

RESEARCH ARTICLE

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Tamarix transpiration along a semiarid river has negligible impact on water resources

Alyson K. McDonald¹, Bradford P. Wilcox², Georgianne W. Moore², Charles R. Hart³, Zhuping Sheng⁴, and M. Keith Owens⁵

Key Points:

- Brush control is unlikely to yield water if transpiration is a small component of the water budget
- The ratio of transpiration to streamflow will affect the impact of brush control on water yields

Correspondence to:

A. K. McDonald,
akmcdonald@ag.tamu.edu

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¹Department of Ecosystem Science and Management, Texas A&M AgriLife, Fort Stockton, Texas, USA, ²Department of Ecosystem Science and Management, Texas A&M University, College Station, Texas, USA, ³Dow AgroSciences, Stephenville, Texas, USA, ⁴Department of Biological and Agricultural Engineering, Texas A&M AgriLife, El Paso, Texas, USA, ⁵Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, Oklahoma, USA

Abstract The proliferation of saltcedar (*Tamarix* spp.) along regulated rivers in the western United States has transformed riparian plant communities. It is commonly assumed that transpiration by these alien plants has led to large losses of water that would otherwise contribute to streamflow. Control of saltcedar, therefore, has been considered a viable strategy for conserving water and increasing streamflow in these regions. In an effort to better understand the linkage between transpiration by saltcedar and streamflow, we monitored transpiration, stream stage, and groundwater elevations within a saltcedar stand along the Pecos River during June 2004. Transpiration, as determined by sap flow measurements, exhibited a strong diel pattern; stream stage did not. Diel fluctuations in groundwater levels were observed, but only in one well, which was located in the center of the saltcedar stand. In that well, the correlation between maximal transpiration and minimal groundwater elevation was weak ($R^2 = 0.16$). No effects of transpiration were detected in other wells within the saltcedar stand, nor in the stream stage. The primary reason, we believe, is that the saltcedar stand along this reach of the Pecos River has relatively low sapwood area and a limited spatial extent resulting in very low transpiration compared with the stream discharge. Our results are important because they provide a mechanistic explanation for the lack of increase in streamflow following large-scale control of invasive trees along semiarid rivers.

1. Introduction

Damming, regulation, and diversion of streamflows have resulted in fragmented and dysfunctional river systems worldwide—including North America, Europe, Asia, Africa, and Australia [Dynesius and Nilsson, 1994; Richardson *et al.*, 2007]. This fragmentation can impede recruitment and persistence of native species [Merritt and Wohl, 2006] while creating an environment conducive to alien plant invasions [Richardson *et al.*, 2007]. A prime example is the riparian landscapes across the western United States that have been altered by the encroachment of alien plants such as saltcedar (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*) [Nagler *et al.*, 2010a]. Concern over this landscape transformation has prompted national legislation calling for large-scale restoration efforts, based on the belief that these alien plants consume more water than the native vegetation (despite a growing body of research that demonstrates this is not the case [Shafroth *et al.*, 2010]). Local, state, and federal governments have already spent tens of millions of dollars on chemical, mechanical, and biological efforts to control saltcedar in the western United States [Shafroth and Briggs, 2008].

Water use by saltcedar has been measured at a number of scales, from the individual plant scale to the stand scale. Plant-scale measurements rely on sap flow [Sala *et al.*, 1996; Owens and Moore, 2007] and stomatal conductance [Anderson, 1982; Devitt *et al.*, 1997]; these measurements yield estimates of annual transpiration ranging from 0.26 m [Hultine *et al.*, 2010] to 1.3 m [Nagler *et al.*, 2009]. At the stand scale, micrometeorological measurements—such as eddy correlation [Cleverly *et al.*, 2006; Weeks *et al.*, 1987] and Bowen ratio [Si *et al.*, 2005]—have been used. Estimates of evapotranspiration (ET) from studies using these methods range from 0.6 to 1.7 m yr⁻¹ [Shafroth *et al.*, 2005; Nagler *et al.*, 2010b].

Despite differences in approach and different estimates of water use, researchers agree that transpiration by riparian vegetation is dependent on several factors: stand density, tree size/age, fetch or width of riparian

area, depth to water table, and environmental conditions (such as air temperature, wind speed, and relative humidity) [Devitt *et al.*, 1997; Glenn *et al.*, 1998; Shafroth *et al.*, 2000].

