HYDROLOGIC IMPACTS OF SALTCEDAR CONTROL ALONG A REGULATED DRYLAND RIVER

A Dissertation

by

ALYSON KAY MCDONALD

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2010

Major Subject: Water Management and Hydrological Science

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Approved by:

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ABSTRACT

Hydrologic Impacts of Saltcedar Control Along a Regulated Dryland River.

(December 2010)

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Co-Chairs of Advisory Committee: Dr. Charles R. Hart
Dr. Bradford P. Wilcox

Tens of millions of dollars have been spent to control *Tamarix* (saltcedar) trees along waterways in the Southwestern United States for the purpose of increasing streamflow yet no increase in streamflow has been demonstrated. The Pecos River Ecosystem Project (PREP) served as a case study to characterize surface and groundwater interaction along the Pecos River in Texas, assess the influence of saltcedar transpiration on stream stage and water table fluctuations, and evaluate the impacts of large-scale saltcedar control on baseflows. This is the first study that has investigated the influence of saltcedar transpiration on surface and groundwater interaction and the first to provide a mechanistic explanation for the lack of measurable increase in streamflow. Neither saltcedar transpiration nor saltcedar removal influenced hydraulic gradients, streambank seepage, or stream elevations. The results of the plot scale studies indicate saltcedar transpiration along the Pecos River is lower than reported elsewhere and therefore may not yield detectable increases in

baseflow. To extend the study to a much larger scale, we analyzed annual baseflows at the downstream end of 340 km river reach from 1999 (pretreatment) through 2009. Surprisingly, baseflows declined for four years after the project began despite additional acreages of saltcedar treatment each year. However, baseflow surged in 2005 and remained higher than the pretreatment year (1999) through 2009. Additional detailed analyses of reservoir release and delivery records and rainfall are needed to better understand contributions of rainfall and flow regulation to this increase. Tracer based studies to determine the relative contributions of releases and groundwater would also enable a better interpretation of the change in baseflows. We did not investigate any other reported benefits, such as restoration of native plant species, or reduced soil salinity, of saltcedar control.

DEDICATION

The dissertation is dedicated to my parents, William C.H. “Bill” Glaze ’69 and Frances C. Glaze.

ACKNOWLEDGEMENTS

I am truly grateful to have a loving and patient family and many dear friends to encourage me along the way. Thank you, Charlie Hart, for extending to me the opportunity to work on this project and for years of support and encouragement. I also am very appreciative of Zhuping Sheng's unwavering guidance and willingness to share his knowledge throughout this entire study. Thank you, Brad Wilcox, for asking tough questions and imploring me to be brave, and Georgianne Moore, a graph guru, for asking the questions to which readers want the answer.

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TABLE OF CONTENTS

LIST OF FIGURES

FIGURE Page

FIGURE Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

In drylands, drainages are important ecological “hot spots“ that support many more species than adjacent xeric uplands (Naiman *et al*., 1993). In dry regions of some countries, humans rely solely on rivers to provide water for drinking and crop production. Despite the ecological and hydrological importance of dryland rivers, dryland hydrology is an under-developed discipline (Tooth, 2000). At present, much of our understanding of river systems comes from studies in humid regions (Nanson *et al*., 2002). Transferring these concepts to arid regions is complicated at best, primarily because of the difference in magnitude and frequency of fluvial events (Graf, 1988; Nanson *et al*., 2002).

Research in dryland river systems is further complicated by human perturbations, especially damming and flow regulation. Erratic rainfall and prevalence of drought in arid regions has led to damming of some rivers to provide a consistent supply of water for municipalities and irrigation. Flow regulation has a variety of downstream effects such as disconnection of channels from floodplains, depletion of sediment and nutrients, reductions in peak flows, increases in median flows, and alteration of aquatic and riparian biotic communities.

This dissertation follows the style of *Hydrological Processes*.

In times of drought, releases from reservoirs are often reduced or curtailed, requiring groundwater to be tapped to meet demands for water. Therefore, effective management of these limited supplies depends on an understanding of the interactions between surface water and groundwater.

The most pervasive habitat change as a result of damming is the proliferation of non-native species and as such restoration efforts are frequently centered on preserving or eliminating organisms of interest rather than ecosystem processes (Stanford *et al.,* 1996). In addition to altered wildlife habitat, reduction in streamflows also have been attributed to *Tamarix* spp. (saltcedar) trees growing along the banks of the Pecos (Weeks *et al*., 1987; Hart *et al*., 2005) and other regulated rivers (Culler *et al*., 1982; Dahm *et al*., 2002) in the Southwestern United States. Local, state, and federal governments have spent tens of millions of dollars on chemical, mechanical, and biological efforts to control saltcedar in the western U.S., with the hope of conserving water resources and restoring native riparian habitat (Shafroth and Briggs, 2008).

What is puzzling is that although most studies at the tree and stand scales have indicated that water savings could be substantial if saltcedar is removed (Nagler *et al*., 2010), particularly if not replaced by shrubs (Wilcox *et al.,* 2006), increases in streamflow as a result of saltcedar removal have not been documented. Why not? Are there in reality no water savings, or are they too difficult to detect at large scales?

Some have suggested that riparian ET is actually a relatively minor component of the water budget (Culler *et al.*, 1982) and that it may be overshadowed by larger-scale factors such as climate variability or groundwater extraction (Welder*,* 1988); or that perhaps mature trees utilize groundwater, not stream water (Dawson and Ehleringe*r*, 1991). Others argue that the interconnections between groundwater recharge and ET are still poorly understood and modification of one could effect compensatory changes in the other (e.g., a reduction in ET) may be balanced by increased groundwater storage, resulting in no detectable change in baseflow (Shafroth *et al.*, 2005).

The Pecos River Ecosystem Project (PREP) served as a case study to characterize surface and groundwater interaction along the Pecos River in Texas, assess the influence of saltcedar transpiration on stream stage and water table fluctuations, and evaluate the impacts of large-scale saltcedar control on baseflows. The Pecos River is a perennial, dryland river system in the southwestern United States. Flowing some 1480 km from its headwaters in northern New Mexico, the river converges with the Rio Grande in southwest Texas (Yuan and Miyamoto, 2005). The major sources of surface water are snowmelt from winter storms in the headwater region, and runoff from warm-season monsoonal rainfall in the lower valley (Yuan *et al.,* 2007). Multiple dams, three in New Mexico and one in Texas, have been constructed to collect and store water to provide a more dependable supply for agricultural irrigation and recreation. Red Bluff Reservoir, completed in 1936, was created by the only dam

on the Pecos River in Texas. Flow into this reservoir is highly dependent on upstream releases from reservoirs in New Mexico. Between 1950 and 1983, New Mexico released less streamflow to Texas than was agreed upon in an interstate compact, causing irrigated agriculture production in the Pecos Valley of Texas to decline sharply. After extensive litigation, New Mexico began complying with the 1948 Pecos River Compact in 1987, but the water came too late for many farmers and today much of the farmland remains fallow (Jensen *et al*., 2006).

The initial phase of the PREP focused on devising the most efficacious way to control saltcedar, assessing changes in river salinity before and after saltcedar control, and computing delivery efficiency of reservoir release to irrigation districts (Clayton 2002). Arsenal® (imazapyr) herbicide applied with a helicopter at a rate of 4 pints per acre proved to be the best control option. Streamflow losses between the reservoir and irrigation districts varied during the irrigation season. Losses were highest (68%) early in the season, leveled off to 39%, and reduced to 43% late in the season as discharge also declined. Clayton (2002) also found no difference in electrical conductivity (EC) that could be attributed to saltcedar control and reported that changes in EC were unrelated to discharge. Since 2001, saltcedar along 480 km of the Pecos River have been treated with herbicide, and burning of dead trees is underway (Gregory and Hatler, 2008).

The central question of this study is: does saltcedar control impact streamflow, groundwater recharge, or both? Are these impacts discernable at the small plot scale? What about the watershed scale? To answer these questions we analyzed stream seepage, hydraulic gradients, and groundwater flow paths at two sites before and after saltcedar control to understand spatial and temporal variability in surface water and groundwater interaction and determine if saltcedar control affected hydrologic interaction and streambank seepage. We also assessed the relationship between hourly measurements of saltcedar transpiration and changes in stream stage to see if transpiration depleted streamflow during peak hours. Correlation between diel transpiration and groundwater fluctuation was also computed to determine if these fluctuations were caused by transpiration. We extended the investigation to the watershed scale by analyzing streamflow near the terminus of the treated area to find out if baseflows increased after saltcedar control.

CHAPTER II

VARIABILITY IN SURFACE AND GROUNDWATER INTERACTION

INTRODUCTION

Unlike rivers in humid regions, flow in dryland rivers typically declines in the downstream direction as a result of transmission losses, which include seepage of streamflow into the aquifer, evaporation, and transpiration. However, much remains to be learned about the nature of the exchange between surface water and groundwater in these landscapes, especially in terms of spatial and temporal variability. For example, is there temporal variability? Is streambank seepage permanently lost? Can losses be reduced by killing riparian vegetation?

Streamflow gain-loss measurements along the Pecos River in New Mexico (Boroughs and Abt, 2003) and Texas (Hoyt, 1904; Grozier *et al.*, 1966; Grozier *et al.,* 1968) showed that stream losses varied with season and flow conditions; but these studies did not investigate near-channel groundwater flow paths nor the mechanisms that control seepage patterns. Interactions between the river and aquifer influence not only the quantity of flow, but also the hydrochemistry of the Pecos River (Yuan and Miyamoto, 2005). Previous research of the Pecos River generated some questions about stream losses that will be addressed in this paper. To better understand the magnitude, variability, and fate of streambank seepage we assessed river stages, groundwater hydraulic gradients, and groundwater flow paths in April, July and September

2001-2003 at two sites along a reach of the Pecos River in West Texas. The specific questions that will be addressed are:

(1) Do seepage rates vary with time?

(2) Where does the seepage go and how does the aquifer respond to streambank seepage?

(3) Will saltcedar control reduce streambank seepage?

STUDY AREA

The Pecos River defines the eastern boundary of the Trans-Pecos region in Texas, bordering the northeastern extent of the Chihuahuan Desert. 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). The study area was a 3-km-long reach of the Pecos River near Mentone, Texas (31.7° N, 103.6° W). Vegetation in the riparian corridor consists mainly of a *Tamarix* spp. (saltcedar) overstory with a sparse understory of grasses, predominantly *Chloris crinita* (trichloris) and *Cynodon dactylon* (bermudagrass). The floodplain is home to scattered *Atriplex canescens* (fourwing saltbush) and *Prosopis glandulosa* (honey mesquite) with patches of perennial grasses. The underlying aquifer at this location consists of thick (up to 900 m), saturated, quaternary alluvial deposits of unconsolidated or partially consolidated sand, silt, clay, and gravel (Ogilbee *et al.,* 1962).

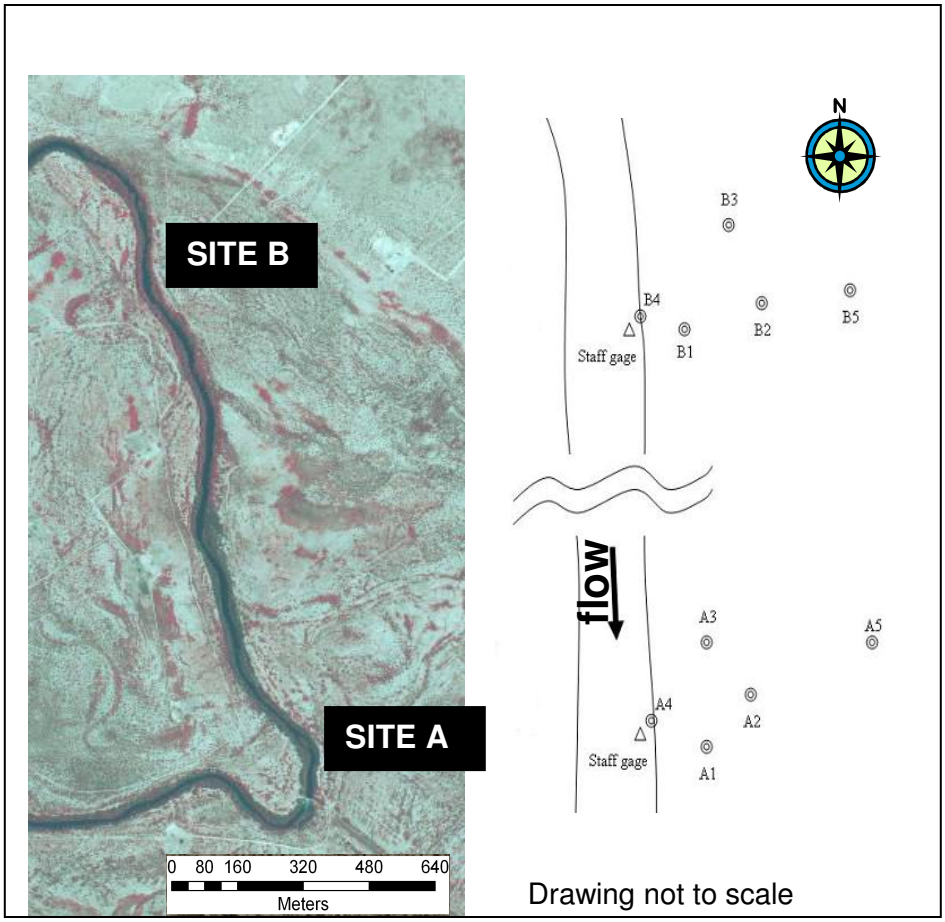


Figure 2.1. Aerial photograph and drawing of monitoring well network at Sites A and B within the PREP study area along the Pecos River, Texas.

METHODS

Water Level Monitoring

In August 2000, water monitoring sites designated A and B, were established within the study area to quantify the effects of saltcedar control on water quality and quantity (Hays, 2003). Groundwater data were collected from a network of monitoring wells along the east bank of the river at both sites for one

year. Herbicide was applied to saltcedar at Site A at the end of the growing season in 2001 while trees at Site B remained untreated.

Well boreholes were excavated by hand with a bucket auger at least to the depth of the water table (Hays, 2003). Borehole depths ranged from about 3 m near the river to almost 6 m in the floodplain. Wells were constructed of 5 cm diameter polyvinyl chloride pipe that was perforated (0.25 mm) along the bottom 1 m. The well pipe was pushed into place by hand and annular space around the well pipe was filled with fracturing sand to mitigate clogging of perforations. Concrete was poured around the well pipe at the soil surface to prevent rainfall and overland flow from entering the borehole. All wells were screened at approximately the same elevation, as they were installed within a two day period and were drilled to depth of water table.

