Sustainability and Vulnerability of Colorado River Delta Riparian Habitat Under Different Climate Change, Environmental Flow, and Agricultural Water Management Scenarios

Agreement Number: R14AP00144

Final Report: June 30, 2017

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Executive Summary

Riparian ecosystems in western North American deserts, such as the lower Colorado River floodplain, provide tremendous environmental and cultural benefits despite comprising a small portion of the overall landscape. Agricultural land conversion, river regulation, consumptive water use, and introduction of non-native species have decreased the extent of riparian area and marginalized habitat quality for native fauna. Public and private interest has recently promoted efforts to preserve and enhance the riparian corridor along the Colorado River in both the United States and Mexico. However, continued human use of the over-allocated river and drought due to climate change signify increasing vulnerability of remnant and restored riparian habitat in the lower Colorado River. Environmental flow deliveries have the potential to mitigate potential groundwater declines caused by water management changes and climate change.

The goal of this project is to determine the extent of riparian habitat in the central region of the Colorado River in Mexico (Reach 4) that can be supported by groundwater under scenarios of altered water management, climate change, and environmental flow deliveries. We used an existing groundwater model (MODFLOW) and remote sensing data to predict depth to groundwater under different scenarios, and then applied results from a depth to groundwater threshold analysis for riparian habitat types to predict the spatial extent of habitat.

We first conducted an analysis of historic and existing groundwater conditions in Reach 4 of the Colorado River Delta to assess groundwater requirements specifically for native riparian vegetation in the Delta. The analysis determined a depth to groundwater threshold of 2.5 m for cottonwood and willow habitat (*Populus freemontii* and *Salix* spp.), and a threshold of 4.0 m for mesquite bosque (*Prosopis glandulosa* and *P. pubescens*). We considered non-riparian habitat to have a depth to groundwater threshold of >4.0 m, while the aquatic habitat (open water and marsh) threshold was <0 m, based on literature values.

To predict the spatial extent of the above habitat types under different scenarios, we used the following groundwater model input categories: 1) environmental flows, 2) agricultural return flows, 3) upstream subsurface inflows, and 4) evapotranspiration. Model inputs at varying levels of baseline/none, low/decreased, and high/increased were developed for each category, based on a set of potential and realistic drivers. For example, drivers of agricultural return flow decreases include irrigation canal lining, fallowing, water transfers, or groundwater pumping, while increases could be caused by a shift to more water-intensive crop types. Riparian corridor evapotranspiration could be impacted by vegetation composition change, saltcedar defoliation from the saltcedar beetle, and warming temperatures. We modeled a total of 14 scenarios using different input combinations.

The modeled scenarios' results show that changes in agricultural return flows are the biggest driver of groundwater increases and decreases and thus riparian habitat potential in Reach 4 and Reach 4 restoration areas (see table and figures on page vi). Changes in evapotranspiration driven by saltcedar beetle defoliation and vegetation composition change did not affect groundwater levels and habitat extent. Changes in upstream subsurface inflows had some impact on groundwater and habitat support, particularly in the upper portion of Reach 4. Environmental flow deliveries significantly affected groundwater levels. Modeled scenarios of low and high levels of environmental flows coupled with decreased agricultural flows and decreased upstream inflows had riparian habitat extent similar to the baseline scenario. Thus, model results determined that environmental flows can mitigate negative impacts of groundwater decline caused by decreased agricultural return flows and decreased upstream inflows.

Our results suggest that riparian habitat in the central Delta region is highly vulnerable to irrigation district agricultural water management decisions, which are in turn influenced by larger-scale national and binational water management decisions. Colorado River flow reductions over the past decade have been attributed to climate change (Udall and Overpeck, 2017). With Colorado River flow declines likely to exceed 20-30% or more by 2050, basin-wide shortages that impact Mexico's Colorado River water

allocation are almost certain. While it is uncertain exactly how water shortages within the Mexicali Valley would be implemented, it is likely that agricultural return flows would be reduced to some extent due to changes in production driven by water availability.

However, environmental flows have the potential to mitigate habitat loss caused by decreased agricultural return flows and decreased upstream inflows. Our results showed that a small amount of riparian habitat will be resilient to groundwater declines; however, restoration site managers could prevent future loss by delivering existing water allocations to restoration areas and acquiring additional water for environmental flows. In particular, if irrigation efficiency projects are planned for the region, reallocating water saved from such projects to environmental flows could mitigate potential habitat loss.

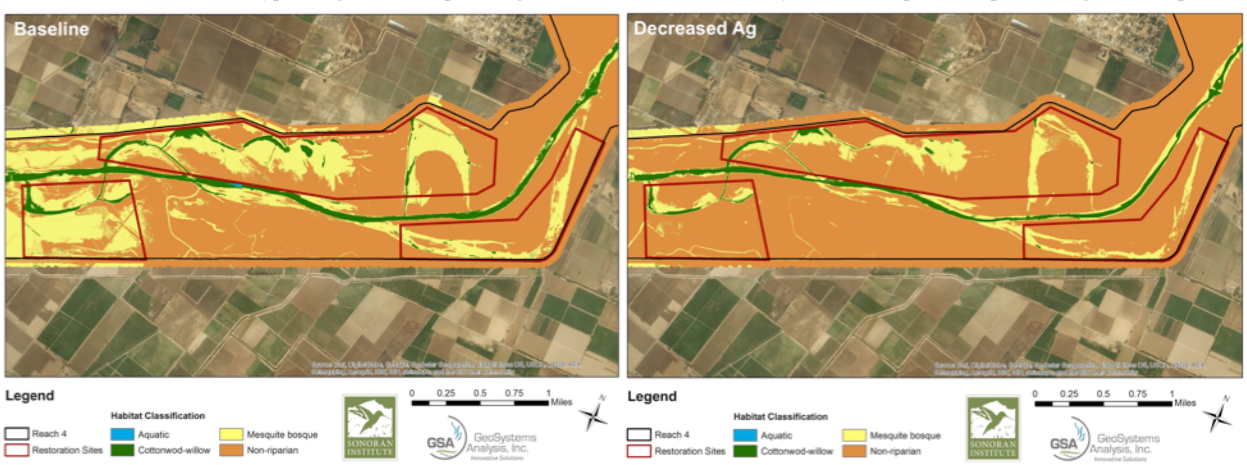
Government agency stakeholders involved in restoration efforts should be aware of riparian habitat vulnerability to groundwater declines and the need for dedicated, protected environmental flows for the region. Additionally, due to Reach 4 (and likely other areas in the lower Colorado River floodplain) riparian habitat sensitivity to groundwater declines, continuous hydrological and vegetation monitoring is needed to assess how groundwater changes are impacting vegetation on the ground. In the case of declining groundwater tables and initial signs of habitat loss, monitoring results will need to be assessed quickly and environmental flows delivered in a timely manner to mitigate habitat loss. One suggestion is to create water management scenarios for different levels of groundwater decline so that water delivery plans are already established and ready for quick implementation.

Results of this project can be used as a decision-making support tool for water managers in the U.S. and Mexico; specifically, water managers are provided with the scientific information needed to assess the ability of Colorado River Delta environmental flows to mitigate impacts of groundwater declines on riparian habitat to increase ecosystem resilience. Additionally, the project can provide a framework for analysis of other river reaches in the U.S. and Mexico with groundwater-dependent habitat.

Habitat Type	**Acres of Habitat Under Each Scenario**				
	Baseline	Increased ag. return flows	Decreased ag. return flows	Low e-flows	Decreased ag. return flows + low e-flows
Aquatic	1	95	0	12	1
Cottonwood-willow	337	1078	228	496	306
Mesquite bosque	1345	1849	580	1830	1171
Non-riparian	4995	3655	5869	4339	5198

Above: *Summary table of habitat type acreage in Reach 4 for 5 representative modeled scenarios (out of 14). (Ag. = agricultural; e-flows = environmental flows).*

Below: *Extent of riparian habitat in baseline (left) and decreased agricultural return flows (right) scenarios in Laguna Grande Restoration Area. Habitat types: light blue=aquatic; green=cottonwood-willow; yellow=mesquite bosque; orange=non-riparian.*



Project Technical Report

1. Introduction

1.1. Project Background

Less than 100 years ago, the Colorado River Delta was a 3,000-square mile expanse of riparian, marsh, and estuarine habitat that supported a multitude of plant, bird, and marine life. Since the mid-1900s however, the Colorado River has not regularly flowed to the sea due to upstream dams and diversions, causing the Delta to gradually be reduced to less than 10 percent of its original size. Despite the lack of surface flows however, the Colorado River riparian corridor in Mexico has proven to be ecologically resilient. Floods in the 1980s and 90s in the region brought back large swaths of native riparian habitat, which still persist today in some areas along the river. Reach 4 (see Figure 1) is one such stretch of the river where shallow groundwater conditions have maintained populations of cottonwood and willow trees. Although flooding events are the primary driver for native tree establishment in this area, it is the local aquifer, which is fed by surface and subsurface agricultural return flows, that sustains the habitat. Typically, there is water in the river channel year-round in Reach 4 due to subsurface agricultural flows, creating vital open-water and wetland habitat within the agricultural landscape.

The riparian, marsh, and open-water areas found in Reach 4 provide critical habitat for both migratory and resident riparian bird species, many of which are protected species or are targets for continent-wide conservation plans. Migratory bird species such as Swainson's hawk, yellow warbler, western tanager, Wilson's warbler, Bell's vireo, and the willow flycatcher find food and cover in the riparian corridor, making it an essential stopover site on the Pacific Flyway migratory route. Riparian generalist and specialist species such as the vermillion flycatcher, yellow-billed cuckoo, blue grosbeak, yellow-breasted chat, and ridgeway rail utilize this area for breeding grounds and as a source of food in the summer months. Other imperiled or endangered species such as the lowland leopard frog and bobcat have been sited several times in restored riparian habitat areas in Reach 4. Due to its ecological importance, the riparian corridor and Reach 4 in particular have been designated as conservation priorities by a binational team of U.S. and Mexican government officials, conservation organizations, and scientists from both the U.S. and Mexico.

Figure 1. Map of the Colorado River riparian corridor in the Delta. Reach 4 is a narrow section of the Colorado River floodplain located in the central Delta region.

Efforts to dedicate environmental flows and restore additional native habitat to the riparian corridor in the Delta have increased in recent years. In 2008, Sonoran Institute and partner organization Pronatura Noroeste secured 1400 acres in Reach 4 for restoration purposes through a land concession agreement with the Mexican government. The land concession, known as the Laguna Grande Restoration Area (see Figure 1), contains open-water habitat and large stands of remnant riparian habitat. Since 2010, Sonoran Institute has restored over 500 acres of riparian habitat in the Laguna Grande site, making this area the densest and largest area of cottonwood and willow habitat in the Colorado River riparian corridor in Mexico.

In November 2012, the U.S. and Mexico passed a binational agreement (known as Minute 319) to dedicate environmental flows to the Colorado River in Mexico and expand restoration efforts

along the riparian corridor. Under the agreement, in 2014 the U.S. and Mexico provided a one-time dedication of 105,392 acre-feet of water as a pulse flow to the Colorado River in Mexico to mimic natural flood events. A coalition of conservation organizations is providing 52,696 acre-feet of water as a steady base flow to the river over the 5-year term. Reach 4 is a primary target for environmental flows and restoration activities under Minute 319. More than two-thirds of the total area designated for active restoration under Minute 319 is located in Reach 4 due to its ability to sustain native riparian habitat. The area has experienced increased surface water presence due to the release of the pulse flow in spring of 2014, and Minute 319 restoration activities are underway. Initial impacts of water deliveries and habitat restoration are being documented through the Minute 319 monitoring program, and models are being developed to determine how much water is required to expand the presence of native riparian ecosystems.

Yet, despite these substantial restoration advances in the past seven years, the riparian corridor in the Delta is increasingly vulnerable to habitat degradation through the lowering of the groundwater table due to drought and alternate agricultural water management actions. Hinojosa et al. (2013) note that the reduction of flows to the riparian corridor in the Delta due to a regional drought since 2002 has led to a decline of habitat quality (a reduction of cottonwood and willow populations) which has in turn led to the decline of many riparian-specific bird species. Decreased river flows due to climate change, out-of-basin water transfers, and the lining of canals are expected to lead to increased depth to groundwater and salinity in local and regional aquifers that affect the Reach 4 area (Hinojosa et al. 2013).

Provided the significant anthropogenic effects on the sustainability of riparian habitat in Reach 4, this area is an excellent location for a pilot project to model the spatial extent of native riparian vegetation that could be supported given various environmental flow, agricultural management, and climate change scenarios. For this project, we utilized a groundwater model developed from the Minute 319 monitoring effort to estimate the spatial extent of the riparian corridor in Reach 4 that could support native riparian vegetation under scenarios representing a range of stress on groundwater resources.

1.2. Related Studies on Riparian Vegetation Dependence on Groundwater

Groundwater depth is dependent on the interaction of surface water, adjacent aquifer depth and flow, and local topography. Surface water (in-stream flow) provides a constant source of infiltration, which can increase the groundwater elevation in adjacent riparian areas. The aquifer depth along the lower Colorado River is largely driven by irrigation for agriculture. Because surface (basin, border, or furrow) irrigation is the primary water delivery method, much of applied water is not lost from the system due to evapotranspiration, but instead returns to the aquifer after percolation through the root zone. Percolated water may flow toward the riparian corridor and/or cause groundwater mounding to within the riparian tree root zone (GeoSystems Analysis, Inc. 2014).

In addition, the local depth to groundwater and presence of groundwater-supported springs is dependent on topography across the riparian corridor, which varies based on the presence of historic backwater channels. Since riparian trees use groundwater that rises into the capillary fringe (Glenn et al. 2013), groundwater elevation is in turn reduced through phreatophytic

vegetation transpiration. The amount of water removed from the system is determined by reference evapotranspiration, vegetation composition, and seasonal changes in water use.

Native riparian trees in the desert Southwest depend on periodic flooding to deposit sediment and provide moist, bares soils for germination and seedling establishment (e.g. Stromberg 1993, Nagler et al. 2005). Survival of seedlings is governed by the rate of groundwater decline after germination, with a slower groundwater decline resulting in higher survival (Shafroth et al. 2000). Once established, long-term survival of trees is dependent on the presence of groundwater within the rooting zone so that trees can utilize water from the capillary fringe (Glenn et al. 2013), the saturated zone immediately above the water table. Native Goodding's willow can root up to 3 m below ground surface, and Fremont cottonwood roots can extend to approximately 5 m below ground surface (Horton et al. 2003). However, the ability of these species to out-compete non-native saltcedar depends on shallower groundwater. In other riparian corridors, the competitive advantage shifts from native to non-native species as depth to groundwater increases (e.g. Gries et al. 2003), and groundwater depth of greater than 2.6 m below ground surface is generalized to favor non-native species (Lite and Stromberg 2005). Once groundwater depth is greater than 3 m, native trees are at a severe disadvantage to non-natives (Stromberg et al. 2006, Horton et al. 2001).

Surface water or saturated soils not only support riparian vegetation, but they are also key attributes for many native animal species. For example, they are key attributes of Southwestern willow flycatcher (*Empidonax traillii extimus*) habitat, and increase habitat quality for numerous other species as well (Bureau of Reclamation 2004, Johnson et al. 2007, McLeod et al. 2008a, McLeod et al. 2008b).

Groundwater depth in riparian corridors is driven by gains from or loss to adjacent rivers, water consumption by phreatophytes, and anthropogenic effects (e.g. irrigation percolation, groundwater pumping, or groundwater drainage). The negative impacts of dewatering on riparian systems are well documented; as surface water and groundwater are removed from the riparian area, the ecological health of the riparian corridor declines (e.g. Stromberg et al. 1996). These impacts have recently been observed in the lower Colorado River basin: groundwater pumping in the limitrophe region (upper Delta) has lowered the groundwater elevation and degraded habitat value of Hunter's Hole (http://www.lcrmscp.gov/conservation/hunters_hole.html). Groundwater declines on the lower Gila River have recently compromised many remnant native vegetation areas (GeoSystems Analysis, Inc. 2012). Groundwater utilization by farmers and municipalities is often driven by the availability of surface water. If less surface water is available for irrigation in the Colorado River floodplain due to decreased yield, as likely for the Colorado River basin (Bureau of Reclamation 2012), it is likely that farmers will increasingly rely on groundwater to satisfy irrigation needs. Alternatively, as surface water resources become more limiting, farmers might be encouraged to increase irrigation efficiency, which is achieved by reducing the amount of water while maintaining production. Unfortunately, increased irrigation efficiency does not necessarily improve riparian or aquatic habitat conditions. In areas where the riparian corridor is dependent on return flows resulting from excessive irrigation and percolation, such as the riparian corridor in Reach 4 of the Colorado River, increased irrigation efficiency can degrade native habitat (e.g. Zhao et al. 2013).

1.3. Project Goals

Although much information is available in the literature on the effects of groundwater depth on native riparian trees, the information has been obtained primarily in other riparian areas, such as the San Pedro River in southeast Arizona. Due to the fact that different environmental conditions (specifically higher temperatures resulting in increased evapotranspirative demand) may result in different groundwater thresholds (e.g. shallower groundwater requirement), we assessed groundwater requirements for native vegetation specifically in Reach 4 of the Delta by correlating pre-pulse flow groundwater elevation with the locations of remnant riparian vegetation. The analysis of historic and existing groundwater conditions allowed for the refinement of threshold depth to groundwater for native riparian vegetation.

We used a groundwater model (MODFLOW) to determine how depth to groundwater in Reach 4 of the Colorado River in Mexico varies due to: 1) environmental flows, 2) agricultural return flows, 3) upstream subsurface inflows, and 4) evapotranspiration. We used results from the groundwater model and the depth to groundwater threshold analysis to determine the extent of riparian habitat that would be supported by groundwater under the different scenarios. Riparian habitat types included aquatic (open water and marsh), cottonwood-willow (*Populus freemontii* and *Salix* spp.), and mesquite bosque (*Prosopis glandulosa* and *P. pubescens*).

Project results can be used as a decision-making support tool for water managers in the U.S. and Mexico; specifically, water managers will be provided the scientific information needed to assess the ability of Colorado River Delta environmental flows to mitigate impacts of groundwater declines on riparian habitat to increase ecosystem resilience. Additionally, the project can provide a framework for analysis of other river reaches in the US and Mexico.

2. Analysis of Historic and Existing Conditions

We conducted an analysis of historic and existing groundwater conditions in Reach 4 of the Colorado River Delta to assess groundwater requirements specifically for native vegetation in the Delta, which may be different than riparian areas previously studied. Our goal was to use realistic groundwater thresholds based on Reach 4 groundwater and vegetation data (Task 1) to spatially assess groundwater support for riparian habitat under different water management and climate change scenarios (Task 2).

2.1. Literature Review

The first aspect of the historic and existing conditions analysis consisted of a literature review on groundwater and riparian vegetation dynamics and factors influencing those dynamics. A brief summary of the literature review as related specifically to development of this task is presented below; an extensive literature review was also conducted to develop groundwater model inputs (see Task 2). A detailed annotated bibliography for Task 1 and Task 2 research is provided in Appendix 1.

Various depth to groundwater thresholds for cottonwood and willow have been presented in the literature. Stromberg (2013) documented rooting depths of 2.1 m for Fremont cottonwood and

Goodding's willow. Similarly, Merritt and Bateman (2012) documented that the frequency of cottonwood and willow decreased dramatically at a depth to groundwater of 2 m. Lite and Stromberg (2005) documented that cottonwood outcompeted saltcedar on the San Pedro River in Arizona when depth to groundwater was less than 2.6 m and varied by less than 0.5 m during the year. However, other studies have suggested cottonwood and willow threshold groundwater depths of 3 m (Horton et al. 2001), 4 m (Glenn and Nagler 2005), or even 5.1 m (Horton et al. 2003).

Per Hultine et al. (2010a), cottonwood and willow also exhibit different sensitivity to groundwater fluctuations; in this study, cottonwood was more sensitive to large annual groundwater fluctuations, while willows were more sensitive to longer-term groundwater reductions. Groundwater threshold depths of 1 m (sandy soils) or 1.5 m (finer-grained soils) have been presented (Caplan et al. 2013). The variability in these literature values for depth to groundwater thresholds highlights the need to develop revised depth to groundwater thresholds specifically for this project.

2.2. Groundwater Threshold Analysis

For the second aspect of the analysis, we correlated pre-pulse flow groundwater elevation with locations of remnant riparian vegetation to determine groundwater thresholds for different habitat types in the Delta. The premise of this analysis is that existing vegetation has withstood environmental conditions since the last significant pulse flow, which occurred in 2002. A major assumption for this analysis is that no new riparian tree recruitment has occurred since the last flow event. Very specific conditions are required for recruitment of these species. Specifically, bare, moist soils must be present during the period of seed dispersal (generally mid-spring to mid-summer), with groundwater declining at a rate that allows seedling roots to follow the capillary fringe (generally less than 3 cm/day; Bhattacharjee et al. 2006). These conditions are not currently present in the Delta; significant peak flows would be required to scour vegetation and provide a slow recession rate for new seedling establishment. Given the lack of recent flows (Hinojosa-Huerta et al. 2013), we feel that it is a relatively safe assumption that existing cottonwood and willow trees outside of active restoration areas were established during this flow, and had to withstand groundwater conditions since, at least up to the point of Minute 319 ecological flow deliveries.

For this analysis, we used available groundwater data from 2002 to 2015 to determine the period with the greatest depth to groundwater, and then found maximum groundwater depth for each piezometer during the peak of the growing season (May – September). The maximum depths to groundwater were then overlaid with existing vegetation maps of Reach 4 based on remote sensing data to estimate depth to groundwater thresholds by habitat type for Reach 4.

2.2.1. Groundwater analysis methods

A total of 39 piezometers were installed in Reach 4 from 2005 to 2014 (see Figure 2 and Figure 3). Twenty-five piezometers were installed between April 2005 and April 2006 (RC1-RC25); two additional piezometers (RC 28 and RC29) were installed in mid 2010; and eight piezometers (CH1-CH8) were installed in 2014 for hydrological monitoring during the pulse flow. Additional piezometers were installed by Sonoran Institute in the Laguna Grande restoration area from 2010-2014 (green points in Figure 3).

To complete this analysis, we requested depth to groundwater information for the 25 piezometers installed in the middle and lower portions of Reach 4 and upper Reach 5 between April 2005 and April 2006. We selected these piezometers because they offer the most complete historic analysis of piezometer data in Reach 4 and include groundwater data prior to irrigation of trees in the Reach 4 restoration sites, which began in 2010. Thus, the groundwater analysis only encompassed lower Reach 4, as piezometers in the upper portion were installed in 2014, the year of the pulse flow delivery. 2014 data show the response to the pulse flow, and would not reflect accurate historic conditions. To facilitate analysis of groundwater trends, piezometers were grouped into eight transects of two to four piezometers. Five transects (eighteen piezometers) are within Reach 4, and three transects (nine piezometers) are within Reach 5.