Transpiration has been correlated with decreased flow in mountain streams [Bond *et al.*, 2002; Wondzell *et al.*, 2010], and its influence on groundwater levels and hydraulic gradients has been observed in prairie potholes [Rosenberry and Winter, 1997]. In forested mountain watersheds, transpiration by streamside trees temporarily reversed the hydraulic gradient and thus groundwater flow direction, causing a gaining reach to become a losing reach during the growing season [Rosenberry *et al.*, 1999]. Clearing of vegetation—riparian and hillslope—has had mixed effects on diel fluctuations in groundwater and streamflow. A summary by Bren [1997] indicated that removal of riparian vegetation may be accompanied by suppression or elimination of diel stream fluctuations and an increase in streamflow. Conversely, clearing of hillslope vegetation may lead to increased groundwater discharge to the stream and amplified diel fluctuations [Bren, 1997].

Although linkages between increased transpiration and reduced streamflow and groundwater have been validated, it has been difficult to demonstrate actual savings of water resulting from control of saltcedar along semiarid rivers [Culler *et al.*, 1982; Welder, 1988; McDonald, 2010; Nagler *et al.*, 2010b]. This is puzzling, because many studies at the tree and stand scales have indicated that water savings could be substantial if saltcedar is removed [Hatler and Hart, 2009; Nagler *et al.*, 2010b]—particularly if the trees are not replaced by other deep-rooted phreatophytes [Wilcox *et al.*, 2006]. Why, then, have increases in streamflow not been observed following removal of saltcedar? Are there in reality no water savings, or are they too difficult to detect at large scales?

We provide some possible answers from our studies on the Pecos River in west Texas, USA. As part of the Pecos River Ecosystem Project (PREP), a research site was established near Mentone (31.7°N, 103.6°W), Texas, for long-term surface water and groundwater monitoring along the Pecos River. Between 2001 and 2005, 4176 ha of saltcedar along 480 km of the Pecos River were treated with herbicide but no increases in streamflow have been observed as a result of these treatments [McDonald, 2010].

A more recent study of surface and groundwater interactions revealed that the reach investigated at the PREP site was a losing reach, even under low-flow conditions [McDonald *et al.*, 2013]—which may explain why no increases in streamflow have been documented at this site. Along a losing reach, any increased water yield obtained via control of saltcedar would enhance aquifer recharge, not streamflow. An alternate, or perhaps concomitant, explanation is that riparian ET is a minor component of the water budget along this reach and does not have a measurable effect on either streamflow or seepage from the river into the alluvial aquifer.

For the current study, we tested the validity of the alternate explanation by analyzing hourly sap flux, stream stage, and aquifer hydraulic gradients in the middle of the growing season during full leaf cover. Specifically, we propose the following:

- H1: Groundwater fluctuations have been observed at this site and have been attributed to ET [Hays, 2003]. If these fluctuations are indeed an effect of ET, then groundwater levels should be negatively correlated with and should somewhat lag hourly transpiration.
- H2: If transpiration reduces streamflow, then the effect should be manifested in the stream stage as a diel fluctuation that is opposite to and somewhat lags transpiration.
- H3: Hydraulic gradients, from the stream toward the riparian zone, should be steeper during times of peak transpiration than when transpiration is low.

2. Study Area

2.1. Pecos River Basin

The Pecos River, a major tributary to the Rio Grande, drains about 91,000 km² in New Mexico and western Texas. From its headwaters in the Sangre de Cristo Mountains in northern New Mexico, the Pecos flows 1480 km across eastern New Mexico and into west Texas, where it converges with the Rio Grande [Yuan and Miyamoto, 2005]. The streamflow is fed by snowmelt from winter storms in the headwaters region and by runoff from warm-season monsoonal rainfall [Yuan *et al.*, 2007]. It is a highly regulated river; there are four dams along the Pecos River in New Mexico and one (Red Bluff) in Texas. Red Bluff Dam was completed in 1936. Since that time, because runoff-generating rainfall events are infrequent, streamflow has been



Figure 1. Low-level aerial photo of the Pecos River, Texas, downstream from Red Bluff Dam.

dictated almost exclusively by dam operations. Historical accounts from the mid to late 1800s describe the river in this region as treeless and lacking a distinct valley. The channel was much wider, up to 20 m, and steep banks restricted crossing to just a few locations. One of these, Pope's Crossing, was inundated with the construction of Red Bluff Dam [Dearen, 1997].

