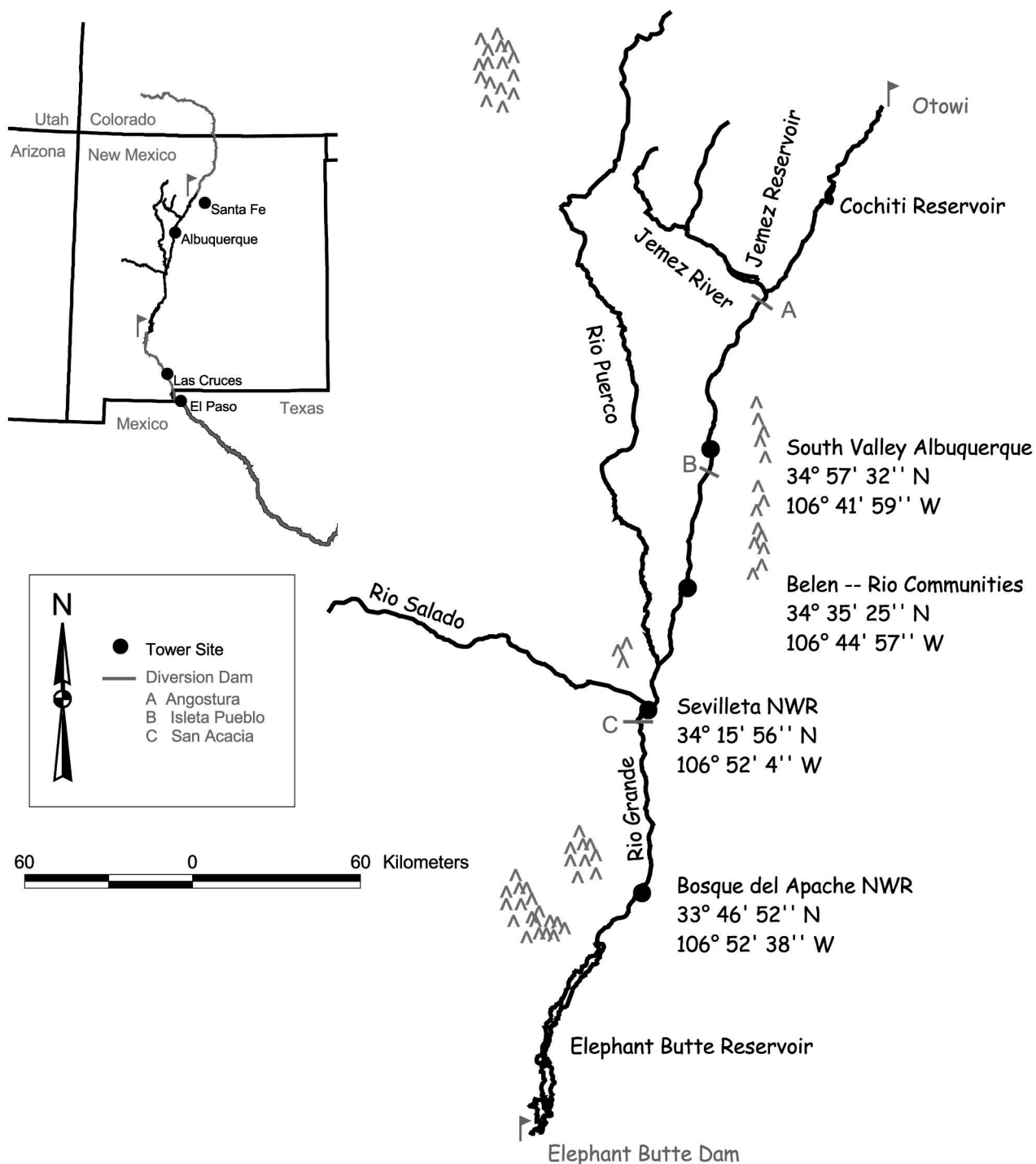


Figure 1. Map showing significant features and location of eddy covariance towers in the Middle Rio Grande evapotranspiration case study.

Butte in 1948 (fig. 1). Between these two points, various economic interests compete with riparian ET for the limited water budget depletions that are allowed. If phreatophytic vegetation, which draws water directly from the shallow alluvial aquifer surrounding the MRG, transpires an excessive amount of water into the atmosphere, fewer diversions from the river are allowed for agricultural, municipal, and industrial uses. A water budget is often constructed to provide the best accounting

of water sources and demands, but the utility of water budgets is constrained by incomplete knowledge of key components in the water budget (Cleverly and others 2002, Dahm and others 2002).

