EFFECTS OF *Arundo donax* L. ON THE HYDROLOGICAL REGIME OF THE RIO GRANDE

A Thesis

by

FAN LI

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

MASTER OF SCIENCE

May 2012

Major Subject: Rangeland Ecology and Management

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Approved by:

Co-Chairs of Committee,	Jason West
	Georgianne Moore
Committee Member,	Gretchen Miller
Head of Department,	Steven Whisenant

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ABSTRACT

Effects of *Arundo donax* L. on the Hydrological Regime of the Rio Grande.

(May 2012)

Fan Li, B.S., Shandong University, China

Co-Chairs of Advisory Committee: Dr. Jason West
Dr. Georgianne Moore

This study investigated the role of an invasive tall cane, *Arundo donax* L. (*Arundo*), in the riparian water cycle. Four 100 meter transects were arrayed perpendicular to the lower Rio Grande in southwest Texas. The first objective was to determine the primary water source for *Arundo* by using naturally occurring stable isotopes. Surface soil, river water, groundwater, precipitation and rhizome samples were collected every month during 2010 and 2011 growing seasons, which coincided with a major flood that saturated soils in the first year followed by extreme drought in the second year. The second objective was to characterize how *Arundo* water use varied with water availability gradients in the riparian zone. Leaf gas exchange and leaf $\delta^{13}C$ were measured along potential moisture gradients. The third objective was to understand the interaction between groundwater and surface water, and whether *Arundo* water use affected daily groundwater fluctuations.

The isotope ratio of rhizome water was consistent with shallow soil moisture uptake and with previous observations of a relatively shallow, fibrous root system. Floodwater from July 2010 persisted in the soil for at least a year despite a severe

drought, and became the dominant water source for *Arundo* during much of the study period. Although the alluvial water table in this floodplain was shallow (< 6 m) and subject to changes in river level, groundwater seemed not to be an important source for *Arundo*, so long as the soil moisture was sufficient.

In this study, *Arundo* was not found to experience soil moisture limitation, and the spatial variability of *Arundo* transpiration was not associated with any soil moisture availability gradients. *Arundo* was found to close its stomata in response to increasing vapor pressure deficit (VPD), causing declining transpiration rate and increasing leaf $\delta^{13}C$ composition. Significant exchange between the river and the alluvial groundwater was reflected in the similarity of isotopic compositions and the high correlation between river and groundwater elevations. Cross correlation analysis showed that over 50% of the diurnal groundwater fluctuations were caused by river stage changes. Consistent with the above ecophysiological and stable isotope results, *Arundo* water use was not found to influence daily groundwater fluctuations.

ACKNOWLEDGEMENTS

I would like to thank my committee co-chairs, Dr. West and Dr. Moore, and my committee member Dr. Miller, for their guidance and support throughout the course of this research. Thanks to Li Kui, Shane Sieckenius, Charles Winfield, Evan Dulin and April Mattox for helping with field and lab work.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to John Goolsby for assistance in initial site selection, and Moody Ranch Foreman John Kincaid for allowing us to access project sites. Thanks also go to the Rio Grande Basin Initiative, who provided the research funding.

Finally, thanks to my family for their encouragement, patience and love.

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CHAPTER I

INTRODUCTION

Ecohydrology is an integrated, interdisciplinary approach to studying the interactions between vegetation and the hydrologic cycle (Newman et al. 2006). Water scarcity has become a global phenomenon as human populations expand. Prolonged drought in arid and semi-arid regions tends to amplify water scarcity (Baron et al. 2002). Riparian zones in arid and semi-arid systems have strong and sometimes sharp gradients in soil moisture availability, and the patterns of plant communities can be affected by water availability. Plant water use influences the hydrological cycle as well; evapotranspiration (ET) represents a significant water loss pathway, especially from riparian zones. Water scarcity results in conflicts between human needs and those of riparian biota. Human alterations of water regimes have dramatically decreased river flows, which caused substantial changes in riparian vegetation (Scott et al. 2000, Stromberg et al. 2007). Therefore, two questions stand out in ecohydrological studies in the semiarid regions: 1) How do hydrological processes affect the water use of vegetation? 2) What are the consequences of land use change and exotic species invasion for hydrological processes? My study focused on aspects of these two questions in a semiarid riparian zone.

Plants introduced into riparian ecosystems cause unique problems as they consume a large amount of resources, compete and replace native species and alter

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This thesis follows the style of Ecology.

hydrological processes (Tickner 2001). Ecohydrological research on semiarid riparian zones has largely focused on the role of woody plants in the water cycle (Owens and Moore 2007, Stromberg et al. 2007, Moore et al. 2008, Nagler et al. 2009, Nippert et al. 2010, Doody et al. 2011). Saltcedar species (*Tamarix* spp.), for example, have been well documented as having a competitive advantage, as compared to native species, in water use and alteration of hydrology due to deeper rooting depth and fast root growth (Shafroth 2000, Lite and Stromberg 2005), the ability to use both groundwater and soil moisture (Busch et al. 1992), wider cavitation safety margin (Horton et al. 2001), and the capacity to lower the alluvial groundwater table (Tickner 2001).

Compared to woody invasive species, there is less comprehensive information on herbaceous invasive species influencing the riparian water cycle (Hultine and Bush 2011, Watts and Moore 2011). *Arundo* is native to East Asia and was purposefully introduced into California from the Mediterranean regions in the early 1800s for erosion control and quickly became naturalized in the southwestern U.S. (Bell 1997). *Arundo* emerges from a single underground rhizome, grows at an extremely high rate (4-10 cm per day under optimal conditions), and can reach as tall as 8 m (Perdue 1958). Once established, *Arundo* can form dense, nearly monocultural stands, change wildlife habitats and modify physical and chemical site characteristics (Bell 1997).

Arundo has been estimated to cover approximately 11,800 acres along the Rio Grande (Yang et al. 2009), yet little is known about its role in the riparian water cycle. Situated in a semiarid region, the Rio Grande River is a significant source of water for human and riparian biota. However, intensive urban and agriculture use have resulted in intermittent and low flows in the lower sections of the river. It is critical to understand vegetation water use in the floodplain for water management, given the high demand for water and the need to maintain or restore river and riparian ecological and hydrological function. This study focuses on the ecohydrological characteristics of *Arundo* in a lower Rio Grande River floodplain, in Val Verde and Kinney counties. Most of this region's existing water supply is obtained from groundwater, which is at the edge of Edwards - Trinity (Plateau) Aquifer, and used for municipal demands and irrigation (TWDB 2012). However, the surface alluvial aquifer is usually hydraulically connected to surface water rather than to the deeper Edwards-Trinity aquifer: gaining water from the stream (river-fed groundwater) or losing water to the stream (precipitation recharged groundwater). This study aims at understanding three questions: 1) To what extent does *Arundo* use groundwater? 2) Does *Arundo* water use vary along water availability gradients? 3) What is the interaction between alluvial groundwater and the river? Does *Arundo* water use affect daily groundwater fluctuations?

There are three major water sources in riparian zones: river-fed groundwater, precipitation recharged groundwater, and precipitation recharged soil moisture. In semiarid and arid regions, it is common that river water infiltrates into the surrounding alluvial aquifer due to the low precipitation recharge. Native trees in semiarid floodplains, such as willows and cottonwoods, depend primarily on alluvial groundwater that is hydraulically connected to the stream (Busch et al. 1992). Therefore, declining groundwater tables from discontinued river flows or groundwater withdrawal could cause large dieback of native species (Stromberg et al. 2005). Saltcedar, on the other hand, has been observed to switch from groundwater to soil moisture when groundwater levels are too low (Busch et al. 1992, Nippert et al. 2010). The high rate of groundwater use of saltcedar could significantly lower riparian groundwater level in arid areas (Tickner 2001).

Arundo was also reported to have a high transpiration rate (Watts and Moore 2011); however, herbaceous species tend to use soil moisture derived from a local meteoric source rather than groundwater due to their shallower root distributions (Darrouzet-Nardi et al. 2006, Pataki et al. 2008). Darrouzet-Nardi et al (2006) used stable isotope analysis to measure the depth of plant water acquisition of sagebrush, a woody shrub, and meadow herbs in Nevada. They found that although some herb species were able to acquire deep soil water (30−60 cm), most herbs used soil moisture in the top 30 cm, while sagebrush used deeper water on average than most herbs. Pataki et al (2008) evaluated access to groundwater using stable isotope on grasses and shrubs in Owens Valley, California, and found that grasses accessed evaporatively-enriched soil water at shallow depths while shrubs utilized groundwater throughout the growing season. Although those studies focused on upland meadow grasses instead of riparian invasive herbs, they provided evidence that grasses are more shallowly rooted than woody species. Therefore, even if *Arundo* transpires more water than saltcedar, it may not lower the water table by using groundwater directly. Thus, to understand whether *Arundo* uses groundwater primarily would add to our knowledge of groundwater conservation. In this study, stable isotope analysis was used to understand the extent to which *Arundo* uses groundwater.

Transpiration exhibits significant spatial and temporal variation, with consequences not only for patterns of soil moisture availability, but also for shallow groundwater level. Plant transpiration rate tends to increase with higher water source availability (Doody and Benyon 2011), but there are exceptions: saltcedar, for example, can maintain a high transpiration rate over a wide range of soil moisture contents and water level depths (Smith et al. 1998, Horton et al. 2001). In this study, leaf-level transpiration rate was used to study whether *Arundo* transpiration variation was related to water availability.

The interaction between groundwater and streams is a basic link in the hydrologic cycle. The growth of riparian vegetation can intercept groundwater that could discharge to the stream (gaining reach), or it can increase the infiltration from the stream to groundwater (losing reach) (Chen 2007). The complex feedbacks among vegetation, groundwater and surface water in the riparian zones can be modified by exotic species invasion (Tickner 2001). For example, the direct use of groundwater by saltcedar can significantly lower riparian groundwater levels in arid areas (Sala et al. 1996). This decline in groundwater level would in turn cause further depression of native riparian species (Scott et al. 1999, Scott et al. 2000, Amlin and Rood 2003, Rood et al. 2003). This study aimed to better understand the groundwater-surface water interaction on the Rio Grande riparian zone and evaluated how *Arundo* water use influenced this interaction.

CHAPTER II

WATER SOURCE PARTITIONING OF *Arundo donax*

INTRODUCTION

Situated in a semiarid region, the lower Rio Grande of Texas is a significant source for agriculture use and drinking water. Intermittent and low flows have become an increasing problem due to over-pumping and drought conditions (Small et al. 2009). Besides human use, riparian vegetation evapotranspiration (ET) is another source of surface water depletion. A study along the Middle Rio Grande in New Mexico showed that riparian vegetation ET could account for up to 50 % of total river depletion (Dahm et al. 2002). Recently, attention has been paid to the expansion of non-native vegetation across floodplains with the concern of increased riparian zone ET, because invasive species may often outperform native species by greater resource uptake (Di Tomaso 1998).

Saltcedar (*Tamarix ramosissima* Ledeb) and giant reed (*Arundo donax* L.) are two common non-native species along the lower Rio Grande (Dahm et al. 2002, Yang et al. 2009). Observations have confirmed that saltcedar, a phreatophyte, extensively consumes shallow groundwater under high evaporative demands (Di Tomaso 1998, Smith et al. 1998). Although the water use of an individual saltcedar plant is comparable to that of native phreatophytes such as cottonwood and willow (Sala et al. 1996, Owens and Moore 2007), saltcedar tends to form larger areas than those native species.

Therefore the invasion could accelerate flow reduction in already stressed rivers such as the Rio Grande.

The ability to use both deep groundwater and soil moisture also contributes to the success of salt cedar relative to the native species it replaces (Shafroth 2000). As obligate phreatophytes, the leaf area of cottonwood and willow declined with the depletion of streamflow and riparian groundwater caused by increased human demands (Lite and Stromberg 2005). Saltcedar has deeper roots than cottonwoods and willows, which allows it to access deeper groundwater (Smith et al. 1998). Additionally, as a facultative phreatophyte, saltcedar can draw moisture from unsaturated zones when groundwater table drops (Busch et al. 1992). *Arundo donax*, an invasive tall cane, also grows in riparian environments with shallow groundwater, but it is not known whether it uses groundwater primarily.

Naturally occurring stable isotope analysis has been widely used to determine water sources for plants. For most terrestrial plants, there is no isotopic fractionation during root water uptake (Wershaw 1966, Dawson et al. 2002, Ellsworth and Williams 2007). Water sources can be determined by comparing the isotope ratios of water extracted from plant stems to those of potential water sources, e.g., precipitation, soil moisture, river water and groundwater. The δ^2H and $\delta^{18}O$ values in precipitation worldwide are closely related, lying on a global meteoric water line (GMWL) ($\delta^2H = 8\delta^{18}O + 10$ ‰) (Craig 1961). Precipitation is a Rayleigh process and is primarily related to air temperature, which controls the position of meteoric water on the meteoric water line. Evaporation loss in surface soil, on the other hand, is a kinetic process, which is primarily affected by relative humidity. Relative humidity affects δ^2H and $\delta^{18}O$ differently, causing surface soil water isotopes falling on an evaporation line with a slope smaller than that of the GMWL. Surface water bodies are typically sources of evaporative enrichment, with isotope ratio being close to, but a bit off of the local meteoric water line (LMWL). Groundwater, which is usually derived from snowmelt and/or winter precipitation, tends to have lower isotope ratios than surface soil moisture and surface water, which are subjected to evaporative processes.

A number of studies have used water stable isotopes to identify the water sources of riparian vegetation. Dawson and Ehleringer (1991) found that riparian trees in northern Utah switched water sources from shallow soil moisture to deep groundwater after maturation. Along the San Pedro River in Arizona, cottonwood and willow near the river were found to use groundwater most of the time, while mesquite in the adjacent uplands shifted between groundwater and soil moisture (Snyder 1998). Busch et al. (1992) also found that cottonwood and willow used only groundwater along the Bill Williams River, while saltcedar used both groundwater and soil moisture. The ability of saltcedar to switch water sources as water table declines was also demonstrated by Nippert (2010) during the 2006 record drought along the Cimarron River in Kansas. Such an ability might allow saltcedar to compete with native species when groundwater level declines and river flow discontinues. All these studies indicate that the water sources can differ among different sized individuals within one species, among different species, along the spatial gradient and among different weather conditions.

Unlike the extensive literature on saltcedar water use, research on water use of *Arundo* is lacking. Like saltcedar, *Arundo* has been assumed to exhibit a high transpiration rate to support its high density and high growth rate (Iverson 1994). Watts (2011) estimated that *Arundo* could transpire an average of 9.1 mm water per day during growing season, which was at high level of riparian vegetation transpiration rate (Shafroth et al. 2005). This is partly due to its high leaf area index (LAI) of 4.5 m^2 m^{-2} (Watts and Moore 2011) as compared to 1.71 m^2 m^{-2} for saltcedar (Hultine and Bush 2011). The high transpiration rate and high LAI indicate that the invasion of *Arundo* could cause higher ET rates from the riparian zone than saltcedar does.

Compared to woody species, herbaceous species tend to use soil moisture derived from a local meteoric source rather than groundwater due to their shallower root distributions (Darrouzet-Nardi et al. 2006, Pataki et al. 2008). Darrouzet-Nardi et al (2006) used stable isotope analysis to measure the depth of plant water acquisition of sagebrush, a woody shrub, and meadow herbs in Nevada. They found that although some herb species were able to acquire deep soil water (30−60 cm), most herbs used soil moisture in the top 30 cm, while sagebrush used deeper water on average than most herbs. Pataki et al (2008) evaluated access to groundwater using stable isotope on grasses and shrubs in Owens Valley, California, and found that grasses accessed evaporatively enriched soil water at shallow depths while shrubs utilized groundwater throughout the growing season. Although those studies focused on upland meadow grasses instead of riparian invasive herbs, they provided evidence that grasses are more shallowly rooted than woody species. Therefore, *Arundo* might use more soil moisture than local groundwater. However, during groundwater well installation *Arundo* was observed to have roots down to the depth of shallow groundwater in our study site. Having access to shallow groundwater suggests that *Arundo* might switch sources to groundwater as soil moisture is depleted. Another potential source for *Arundo* is river water, since *Arundo* LAI and transpiration rate were found to increase as it grew closer to the river (Watts and Moore 2011). In this study, stable isotope techniques were used on *Arundo* along the lower Rio Grande River to examine: 1) the extent to which *Arundo* uses groundwater and 2) whether *Arundo* switches to groundwater when there is low soil moisture content.

STUDY SITE

The study site is located at Rancho Rio Grande, TX (29°14'44.39"N, 100°47'38.62"W). The mean annual precipitation is 477 mm per year and monthly average temperatures range from 10 °C to 27 ℃ (NOAA 2011). The aquifer in the floodplain is at the edge of Edwards - Trinity (Plateau) Aquifer outcrop.

Four transects were established perpendicular to the Rio Grande River. Two transects were located in concave meanders (Transect 1 and Transect 4), and the other two located in convex meanders (Transect 2 and Transect 3). The length of transects from 1 to 4 are 102 m, 103 m, 127 m and 73 m respectively, and the distance between Transect 1 (north end) to Transect 4 (south end) is approximately 10 km.

Inside each transect, a cleared 2-m-wide trail was established for access (Fig 2.1). Nine 1 m × 1 m plots (P1-P9) were placed at equal distances along each transect for soil moisture measurement. On the opposite side of the trail, five 1 m × 1 m plots were used for destructive measurements, such as soil coring and isotope sample collection. Eight groundwater wells were installed in March 2010, two wells at opposite ends of each transect (P1 and P9).

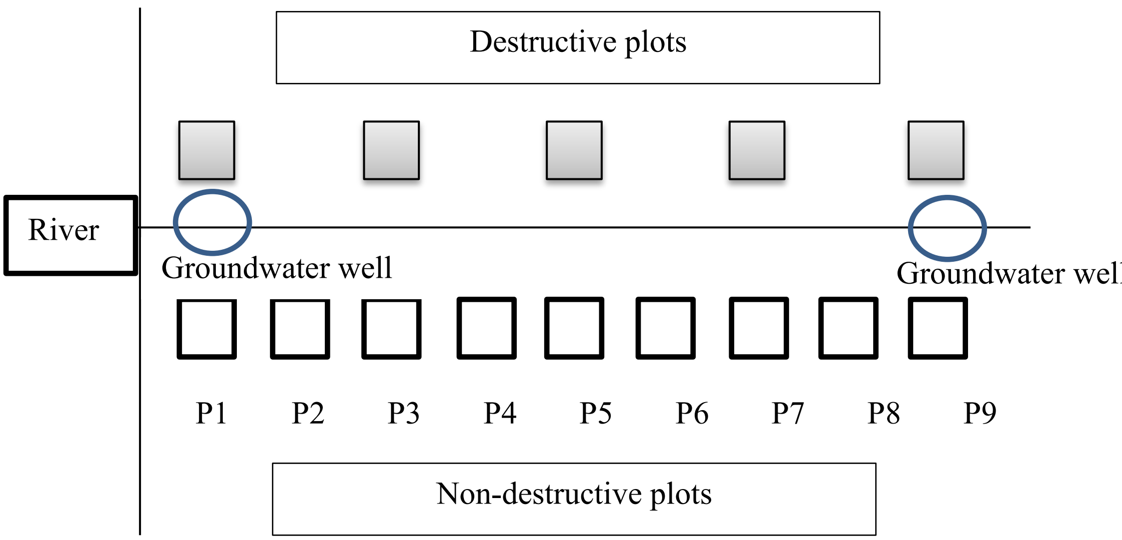

Fig 2.1 Plot layout for each transect. Nine plots (P1-P9 from river to upland) were established on one side of the trail for non-destructive measurements, such as gas exchange and soil moisture. On the opposite side of the trail, five plots were used for destructive measurements, such as soil coring and isotope sample collection. Two groundwater wells were installed at opposite ends of each transect.

The year of 2010 was a relatively wet and cool year compared to 30-year climate normal (1981-2010) (Table 2.1). Total precipitation from May to August 2010 was 417 mm, twice the normal rainfall amount for this period. A flood event happened in July 2010, which was caused by water released from the Amistad Dam upstream in response to Hurricane Alex (Fig 2.2). As a result, all sites were partially to fully inundated from

July 7th to July 15th, and the river stage continued to stay at higher than normal levels until the end of August. After the flood, the area experienced a drought with lower precipitation and higher monthly average temperature than climate normal.