Today, the transition from riparian to abandoned floodplain vegetation is abrupt (Figure 1). Dam regulation has made flooding and overbank flow rare occurrences. The channel is incised and no longer connected to the broad ancestral floodplain. In other words, the 200 km stretch of the Pecos River below Red Bluff Dam bears little resemblance to its former self, and there remain no "natural" riparian zones.

2.2. Study Site

The study site, referred to above as the PREP site, is a 3 km long reach of the Pecos River near Mentone, Texas, some 40 km downstream from Red Bluff Dam. The climate is semiarid and subtropical. The growing season is typically 195 days and mean annual precipitation is 330 mm, most of which occurs between June and October [Rives, 2002].

On the basis of soil hydraulic properties, kind and density of vegetation, and landscape position, the study area was divided into three zones: stream bank, riparian, and floodplain (Figure 2). The stream bank zone extends tangentially about 1.2 m from the edge of the river to the edge of the riparian zone; the riparian zone is about 24 m wide; and the adjacent floodplain zone extends a distance of 30.5 m from the edge of the riparian zone.

Vegetation in the stream bank and riparian zones consists of *Tamarix chinensis* Lour. (saltcedar) overstory with a sparse understory of salt-tolerant grasses, mainly *Chloris crinita* (trichloris), *Distichlis spicata* (inland saltgrass), and *Cynodon dactylon* (Bermudagrass). The floodplain zone is sparsely vegetated with scattered *Atriplex canescens* (fourwing saltbush) and *Prosopis glandulosa* (honey mesquite), as well as patches of perennial grasses. Soils are predominantly loamy or sandy, with clay and gravel lenses. The aquifer consists of thick (up to 900 m), saturated, Quaternary alluvial deposits of unconsolidated or partially consolidated sand, silt, clay, and gravel and is underlain by Tertiary-age volcanic rocks [Ogilbee et al., 1962].

3. Methods

3.1. Transpiration

A heat-dissipation technique (after Granier [1987]) was used to measure sap flux per unit of sapwood in a 238 m² plot located within the PREP site.

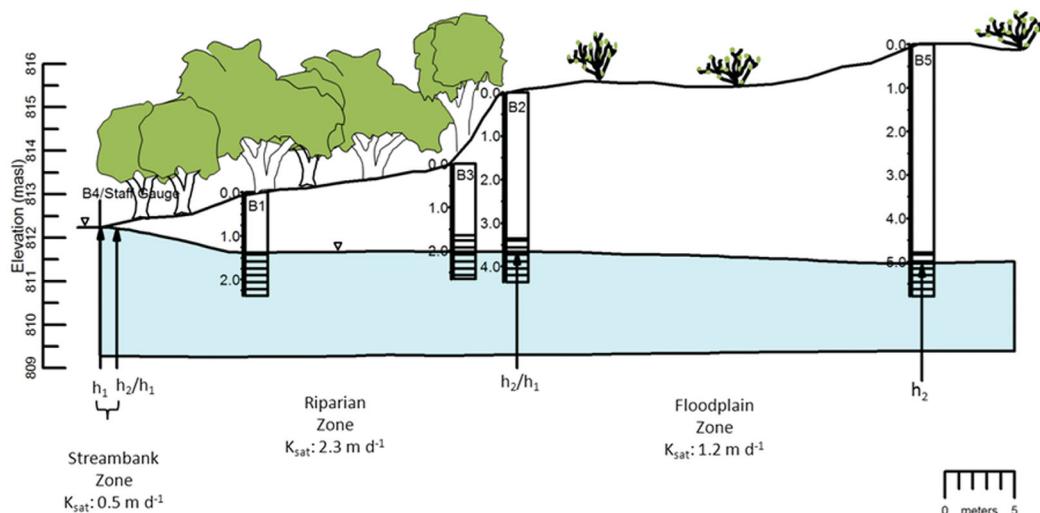


Figure 2. Conceptual model of right (east) bank of the Pecos River, Texas, depicting the width of the three zones delineated for study and wells B1–B5. Saturated hydraulic conductivity (K_{sat}) is given for each zone.