The monitoring wells closest to the river were beneath the saltcedar canopy and arranged in a triangular configuration (Figure 2.1): near the bank (A1 and B1), between the bank and the terrace (A3 and B3), on the terrace at the edge of the saltcedar stand (A2 and B2). This triangular configuration made it possible to map groundwater contours and determine flowpaths as described by Heath (1982) and Kasenow (2001). Wells A5 and B5 were in the abandoned floodplain. Depths of water in the monitoring wells were measured with pressure transducers having an accuracy of ±0.2% of the maximum depth range. These transducers were designed to measure water depths from 0 ft–15 ft, therefore the accuracy was ±0.03 ft, or ± 9.14 mm. Water depths in the monitoring wells were

recorded at hourly intervals with a battery-powered datalogger. At each site, the water level of the river was measured continuously with a pressure transducer and a staff gauge was placed next to it for the purpose of converting river depth to river stage and river stage to elevation.

Aquifer Hydraulic Properties

During monitoring well installation, Hays (2003) sampled soils at 30-cm increments to the depth of the water table and analyzed the samples for particle-size distribution (PSD) to determine soil texture. Duplicate slug tests (Bouwer and Rice, 1976) consisting of a rapid application of 5 L of water, were conducted in each monitoring well in 2006 to estimate saturated hydraulic conductivity (K_{sat}) of the screened layer. There were no wells in the streambank zone so K_{sat} was estimated for both sites based on soil PSD (Kasenow, 2001).

Streambank Seepage and Groundwater Flow Rates

Land-surface elevations at each monitoring well and both staff gauges were surveyed using a Trimble Model R8 global positioning system with real time kinematic positioning. The vertical accuracy with this instrument was ±1.5 cm. The survey control was a National Geodetic Survey benchmark located nearby and the vertical datum was NAVD88. Geographic coordinates, wellhead elevations, water depths, and river-stage elevations were processed using RockWare 2006, revision 2008.3.28, to create topographical and water-table contour maps for each week in April, July, and September (representing early, mid, and late growing season, respectively), 2001–2003.

On the basis of soil hydraulic properties, kind and density of vegetation, and landscape position, the valley was divided into three zones: streambank, riparian, and floodplain (Figure 2.2). The streambank zone extended tangentially about 1.2 m from the edge of the river to the edge of the riparian zone. The riparian zone was about 24 m wide. The adjacent floodplain zone extended from the edge of the riparian zone to the wells, a distance of 37.5 m at Site A and 30.5 m at Site B (Figure 2.2). Autoregression (Shumway and Stoffer 2000) and Tukey's HSD mean separation (Zar, 1996) statistical tests were used to determine significant differences in hydraulic gradient for all zones, months and years at each site.

Seepage in the streambank zone and flow rates (cms km^{-1}) in the riparian and floodplain zones were calculated using Darcy's Law (Hiscock, 2005) and heads from the contour maps, computed hydraulic gradients, and saturated hydraulic conductivity. Cross sectional flow area was equal to aquifer thickness (7.5 m) multiplied by length of stream segment (1 km), which was selected to allow for comparison with results of previous gain-loss studies (Grozier *et al.*, 1966 and Grozier *et al.*, 1968).

Autoregression (Shumway and Stoffer 2000) and Tukey's HSD mean separation (Zar, 1996) statistical tests were used to determine significant differences in hydraulic gradient for all zones, months and years at each site.

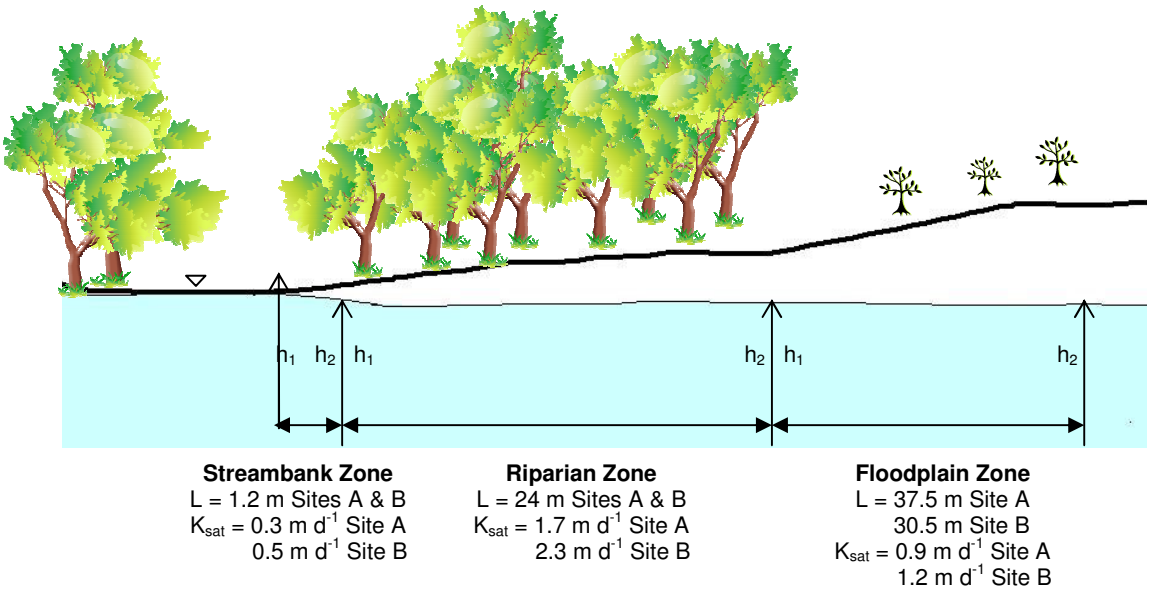


Figure 2.2. Conceptual model of right (East) bank depicting width and soil saturated hydraulic conductivity for three zones within the PREP study area along the Pecos River, Texas. Drawing not to scale.

RESULTS

Spatial and Temporal Variability in Streambank Seepage and Groundwater Flow Rates

Seepage and groundwater flow rates are positively related to K_{sat}, which is static and also to the hydraulic gradient, which is dynamic. Saturated hydraulic conductivity was highest at well B3 and similar at all other locations (Table 2.1). Hydraulic gradients differed significantly ($P < 0.05$) from one zone to another at

both sites, but were consistent within zones, except for the streambank (Figure

Zone	Monitoring well	Site A K_{sat} (m d^{-1})	Site B K_{sat} (m d^{-1})
riparian	1	2.1	1.2
riparian	2	1.8	1.6
riparian	3	.	4.3
floodplain	5	0.9	1.2
streambank	--	0.3	0.5

2.3).

Table 2.1. Soil saturated hydraulic conductivity from 7 monitoring wells located in three zones at Sites A and B within the PREP study area along the Pecos River, Texas.

'.' Denotes missing data

Analysis of variance and mean separation were computed to determine whether hydraulic gradients varied significantly across months within years and also in the same month across years (Table 2.2). Hydraulic gradients varied across months at Site A in 2001. Prior to a reservoir release, gradients in the streambank zone were steep while water levels were relatively gentle in the riparian and floodplain zones (Figure 2.3). After the release began, groundwater levels surged upward causing the gradient and Darcy flow rate to decline (Figure 2.4). Gradients during the same month at Site A showed no significant differences from year to year (Table 2.2). Due to equipment failure, gradients and seepage for Site A in April 2002 could not be computed.

Both monthly and inter-annual variability were observed at Site B (Figure 2.3). Gradients in July and September varied from year to year. In 2002, seepage and flow rates were low early in the growing season (April), then increased significantly in July and September in response to declining groundwater levels, due to curtailed reservoir releases, and rainfall events that resulted in short-term rises in stream stage (Figure 2.6). These hydrologic conditions also contributed to significant interannual variability. Hydraulic gradients peaked in July and September 2002 and were significantly higher than for the same months in 2001 and 2003.

Trends in flow rate (cms km^{-1}) generally followed this pattern: streambank < riparian > floodplain. Flow rate was greatest in the riparian zone during all observation periods at Site A and during most periods at Site B. Flow rate into the floodplain from the riparian zone was often minimal, except when floodwaves in the stream propagated through the riparian zone and into the floodplain—as was observed in April 2001 (Figure 2.5).

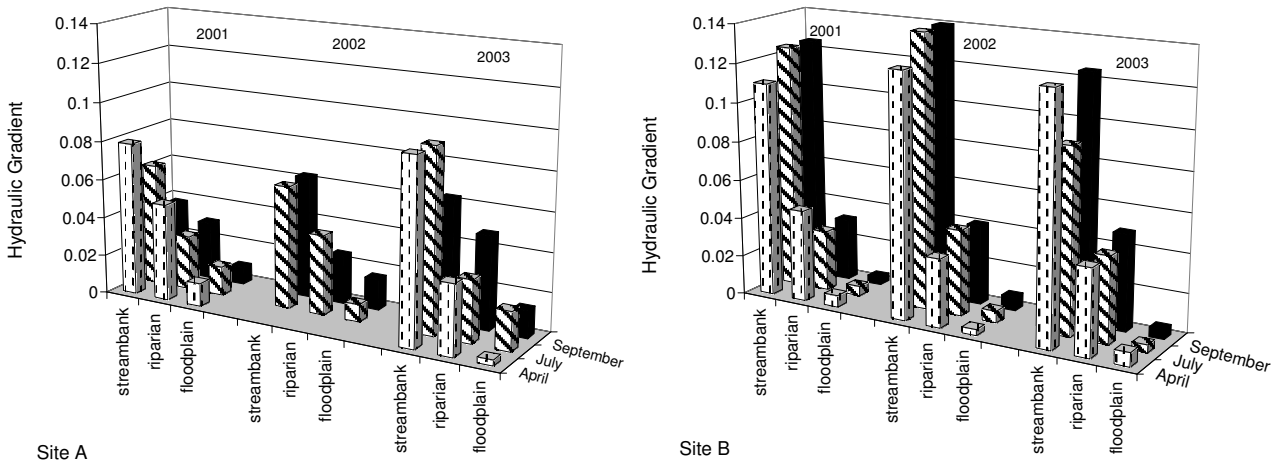


Figure 2.3. Hydraulic gradients in streambank, riparian and floodplain zones in April, July and September 2001-2003 at Sites A and B within the PREP study area along the Pecos River, Texas.

Table 2.2. Mean river elevation and hydraulic gradients in April, July and September 2001-2003 for three zones at Sites A and B within the PREP study area along the Pecos River, Texas.

		Site A				Site B			
		River Elevation	Hydraulic Gradient			River Elevation	Hydraulic Gradient		
Year	**Month**	**(masl)**	**Streambank**	**Riparian**	**Floodplain**	**(masl)**	**Streambank**	**Riparian**	**Floodplain**
2001	April	812.652	0.079*Aa*	0.049*Aa*	0.013*Aa*	813.072	0.109*Aa*	0.047*Aa*	0.006*Aa*
	July	812.576	0.063*ABa*	0.028*Aa*	0.015*Aa*	813.034	0.125*Ab*	0.031*Aa*	0.005*Aa*
	September	812.317	0.037*Ba*	0.030*Aa*	0.009*Aa*	812.576	0.125*Ab*	0.032*Aa*	0.004*Aa*
2002	April	.	.	.	.	812.348	0.125B*a*	0.034*Aa*	0.003*Aa*
	July	812.157	0.063*Aa*	0.041*Aa*	0.009*Aa*	812.538	0.219*Aa*	0.044*Aa*	0.006*Aa*
	September	812.100	0.063*Aa*	0.025*Aa*	0.016*Aa*	812.500	0.203*Aa*	0.040*Aa*	0.007*Aa*
2003	April	812.005	0.094*Aa*	0.036*Aa*	0.003*Aa*	812.500	0.125*Aa*	0.044*Aa*	0.007*Aa*
	July	812.119	0.094*Aa*	0.032*Aa*	0.019*Aa*	812.576	0.094*Ab*	0.044*Aa*	0.004*Aa*
	September	812.195	0.063*Aa*	0.048*Aa*	0.014*Aa*	812.500	0.125*Ab*	0.048*Aa*	0.005*Aa*