Table 2.1. Precipitation and temperature data from National Weather Service Del Rio Station (COOP ID: 412360) (NOAA 2011)

	Temperature (℃)				**Precipitation (mm)**			
	May	June	July	August	May	June	July	August
2010	25.2	29.4	28.5	31.1	265	18.0	119.9	14.5
2011	26.4	30.6	31.0	32.3	27.2	11.4	9.4	114
Climate normal	25.4	27.5	29.6	29.1	58.6	59.4	51.3	54.9

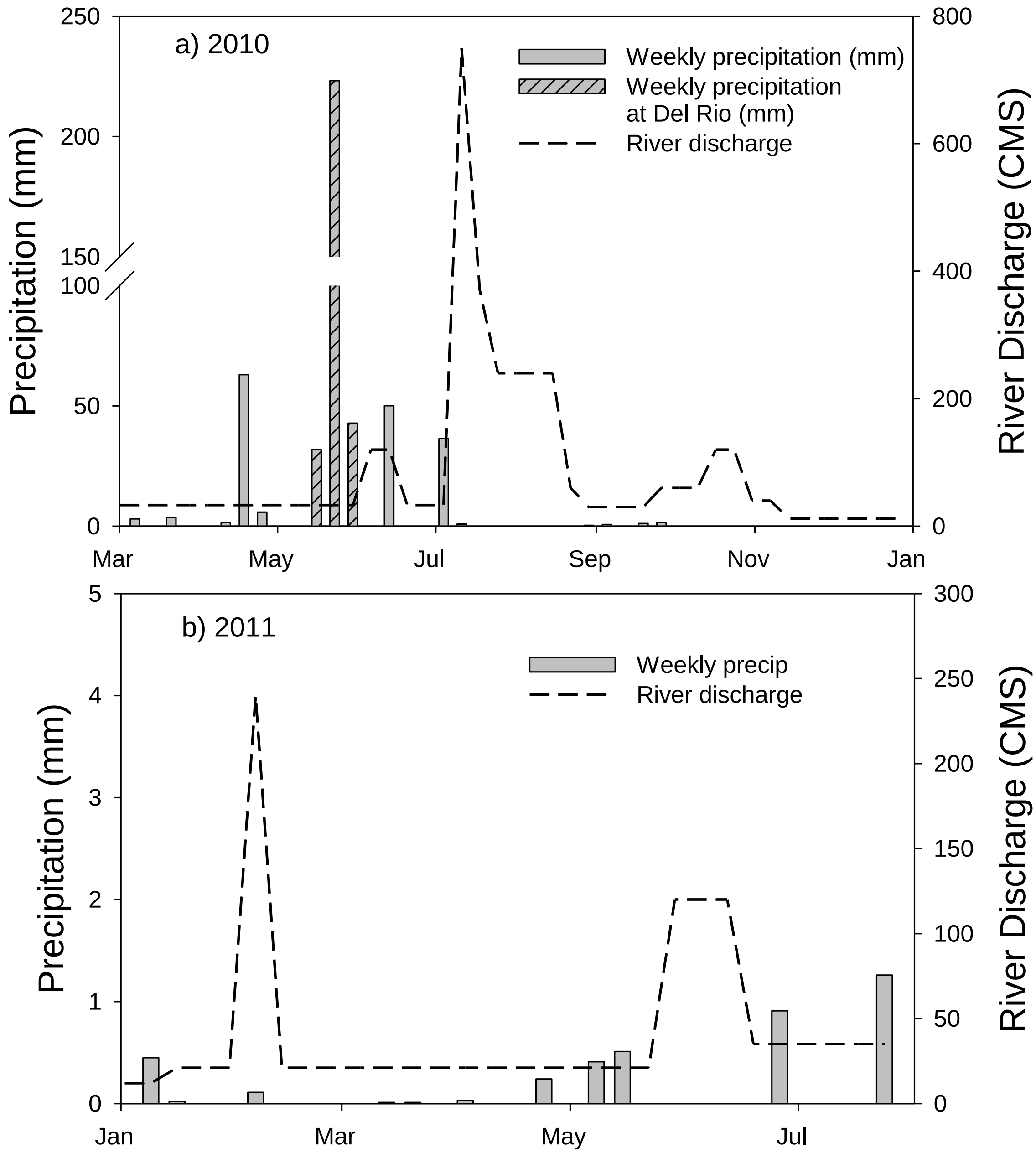

Fig 2.2 Weekly precipitation in mm (black bar) and river discharge in daily average cubic meters per second (dashed line) from March 2010 to July 2011. Precipitation data from our field site were missing for the month of May 2010 at which time precipitation data from Del Rio (IBWC) were substituted (shaded bar). Note the scale differs between the two graphs.

METHODS

Sample collection

Plant samples were taken from odd-numbered plots in each transect. Since isotopic fractionation occurs in leaves during transpiration or from unsuberized stems, underground rhizomes were excavated for access to unfractionated water inside plant stems (Barnard et al. 2006). At the same time, surface soil samples were collected from next to that rhizome. The soil sample was normally within the top 10 cm, and had a volume about 8 ml (three quarters of the 12 ml collecting vial). All samples were immediately placed in 12 ml glass vials with Polyseal cone caps and sealed with parafilm. They were then stored frozen until analyzed.

Groundwater samples were collected from the piezometers using an inertial pump (Delerin Standard Flow 25 mm O.D., Waterra USA Inc, Bellingham, WA). Before taking groundwater samples, approximate 4 L water was pumped out, a value equal to at least one well volume. Monthly precipitation water was collected using a 4L plastic bottle which contained a layer of mineral oil. To further prevent evaporation, the sides of the bottle were covered with foil. River water samples were collected from the river surface near the river bank using a 3 L bucket. Well mixed subsample was taken from the bucket. All water samples were sealed using parafilm in 125mL wide mouth polypropylene bottles, and stored at 3℃ until analysis.

All plant and water samples were collected on the same day of each trip. The monthly precipitation sample for March 2010 was lost during transport. However, the surface soil samples were collected only two days after the rainfall event on March 15th

(2.286 mm). Since the surface soil had been previously very dry, the lowest isotopic values of those soil samples were used as an estimate of the isotope ratio of that precipitation event.

Soil cores were taken on July 28th 2011 to study the isotopic composition of deep soil moisture. In each transect, 2-meter soil cores were taken in Plot 1 and Plot 9, while 1- meter soil cores were taken in Plot 3, Plot 5 and Plot 7. Samples were taken from the bottom layer of each 61 cm (2 feet) segment for isotope analysis.

Sample preparation and isotopic analyses

Water in rhizomes and soils was extracted using the a cryogenic vacuum distillation method (West et al. 2006). The test tube containing frozen sample was first cooled with liquid nitrogen to -196 ℃ , and then non-condensable gas inside the tube was pumped out. After that, the test tube was heated with boiling water under vacuum, while another collection tube was cooled with liquid nitrogen to collect water that was driven off the sample. The water was then stored in a 300 µL microvial for isotopic analysis.

The hydrogen and oxygen isotopes of waters were analyzed on a high temperature conversion/elemental analyzer (TC/EA) coupled to an isotope ratio mass spectrometer (IRMS) and corrected to two reference waters, with one “check” reference all characterized with respect to Standard Mean Ocean Water/ Standard Light Antarctic Precipitation (SMOW/SLAP) (1σ = 1.5 ‰ for H, 0.5 ‰ for O) .

The isotopic compositions of a water sample are reported relative to the Vienna Standard Mean Ocean Water (VSMOW) reference for both hydrogen and oxygen, and expressed in delta notation (δ) and multiplied by 1000 (Clark 1997):

$$\delta\ (‰) = [(R_{sample}/R_{standard})-1] \times 1000$$

where R_{sample} and $R_{standard}$ are the ratios of the abundance of the heavy to the light isotope, expressed as $^{2}H/^{1}H$ or $^{18}O/^{16}O$.

Soil moisture and groundwater depth measurement

Volumetric soil moisture content was measured using a Diviner 2000 capacitance sensor (Sentek Pty, Stepney, South Australia). The portable probe volumetric measured soil moisture content at regular intervals of 10 cm down through the soil profile to 1.6 m. Measurements were taken at the same time as leaf gas exchange measurements.

Groundwater levels were also measured using a water level indicator each time gas exchange measurements were made (Solinst Canada Ltd., Georgetown, Canada). Relative elevation and the distance from the river for each plot were measured in July, 2010 using Leica TC405 total station (Leica Geosystems, South Pasadena, CA). The depth to groundwater was calculated as the vertical distance between the plot surface and the water table. Since there were only two wells per transect, the aquifer surface was assumed to be a straight line along each transect in interpreting our results, though it is recognized that groundwater flowpaths can be somewhat more complex.

Statistical analysis

Linear regression was used to evaluate relationships between rhizome isotope values and environmental factors, including distance from the river and depth to groundwater. Correlations were considered significant when $p < 0.05$. Statistical analyses were conducted in JMP (SAS Institute Inc., Cary, NC, USA).

RESULTS

Since precipitation is the major input into the hydrologic cycle, the stable isotopic composition of ^{2}H and ^{18}O of local precipitation is more important to the study of vegetation water use. The local meteoric water line was constructed as a baseline for comparing isotopic composition of different water sources in this region. The regression of local monthly precipitation from June 2010 to July 2011(Fig 2.3) yielded a line with slope of 6.7, and intercept of 2.2 ($n = 8$, $R^2 = 0.95$).

The $\delta^{2}H$ and $\delta^{18}O$ values of groundwater (Fig 2.4, blue square) and river water (Fig 2.4, grey triangle) were similar, indicating close interactions. The mean $\delta^{18}O$ value of river water was −3.67 ‰, while that of groundwater was −3.60 ‰. The flood which occurred in July 2010, had water with a uniquely low isotope ratio along the local meteoric water line, with a mean $\delta^{18}O$ value of −7.48 ‰ (s.d. = 0.27) and mean $\delta^{2}H$ value of −46.5 ‰ (s.d. = 2.1) (Fig 2.4, yellow square). Surface soil water (Fig 2.4, brown circle) had large variations in isotope ratio. Linear regressions of surface soil water had a lower slope than that of the LMWL, ranging from 1.55 to 6.17.

The rhizome isotopes exhibited high variation both before and after the flood event. The variation was within the range of all potential water sources before the flood

(Fig 2.5, a), but it often fell outside the range of groundwater and surface soil after the flood (Fig 2.5 c-h). During summer 2011, the mean river/groundwater $\delta^{18}O$ value was −3.71 ‰ (s.d. = 0.33), while the lowest rhizome $\delta^{18}O$ value was −4.89 ‰ (12 samples out of 100 total samples had $\delta^{18}O$ value below −3.71 ‰). The only water source with a similarly low $\delta^{18}O$ value was the flood event in July 2010 (Fig 2.5, yellow square). It indicated that flood water persisted in deep soil layers and was used by *Arundo*.

With the exception of the very surface layers being enriched by evaporation, the bulk of the soil had isotope ratios much lower than recent rainfall and instead was quite similar to flood water values (Fig 2.6). The low end of $\delta^{18}O$ values in soil ranged between –7 ‰ and −5 ‰, while flood water $\delta^{18}O$ values ranged between −7.71 ‰ and −7.10 ‰. Rhizome values were scattered across the full range of soil water values observed at a variety of soil depths, suggesting soil moisture was the primary water source. However, soil at around 50-75 cm had $\delta^{18}O$ values similar to groundwater and river water, making it difficult to tell whether *Arundo* used any groundwater. Based on the fact that soil at 50-75 cm had a mean volumetric moisture content of 24.3% (s.d. = 7.11) even in the middle of July (Fig 2.7), there was ample soil moisture to sustain the plants without reliance on groundwater throughout the summer. Considering the variation of distance from the river and depth to groundwater within each transect, one would assume that the proportion of river or groundwater usage varies along environmental gradients. However, except that rhizome $\delta^{18}O$ values increased with distance from river in July 2011, no consistent trend was found in rhizome $\delta^{18}O$ values along environmental gradients in summer 2011 (Fig 2.8, Fig 2.9).

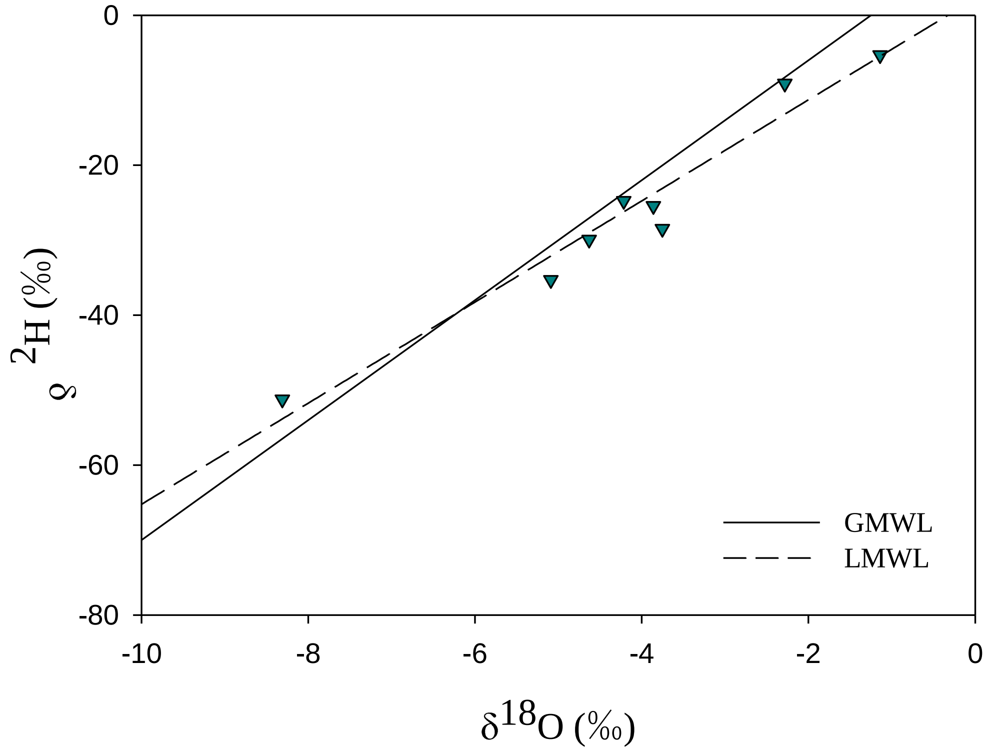

Fig 2.3 The local meteoric water line (LMWL). The LMWL was developed using δ^2H and $\delta^{18}O$ of monthly precipitation samples (inverted triangle) collected in the study site from June 2010 to July 2011 ($\delta^2H = 6.7\delta^{18}O + 2.2$ ‰). The global meteoric water line (GMWL) is shown for reference ($\delta^2H = 8\delta^{18}O + 10$ ‰) (Craig 1961).

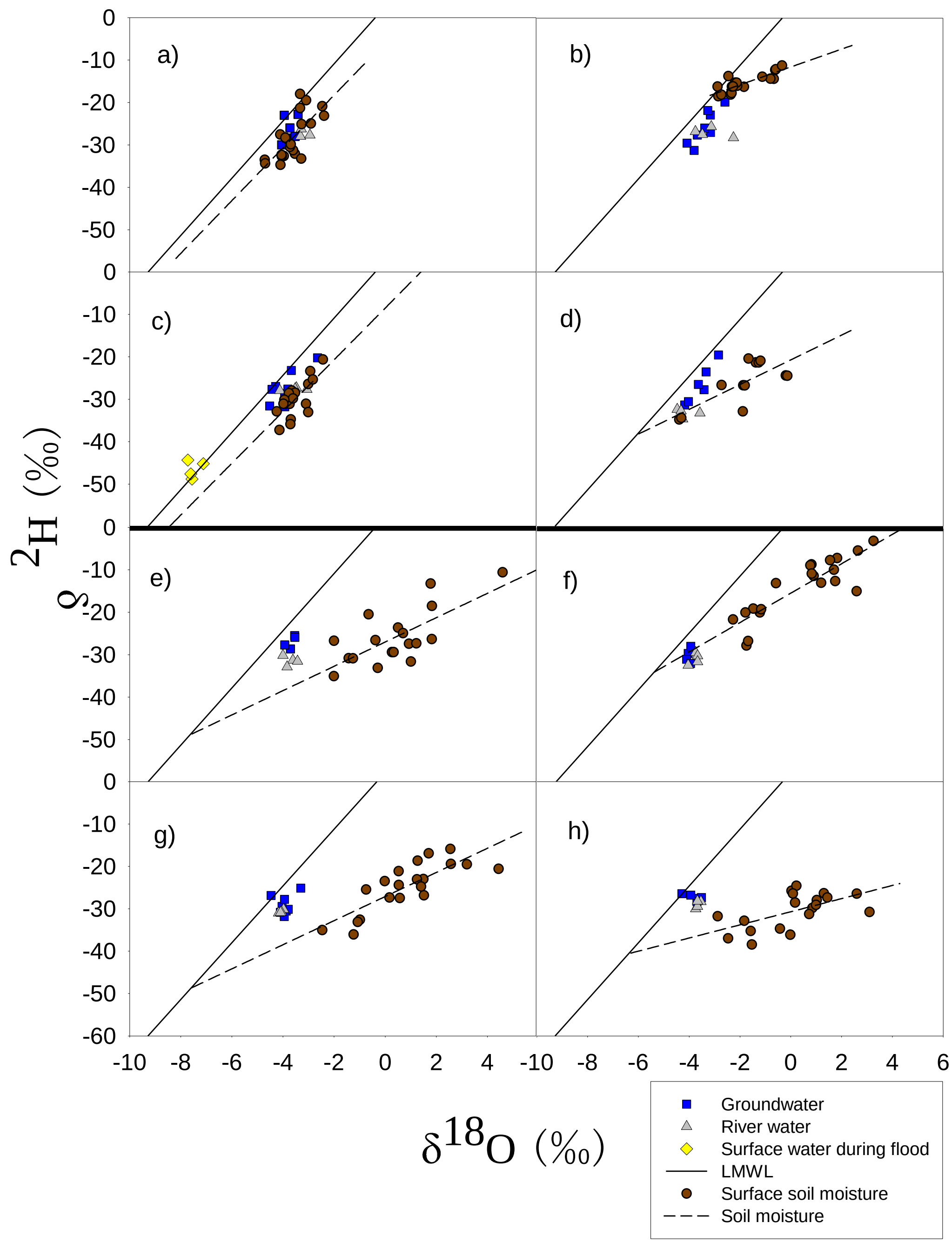

Fig 2.4 The isotopic composition of environmental water across two summers. The LMWL (solid line) was plotted in each panel for reference. Except for water collected during flood, all samples were collected on the same day in a given month, 3/17/2010, 6/14/2010, 7/24/2010, 8/12/2010, 4/8/2011, 5/14/2011, 6/10/2011 and 7/14/2011 from a) to h). The dashed lines in each panel indicate the evaporation effects plus any variations in precipitation inputs or mixing. The lower the slope of the dashed line, the lower the relative humidity is. Water during flood was collected on the floodplain on 7/6/2010.

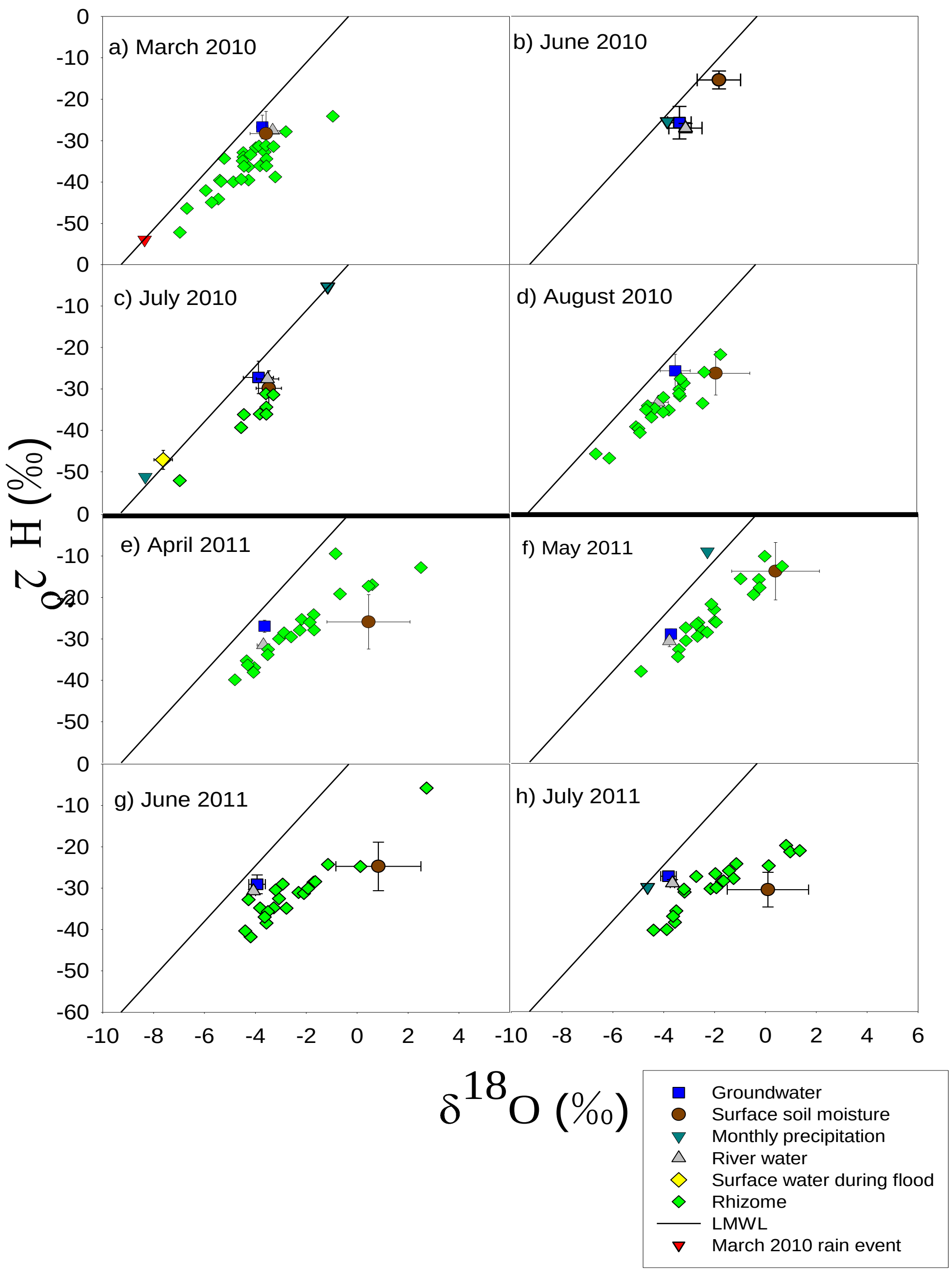

Fig 2.5 The isotopic composition of rhizome water and averaged water sources. Error bar stands for one standard deviation, and samples were collected on 3/17/2010, 6/14/2010, 7/24/2010, 8/12/2010, 4/8/2011, 5/14/2011, 6/10/2011 and 7/14/2011 from a) to h). The LMWL (solid line) was plotted in each panel for reference. Except for monthly precipitation and water during flood, all samples were collected on the same day of each month. Due to analysis problems, all June and some July rhizome samples are missing $\delta^{18}O$ values. Due to the loss of the monthly precipitation sample for March 2010, the previously dry surface soil collected two days after the rainfall event on March 15th was used as an estimate of the isotope ratio of that precipitation event (see Method for detail).