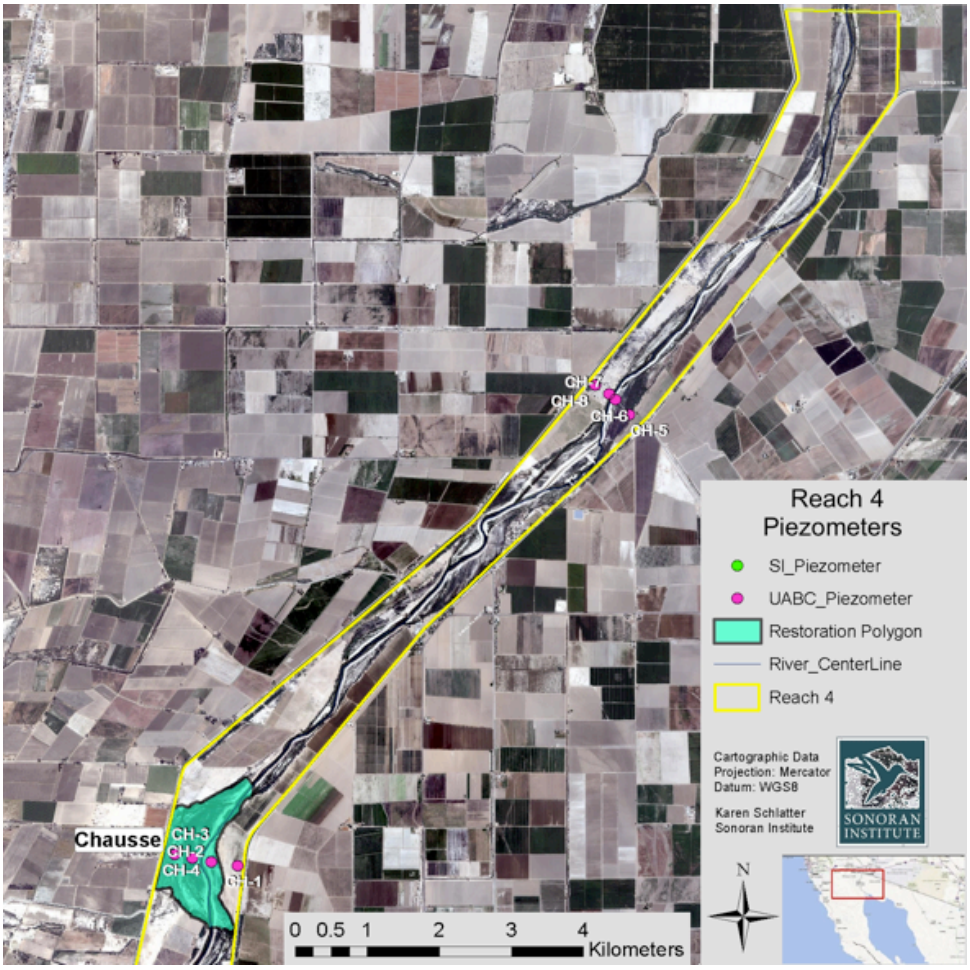


Figure 2. Piezometer locations in upper Reach 4 (installed in 2014).

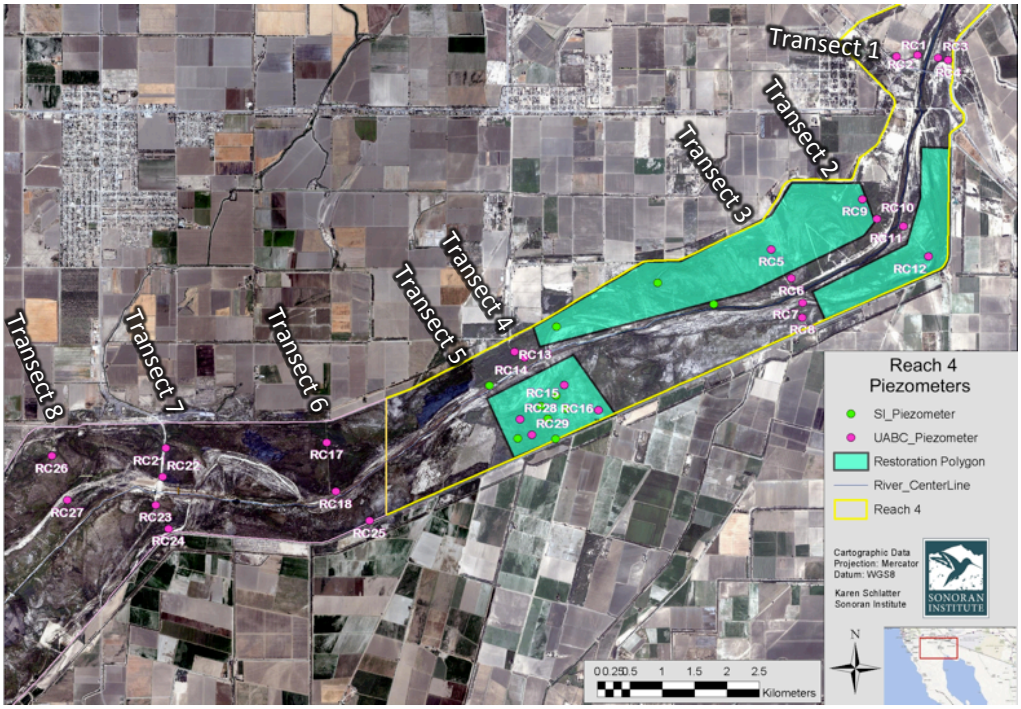


Figure 3. Piezometer locations in lower Reach 4.

Groundwater depths at piezometer locations have been monitored by various organizations over the years, with data primarily collected by the Universidad Autónoma de Baja California (UABC) and Pronatura Noroeste. Between April 2005 and October 2007, UABC sounded piezometers approximately once per month, recording groundwater depth from the top of the piezometer pipe. Data collection was then halted until UABC continued monthly sounding September 2009 through November 2010. No data were collected again until Pronatura Noroeste collected data between May 2011 and December 2013. Unlike prior monthly sounding by UABC, piezometers were sounded six times during 2011, nine times during 2012, and nine times during 2013. Additionally, not all piezometers were sounded on every monitoring event. Finally, UABC resumed monthly sounding in July 2014 following the Minute 319 pulse flow. Extensive additional data became available in 2014 associated with Minute 319 monitoring; however, these data are indicative of the aquifer response to the pulse flow, which enhanced groundwater conditions compared to previous years. As previously mentioned, 2014 groundwater data are not useful from a native species groundwater threshold perspective, as they do not represent the most adverse conditions observed by existing vegetation over the period of interest.

To determine groundwater depth from the ground surface, the height of the piezometer tubes above the ground was subtracted from the depth to groundwater measurements. Datasets were combined into one Microsoft Excel spreadsheet to look at trends over the data collection period. Depth to groundwater data were also converted to groundwater elevation to allow determination of gradients and flow directions.

2.2.2. Historic groundwater data analysis and results

We assessed data collected between April 2005 and December 2014 to determine trends and the period of maximum depth to groundwater (see "R14AP00144_SI_Oct-2015_Report" for groundwater data by transect). Results show that seasonal trends are clearly present in the 2005 to 2007 data collection period; groundwater was highest in the spring and lowest in late summer (discussed further in later sections). Unfortunately, a large data gap in 2008 and 2009 limits our ability to determine groundwater trends during this time period. Recorded depth to groundwater measurements were much more variable during the 2011 to 2013 data collection period. It cannot be determined at this point if groundwater depth was more variable or if data quality limitations exist. Following the large earthquake of April 2010, higher variation would have been anticipated due to changes in irrigation management (many canals were unusable for some period of time after the earthquake).

Qualitatively, it appears that groundwater was probably deepest for the 2005 to 2007 period for piezometers in Transect 1, Transect 2, Transect 4, and Transect 6 (Figure 3). Groundwater might have declined somewhat (less than 0.5 m) for piezometers in Transect 3 and Transect 8 (Transect 8 is outside the Reach 4 boundary). No trends are apparent in Transect 7. The limited dataset for transect 5 precludes any trend analysis.

As discussed previously, historically available depth to groundwater data was limited and sometimes of uncertain quality. Ideally, we would have had a continuous dataset since the last major flow event, and thresholds for groundwater would be determined based on the maximum depth to groundwater during the growing season since that flow event. This depth to groundwater analysis approach also is in direct alignment with the objectives of the groundwater modeling scenarios; specifically, vegetation composition potential will be based off the "worst" (deepest) groundwater during the growing season. Other factors likely eliminated areas of native trees (e.g. wildfire); however, remaining trees have survived in the experienced conditions, indicating that groundwater had not exceeded the zone of accessibility for remaining cottonwood and willow since the last significant flow events.

Because there were no observable, significant downward trends of groundwater over time in the primary area of interest (Reach 4), we decided that data collected between April 2005 and October 2007 were representative of groundwater conditions experienced by existing vegetation. We also perceived these data to have the highest consistency and quality.

For the groundwater threshold analysis, we used the available data to estimate the maximum groundwater depth for each piezometer during the peak of the growing season (May through September) between 2005 and 2007. Data from this time period were plotted in Microsoft Excel with day of year (DOY) on the x-axis and depth to groundwater on the y-axis. For many piezometers, depth to groundwater was obviously different between years. For these cases, the shallower depth to groundwater year was removed from the dataset since we were interested in worst-case conditions. In other cases, month-to-month variation was sometimes high. This could have indicated a change in groundwater conditions due to an episodic event (e.g. adjacent irrigation or water removal) that did not necessarily represent groundwater and capillary fringe conditions (water availability for trees) during this month. Large outliers, such as month-to-

month variation of nearly one meter (e.g. RC10 in February 2007) were removed from the dataset, whereas other fluctuations of 5-10 cm were not.

To predict maximum depth to groundwater during the peak growing season, summary datasets were imported to JMP V6 (SAS Institute, Cary, NC), and fourth to sixth-order polynomial functions were fit to predict depth to groundwater from the DOY. The resulting prediction equations are presented by transect in Figure 4 through Figure 10. Transect 5 is not included because data were not available in 2005-2007. To estimate a monthly average DTW, the polynomial equations were fit to the midpoint DOY for each month. The lowest value for May through September was then selected and used for the depth to groundwater threshold analysis. Selected groundwater values for the threshold analysis are highlighted (solid yellow points) in in Figure 4 through Figure 10.

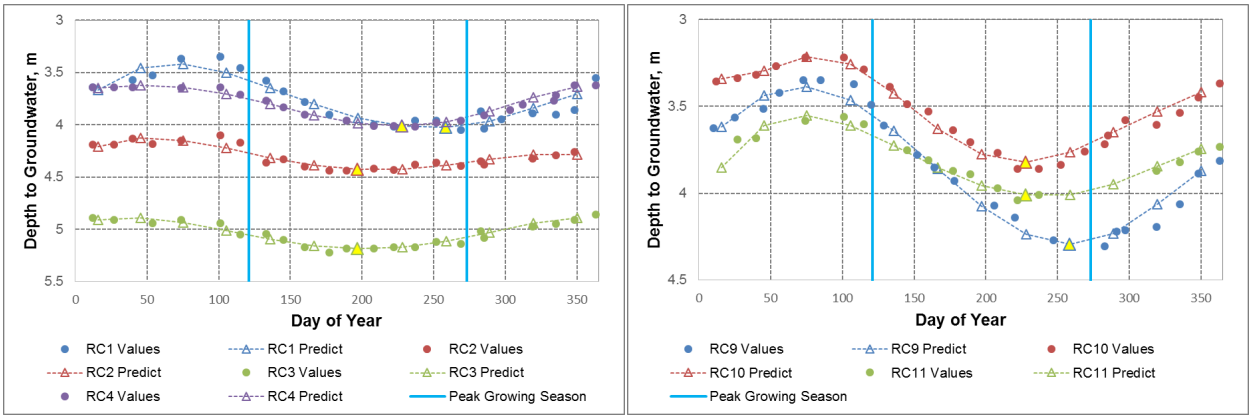


Figure 4 and Figure 5. Observed (solid points) and fitted (hollow points with dashed line) depth to groundwater versus day of year for piezometers in Transect 1 (left) and 2 (right). Yellow highlighted points indicate values used for threshold analysis.

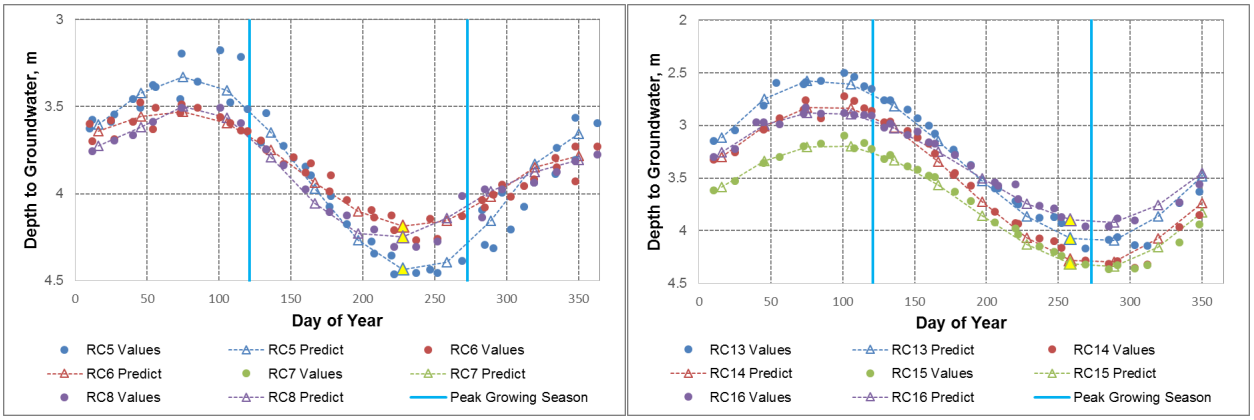


Figure 6 and Figure 7. Observed (solid points) and fitted (hollow points with dashed line) depth to groundwater versus day of year for piezometers in Transect 3 (left) and 4 (right). Yellow highlighted points indicate values used for threshold analysis.

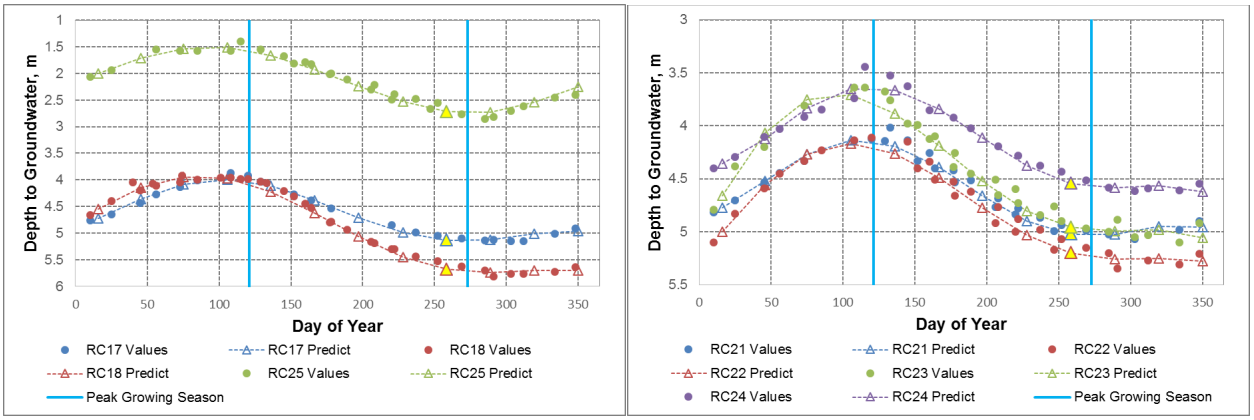


Figure 8 and Figure 9. Observed (solid points) and fitted (hollow points with dashed line) depth to groundwater versus day of year for piezometers in Transect 6 (left) and 7 (right). Yellow highlighted points indicate values used for threshold analysis.

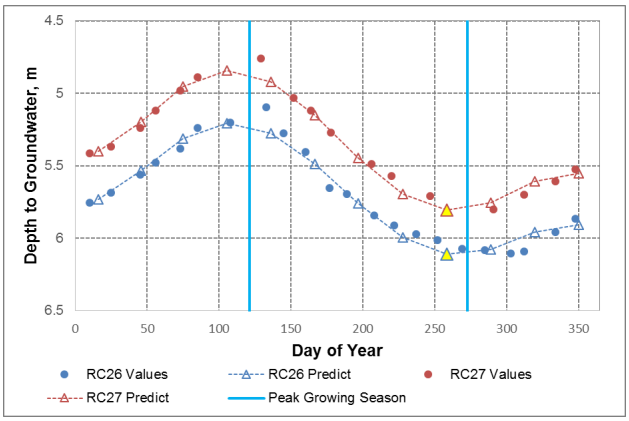


Figure 10. Observed (solid points) and fitted (hollow points with dashed line) depth to groundwater versus day of year for piezometers in Transect 8. Yellow highlighted points indicate values used for threshold analysis.

To estimate maximum depth to groundwater across the sampled portion of Reach 4, maximum peak growing season values, estimated as described above, were converted to groundwater elevation. Groundwater elevation was interpolated and extrapolated for the portions of Reach 4 and Reach 5 well characterized by piezometer locations. Finally, groundwater elevation was converted back to depth to groundwater. The process was completed as follows:

1. A two-dimensional point shapefile was created from piezometer coordinates.
2. The two-dimensional shapefile was converted to three-dimensional in ESRI ArcGIS by assigning the z-value from a Light Detection and Ranging (LiDAR) derived Digital Elevation Model (DEM) available from Minute 319-related analysis (discussed further in later sections).
3. The piezometer shapefile was joined with a table containing the maximum peak growing season depth to groundwater as determined by the process described above.
4. The maximum depth was subtracted from the LiDAR elevation in the 3-D piezometer shapefile to determine the groundwater elevation at the piezometer location.
5. Groundwater elevations were then interpolated into a 3-m by 3-m grid via the ESRI Spatial Analyst extension “Spline with Barriers” tool. The analysis “barrier” was

constrained laterally by flood control levees, downstream by the extent of the piezometers, and upstream by approximately 1.5 km up-gradient (the distance we were confident that the groundwater data effectively represent).

6. Finally, depth to groundwater across the interpolated and extracted area was determined by subtracting the groundwater elevation grid from the LiDAR DEM for the entire analysis area. The resulting grid contained the predicted depth to groundwater for each 3m x 3m cell.

The resulting depth to groundwater interpolations and extrapolations are presented in Figure 11. As anticipated, the shallowest depth to groundwater was generally in lower-elevation areas adjacent to the main channel and along historic river meanders through Reach 4.

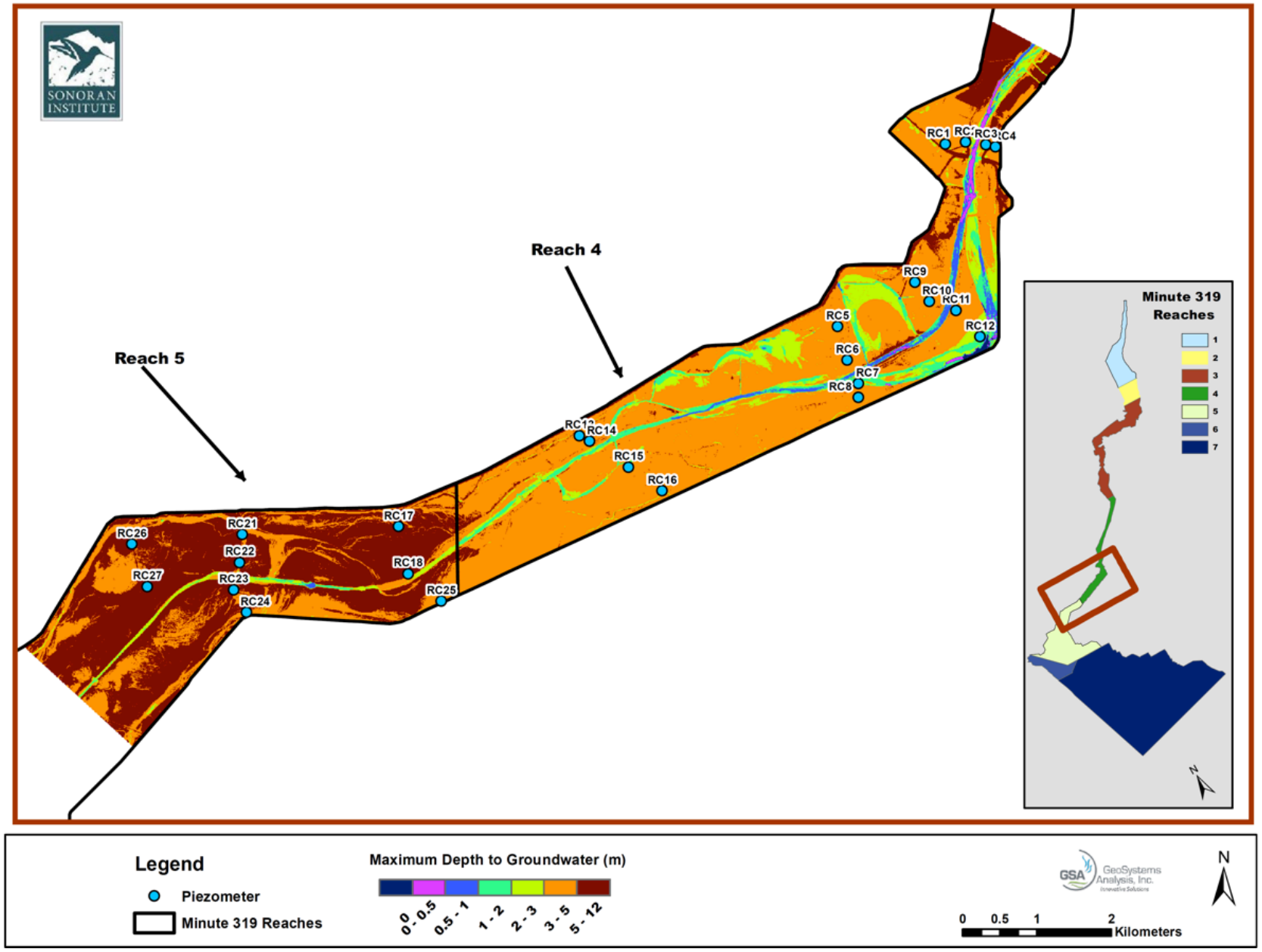


Figure 11. Interpolated and extrapolated maximum growing season depth to groundwater for April 2005 through October 2007

2.2.3. Vegetation inputs

Through Minute 319 monitoring program, the US Bureau of Reclamation processed LiDAR and spectral imagery to create project-scale vegetation maps for the Colorado River riparian corridor in Mexico. Methods are summarized briefly below.