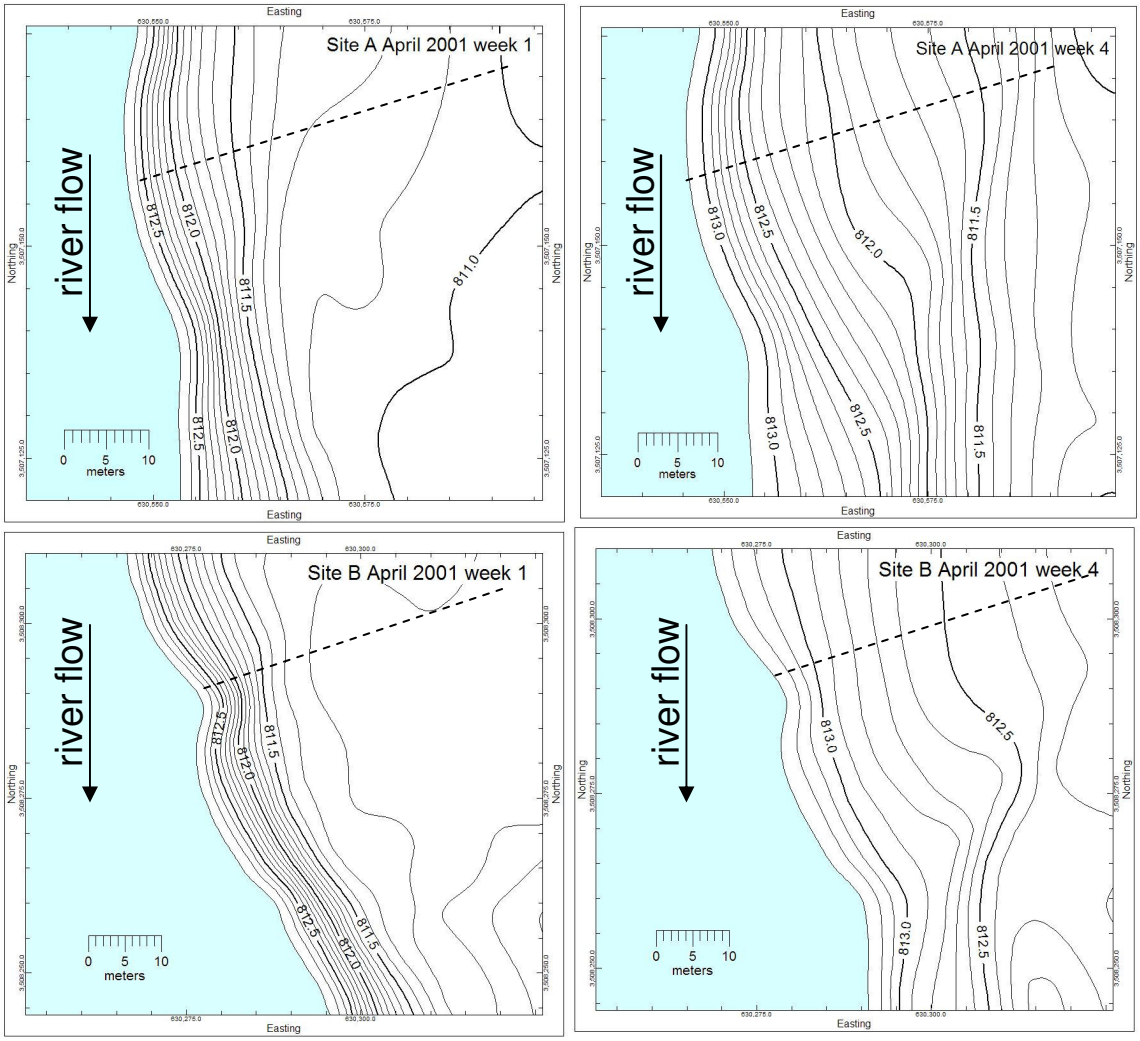
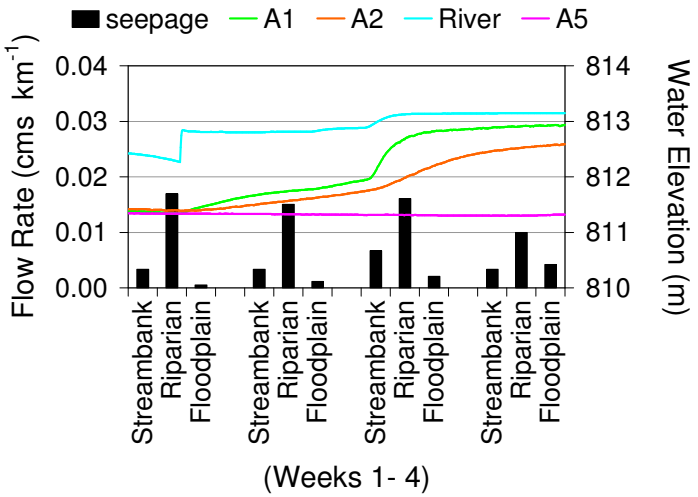


Figure 2.4. Groundwater contour maps from weeks 1 and 4, April 2001 at Sites A and B within the PREP study area along the Pecos River, Texas.

Influence of Saltcedar Control on Streambank Seepage and Groundwater Flow Rates

Hydraulic gradients at Site A were not significantly different after saltcedar control (Table 2.2). This indicates that the stress created by saltcedar transpiration is

not substantial enough to alter the hydraulic gradients nor increase streambank seepage.



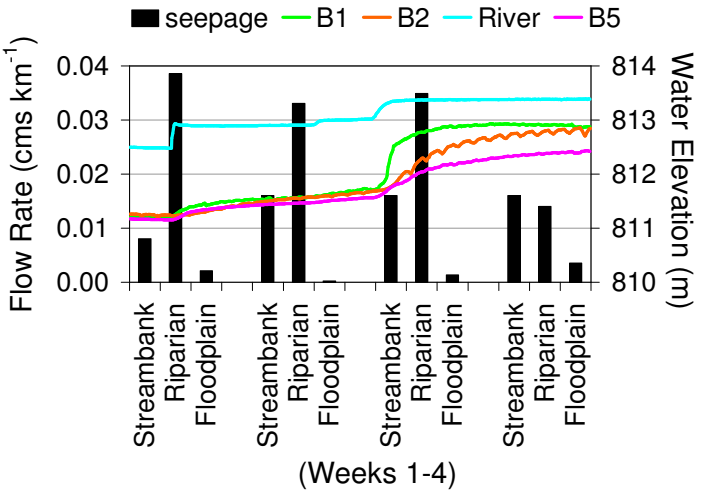


Figure 2.5. Flow rate in three zones at Sites A and B in April 2001 within the PREP study area along the Pecos River, Texas.

DISCUSSION

Are Seepage Rates Temporally Variable?

Monthly differences were measured at Site B only in 2002 and at Site A only in 2001 (Figure 2.4). There were no differences in seepage for the same month among years at Site A. Differences in reservoir operation did influence seepage patterns. Hydraulic gradients were enhanced under two conditions: (1) elevated stream stage caused by a reservoir release or rainfall as seen in July 2002 (Figure 2.6) and (2) when groundwater levels were low due to extended periods of no irrigation release such as week 1 in April 2001 (Figure 2.4). This is in agreement with the observation by Clayton (2002) that delivery of reservoir releases was less efficient at the beginning of the irrigation season. The steep hydraulic gradient caused by depressed groundwater levels causes enhanced streambank seepage into the riparian zone until groundwater levels begin to rise. Overall, assuming K_{sat} values were similar, hydraulic gradients and thus seepage were higher at Site B than Site A. This may be partially attributed to a small dam located downstream from Site A. The dam, constructed of broken concrete and large rocks, reduces flow velocity and may also reduce the decline in groundwater levels during non-release periods.

Monthly seepage losses remained relatively constant, between –0.014 and –0.022 cms km^{-1} at Site B and between –0.008 and –0.016 cms km^{-1} at Site A, with mean monthly flows ranging from 0.09 to 7 cms. These seepage losses were within the range of those previously reported. In 1964 and 1967,

streamflow gain/loss studies were conducted between Red Bluff Reservoir and Orla (about 27 km upstream from the study area). From the 1964 study, it was found that with a reservoir discharge of 3.65 cms, losses along that reach were –0.007 cms km^{-1} (Grozier *et al*., 1966); and from the 1967 study, under much higher flow conditions (15.5 cms), losses were reported to be –0.043 cms km^{-1} (Grozier *et al*., 1968).

Where Does Seepage Go and How Does the Aquifer Respond to Streambank Seepage?

Temporary and seasonal reversals in hydraulic gradient have been observed in a range of geomorphic settings, including mountain streams in New Mexico (Wroblicky *et al*., 1998), lowland agricultural watersheds in Ontario (Duval and Hill, 2006), and glacial-fill aquifers in New Hampshire (Harte and Kiah, 2009). The river was losing or discharging water into the aquifer at both sites during all observations periods (Figure 2.7). No reversal was observed in this study, even during low-flow conditions in 2002 and 2003 when there were no releases from Red Bluff Reservoir for irrigation and stream discharge was very low.

Seepage leaves the river through the streambank and flows laterally into the riparian zone. Only a small portion of this water enters the floodplain zone, except during periods of high flow, when the hydraulic gradient is steeper towards the floodplain. The relatively small amount of water that is transmitted to the floodplain suggests that water is coming from source(s) other than direct

streambank seepage. Stated another way, if only a small percentage of the water entering the riparian zone is moving into the floodplain, the remainder must be flowing parallel to the channel or downward. Periodically, at both sites, groundwater in the riparian zone flowed somewhat parallel to the river channel—especially during steady river conditions such as nonrelease periods (Figure 2.4). However, lateral flow dominated during the entire study.

Will Streambank Seepage Decline as a Result of Saltcedar Control?

Influence of transpiration on groundwater levels and hydraulic gradients has been observed in prairie potholes (Rosenberry and Winter, 1997) and along streambanks in forested mountain watersheds (Rosenberry *et al*., 1999). Transpiration by streamside trees temporarily induced infiltration of streambank seepage by reversing the hydraulic gradient, causing a gaining reach to become a losing reach during the growing season (Rosenberry *et al*., 1999). Given that this stream reach was always losing or discharging to the aquifer, a reversal in hydraulic gradient due to induced infiltration is not possible. However, an increase in hydraulic gradient away from the streambank is possible.

Hydraulic gradients at Site A were not significantly different in any of the zones following saltcedar control. Some possible explanations for this are that the stress created by transpiration is not substantial enough to alter hydraulic gradients, or that induced infiltration was occurring simultaneously and masked by rapid increases in stream stage or decline in groundwater levels.

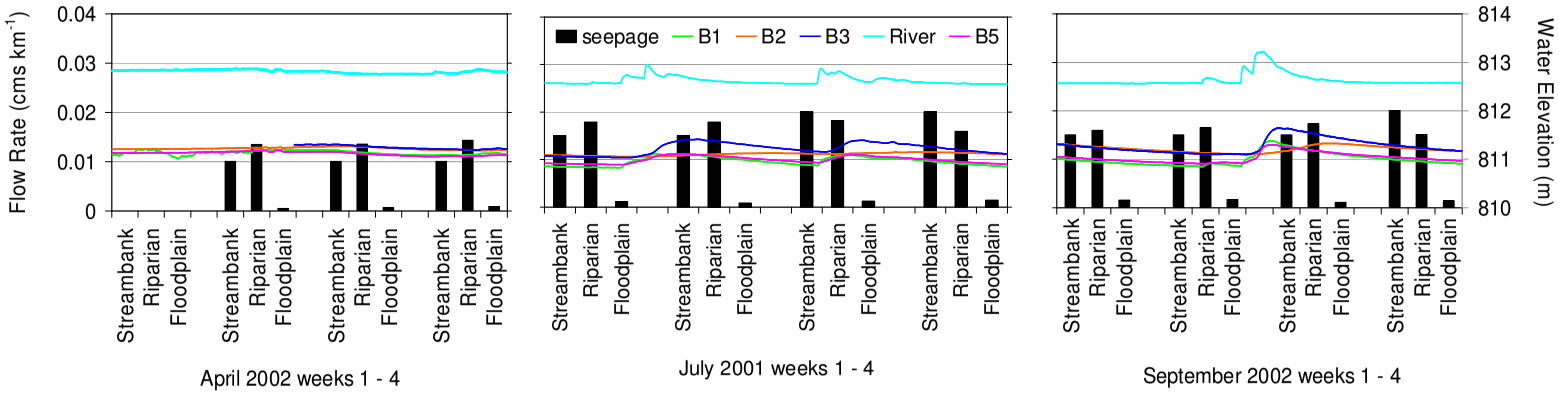


Figure 2.6. Flow rate and groundwater and stream elevations in three zones April, July and September 2002 within the PREP site along the Pecos River, Texas.

CONCLUSIONS

Along this reach the river was losing water to the aquifer even under low-flow conditions; but the mechanisms controlling the seepage differed. Seepage increased not only during high-flow events but also when the water table was declining. *Tamarix* (saltcedar) control did not affect hydraulic gradients or reduce streambank seepage and given that this is a losing reach, streamflow will not be enhanced by controlling saltcedar.

Evidence of parallel flow in the riparian zone was observed only under certain hydrologic conditions. Parallel flow was not anticipated and the monitoring well network was not designed to assess parallel flow. In the future, grids of nested monitoring wells, screened at various depths, can provide information about possible causes of high flow rate within the riparian zone; namely, flow parallel to the channel and vertical flow from the stream or from deep within the aquifer. Time lags and larger scale processes also play a role in groundwater flow paths within the riparian zone. This new information can be used to modify or refine the conceptual model.

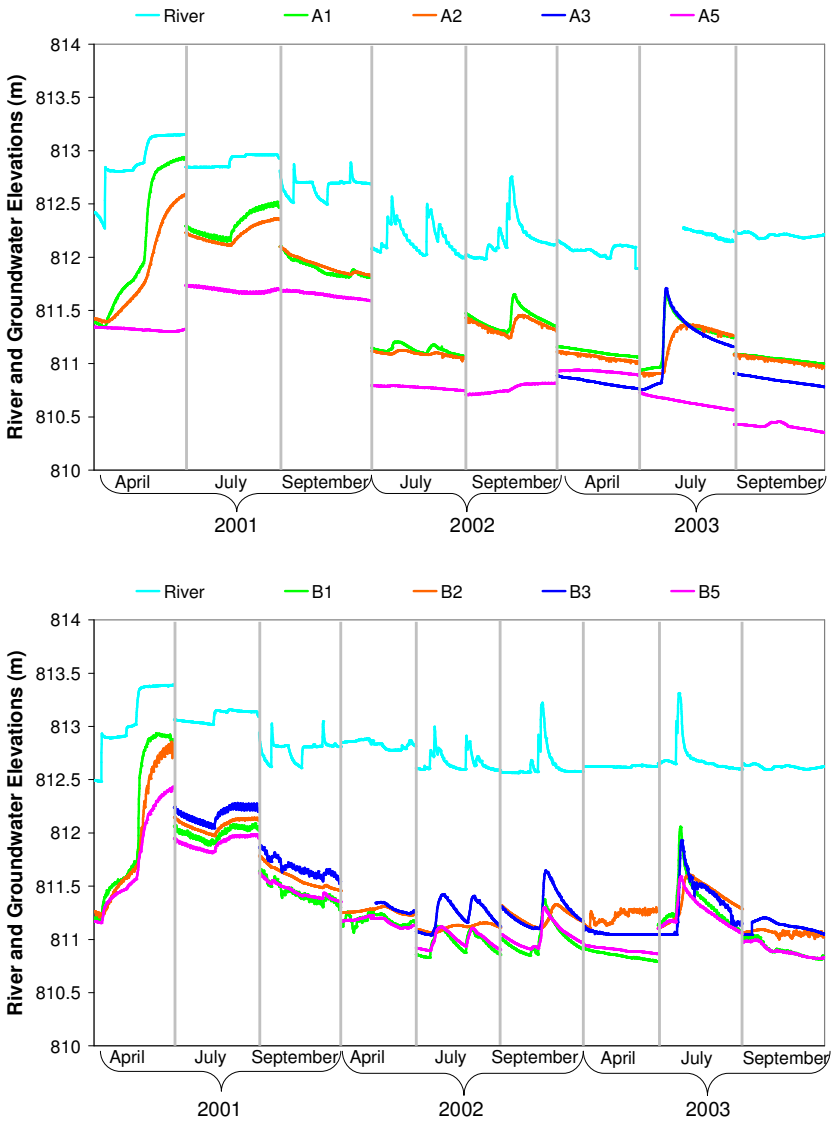


Figure 2.7. River and groundwater elevations at Sites A and B, April, July and September 2001-2003 within the PREP study area along the Pecos River, Texas.