Nine trees (1–20 m from the stream bank) were instrumented with sap flow sensors to a depth of 10 mm: three trees located along the stream bank, three in the middle of the riparian zone, and three along the border between the riparian zone and abandoned floodplain. The ages of the trees are not known, but root-crown diameters ranged from 4 to 28 cm with a mean diameter of 16 cm. Sapwood depth, which typically varies with tree size, age, and stand density, was shallow and irregular in these trees, reaching its greatest thickness in faster-growing “lobes” around the tree circumference. We made every effort to insert sensors in active sapwood by selecting insertion sites where active growth was apparent, increasing the likelihood that measured sap flux rates would be maximal. Sensors that did not meet these criteria were eliminated from analysis. After sensor installation, the trunk of each tree was wrapped with foil insulation to minimize any influence of ambient air temperature on the measurements. From day of year (DOY) 153 through DOY 182 (1–30 June 2004), readings were taken every 30 s and averaged over 30 min intervals. The data were corrected for influences of ambient air temperature and direct insolation [Do and Rocheteau, 2002], by means of unheated paired probes.

Once the sap flow measurements were complete, the sensors were removed and every tree in the plot ($n = 61$) was cut as close to the soil surface as possible for quantifying sapwood area (SWA). Active xylem tissue was differentiated by staining fresh-cut stems with methyl blue dye, and SWA per unit ground area was quantified by digitizing sapwood on photographs of cut stumps (Figure 3). Total SWA in the plot was $7 \times 10^{-4} \text{ m}^2 \text{ m}^{-2}$ ground area. The ratio of SWA to basal area was 0.24 ± 0.13 . When no spatial or size-related variation in sap velocity was found among the measured trees, sap flux measurements for individual trees were scaled to stand-level transpiration by multiplying the mean flux per unit sapwood by the SWA per unit ground area and summed for each day.

3.2. Water Monitoring

Groundwater data were collected during June 2004 (DOY 153 through DOY 182) from a network of four monitoring wells equipped with pressure transducers. The monitoring wells closest to the river were beneath the saltcedar canopy and arranged in a triangular configuration: B1 near the bank, B3 between the bank and the terrace, and B2 on the terrace at the edge of the saltcedar stand (Figure 2). This configuration made it possible to map groundwater contours and determine flow paths, as described by Heath [1982] and Kasenow [2001]. Well B5 was located in the abandoned floodplain. Water depths in the monitoring wells were measured each hour with pressure transducers having an accuracy of $\pm 0.2\%$ of the maximum depth range. These transducers were designed to measure water depths from 0 to 15 ft; therefore, the accuracy was ± 0.03 ft, or ± 9.14 mm. In addition, a pressure transducer was installed in the river (B4/staff gauge) to continuously measure water levels. At each wellhead, the land-surface elevation was surveyed with Trimble Model R8 GPS instrumentation through Real Time Kinematic (RTK) positioning, with a vertical accuracy



Figure 3. Cross sections of saltcedar stumps harvested from the PREP site along the Pecos River near Mentone, Texas. Sapwood is delineated by red outlines. Ruler length is 15 cm.

of ± 1.5 cm. A nearby National Geodetic Survey benchmark was used as the survey control for converting water levels to elevations.

3.3. Groundwater Contours and Hydraulic Gradients

Geographic coordinates, wellhead elevations, water depths, and stream-stage elevations were processed with RockWare 2006, revision 28 March 2008, to create topographical and groundwater contour maps. Groundwater contours were computed for two time periods for each day in June 2004: 04:00–06:00 CDT (A.M.) and 15:00–17:00 CDT (P.M.). These periods correspond to the hours of minimal and maximal sap flow, respectively (Figure 4).

We computed hydraulic gradients for the same time periods, for the stream bank, riparian, and abandoned floodplain zones, using head measurements from the groundwater contour maps and the staff gauge.

$$\text{Hydraulic gradient } (i) = \frac{h_1 - h_2}{L} \quad (1)$$

where h_1 is the hydraulic head at location 1, h_2 is the hydraulic head at location 2, and L is the distance between h_1 and h_2 .