LiDAR point cloud data were collected both before and after the pulse flow, with the pre-pulse dataset obtained in March 2014. World View 2 Imagery from September 2013 was used as the multi-spectral and pan-chromatic dataset. Classified point cloud data were used to determine vegetation height or the presence of bare earth (no vegetation). An object-based image analysis was used to join vegetation height and multispectral imagery data and estimate:

- Vegetation Canopy Height
- Predominant Vegetation Type
- Anderson-Ohmart (A-O) Classification Structure and Vegetation Type
- Crown Closure
- General Land Cover Classes (e.g. Land, Water)

The vegetation type and A-O classifications were calibrated based on field observations of vegetation types. The products of this analysis included georeferenced canopy-scale (individual trees in many cases) and A-O scale vegetation maps, which could then be intersected with the historic groundwater level information.

The depth to groundwater grid created from maximum 2005-2007 growing depth values was converted to a point shapefile and then intersected with various 2013 vegetation mapping layers:

- A-O structure level (coarser resolution) classification
- Canopy level classification (finer resolution, detecting even individual trees in some cases)
- Canopy height
- Burn scars

The resulting shapefile assigned the class value from each of the four vegetation mapping layers to the depth to groundwater point predicted at that point. Resulting points were exported to MS Excel for additional analysis.

2.2.4. Statistical analysis

We used various iterations of analysis to determine the relationship between 2005-2007 depth to groundwater and vegetation type results from the March 2014 remote sensing analysis. For the first attempts, we plotted the cumulative distribution functions of vegetation classes versus depth to groundwater. Cumulative distribution functions (the percent of the grid cells with a depth to groundwater less than that at the given point) were determined using sorted values. This was completed for both the canopy-level (Figure 12) and structure-level (Figure 13) classes provided from the remote sensing analysis.

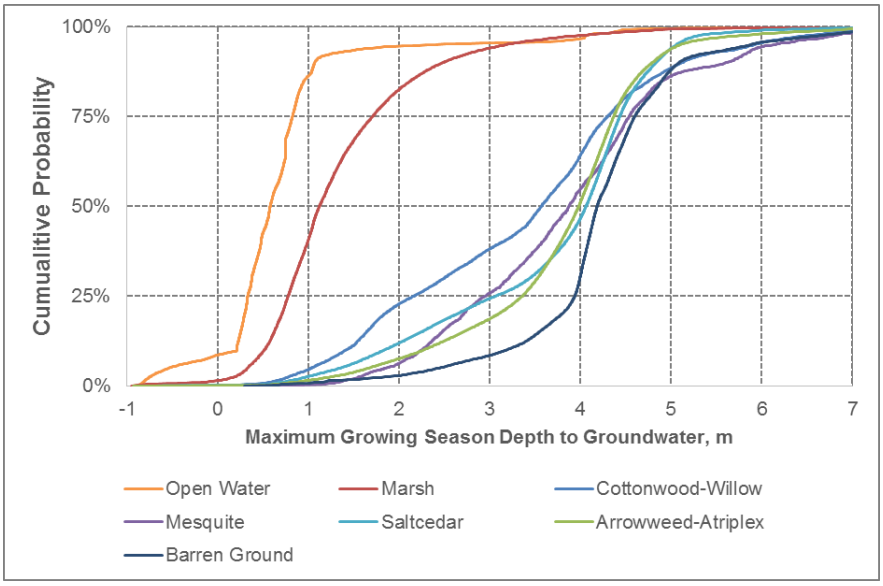


Figure 12. Cumulative distribution functions for canopy-level vegetation classes versus 2005-2007 maximum growing season depth to groundwater.

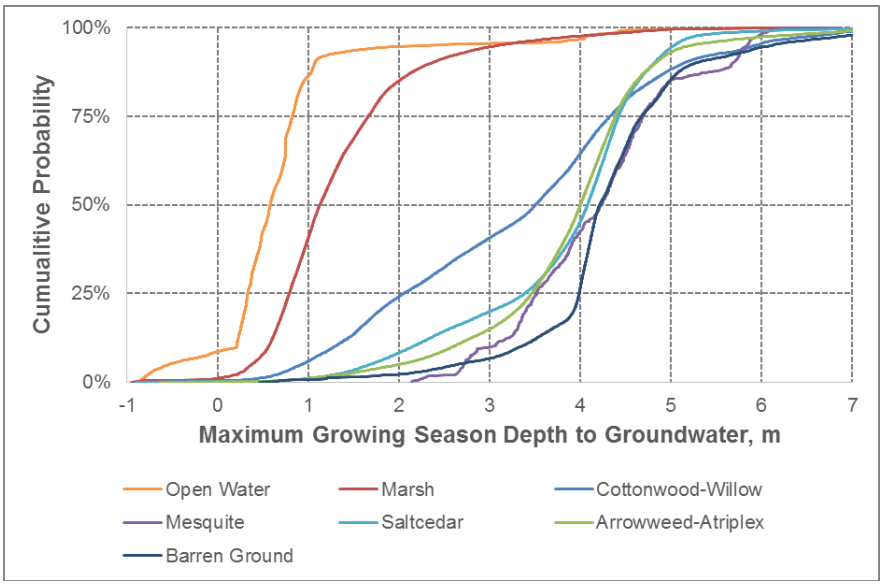


Figure 13. Cumulative distribution functions for structure-level vegetation classes versus 2005-2007 maximum growing season depth to groundwater.

Generally, the distributions followed the anticipated pattern, with shallower groundwater present for more mesic habitat types (open water, marsh, cottonwood-willow). Also, the inflection point for open water at approximately 30 cm depth to water reflects deeper groundwater during 2005-2007 than in March 2014. Fifty percent of cottonwood-willow grid cells for the canopy level model had a depth to groundwater less than approximately 3.5 m. Unfortunately, no sharp inflection points were observed in the curves for the key habitat types of cottonwood-willow or mesquite, so this analysis did not provide us with clear thresholds to use for the groundwater model results analysis. Additionally, over 10% of cottonwood-willow canopy cover per the remote sensing analysis was present in areas that experienced depth to groundwater of over 5 m during 2005-2007.

We suspected that the lack of clear thresholds could be attributed to several factors. First, each 3 m by 3 m grid cell was considered an independent event; that is, each grid cell with a given cover type was assumed to be supported by the groundwater level in that grid cell. For large trees, this assumption is likely invalid because one tree canopy can cover multiple grid cells. This is especially important in areas with high topographical variation. For example, a cottonwood tree rooted along the steep main channel bank (where depth to groundwater is close to 0) could have a canopy that extends laterally beyond the bankline where depth to groundwater is several meters. However, with the initial analysis, it would be assumed that the depth to groundwater on top of the bankline supported a cottonwood tree, thus artificially over-estimating the depth to groundwater that could support the tree.

It is also possible that trees survived the relatively poor groundwater conditions experienced during 2005 and 2007, and then continued growing in subsequent years. There are points of accidental, direct deliveries of surface water that could be artificially supporting riparian trees in deep groundwater areas. Finally, it is likely that in some cases other species of tall trees were assigned the cover type of cottonwood-willow based on assignment rules in the Lidar analysis. Along the margins of Reach 4 (along the levees), non-native species such as eucalyptus are common, and athel tamarix (*Tamarix aphylla*) occurs in the riparian corridor.

To attempt to correct for these likely sources of error, we re-ran the analysis using several techniques. First, instead of using each canopy-scale grid cell as an independent event, we used summary statistics for cover-type polygons to include minimum depth to groundwater and median depth to groundwater. Unfortunately, this similarly resulted in a lack of threshold response, with many areas where depth to groundwater was much deeper than anticipated.

Finally, we re-ran the canopy-scale model results using an occupancy analysis binned by 0.5-m intervals. We first determined the percent of cells within each 0.5-m interval that were assigned as a given cover type (Figure 14). To aid in interpretation, we then normalized the results to determine the frequency of cottonwood-willow or mesquite in a given depth to groundwater interval compared to the interval with highest occupancy (Figure 15). We omitted results for grid cells where the historic depth to groundwater was greater than 5 m for the following reasons:

- 94% of Reach 4 had a depth to groundwater of less than 5 m for 2005-2007.
- Many of the areas with depth to groundwater greater than 5 m were located along the margins of Reach 4, where vegetation was likely to be inaccurately assigned (due to presence of large, planted trees of other species).
- The combination of these two factors could result in an artificially high occupancy of cottonwood-willow and mesquite in areas where depth to groundwater was greater than 5 m.
- Restoration practitioners in the area are not using areas with high depth to groundwater for active restoration implementation; therefore, the support of cottonwood, willow, and/or mesquite in these areas is not relevant for management.

The results for occupancy of cottonwood-willow and mesquite by depth to groundwater category showed that the absolute frequency for cottonwood-willow ranged from less than 1% to approximately 4% (Figure 14). The absolute frequency for mesquite ranged from 0% to 0.4%. Normalized results showed that the maximum frequency for cottonwood-willow was in the 1.5-2

m depth to water category, and the maximum frequency for mesquite was in the 2-2.5 m depth to water category (Figure 15).

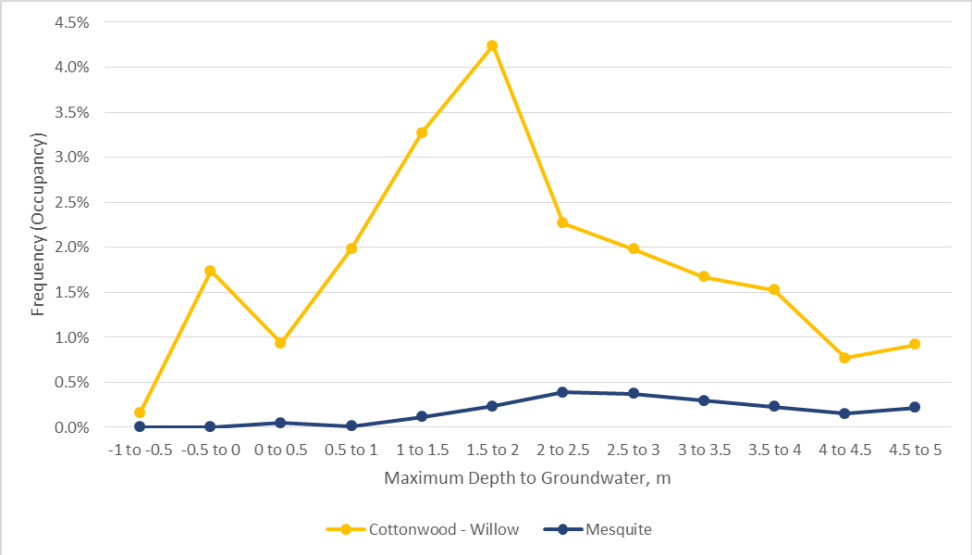


Figure 14. Frequency of cottonwood-willow and mesquite vegetation types based on the canopy-scale model in depth to groundwater categories in Reach 4.

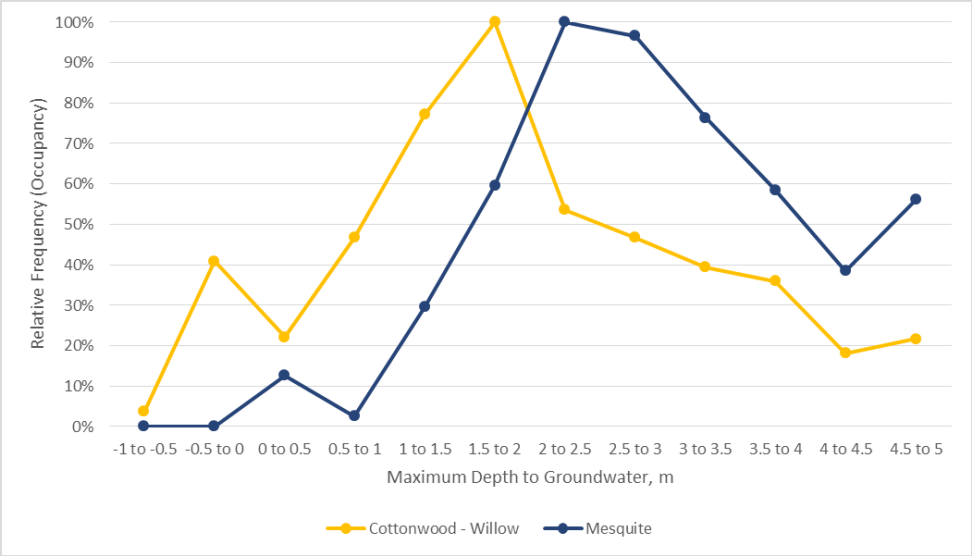


Figure 15. Relative frequency (occupancy in the groundwater category relative to the maximum occupancy observed) of cottonwood-willow and mesquite vegetation types based on the canopy-scale model in depth to groundwater categories in Reach 4.

To determine thresholds to use for the groundwater model results analysis, we considered the relative frequency for deeper depth to groundwater categories along with on-the-ground observations and restoration design criteria used in Reach 4. These are relevant considerations, as the primary method for additional habitat creation in Reach 4 is likely to be active restoration. For restoration design, Sonoran Institute uses 2.5 m depth to groundwater as a threshold for cottonwood-willow, and 3.5 m depth to groundwater as a threshold for mesquite. In this analysis,

relative occupancy stays above 50% for cottonwood-willow up to 2.5 m depth to groundwater and up to 4.0 m for mesquite. Based on this combination of factors, we decided to use 2.5 m depth to groundwater as the threshold for cottonwood-willow, and 4 m for mesquite.

The above analysis did not apply for the open water or marsh habitat types since thresholds are better established in the literature and local management plans (Bureau of Reclamation 2004). For emergent marsh, surface water must be present throughout the growing season, but relatively shallow (i.e. less than 2m). Open water habitat requires perennial surface water deep enough to prevent colonization by emergent marsh vegetation (generally greater than 2 m above ground surface).

3. Groundwater Model Development

3.1. Modeling Objectives

We proposed to address how environmental flows, agricultural water management, and groundwater pumping affect groundwater levels, which in turn affect riparian habitat quality in the Colorado River Delta in Mexico. Environmental flows in the Delta have consisted of "pulse" flows, "base" flows, and irrigation to restoration sites (IBWC 2014). Pulse flows are defined here as high magnitude flows delivered to the mainstem of the river primarily through Morelos Dam. Base flows are defined as low magnitude flows delivered through the irrigation canal system to historic side channel meanders and/or the river mainstem. Additional flows can be delivered through the canal system as irrigation to high priority restoration.

Based on extensive conversations with the project team and with other participants of the Minute 319 Science Team, we determined that the critical functions of pulse flows in terms of supporting riparian habitat include new vegetation establishment ("passive restoration" in which flows scour existing vegetation to create moist, bare substrate for seedling establishment) and salinity reduction within soils, surface water, and groundwater. However, pulse flows at the magnitude needed to establish new vegetation are only likely to occur every 5-10 years, whether they are managed or natural flood events. Preliminary observations provided by the Minute 319 Hydrology Monitoring Team indicate that the Minute 319 pulse flow increased groundwater elevations in Reach 4 for a period of months. Therefore, shallow regional groundwater must support riparian vegetation for extended periods between pulse flows. Since the time of major dam construction on the Colorado River, varying amounts of agricultural return flows, a result of irrigation distribution inefficiency (i.e. canal seepage and spillage) and irrigation application inefficiency (recharge of some portion of irrigation through the root zone and into the shallow aquifer), have maintained these required shallow groundwater levels (Carrillo-Guerrero 2008, Hinojosa-Huerta et al. 2013).

The extent of shallow groundwater could likely also be enhanced by base flows. Base flows and restoration irrigation flows have been delivered by the Colorado River Delta Water Trust to target restoration sites in Reach 4 since 2008, and have increased in quantity in recent years under the Minute 319 binational agreement. Under Minute 319, approximately 50,000 acre-feet of water will be delivered as base flows from 2012-2017, and over half of the total base flow

deliveries thus far have been targeted for Reach 4 (Yamilet Carrillo, presentation at March 2015 Minute 319 Science Team Meeting, Mexicali, Mexico).

Given the above information, we agreed that the most appropriate use of the project modeling effort is to determine the *lowest groundwater levels* for the riparian corridor, which occurs between pulse flow events, and predict areas of different habitat types that could be supported under different scenarios based on those lowest groundwater levels. Provided a matrix of combined environmental flows (low magnitude flows and restoration site irrigation), agricultural water management, and climatologic factors (discussed further in following sections), we modeled the area of groundwater-dependent vegetation that could be supported in Reach 4.

3.2. Key Water Balance Concepts

To define our model scenarios, we first identified primary water inputs and outflows. There are three main sources of groundwater for Reach 4: 1) recharge from agricultural applications; 2) groundwater inflows from upstream areas; and 3) groundwater recharge from low-magnitude flow deliveries and irrigation to restoration sites. Precipitation was also included in the model scenarios, but the relative contribution of this water source to groundwater levels is nominal; mean annual precipitation at the Yuma Valley Arizona Meteorologic Network station (approximately 60km NE of Reach 4) between 2003 and 2014 was 58 mm, or less than 3% of the mean annual reference evapotranspiration (1,990 mm via Penman-Monteith method, data available online at cals.arizona.edu/azmet/02.htm). The three outflows for water from Reach 4 are groundwater outflow, surface water outflow, and evapotranspiration (ET) (plant water transpiration and evaporation from open water and bare soils).

3.2.1. Water inputs

Water input variables include the amount of groundwater inflow from surrounding agriculture, groundwater inflow from upstream, and the location and volume of environmental flow deliveries. The amount of groundwater inflow from agriculture varies depending on the gradients between the agricultural zones and the riparian corridor. These gradients are dictated by the amount of groundwater pumping and amount of groundwater recharge of irrigation and the resulting groundwater. Upstream subsurface inflows can vary due to upstream agricultural applications, groundwater pumping, precipitation events, and environmental flow deliveries. Environmental flows are delivered in varying quantities from points in and above Reach 4, and additionally, restoration irrigation water is delivered to several locations in Reach 4.

Higher groundwater pumping in the agricultural areas would reduce groundwater levels below the fields, decrease gradients to the riparian corridor, and reduce groundwater flow into the riparian corridor. While the maximum amount of groundwater pumping is capped by legal restrictions (Yamillet Carrillo, Delta Water Trust, personal communication, 2015) surface water use is favored because it is less expensive than pumping.

Groundwater recharge from irrigation is inversely related to irrigation distribution efficiency and application efficiency: if no canal seepage occurred, and water was perfectly distributed across agricultural fields in amounts equal to crop ET demand, recharge would be eliminated and no agricultural return flow would reach the riparian corridor. While this situation is not anticipated,

it is likely that irrigation efficiency will be increased in the future by, for example, drip irrigation. Changes in crop type could also alter agricultural return flows. If more drought-tolerant crops are planted, requiring less frequent irrigation, the amount of return flow would also be decreased. Assuming similar application efficiency, the reduction in recharge would be proportional to the reduction in number of irrigation events. Similarly, deficit irrigation, which is increasingly used in water-stressed regions to conserve water while accepting some level of decrease in crop yield, would result in decreased agricultural return flow. Many of these changes in agricultural return flows are likely to be driven by climate change. If precipitation in the Colorado River Basin is reduced as currently projected, it is likely that less surface water will be available for irrigation. This change could drive a shift toward more efficient irrigation, adoption of lower water use crops, and fallowing.

3.2.2. Water outflows

Contributing factors for water outflows include potential changes in ET and surface water and groundwater outflow rates. Evapotranspiration in the riparian corridor could change as a result of vegetation changes, increased surface water and soil moisture, and higher temperatures caused by climate change. Plant water use varies by species; generally, native cottonwood (*Populus fremontii*) and willow (*Salix* spp.) trees use more water than non-native saltcedar (*Tamarix* Spp.), which uses about the same amount of water as native mesquite species (*Prosopis* spp.) (Nagler et al. 2005). All of these species transpire more water than native shrubs such as arrowweed (*Pluchea sericea*) (Nagler et al. 2005). If species composition changed either naturally or through managed revegetation efforts, the amount of ET would change accordingly. Water use can also vary among individuals within species due to levels of stress and water availability.

Water use of saltcedar is likely to change due to the presence of one or more species of the saltcedar leaf beetle (*Diorhabda* spp.), which is anticipated to arrive in the Delta by migration within the next ten years (Ben Bloodworth, Tamarisk Coalition, personal communication December 2014). Initial defoliation causes some level of transpiration reduction (Nagler et al. 2012), and repeated defoliations can result in saltcedar mortality. In addition, higher temperatures and lower humidity due to climate change are generally predicted to lead to higher water use by vegetation (increased reference evapotranspiration, ET_0). However, changes in water use are confounded by increased atmospheric carbon dioxide, which can lead to increased water use efficiency (WUE) by native vegetation (e.g. Perry et al. 2013).

Surface water outflows from Reach 4 would increase if environmental flow rates were greater than the infiltration capacity of the riparian corridor, i.e. water delivered to the corridor that does not percolate would instead flow downstream into Reach 5. Groundwater outflow from Reach 4 would increase if groundwater levels in Reach 4 were increased relative to surrounding groundwater levels—for example, if the gradient downstream to Reach 5 increased. If groundwater in the corridor became higher than that of the surrounding agricultural area, groundwater would then flow laterally out of the corridor.

To develop the model inputs, we sought to provide realistic groundwater conditions that would be expected under each scenario, which required additional research, consultation with outside experts, and/or GIS work.

3.3. Drivers and Model Inputs

3.3.1. Agricultural return flows

Agricultural irrigation in the Mexicali Valley is independent of surface water releases to the Colorado River. Irrigation activity is primarily related to:

- Precipitation events
- Agricultural land use
- Crop type
- Time of year (related to crop life cycle and season). For irrigation districts 8 and 22 (located adjacent to Reach 4), the highest volumes of water are applied from February through April during times of significant crop growth; 32-36% of total annual irrigation water volume is applied at this time. The lowest volumes are applied in June through August (12-17% of total annual irrigation water volume).
- Water surface delivery efficiency. Irrigation efficiencies range from 0.85- 0.68 (in other words, 15-32% of applied irrigation water is recharged to the aquifer; Feirstein et al., 2008).

Thus, the following drivers could cause changes in agricultural return flow volumes:

- Change in water availability (surface and groundwater)
- Change in crop type
- Change in land use (for example, an increase/decrease in active agricultural areas)
- Change in groundwater recharge due to lining of irrigation canals

To estimate how each component listed above would affect agricultural return flow, an extensive analysis of data not currently available would be required. In addition, incorporating the specific drivers into the groundwater model would be highly complex. As such, we assigned a percent of water surface efficiency for each scenario that could be caused by the drivers listed above based on a range previously provided in the literature.