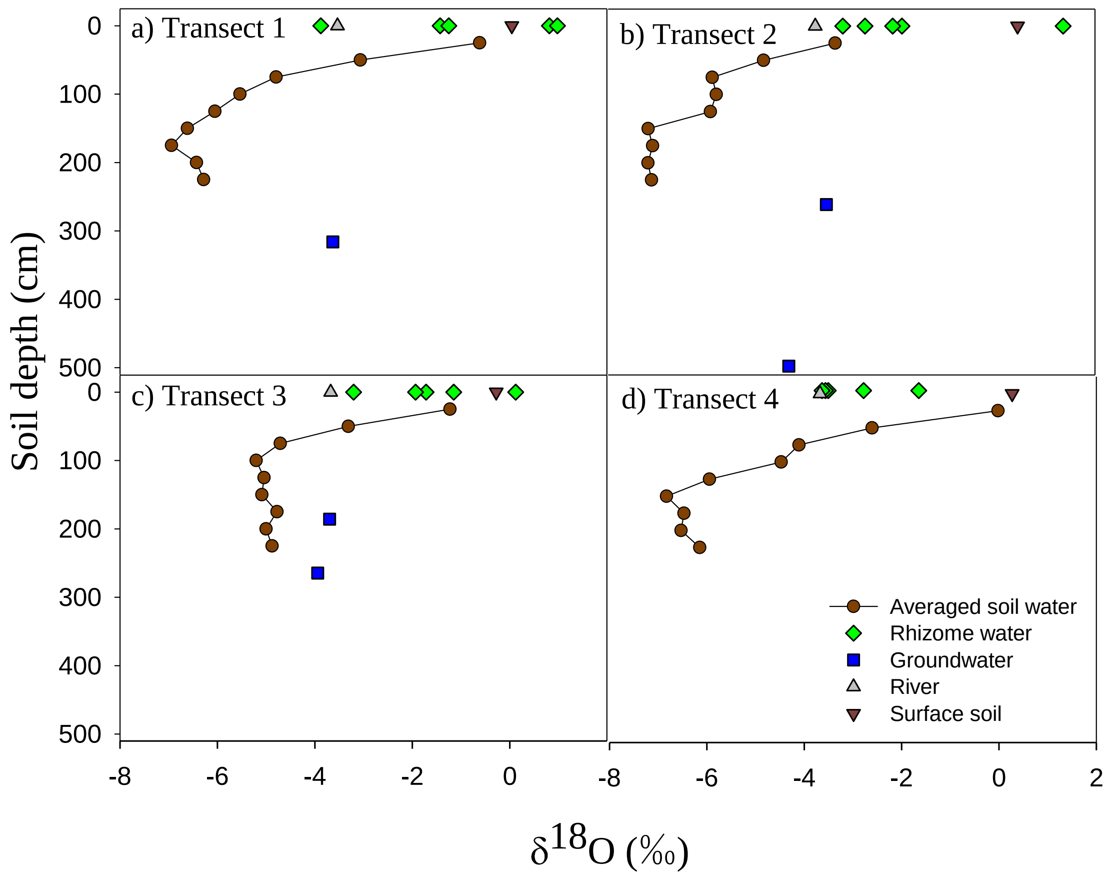

Fig 2.6 The $\delta^{18}O$ values of surface soil moisture, rhizome water, groundwater and river water on July 14th 2011. The $\delta^{18}O$ values of soil profiles collected on July 28th were plotted by depth. The $\delta^{18}O$ values of soil water were averaged across each transect (panels a-d), and the $\delta^{18}O$ values for rhizome water and river water were plotted at depth = 0. The $\delta^{18}O$ values of groundwater were plotted by depth. The groundwater wells in Transect 4 had dried out, so there was no groundwater sample in Transect 4 on July 14th.

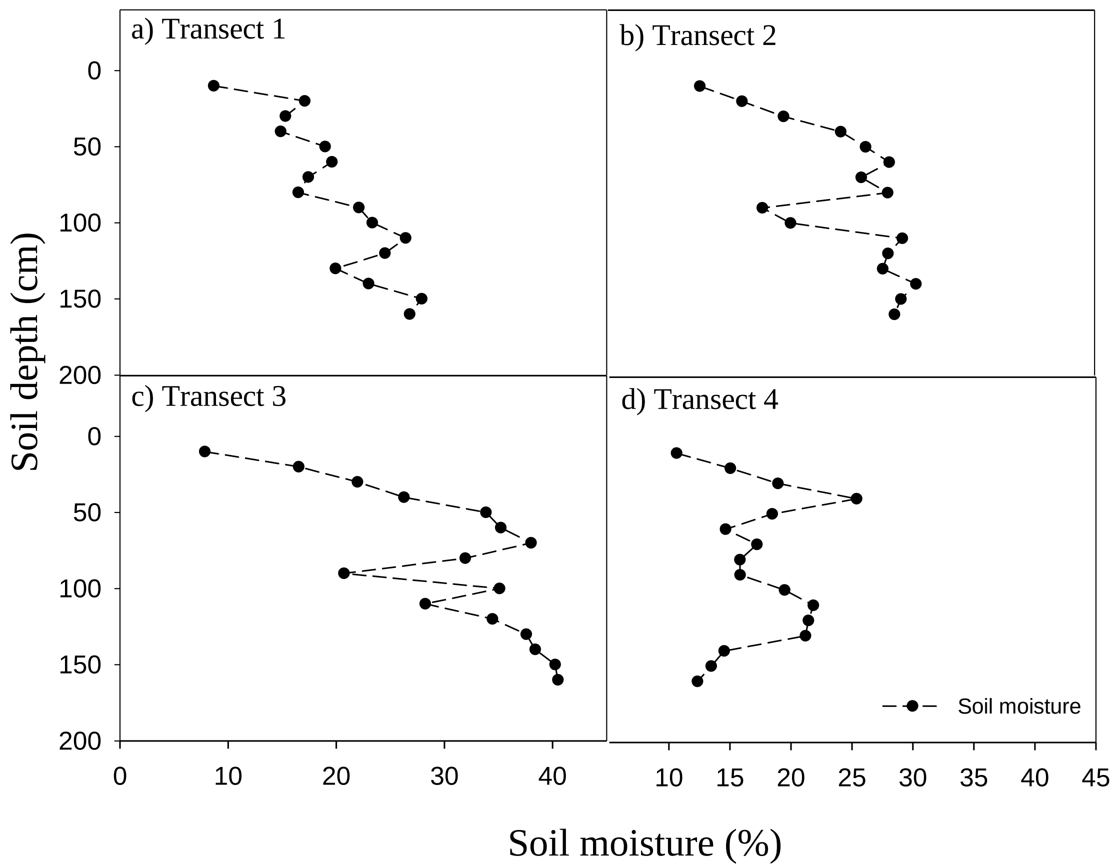

Fig 2.7 Volumetric soil moisture content measured on July 12th and 13th. Soil moisture content was averaged across transect and was plotted by depth.

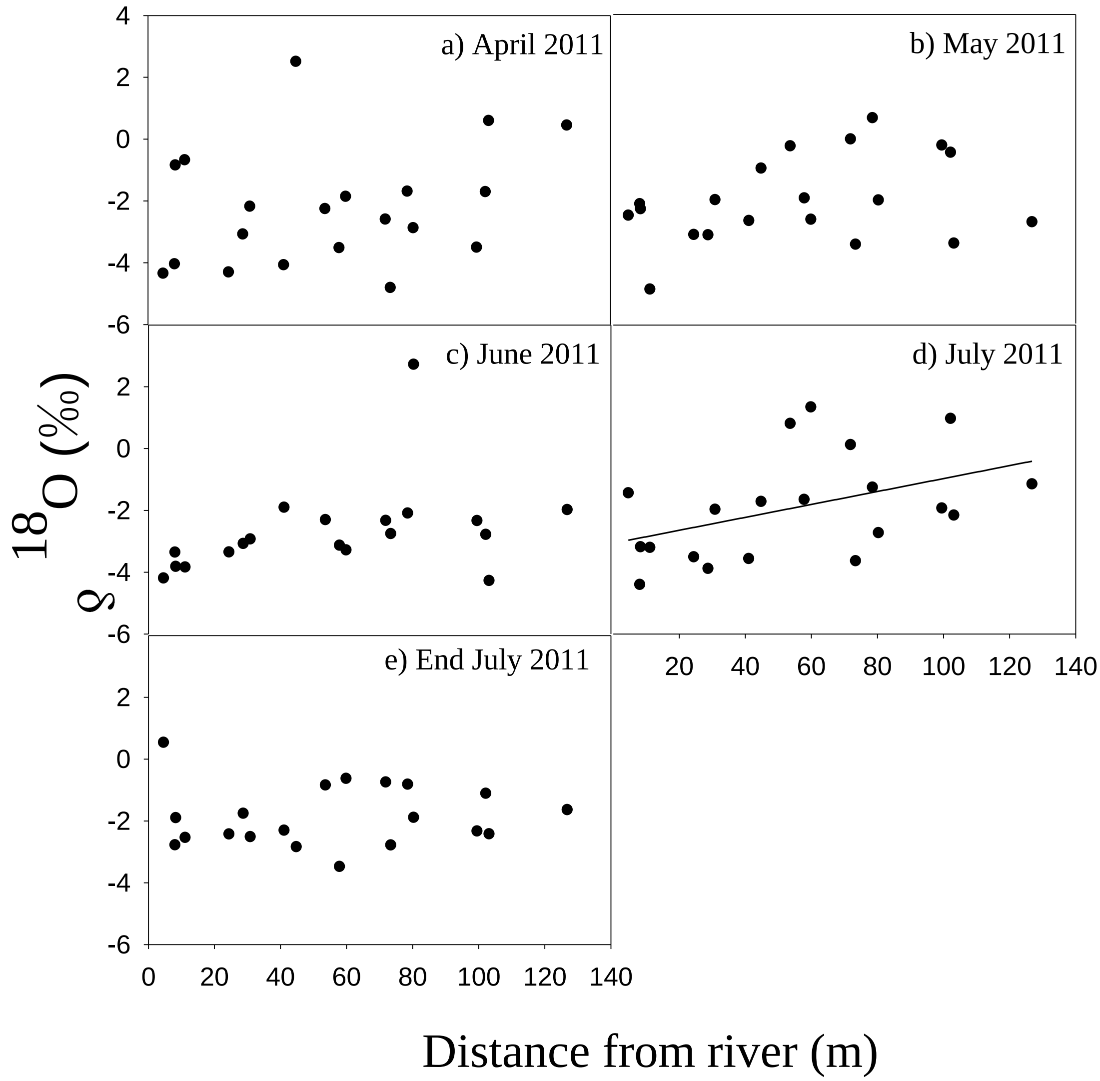

Fig 2.8 Variation of rhizome $\delta^{18}O$ values in summer 2011 in response to distance from the river. No significant relationship was found in linear regressions except for July 2011 (d, p = 0.0474*, R^2=0.201) ($p > 0.05$).

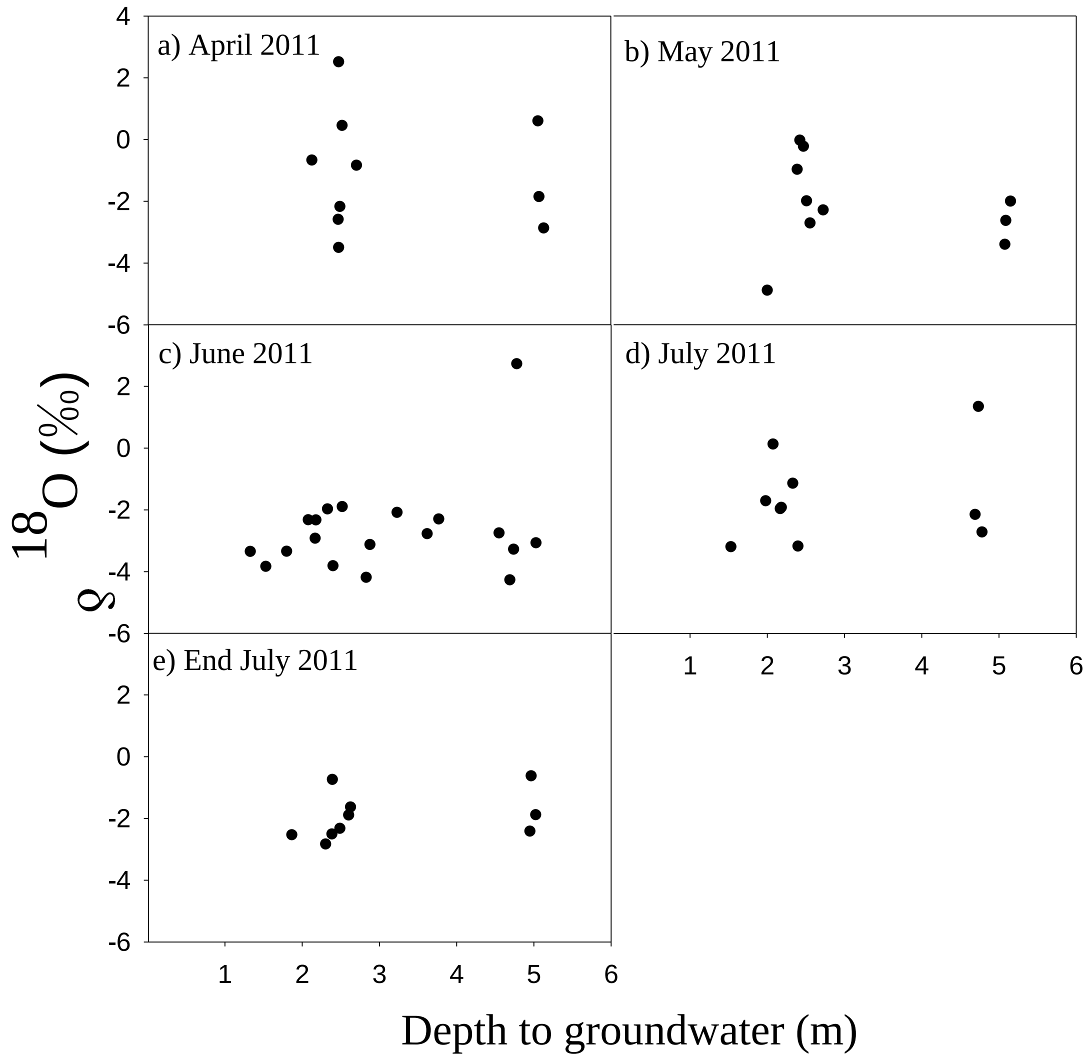

Fig 2.9 Variation of rhizome $\delta^{18}O$ values in summer 2011 in response to depth to groundwater. No significant relationship was found in linear regressions ($p > 0.05$). The wells away from river in T1 and T4 were dried out during summer 2011 except for June.

DISCUSSION

Many past studies in semiarid and arid regions have successfully partitioned the potential plant use based on the differences in water isotope ratios between precipitation, groundwater and soil water in difference depths (Weltzin and McPherson 1997, Snyder and Williams 2000, Williams and Ehleringer 2000, Darrouzet-Nardi et al. 2006, Li et al. 2006, McCole and Stern 2007, Nippert et al. 2010). Precipitation is a Rayleigh process, and is primarily related to air temperature, which leads to marked differences between the isotopic composition of summer and winter precipitation (Clark 1997). Because of the differences in the seasonal precipitation input and evaporation process in surface layers, isotopic gradients exist in the unsaturated zone (Ehleringer and Dawson 1992). Such isotopic gradients provided the basis for estimating water use from different soil layers. Weltzin and McPherson (1997) used stable isotope analysis on determining rooting depths of coexisting trees and grasses in a temperate savanna dominated by *Quercus emoryi* Torr. in Arizona. Darrouzet-Nardi et al (2006) measured the depth of plant water acquisition of sagebrush, a woody shrub, and meadow herbs in Nevada. A study conducted in a cold semiarid region of northeastern Mongolia used stable isotope analysis to determine seasonal variation of water source for a montane larch (Li et al. 2006). Winter precipitation has higher possibility to recharge into deep groundwater considering the high evaporation and transpiration rate in summer in semiarid and arid regions. Therefore, the isotope ratios of deep groundwater are usually lower than summer precipitation and surface soil, which leaded to studies on separating regional groundwater versus soil moisture uptake of semiarid or arid riparian phreatophyes

(Snyder and Williams 2000, Nippert et al. 2010). Mccole and Stein (2007)used the differences in groundwater and soil moisture isotopes on determining the seasonal water sources of *Juniperus ashei* and found a shift of groundwater use in dry summer to soil moisture use in moist winter. Riparian groundwater, however, is usually hydraulically connected to the surface, which means their isotope ratios are tightly linked (Snyder and Williams 2000, Hunt et al. 2005). The similarity of isotopic compositions between riparian groundwater and surface water makes it difficult to separate these two water sources of riparian vegetation.

As with those studies, differences among isotope ratios for precipitation, groundwater, and surface soil water were also found in this study. Several mechanisms could be responsible for the observed isotopic differences. Evaporation caused heavy isotopes to accumulate in the surface soil as it dried out following a precipitation or flood event. Reservoirs and lakes are typically sources of evaporative enrichment, consistent with the river and groundwater being close to, but a bit off of the LMWL. However, this study could not rely solely on traditional water source partitioning methodology to determine water sources for several reasons. First, the floodplain in this study has a shallow, flat aquifer (data shown in Chapter 3). The similarity of isotopic compositions between groundwater and river water indicated their close interaction. It also means that there was no way to separate the use of river water from groundwater based on water isotopes alone. Second, the flood water with a low isotopic composition recharged the whole soil column, causing deep soil layers with isotope ratio lower than that of groundwater. Third, the isotope ratio of river water and groundwater were similar to that of soil moisture at depth between 50−75 cm. The lack of a meaningful distinction between shallow soil moisture and groundwater made it difficult to tell to what extent *Arundo* used groundwater.

As an herbaceous species, *Arundo* has been found with fibrous root system concentrated in shallow soil layers (Kui 2011). Therefore it has a higher dependency on soil moisture than groundwater. Several months after the flood in July 2010, deep residual soil moisture became an important source during a period of low precipitation input. Rhizome water isotopes showed evaporative enrichment after the flood, but they tended to follow a mixing line that points towards flood water isotope values even in summer 2011. This suggested a strong dependency on flood recharged deep soil moisture during a low precipitation period.