Better understanding of riparian corridor ET is crucially important for managing water resources and predicting water availability. Open water and riparian water loss to the atmosphere is believed to be the greatest single depletion of water from the MRG, ranging between

30 and 75 percent of the total inflow at Otowi (Cleverly and others 2002). Discounting reservoir evaporation, water losses from the riparian corridor is thought to be between 20 and 50 percent of the total inflow at Otowi (Dahm and others 2002). However, these evaporation and evapotranspiration rates are theoretical in nature, while direct measurements have recently contributed a great deal to ensuring that the most accurate ET estimates are obtained (Goodrich and others 2000).

When considering the large volumes of water potentially escaping the riparian corridor, as well as our uncertainty regarding the accuracy of this estimated ET, a central question regarding our ability to manage riparian ET has arisen. Specifically, managers wish to know whether certain vegetation can be removed from the ecosystem to decrease depletions. In particular, can non-native species be removed to both improve habitat for endangered species as well as reduce ecosystem ET. The culprit in the southwestern United States is saltcedar (*Tamarix* spp.), a plant from Eurasia that has been accused of extravagant, and often unrealistic, ET rates. However, a great deal of controversy remains surrounding the issue of saltcedar ET: whether ET is greater than that for native vegetation such as dense cottonwood forests, and whether gains in gauged stream flow will result from removal of saltcedar (Weeks and others 1987).

The MRG provides a background for addressing these issues and improving our ability to predict riparian ET, where we have been using state-of-the-art three-dimensional eddy covariance (3SEC) systems arrayed at various locations along the MRG to elucidate the roles of vegetation, hydrology, and atmospheric conditions in controlling riparian ET.

Riparian Evapotranspiration

Riparian evapotranspiration is the process by which open water and soil water is translocated to the atmosphere as vapor. Interactions between groundwater, vegetation, and atmospheric conditions can either restrict or enhance actual ET, depending upon the conditions themselves. As the term evapotranspiration implies, evaporation from open water or soil and transpiration from vegetation are combined into a single water loss term. This composite flux is measured directly using the 3SEC system, which is considered to be the standard by which wetland ET is evaluated (Drexler and others 2004).

The vegetation along the MRG is phreatophytic, meaning that its roots are connected directly to the capillary fringe of the water table (Smith and others 1998). Some of these plants are facultative phreatophytes, meaning that they may obtain water from both the capillary

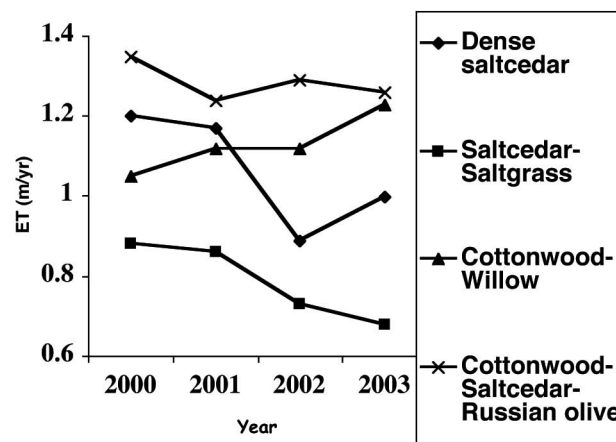


Figure 2. Annual ET from each of the sites illustrated in figure 1 over the years 2000 through 2003.

fringe and the vadose zone. Examples of such plants are saltcedar and mesquite (*Prosopis* spp.), both of which are able to maintain function soil water potentials intermediate between obligate riparian species and upland species (Busch and others 1992, Pockman and Sperry 2000). Conversely, cottonwood is extremely vulnerable to soil drying, allowing partial crown dieback under water table drawdown (Cooper and others 2003, Rood and others 2003). In one instance, among a population of young cottonwood along a drying ephemeral reach, has cottonwood shown any proclivity toward use of soil water in addition to groundwater (Snyder and Williams 2000).

Variability in annual ET rates along the MRG is very high (fig. 2). Before the current drought, ET rates were highest from cottonwood forests with a thick saltcedar understory—1.35 m/yr (4.4 acre-ft/acre-yr)—and from dense saltcedar stands—1.2 m/yr (3.4 acre-ft/acre-yr). As the drought developed, ET rates fell to below 0.7 m/yr (2.2 acre-ft/acre-yr) at the saltcedar/saltgrass site. Seemingly, cottonwood forests are unaffected by drought—maintaining ET rates up to 1.3 m/yr (4.2 acre-ft/acre-yr). However, groundwater levels have remained shallow at these sites due to Albuquerque wastewater amendments and irrigation delivery structures.