Three inputs will be modeled for agricultural return flow: current levels, less return flow, and higher return flow.

a) Baseline agricultural flows:

In the current agricultural flow scenario, drivers include baseline irrigation water applications and baseline crop ET. Alternatively, flow volumes could be maintained through increased irrigation application with a higher crop ET rate (net recharge remains the same). The model input is net recharge at baseline levels, which is estimated to be 15-32% of irrigation diversions (Feirstein et al. 2008). We used 80% irrigation efficiency for the model, in which 20% of applied irrigation becomes recharge.

b) Decreased agricultural flows:

A scenario of reduced agricultural flows could be driven by several different interacting factors. Although initially we considered increased on-farm irrigation efficiency to be one potential driver of reduced return flows, further research has shown that irrigation efficiency is actually

already very high in the Mexicali Irrigation District (MID); only approximately 10% of applied agricultural flows percolates to subsurface flows, as compared to approximately 40% in the California Palo Verde Irrigation District (Carrillo-Guerrero 2013). Additionally, a further reduction in irrigation application is actually undesirable, as a sufficient amount of surface irrigation is required to maintain salinity levels for agricultural production (Ingeniero Robles, CONAGUA, personal communication). Canal seepage in the MID however does currently contribute to subsurface flows at an estimated 23% in losses (Carrillo-Guerrero 2013). Some of these losses are recovered for agricultural purposes through groundwater pumping, while the rest remains as shallow groundwater. Thus, canal lining in MID is a viable driver that could potentially reduce return flows.

In addition, as water becomes scarcer in the Mexicali Valley due to prolonged drought and climate change, farmers may fallow land and sell water rights to other users, particularly nearby cities. Cities have both increasing water demand due to growing populations, and the funds to purchase higher priced water. Furthermore, the combination of rising water prices in the Mexicali Valley and falling wheat and cotton commodity prices means that more farmers are selling or renting their water rights to other water users; this is likely to continue at an increasing rate in the future (Ingeniero Robles, CONAGUA, personal communication). In addition to increased fallowing and the sale of irrigation water rights, river shortages could lead to a reduction in water allocated to farmers by the irrigation districts, which would also affect the total applied volume. In an extreme situation, the reduction of agricultural irrigation applications could lead to the hypersalinization of soils and the underlying aquifer, creating a negative feedback loop where additional farmers must fallow land and sell water rights.

Given the above drivers, we determined that a reduction of agricultural return flows by two-thirds the current amount is a possible future scenario. This would mean a reduction in recharge of water deliveries to irrigation districts (varying by district) by 15%.

c) Increased agricultural flows:

An increased return flows scenario could be driven by farmers switching to higher water use crops or surpluses of agricultural water in the system. For this scenario, higher applied water would result in increased recharge volume even at the same recharge rates. However, to simplify model inputs, we instead maintained the volume of applied water and decreased efficiency (increased recharge) to represent this scenario. Under the increased agricultural flows scenario, 30% of applied irrigation becomes recharge.

- Baseline: 80% (20% of applied irrigation becomes recharge)
- Decreased agricultural return flow: 85% (15% of applied irrigation becomes recharge)
- Increased agricultural return flow: 70% of efficiency (30% of applied irrigation becomes recharge)

The application efficiency for each scenario was applied to actual irrigation volumes for irrigation districts (2, 8, and 22) in Reach 4 for the 2005-2006 agricultural water cycle (September 2005 – September 2006), as this was the only full water year irrigation data available to us at the time. Figure 16 below shows the volumes of agricultural recharge under the three different scenarios using 2005-2006 monthly irrigation application volumes.

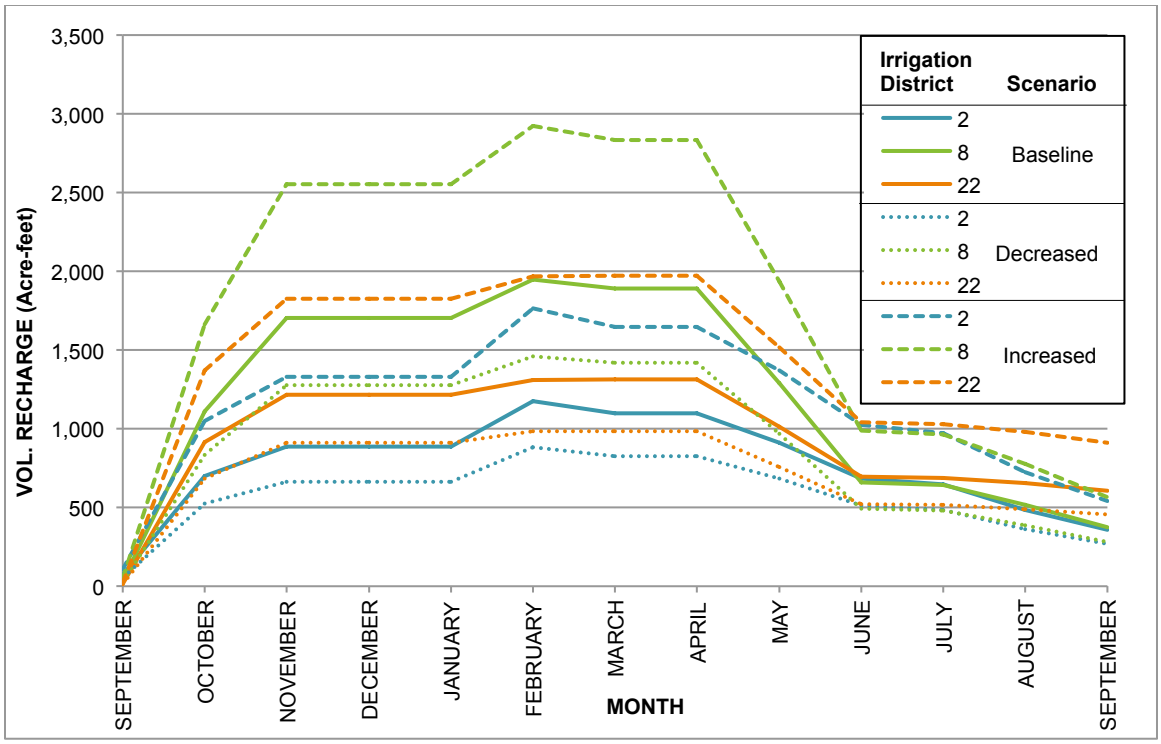


Figure 16. Volume (acre-feet) of aquifer recharge per month in the baseline, decreased, and increased agricultural return flow scenarios using 2005-2006 irrigation water volumes.

3.3.2. Environmental flows

As we are not considering pulse flow deliveries in this model, environmental flow deliveries that impact groundwater in Reach 4 include low magnitude deliveries (base flows) and restoration site irrigation. The Colorado River Delta Water Trust manages and executes base flow and restoration site irrigation deliveries for the Colorado River in Mexico. At the time of writing this report, the Trust owned approximately 8,100 acre-feet/year of permanent water rights and leased additional amounts for the provision of base flows to the river mainstem and restoration sites under Minute 319. To determine appropriate base flow and irrigation water scenarios, we took these amounts into consideration as well as environmental flow volumes and delivery points proposed during negotiations of a new binational agreement.

As part of the US-Mexico negotiation process for a new binational water management agreement (known as Minute 32X), four annual environmental flow scenarios were proposed by the binational negotiation team. A sub-group of scientists, including Sonoran Institute, developed restoration scenarios and potential benefits for each water volume proposed. Based on these restoration scenarios and further discussion with the modeling team at the University of Baja California, we determined that three environmental flow delivery scenarios would adequately reflect the range of scenarios developed in the 32X process while also reducing model complexity. The scenarios utilize eight delivery point locations (Figure 17) and were divided between delivery point locations based on current allocations and projected restoration site needs (Table 1). Total flow amounts vary from none to high.

The groundwater model was manipulated to reflect changes in environmental flow delivery amounts by incorporating different surface water stage values at various locations along the river and meander sites.

a) No environmental flows

Although a scenario of no environmental flows is unlikely to occur in the future, it is important to consider the dependence of the system on base flows and restoration irrigation flows. A scenario could arise in which the Delta Water Trust is forced to sell or lease their water rights to farmers due to shortages, resulting in no base flow or restoration site irrigation deliveries in Reach 4. Alternatively, the Trust could decide to prioritize restoration sites in different areas of the river and stop delivering flows to Reach 4.

b) Low environmental flows

The low environmental flow scenario has base flow and restoration irrigation inputs under the lowest annual volume proposed under the 32X negotiations. Under this volume scenario, approximately 3,900 acre-feet would be delivered to Reach 4 in the form of base flows to river and meander channels and irrigation to restoration sites for maintenance and restoration ofriparian habitat (see Table 1).

c) High environmental flows

The high environmental flow scenario will have base flow and restoration site irrigation inputs to Reach 4 under the highest annual volume proposed under 32X. Under this scenario, approximately 16,500 acre-feet would be delivered to Reach 4 to irrigate new and existing restoration sites and provide low flows to the river mainstem and meanders for habitat maintenance (Table 1). Short-term flow deliveries (flows not delivered annually) to reach 4 under the high volume scenario were not included in the annual baseflow delivery amount.

Thus, the Reach 4 environmental flow scenarios are as follows:

- No base flows
- Low environmental flows (3,897 acre-feet per year)
- High environmental flows (16,497 acre-feet per year)

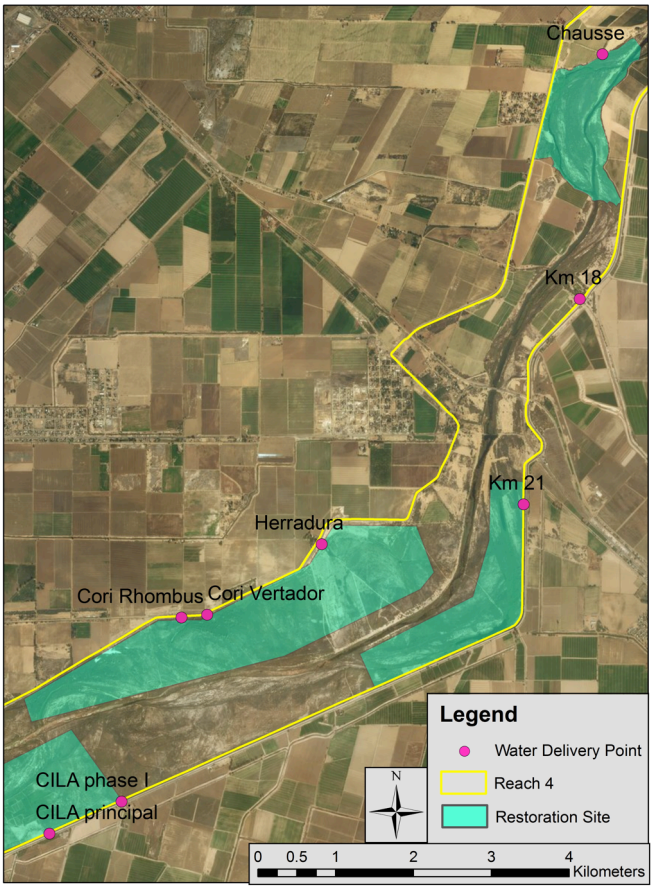


Figure 17. Location of existing water delivery points in Reach 4

Table 1. Base flow and restoration site irrigation delivery amounts and locations. Meander and river delivery locations are base flow delivery points, while irrigation locations represent deliveries for irrigation of restoration sites.

Scenario	Month	Delivery Locations and Amounts (acre-feet/year)											Total
		Chausse (meander)	Km 18 (river)	Km 21 (meander)	Herradura (meander)	Herradura (irrigation)	Cori vertador (meander)	Cori Rhombus (irrigation)	CILA phase I (meander)	CILA phase I (irrigation)	CILA principal (meander)	CILA principal (irrigation)	
None	-	0	0	0	0		0		0			0	**0**
Low	October	12.3	0.0	20.6	5.2	43.1	5.2	43.1	2.0	21.0	1.0	31.5	
	November	4.1	0.0	6.9	1.7	44.1	1.7	44.1	0.7	21.5	0.3	32.2	
	December	0.0	0.0	0.0	0.0	15.8	0.0	15.8	0.0	7.7	0.0	11.6	
	January	4.1	0.0	6.9	1.7	15.8	1.7	15.8	0.7	7.7	0.3	11.6	
	February	20.5	0.0	34.3	8.7	30.7	8.7	30.7	3.3	14.9	1.7	22.4	
	March	40.9	0.0	68.5	17.3	57.9	17.3	57.9	6.5	28.2	3.3	42.3	
	April	65.4	0.0	109.6	27.7	70.3	27.7	70.3	10.4	34.2	5.3	51.4	
	May	77.7	0.0	130.2	32.9	86.1	32.9	86.1	12.4	41.9	6.3	63.0	
	June	81.8	0.0	137.0	34.6	101.9	34.6	101.9	13.0	49.7	6.6	74.5	
	July	53.2	0.0	89.1	22.5	105.1	22.5	105.1	8.5	51.2	4.3	76.8	
	August	28.6	0.0	48.0	12.1	88.5	12.1	88.5	4.6	43.1	2.3	64.7	
	September	20.5	0.0	34.3	8.7	73.7	8.7	73.7	3.3	35.9	1.7	53.9	
	Total	**409**	**0**	**685**	**173**	**733**	**173**	**733**	**65**	**357**	**33**	**536**	**3897**
High	October	12.3	2520.0	20.6	5.2	43.1	5.2	43.1	2.0	21.0	1.0	31.5	
	November	4.1	0.0	6.9	1.7	44.1	1.7	44.1	0.7	21.5	0.3	32.2	
	December	0.0	0.0	0.0	0.0	15.8	0.0	15.8	0.0	7.7	0.0	11.6	
	January	4.1	0.0	6.9	1.7	15.8	1.7	15.8	0.7	7.7	0.3	11.6	
	February	20.5	0.0	34.3	8.7	30.7	8.7	30.7	3.3	14.9	1.7	22.4	
	March	40.9	0.0	68.5	17.3	57.9	17.3	57.9	6.5	28.2	3.3	42.3	
	April	65.4	0.0	109.6	27.7	70.3	27.7	70.3	10.4	34.2	5.3	51.4	
	May	77.7	0.0	130.2	32.9	86.1	32.9	86.1	12.4	41.9	6.3	63.0	
	June	81.8	2520.0	137.0	34.6	101.9	34.6	101.9	13.0	49.7	6.6	74.5	
	July	53.2	2520.0	89.1	22.5	105.1	22.5	105.1	8.5	51.2	4.3	76.8	
	August	28.6	2520.0	48.0	12.1	88.5	12.1	88.5	4.6	43.1	2.3	64.7	
	September	20.5	2520.0	34.3	8.7	73.7	8.7	73.7	3.3	35.9	1.7	53.9	
	Total	**409**	**12600**	**685**	**173**	**733**	**173**	**733**	**65**	**357**	**33**	**536**	**16497**

3.3.3. Upstream subsurface inflows

Groundwater levels in Reach 4 are not just affected by nearby agricultural water applications and direct base flow deliveries to the reach; upstream agricultural applications, groundwater pumping, and baseflow deliveries also affect subsurface flows. We propose three scenarios for changes in upstream subsurface inputs to Reach 4: high inflow rates, low inflow rates, and moderate inflow rates.

Variation in upstream subsurface inflows was represented by assigning monthly groundwater elevations at the upstream boundary of Reach 4. Groundwater data from piezometer transects in (RC1-RC4) and upstream of (P9-P12) Reach 4 (Figure 18) were used to justify groundwater model upstream boundary conditions used for the different scenarios. Groundwater data for the upstream piezometer transect were available for March 2014 through December 2015, which provided a range of groundwater levels due to the pulse flow in 2014 and seasonal groundwater trends. Groundwater data for the downstream piezometer transect were available beginning in 2005.

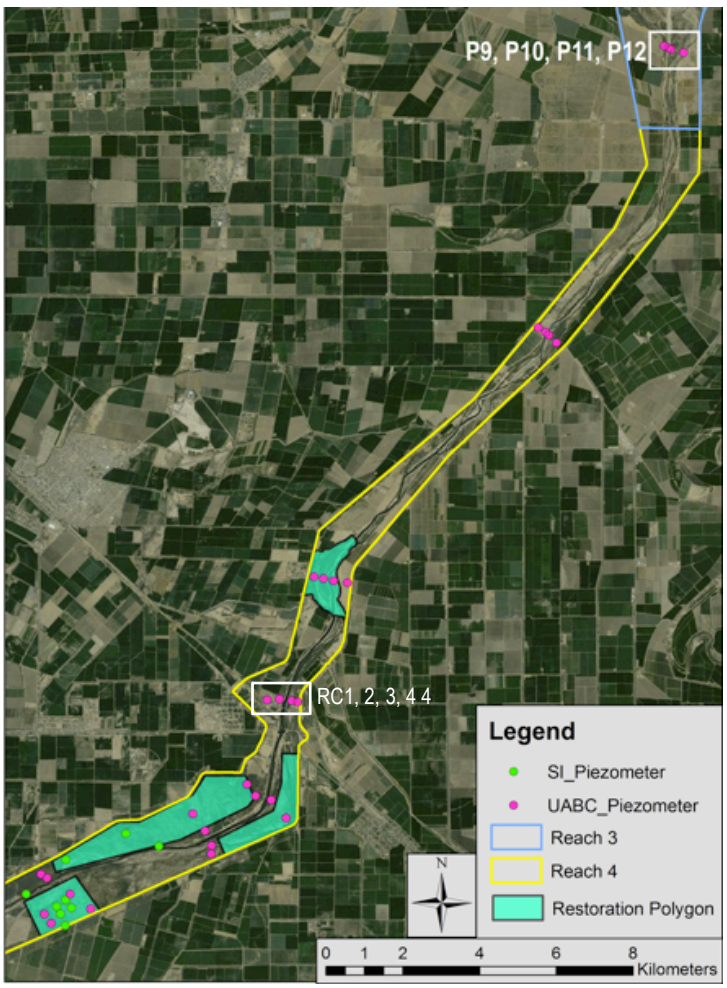


Figure 18. Map of Reach 4 and lower Reach 3 showing location of piezometers P9-P12 just upstream of the Reach 4 upper boundary.

a) Increased upstream subsurface inflow

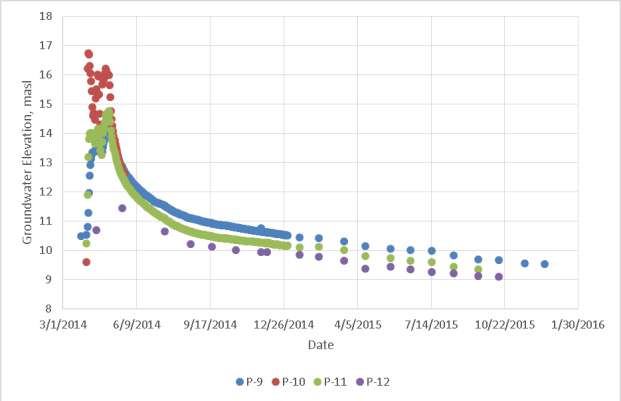
In 2014, approximately 41% (4,135 acre-feet) of the total baseflow water amount (10,085 acre-feet) was delivered to the Colorado River mainstem at Morelos Dam (Yamillett Carrillo, Delta Water Trust Director, Minute 319 Science Team March 2015 Meeting presentation), and a similar percentage was delivered at Morelos Dam in 2015. If the Delta Water Trust continues to acquire water for base flows, deliveries at Morelos Dam could provide a substantial influx of water to the Mexicali Valley aquifer, ultimately impacting subsurface inflows to Reach 4.

An additional potential driver of increased upstream subsurface inflows is more extreme rainfall events due to climate change. *El niño* effects could be more frequent and intense (Cai et al. 2014), which could lead to flooding events on the lower Colorado River and Gila River in the U.S., where no water storage capacity currently exists (and excess water is released to Mexico through Morelos Dam).

To obtain a realistic estimate of an increased upstream inflow scenario, we started by looking at data during and after the 2014 pulse flow from the P9-P12 transect to assess levels and trends over time. First, continuous groundwater data collected during the pulse flow in 2014 was combined with manually sounded monthly groundwater data to ensure compatibility of datums and consistency in trends. In all piezometers, the pulse flow arrival was evident (Figure 19), but the response in P12 was more gradual as it is farther away from the channel. A steady decrease occurred in all piezometers following the initial pulse flow recession through the end of December 2015. This suggests that water from the pulse flow, base flows, and/or incidental flows in 2015 continued to influence groundwater levels, since levels at the end of 2015 did not stabilize to pre pulse levels.

Data for the P9-P12 piezometer transect was not available prior to March 2014, so we next plotted groundwater elevation versus day of year to see if the 2015 groundwater elevation data could be used as a surrogate for early season data to represent elevated baseline groundwater that would be present in consistent wet years. The early 2015 data fit well with the 2014 trend (Figure 20). Data past mid-March 2015 was then eliminated to obtain a representative high inflow groundwater scenario over the year, and P10 data was removed due to a lack of data (data were only available during and immediately after the pulse flow; see Figure 21). The data used to simulate the annual groundwater hydrograph over the pulse flow year is presented in Figure 21.

We then reduced the variability in the curves during the 2014 pulse flow to create a more stable hydrograph and provide more representative monthly average. For curves during the pulse flow, we interpolated between key points in the groundwater hydrograph. After the pulse flow peak, transducer data were used to obtain daily mean groundwater elevation. Linear interpolation was used to get average daily values when there were gaps between points. The average of the daily values, by month, was then obtained from the daily values and the data were plotted by date instead of day of year (Figure 22).



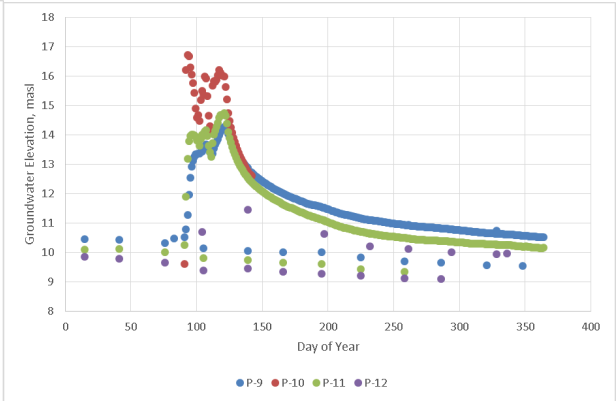
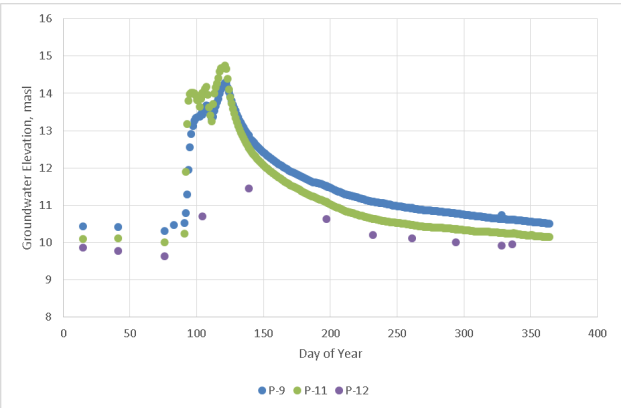


Figure 19. (left) Combined pressure transducer (daily means) and manual sounding results for the P9 - P12 transect, March 2014 through December 2015.
Figure 20. (right) Combined pressure transducer data (daily means) and manual sounder readings versus day of year for March 2014 through December 2015.