3.4. Statistics

Fourier transform analysis was used to detect periodicity, or cyclical patterns, in water level and transpiration data. Fluctuations in stream stage, groundwater, and transpiration were tested via spectral analysis (SAS PROC SPECTRA) to determine whether variability was merely random white noise [Shumway and Stoffer, 2000] or a temporal pattern was present. Data were detrended prior to spectral analysis by specifying the ADJMEAN option in the spectral procedure. If the test showed variability was significantly different from white noise, frequency, and periodicity were further analyzed via SAS PROC SPECTRA.

To explore the coupling between transpiration and declines in stream stage and groundwater levels, Spearman correlations were computed for each 1 h lag from 0 to 24 h [Bond et al., 2002, Wondzell et al., 2010].

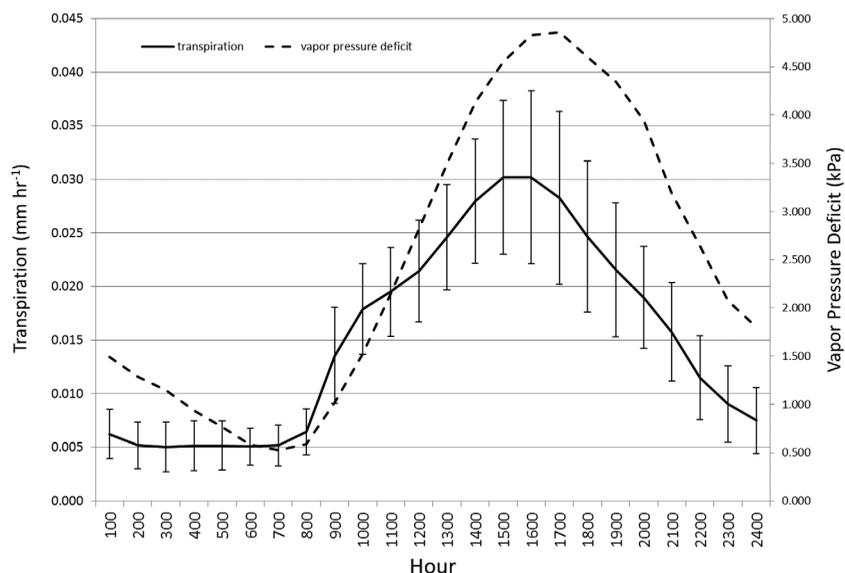


Figure 4. Hourly transpiration (mean \pm SD) and vapor pressure deficit at the PREP site, DOY 153–DOY 182 (1–30 June).

Then data for time lags with the greatest negative correlations were analyzed using regression analysis, to assess the strength of the relationship between transpiration and changes in water levels.

The SAS GLM procedure was used to test for significant effects of time period (A.M. versus P.M.) and of zone (stream bank, riparian, or floodplain) on hydraulic gradients; and Tukey’s studentized range HSD was used for post hoc mean separation analysis.

4. Results

4.1. Transpiration and Water Elevations

Spectral analysis revealed a diel cycle; a 24 h cycle was detected in transpiration, well B3 water levels, and stream stage. Mean daily transpiration was 0.29 ± 0.02 mm and typically peaked sometime between 15:00 and 17:00 CDT; minimum transpiration was observed between 04:00 and 06:00 CDT (Figure 4). In early June, groundwater fluctuations were evident from the hydrograph for well B3 (Figure 5), located in the riparian zone (data from the other wells were not significantly different from random white noise). After DOY 169 (17 June) vapor pressure deficit and transpiration declined and the amplitude and shape of diel fluctuations in B3 changed as well (Figure 5). A very faint diel pattern in stream stage was observed between DOY 159 and 174 (7–22 June). The continual increase in both stream and groundwater elevations reflects reservoir releases during the month of June; and rainfall on DOY 176 (24 June) caused a spike in the stream and in well B1 hydrographs. Depth to the water table in the riparian zone was ≤ 1 m during the entire observation period.