Currently, water from the reservoir is released to irrigators downstream in large “blocks,” mainly for the spring and summer growing seasons and very little or none during the dormant or winter season. Seepage rate is enhanced during

these block releases and more water is transferred to the floodplain. If releases were to be continued during the dormant season, losses to the floodplain could be minimized and higher groundwater levels during the dormant season may also support a broader range of riparian plant species.

The Pecos River Ecosystem Project has accomplished the initial goal of killing much of the saltcedar along the main channel and tributaries and burning of dead debris has begun. Transpiration by saltcedar did not increase streambank seepage and because this is a losing reach, any water salvaged by eliminating saltcedar will not enhance streamflow along this reach but may contribute to aquifer recharge. However, saltcedar control has potential to alter surface and groundwater interactions. During high flow events, accelerated erosion may occur along the exposed banks where saltcedar has been sprayed and burned. Erosion and deposition of bank sediments may also modify surface and groundwater interactions via changes in channel morphology such as aggradation of the streambed. These findings can be used to advance basic conceptual models of dryland river systems and predict hydrologic behavior in response to changes in timing and magnitude of streamflows and removal of riparian vegetation.

CHAPTER III

CORRELATION BETWEEN SALTCEDAR TRANSPIRATION AND FLUCTUATIONS IN STREAM STAGE AND GROUNDWATER

INTRODUCTION

Riparian landscapes across the western United States have been transformed by damming, flow regulation, and the encroachment of nonnative shrubs saltcedar (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*) (Nagler *et al*., 2010). It has been commonly assumed that this transformation has resulted in the loss of large amounts of water, via riparian transpiration, that would otherwise be available for streamflow. This prompted the Salt Cedar and Russian Olive Control Demonstration Act signed into law in 2006 (Shafroth *et al.*, 2010). Already, local, state, and federal governments have spent tens of millions of dollars on chemical, mechanical, and biological efforts to control saltcedar in the western U.S., with the hope of conserving water resources and restoring native riparian habitat (Shafroth and Briggs, 2008) and there are active control projects in California, New Mexico, Colorado, Texas, Montana, North Dakota, South Dakota, Wyoming, Nebraska, and Kansas.

There have been few documented cases of diminished streamflow caused by saltcedar encroachment. Early research on saltcedar indicated that it used substantially more water than native trees. The latest reports indicate saltcedar water use is similar to native riparian trees (Glenn and Nagler, 2005; Shafroth *et*

al., 2005; Owens and Moore*,* 2007). Water use by saltcedar has been measured at a number of scales from that of individual plants to that of watersheds (Nagler *et al.*, 2009; Shafroth *et al.*, 2005) (Wilcox *et al.*, 2006). Plant-scale measurements rely on sap flow (Sala *et al.*, 1996; Devitt *et al.*, 1997) and stomatal resistance (Anderson, 1982). At the field scale, micrometeorological measurements—such as eddy correlation (Weeks *et al.*, 1987) and Bowen ratio (Si *et al.*, 2005) have been used. Estimates of evapotranspiration (ET) from these kinds of studies range from 0.6 to 1.7 m yr^{-1} (Shafroth *et al.* 2005, Nagler *et al.,* 2009). Another way of assessing water use at the field scale is to evaluate the diel changes in groundwater levels**,** as pioneered by White (1932) and subsequently refined by Loheide *et al.,* (2008) and Butler *et al.*, (2007).

Despite differences in approach and estimates of water use, researchers agree that water use by riparian vegetation is dependent on several factors**:** stand density, tree size, fetch or width of stand, depth to water table, and environmental conditions (such as atmospheric gradient) that drive transpiration (Devitt *et al.*, 1997; Glenn *et al.,* 1998; Shafroth *et al.*, 2000; Hays, 2003).

Actual savings of water resulting from control of saltcedar and Russian olive along semi-arid rivers have been difficult to demonstrate (Nagler *et al.*, 2010). This is puzzling because many studies at the tree and stand scales have indicated that water savings could be substantial if saltcedar is removed (Nagler *et al.*, 2010), particularly if not replaced by native shrubs (Wilcox *et al.,* 2006), and yet increases in streamflow as a result of saltcedar control have not been

documented. Why not? Are there in reality no water savings, or are they too difficult to detect at large scales? Some have suggested that riparian ET is actually a relatively minor component of the water budget (Culler *et al.*, 1982) and that it may be overshadowed by larger-scale factors such as climate variability or groundwater extraction (Welder*,* 1988). Others argue that the interconnections between groundwater recharge and ET are still poorly understood and modification of one could effect compensatory changes in the other,e.g., a reduction in ET may be balanced by increased groundwater storage, resulting in no detectable change in baseflow (Shafroth *et al.*, 2005).

Transpiration has been correlated with decline in flow in mountain streams (Bond *et al.*, 2002; Wondzell *et al.*, 2010) and the influence of transpiration on groundwater levels and hydraulic gradients has been observed in prairie potholes (Rosenberry and Winter, 1997) and along streambanks in forested mountain watersheds (Rosenberry *et al.*, 1999). Transpiration by streamside trees temporarily reversed the hydraulic gradient and thus flow direction, causing a gaining reach to become a losing reach during the growing season (Rosenberry *et al.,* 1999).

Clearing of riparian and hillslope vegetation has had mixed effects on diel groundwater and streamflow fluctuations. A summary by Bren (1997) indicated removal of riparian vegetation may be accompanied by suppression or elimination of diel stream fluctuations accompanied by an increase in streamflow.

Conversely, amplitude of stream fluctuations may increase in response to additional inputs of groundwater from the hillslope after clearing.

Since 2001, saltcedar along 480 km of the Pecos River have been treated with herbicide as part of the Pecos River Ecosystem Project (PREP); yet there have been no reports of increased streamflow (Hart *et al*., 2005). Hays (2003) estimated water loss from a saltcedar stand at this site (called the PREP site) using analyses of diel groundwater fluctuations. His estimates indicated that water loss, including evaporation and transpiration, was about 2.5 m during the 2001 growing season. This estimate was subsequently refined by Hatler and Hart (2009), who modified Hay's technique and came up with an estimate of 1.18 m for 2001. They also analyzed groundwater fluctuations for 5 years following saltcedar control and estimated the potential salvage to range from 0.3 m in 2002 to 0.7 m in 2003. After 2003 estimated salvage declined and by 2006 it was negligible due to transpiration by saltcedar regrowth and other riparian vegetation (Hatler and Hart, 2009).

As mentioned in Chapter II, this is a losing reach even under low-flow conditions—which may explain why increased streamflows have not been documented at this site. Along a losing reach, water seeps through the river bed, river banks, or both and flows into the shallow aquifer under the influence of hydraulic gradient. Therefore, under these conditions, water salvage from saltcedar control 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 streamflow or seepage from the river into the alluvial aquifer. In an effort to better understand the linkage between transpiration by saltcedar and streamflow, we monitored transpiration, stream stage, and groundwater elevations within Site B, the untreated site, within the PREP study area from April through June 2004. Our specific goal was to determine to what extent transpiration by saltcedar may affect streamflow. Specifically we propose that:

H1: The study site is situated along a losing reach of the Pecos River. If transpiration reduces streamflow, then the effect should be manifested in the stream stage as a diel fluctuation that is opposite and somewhat lagged compared to transpiration.

H2: Groundwater fluctuations have been observed at this site and have been attributed to ET. If these fluctuations are indeed an effect of ET, then hourly transpiration rates should be negatively correlated with groundwater levels and this relationship should be strongest around the hour of daily maximum transpiration.

METHODS

Water Monitoring

Stream and groundwater data were collected from Site B (untreated site) within the PREP study area described in detail in Chapter I.

Transpiration

A heat-dissipation technique (after Granier (1987)) was used to measure sap flux in saltcedar stems (Moore and Owens, unpublished data). Data were corrected for influence of background temperature such as ambient air temperature and direct insolation (Do and Rocheteau, 2002) using readings from trees similarly equipped but without heat probes. Readings were taken every 30 seconds and averaged over 30-minute intervals. Once the sapflow measurements were complete, sensors were removed and trees were cut as close to soil surface as possible. Active xylem tissue was differentiated by staining fresh-cut stems with methyl blue dye and sapwood area per unit ground area was quantified by digitizing sapwood on digital photographs of cut stumps (Figure 3.1).

Data Analyses

Rapid changes in streamflow such as a rain event or at the beginning of a reservoir release overshadow diel signals in stream stage and groundwater levels so data during these time periods were not analyzed. Prior to spectral analysis (Shumway and Stoffer, 2000) stream stage and transpiration data for each month were tested to determine if variability was merely random white noise (Shumway and Stoffer, 2000). If the test showed variability was significantly different from white noise then spectral analysis was used to further analyze frequency and periodicity. For each day, changes in hourly stream stage elevation were lagged behind hourly transpiration by 0-23 hours and the Pearson

correlation coefficient between changes in stream stage and transpiration was computed for each time lag. The same procedures were conducted to determine the correlation between transpiration and changes in groundwater elevation.

RESULTS

Dynamics and Magnitude of Transpiration

As anticipated, transpiration exhibited a strong diel pattern throughout the three month study. Mean daily transpiration was highest in April at 0.45 mm d^{-1}. It declined to 0.31 mm d^{-1} in May and increased to 0.36 in June. Transpiration typically peaked around 1600 hour (4 p.m.), whereas minimum transpiration was frequently observed between the hours 2400 and 400 (midnight and 4 a.m.) (Figure 3.2).

Fluctuations in Stream Stage

Fluctuations in stream stage during April were found to be random white noise. In May, stream fluctuations were not random, but spectral analysis revealed multiple 8 hour cycles. These fluctuations were not apparent from a visual examination of the data and it cannot be confirmed if those cycles coincided with transpiration cycles. No further analyses were conducted for stream elevations in April and May.

Spectral analysis of the June stream stage indicated a 24 hour cycle despite very small, < 10 mm, diel fluctuations. Pearson correlation was strongest (-0.35;

P<0.0001) at hour 1600, meaning that the sharpest decline in stream stage occurred during hour 1600 or 4 p.m.

Figure 3.1 Photos of saltcedar stump cross sections, and delineation of sapwood area, harvested from the PREP study area along the Pecos River, Texas.

Groundwater Fluctuations

Groundwater fluctuations in April and May were either absent or overshadowed by rainfall events and reservoir releases much of the time. When fluctuations were observed, transpiration data were missing (Figure 3.3). The amplitude of the fluctuations in May was generally less than 50 mm. In June, groundwater fluctuations were observed only in well B3, which was situated in the center of the riparian zone and amplitudes were between 50 and 100 mm (Figure 3.4). The lack of diel cycle in well B1, also located within the saltcedar, may be due to the fact that the area surrounding well B1 was inundated after June 13th. The highest correlation between hourly transpiration and groundwater fluctuations in well B3 was -0.47 at lag 20 or 8 p.m..

DISCUSSION

If fluctuations in stream and groundwater levels are caused by transpiration, then daily transpiration should be positively related to the amplitude of stream and groundwater fluctuations. Results of statistical analyses for June indicated hourly transpiration was correlated with changes in stream and groundwater levels but when daily totals from all three datasets are compared, these relationships are not apparent (Figure 3.5). The amplitudes in stream and groundwater seem to be independent of transpiration. The very large stream amplitudes are associated This indicates that there are factors other than

transpiration contributing to fluctuations in stream and groundwater levels and that local scale processes are a product of the integrated stream-aquifer network.

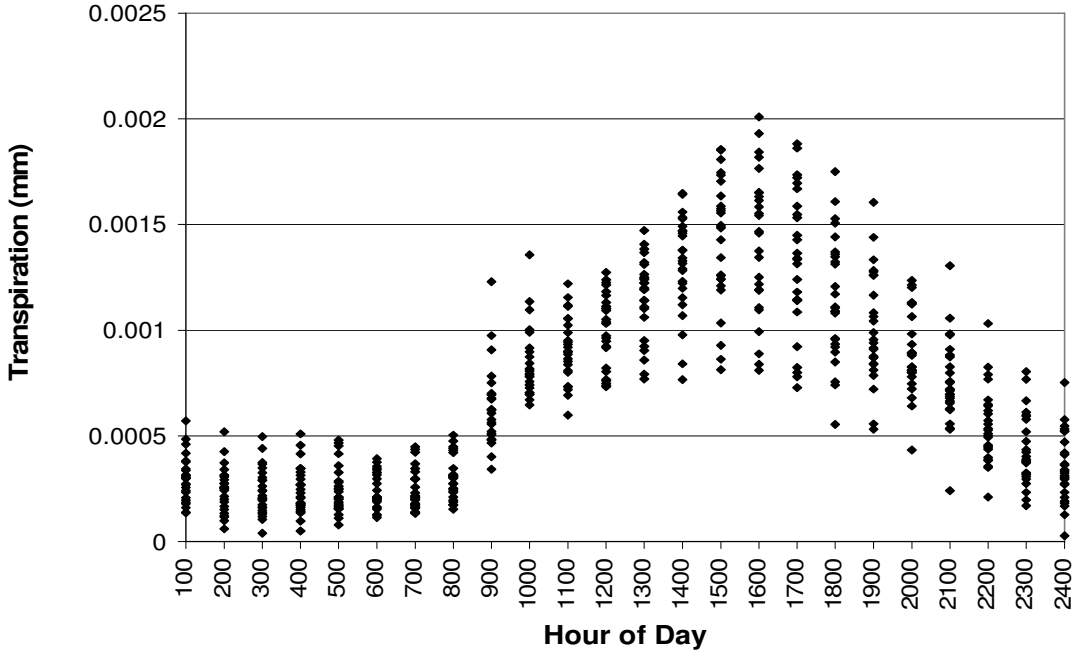


Figure 3.2. Hourly transpiration in June 2004 at Site B within the PREP study area along the Pecos River, Texas.

Wondzell *et al.* (2010) reached a similar conclusion about causes of streamflow depletion in a gaining stream in Oregon. Local scale riparian transpiration was not substantial enough to generate diel stream fluctuations and concluded that conceptual models that attempt to link local scale processes to changes in stream and groundwater are inadequate. Instead, a conceptual model of the entire stream, adjacent riparian zones, and in some cases the hillslopes was needed to understand the changes in streamflow, which is an integrated response from a much larger portion of or perhaps the entire watershed.