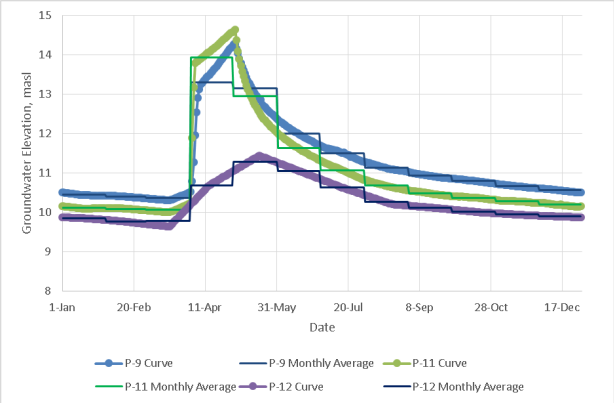


Figure 21. (left) Selected data used to represent increased upstream inflows (a high-flow year) that would occur with initial elevated groundwater levels followed by a lower magnitude flow.
Figure 22. (right) Smoothed curves and monthly time-steps to represent upstream inflows (a high-flow year) that would occur with initial elevated groundwater levels followed by a lower magnitude flow.

The groundwater curve shown in Figure 22 is likely different than what would be expected under an increased inflow scenario caused by future environmental flows and/or accidental flow releases from Morelos Dam. First, the total water input is likely to be lower than that provided by the 2014 pulse flow. Approximately 90,000 acre-feet (af) of water was delivered to the Colorado River mainstem via Morelos Dam and the Km27 spillway (delivery points upstream of Reach 4). Conversely, for water delivery scenarios being proposed in the 32X binational negotiations, approximately 14,000 af of water per year is proposed for delivery to Reach 1 via Morelos Dam during non-pulse flow years (as a reminder, we decided to focus on modeling changes in groundwater levels in non-pulse flow years to determine the *lowest* groundwater levels for the riparian corridor under the various scenarios). This water is likely to be delivered evenly over the growing season and as a "pulse." Consequently, approximately half of the 14,000 af (7,000 af) would be released during the first half of the growing season, when a pulse of reduced amplitude could be observed in Reach 4.

Incidental flow volume inputs are less certain; we used an incidental flow release that occurred in May 2015 as an example incidental flow event. A rainstorm event in May 2015 on the Lower Gila River resulted in the release of approximately 23,000 af of water from Morelos Dam into Mexico. The combined amount of these two flow volumes (7,000 af of environmental flows plus 23,000 af of incidental flows) is approximately one-third of the Minute 319 pulse flow volume. While the percent of inflow to Reach 4 is not necessarily scalable, an increase in groundwater levels of approximately one-third of that observed during the pulse flow is likely within the range of outside influence that could also occur in future years. Therefore, for the increased inflow scenario, we scaled the magnitude of groundwater increase by one-third of that observed during the pulse flow. The process was as follows (also see Table 2):

- For each piezometer, we determined the minimum average monthly elevation for the curves.
- For each month, we determined the difference between monthly average elevation and the minimum monthly average elevation.
- We then divided the difference by 3 (scaling to 1/3).
- The 1/3-scaled monthly difference was added to the minimum elevation to determine an elevation by month.

Second, the timing of future environmental flows is likely to be different than the original curves proposed in Figure 22. Historical flow data indicates that natural floods occurred later in the year (June or July) compared to the Minute 319 pulse flow (April-May). Furthermore, environmental flows are more easily delivered after mid-April, once irrigation demands begin to decline. For the purposes of this project, we assumed that environmental flow inputs are likely to be highest in May and June. To reflect this hydrograph, the scaled monthly mean groundwater elevations were shifted to be one month later than for 2014. The resulting groundwater elevation values are shown in Table 3. Groundwater hydrographs for each piezometer, scaled and adjusted by month, are shown in Figure 23. The mean groundwater elevation across the three piezometers is shown in Figure 24. For groundwater modeling in this project, we plan to use the mean of the P9-P12 transect (presented in Table 3) as the upstream boundary conditions for the High Inflow Boundary Condition scenario.

Table 2. Step-wise calculations to scale 2014-2015 monthly groundwater elevations of P-9, 11, and 12 by 30%. Yellow highlighted cells indicate the minimum mean monthly elevation; green highlighted cells indicate the maximum.

Month	Average Elevation			Meters above min			1/3 Scaling, m above min			Adjusted Monthly Elevation		
	P-9	P-11	P-12	P-9	P-11	P-12	P-9	P-11	P-12	P-9	P-11	P-12
January	10.46	10.12	9.85	0.08	0.05	0.09	0.03	0.02	0.03	10.40	10.09	9.79
February	10.40	10.09	9.76	0.03	0.02	0.00	0.01	0.01	0.00	10.38	10.08	9.76
March	10.37	10.07	9.79	0.00	0.00	0.02	0.00	0.00	0.01	10.37	10.07	9.77
April	13.30	13.94	10.68	2.93	3.87	0.92	0.98	1.29	0.31	11.35	11.36	10.07
May	13.15	12.95	11.29	2.78	2.87	1.53	0.93	0.96	0.51	11.30	11.03	10.27
June	12.01	11.64	11.06	1.64	1.57	1.30	0.55	0.52	0.43	10.92	10.60	10.20
July	11.50	11.07	10.64	1.13	1.00	0.88	0.38	0.33	0.29	10.75	10.41	10.06
August	11.14	10.68	10.28	0.77	0.61	0.51	0.26	0.20	0.17	10.63	10.28	9.94
September	10.94	10.49	10.13	0.56	0.41	0.36	0.19	0.14	0.12	10.56	10.21	9.88
October	10.80	10.38	10.02	0.43	0.30	0.26	0.14	0.10	0.09	10.51	10.17	9.85
November	10.67	10.28	9.95	0.30	0.21	0.18	0.10	0.07	0.06	10.47	10.14	9.83
December	10.56	10.20	9.90	0.19	0.12	0.13	0.06	0.04	0.04	10.44	10.11	9.81

Table 3. Proposed upstream boundary conditions for "increased upstream inflow" scenarios, approximating the influences of environmental flows on a scale of 1/3 of the Minute 319 pulse flow.

Month	Adjusted Elevation and Month			
	P-9	P-11	P-12	Mean
January	10.44	10.11	9.81	10.12
February	10.40	10.09	9.79	10.09
March	10.38	10.08	9.76	10.07
April	10.37	10.07	9.77	10.07
May	11.35	11.36	10.07	10.93
June	11.30	11.03	10.27	10.87
July	10.92	10.60	10.20	10.57
August	10.75	10.41	10.06	10.40
September	10.63	10.28	9.94	10.28
October	10.56	10.21	9.88	10.22
November	10.51	10.17	9.85	10.18
December	10.47	10.14	9.83	10.15

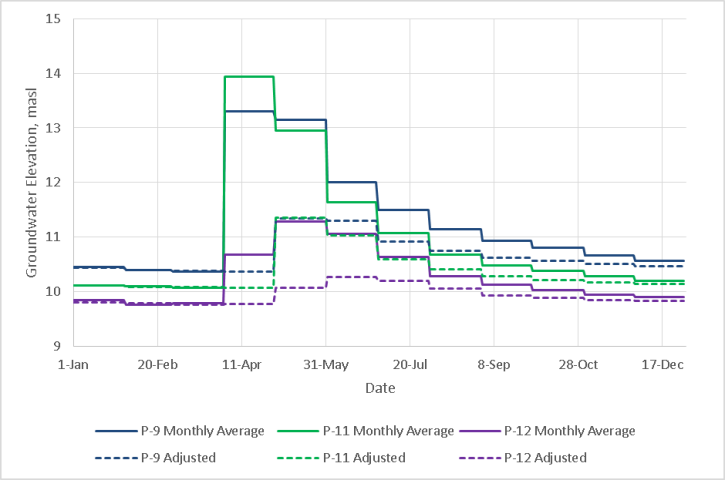


Figure 23. Mean monthly groundwater elevation for representative 2014-2015 data for P9, P11, and P12 data (solid lines) and scaled, seasonally adjusted groundwater levels in increased upstream inflow scenarios.

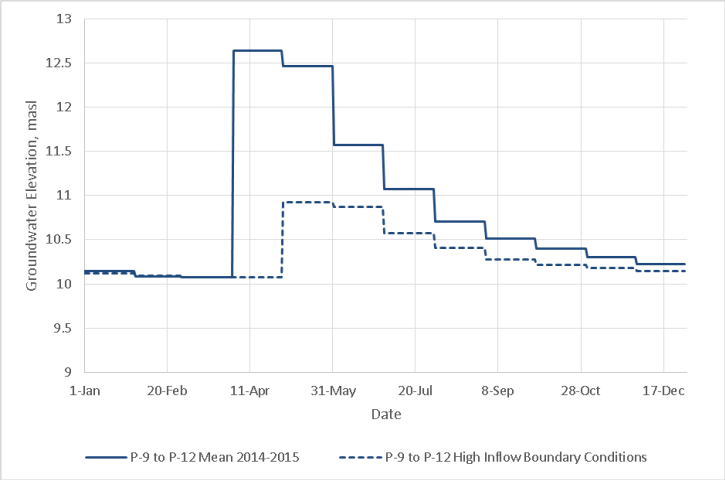


Figure 24. Mean monthly groundwater elevation for representative 2014-2015 data averaged across P9, P11, and P12 (solid lines) and scaled, seasonally adjusted groundwater levels in increased upstream inflow scenarios.

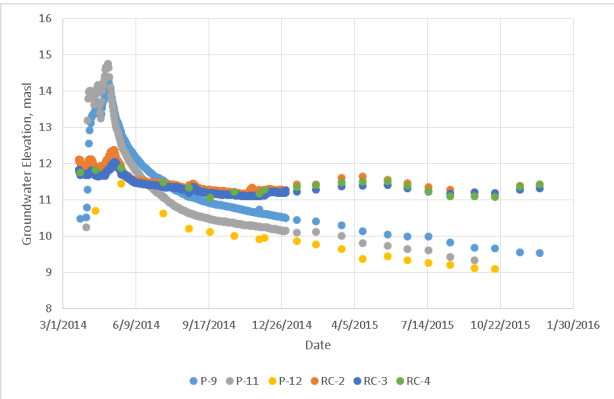
b) Decreased upstream subsurface inflow

Decreased upstream subsurface inflow could be caused by a reduction in agricultural water applications upstream in the U.S. and Mexico (either due to fallowing or less water available for irrigation, similar to the decreased agricultural return flow scenarios, but on a larger scale) and/or increased groundwater pumping in the limitrophe region in the U.S. and Mexico.

To obtain a realistic low inflow boundary condition for Reach 4, we estimated what groundwater conditions might have been at the Reach 3 P9-P12 piezometer transect during low flow periods. Based on prior analysis for Reach 4, the deepest (lowest-elevation) groundwater period we have data for is 2005 to 2007. However, the P9-P12 piezometers were installed in March 2014, and 2005-2007 data are unavailable. To approximate low-inflow boundary conditions (equivalent to deepest groundwater at P9-P12), we used relative differences between piezometer transects RC1-4 (in Reach 4; see Figure 18) and P9-12 during 2014 and 2015.

First we compiled and plotted data for RC1-RC4 and P9-P12 to compare and assess groundwater trends. The groundwater response during the pulse flow was much greater (higher rate of increase and to higher groundwater elevation) in the upper transect (P9-P12) compared to the lower transect (RC1-4) (Figure 25). However, groundwater levels declined rapidly in the P9-P12 transect, and after August 2014, the groundwater gradient reversed, so that groundwater elevation was higher in mid Reach 4 than in lower Reach 3. Based on limited data, this appears to have been the relationship prior to the pulse flow as well.

Plotting the difference in mean groundwater elevation between the transects (Figure 26) shows that the difference in groundwater levels had more or less stabilized beginning in April 2015, with a groundwater elevation approximately 1.7 m higher for RC2-RC4 than for P9, P11, and P12. These results suggest that we could approximate the low-flow upstream boundary conditions by setting the water elevation at P9-P12 to 1.7 m lower than the 2005-2007 monthly means for RC1-RC4 (shown in Figure 27 as depth to groundwater).



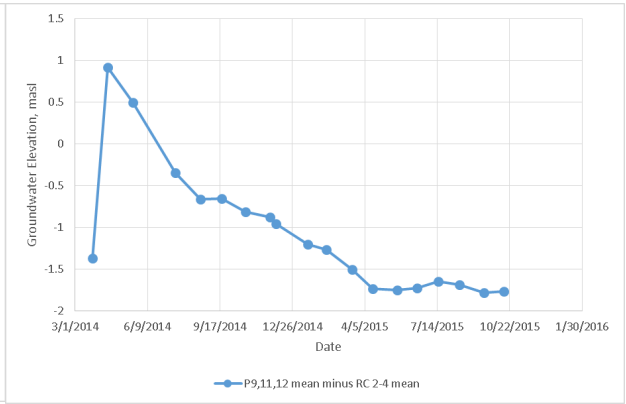


Figure 25. (left) Pressure transducer and manual measurements of groundwater elevation in 2014 and 2015. Figure 26. (right) The difference in mean groundwater elevation between the P9- P12 transect and the RC2-4 transect. Note that only one P9 data were available in the P9-12 transect for the March 2014 data point.

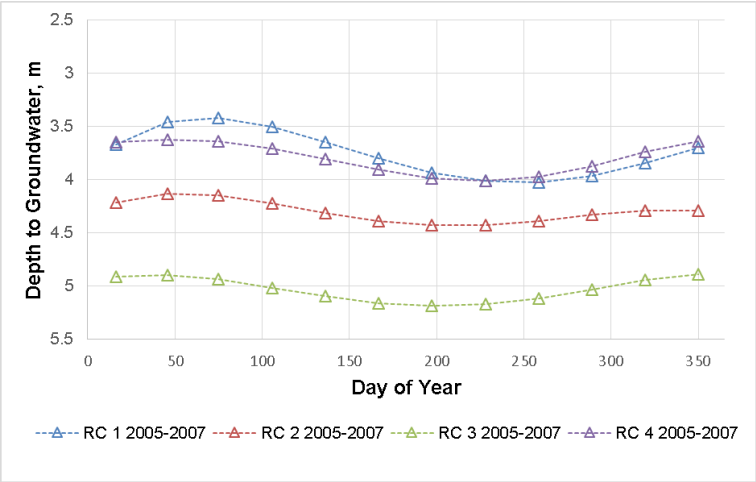


Figure 27. Previously developed depth to groundwater curves to approximate 2005-2007 monthly means for transect RC1-RC4.

We then converted the depth to groundwater data to groundwater elevation to obtain the monthly mean groundwater elevation at the RC1-RC4 transect for 2005-2007. To approximate the mean groundwater elevation at P9-P12, 1.7 m was subtracted from each monthly average. The resulting curves are plotted in Figure 28.

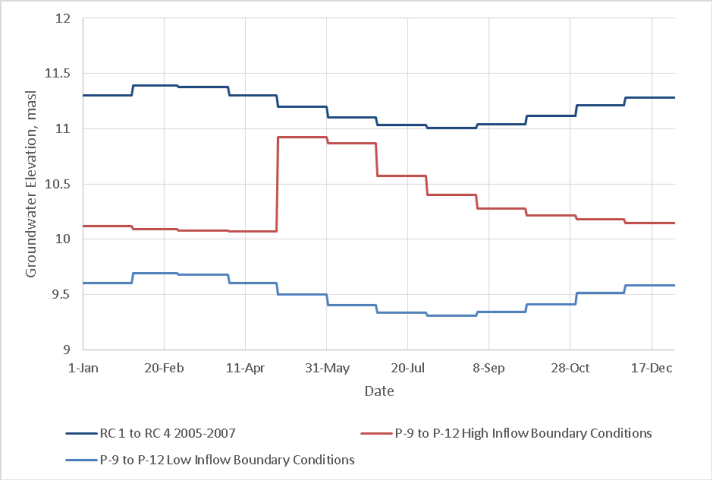
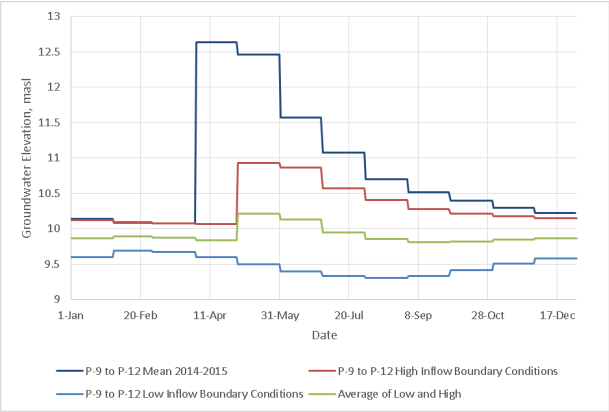


Figure 28. RC1-RC4 2005-2007 data plotted with proposed increased inflow and decreased inflow boundary condition curves.

c) Baseline upstream subsurface inflow

The scenario of moderate upstream subsurface inflows would most likely represent a typical year of agricultural water applications and water management in 2005-2007 (baseline).

To obtain baseline inflow boundary conditions, we first considered using the mean of the decreased and increased inflow boundary condition curves for the entire year. As shown by the groundwater curves (Figure 29), using the mean of the increased and decreased inflow scenarios for the moderate inflow would result in an increase in groundwater elevation beginning in May, which would indicate some inflow of water from upstream (not desired to be included in the model of intermediate inflow boundary conditions). Thus to create the final curves, we used the mean of increased and decreased inflow boundary conditions for January through April and September through December, and then used a linear interpolation to develop upstream groundwater elevation curves between May and August. The final curves are shown in Figure 30, and presented in Table 4.



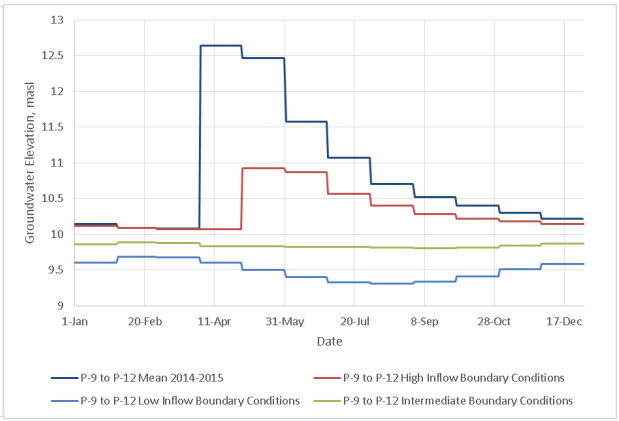


Figure 29. Potential increased, decreased, and baseline upstream inflow curves, using the mean monthly groundwater elevation to obtain the intermediate conditions
Figure 30. Final increased, decreased, and baseline upstream inflow curves

Table 4. Final baseline, increased, and decreased upstream subsurface inflow scenarios, represented by the mean elevation above sea level at the P9-P12 transect in lower Reach 3.

Month	Groundwater Elevation (m)		
	Increased Inflow	Decreased Inflow	Baseline Inflow
January	10.12	9.60	9.86
February	10.09	9.69	9.89
March	10.07	9.68	9.88
April	10.07	9.60	9.84
May	10.93	9.50	9.83
June	10.87	9.40	9.83
July	10.57	9.33	9.82
August	10.40	9.31	9.81
September	10.28	9.34	9.81
October	10.22	9.41	9.82
November	10.18	9.51	9.85
December	10.15	9.58	9.87

3.3.4. Riparian corridor evapotranspiration

Three different riparian evapotranspiration (ET) scenarios were modeled in this project. The first (baseline) assumes current vegetation composition and environmental conditions. The increased ET scenario was used to model potential changes that could occur due to climate change (hotter and drier) and/or vegetation composition changes (revegetation of saltcedar areas with some portion of native riparian trees, which may use more water). The decreased ET scenario was used to model potential impacts of saltcedar removal and/or the arrival of the saltcedar leaf beetle. Due to the different active restoration plans across environmental flow scenarios, different vegetation class assignments were also required depending on the environmental flow input scenario. Additionally, in low and high baseflow scenarios, active restoration areas would be irrigated, and a recharge component was included. Finally, there is some active agricultural land

in the riparian corridor, which would also experience recharge. This following sections detail how these model inputs were assigned across scenarios.

Riparian Evapotranspiration in the Colorado River Delta

To inform input scenarios for the Reach 4 groundwater model, we compiled estimates presented in the literature or used for US Bureau of Reclamation regional water budgets (Table 5). ET estimates in the literature vary widely for several reasons, including different data collection methods (e.g. remote sensing versus ground-based) and geography (ET rates are higher in hotter, drier regions). In some cases, annual estimates must be calculated or inferred, as estimates are often presented for different timeframes (annual, monthly, or daily).

Table 5. Range of annual evapotranspiration rates by habitat type presented in key literature.

Habitat Type	Annual ET, m/year	Citations
Open Water	1.8	Lower Colorado River Water Accounting[1]
Marsh	1.8-1.95	Lower Colorado River Water Accounting; Glenn et al. 1995
Cottonwood-Willow	1.2-1.56+	Nagler et al. 2005; Nagler et al. 2007; Nagler et al. 2008; Dahm et al. 2002; Hartwell et al. 2010
Mesquite	1-1.11	Nagler et al. 2005; Lower Colorado River Water Accounting
Saltcedar	0.75-1.2	Dahm et al. 2002; Lower Colorado River Water Accounting; Murray et al. 2009; Nagler et al. 2005
Bare Ground	0.83	Lower Colorado River Water Accounting

[1]See http://www.usbr.gov/lc/region/g4000/wtracct.html.

Due to these variations, we determined that the most appropriate way to estimate monthly ET for Reach 4 of the Colorado River Delta was to use methods developed and used by the Bureau of Reclamation for Lower Colorado River Water Accounting (LCRWA) (Bureau of Reclamation 2016). LCRWA was developed specific to this region, using data collected along the lower Colorado.

For this process, the Bureau of Reclamation uses crop coefficients (K_c) to estimate daily actual ET (ET_a) from reference ET (ET_0), as follows:

$$\mathrm{ET_a} = \mathrm{ET_0} \times \mathrm{K_c}$$

Daily crop coefficients are assigned based on habitat type ("crop"), such that plant communities that use more water (e.g. marsh, open water, and cottonwood-willow) have higher K_c values than plant communities that use less water (sparse saltcedar, barren soil). LCRWA daily K_cs are based on numerous local datasets. A K_c is provided for each crop (habitat type) for day-of-year 1 through day-of-year 365. Table 6 presents the crops used for LCRWA and the Anderson and Ohmart (1984)-based riparian cover types (hereafter A-O cover type) they are used to represent. The A-O cover types correspond to the vegetation cover maps and shapefiles for Reach 4 provided through Minute 319.