In this case, groundwater and river water had isotope ratios similar to those observed in soils at around 50-75 cm depths. Based on isotope data only, we cannot determine whether *Arundo* uses groundwater or not. However, since the range of soil moisture isotope ratios covered the isotope ratios of rhizome water, and the soil moisture content in top 1.6 m was within the range of plant available water content, it is more logical that *Arundo* tended to use soil moisture. Across each transect, depth to groundwater varied from 1 m to 5 m over space, making groundwater not a stable source for *Arundo*. The lack of consistent trends between rhizome δ^2H and δ^{18}O values and depth to groundwater provided additional evidence to support that groundwater was not an important source when soil moisture content was sufficient. Previous results demonstrated that *Arundo* maintained most of its total belowground biomass in the top 1 m soil layer, and it decreased rapidly with soil depth (Kui 2011). This gives *Arundo* a great advantage in exploiting water available in the unsaturated zone.

Based on stable isotope, soil moisture, and root biomass distribution, we concluded that groundwater was not an important source for *Arundo*. This allowed estimation of the depth of uptake in 2011 based on soil water isotopes only. This estimation was based on two assumptions. First, it assumed that the $\delta^{18}O$ values of the soil profile changed linearly. Although we understood that was not the case, the overall pattern within the soil profile was unlikely to change (Darrouzet-Nardi et al. 2006, Wang et al. 2010). Large isotopic differences between deep soil and surface soil allow for estimating the depth of uptake (Phillips 2001). Second, it was assumed that root distribution was linear and roots took up equal amount of water at the two endpoints. It was recognized that *Arundo* had most of its roots maintained at shallow soil layers (Kui 2011), but this estimation allowed an understanding of minimum extent of root system.

Since there was only one set of deep soil samples, it was assumed that the isotopic composition of deep soil remained the same throughout the summer in 2011 for the purposes of estimating rooting depth. The lowest $\delta^{18}O$ value from the soil core in each transect was used as one endpoint in the linear mixing model with its depth from the soil core. The other endpoint was the averaged $\delta^{18}O$ values for surface soil samples. The $\delta^{18}O$ values of surface soil (all from top 10 cm) were averaged across months for each plot, and the depth for surface soil samples were assigned to be 10 cm. Therefore, 20 linear mixing models were generated, one for each plot. By applying rhizome isotope ratios (averaged as surface soil samples) to the corresponding linear model, a minimum extent of root uptake was estimated (Fig 2.10).

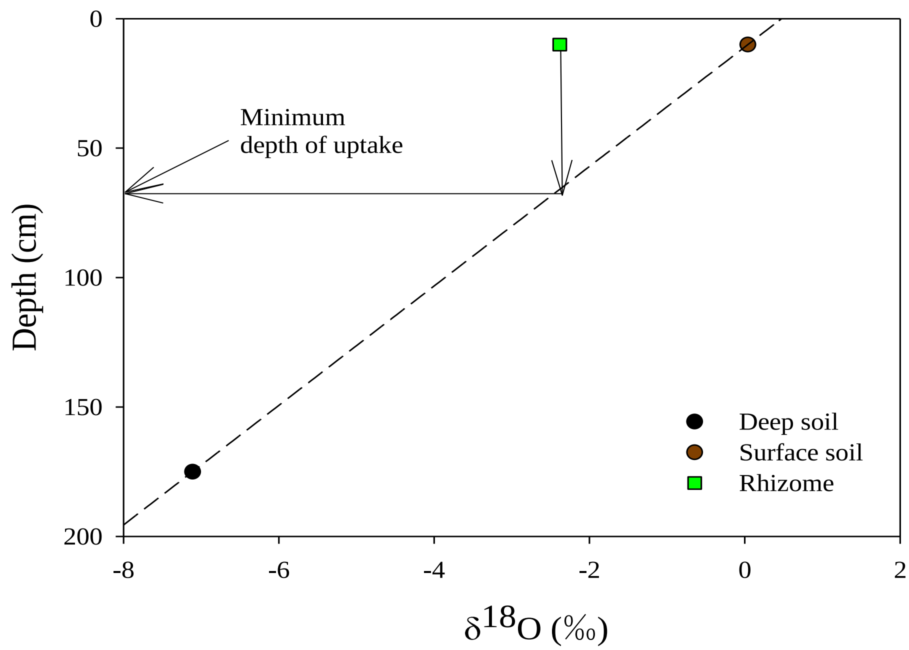

Fig 2.10 Conceptual model for estimating minimum depth of uptake

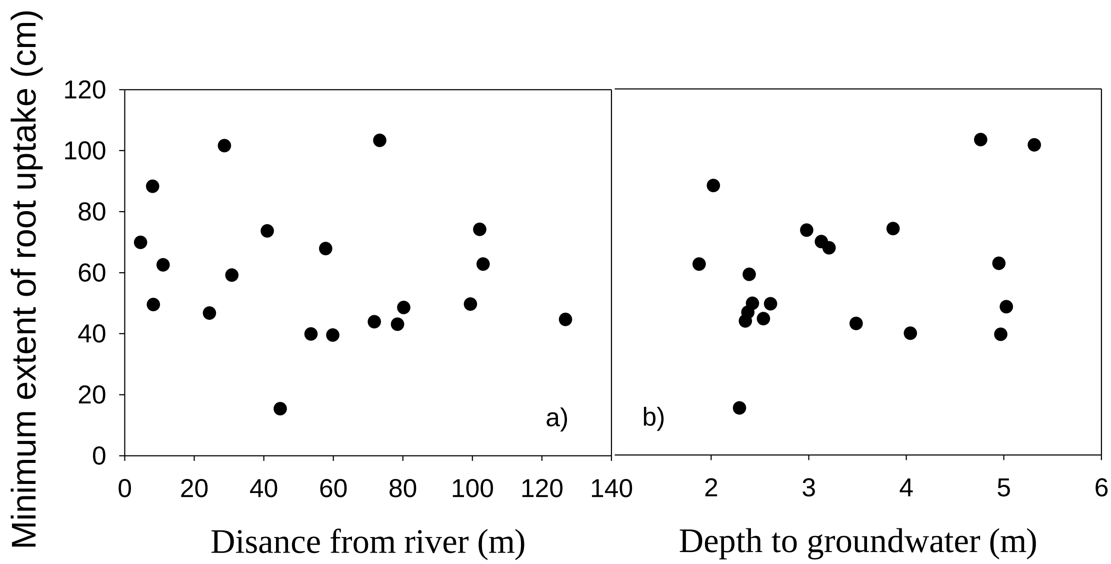

Fig 2.11 Variation of minimum extent of root uptake in summer 2011 in response to distance from the river and averaged depth to groundwater. No significant relationship was found in linear regressions between minimum extent of root uptake and distance from river (a), minimum extent of root uptake and depth to groundwater (b) ($p > 0.05$).

There was no significant relationship between minimum depth of water uptake and depth to groundwater (p = 0.4918, n =20), or distance to river (p = 0.0775, n = 20) (Fig 2.11). The lack of consistent trends for rhizome isotope ratios and minimum depth of uptake along the environmental gradient provided additional support for our conclusion that groundwater was not an important source for *Arundo*. While it was this estimation was based on several assumptions, it allowed relating relative usage of soil moisture in different layers to environmental gradients. If *Arundo* had great dependency on groundwater, it is likely that its water use pattern would be affected by the vertical depth to groundwater. However, such relationship was not found in this case.

Although the precipitation input was only 4.5 mm from August 1st 2010 to August 1st 2011, *Arundo* appeared not to experience soil water deficit in summer 2011.

Top 1 m soil moisture content was the lowest in July 2011, with the mean of 21% (data shown in Chapter 3), comparing to a field capacity of 37% based on the soil texture in general (Jiang et al. 2007, Kui 2011). The reason for the sufficient soil moisture content was the flood event that brought upstream excessive hurricane water into the floodplain, completely saturating the soil column. This strongly suggests that most of water transpired by *Arundo* in our case was meteoric water instead of local groundwater or river water. Even though a small number of roots reaching the groundwater table were observed during well installation, their presence alone did not necessarily mean root water uptake was significant from this depth (Ehleringer and Dawson 1992).

The flood water persisted in the soil for a year despite a severe drought, benefiting riparian vegetation by increasing water availability in the unsaturated zone. This suggests that isolated high flow events could be critical to the survival of riparian vegetation during a severe dry growing season, when the unsaturated zone would otherwise be too dry for plants to extract water. Until the end of July 2011, the mean soil moisture content was about 0.3 m^3/m^3, with a mean depth of the soil column across transects was about 3 m. Therefore, there was about 0.9 m water stored in the soil column. Assuming transpiration was the only way of soil water depletion and *Arundo* could maintain a transpiration rate at 9 mm/day (Watts and Moore 2011), the floodwater would last for about 100 days without additional precipitation input. If the drought was to continue for another year, the soil moisture would be depleted. Once the soil moisture is depleted, it is very likely that *Arundo* would switch to using primarily groundwater to facilitate their growth (McCole and Stern 2007, Nippert et al. 2010). Future research is needed to investigate *Arundo* water use when water content in the unsaturated zone is low.

Overall, this study provided information on *Arundo* water use pattern in the semiarid riparian ecosystems. Unlike riparian phreatophytes, *Arundo* does not use groundwater as its primary water source as long as soil moisture was sufficient. This characteristic suggested that the removal of *Arundo* may not have significant impact on groundwater levels or streamflow volumes. On the other hand, the replacement vegetation like cottonwood, willow, and saltcedar have high dependency on groundwater (Busch et al. 1992, Snyder 1998, Nippert et al. 2010). Future study with *in situ* comparisons between *Arundo* and potential replacement vegetation would provide more knowledge on regional water preserve.

This study provided information on *Arundo* water use pattern in the semiarid riparian ecosystems. First of all, unlike riparian phreatophytes, *Arundo* does not use groundwater as its primary water source when soil moisture was sufficient. Secondly, so long as soil moisture is available, *Arundo* apparently does not need to switch to groundwater at any point in time. Future study on water source partitioning during soil water stress would further improve the knowledge on how *Arundo* behaves during hydrologic extremes.

CHAPTER III

THE EFFECTS OF VEGETATION WATER USE ON THE INTERACTIONS BETWEEN RIVER WATER AND GROUNDWATER

INTRODUCTION

The interaction between groundwater and surface water is an important hydrologic process. The exchange process partly depends on the permeability of sediment layers (Brunke and Gonser 1997). Because of the typical heterogeneity of those sediments, there can be many rapid and slow pathways connecting the river and groundwater. In general, groundwater that is hydraulically connected to the surface body either flows towards the surface body (gaining streams) or flows towards the floodplain (losing streams). The interaction may vary spatially - a stream gaining in some reaches and losing in others, or temporally – reversed hydraulic gradients due to human activities or natural flood event (Francis et al. 2010, Simpson and Meixner 2012).

Losing streams are common in semiarid regions because of the low precipitation recharge. Consequently, plants relying on groundwater in these systems are also affected by the streamflow. Stream diversion and ground-water pumping for human use have caused river dewatering and alluvial aquifer decline in southwestern United States (Rood et al. 2003). This has led to the decline of many native riparian phreatophytes, and increased the drought-tolerant invasive species (Rood et al. 2003, Lite and Stromberg 2005). However, others have pointed out that damming can benefit downstream vegetation growth by providing consistent stream flow (Duke et al. 2007). Duke et al

(2007) conducted a 3-year water balance study along a low order stream Texas, and found that the presence of the upstream dam provided continuous stream water flow, which contributed nearly half of the total inputs in that site.

The growth of riparian vegetation can also influence the interaction between groundwater and surface water. Chen (2007) found that riparian vegetation can intercept groundwater that would otherwise discharge to the stream (gaining reach), or it can increase the infiltration from the stream to groundwater (losing reach). Such influences will be exaggerated as riparian vegetation groundwater ET rate increases. The direct use of groundwater by riparian vegetation could cause daily groundwater fluctuations. Bond et al. (2002) found that the existence of riparian vegetation intercepted baseflow and induced diurnal fluctuations in streamflow. The influence of vegetation ET on groundwater fluctuations was recognized in the early work of White (1932). Diurnal water table fluctuations have been also reported by others; shallow groundwater tables in vegetated riparian zones decline during daytime when transpiration is high and are recharged during the night when transpiration is negligible (Loheide et al. 2005, Butler et al. 2007, Martinet et al. 2009).

The complex feedbacks among vegetation, groundwater and surface water in the riparian zones can be modified by exotic species invasion (Tickner 2001). For example, the direct and high use of groundwater by saltcedar can significantly lower riparian groundwater levels in arid areas (Sala et al. 1996). This decline can, in turn, cause further depression of native riparian species, *Populus* and *Salix* (Scott et al. 1999, Scott et al. 2000, Amlin and Rood 2003, Rood et al. 2003) . Like woody exotic species, non-woody invasive species can also alter the dynamics between vegetation and geomorphology in riparian systems (Bell 1997), yet little is known about the interactions between non-woody vegetation and the water cycle in the riparian zones.

Arundo is an herbaceous graminoid exotic species that has spread widely along the rivers in the southwestern United States. Once established, *Arundo* can form dense, nearly monocultural stands, change wildlife habitats and modify physical and chemical site characteristics (Bell 1997). *Arundo* often causes a faster, narrower stream flow, and undercuts the banks of the river. When that happens, large stands of *Arundo* break away from the bank and float downstream, often causing damage to bridges, roads, and water intake facilities (Seawright et al. 2009). Research has been conducted to better understand environmental factors influencing its invasion and developing better control methods (Bell 1997, Boose and Holt 1999, Culliney 2005, Quinn et al. 2007, Seawright et al. 2009), but little is known about factors affecting *Arundo* water use and how it will affect groundwater-surface water interaction.

Although *Arundo* has a relatively high transpiration rate and leaf area index (Watts and Moore 2011), most of its roots were found in the top 1 m soil layers in spite of observations of roots at groundwater depths (Kui 2011). Therefore, *Arundo* may not access groundwater to a great extent and unlike riparian phreatophytes, it may not have a large influence on the interaction between groundwater and surface water. This research is aimed at better understanding the groundwater-surface water interactions along the lower Rio Grande River and evaluating how *Arundo* water use influences this interaction.

The interaction between the river and groundwater was assessed by measuring river and groundwater table elevation. For gaining reaches, the elevation of the water table must be higher than the level of the river surface; for losing reaches, the river surface has higher elevation (Kalbus et al. 2006). Continuously monitored river stage and groundwater fluctuations were compared to calculate correlation coefficient for understanding the phase relationship between river and groundwater fluctuations. The hypothesis is that the groundwater in this floodplain is hydraulically well connected to the river, and *Arundo* water use does not cause daily groundwater fluctuations.

Water availability limits riparian vegetation ET (Williams et al. 2006). Doody and Benyon (2011) found that the introduced willows in Australia growing on the bank had similar ET rate as native species and was lower than willows growing in the stream. Therefore they suggested higher possibility of water salvage by removing willows growing in the stream where water availability is greatest. Besides the inherent water availability gradients along the stream-to-upland transition, depth to groundwater and soil moisture distributions also vary spatially in riparian zones. Devitt et al (1997) found that saltcedar stands had lower ET as the groundwater table and soil moisture content declined, and they suggested an evaluation of water availability before calculating saltcedar stand ET rate. However, other studies also reported that saltcedar was more tolerant of low moisture levels and declining water table rates than many native species, and identified such tolerance as one of the factors that gives saltcedar its competitive advantage (Smith et al. 1998, Horton et al. 2001).

Arundo was reported to have a lower transpiration rate with distance from the river (Watts and Moore 2011). However, as a clonal species, *Arundo* was found to have the capability of exploiting water from areas with greater availability and transporting through its interconnected rhizomes (Kui 2011). The rhizome integration could benefit the plants maintaining high transpiration rate in resource-patchy riparian areas. Other situations could also ameliorate the impact of water supply fluctuations on spatial transpiration variations. For example, over-bank flooding could percolate through soil and dampen the water availability gradients in the floodplain. Therefore, understanding the factors affecting the spatial variations of *Arundo* transpiration would help riparian water budget estimation. In this study, *Arundo* leaf-level transpiration rate was measured to test the hypothesis that *Arundo* transpiration rate would vary along hydrologic gradients.

STUDY SITE

The study site is located at Rancho Rio Grande, TX (29°14'44.39"N, 100°47'38.62"W). The mean annual precipitation is 477 mm per year and monthly average temperatures range from 10 °C to 27 °C (NOAA 2011). The aquifer in the floodplain is at the edge of Edwards - Trinity (Plateau) Aquifer (outcrop).

Four transects (T1-T4) were established perpendicular to the Rio Grande River. Two transects were located in concave meanders (Transect 1 and Transect 4), and the other two were located in convex meanders (Transect 2 and Transect 3). The length of transects from 1 to 4 are 102 m, 103 m, 127 m and 73 m, respectively, and the distance between Transect 1 (north end) to Transect 4 (south end) is approximately 10 km. Inside each transect, a cleared 1-m-wide trail was established for access. Nine 1 m × 1 m plots (P1−P9) were placed at equal distances along each transect for gas exchange and soil moisture measurement. Eight groundwater wells were installed in March, 2010, two wells at opposite ends of each transect (P1 for near-river well and P9 for away-river well) (Fig 2.1).

METHODS

Leaf gas exchange measurement

Leaf gas exchange was measured on the second fully expanded leaf of one selected stem in every plot using the LI-COR 6400 leaf gas exchange system (Li-Cor, Lincoln, Nebraska), with a red and blue light source and CO_2 injector. The light output was set to 1600μmol mol^{-1} s^{-1} based on an in-chamber quantum sensor reading, with air flow rate set to 400 μmol s^{-1} and CO_2 concentration set to 385μmol/mol. We modified the water scrub amount as a coarse way to match ambient relative humidity. There were five sets of measurements for each month in summer, 2011: Apr 8-9, May 13-16, June 10-13, July 12-13, and July 28-29.

Leaf carbon stable isotope ratio

Leaves used for photosynthesis measurements were collected and then dried at 60 °C overnight. Leaves were then ground using a ball mill (Retsch, Newtown, PA). Subsamples of leaves (1.5 mg ± 10 %) were analyzed with an Isotope Ratio Mass Spectrometer coupled to an Elemental Analyzer.

Leaf carbon stable isotope ratio was expressed as $\delta^{13}C$ relative to the reference standard, Pee Dee Belemnite (PDB) (Dawson et al. 2002):

$$\delta^{13}C\ (‰) = (R_{sample} / R_{standard} - 1) \times 1000\ ‰$$

where R_{sample} and $R_{standard}$ stand for $^{13}C/^{12}C$ ratios in the sample and standard.

Soil moisture measurement

Volumetric soil moisture content was measured on the same day as leaf gas exchange measurements, using a Diviner 2000 capacitance sensor (Sentek Pty, Stepney, South Australia). The PVC access tubes were installed in 2009 in odd-numbered plots of each transect, 2 meters perpendicular distance from those plots where gas exchange was measured. The portable probe measured soil moisture content at regular intervals of 10 cm down through the soil profile to 1.6 m.

Elevation survey and groundwater level measurement

Relative elevation, with 5" angle accuracy and 2 mm distance measurement precision, was measured in July, 2010 using a Leica TC405 total station (Leica Geosystems, South Pasadena, CA). At 10-m distances, vertical accuracy of the instrument is 0.2 mm. Accuracy diminishes with distance; whereas, at 100-m distances, it is only 2 mm. Measurements were typically made at 10-m distances apart, but accumulated errors across the length of the entire transect (from P1 to P9) were up to +/- 1.8 mm. The lowest plot of each transect was defined as elevation zero, which means that reported elevations were relative to each other within each transect.

Eight 2-inch diameter piezometers were installed in March, 2010, two wells at opposite ends of each transect. The piezometer consisted of a screened PVC pipe, capped at the top. Each piezometer partially penetrated the aquifer, about 0.6 m beneath the water level when installed. The length of the piezometers ranged from 2.4 m to 6 m. Slits were cut along the lower part 50 cm of pipe, and covered by sand.

Point measurements of groundwater level were made at the same time of gas exchange measurement using a water level indicator (Solinst Canada Ltd., Georgetown, Canada). The water level below the top of each piezometer pipe was determined when the reading remained stable for at least one minute. The depth to groundwater was calculated as the vertical distance between the plot surface and the water table. Since there were only two wells per transect, the aquifer surface was assumed to be a straight line along each transect. We recognize that groundwater hydraulic gradients are likely more complex than this and do not attempt to describe these in any detail.

Continuous water level measurement and time lag correlations

Water level loggers (Global Water Instrumentation, Gold River, California) were installed in the river and two of the piezometers since August 2010 on a rotational basis.

All three loggers were installed in the same transect for one month, and then they were transferred to another transect randomly.

Groundwater-river water exchange measurement

Slug tests were conducted in each well in June 2011 to estimate horizontal hydraulic conductivity under in-situ conditions (Butler 1998). The static water level in the piezometer was determined before each slug test by measuring the depth to water periodically for 3 minutes, 10 times per second, and taking the average of the readings. Time zero was set at the moment a known volume was added or removed. Then the depth to water and the time of each reading was recorded 10 times per second on the water level logger until the water level remained static. All measurements were replicated three times to ensure precision.