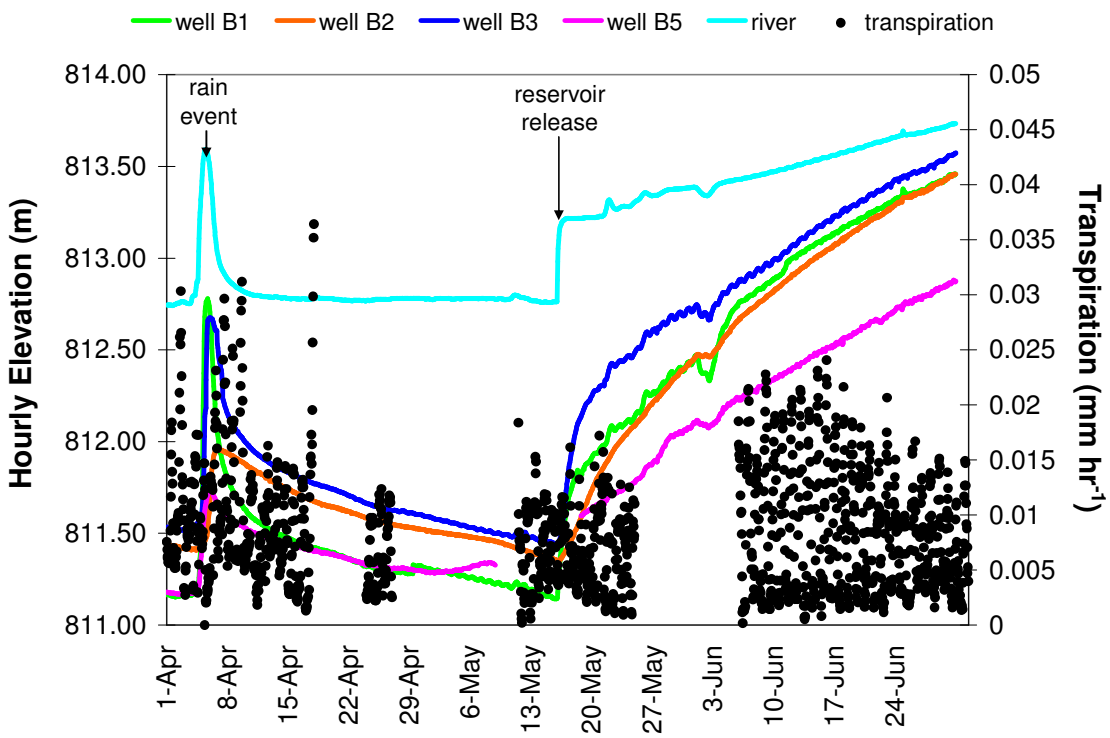


Figure 3.3. Hourly stream stage, groundwater elevations, and transpiration April – June 2004 at Site B within the PREP study area along the Pecos River Texas.

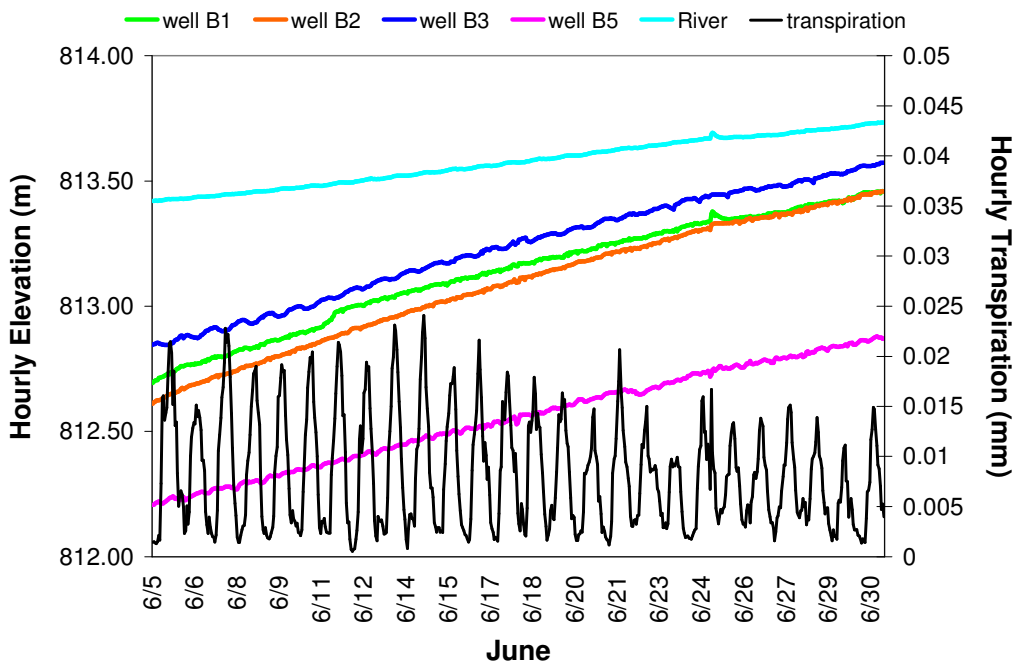


Figure 3.4. Diel fluctuations in stream stage and groundwater in well B3 and total daily transpiration in June 2004 at Site B within the PREP study along the Pecos River, Texas.

Saltcedar transpiration was weakly coupled to changes in stream stage and groundwater elevations during this study. Possible reasons for this are (1) low transpiration rates by saltcedar on the Pecos and (2) relatively low tree density and small aerial extent of trees as a function of narrow riparian corridor. Although transpiration demonstrated a strong diel pattern, rates were much less than observed elsewhere. On a stand basis transpiration ranged from 0.3 to 0.4 mm d^{-1}, or about 0.08 m yr^{-1}. Using the same methodology Moore *et al.*, (2008) found that transpiration rates in a saltcedar stand on the Rio Grande were about

10 times higher. The primary reason, we believe, for the low transpiration rates is that the trees at the PREP site have low sapwood area (SWA). This is a function of tree age and density. Sapwood is the active part of the xylem tissue in the plant trunk and stems that transports water and nutrients from the roots to the leaves. SWA in the mature stand at the PREP site was 0.07 m^2 m^{-2} ground area compared to 0.31 m^2 m^{-2} in the dense, young stand beside the Rio Grande in New Mexico (Owens and Moore, 2007).

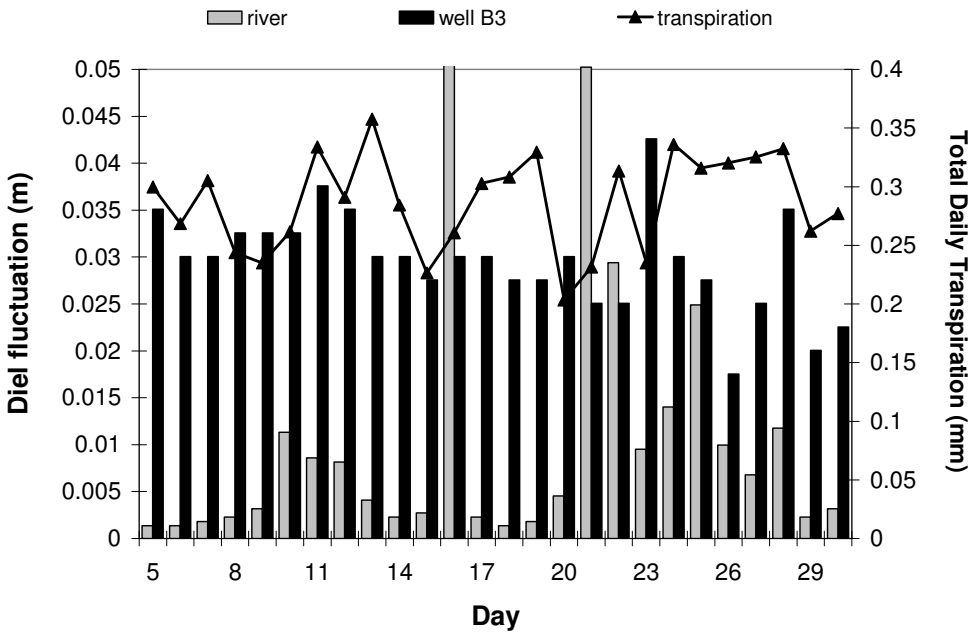


Figure 3.5. Comparison of saltcedar transpiration (sap flux) and evapotranspiration April – June 2004 at Site B within the PREP study area along the Pecos River, Texas.

For many species older or taller trees differ from shorter, younger trees. These differences include photosynthesis, leaf area:sapwood area ratio, stomatal conductance to water vapor (Ryan *et al.,* 2006), sapwood area growth rates and sap velocity (Forrester *et al*., 2010). Saltcedar was not included in the 51 species reviewed by (Ryan *et al.,* 2006), though saltcedar water use has been reported to decline with age (Bureau of Reclamation, 1973 cf Nagler *et al*., 2010). In addition to low SWA, plant density was also lower. Saltcedar density at the PREP site was 2,563 trees ha^{-1} compared with 10,700 plants ha^{-1} on the Rio Grande (Moore *et al*., 2008).

Other factors contributing to the weak coupling between transpiration and stream stage may be the relatively narrow riparian zone at the Pecos and the magnitude of transpiration compared with streamflow. Width of the riparian zone at the PREP site was about 40 m on each side of the river in contrast to the Colorado River, where the riparian zones may be as much as 1.5 km wide (Nagler *et al*., 2008) and the Middle Rio Grande with floodplains 1.5 to 10 km wide (Dahm *et al*., 2002). Streamflow from April through June 2004 ranged from 0.17 to almost 10 cms. Mean daily transpiration was about 0.35 mm. Boreal forests reduced streamflow by as much as 30-50% during the summer dry season, when discharge was 0.02 cms (Kobayashi *et al.,* 1990). Transpiration by *Pseudostuga menzieisii* (Douglas fir) was between 1 and 3 mm d^{-1} and contributed to a strong diel signal in a small, mountain catchment where streamflow was between 0.01 cms to 0.001 cms (Bond *et al*., 2002). Bren

(1997) noted that fluctuations were only observed during low flow and likely occurred during high flow as well but were obscured.

In addition to the factors listed above, soil and water salinity, weather, and depth to water table all have been documented to affect saltcedar transpiration (Devitt *et al*., 1997; Glenn *et al.,* 1998; Shafroth *et al*., 2000; Hays, 2003). As early as 1970, van Hylckama observed that saltcedar water use declined as water salinity reached 3.83 S m^{-1}, the maximum tolerated by saltcedar. Sala *et al*. (1996) observed the limiting effect of salinity on transpiration at a site along the Virgin River in Nevada, USA, where soil salinity was 2.5 S m^{-1}. Soil electrical conductivity (EC) reported for this area ranged from 0.06 to 0.15 S m^{-1} (Clayton, 2002) and groundwater salinity within the riparian zone at the PREP site in 2005 and 2006 (unpublished data) varied from 0.1 – 1.5 S m^{-1}, well below the tolerance noted by van Hylckama (1970). Additionally, soil and groundwater EC along the Pecos River was comparable to values reported by Nagler *et al*. (2008) along the Colorado River in Arizona, but saltcedar transpiration there was much higher, 3.7-9.5 mm d^{-1}.

Maximum depth to the water table in the riparian zone was around 2 m in early April before irrigation releases began. Mean daily transpiration was also greatest during this month suggesting that depth to water table was not a contributing factor to low transpiration rates.

Weather conditions, specifically vapor pressure deficit (VPD), may also play a role. Transpiration is positively related to atmospheric vapor pressure

deficit. VPD would be valuable to make comparisons across sites. Water availability is often assessed, but the demand should also be considered.

Depth to water table in the riparian zone was never greater than 2 m during the study and was deepest in April when mean daily transpiration was highest. Therefore transpiration does not appear to have been limited by depth to water table.

Hatler's (2008) estimates of water loss are up to 10 times higher than transpiration during the same time period (Figure 3.6). There are two possible explanations for these differences. One explanation is that the White method is accurate and differences are due to high rates of soil evaporation and direct evaporation from the stream, not transpiration. The other explanation is that the White method, even though conservatively applied, overestimated stand water use.

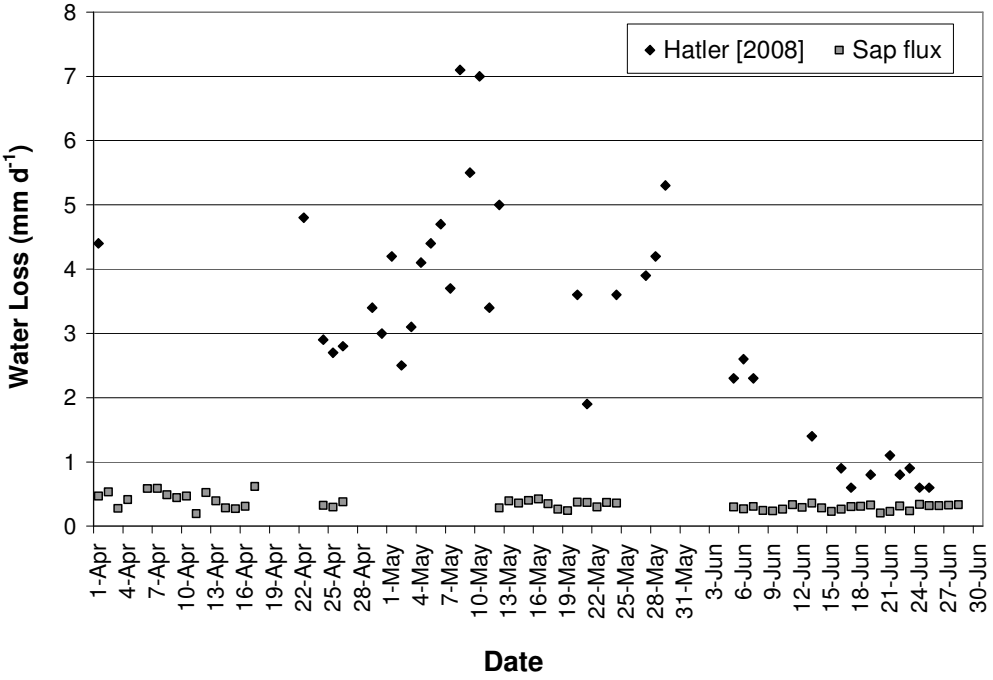


Figure 3.6. Comparison of saltcedar transpiration (sap flux) and evapotranspiration April – June 2004 at Site B within the PREP study area along the Pecos River, Texas.