Table 6. Crop names used for Lower Colorado River Water Accounting, and the Anderson and Ohmart cover types they are applied to. Provided by the US Bureau of Reclamation (Jeff Milliken, Remote Sensing and GIS Scientist, US Bureau of Reclamation, Lower Colorado Regional Office).

LCRWA Crop	Anderson and Ohmart Cover[1]
USGS Barren	Bare Ground
Mixed Veg Low	Atriplex
Mixed Veg Low	Arrowweed
Cottonwood-Willow	Cottonwood-Willow
Marsh	Marsh
Saltcedar Dense	SC-I; SC-II; SC-III
Mixed Veg Medium	SC-IV; SC-V
Mixed Veg Low	SC-VI
Saltcedar Dense	SM-I; SM-II; SM-III
Mixed Veg Medium	SM-IV; SM-V
Mixed Veg Low	SM-VI
Saltcedar Dense	HM-I; HM-II; HM-III
Mixed Veg Medium	HM-IV
Mixed Veg Low	HM-V; HM-VI
Saltcedar Dense	SH-I; SH-II; SH-III
Mixed Veg Medium	SH-IV
Mixed Veg Low	SH-V; SH-VI

[1]See Anderson and Ohmart (1984)

For groundwater modeling in this project, we required monthly ET_a estimates, which we obtained through a two-step process:

- Obtain representative estimates for ET_0.
- Apply K_c values to convert ET_0 to ET_a.

We downloaded all available daily ET_0 and precipitation data for The University of Arizona Meteorological Network (AZMET 2016) weather stations closest to Reach 4. These stations are Yuma North Gila, Yuma Valley, and Yuma South. Data are available for Yuma North Gila and Yuma Valley beginning in January 1999. Data collection at Yuma South began in 2010, and lacks data for the summer of 2013. Therefore, we analyzed data for only the Yuma North Gila and Yuma Valley weather stations for this project.

The ET_a equation presented above was then applied for each weather station, day, and crop for January 1, 1999 through December 31, 2015. The data were summed by month across years (i.e. the total ET_0 and ET_a was obtained for each month for the 16 years), and then averaged by month to obtain the average ET0 and ETa on a monthly timestep. Finally, we obtained the mean monthly ET0 and ETa between Yuma North Gila and Yuma Valley (Figure 31 and Table 7). Results of this analysis, especially annual ET rates, correspond well to literature values. This provides additional confidence in using this method to generate ET estimates for groundwater models in the Colorado River riparian corridor in Mexico. However, it should be noted that the presented values provide the *average* expected ET rates. The ET for a given cover type will vary

based on local conditions, principally the depth of groundwater (shallow groundwater enhances water availability for woody plant cover and understory species, thereby promoting increased ET rates).

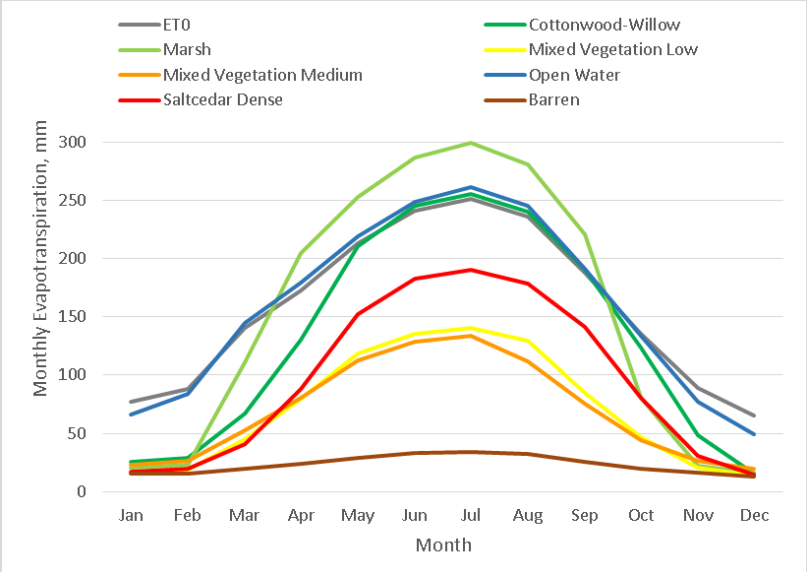


Figure 31. Estimated mean monthly evapotranspiration by land cover type for the Yuma area based on 1999-2015 data for the Yuma Valley and Yuma North Gila AZMET weather stations.

Table 7. Mean monthly reference evapotranspiration, and estimated evapotranspiration for cover types in the Colorado River Delta based on Yuma Valley and Yuma North Gila AZMET weather station data (1999-2015) and Bureau of Reclamation Lower Colorado Accounting crop coefficients.

Month	ET_0, mm	Estimated Monthly Evapotranspiration by Crop, mm						
		Cottonwood-Willow	Marsh	Mixed Vegetation Low	Mixed Vegetation Medium	Open Water	Saltcedar Dense	Barren
Jan	77	26	20	16	23	66	17	15
Feb	88	29	23	19	27	84	20	16
Mar	140	67	111	45	52	145	40	20
Apr	173	130	205	80	80	179	88	23
May	213	210	253	119	113	219	153	29
Jun	241	245	287	135	129	248	183	33
Jul	252	256	299	141	134	262	190	34
Aug	236	240	280	129	112	245	179	32
Sep	188	191	221	85	75	191	141	26
Oct	135	123	80	47	44	134	80	19
Nov	89	49	22	21	27	77	31	16
Dec	65	15	16	13	20	49	15	13
Total	**1,896**	**1,581**	**1,818**	**849**	**836**	**1,900**	**1,136**	**276**

Evapotranspiration Inputs for the Reach 4 Groundwater Model
We are aware of two model packages used to incorporate ET into Modflow groundwater models. First, the standard Modflow ET package can be used to assign one "maximum" ET rate to each model grid cell for each time step. This maximum ET is achieved when groundwater is at the ground surface (0 m depth to water). The ET rate then decreases to a rate of 0 at the "extinction depth." The extinction depth is assigned to specify the groundwater depth at which direct ET of groundwater would cease (i.e. deeper than accessible by phreatophyte roots). A linear decline in ET is assumed between the maximum ET flux at 0 m depth to water and the extinction depth. This ET package automatically incorporates groundwater depth and ET feedbacks. For example, if groundwater depth decreases due to changes in model inputs, ET rates increase. This results in a groundwater depth increase, which reduces ET. This iterative process repeats until the feedbacks reach equilibrium and a final groundwater depth is found.

There are two primary limitations to using this standard ET package. First, the linear relationship between groundwater depth and ET rate is not accurate; the actual relationship is curvilinear (Baird and Maddock 2005). The second limitation is that one ET rate must be assigned to each model cell. Therefore, curves for different A-O cover types within a polygon (due to groundwater/ET relationships that vary by cover type) cannot be accommodated. The assumption must be made that cover type would change with a change in groundwater depth. This assumption is valid for some cover types. For example, if a non-marsh or open water cover type becomes inundated, the cover type would then change to marsh or open water, and it would immediately exhibit ET rates of the new cover type. However, vegetation type changes (e.g. saltcedar to cottonwood-willow) are not likely to occur just by a change in groundwater depth.

The second ET package option is to use the add-on RIP-ET package, as described by Baird and Maddock (2005). Using RIP-ET, segmented linear relationships can be prescribed to provide a curvilinear approximation of the relationship between ET and groundwater depth. Additionally, fractional cover types can be accommodated within each model grid cell. There are two primary limitations with this method. First, detailed curves must be developed for each cover type, for which limited data are available, and a maximum possible ET must be assigned for each cover type, for which data are not typically available. As previously described for Table 5, presented literature values are typically average or representative rates, not the maximum possible ET. There are also limited datasets available to establish curvilinear relationships between depth to groundwater and ET by cover type. Due to these factors, ET errors in the model are not likely to be any lower than those anticipated from the standard ET package. Second, in the case of the riparian area, cover types will sometimes change as a result of model scenarios. For example, an area that is barren could become open water and thus require a re-assignment of cover type and ET curve.

Given these limitations, we determined that the standard ET package presents the optimal combination of accuracy and feasibility for this project.

ET Model Input Development Process
The goal of ET input development was to allow the model to assess the impacts of a change in ET of saltcedar. The ET change could be an increase, representing conversion of saltcedar to

native vegetation, or a decrease, representing defoliation of saltcedar by the saltcedar leaf beetle. Thus we developed three different annual ET curves:

- Native vegetation types
- Saltcedar without beetle impacts
- Saltcedar following defoliation by the leaf beetle

To develop the three ET curves, we used an iterative process to determine which maximum ET rate (ET for a given cover type when the depth to groundwater is 0 m) would result in an ET rate that approximates the LCRWA ET estimate at a groundwater depth representative of where cover types were observed in Reach 4. For saltcedar cover types, we started with the assumption of a maximum annual ET of 1.5 m per year (this approximates the maximum annual values found in the literature). Then we scaled the monthly LCRWA-estimated ET accordingly to determine a maximum monthly ET (depth to water of 0 m all year) for all saltcedar cover types. The LCRWA ET for saltcedar dense was 1.136 m/year instead of 1.5 m/year. To achieve a maximum annual ET of 1.5 m, we increased each monthly ET depth by 32%.

For non-saltcedar cover types, we assigned a maximum monthly ET of the A-O cover type with the highest monthly ET. For April through September, the cover type with highest ET is marsh, and for all other months it is open water. The result was a maximum annual ET (depth to water less than or equal to 0 m) of 2.1 m.

We looked at various potential extinction depths to see how they corresponded to LCRWA ET estimates by cover type. Using an extinction depth of 8 m for both ET curves provided reasonable outputs:

- Open water/Marsh ET was approximated when the year-round depth to groundwater was 0.5 m.
- Cottonwood-Willow and Saltcedar average ET was approximated when the year-round depth to groundwater was 2 m.
- Mesquite average ET was approximated when the year-round depth to groundwater was between 4.5 and 5 m.
- Barren ground ET was approximated when the year-round depth to groundwater was 7 m.

Based on the analysis of existing cover types in the Delta (refer to Section 2), these are reasonable assumptions. Open water and marsh require water at or near the surface, and maximum cottonwood-willow cover occurred between 1.5 and 2 m depth to water.

To determine ET curves for saltcedar following defoliation by beetles, we used Liebert et al. (2016) to adjust baseline maximum saltcedar ET on monthly timesteps. For each month, we used the pre-beetle and post-beetle ET to determine a percent reduction in monthly ET. This analysis is presented in Table 8. This percent reduction was then applied to the maximum monthly saltcedar ET values.

Table 8. Monthly ET effects of saltcedar beetles, from Liebert et al. 2016.

Month	Monthly ET, mm			Percent Reduction
	Pre-Beetle	Post-Beetle	Reduction	
January	18	21	-3	-17
February	18	25	-8	-43
March	35	43	-8	-23
April	95	96	-2	-2
May	178	183	-5	-3
June	208	180	28	13
July	199	156	44	22
August	192	116	76	40
September	142	89	54	38
October	90	73	16	18
November	46	38	9	19
December	25	21	4	16
Annual	1245	1041	205	16

The maximum annual ET curves for each cover type (non saltcedar, saltcedar, and beetle-affected saltcedar) are presented in Figure 32. The maximum annual ET represents a scenario in which groundwater is at the surface for all months (this is the maximum potential difference between ET curves). Using the max annual ET monthly timesteps, we created cumulative annual evapotranspiration curves for a hypothetical 0 m depth to groundwater scenario (Figure 33).

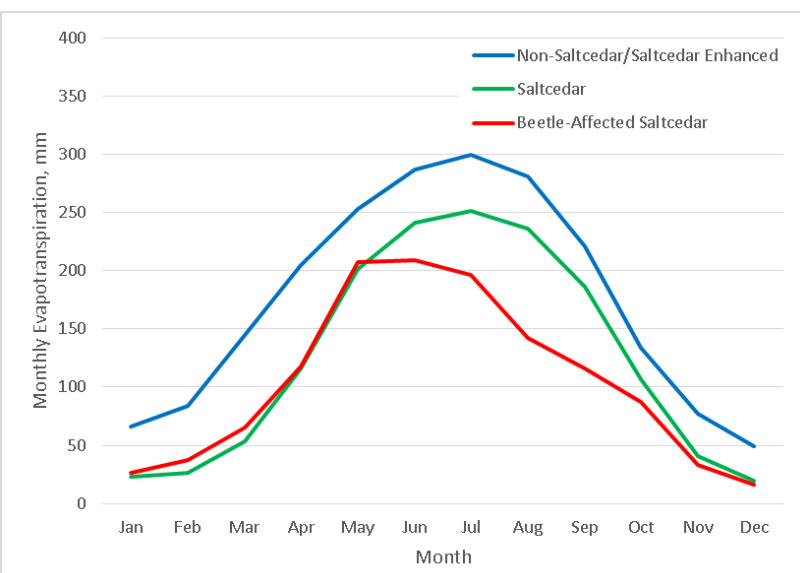


Figure 32. Maximum monthly (0 m depth to groundwater hypothetical example) evapotranspiration for the groundwater modeling scenarios.

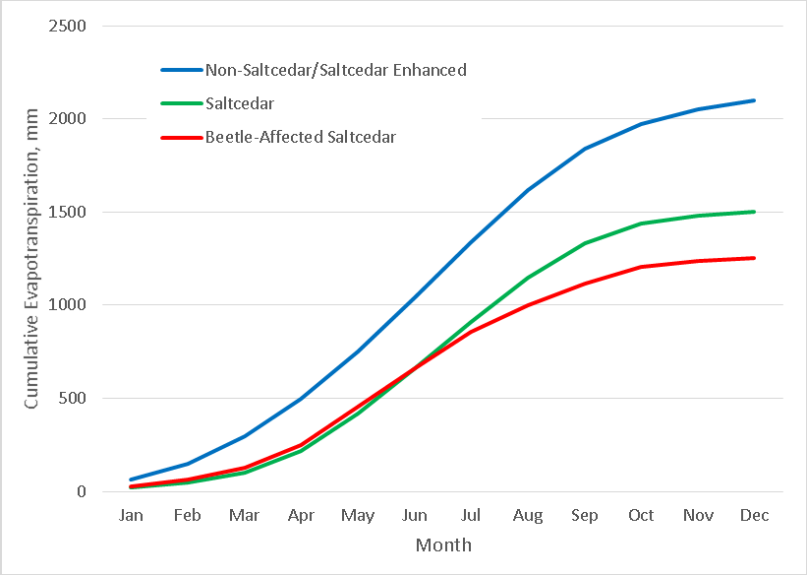


Figure 33. Maximum annual evapotranspiration (0 m depth to groundwater hypothetical example) for the groundwater modeling scenarios.

a) Baseline ET:

For the baseline ET model inputs, we used the fractional cover of saltcedar, non-saltcedar, and agricultural A-O cover types to determine the area-weighted maximum monthly ET in each model grid cell. ET of groundwater in agricultural areas within the corridor was assigned as 0 since a net recharge rate was assigned via recharge inputs (refer to Section 3.3.1).

b) Increased ET:

For the increased ET (or enhanced corridor) scenario, we used the non-saltcedar ET rates for all non-agricultural cover types. This assignment 1) allows the maximum ET to exceed saltcedar ET rates; and 2) results in a higher ET rate at all groundwater depths less than the extinction depth.

c) Decreased ET:

For the decreased ET (saltcedar beetle) scenario, we reduced the maximum saltcedar ET rate by monthly reductions presented by Liebert et al. (2016) and then re-constructed the fractional maximum ET by model grid cell to incorporate the beetle effects.

To get an initial assessment of potential effects of ET changes in the riparian corridor, we assess the impacts given 0 m depth to groundwater for all months of the year across the entire corridor. Because depth to groundwater will be greater than 0 for most areas, these represent higher ET values and bigger differences than were expected from model outputs. Monthly ET volumes for baseline, increased, and decreased ET scenarios are presented in Figure 34.

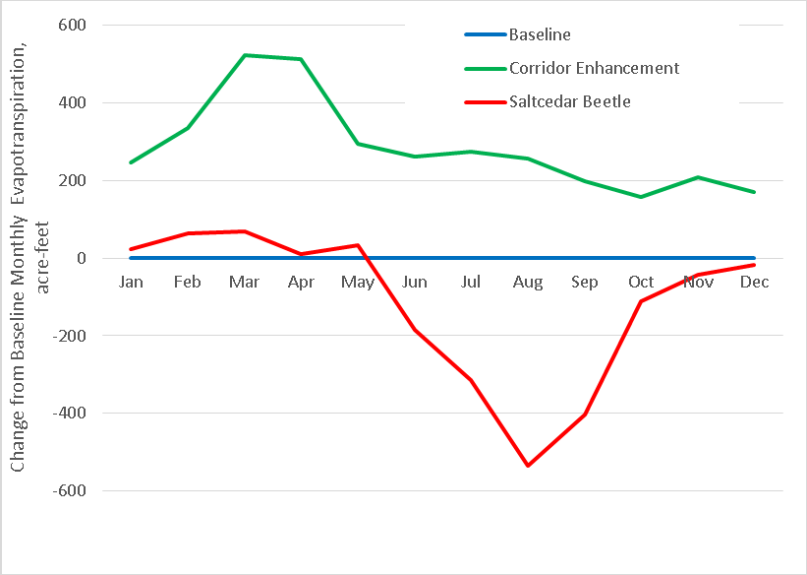


Figure 34. Change in monthly ET volumes predicted by different vegetation scenarios given the above specifications and a depth to groundwater less than or equal to 0 m for all grid cells for all months.

Additionally, we took into account the base flow and restoration irrigation application when determining ET model inputs. The volume of environmental flow deliveries will affect the amount of restoration area and thus vegetation cover in Reach 4. Restored areas were always assigned the riparian ET values since they will not be the saltcedar A-O cover type. For the scenarios without environmental flow deliveries, we used restoration areas that were present in 2013. In these scenarios, riparian restoration areas will not be irrigated. Therefore, for the scenarios with no restoration irrigation inputs, we eliminated groundwater recharge in current or proposed future irrigated restoration sites. Recharge from agriculture in the riparian corridor was still included. There are three different recharge inputs for the no baseflow scenario that relate to baseline agricultural recharge, decreased agricultural recharge, or increased agricultural recharge for scenarios that have no baseflow.

For the low or high environmental flow scenarios, new restoration sites would change vegetation cover. The three different ET inputs for the low and high environmental flow scenarios were adjusted to reflect the fractional cover of each model grid cell that would be restored. Additionally, irrigated restoration would experience recharge. We included a recharge component for the portions of model grid cells that would fall within irrigated restoration sites. We assumed 20% of water delivered as irrigation would become recharge, equal to the recharge rate assigned for agriculture under the baseline agricultural return flow scenarios. Non-irrigated portions of the restoration sites were assigned a recharge rate of 0.

3.4. Model Input Volumes

Based on the development of model inputs described in previous sections, monthly water input volumes were specified for each category/level and integrated into the model. A summary of the total annual water volume for the input categories of agricultural return flows, riparian corridor ET, and environmental flow deliveries is provided in Table 9. Note that the upstream subsurface inflows volume is not provided; this category was integrated into the model by altering the

model upper boundary condition. Also note that volumes listed for riparian corridor ET scenarios do not represent the actual model inputs; values presented are the total annual volume of water evapotranspired under the different scenarios.

The comparison of these volumes provides an initial indication of the magnitude of impact each category/level may have on depth to groundwater and habitat potential. For example, the difference between the increased and the baseline agricultural return flows levels is approximately 9,000 acre-feet and the difference between the baseline and decreased is 8,000 acre-feet. On the other hand, the difference between the baseline and increased ET levels is approximately 3,000 acre-feet, and approximately 5,000 acre-feet for the decreased to baseline comparison. Environmental flow volumes have a magnitude of 4,000 acre-feet in the low flow scenario to nearly 16,500 for the high flow scenario. The annual water volumes presented however do not adequately reflect the monthly variation in inputs, which ultimately drive the final model groundwater elevation outputs.

Table 9. Total annual water volume for model input categories/levels. Note that the upstream subsurface inflows volume is not provided; this was integrated into the groundwater model by altering the upper boundary condition.

Input Category	**Input Level**	**Total annual volume (acre-feet)**
Agricultural Return Flows	Baseline	37,426
	Increased	56,140
	Decreased	28,070
Riparian Corridor ET	Baseline	36,011
	Increased	39,446
	Decreased	34,603
Environmental Flow Deliveries	None	0
	Low	3,897
	High	16,497

3.5. Scenario Selection for Modeling

For each groundwater model input category (agricultural return flows, ET, environmental flow, and upstream inflows), there were three levels (baseline/none, decreased/low, increased/high), which made for total of 81 possible model input combinations, or scenarios (see groundwater scenario matrix (Table 10). The actual modeling component of this project (see next section) was conducted by the UABC, a Mexican university, and thus was not supported by project funds (direct or matching). Due to the extensive time and associated costs required to run all 81 scenarios in the groundwater model by the UABC, and the limited outside funds available for this work, we selected a subset of scenarios to model.

Table 10. Scenario matrix for Reach 4 groundwater assessment model.

Input Category	Input Level	Input Amount	Data Inputs
Agricultural Return Flows	Baseline	20% return of 2005-2006 ag deliveries	Monthly recharge assigned by irrigation district (assigned flux boundary conditions). Ag areas within the riparian corridor included in the model by assigning monthly recharge rates for parcels. Assumed the average recharge rates of the three irrigation districts outside the corridor (i.e. each ag polygon in the corridor was not assigned to a district).
	Increased Return Flows	30% return of 2005-2006 ag deliveries	
	Reduced Return Flows	15% return of 2005-2006 ag deliveries	
Riparian Corridor ET[1]	Baseline	Current (based on data being compiled for Minute 319), variable by month	**If no environmental flows**, max ET values based on A-O scale Minute 319 veg classifications from Jeff Milliken. ET of 0 for agricultural areas in corridor. Max potential annual ET for saltcedar cover types set at 1.5 m/year, for non saltcedar cover types 2.1 m/year, both with extinction depth of 8 m.
			If low or high environmental flows, adjusted Veg classifications based on projected restoration (some saltcedar areas changed to non-saltcedar). No ET assigned for agricultural areas in corridor. Max potential annual ET for saltcedar cover types set at 1.5 m/year, for non saltcedar cover types 2.1 m/year, both with extinction depth of 8 m.
	Increased ET	Saltcedar converted to mixed native habitats on the A-O scale, variable by month	**For all environmental flow scenarios**, all non-ag portions of the riparian corridor assigned the non-saltcedar ET formula, with maximum annual ET of 2.1 m, extinction depth of 8 m.
	Decreased ET	ET reduced in saltcedar A-O scale cover types based on saltcedar beetle effects, variable by month	**If no environmental flows**, reduced saltcedar ET based on A-O scale Minute 319 veg classification from Jeff Milliken. Maximum ET reduced from 1.5 m/year to 1.3 m/year. Extinction depth of 8 m. No changes to ag.
			If low or high environmental flows, beetle effects not included in areas that would be restored in the 5-year time horizon. Saltcedar areas that would be restored are assigned the higher maximum potential ET rate of 2.1 m/year. No changes to ag.
Environmental Flow Deliveries	None	0	No restoration site irrigation, no deliveries to meanders or river channel.
	Low Levels	3,897 af/year, variable by month	Assigned monthly irrigation volumes by restoration site (2,359 acre-feet per year total). Included in the model by assigning 20% recharge of irrigation deliveries. Backwater flow deliveries (1,538 acre-feet per year total) included in the model by assigning hydraulic head values at meander delivery locations.
	High Levels	16,497 af/year, variable by month.	Monthly irrigation and backwater deliveries from "low levels" scenario above included, along with direct river inputs at the KM18 spillway between June and October, represented in the model by assigning hydraulic head values at channel delivery locations.