The results were analyzed by the Hvorslev method (Butler 1998) for partially penetrating wells in an unconfined aquifer. The equation is given as follows:

$$\mathrm{K} = \frac{r^2 \ln(\frac{L}{R})}{2LT_0}$$

Where K is hydraulic conductivity in m/d, L is the length of the screen in m, R is the radius of the augured hole in m, r is the radius of the well casing in m, and T_0 is the time taken for the water level reaching 37% of the initial change (H'). The initial head change is calculated as:

$$\mathrm{H'} = \frac{\mathrm{H-h}}{\mathrm{H-H_0}}$$

Where H is the initial water level prior to removal or adding the slug, H_0 is the water level at time 0, and h is recorded water level at any given time after initial pertubation, A plot of ln (H') versus time should yield a straight line with a slope of c. T_0 equals $-1/c$ for slug adding test and 1/c for slug extraction test.

Soil texture measurement

Soil texture was determined from samples collected during groundwater well installation using a hydrometer method after being sieved down to 2 mm (Bouyoucos 1962). After dried in the oven at 110^0C, 50 g of sieved soil was soaked in 50 ml of dispersal agent ($NaSO_4$ solution) for 12 hours. The suspension was mixed for 5 minutes using a soil dispersion mixer (Colonial Scientific Inc, Richmond, VA), and then transferred into a 1-L jar and brought to mark with distilled water. After stirring 20 times using a stirring rod, 20-second and 2-hour readings from hydrometer were recorded to determine sand and clay content, respectively.

Statistical analysis

Monthly averaged measurements were compared using one-way ANOVA and the Tukey HSD. Correlation between transpiration and environmental factors or vapor pressure deficit was evaluated with linear regression. The F-statistic in all statistical analysis was considered significant at $\alpha = 0.05$. Statistical analyses were conducted in JMP (SAS Institute Inc., Cary, NC, USA).

Continuous water levels were recorded at 15 min intervals. A built-in cross-correlation (xcorr) function in MATLAB (The Mathworks Inc.) was used to calculate time lags and the strength of correlation between groundwater fluctuations and streamflow records at the study site. Correlation analysis was based on data that was monitored continuously for at least two weeks.

RESULTS

Both transpiration and stomatal conductance peaked in April (Fig 3.1). The mean transpiration rate was 5.88 mmol · m^{-2} · s^{-1} in April, while mean stomatal conductance was 0.31 mol · m^{-2} · s^{-1}. They declined into the summer, as monthly vapor pressure deficit increased. Meanwhile, leaf $\delta^{13}C$ values were the highest in June and July, consistent with the observed declines in stomatal conductance. However, the observed decline in transpiration, decline in stomatal conductance, and corresponding increase in water use efficiency were not associated with a decline in soil moisture or groundwater depth. Instead, soil moisture content in the top 1 m and depth to groundwater were not significantly different from month to month throughout the summer.

Transpiration and stomatal conductance of each plot across different months were negatively related to VPD at the same time of each measurement, while leaf $\delta^{13}C$ values were positively related to daily average VPD (Fig 3.2). Across transects, distance from river ranged from 10 m to 130 m, depth to groundwater varied from 1 m to 6 m, and soil moisture content ranged from 6% to 48%. However, no consistent relationship was found between transpiration and distance from river, depth to groundwater, or soil moisture content in the top 1 m when averaged for each plot across the summer, except that transpiration rate declined with increased depth to groundwater in May (Fig 3.3) (See APPENDIX A for transpiration by transect for each measurement day).

The highest water level was measured after the flood event in July, 2010, when the river stage began to subside and groundwater flowed into the river except for Transect 2, where the river lost water to the groundwater (Fig 3.4). The head gradient differences between the two wells of each transect were the highest at that time, ranged from 0.2827 m/m to 0.5072 m/m. By August 20^{th} 2010, the river discharge gradually went down from 750 cubic meters per second to the average levels before flood (33 cubic meters per second) (Fig 2.2). At the end of October, groundwater levels and the gradient between the two wells in each transect were about 1.5 m lower than that in July. Beyond that time, groundwater did not flow into the river any more for the duration of this study (data in other months not shown). In June 2011, the end of the study period, groundwater in all transects were flowing towards the floodplain, with the head pressure gradients of 0.0811 m/m, 0.5765 m/m, 0.4459 m/m and 0.0800 m/m, respectively (the detection limit of vertical gradient was 0.001 m/m).

Correlations between river stage and groundwater level fluctuations were very high (Table 3.1), showing streamflow fluctuations accounted for over 50% of daily groundwater changes (See APPENDIX B for continuous groundwater and river water fluctuations by transect for each month). High saturated hydraulic conductivities and coarse sediment were found in the floodplain (Table 3.1) (See APPENDIX C for plots of water level recovery as a function of time for each groundwater well). Consistently, the time lags between river stage and groundwater level fluctuations were small, within 1.5 hours, except for T3P9 well. The groundwater level in the T3P9 well lagged behind the T3 river elevation by 6 hours in conjunction with the lowest sand percentage among all well locations.

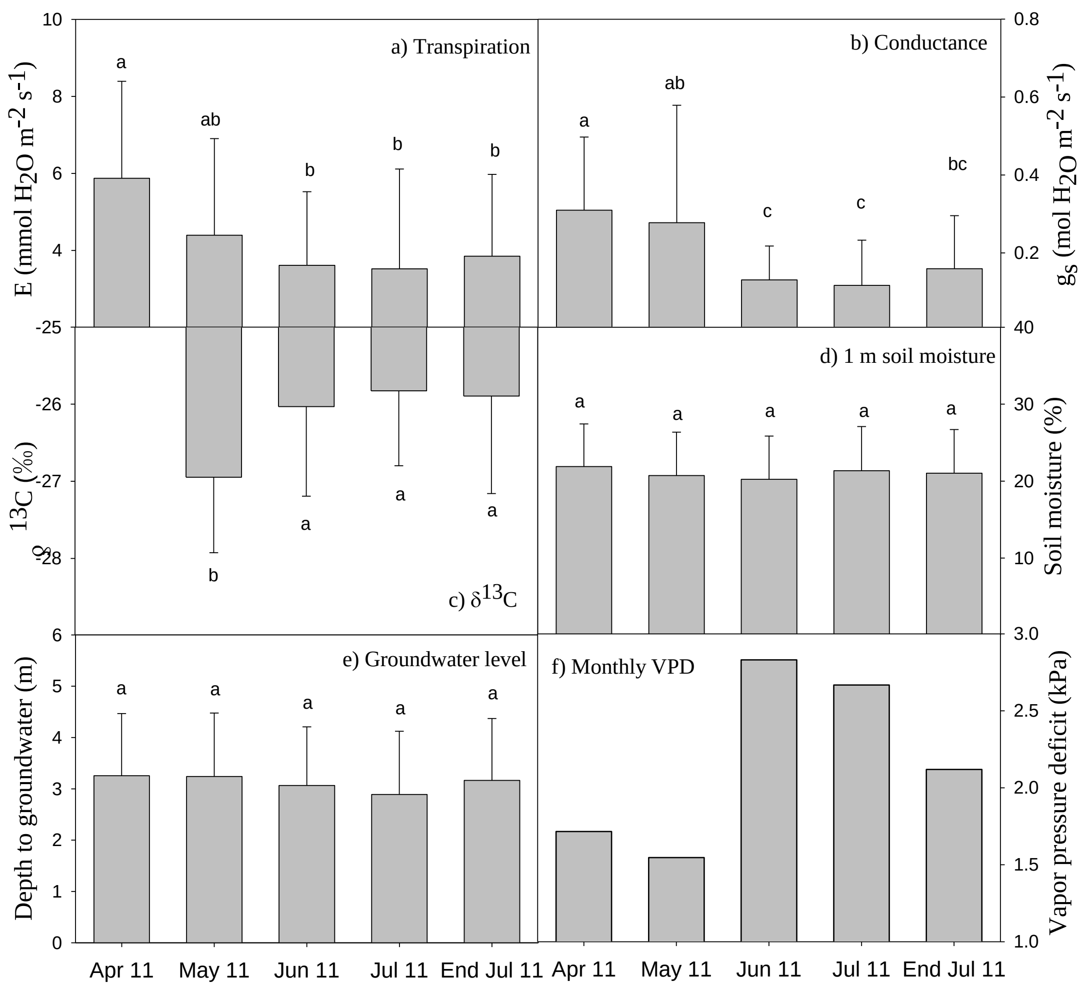

Fig 3.1 Monthly variations of leaf level transpiration (a), stomatal conductance (b), leaf $\delta^{13}C$ (c), top 1 m soil moisture (d), depth to groundwater (e) and vapor pressure deficit (f) during summer, 2011. Shown are mean values across all plots and standard error bars, except monthly vapor pressure deficit that was calculated from monthly average temperature and relative humility. The letters represent the significant difference between groups according to Tukey's HSK comparison. Leaf samples were not collected in April 2011 .

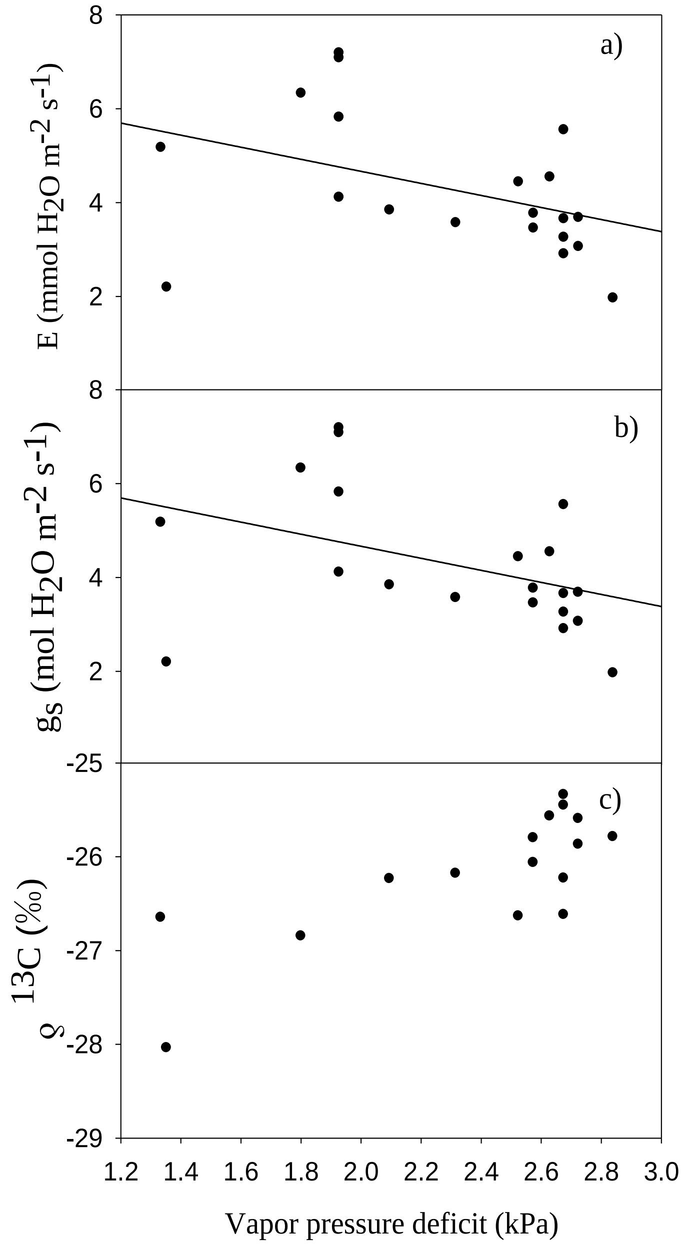

Fig 3.2 Variation of leaf-level transpiration (a), stomatal conductance (b), and leaf $\delta^{13}C$ (c) in response to vapor pressure defict changes. Transpiration, stomatal conductance and leaf $d^{13}C$ values were averaged for each transect of each month in 2011; vapor pressure deficit was calculated based on daily averaged temperature and relative humility for each measurement. a): polynomial relationship, $p = 0.0086^*$, $R^2 = 0.429$, $n = 20$. b): polynomial relationship, $p = 0.0060^*$, $R^2 = 0.452$, $n = 20$. c): linear relationship, $p = 0.0005^*$, $R^2 = 0.592$, $n = 16$.

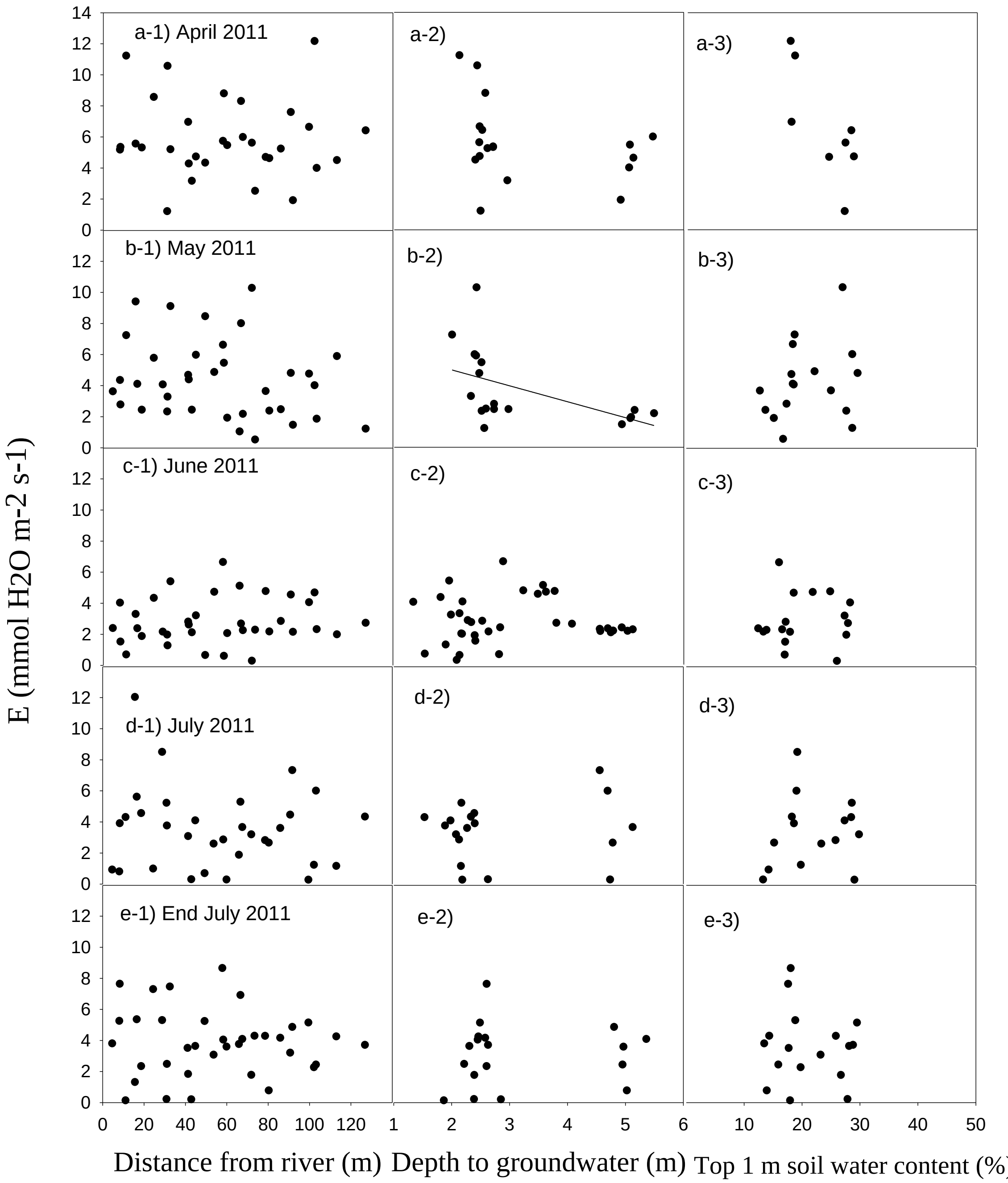

Fig 3.3 Variation of leaf-level transpiration in response to distance from river (panel 1), depth to groundwater (panel 2), and top 1 m soil water content (panel 3). No significant relationship was found in linear regressions except for transpiration rate and depth of groundwater in May 2011 (b-2, p = 0.0253*, R^2=0.2754) ($p > 0.05$).

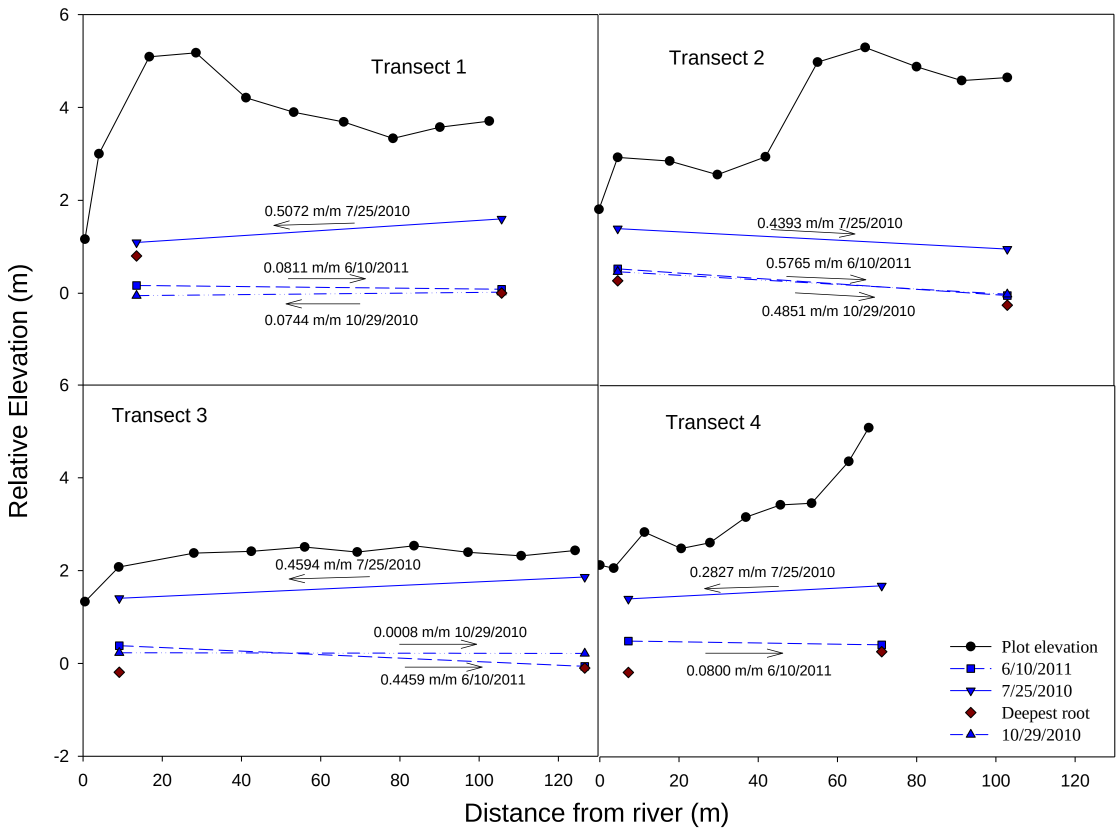

Fig 3.4 Cross-section of four transects with groundwater levels. The shallowest groundwater level (7/25/2010), the detectable deepest groundwater level (6/12/2011), and the groundwater level at the time when river became a losing reach (10/29/2010) are shown for each transect. The elevations are relative within each transect. The arrow points to the direction of water flow. The number above each arrow was the hydraulic gradient between two wells. The largest depth where root exists observed during piezometer installation was plotted (dark red diamond).

Table 3.1 Summary table of phase shift between river stage and groundwater level, near-river (P1) and away-river (P9), together with saturated hydraulic conductivity for each well and soil texture at the point where slug test was conducted. Continuous data in Transect 4 and T1P9 well were not available during the study period. For away-river groundwater level, only Transect 2 and Transect 3 had available data.

Correlation	Time Lag (hr)	Pearson's Correlation Coefficient	Continuous Data	Saturated hydraulic conductivity (m/s)	Sand%
T1 river vs. T1P1 groundwater	1	0.89	March 4th to April 5th 2011	2.90×10^{-5}	71.2
T2 river vs. T2P1 groundwater	0	1	May 17th to June 9th 2011	9.5×10^{-6}	53.4
T3 river vs. T3P1 groundwater	1.25	0.87	Oct 29th to Nov 30th 2010	7.11×10^{-5}	90.6
T2 river vs. T2P9 groundwater	0	0.78	Aug 17th to Aug 30th 2010	1.51×10^{-5}	72.6
T3 river vs. T3P9 groundwater	6	0.52	Oct 15th to Oct 28th 2010	7.48×10^{-5}	34.4

DISCUSSION

In order to understand the spatial variations of *Arundo* water use, leaf-level transpiration was related to distance from river, depth to groundwater, top 1 m soil moisture content and vapor pressure deficit (VPD). Among the variables examined, VPD was the only variable that explained the variation in gas exchange *Arundo* stomatal conductance reduced in response to increased VPD perhaps to prevent cavitation. saltcedar was found to have wide cavitation safety margin and loose stomatal regulation of water loss under high VPD (Horton et al. 2001). The response of *Arundo* stomata to increased VPD suggested that *Arundo* would not maintain a high transpiration rate throughout the whole growing season, which should be considered in riparian water balance calculation.