The lag, or phase shift, between hourly transpiration and changes in groundwater elevation in well B3 was about 7 h ($\rho = -0.46$; $p \leq 0.10$), but regression analysis of transpiration and water levels at t-7 resulted in an R^2 of 0.16 ($p \leq 0.05$), indicating that transpiration accounts for only 16% of the variability in water level in well B3 (Figure 6). The lag between transpiration and change in stream stage occurred at t-17 hours ($\rho = -0.35$; $p \leq 0.10$), but regression analysis showed that saltcedar transpiration had no effect on stream stage ($R^2 = 0.0045$; $p \leq 0.05$) (Figure 6).

4.2. Hydraulic Gradients

Hydraulic head was always higher in the stream than in the alluvial aquifer. Mean hydraulic gradients within each zone were not significantly different during peak transpiration (P.M.) than during minimal transpiration (A.M.) (Figure 7). Across zones, hydraulic gradients were not significantly different during the A.M. hours ($p \leq 0.38$), but were significantly higher in the stream bank zone than in the floodplain

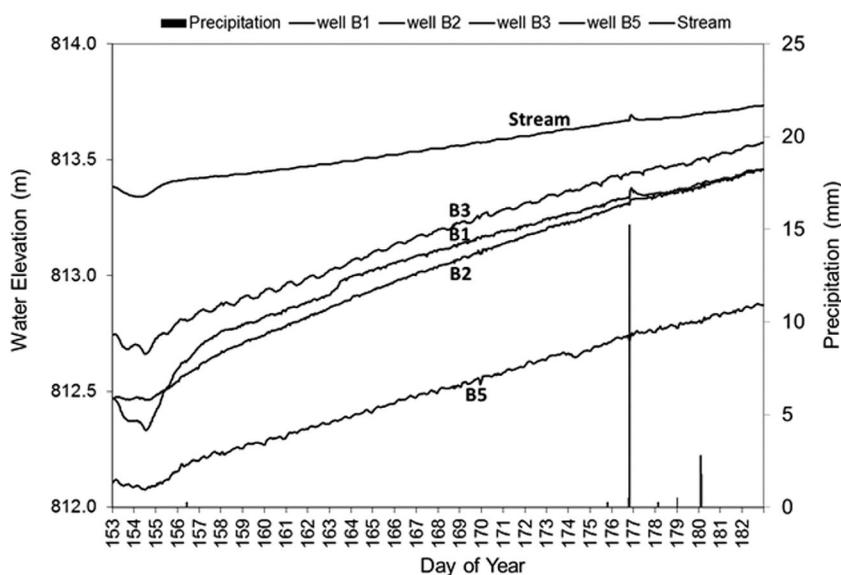


Figure 5. Hourly groundwater elevations, stream stage, and precipitation at the PREP site during June 2004.

zone during the P.M. time period. Gradients in the riparian zone did not differ significantly from those in the other zones (Figure 7).

5. Discussion

We examined hourly transpiration along with hourly changes in stream stage and groundwater levels—with the assumption that a strong linkage would be manifested in the stream stage as a diel fluctuation that is opposite to and somewhat lags transpiration. Although transpiration demonstrated a strong diel pattern, we found it had little if any effect on stream stage and was only weakly coupled with diel groundwater fluctuations. Additionally, we had hypothesized that hydraulic gradients, from the stream toward the riparian zone, should be steeper during times of peak transpiration than when transpiration is low. However, a comparison of hydraulic gradients within the stream bank, riparian, and floodplain zones during peak and minimum water-use periods failed to indicate a linkage between transpiration and hydraulic gradients in any zone. In fact, the hydraulic gradient in the riparian zone was not significantly different during periods of peak transpiration than when transpiration was minimal.

We suggest that this weak coupling is due primarily to low rates of transpiration. Stand transpiration was 0.3 mm d^{-1} , which is much lower than reported elsewhere. Using the same methodology, *Owens and Moore* [2007] found that the transpiration rate in a saltcedar stand on the Rio Grande in New Mexico was greater by an order of magnitude. The primary reason, we believe, for the low transpiration rates at the PREP site is that—because of low vigor—these trees have a small SWA-to-basal-area ratio. On the basis of stem sizes, we inferred that the trees at the Pecos site are mature and those at the Rio Grande site are young. Tree trunks at the Pecos site had rough bark and deep lobes (Figure 3), which are characteristics of mature plants. Saltcedar plants along the Rio Grande had many small, smooth barked stems. In the mature stand at the PREP site, SWA was $7 \times 10^{-4} \text{ m}^2 \text{ m}^{-2}$ ground area, whereas in the young, dense stand at the Rio Grande site, it was $3.1 \times 10^{-3} \text{ m}^2 \text{ m}^{-2}$ [Owens and Moore, 2007]. In addition to low SWA, plant density at the PREP site ($2563 \text{ trees ha}^{-1}$) was much lower than at the Rio Grande site ($10,700 \text{ trees ha}^{-1}$) [Owens and Moore, 2007].