Upstream Subsurface Inflow	Moderate/ Baseline	Average of the inflows below, excluding periods affected by spring flows	Assigned groundwater elevations by month for the P-9 to P-12 piezometer transect in lower Reach 3. Mean of decreased and increased scenarios between September and April, linear interpolation between April and September.
	Decreased Subsurface Inflow	Estimated 2005-2007 upstream boundary groundwater conditions	Mean P-9 to P-12 transect groundwater elevation estimated as 1.7 m lower than the RC-1 to RC-4 groundwater elevations in 2005-2007. Peak of 9.7 m in February, lowest 9.3 m in August.
	Increased Subsurface Inflow	1/3 of groundwater elevation increase seen during the Pulse Flow	Mean P-9 to P-12 elevation peak of 10.9 m in May, lowest of 10.1 m in April.

First, we ran the baseline scenario (all inputs at baseline or none) and then a subset of scenarios to test the sensitivity of groundwater levels to each model input category at high and low levels while all other components were maintained at baseline. This was a way in which to assess the relative importance of each input category and use the results as a basis for determining what additional scenarios should be modeled. The initial scenarios included the following:

1) **Baseline:** baseline agricultural return flows; baseline ET (with no environmental flows); no environmental flows, baseline upstream inflows.
2) **Baseline plus increased ag**: increased agricultural return flows; baseline ET (with no environmental flows); no environmental flows, baseline upstream inflows.
3) **Baseline plus decreased ag:** decreased agricultural return flows; baseline ET (with no environmental flows); no environmental flows, baseline upstream inflows.
4) **Baseline plus increased upstream boundary condition (inflow):** baseline agricultural return flows; baseline ET (with no environmental flows); no environmental flows, increased upstream inflows.
5) **Baseline plus decreased upstream boundary condition (inflow):** baseline agricultural return flows; baseline ET (with no environmental flows); no environmental flows, decreased upstream inflows.
6) **Baseline plus increased ET:** baseline agricultural return flows; increased ET; no environmental flows, baseline upstream inflows.
7) **Baseline plus decreased ET:** baseline agricultural return flows; decreased ET (with no environmental flows); no environmental flows, baseline upstream inflows.
8) **Baseline plus low environmental flows:** baseline agricultural return flows; baseline ET (with low environmental flows); low environmental flows, baseline upstream inflows.
9) **Baseline plus high environmental flows:** baseline agricultural return flows; baseline ET (with high environmental flows); high environmental flows, baseline upstream inflows.

Results of these scenarios (further discussed in Task 3) showed that changes in ET had little to no impact on groundwater elevations, while changes in agricultural return flows and environmental flows had significant impacts. Based on these results, we decided to run the following additional scenarios in the groundwater model, so that a total of 14 scenarios were modeled.

10) **Worst case scenario:** decreased agricultural return flows; baseline ET (with no environmental flows); no environmental flows; decreased upstream inflows
11) **Worst case plus low environmental flows:** decreased agricultural return flows; baseline ET (with low environmental flows); low environmental flows; decreased upstream inflows
12) **Worst case plus high environmental flows:** decreased agricultural return flows; baseline ET (with high environmental flows); high environmental flows; decreased upstream inflows

13) **Decreased ag plus low environmental flows:** decreased agricultural return flows; baseline ET (with low environmental flows); low environmental flows; baseline upstream inflows
14) **Decreased ag plus high environmental flows:** decreased agricultural return flows; baseline ET (with high environmental flows); high environmental flows; baseline upstream inflows

3.6. Groundwater Model

Based on the above development of model inputs, the project team worked with UABC scientists (via teleconference and meetings in the U.S.) to assure that model scenarios were designed and implemented correctly to support delineation of areas that will support native riparian vegetation.

Rodríguez-Burgueño (2012) initially developed a groundwater flow model of the Mexicali Valley aquifer using Local Grid Refinement (LGR) package of MODFLOW 2005 software. The objective of the model was to develop a child model of the lower area of Reach 4 from a parent model of the regional aquifer in order to obtain useful data for restoration purposes. To accommodate the current project scope, UABC revised and developed a new parent model (cell size 2 km^2 with refined area cell size of 375 m^2) and child model (minimum cell size of 125 m^2; maximum cell size 125 x 666 m) (Figure 35) based on the previous model (Rodríguez-Burgueño, 2012). For the parent model, a new data set of information was created in order to evaluate different scenarios. The child model was extended to encompass the entire Reach 4 area, including in the model domain areas outside the riparian corridor.

Input data to the model were developed in a GIS database, including recharge, evapotranspiration, upstream flow boundary condition, and baseflows. The GIS files were then imported into Model Muse with the monthly values for each file according to the prescribed scenario; a monthly time-step was used for simulations. Recharge (RCH package) data included two different data sets: 1) recharge from the infiltration of water deliveries from the agricultural irrigation district; and 2) recharge from agriculture lands inside the riparian corridor. Evapotranspiration was added to the model using an ET package, which incorporated evapotranspiration rate (according to the scenario), evapotranspiration surface from LiDAR data, and extinction depth (8 m). River surface water elevations for baseflow inputs were obtained from HecRas simulations for flow deliveries from 11 delivery locations along Reach 4. Based on the HecRas results, surface water elevation data for each scenario was incorporated into the model using the river package (RIV). Upper boundary conditions were altered using the time-variant specified-head package (CHD).

Additional information on the UABC groundwater model can be found in the model report (Appendix 2).

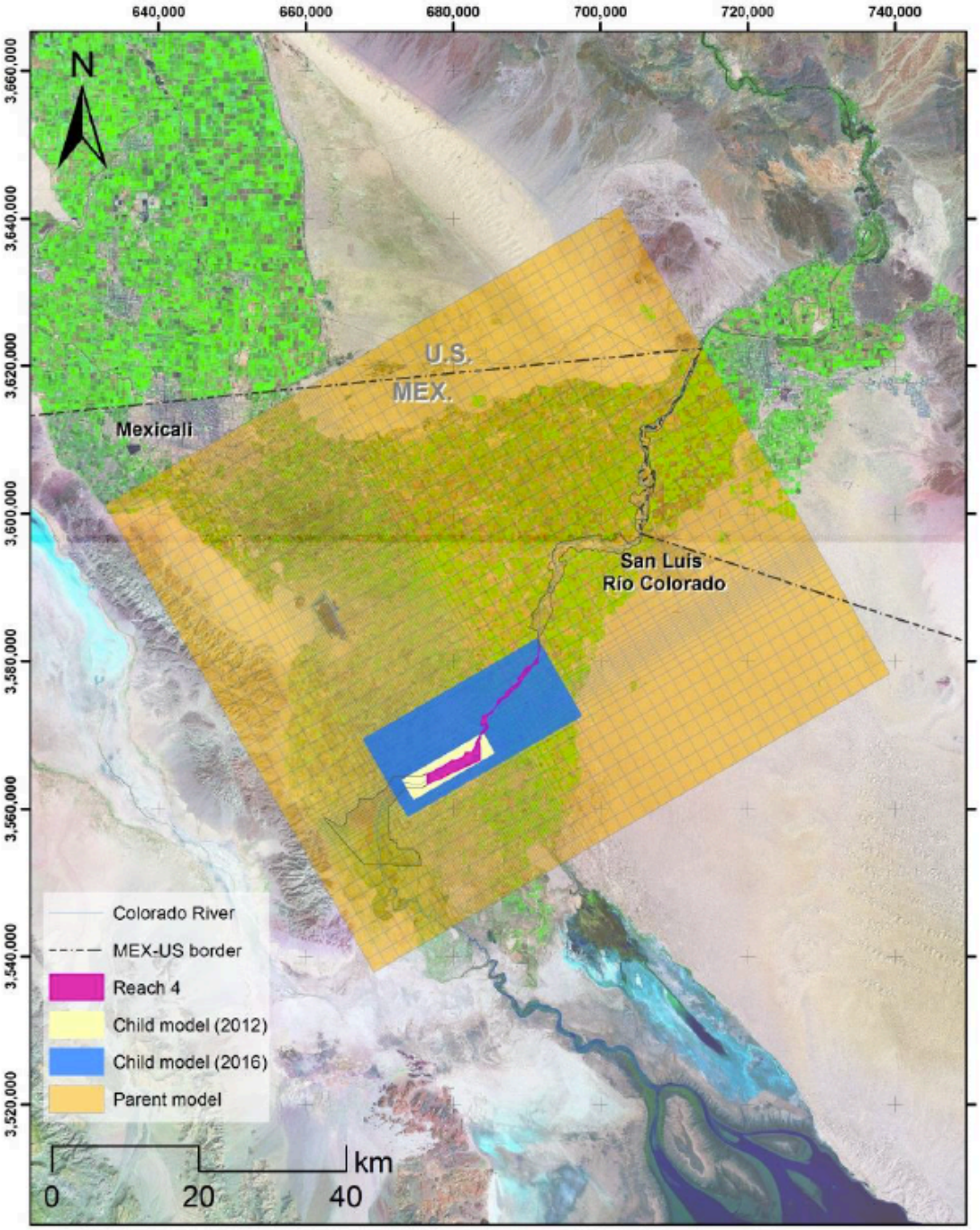


Figure 35. Domain of the groundwater model of the Mexicali Valley aquifer (parent) and child model domains.

4. Spatial Analysis of Model Results

4.1. Analysis Methods

To estimate the groundwater depth throughout Reach 4 for each modeled scenario, we overlaid LiDAR topography data with geo-referenced groundwater elevation outputs from MODFLOW. The resulting grid was reclassified to predict where groundwater would be 1) above ground surface (perennial aquatic habitat), 2) within 2.5 meters of ground level (cottonwood and willow habitat), 3) within 4 meters of ground level (mesquite bosque habitat), and 4) greater than 4 meters (non-riparian habitat). Results were used to develop maps of habitat spatial distributions and calculate the areas falling within the aquatic and riparian habitat categories.

We used the September groundwater elevation model outputs for processing and analysis. We initially proposed to map habitat distribution during the month of maximum depth to groundwater. The groundwater model predicted minimum depth to groundwater (shallowest groundwater) in May, with groundwater levels declining through November, when depth to groundwater was greatest across all model scenarios. However, by October and November, riparian trees in the Delta are entering dormancy and do not require groundwater; evapotranspiration levels are very low, as shown in Section 3.3.4 of this report. Instead of using November results, we used results from September, as during September, riparian vegetation is still actively transpiring.

4.1.1. Depth to groundwater

Model results from the selected 14 scenarios were processed using ARCMAP GIS tools to determine the predicted depth to groundwater (DTW) over the model area. A 1-meter digital elevation model (DEM) based on a post-pulse flow LiDAR survey was used to determine land surface elevation for the model area. The post-pulse DEM did not account for channel bathymetry, but rather, had a hydroflattened surface over the stream channel area. However, a pre-pulse flow DEM had incorporated bathymetry of the main river channel, but did not include bathymetry for any areas outside of the main river channel[1]. Bathymetry was estimated by subtracting a pre-pulse DEM (which incorporated bathymetry data) from the post-pulse DEM using the ARC GIS raster calculator tool with a 1-meter grid cell resolution. The resulting layer was clipped along the boundary of the wetted river channel, which was clearly identifiable in the output layer; the associated values represented channel depth. The estimated channel depth was then subtracted from the post-pulse DEM using the raster calculator tool to create a corrected post-pulse DEM where the channel bottom was represented as the land surface elevation over the wetted channel area.

Model results for all scenarios were converted from a shapefile grid to a raster layer using the ARCGIS 'convert to raster' tool. Subsequently, the model results raster (groundwater elevation) was subtracted from the corrected post-pulse DEM using the raster calculator tool to generate a

[1] Areas of low elevation exist in historic river meanders in Reach 4, which typically have surface water present year-round; however because bathymetry data were not available for these areas, estimates of depth to groundwater may not be accurate due to a hidroflattened LiDAR dataset.

raster layer representing the estimated depth to groundwater over the Reach 4 area for all scenarios. Results were first displayed using a color gradient to represent 0.5 m DTW increments to visualize spatial differences and also differences between scenarios.

The zonal histogram tool was then applied to the DTW results for each model output to evaluate the number of cells within each DTW increment for the Reach 4 area and the restoration areas. Each cell represented 1 m² in area, the same resolution as the LiDAR DEM. The resulting histograms were compiled in Excel and converted into acres for tabular summaries. These analyses were completed for the overall Reach 4 area and independently for the four restoration areas within Reach 4: Chausse, CILA, Cori, and Laguna Larga.

4.1.2. Difference from baseline

To better visualize impacts of altering the model inputs, we estimated the difference in predicted groundwater elevation of the "baseline" model scenario (with all inputs at baseline or 0) relative to alternative management scenarios. To find the difference, we subtracted the baseline scenario groundwater elevation from the alternative management scenario groundwater elevations for the Reach 4 area using the raster calculator tool. Results were displayed for each scenario using a color gradient (Appendix 3).

4.1.3. Habitat potential analysis

DTW histogram results were summarized in Excel to determine the areal extent (acres) for each habitat DTW threshold category, which included the following:

- Aquatic habitat (open water and marsh): DTW ≤ 0 m
- Cottonwood-willow habitat: > 0 and ≤ 2.5 m
- Mesquite bosque habitat: > 2.5 and ≤ 4.0 m
- Non-riparian habitat (desert shrub/upland): > 4.0 m

Areal summaries were produced for the total Reach 4 area and four restoration areas within Reach 4: Chausse, CILA, Cori, and Laguna Larga. Habitat potential maps were created for the 14 scenarios at two different scales: 1) Reach 4 study area and 2) the Laguna Grande restoration area, which encompasses CILA, Cori, and Laguna Larga (Appendices 4 and 5, respectively.)

4.2. Results

4.2.1. Difference from baseline

An initial assessment of difference from baseline figures for scenarios 2-9 (see section 3.4) was used to determine sensitivity of groundwater elevation to altered model inputs and decide which additional scenarios would be selected for modeling.

Results from the difference to baseline analysis for scenarios 2-9 showed the following:

- The increased agricultural return flow scenario (2) caused an increase in groundwater elevation up to 1.34 m in the lower section of reach 4 (in Laguna Grande), but had lesser impacts in the uppermost section (0-0.5 m change from baseline). The decreased agricultural return flow scenario (3) resulted in a decrease in groundwater elevation of up

to 0.7 m in the lowermost section of Reach 4, with lesser impacts in the uppermost section of Reach 4 (0 to -0.2 m change from baseline).

- Increasing/decreasing upstream inflows while holding other model inputs at baseline or zero (scenarios 4 and 5) caused an increase/decrease of groundwater elevations from 0.04 to 0.42 m, with the greatest difference in the uppermost section of Reach 4, and the least difference in the lowermost section of Reach 4.
- The increased and decreased ET scenarios (holding all other inputs at baseline or zero; scenarios 6 and 7) had little to no impact on groundwater elevations; difference to the baseline scenario ranged from 0.005 to 0 m.
- Low environmental flow inputs (scenario 8) caused an increase in groundwater elevation of up to 0.58 m in the lowermost section of Reach 4, which was not significantly less than the high environmental flow input scenario.
- High environmental flow inputs (scenario 9) increased groundwater elevation by 0.60 m in the lowermost section of Reach 4, but caused minimal groundwater increases in the uppermost section.

The results from the difference to baseline analysis for scenarios 2-9 led us to conclude that modeled ET effects were not significant. As such, we did not assess the effects of ET changes (i.e. they were maintained at baseline) in any of the additional scenarios selected for modeling.

Since the primary goal of this project is to determine potential impacts of climate and water management changes on groundwater and riparian habitat, we wanted to model what we considered would be the worst case scenario (10), in which upstream inflows decreased, agricultural returns decreased, and there were no environmental flow inputs (ET was not altered for reasons mentioned above). It was also critical to assess the potential of low and high environmental flows to mitigate groundwater declines for the worst-case scenario (scenarios 11 and 12). Lastly, because agricultural return flows had such a significant impact on groundwater levels in the initial scenario model runs, we wanted to assess the potential of low and high environmental flows in mitigating the negative impacts from just decreased agricultural return flows (scenarios 13 and 14).

Results from the difference to baseline analysis for scenarios 10-14 showed the following:

- The worst-case scenario (10) decreased groundwater levels ranging from 0.31-0.80 m compared to baseline.
- The worst-case plus low environmental flows scenario (11) decreased groundwater levels ranging from 0.09-0.55 m compared to baseline.
- The worst-case plus plus high environmental flows scenario (12) decreased groundwater levels ranging from 0.04-0.55 m compared to baseline, similar to scenario 11.
- Decreased agricultural return flows plus low environmental flows (13) decreased groundwater levels in some areas by up to 0.4 m, while in other areas groundwater levels increased by up to 0.11 m, compared to baseline.
- The decreased agricultural return flows plus high environmental flows scenario (14) decreased groundwater levels ranging from 0.34-0.00 m compared to baseline. These results are similar to scenario 13.

4.2.2. Depth to groundwater

We plotted the cumulative percent of land area falling within 0.5 depth to groundwater increments for the different scenarios in Reach 4 (Figure 36). The cumulative distribution effectively shows which scenarios have similar land area percentages of groundwater depths and which scenarios are most extreme in terms of shallow and deep groundwater. For example, in the increased agriculture return flows scenario (2), 10% of the Reach 4 area has within 2 m DTW, compared to only 3% in the decreased ag (3) and the worst case (10) scenarios. Low and high environmental flow scenarios (8 and 9) have very similar cumulative distributions. Coupled with decreased agricultural return flows, low and high environmental flows in modeled scenarios result in groundwater levels nearly back to baseline conditions. The worst-case scenario is mostly mitigated by either low or high environmental flows.

Based on similarities between scenarios and the fact that some scenarios (such as ET increases and decreases) had little impact, a subset of scenario results that adequately represent the range of the 14 scenarios are presented in Figure 37: baseline; increased agricultural return flows; decreased agricultural return flows; low environmental flows; and decreased agricultural return flows plus low environmental flows.

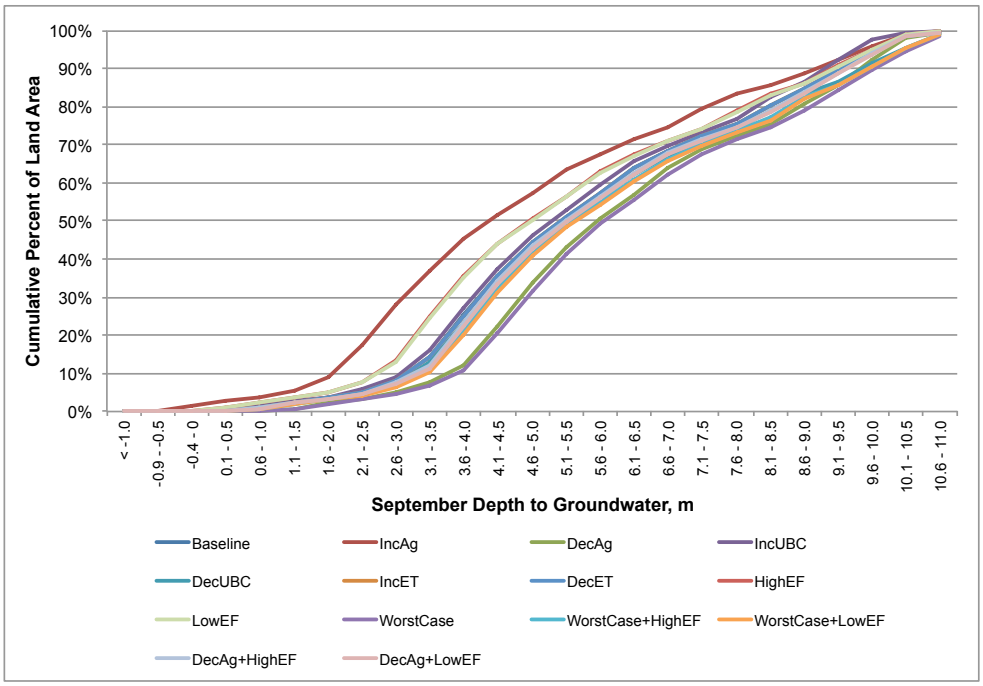


Figure 36. Cumulative percent of land area in Reach 4 within 0.5 depth to groundwater increments for the 14 scenarios.

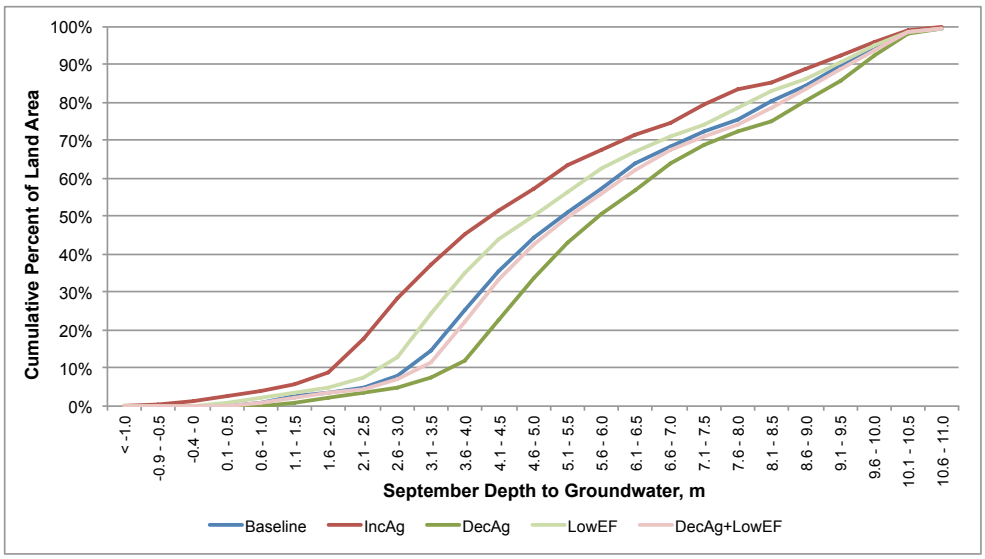


Figure 37. Cumulative percent of land area in Reach 4 within 0.5 depth to groundwater increments for 5 scenarios representative of the 14 scenarios.