Arundo transpiration rate did not vary along a water availability gradient during study period. Although transpiration rate was found to decline with increased depth to groundwater in May 2011, no consistent trend was found along other environmental gradients or in other months. During the study period, *Arundo* did not experience soil water deficit. Although top 1 m soil moisture content varied between 6% and 48% in space scale, such a large amount of variation can be partly explained by different soil textures (Kui 2011). A previous study found that *Arundo* had the capability of exploiting water from areas with higher water availability and then transport through its interconnected rhizomes (Kui 2011). Therefore, even though individual plants grew in locations that tended to be wetter or drier, it did not affect *Arundo* transpiration rate.

The mean soil moisture content stayed around 0.2 $mm \cdot mm^{-1}$ from month to month during summer 2011. One possible explanation of this relative stability in soil moisture in spite of likely significant daytime uptake is the possibility of hydraulic lift. Most of *Arundo*'s underground biomass was contained in the top 1 m (Kui 2011). Redistribution of deep soil water or shallow groundwater to upper soil layers would enhance its water and nutrient uptake (Caldwell et al. 1998). However, we did not have direct evidence to support the existence of hydraulic lift. Further study is needed to verify whether *Arundo* has the ability for hydraulic redistribution.

Only knowing vegetation water use pattern is not enough for understanding riparian ecohydrology. The interaction between the groundwater system and stream is a basic link in riparian water cycle. Based on the water level measurements, the Rio Grande River in our study site was losing water into the alluvial aquifer during low flow periods. The hydraulic head gradient in the riverbank reversed after the flood event; water stored in the river bank discharged into the river. Dam storage-release cycle has been recognized to affect the magnitude and direction of groundwater and hyporheic flow (Francis et al. 2010). The diurnal cycle at this site was also influenced by the dam storage-release cycle, accounting for more than 50% of water table fluctuations. Although the groundwater fluctuations induced by vegetation transpiration has been widely observed (Bond et al. 2002, Butler et al. 2007, Martinet et al. 2009), for aquifers hydraulically connected to the surface water, the water table also fluctuates in response to the nearby surface water body (Zhu et al. 2011). In our case, lack of continuous water use data of *Arundo* made it difficult to link water table fluctuation patterns to vegetation water use directly. Considering its dependency on soil moisture rather than groundwater during our investigation (Chapter II), *Arundo* water use is not likely to cause large alterations of groundwater-surface water interaction.

The fast groundwater/river water exchange in our study site indicated that the continuous river flow could benefit the growth of riparian phreatophytes by providing a relatively stable water source into the alluvial aquifer (Duke et al. 2007). Although our stable isotope investigation found that *Arundo* had higher dependency on soil moisture than groundwater, we cannot ignore the positive effects brought by the river on *Arundo* water use, because the soil moisture transpired by *Arundo* in 2011 was recharged by upstream dam release. The supplemental water source extended the growing season, allowing continued transpiration of *Arundo*.

In conclusion, *Arundo* gas exchange variability was not associated with any gradients in soil moisture, depth to groundwater, or distance from the river. During the study period, sharp soil moisture gradient was not observed due to the flood event and the possibility of hydraulic lift. When soil moisture is not limiting, stomata closes in responding to increasing VPD, leading to reduced transpiration rate and higher water use efficiency (Meinzer et al. 1997). The Rio Grande River in our study site was losing water into the alluvial aquifer during low flow periods. The water table in this floodplain was shallow and sensitive to changes in river level. Cross correlation analysis showed that over 50% of the diurnal groundwater fluctuations were caused by river stage changes. *Arundo* water use was not found to have significant influences on daily groundwater fluctuations.

CHAPTER IV

CONCLUSIONS

Naturally occurring stable isotope analysis was used to determine the primary water source of the invasive species *Arundo donax* (L.) in the lower Rio Grande basin. Evidences were found in this study to conclude that *Arundo* used soil moisture as its primary source. The isotope ratio of rhizome water supported the assumption that *Arundo* did not behave like a phreatophyte and its fibrous root system was concentrated in shallow soil layers. Although roots were observed at the depth of groundwater table (4.8 m by personal observation), their presence alone did not necessarily mean root water uptake was significant from this depth.

Flood water, which originated with hurricane driven rainfall, persisted in the soil for a year despite a severe drought, increasing water availability in the unsaturated zone. *Arundo* was not observed to switch sources when soil moisture was available. Due to lack of precipitation inputs in 2011, flood water was the dominant source of water for *Arundo* during drought. If the drought were to continue another year, it is not clear how much longer this water source would last, and whether *Arundo* would use more groundwater to facilitate their growth in a drought. For example, juniper trees growing on the Edwards Plateau were found to change their dominant water sources to groundwater as soil water content declined (McCole and Stern 2007). Mesquite could also shift between groundwater and soil moisture in response to changing climatic and hydrologic conditions (Snyder 1998). Future research is needed to investigate how *Arundo* responds to soil moisture stress.

Arundo transpiration exhibited spatial variability during summer 2011, but trends were not associated with any gradients in soil moisture, depth to groundwater, or distance from the river. Considering the primary water source for *Arundo* in the year of 2011 was deep soil moisture recharged by the flood, one could expect the lack of relationship between transpiration rate and access to groundwater and river water. No trends of transpiration with soil moisture gradient suggested that *Arundo* transpiration rate was not affected by location-to-location soil moisture variations. This was consistent with previous finding that *Arundo* had the capability of exploiting water from areas with greater availability and transporting through its interconnected rhizomes (Kui 2011). The rhizome integration could ameliorate impacts of future water stress on *Arundo* water use, and help it compete with native species. Future research on understanding how both *Arundo* and native species respond to soil and atmospheric water stress could provide further information of the *Arundo* invasion effects on riparian water cycle.

The similarity of isotopic compositions and high correlation coefficient between groundwater and river water indicated that significant exchange between the river and the floodplain. For aquifers hydraulically connected to the surface water, water table fluctuates in response to the nearby surface water body (Zhu et al. 2011). Our results showed that dam storage-release cycle accounted for over 50% of the diurnal groundwater fluctuations. Although groundwater fluctuations could be induced by phreatophyte water use (Bond et al. 2002, Butler et al. 2007, Martinet et al. 2009), *Arundo* had low dependency on groundwater when soil moisture content was sufficient. Therefore, *Arundo* water use was not found to have significant influences on daily groundwater fluctuations during the study period.

Like many other rivers in semiarid/arid regions, the Rio Grande River in our study site was losing water into the alluvial aquifer during low flow periods (Lamontagne et al. 2005, Lite and Stromberg 2005). Water table in floodplain was shallow and subject to changes in river level. The hydraulic head gradient in the riverbank reversed after the flood happened, causing water stored in the river bank to discharge into the river. The upstream dam had large effects on the magnitude and direction of groundwater and hyporheic flow (Francis et al. 2010).

This study was an important step towards understanding the water use pattern of *Arundo* along the Rio Grande River and how it interacts with environmental factors in the riparian zones. The possibility of *Arundo* using groundwater cannot be totally ruled out because there was not a meaningful distinction between groundwater and shallow soil moisture. Given the importance of water resources in lower Rio Grande Valley, calculating the amount of groundwater consumed by *Arundo* may give us insights for invasion management aimed at water conservation. Floodwater from July 2010 persisted in the soil for at least a year despite a severe drought, and became the dominant water source for *Arundo*. Without the flood water, *Arundo* might experience soil water stress with low precipitation input in the year of 2011, and was forced to reduce its transpiration rate. Although *Arundo* performances were negatively affected by flooding in a short time period (Kui 2011), the flood event provided benefits to *Arundo* growth in a longer term. More research should explore how flood frequency and inundation duration affect *Arundo* performance and how that might relate to dam release policies.

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APPENDIX A

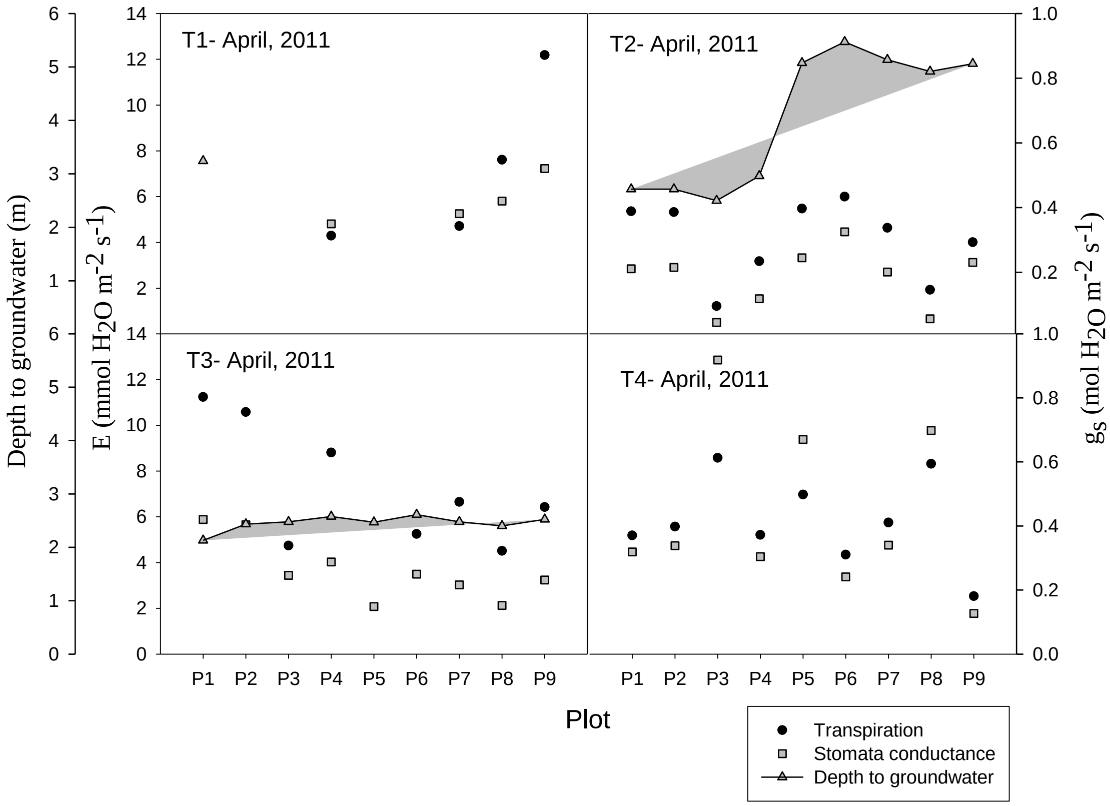

Fig A-1. Individual measurement of leaf level transpiration (black dot), stomatal conductance (gray square) and depth to groundwater (gray triangle) in April, 2011. The away-river groundwater well in Transect 1 and two wells in Transect 4 were dried out during the trip in April.

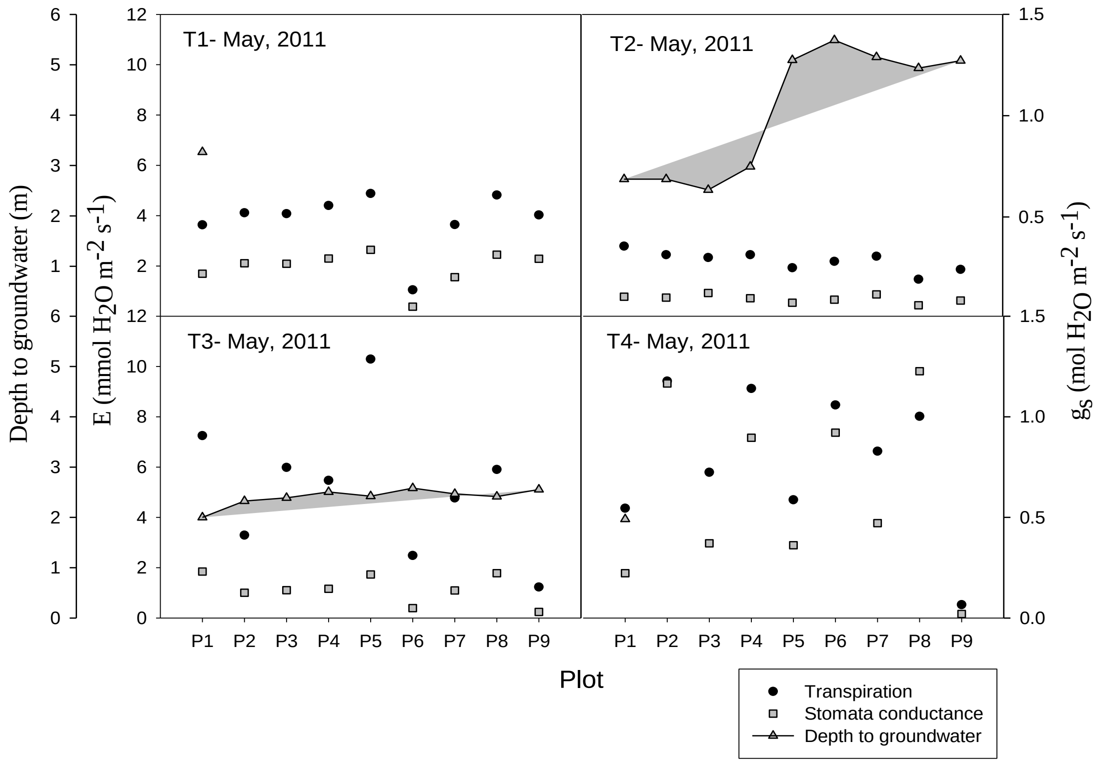

Fig A-2. Individual measurement of leaf level transpiration (black dot), stomatal conductance (gray square) and depth to groundwater (gray triangle) in May, 2011. The away-river groundwater well in Transect 1 and Transect 4 were dried out during the trip in May.

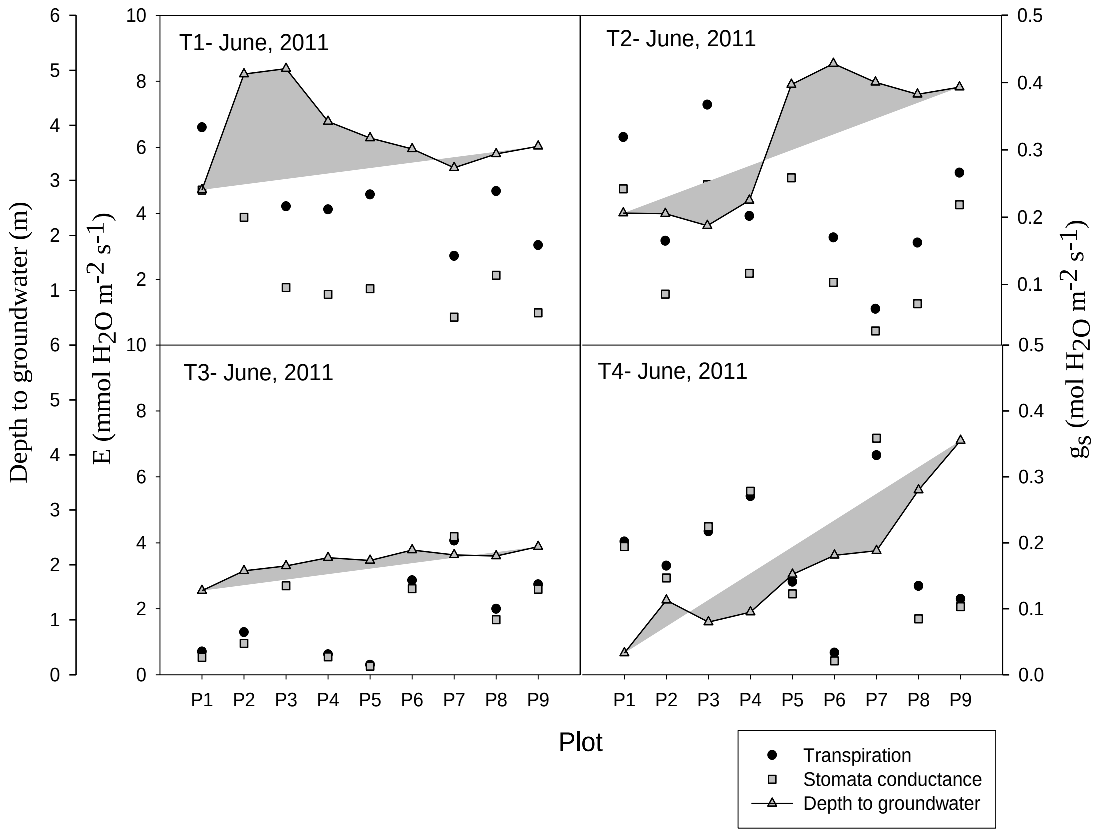

Fig A-3. Individual measurement of leaf level transpiration (black dot), stomatal conductance (gray square) and depth to groundwater (gray triangle) in June, 2011.

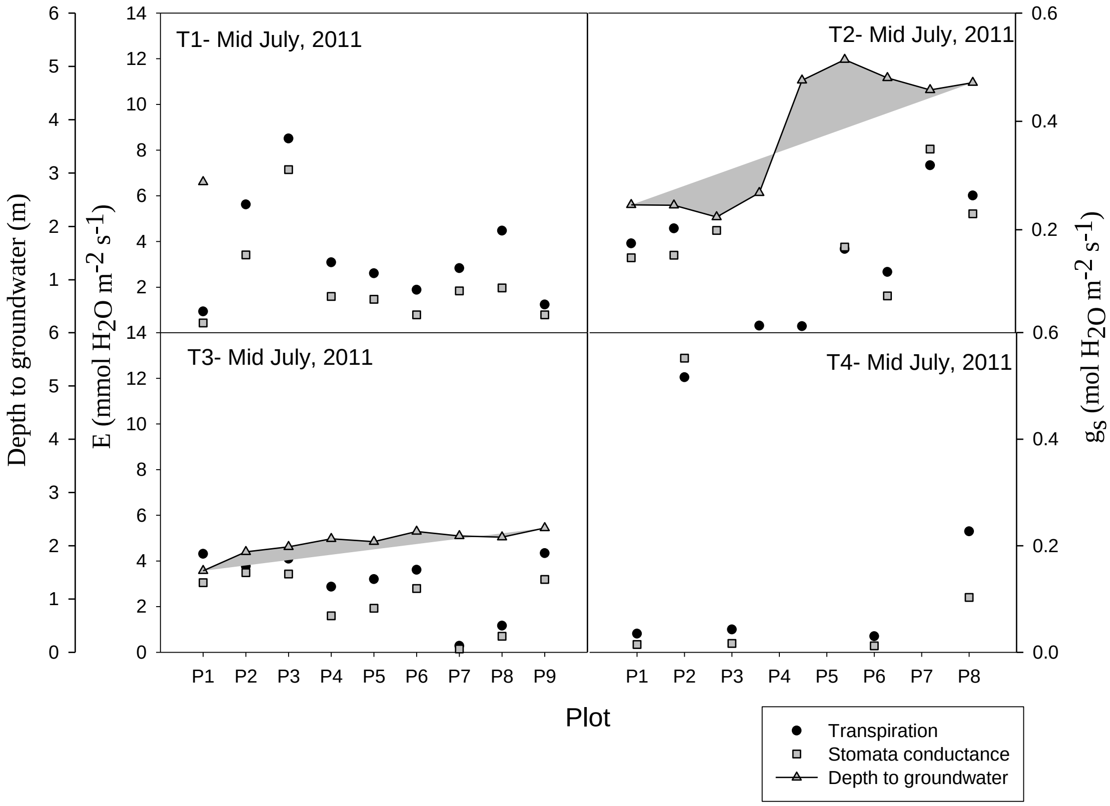

Fig A-4. Individual measurement of leaf level transpiration (black dot), stomatal conductance (gray square) and depth to groundwater (gray triangle) in the middle of July, 2011. The away-river groundwater well in Transect 1 and two wells in Transect 4 were dried out during the trip in the middle of July.