A review by *Ryan et al.* [2006] of 51 species of trees documented a number of differences between older or taller trees and younger or shorter trees. These differences include photosynthesis, leaf area, SWA-to-basal-area ratio, stomatal conductance [McDowell et al., 2002; Ryan et al., 2006], SWA growth rates, and sap velocity [Forrester et al., 2010]. Smaller plants grow faster and use more water per unit leaf area than large plants

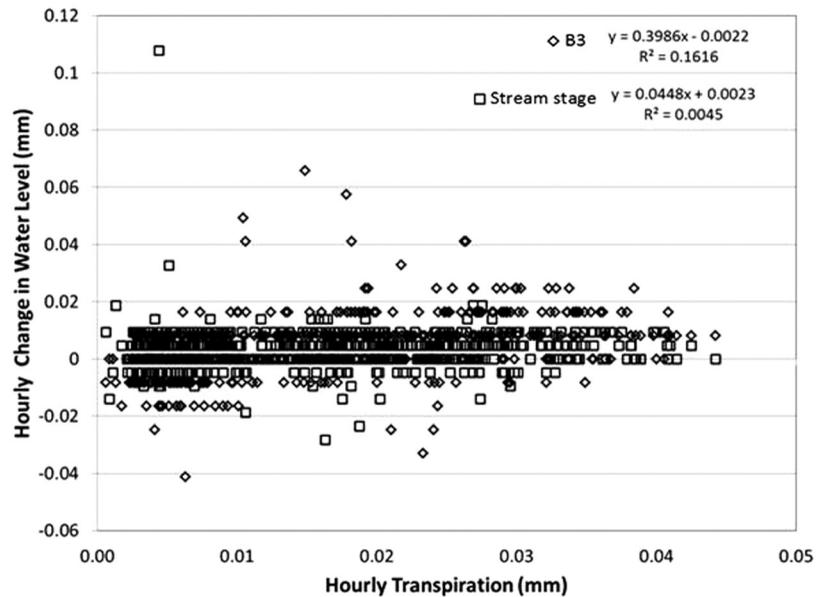


Figure 6. Pearson correlation of hourly saltcedar transpiration and changes in groundwater elevation ($t-7$) in well B3 and in stream stage ($t-17$) at the PREP site during June 2004 ($p \leq 0.05$).

[Medeiros and Pockman, 2010]. *Tamarix* was not included in the 51 species reviewed by Ryan *et al.* [2006], though saltcedar water use has been reported to decline with age [Nagler *et al.*, 2010b].

The coupling between transpiration and streamflow is influenced not only by the amount of transpiration but also by the magnitude of riparian transpiration relative to streamflow. At the PREP site, this coupling was found to be weak: mean daily transpiration during June 2004 was about 0.3 mm and streamflow in the Pecos River ranged from $8 \text{ m}^3 \text{ s}^{-1}$ to almost $12 \text{ m}^3 \text{ s}^{-1}$. By contrast, at a steep, forested watershed in western Oregon, where transpiration and streamflow were observed to be tightly coupled, daily transpiration rates by Douglas fir were between 1 and 3 mm and streamflow ranged from only 0.001 to $0.01 \text{ m}^3 \text{ s}^{-1}$ [Bond *et al.*, 2002]. Another influencing factor is the width of the riparian corridor. The relative magnitude of