Groundwater

Transpiration by cottonwood is uninhibited by groundwater accessibility whenever the water table is within three meters of the surface (Horton and others 2001). When groundwater is drawn down deeper, transpiration declines with increasing crown dieback (Scott and others 1999, Rood and others 2000). Goodding willow is found in habitats similar to those where cottonwood is more likely to be located, preferentially occupying sites with shallow water table, high soil water content, and

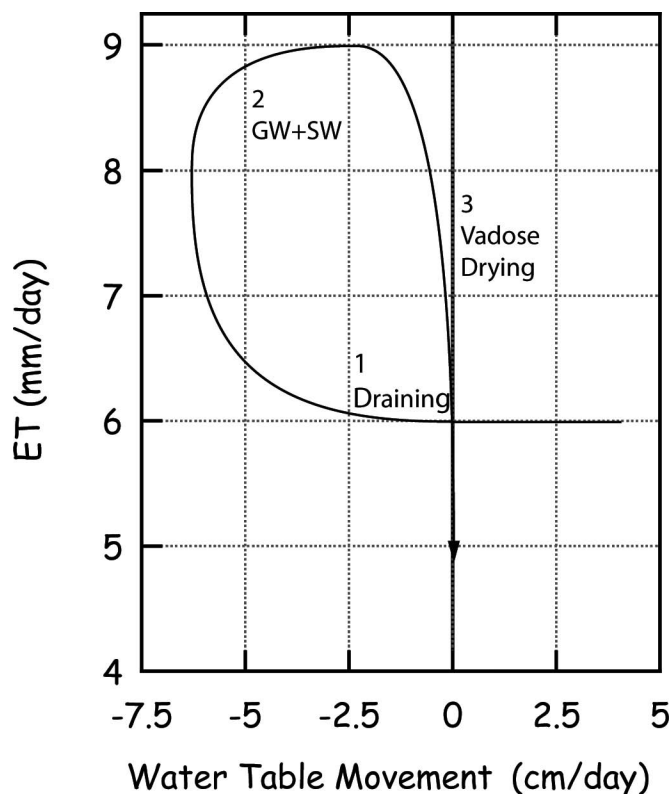


Figure 3. Daily average ET during a period of extended groundwater decline indicated by negative changes in the water table depth. ET does not initially increase, showing a lag between decline of the water table and dewatering of the capillary fringe (1). As roots are taking up water at the deepened capillary fringe and the vadose zone, ET increases (2), until the upper layers are emptied and saltcedar returns to predominately groundwater sources (3).

low salinity (Busch and Smith 1995). Conversely, coyote willow can tolerate dryer conditions, much like saltcedar or mesquite (Busch and Smith 1995). The hydrologic conditions under which these species are found have implications for predicting how willows might respond to groundwater decline, in which Goodding willow ET is expected respond to groundwater depth as does cottonwood, while ET from coyote willow is expected to respond more like saltcedar.

Saltcedar transpiration is not restricted by depth to groundwater as it is in cottonwood. In Arizona, saltcedar was unaffected by groundwater depths of up to 10 meters (Horton and others 2001). In China, from where one common species of non-native saltcedar originates, transpiration was found to remain unchanged, even when the water table was dropped to 25 meters below the surface (Gries and others 2003). Even though saltcedar ET is not dependent upon depth to the water table, saltcedar ET does respond to changes in water table depth, increasing while the groundwater is falling (fig. 3).

Figure 3 illustrates the mutual effects of drought resistant xylem (Pockman and Sperry 2000), facultative

phreatophytic habits (Busch and others 1992), and a combination of drought tolerance and spendthrift stomatal conductance depending upon the conditions (Cleverly and others 1997). Hysteresis is generated in this relationship between groundwater changes and saltcedar ET due to the time lag between groundwater decline and soil water desaturation, during which time tap root elongation is negligible. Increased ET rates in association with sustained groundwater decline occur because active roots left behind by the elongating taproot continue to exploit soil water resources left behind by the retreating groundwater (fig. 3).

Vegetation

A very general relationship between average ET and leaf area index (LAI) along the MRG was observed in 2000 (Dahm and others 2002). LAI is a measure of the leaf surface above a unit area of ground. Along the MRG, LAI ranges from 1.7 ± 0.1 in a saltcedar/saltgrass mosaic to 3.7 ± 0.1 at a dense saltcedar site. Monthly ET-LAI observations during 2001 through 2003 illustrate that this relationship is curvilinear—ET increases rapidly with increases at low LAI, and ET comes to a plateau near LAI values of three and above. This upper plateau indicates the limiting effect of self-shading; in which upper canopy leaves completely shade lower leaves and sub-canopy layers. Deep shading of lower canopy layers severely restricts the energy available to evaporate water from within the leaf.

Remote sensing technology that can discriminate LAI above three holds the best promise for deriving basin-wide scaled ET estimates. One metric that matches LAI closely when LAI is less than three is the normalized difference vegetation index (NDVI), computed as

$$NDVI = \frac{NIR - Rd}{Rd + NIR},$$

where Rd and NIR are pixel reflectance of red and near infrared light, respectively (Pearcy and others 1991). The utility of NDVI declines rapidly when LAI is greater than three because absorbance of red light by chlorophyll is complete in the upper few leaf layers. Middle-frequency infrared (MIR), like NIR, is not as effectively absorbed by chlorophyll. ET, LAI, and species composition maps were developed using spectral fingerprints for forests of varying species composition along the MRG. From this analysis, the leaf area transpiration index (LATI) was developed ($LATI-ET \ r^2 = 0.93$).