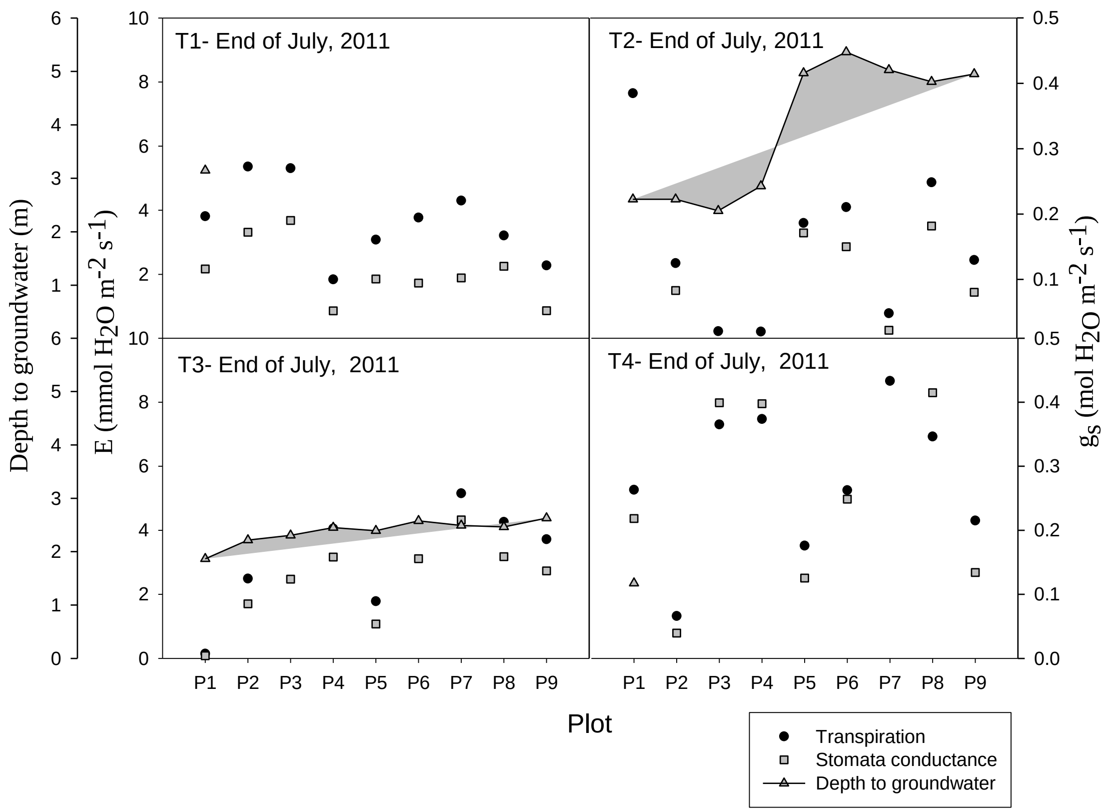

Fig A-5. Individual measurement of leaf level transpiration (black dot), stomatal conductance (gray square) and depth to groundwater (gray triangle) in the end of July, 2011. The away-river groundwater well in Transect 1 and Transect 4 were dried out during the trip in the end of July.

APPENDIX B

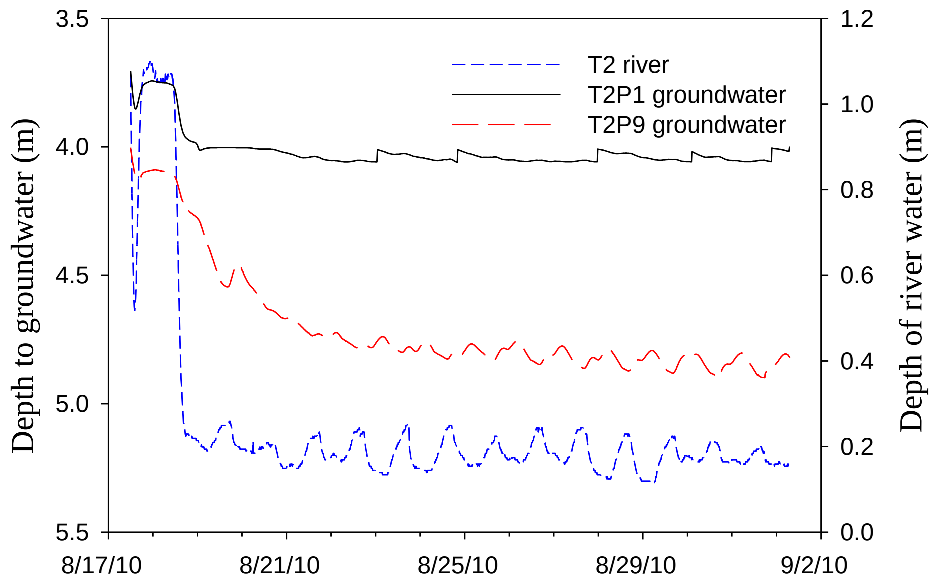

Fig B-1. Groundwater and river time-series data from August 17th, 2010 to August 30th, 2010. The depth to groundwater was recorded from ground to water level. The depth of river water was measured from the end of the sensor to the surface.

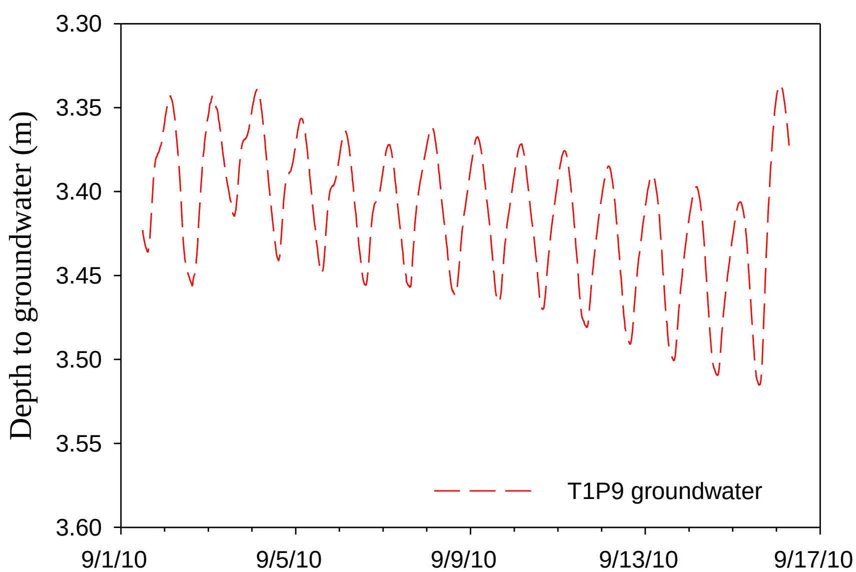

Fig B-2. Groundwater time-series data from September 1st, 2010 to September 16th, 2010. The depth to groundwater was recorded from ground to water level.

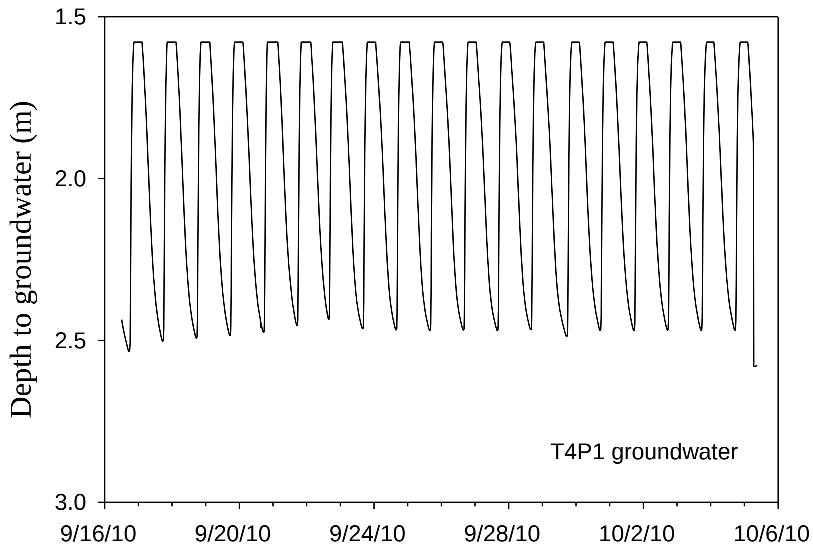

Fig B-3. Groundwater time-series data from September 16th, 2010 to October 5th, 2010. The depth to groundwater was recorded from ground to water level.

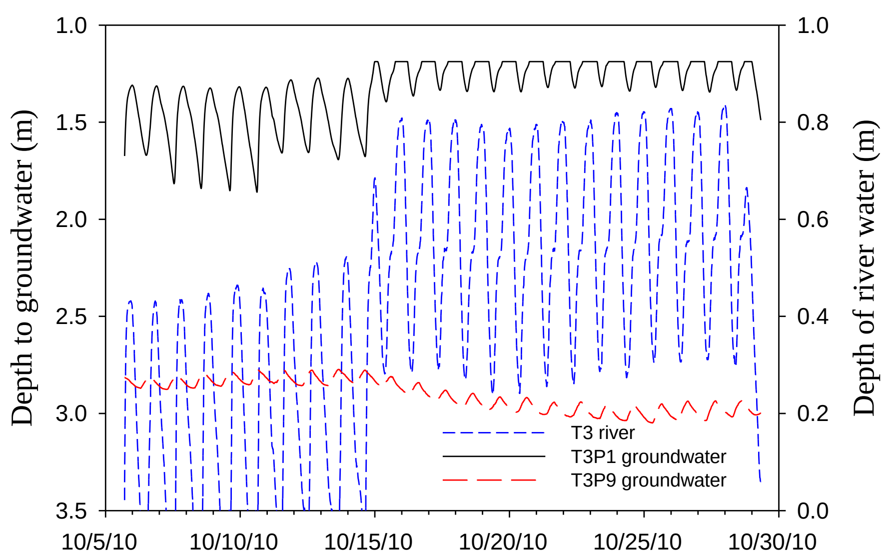

Fig B-4. Groundwater and river time-series data from October 5th, 2010 to October 30th, 2010. The depth to groundwater was recorded from ground to water level. The depth of river water was measured from the end of the sensor to the surface.

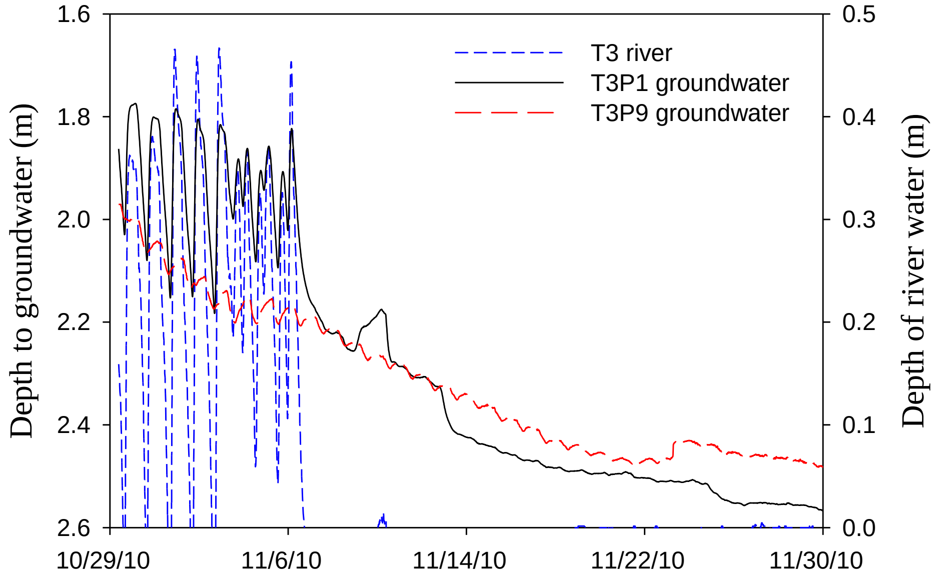

Fig B-5. Groundwater and river time-series data from October 29th, 2010 to Novermber 30th, 2010. The depth to groundwater was recorded from ground to water level. The depth of river water was measured from the end of the sensor to the surface.

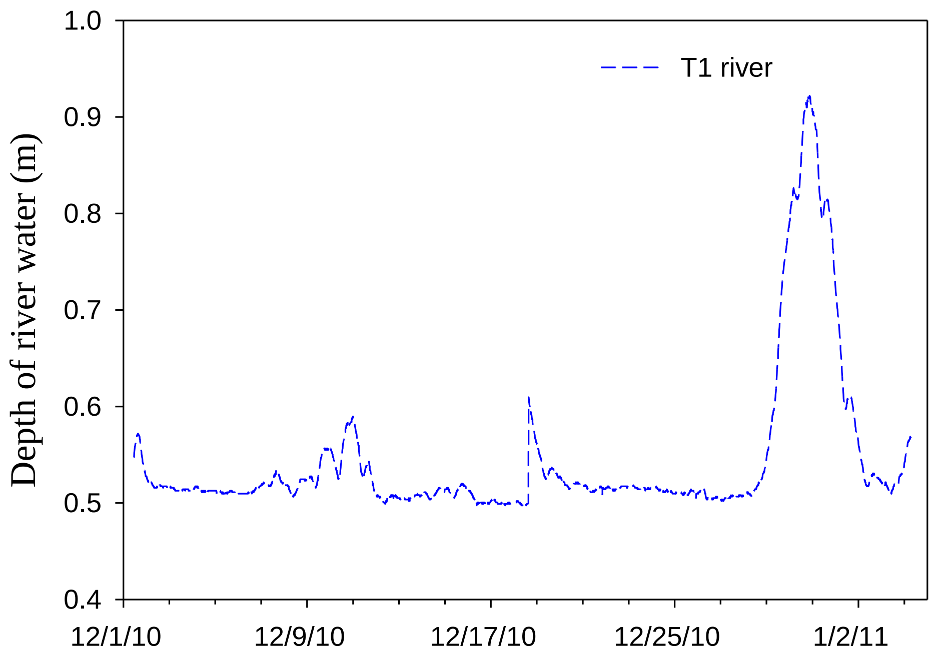

Fig B-6. River time-series data from December 1st, 2010 to January 4th, 2011. The depth of river water was measured from the end of the sensor to the surface.

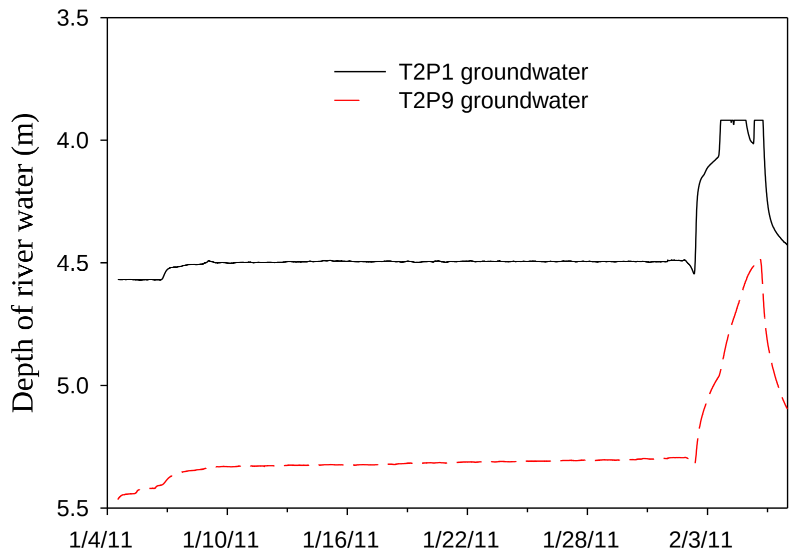

Fig B-7. Groundwater time-series data from January 4th, 2011 to February 7th, 2011. The depth to groundwater was recorded from ground to water level.

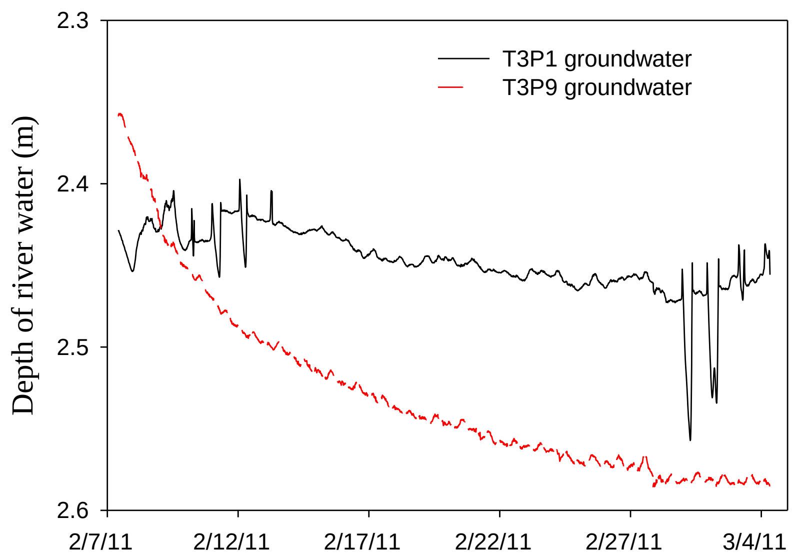

Fig B-8. Groundwater time-series data from February 7th, 2011 to March 4th, 2011. The depth to groundwater was recorded from ground to water level.

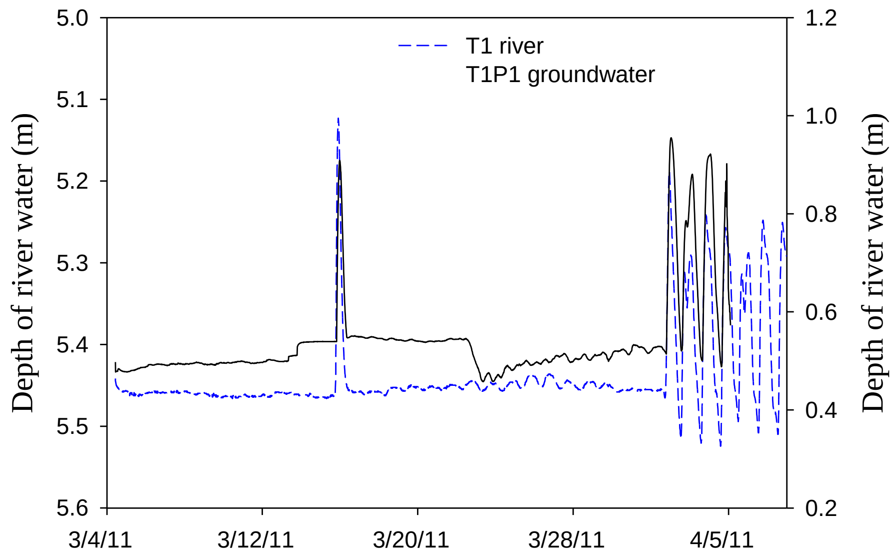

Fig B-9. Groundwater and river time-series data from March 4th, 2011 to April 5th, 2011. The depth to groundwater was recorded from ground to water level. The depth of river water was measured from the end of the sensor to the surface.

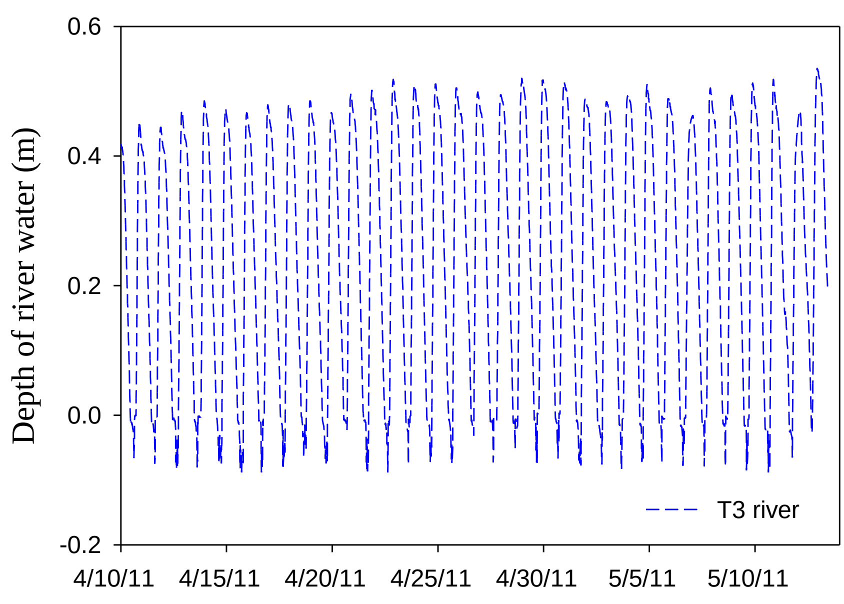

Fig B-10. River time-series data from April 10th, 2011 to May 13th, 2011. The depth of river water was measured from the end of the sensor to the surface.