CONCLUSIONS

Transpiration, as determined by sap flow measurements, exhibited a strong diel pattern whereas stream stage did not. Diel fluctuations in groundwater levels within the riparian zone were observed, but only under certain hydrologic conditions, and were not strongly correlated with transpiration. The primary reason, we believe, for this weak linkage is very low transpiration rates owing to tree maturity and relatively low tree density. These findings are important because they provide one possible mechanistic explanation for why

increased streamflows have not been observed on the Pecos River and elsewhere following large scale control of saltcedar. Transpiration rates for saltcedar on the Pecos are lower by a factor of up to 10, than measured at other locations. Tree density and total sapwood area also are much lower at this location. Interpretation of these results should be tempered by the fact that transpiration was measured at only one location; however, on the basis of visual inspection, we believe that it is representative of the Pecos River along the 140 km stretch between Red Bluff Reservoir to the city of Pecos, Texas.

CHAPTER IV

STREAM CONNECTIVITY AND EFFECTS OF SALTCEDAR CONTROL ON BASEFLOW

INTRODUCTION

Control of *Tamarix* (saltcedar) trees along rivers in the Southwestern U.S.A. has been advocated as a means to increase streamflows. Removal of riparian and hillslope vegetation has generated increased streamflows in humid regions of Australia (Bren, 1997) and in forested mountain catchments in the Pacific Northwest, U.S.A. (Jones and Post, 2004) yet clearing of saltcedar along semiarid waterways has not. This is, in part, due to the fact that few studies have actually measured streamflow responses. The majority of studies instead have focused on estimating or demonstrating that saltcedar uses copious amounts of water relative to other riparian vegetation and that removal of this plant would surely result in enhanced streamflow. The linkages between saltcedar transpiration and surface and groundwater were evaluated at the small plot scale in Chapter II. Saltcedar transpiration was weakly correlated with changes in stream stage and was out of phase with diel groundwater fluctuations. Still, estimates of water salvage from the same study area were substantial (Hatler and Hart, 2009). To extend those studies to a larger scale, maximum potential increase in annual streamflow from saltcedar control was

computed and baseflows downstream of the project were analyzed to determine whether this savings was realized.

It is important to identify gaining and losing reaches along a river in order to predict if and where the water salvage should be detected. Along gaining reaches, an increase in streamflow should be detected if saltcedar control leads to measurable water salvage. Conversely, along losing reaches, salvaged water would not contribute to baseflow, instead it would enhance aquifer recharge. The river reach within the PREP study area is a losing reach (Chapter I). Thus, any salvaged water would seep into the aquifer and would not increase streamflows along this reach. Additionally, if the river is losing along its entire length, as is common with dryland rivers, there will be no signal in the streamflow.

In addition to identifying gaining and losing reaches, a correlation analysis of streamflows at multiple gauging stations can also be ehlofpul to understand stream connectivity or the continuity of flow from upstream to downstream. When assessing a large scale project such as the PREP, stream connectivity is a requirement to adequately assess a large scale project using streamflow data fro a gauge near the terminus of the treated area.

The objectives of this research were to (1) Conduct a detailed analysis of streamflow to assess stream connectivity and identify gaining and losing reaches using data from 6 USGS stream gauges along the Pecos River in Texas and (2) compute potential annual increase in streamflow from saltcedar control

along the Upper Pecos River and (3) analyze streamflow near Girvin to determine whether this increase was realized.

STUDY AREA

The Pecos River Basin

This study focuses on the Pecos Basin in Texas, which was divided into upper and lower reaches. The upper reach begins at Red Bluff Reservoir at the border between New Mexico and Texas and extends downstream to near Girvin, Texas. Much of the floodplain has been cleared to farm the deep alluvial soils, though irrigated acreage has declined over the years (Jensen *et al*., 2006). Farmers in 7 irrigation districts along the Upper Pecos River in Texas purchase water that is released from Red Bluff reservoir. When stored water is not being released for irrigation, discharge from the dam is about 0.34 cms. Mean annual rainfall in this area is about 280 mm. About 65% of the total area of treated saltcedar was along this upper reach. The lower reach stretches from Girvin to Langtry, which is near the confluence with the Rio Grande. Discharge is much higher in this reach due to increased mean annual rainfall of approximately 381 mm and the existence of shallow soils over fractured bedrock, which allows rapid transmission of rainfall runoff to the stream channel.

METHODS

Stream Connectivity

Until 2007 there were only three stream gauges along the 400 km of Pecos River in Texas: 1) United States Geological Survey (USGS) #08412500 near Orla; 2) USGS #8446500 near Girvin; and 3) International Boundary and Water Commission (IBWC) gauge #0844741008 near Langtry, which is near the confluence with the Rio Grande (Figure 4.1). In 2007 additional gauges were installed near the city of Pecos (#08420500), near Grandfalls (#08437710), near Sheffield (#08447000) and near Pandale (#08447300). Clayton (2002) reported that water released from Red Bluff never reached the gauge near Girvin. Stream connectivity is essential if impacts of saltcedar control on streamflow are to be assessed, as much of the treated area is above Girvin and the effect or signal should be concentrated there. We plotted daily mean discharge at all 7 stations and computed gain-loss for the 6 segments between gauges and computed Spearman correlation of streamflow with daily time lags, 1-30 to better understand the downstream connectivity. Streamflow data were retrieved from the USGS National Water Information System (NWIS) database website.

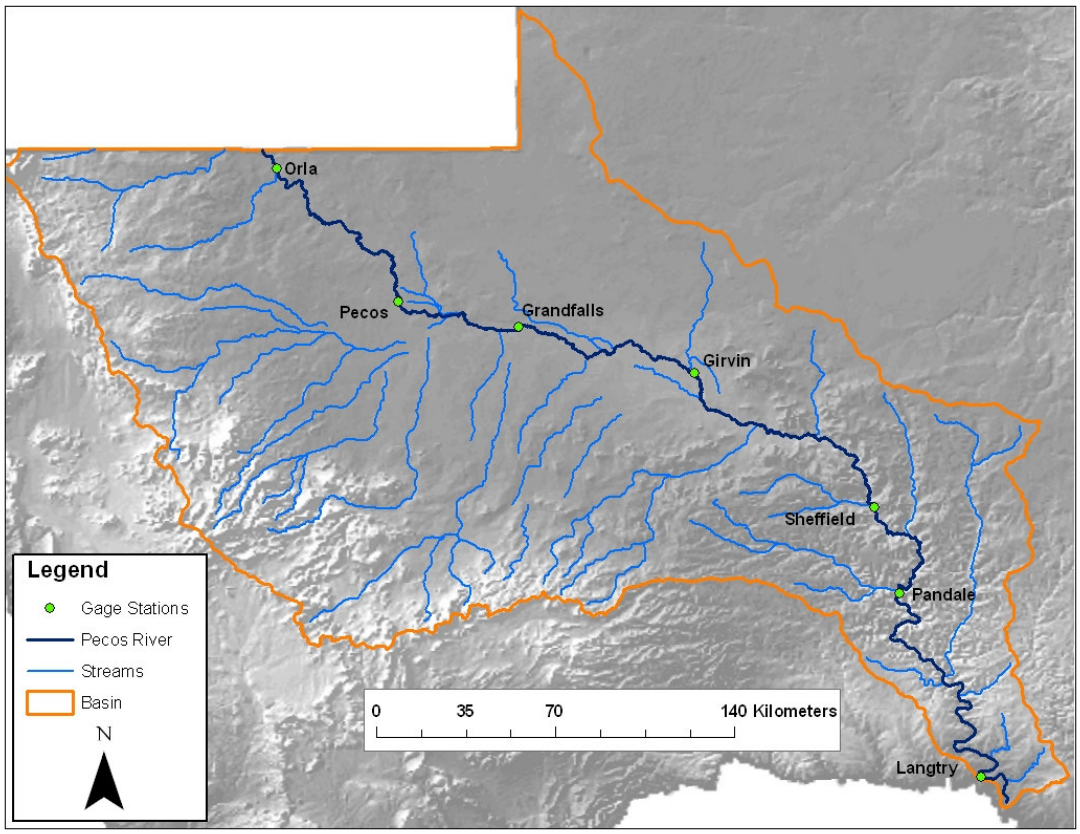


Figure 4.1 Map of Pecos River Basin in Texas and locations of 7 USGS stream gauges.

Maximum Potential Increase in Streamflow Along the Upper Pecos River

Hatler and Hart (2009) estimated potential water salvage from saltcedar control for 5 years following herbicide application. For the first three years after treatment began, mean annual salvage was 0.27 m, 0.68 m, and 0.38 m respectively. In years four and five, salvage sharply declined due to transpiration of saltcedar regrowth and other riparian vegetation (Hatler and Hart, 2009). A 'best case scenario' for increasing streamflows by controlling saltcedar was estimated using peak salvage of 0.68 m yr^{-1}. Projected annual

increase in streamflow volume was estimated by multiplying the area of saltcedar treated each year from 1999 thru 2005 (Hart, 2005) by 0.68 m yr^{-1}. Water salvage diminished significantly in the 4th year after treatment. Therefore, projected increase in streamflow each year from 2000-2005 was equal to the accumulation of water savings during the three preceding years.

Raster Hydrograph of Streamflow near Girvin

The initial step in assessing the streamflow regime near Girvin was to create a picture of daily steamflow for the entire period of record, 1939-2010 using Koehler's (2004) technique. The picture is a raster image comprised of unique pixels that represent mean daily streamflow. Surfer®8 surface modeling software was used to build a three dimensional grid of the streamflow record. The short time scale (day) was plotted along the horizontal x axis and water year was plotted along the vertical y axis. The third, z, dimension was mean daily discharge. A raster image of the grid also was generated using Surfer®8.

Baseflow near Girvin

Climatic variability and reservoir operation cause inter- and intra-annual variability in streamflow along the Upper Pecos River and would likely overshadow effects of saltcedar control on streamflow. Reservoir releases and rainfall can cause extreme, rapid fluctuations in streamflow. Therefore we conducted baseflow separation of streamflow near Girvin for water years 1999 – 2005 and computed analysis of variance to detect mean monthly baseflows that were significantly different than 1999 (pre-saltcedar treatment).

Stream discharge is comprised of baseflow, or groundwater discharge, and quickflow. Quickflow is the product of overland flow, interflow, and direct precipitation into the channel. Water salvaged via saltcedar control would contribute to baseflow, not quickflow, so a hydrograph analysis or baseflow separation was necessary to determine whether saltcedar control increased baseflows.

Baseflow separation according to the local minimum technique was accomplished using the Web-based Hydrograph Analysis Tool (WHAT) (Lim *et al.*, 2005). This technique tends to overestimate baseflow may be overestimated during storm events lasting several days (Lim *et al.*, 2005) so results will be biased toward a positive response to saltcedar control.

RESULTS

Stream Connectivity

Although stream gauges at Pecos, Grandfalls, and Sheffield have only been in place since 2007 spatial and temporal and spatial trends are evident in upper and lower reaches.

Table 4.1. Spearman correlation coefficients of streamflow in 6 stream segments along the Pecos River in Texas.

Stream Segment	Spearman Correlation Coefficient			
	November – March	**P**	**April - October**	**P**
Orla to Pecos	0.59	<0.0001	0.63	<0.0001
Pecos to Grandfalls	0.52	<0.0001	0.98	<0.0001
Grandfalls to Girvin	0.58	<0.0001	0.43	<0.0001
Girvin to Sheffield	0.62	<0.0001	0.72	<0.0001
Sheffield to Pandale	0.76	<0.0001	0.87	<0.0001
Pandale to Langtry	0.72	<0.0001	0.75	<0.0001

Comparison of stream gauge hydrographs and difference in discharge among stations in the Upper reach indicated differences attributable to seasons and necessitated separate correlation analyses. November through March is the dormant season and reservoir releases for irrigation are infrequent. Irrigation season, April through October, coincides with the growing season and the majority of annual rainfall also occurs during these months. Introducing hourly time lags improved correlation in only two cases: a 4 hour lag between Girvin and Sheffield during November – March and a 1 hour lag between Sheffield and Pandale in April – October. Stream connectivity (Table 4.1) in the segment between Orla and Pecos was not markedly different in the two seasons and was consistently a losing reach. Losses were between 50% and 75%

during the growing season (Figure 4.2) and the time lag between peaks at Orla and Pecos ranged from 3 to 6 days (Figure 4.3). Flow near Grandfalls is typically lower during irrigation season as nearly all of the streamflow is diverted above this gauge (personal communication, Red Bluff Water and Power Control Board).

Conversely, flow in the next segment from Pecos to Grandfalls increased as much as 150% during the dormant season and time lag between peak flows was about 3 days. This segment has also been identified as having unacceptably low levels of dissolved oxygen (DO) during the summer (Texas Commission on Environmental Quality, 2008). Low DO is often a symptom of warm, shallow, and slow moving water.

The time lag between Grandfalls and Girvin is 6 – 8 days (Figure 4.3) although Spearman correlation was not stronger for this or any other time lag. Baseflow nearly doubled during the dormant season, but correlation did not differ much between the two seasons. During irrigation season, releases are evident in hydrograph; flow is flashier and baseflow declines due to diversion and evaporation.

The segment between Girvin and Sheffield marked the beginning of the Lower Pecos River. Flow was more variable during the irrigation season, just as it was within the Upper Pecos. Unlike the Upper Pecos; however, it is consistently gaining (Figure 4.2). Correlation was higher during the growing season and a time lag of 4 days represented the highest correlation during the

dormant season. Some of the peaks in Girvin hydrograph were dampened at Sheffield (Figure 4.4), yet baseflow was typically higher at Sheffield. This suggests that there are gaining and losing reaches along this 25 km reach of the river.

Streamflow increased substantially between Sheffield and Pandale, often as much as 200% (Figure 4.2). Gains were higher during April to October than November to March. A spring fed tributary, Independence Creek, consistently contributes about 1 cms and often doubles the flow of the main Pecos River (Figure 4.4).

The final segment that was analyzed was between Pandale and Langtry. Given its close proximity to the confluence, flow at Langtry provides an accurate estimate of the contribution of the Pecos River to the Rio Grande.