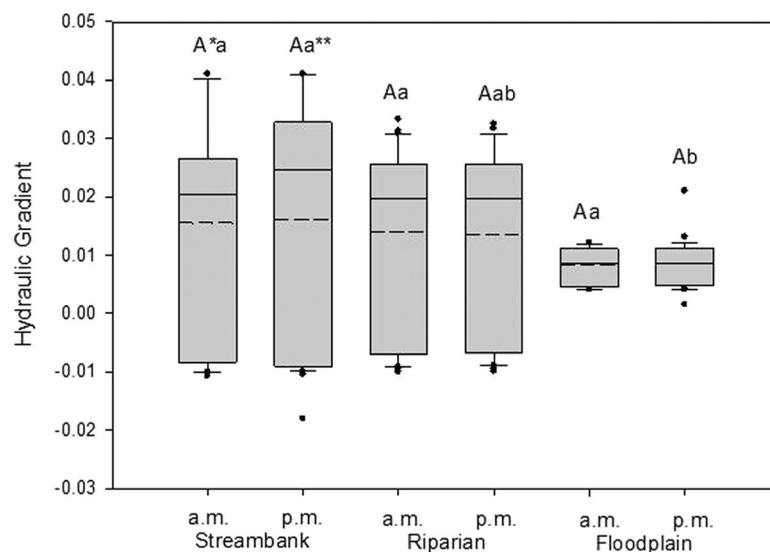


Figure 7. Boxplots comparing hydraulic gradients for the three zones during two time periods: 04:00–06:00 CDT (A.M.) and 15:00–17:00 CDT (P.M.). Dashed lines represent means. *Means represented by the same capital letter are not significantly different within the same zones (stream bank = $p \leq 0.68$; riparian = $p \leq 0.95$; and floodplain = $p \leq 0.77$). **Means represented by the same lowercase letter are not significantly different ($p \leq 0.15$) across zones.

transpiration will be smaller where the riparian corridor is narrow. At the PREP site, the riparian zone extends only about 40 m on each side of the river, whereas the riparian zones of the Colorado River may be as wide as 1.5 km [Nagler *et al.*, 2009] and those of the Middle Rio Grande 1.5–10 km [Dahm *et al.*, 2002]. The stark transition between the narrow riparian zone and relatively unvegetated floodplain (Figure 1) further suggests that growing conditions at the PREP site were suboptimal.

It has been suggested that transpiration rates of saltcedar and other phreatophytes is at or near potential ET because the plants are extracting water from the saturated zone, where supply is not limited. However, Glenn *et al.* [2013] demonstrated that salinity-stressed saltcedars transpire only 30% of potential ET. It was noted by van Hylckama [1970] that water use by saltcedar declined as water salinity approached 3.83 S m^{-1} , the maximum tolerated by this species. In addition, transpiration is limited by elevated salt levels in soils, as observed by Sala *et al.* [1996] at a site along the Virgin River in Nevada, USA. Downstream from Carlsbad, New Mexico, where the Pecos River flows through thick evaporite deposits, the water quality is known to be poor, and salts become further concentrated via lake evaporation in Red Bluff Reservoir upstream of the PREP site. Soil salinity along the Pecos River in west Texas ranges from 0.06 to 0.15 S m^{-1} [Clayton, 2002], and data for the years 2003–2006 (unpublished) record groundwater salinity within the riparian zone at the PREP site as varying from 0.1 to 1.9 S m^{-1} . Salinity data recorded at the U.S. Geological Survey stream gauging station near the city of Pecos, about 30 km downstream, show similar values and variability in surface water salinity [United States Geological Survey National Water Information System, 2014].

6. Conclusions

Along the losing reach of the Pecos River that is the subject of our research, we found a coupling between transpiration and groundwater fluctuations in only one monitoring well, and that coupling was weak: it altered neither stream stage nor hydraulic gradients. A primary reason for this weak coupling is that transpiration rates for saltcedar at our site are lower by a factor of 10 than those measured at other locations.

These findings are important because they provide a plausible explanation for why streamflow on the Pecos does not appear to have been increased by the large-scale removal of saltcedar. In other words, if saltcedar transpiration is not closely coupled to streamflow, control of saltcedar is not likely to have any influence on streamflow. Further, our findings provide a framework for future evaluations of the potential for salvaging water or increasing streamflow via management of riparian vegetation. First, we recommend in situ measurement of transpiration; this study and others have demonstrated the variability of transpiration depending on environmental conditions as well as plant physiology and phenology. Second, a comparison of transpiration rates versus streamflow will indicate whether or not it is possible to detect a change in streamflow resulting from reduced transpiration.

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