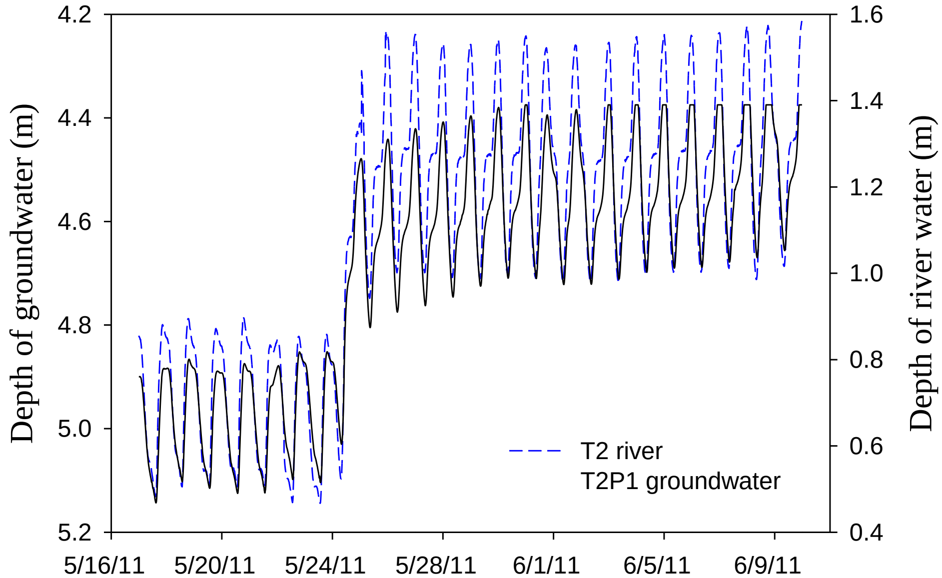

Fig B-11. Groundwater and river time-series data from May 16th, 2011 to June 9th, 2011. The depth to groundwater was recorded from ground to water level. The depth of river water was measured from the end of the sensor to the surface.

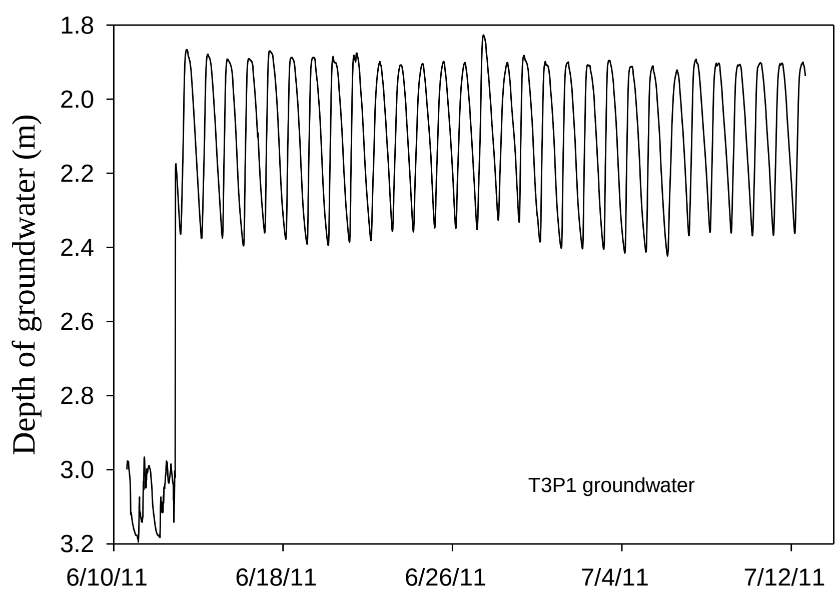

Fig B-12. Groundwater time-series data from June 10th, 2011 to July 13th, 2011. The depth to groundwater was recorded from ground to water level.

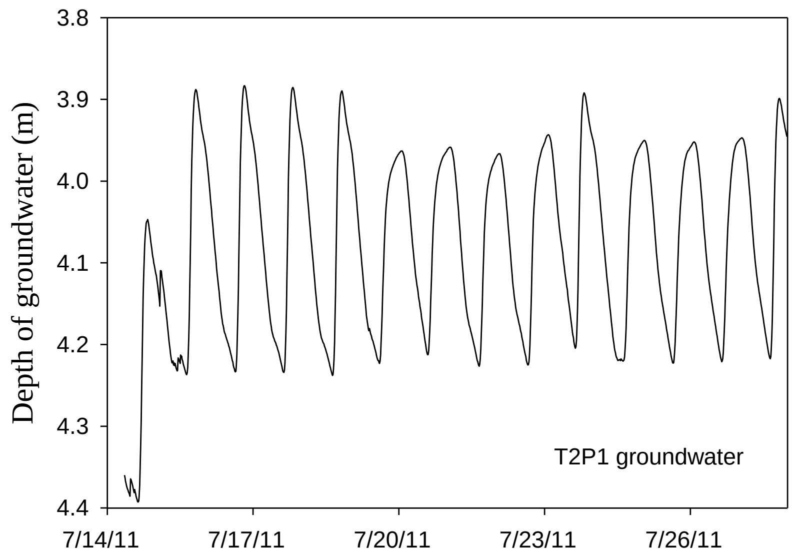

Fig B-13. Groundwater time-series data from July 14th, 2011 to July 27th, 2011. The depth to groundwater was recorded from the top of the well pipe to water level.

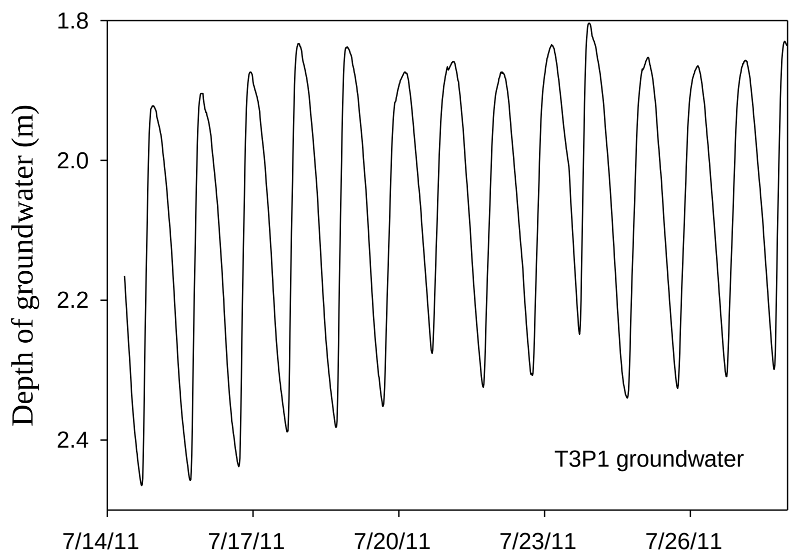

Fig B-14. Groundwater time-series data from July 14th, 2011 to July 27th, 2011. The depth to groundwater was recorded from the top of the well pipe to water level.

APPENDIX C

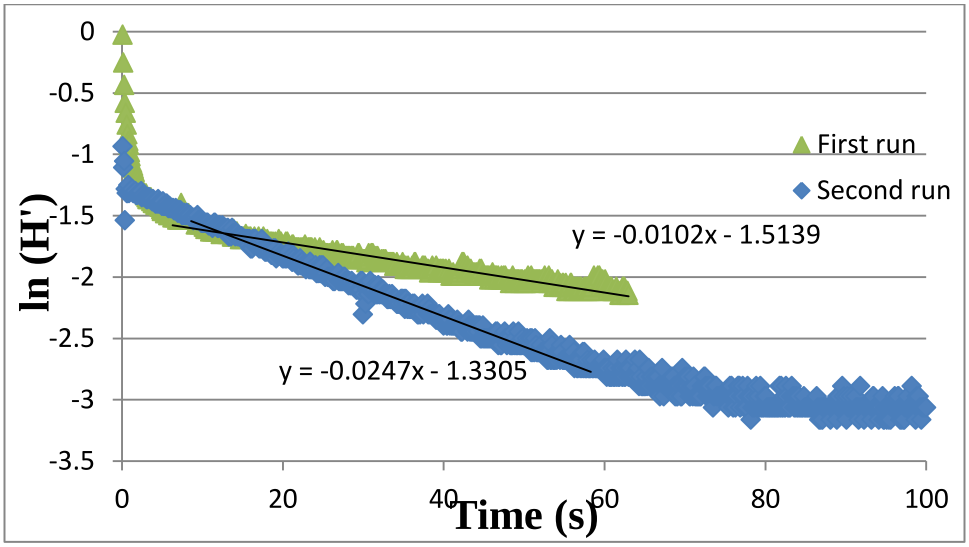

Fig C-1. Groundwater recovery during Slug Tests in near-river groundwater well in Transect 1 (T1P1). Measurement was replicated three times on June 12th, 2011. Two groups of data could be used in analysis. The average hydraulic conductivity value for this well was estimated to be 2.9×10^{-5} m/s.

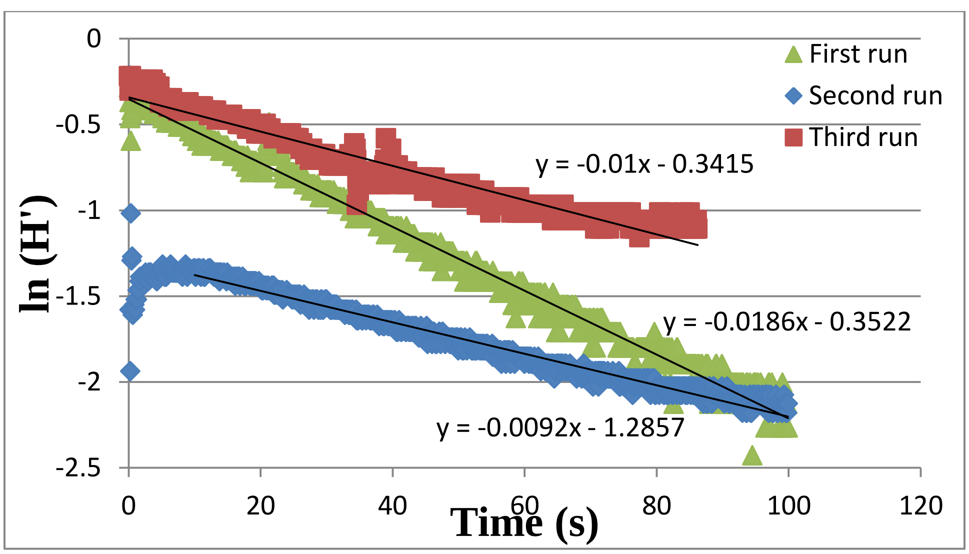

Fig C-2. Groundwater recovery during Slug Tests in away-river groundwater well in Transect 1 (T1P9). Measurement was replicated three times on June 12th, 2011. The average hydraulic conductivity value for this well was estimated to be 2.09×10^{-5} m/s.

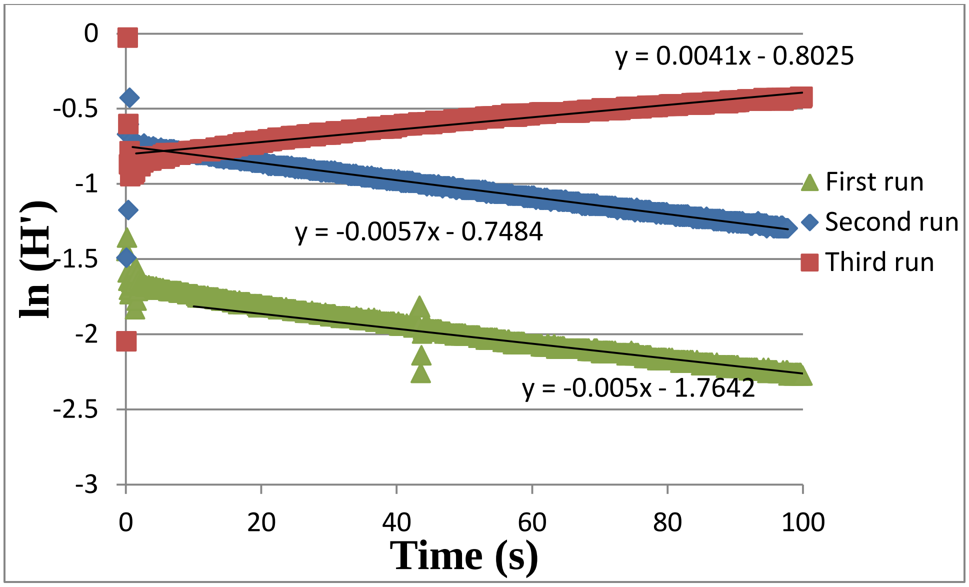

Fig C-3. Groundwater recovery during Slug Tests in near-river groundwater well in Transect 1 (T2P1). Measurement was replicated three times on June 12th 2011, with the third run a slug extraction test. The average hydraulic conductivity value for this well was estimated to be 9.5×10^{-6} m/s.

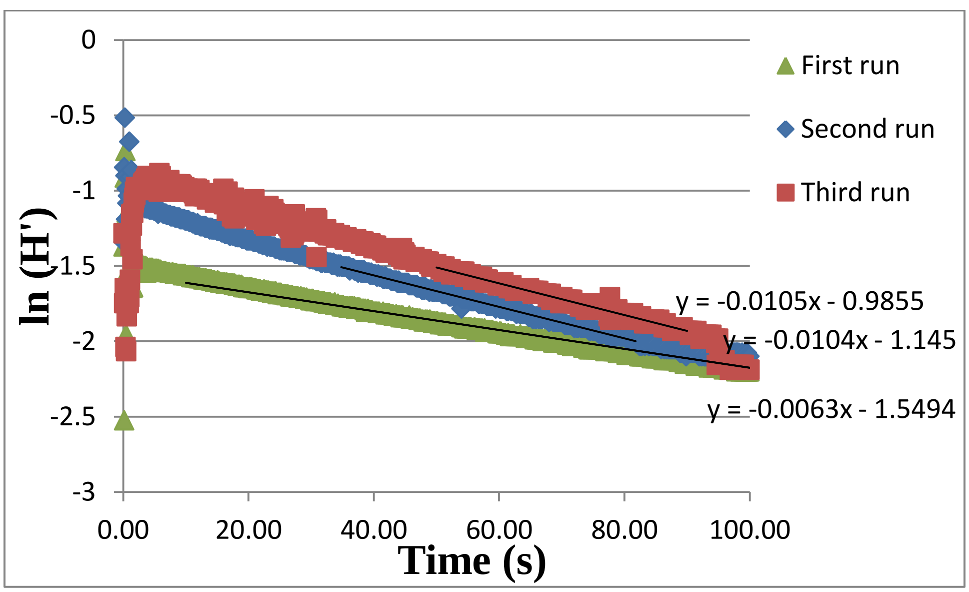

Fig C-4. Groundwater recovery during Slug Tests in away-river groundwater well in Transect 2 (T2P9). Measurement was replicated three times on June 12th, 2011. The average hydraulic conductivity value for this well was estimated to be 1.51×10^{-5} m/s.

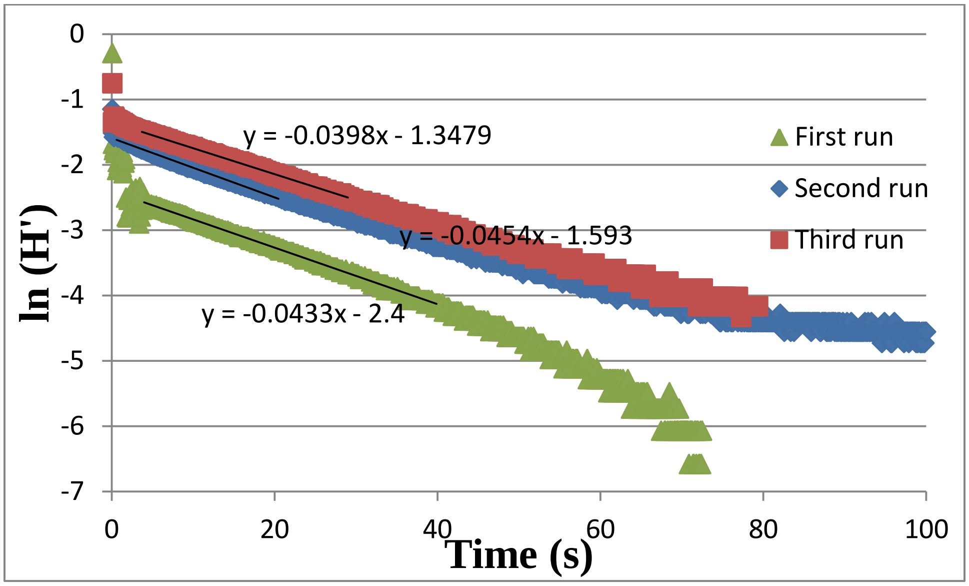

Fig C-5. Groundwater recovery during Slug Tests in near-river groundwater well in Transect 3 (T3P1). Measurement was replicated three times on July 13th, 2011. The average hydraulic conductivity value for this well was estimated to be 7.11×10^{-5} m/s.

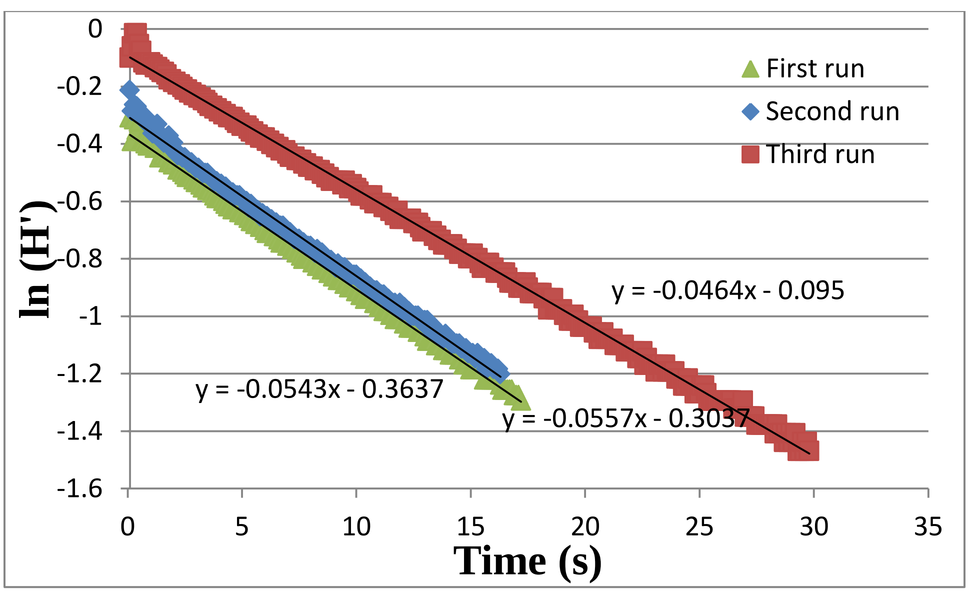

Fig C-6. Groundwater recovery during Slug Tests in away-river groundwater well in Transect 3 (T3P9). Measurement was replicated three times on July 13th, 2011. The average hydraulic conductivity value for this well was estimated to be 7.48×10^{-5} m/s.

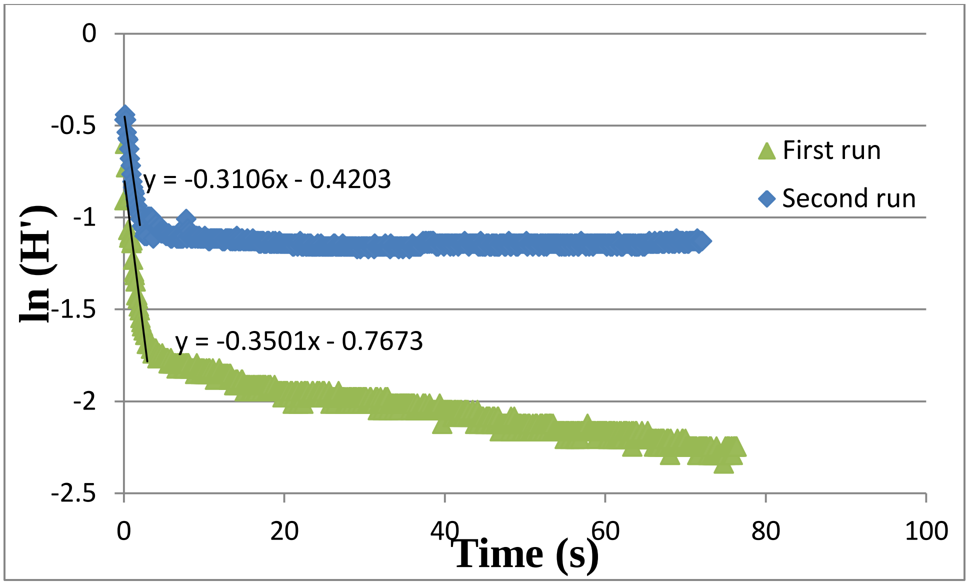

Fig C-7. Groundwater recovery during Slug Tests in near-river groundwater well in Transect 4 (T4P1). Measurement was replicated three times on June 13th, 2011. Two groups of data could be used in analysis. The average hydraulic conductivity value for this well was estimated to be 5.49×10^{-4} m/s.

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