Maximum Potential Increase in Streamflow Along the Upper Pecos River

Expected flow increase at Girvin during the first year following initial saltcedar control was only 0.06 cms (Table 4.2) but steadily increased due to additional area of saltcedar treatment and accumulation of water salvage from previous years. In 2003 and 2004, the potential gain exceeded annual baseflow by more than 100%, but baseflow was abnormally low in 2002 and 2003.

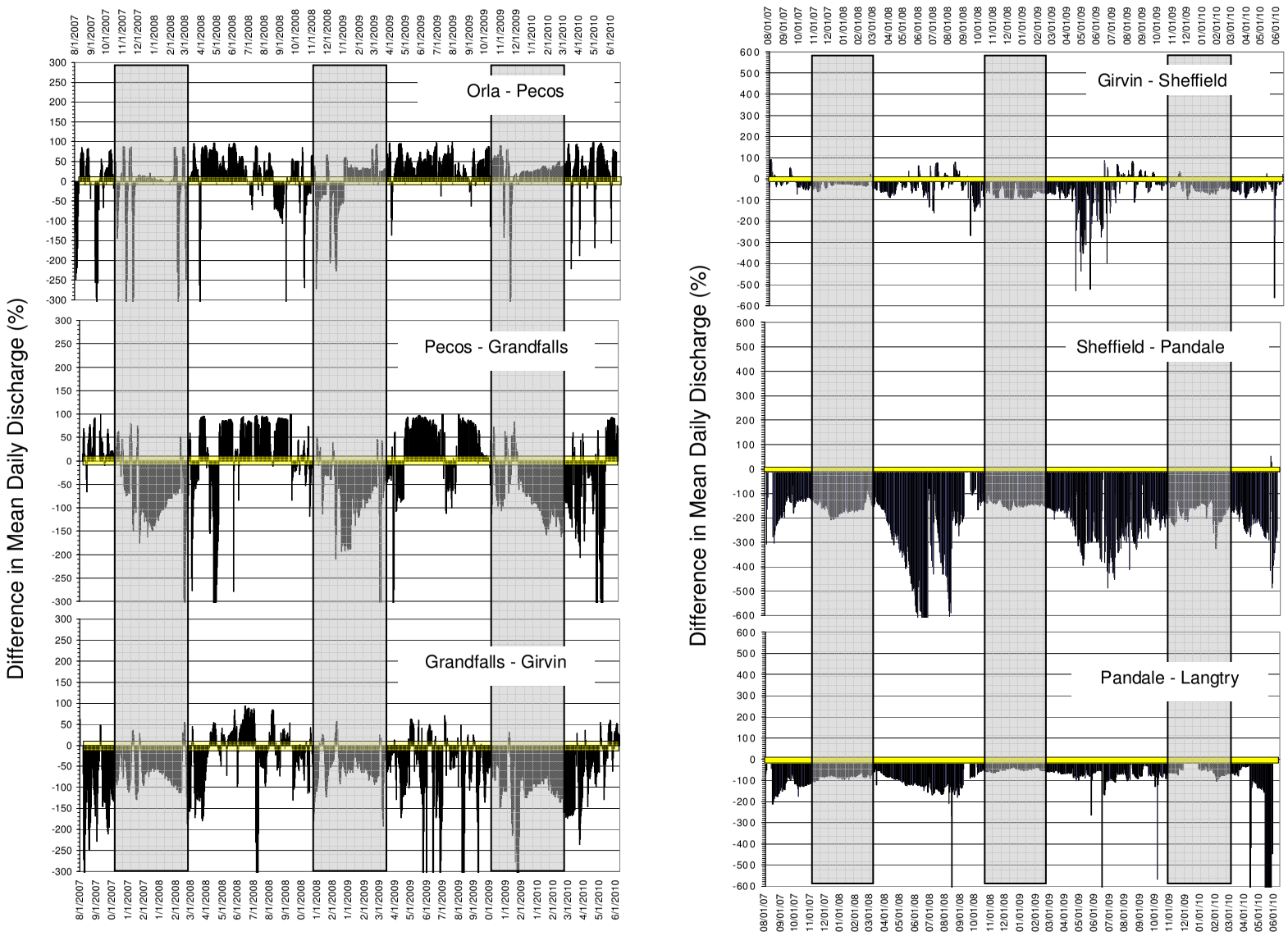


Figure 4.2. Percent difference in mean daily discharge for 6 stream segments along the Pecos River, Texas.

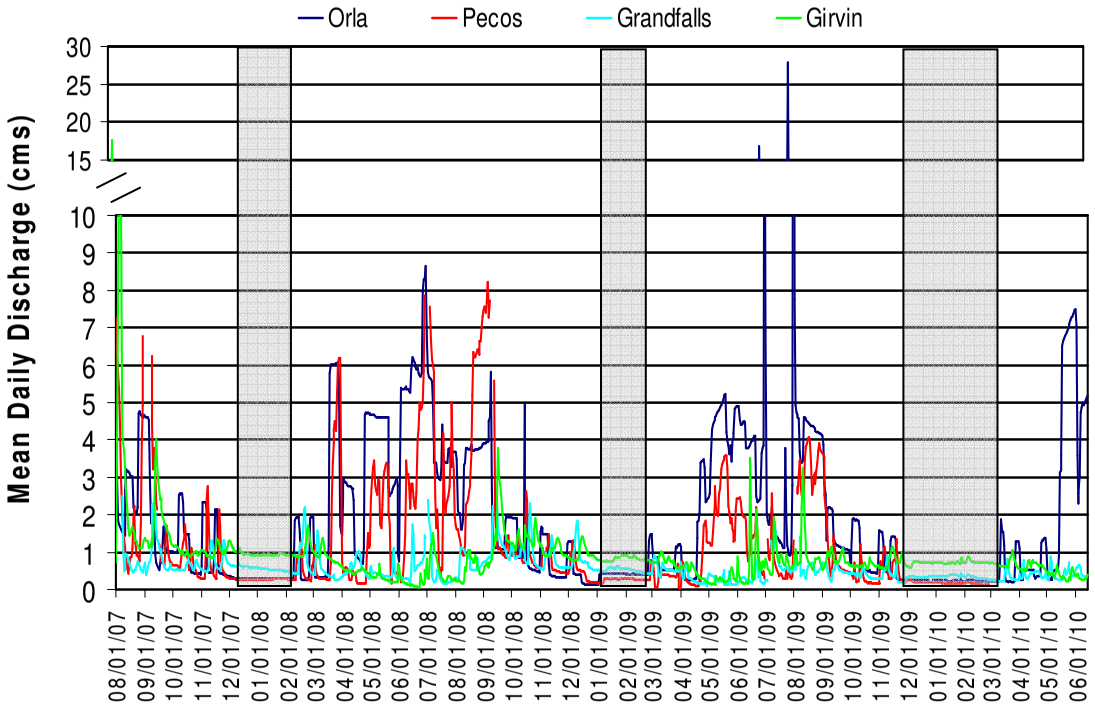


Figure 4.3. Mean daily discharge along Upper Pecos River in Texas at USGS gauges #08412500 near Orla, #08420500 near Pecos, #08437710 near Grandfalls, and #08446500 near Girvin from August 2007 thru May 2010.

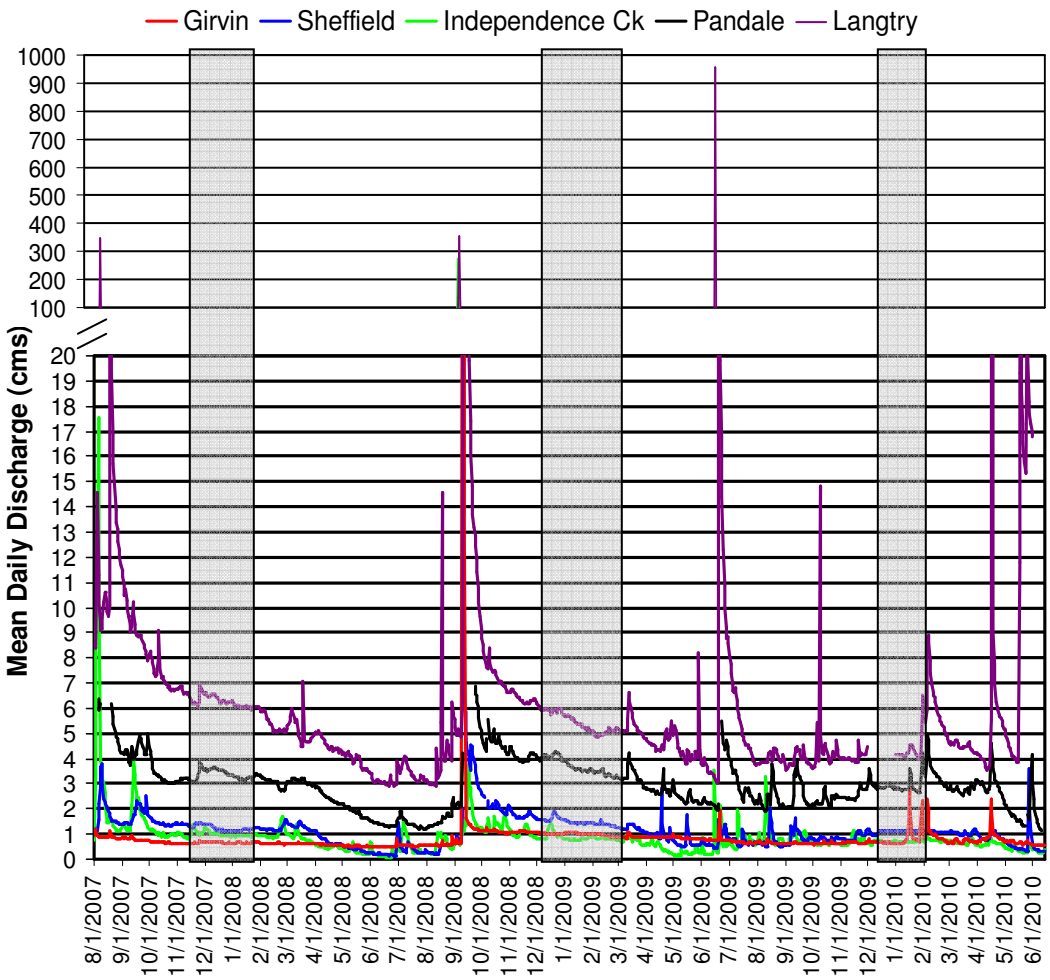


Figure 4.4. Mean daily discharge along Lower Pecos River in Texas at USGS gauges #08446500 near Girvin, #08447000 near Sheffield, #08447020 on Independence Creek, #08447300 near Pandale, and International Boundary and Water Commission (IBWC) gauge #0844741008 near Langtry from August 2007 thru May 2010.

Table 4.2. Saltcedar area treated along the Upper Pecos River in Texas 1999 – 2005 and estimated water salvage, expected streamflow increase, and mean annual baseflow at USGS gauge #8446500 near Girvin, Texas.

Year	Area (ha)	Water Salvage* (m)	Annual Salvage (m^3)
1999	266.40	---	---
2000	273.68	0.68	1861052.63
2001	573.68	0.68	3901052.63
2002	922.67	0.68	6274170.04
2003	378.95	0.68	2576842.11
2004	79.76	0.68	542348.18
2005	193.12	0.68	1313198.38
TOTAL	2688.26		18,280,161.94

*from Hatler and Hart (2009)

Raster Hydrographs and Flow Class Analysis of Streamflow at Girvin

The maximum recorded discharge at this gauge was 550 cms in 1941 (Figure 4.5). Flood flows were substantial enough to fill Red Bluff Reservoir to capacity three times. From 1940 thru about 1952, streamflow at Girvin was relatively constant throughout the year. Afterwards baseflows declined dramatically during the irrigation season, which is typically April thru October.

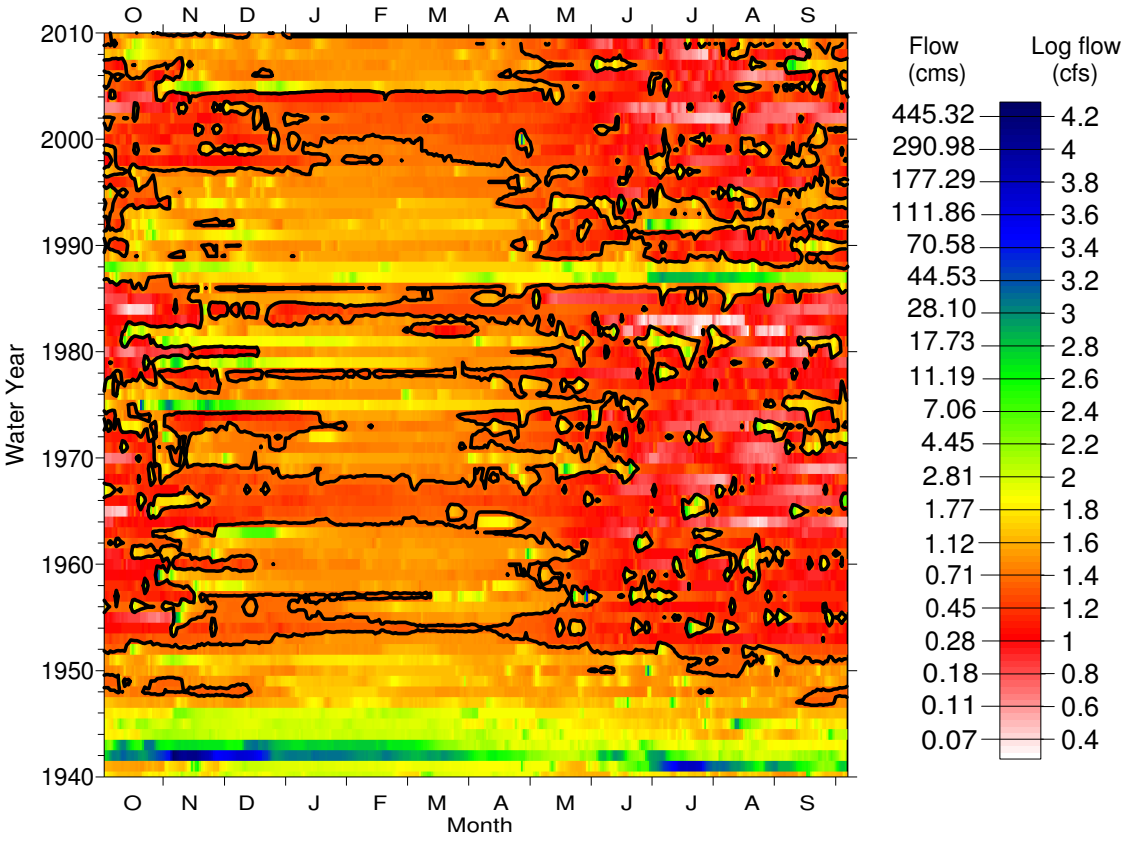


Figure 4.5. Raster hydrograph of mean daily Pecos River flow from 1940 to 2010 at USGS gauge #8446500 near Girvin, Texas. Contour delineates baseflow conditions of 22 cfs or 0.63 cms.