Ground reconnaissance of LATI method was performed by collection of LAI and groundwater chemistry data at multiple sites along the MRG. High concentrations of chloride in groundwater result in higher LAI

and ET from saltcedar-dominated sites, but high groundwater chloride levels at cottonwood-dominated sites resulted in reduced LAI and ET. Saltcedar ET is not strongly affected by nitrate or ammonium concentrations in the groundwater, but cottonwood ET is enhanced by high concentrations of these nitrogen-containing nutrients. At one cottonwood site downstream from the Albuquerque wastewater treatment plant (fig. 1), LAI, ET, and groundwater concentrations of nitrate and ammonium are all high.

Atmosphere

An analysis of ET anomalies was performed at each site to determine those conditions that were greater or lesser than average ET (Mo and Juang 2003). Stepwise general linear regression can then be used to analyze the role of micrometeorological conditions on large, multi-seasonal datasets ($n \sim 20$ per year). While time series data contains observations that are neither independent nor identically distributed (i.i.d.), computed anomalies are statistically derived observations that do not violate the i.i.d. assumptions of general linear regression.

Topography was most directly related to differences in ET covariances. For example, the northern two sites illustrated in figure 1 show ET spikes and dips in response to heat stress effects due to heat transfer from the nearby mesa (table 1). Boundary layer stability typically results from such mesoscale conditions, and ET declines in response to such lateral winds because these winds expose stress intolerant cottonwoods to higher vapor pressure deficit (VPD). As VPD increases, stresses upon tissue water increases due to the enhance vapor gradient between the leaf's interior and the surrounding air.

The southern sites are located near large mountains that are associated with greater cold air drainage. Warmer daytime temperatures are moderated by cooler nighttime temperatures in this area, and ET anomalies are related to local turbulence, VPD, and the range of diel temperature extremes (table 1) (Cooper and others 2003). It is at these sites where precipitation events lead to a sharp decline in ET. On days with measurable precipitation, (1) net radiation dips due to cloud-shading, (2) daytime high temperature dips, (3) atmospheric humidity increases, (4) vapor pressure deficit dips due to two and three, and (5) turbulence is high due to the convective nature of typical monsoon storms that develop of mountain ranges.

Additional cold air drainage at the southern sites serves to shorten the growing season, further restricting annual ET. The final hard freeze in the spring at the

Table 1. Results from stepwise multiple regression between ET anomalies and micrometeorological conditions.

Dominant vegetation	Variables ^a
Saltcedar	q^* , u^* , VPD, Temperature, Precipitation
Cottonwood	H , R_n , v , $v \times u$
^a q^* : Surface scale for vapor flux	
u^* : Friction velocity	
H : Sensible heat flux	
R_n : Net radiation	
v : Wind speed tangential to the riparian corridor	
u : Wind speed along the riparian corridor	

southern site is about one week later than at the northern site. Likewise, the first autumnal freeze in the south precedes senescence in the north by one week. Comparison of ET from these cottonwood and saltcedar sites can be achieved by considering differences in season length—cottonwoods in the south would experience similar shortening of the growing season and saltcedars in the north leaf-out and senesce earlier than in the south.

Considering all of these conditions that reduce annual ET from the saltcedar stands along the MRG, it is surprising that dense saltcedar has had peak water use exceeding 10 mm/day on 17 days from between 2000 through 2004. Although water use by saltcedar stands may be limited for much of the year, the vegetation itself is able to maintain extremely high ET rates for short periods when VPD is high, surface flooding is occurring in which floodwaters are perched above a clay lens, or the water table is rapidly declining.

Potential Water Salvage

The potential to save water by manipulating vegetation characteristics is dependent upon changes in leaf area index that are achieved by a given restoration project. If saltcedars are thinned, in combination with replacement by saltgrass, sacaton grass, or rabbitbrush (*Chrysothamnus nauseosus*), LAI and ET will be potentially decreased by up to 0.2 m/yr (0.7 acre-ft/acre-yr) (fig. 2). The reverse is also true—LAI and ET would increase if a low LAI saltcedar site were converted to a dense cottonwood site by cottonwood pole planting in high density. Increases in water use would also be observed in those all-too-common restoration attempts that do not successfully kill saltcedar, allowing the vegetation to resprout in greater density than before the restoration attempt. In any case, coordinated restoration efforts that successfully achieve historical grassland/cottonwood/willow mosaics would reduce ET rates while maintaining habitat resources for species that are now endangered.

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