We also summarized results for the combined 4 restoration sites: Chausse, CILA, Cori, and Laguna Larga (Figure 38). Given that sites are selected for restoration based in part on suitable DTW for riparian species, it is not surprising that in general, greater percentage of land areas in restoration sites have shallower DTW than land areas in all of Reach 4.

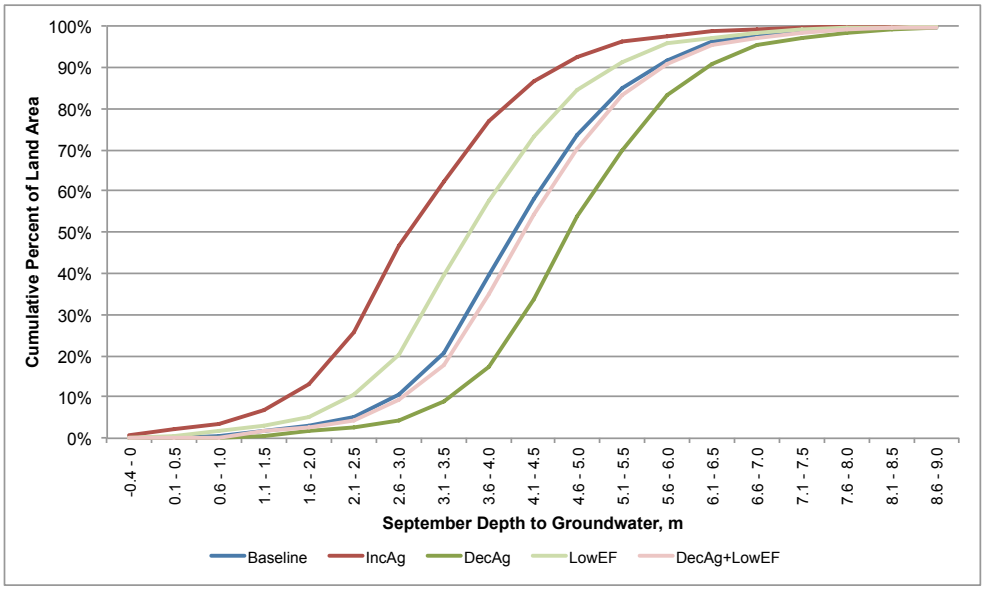


Figure 38. Cumulative percent of land area in the Reach 4 restoration sites (Chausse, CILA, Cori, and Laguna Larga) within 0.5 depth to groundwater increments for 5 representative scenarios.

4.2.3. Habitat potential analysis

Depth to groundwater results were grouped into habitat potential classifications based on results of the groundwater threshold analysis (Task 1, Section 2) and the depth to groundwater land percent areas of the modeled scenarios. Due to the unavailability of bathymetry data for areas outside of the main channel, there was a relatively small area in Reach 4 with depth to groundwater of <0. Thus, we decided to group open water and marsh habitat in the same DTW category of <0. The habitat classifications were as follows:

- Aquatic habitat (open water and marsh): DTW ≤ 0 m
- Cottonwood-willow habitat: DTW > 0 and ≤ 2.5 m
- Mesquite bosque habitat: DTW > 2.5 and ≤ 4.0 m
- Non-riparian habitat: DTW > 4.0 m

Habitat potential (acres) across Reach 4 for the three riparian habitat types is presented by scenario in Figure 39 and Table 11. The Reach 4 acreage summaries show that scenarios of agricultural return flow increases and decreases most significantly impact the extent of riparian habitat potential. The amount of cottonwood-willow habitat more than triples from the baseline scenario (337 acres) to the increased agricultural return flows scenario (1078 acres), while aquatic habitat goes from a 1-acre baseline to 95 acres. Alternatively, in the decreased agricultural return flows scenario, the total riparian habitat (aquatic, cottonwood-willow, and mesquite bosque) declines from approximately a 1680-acre baseline to 800 acres. When decreased agricultural return flows are combined with decreased upstream inflows (the worst case scenario), the total riparian habitat potential extent drops to 725 acres. Increased and decreased in ET had little impact on the habitat acreages, as was expected based on previously discussed groundwater and difference to baseline results.

Environmental flows also substantially impacted riparian habitat potential, with low environmental flows increasing the total riparian habitat potential in Reach 4 to 2340 acres. The difference in riparian habitat acreage between high and low environmental flows was minimal however, with high environmental flows increasing riparian habitat extent to 2365 acres. Negative impacts of decreased agricultural return flows on habitat were nearly mitigated by environmental flows, with 1480-acre and 1540-acre riparian habitat extent for decreased ag plus low and high flows, respectively, as compared to the 1680-acre baseline. The worst-case scenario was mitigated to some extent by environmental flows with 1345 acres of riparian habitat potential for the worst case plus low flows scenario and 1450 acres for the worst case plus high flows.

Aquatic habitat was generally low for most scenarios, increasing to 12 acres in the low and high environmental flow scenarios, and to 95 acres for the increased agricultural return scenario. Aquatic habitat (groundwater depths ≤0) may be artificially low in the modeled results however because the DEM used to determine depth to groundwater from groundwater elevation did not include bathymetry for any areas outside of the main river channel, as previously noted. Ground surface elevation of old river oxbows and backwater areas that typically have year-round surface water present may not have been accurate due to the hydroflattened LiDAR dataset.

Cottonwood-willow habitat potential appears to be more sensitive to agricultural return flow increases than mesquite bosque; cottonwood-willow habitat increased from the baseline by a

factor of 3.2, while mesquite increased by a factor 1.3. Conversely, mesquite bosque habitat was more sensitive to agricultural return flow decreases; mesquite habitat acreage was 43% of the baseline while cottonwood-willow habitat acreage was 67% of the baseline. Low environmental flows increased cottonwood-willow and mesquite bosque habitat by factors of 1.5 and 1.4, respectively, in Reach 4.

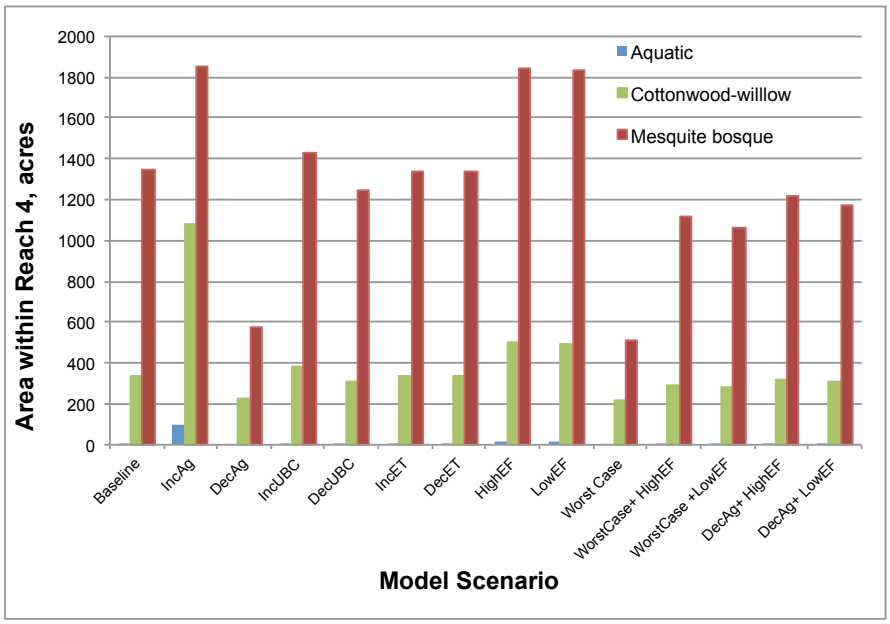


Figure 39. Estimated number of acres of riparian habitat types in Reach 4 by scenario.

Table 11. Estimated number of acres of riparian habitat types in Reach 4 by scenario.

	Acres of Habitat Under Each Scenario													
Habitat Type	Baseline	IncAg	DecAg	IncUBC	DecUBC	IncET	DecET	HighEF	LowEF	Worst Case	WorstCase + HighEF	WorstCase +LowEF	DecAg+ HighEF	DecAg+ LowEF
Aquatic	1	95	0	2	1	1	1	12	12	0	0	0	1	1
Cottonwood-willlow	337	1078	228	379	313	336	336	506	496	215	293	284	318	306
Mesquite bosque	1345	1849	580	1428	1246	1340	1342	1848	1830	509	1120	1062	1222	1171
Non-riparian	4995	3655	5869	4868	5118	5001	4998	4310	4339	5952	5262	5330	5137	5198

The number of acres in the combined restoration sites (Chausse, CILA, Cori, and Laguna Larga) for each habitat type by scenario are presented in Figure 40 and Table 12. Results follow the same general trends as for Reach 4. Similarly, cottonwood-willow habitat potential is more sensitive to agricultural return flow increases than mesquite bosque; cottonwood-willow habitat increased from the baseline by a factor of 4.9, while mesquite increased by a factor 1.5. Mesquite bosque habitat was slightly more sensitive to agricultural return flow decreases; mesquite habitat acreage was 42% of the baseline while cottonwood-willow habitat acreage was 52% of the baseline. Low environmental flows increased cottonwood-willow and mesquite bosque habitat by factors of 2.1 and 1.4, respectively, in the target restoration sites.

The lack of aquatic habitat for all but one scenario (increased agricultural return flows) in the combined restoration areas as compared to Reach 4 is due to the fact that CILA, Cori, and

Laguna Larga restoration land concession areas exclude the river channel; only the Chausse restoration concession includes the river channel.

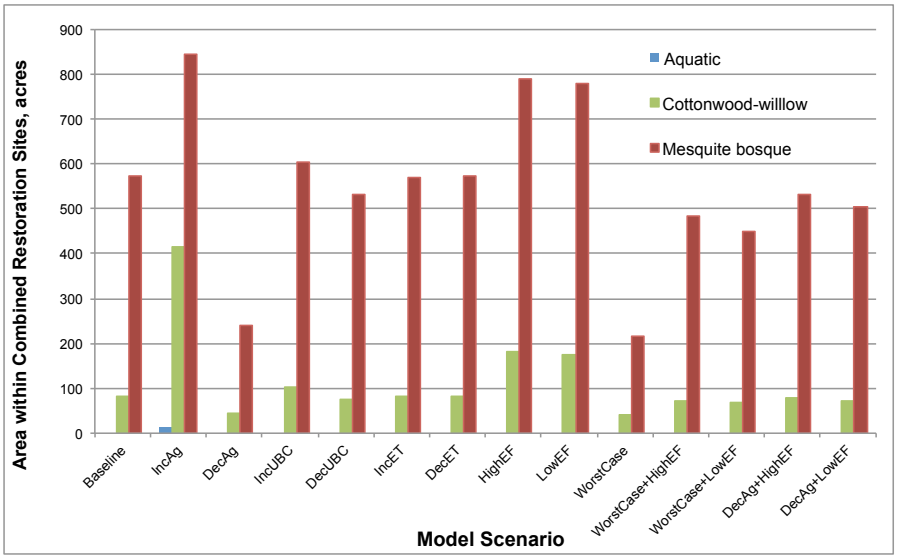


Figure 40. Estimated number of acres of riparian habitat types in combined restoration sites (Chausse, CILA, Cori, Laguna Larga) by scenario.

Table 12. Estimated number of acres of riparian habitat types in combined restoration sites (Chausse, CILA, Cori, Laguna Larga) by scenario.

	Acres of Habitat Under Each Scenario													
Habitat Type	Baseline	IncAg	DecAg	IncUBC	DecUBC	IncET	DecET	HighEF	LowEF	Worst Case	WorstCase +HighEF	WorstCase +LowEF	DecAg +HighEF	DecAg +LowEF
Aquatic	0	12	0	0	0	0	0	0	0	0	0	0	0	0
Cottonwood-willlow	84	414	43	101	77	83	84	181	176	41	71	67	78	73
Mesquite bosque	573	844	241	605	532	571	572	789	781	215	483	450	530	504
Non-riparian	996	382	1368	946	1043	998	997	683	696	1397	1098	1135	1044	1075

5. Conclusions

Analysis of historic and existing conditions

Based on our analysis of historic and existing groundwater conditions, the depth to groundwater threshold of cottonwood and willow habitat in Reach 4 is 2.5 m. As previously mentioned, native Goodding's willow can root up to 3 m below ground surface, and Fremont cottonwood roots can extend to approximately 5 m below ground surface (Horton et al. 2003). However, the ability of these species to out-compete non-native saltcedar depends on shallower groundwater. In other riparian corridors, the competitive advantage shifts from native to non-native species as depth to groundwater increases (e.g. Gries et al. 2003), and groundwater depth of greater than 2.6 m below ground surface is generalized to favor non-native species (Lite and Stromberg, 2005). Once groundwater depth is greater than 3 m, native trees are at a severe disadvantage to non-natives (Stromberg et al., 2006; Horton et al. 2001). Results from our analysis supported these previous studies in that a relatively small area with cottonwood-willow vegetation cover had depth to groundwater greater than 2.5 m.

The analysis also determined that the depth to groundwater threshold of mesquite bosque was 4.0 m, which is a more conservative threshold than what is found in the literature. It is important to note that the mesquite bosque vegetation class used in the remote sensing vegetation mapping included both honey mesquite (*Prosopis glandulosa*) and screwbean mesquite (*P. pubescens*). While honey mesquite can have a rooting depth anywhere from 9 – 15 m below the surface (Stromberg 2013), screwbean mesquite has a much shallower rooting depth of less than 4 m (Anderson 1996). On-site observations in Reach 4 suggest that the majority of remnant mesquite habitat in the area is composed primarily of screwbean mesquite; thus, it follows that our depth to groundwater threshold for this habitat type is more closely aligned with the threshold for screwbean mesquite.

While the historic and current groundwater conditions analysis was not conducted for open water or marsh habitat types, it did provide interesting information on establishment dynamics. The analysis shows that open water and emergent marsh vegetation was present in 2013 where surface water was not present in 2005-2007. This is not entirely unexpected, since the period of groundwater analysis was 6 years or more before imagery was collected and used for habitat distribution analysis. Our results indicate that 1) groundwater levels in September 2013 through March 2014 (immediately before the Minute 319 pulse flow) were higher than the minimum growing season values from 2005-2007 and 2) these habitat types established after the groundwater levels increased. For open water habitat, this is not surprising since there are minimal requirements for establishment (all that is required is water presence). For marsh habitat, this result indicates that emergent marsh vegetation established in areas with shallow surface water between 2005-2007 and 2013. There is high availability of propagule sources in Reach 4, and thus colonization is expected if more water becomes available; in restoration sites, we observe that marsh vegetation readily establishes when water is added to river meanders and no active planting is necessary.

Modeling Groundwater Support for Riparian Habitat

In our interpretation of model results, we should note the caveat that results presented here are specific to the groundwater model utilized in this project and the methods used to integrate model inputs. For example, surface water inputs were incorporated into the groundwater model by specifying river surface water elevations obtained from HecRas simulations; this method likely does not adequately capture real surface water-groundwater interactions. Based on groundwater observations at the Laguna Grande restoration area, environmental flow deliveries to Km21 of 1-2 cms even for just 30 days significantly increases groundwater levels in the restoration areas, generally in the range of 0.5-1.5 meters. Based on these observations, we might expect that scenarios with high environmental flows would be significantly different than those with low environmental flows, which was not the case under this model, potentially due to the surface water representation limitations. Similarly, upstream surface water inflows were incorporated into the model by altering the upper boundary condition of the model, which likely does not adequately capture groundwater-surface water interactions, particularly over time. Thus, methods of incorporating model inputs representing surface water change may have made the model less sensitive to these factors than in reality, with resulting muted groundwater level change for these scenarios.

The lack of significant groundwater level change with ET input alterations could be due to several different factors. First, any declines in groundwater levels within the riparian corridor might be quickly mitigated by inflows from adjacent agriculture. Relatively small changes in ET water volumes might also be minor compared to the large differences in water volume inputs from environmental flows and agricultural inputs. Finally, it is possible that the ET package used in the model did not adequately reflect the relationship between different land cover types' ET and groundwater, and so modeled groundwater elevations resulting from changes in ET may not be accurate. However, modeled results suggest that changes in vegetation cover due to restoration activities and defoliation from the saltcedar beetle would not substantially alter groundwater availability and current habitat composition.

The modeled scenarios' results show that changes in agricultural return flows are the biggest driver of groundwater increases and decreases and thus riparian habitat potential in Reach 4 and Reach 4 restoration areas. Given the total volumes represented by agricultural return flow model inputs (see Section 3.4), these results are not surprising. Results suggest that sustainability of riparian habitat in the central Delta region is highly vulnerable to irrigation district agricultural water management decisions, which are in turn influenced by larger-scale national and binational water management decisions. Colorado River flow reductions over the past decade have been attributed to climate change; flows declined by nearly 20% during 2000-2014 compared to the 1906-1999 average, with much of the loss attributed to warming temperatures (Udall and Overpeck, 2017). With Colorado River flow declines likely to exceed 20-30% or more by 2050, basin-wide shortages that impact Mexico's Colorado River water allocation are almost certain. While it is uncertain exactly how water shortages within the Mexicali Valley would be implemented, it is likely that agricultural return flows would be reduced to some extent due to changes in production driven by water availability.

Results from this study suggest that existing cottonwood-willow habitat in Reach 4 may possess some resilience to groundwater decline caused by decreased agricultural return flows; approximately 70% of cottonwood-willow habitat in the baseline scenario was still supported in decreased agricultural return flows scenario in Reach 4. However, in the Reach 4 restoration sites, only about 50% of cottonwood-willow baseline habitat was supported in the decreased agricultural flows scenario. The higher vulnerability of existing and restored cottonwood-willow habitat in Chausse, CILA, Cori, and Laguna Larga to groundwater declines suggests that monitoring and adaptive management of these areas will be critical to long-term survival.

Mesquite habitat appears to be more vulnerable than cottonwood-willow habitat with only approximately 40% of baseline habitat supported in the decreased agricultural return flows scenario for Reach 4 and within the restoration areas. This is likely due to the location of potential mesquite habitat in the upper terrace areas, where depth to groundwater is close to the 4 m threshold; as a result, small increases in depth to groundwater can shift a larger area into the >4 m habitat category. The location of existing cottonwood-willow habitat in lower elevation meander and river channel areas likely means that small increases in depth to groundwater have less impact on shifting areas into the >2.5 m category. Nevertheless, the observation that mesquite habitat may be more susceptible to groundwater declines in Reach 4 is an interesting outcome that could be correlated with the current lack of mesquite habitat in Reach 4 and the riparian corridor in Mexico. As with cottonwood and willow habitat, areas of existing and

restored mesquite bosque habitat in Reach 4 will likely require monitoring and adaptive management for long-term survival.

Model results show that environmental flow deliveries have the potential to mitigate negative impacts of groundwater decline on riparian habitat. The political and institutional framework to achieve Delta environmental flows has already been established through the Colorado River Delta Water Trust and U.S.-Mexico agreement Minute 319, which have been successful in delivering environmental flows to the Delta in the past. Future environmental flow deliveries to support riparian habitat are likely to continue (with or without a new binational water agreement), but the amount of water available for such deliveries will vary. Our results suggest that sustained restoration site irrigation flows and, similarly, agricultural irrigation flows have greater impacts on groundwater than higher volume, shorter duration deliveries to the mainstem. This could however be a product of the model itself, as previously discussed. Essentially, results suggest that increasing groundwater availability from environmental flow deliveries will lead to greater riparian habitat potential and greater resilience to other water management impacts.

Results from the increased agricultural return flows scenario show the great potential for cottonwood-willow habitat in Reach 4 when groundwater levels are augmented. Within the Reach 4 restoration sites, augmented groundwater levels caused an increase in cottonwood-willow habitat potential by nearly 500%. This suggests that current restoration areas could be greatly improved by additional water in the system.

Thus, a key takeaway from our study is that environmental flows will be critical for mitigating expected groundwater declines and habitat loss from reduced agricultural return flows. Although some riparian habitat will be resilient to groundwater declines, restoration site managers could prevent future loss by delivering existing water allocations and acquiring additional water for environmental flows. Similarly, government agency stakeholders involved in restoration efforts (including the International Boundary and Waters Commission U.S. and Mexican sections, U.S. Bureau of Reclamation, Mexican National Water Commission, and others) should be aware of riparian habitat vulnerability to groundwater declines and the need for dedicated, protected environmental flows for the region. Lastly, due to Reach 4 (and likely other areas in the riparian corridor in Mexico) riparian habitat sensitivity to groundwater declines, hydrological and vegetation monitoring is needed to assess how groundwater changes are impacting vegetation on the ground. In the case of declining groundwater tables and initial signs of habitat loss, monitoring results will need to be assessed quickly and environmental flows delivered in a timely manner to mitigate habitat loss. One suggestion is to create water management scenarios for different levels of groundwater decline so that water delivery plans are already established and ready for quick implementation.

6. Deliverables Summary

- Task 1 – Historic and current conditions assessment of Reach 4: completed; see section 2 of final report.
- Task 2 – Development of groundwater model: completed; see section 3 of final report.
- Task 3 – Spatial analysis of model results: completed; see section 4 of final report.
    - GIS database with model outputs and PDF maps were submitted with final report.
    - Seasonal maximum depth to groundwater (see GIS results; DTW_september_wbathimetry.gbd)
    - Extent of riparian vegetation based on predicted levels of groundwater and surface water under proposed scenarios (see Appendices 4 and 5)
- Task 4 – project final report: completed; submitted to Desert LCC June 30.
- Summary of technical report for water managers: completed; see executive summary. Will be shared with Minute 319 Science Team by July 31, 2017.
- Publication in scientific literature: to be completed by December 2017.
- Final presentation to DLCC Team: completed June 21, 2017.
- Final presentation to Minute 319 Science Team and other interested parties: completed June 22, 2017.
- Presentations at Scientific Conferences:
    - Karen Schlatter presented the project and initial results at the Central Rockies Society for Ecological Restoration Conference in March 2017.
    - Matt Grabau presented the project and initial results at the Bureau of Reclamation Lower Colorado River Terrestrial and Riparian Conference in January 2016.
- A scientific poster on the project was presented on behalf of Sonoran Institute by the DLCC group at the Western Landscape Conservation Cooperative and Southwest Climate Science Center Meeting at Pacific Grove, CA, October 2016 (see Appendix 6).
- Publication of project maps, data analysis summaries and figures, reports, and scientific articles on Sonoran Institute website: to be completed by July 31, 2017.

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(See Appendix 1 for annotated bibliography of literature review)

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