During summer 1983 flow at Girvin diminished to less than 0.7 cms. This happened again in July 2002 and July 2008. Periods of higher flow can be seen in winter 1963, 1976, much of 1987, summer 1994 and fall 2005. No abrupt or sustained increase in flow was observed in the raster hydrograph after 1999 (Figure 4.5) and winter baseflows from 2000 – 2004 were less than in 1999 (pre-treatment).

Pre- and Post-Treatment Baseflow at Girvin

Baseflow steadily declined for 5 years following saltcedar control but surged in 2005, the sixth year after treatment (Figure 4.6). The peak increase in streamflow from water salvage should have occurred in 2004. Annual baseflow in 2005 was exceeded 2005 only 7 years since 1970. However, this surge does not agree with Hatler and Hart (2009) findings that water salvage declined sharply in the fourth year after treatment and hence does not correspond with our 'best case scenario' (Table 4.2).

DISCUSSION

Streamflow near Girvin did not increase following a large scale saltcedar control project that began in 1999. We predicted baseflow to increase each year from 2000 to 2004 and then decline (Table 4.2). However, streamflow declined for four years after treatment and then increased sharply in 2005. It is unlikely that post-treatment baseflows were underestimated. In fact, the local minimum baseflow separation technique often overestimates baseflows (Lim *et al.*, 2005).

Some explanations for these unexpected results are increased streamflow was overshadowed by flow regulation and drought or the 'best case scenario' overestimated the potential increase in streamflow. Additionally, higher baseflows from 2005-2009 suggest there may be a lag time in the response to saltcedar control. A more detailed assessment of groundwater flowpaths as well as tracer based studies to partition streamflow at Girvin may provide insight to relative contribution and source of groundwater to the segment between Grandfalls and Girvin.

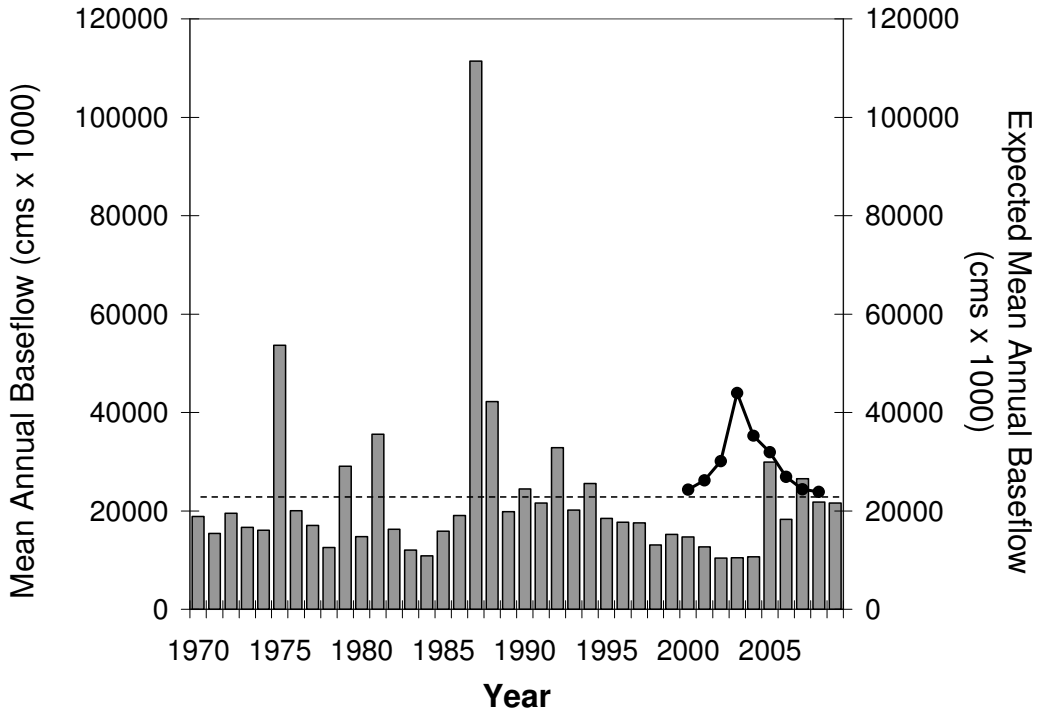


Figure 4.6. Annual baseflow from 1970 – 2009 and expected annual baseflow from 2000-2005 at USGS gauge #8446500 near Girvin, Texas.

Irrigation releases were curtailed in 2002 and 2003 (personal communication, Red Bluff Water and Power Control Board) and this may have obscured any increase in streamflow. Conversely, more water was released in 2004, when peak increases were predicted, than in 1999 (Figure 4.7) yet baseflows were higher in 1999. Additionally, the hydrographs (Figure 4.3) show that the majority of water released for irrigation is diverted above Grandfalls, so flow regulation cannot be the overriding cause of diminished baseflows after 1999.

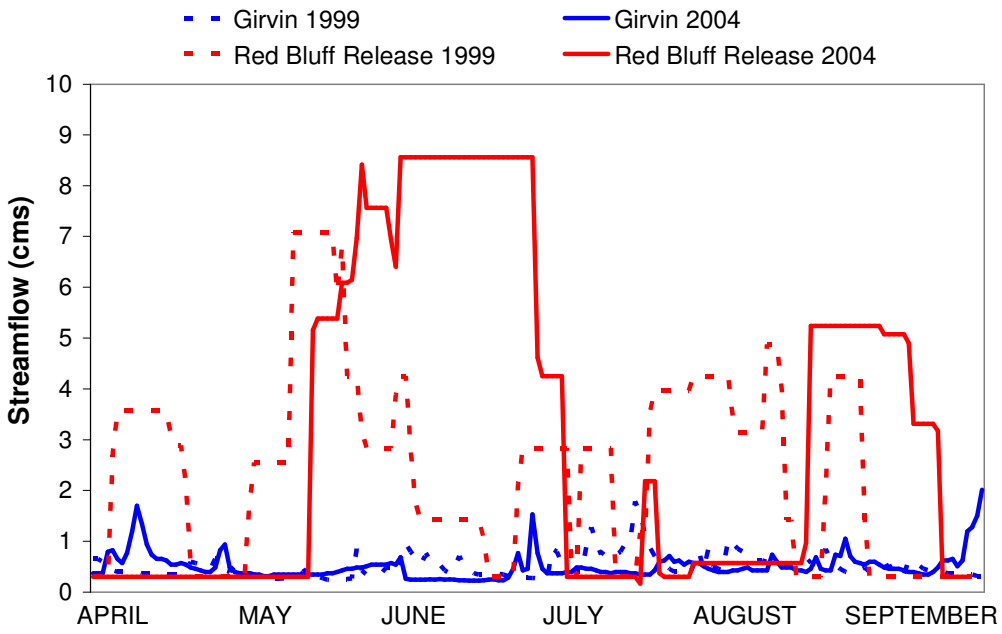


Figure 4.7 Daily release from Red Bluff Reservoir and daily streamflow at USGS station #8446500 near Girvin, April – September 1999 and April – September 2004 along the Pecos River, Texas.

Drought conditions may also eclipse short-term increases in baseflow. Weather stations in the Trans-Pecos region of Texas are sparse and the periods of record are short or discontinuous (National Climate Data Center, 2010). The nearest weather station with data from 1999-2009 is NOAA cooperative ID station #413280 at Ft. Stockton, about 65 km west of Girvin stream gauge. Total annual rainfall declined in post-treatment years compared to pre-treatment, except for 2004 and 2005 (Figure 4.8). This additional moisture may have enhanced baseflows in 2005 and 2006 via rainfall recharge and delayed groundwater movement to the river.

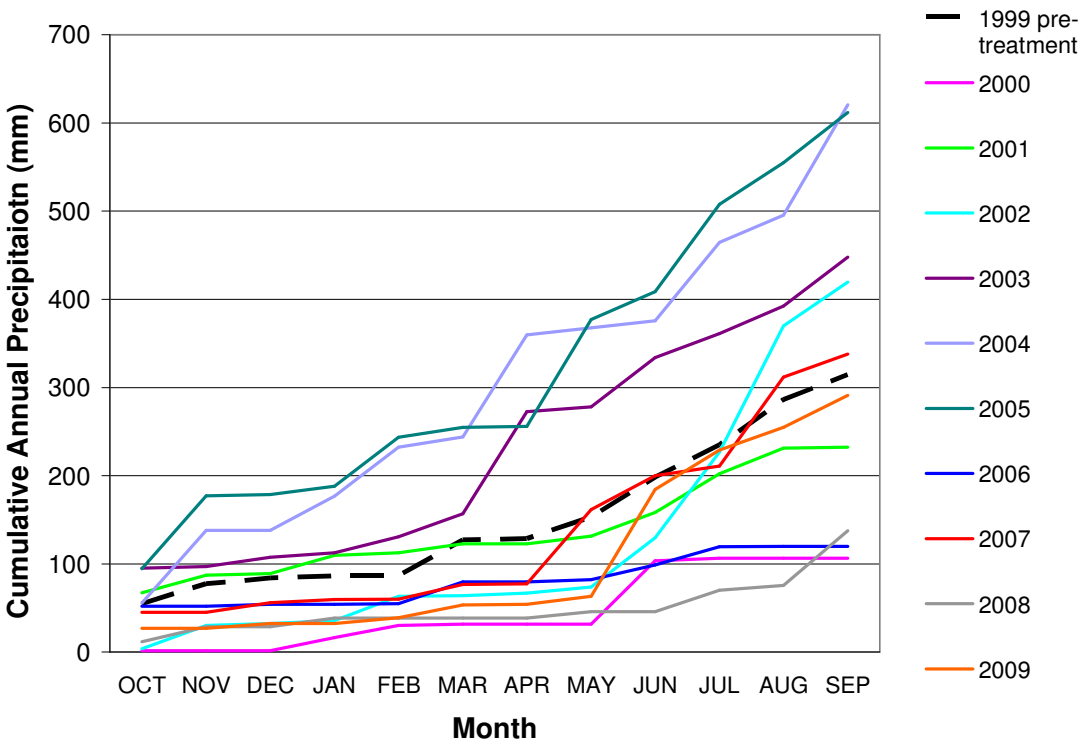


Figure 4.8. Cumulative annual precipitation 1999-2009 at NOAA cooperative ID station #413280 in Fort Stockton, Texas.

The predicted increases in streamflow were based on the highest mean annual water salvage reported by Hatler and Hart (2009). This may have resulted in an overestimate of streamflow increase. Likewise, if water salvage was overestimated, then any increases in streamflow would also be overestimated.

CONCLUSIONS

Contrary to a previous report, flows at Girvin were correlated with streamflows at Orla. The hydrographs show that during high flow events, without diversion, the lag time is about 9 days. In fact, from August 2007 thru June 2010, more than a dozen releases were evident as far downstream as Sheffield. Future hydrologic studies along the Pecos River should separately assess data from the dormant and irrigation seasons, as there is seasonal variability in gains, losses and connectivity.

Baseflows at Girvin did not increase as predicted following saltcedar control. Instead, baseflow declined each year following saltcedar control then increased substantially in 2005. A cursory analysis of some potential factors, such as drought and flow regulation, was inconclusive but suggests that these factors did not overshadow the effects of saltcedar control. We conclude that our ‘best case scenario’ of increased streamflows was overestimated.

CHAPTER V

SUMMARY

In an effort to quantify the hydrologic impacts of saltcedar control on the Pecos River, we assessed stream elevations, hydraulic gradients, groundwater flow paths, streambank seepage, and saltcedar transpiration at hourly and seasonal time scales along a 1.5 km reach of the river. Neither saltcedar transpiration nor saltcedar removal influenced hydraulic gradients, streambank seepage, or stream elevations. To extend the study to a much larger scale, we analyzed annual baseflows at the downstream end of 340 km river reach from 1999 (pretreatment) through 2005. Surprisingly, baseflows declined for four years after the project began despite additional acreages of saltcedar treatment each year. In 2005, baseflows surged and remained higher than pretreatment through 2009. This suggests that increases in baseflow from saltcedar control may be delayed. Continued assessment of baseflows at Girvin along with a tracer-based study of relative contributions of quickflow and baseflow to streamflow may indicate whether this sustained increase can be attributed to saltcedar control. We briefly examined some potential confounding factors such as reservoir releases and rainfall but could not confirm that these factors could have overshadowed predicted increases in baseflow from 2000-2004. We do not suggest that saltcedar control caused the decline in streamflow and additional studies are needed to determine the reason for reduction in baseflow

from 2000-2004. Sap flux measurements indicate saltcedar transpiration along the Pecos River is much lower than reported elsewhere and that water salvage from saltcedar control may be undetectable in the stream or groundwater. We did not investigate any other reported benefits, such as restoration of native plant species, or reduced soil salinity, of saltcedar control.

Additional findings are related to surface and groundwater interaction and stream connectivity. Stream seepage was controlled by both river stage and groundwater levels in the riparian zone. Groundwater flow rates within the riparian zone were greater than the sum of streambank seepage and the flow rate out to the floodplain. This indicates groundwater flow in the riparian zone comes from a source other than local streambank seepage, such as parallel flow and lateral hyporheic exchange between the river and the riparian zone. This is supported by groundwater contours during steady conditions.

The Pecos River in Texas is predominantly a gaining river, which is uncommon in drylands. Stream connectivity is likely maintained predominantly by hyporheic exchange and less so by groundwater discharge, but additional studies using isotopes and other environmental tracers are needed for verification.

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APPENDIX A

WATER ELEVATION DATA

Data associated with this appendix can be found in the supplemental files

APPENDIX B

DARCY FLOW

Data associated with this appendix can be found in the supplemental files

APPENDIX C

WATER ELEVATION DATA AND TRANSPIRATION DATA

Data associated with this appendix can be found in the supplemental files

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