Minute 319

Colorado River Limitrophe and Delta

Environmental Flows Monitoring

Interim Report

May 19, 2016

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10 April 2014

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Authority

This report and study was carried out by the United States and Mexico in accordance with Section III.6-Water for the Environment and ICMA/ICS Exchange Pilot Program under Minute 319 of the International Boundary and Water Commission, United States and Mexico entitled "Interim International Cooperative Measures in the Colorado River basin through 2017 and Extension of Minute 318 Cooperative Measures to address the continued effects of the April 2010 earthquake in the Mexicali Valley, Baja California", dated November 20, 2012. This interim report was prepared as a step in furtherance of Minute No. 319 Art. III.6.f, and includes information on the environmental results achieved by the delivery of water pursuant to the pilot program.

Participating Agencies
International Boundary and Water Commission
United States and Mexico

For the United States:
Environmental Defense Fund
National Audubon Society
Sonoran Institute
The Colorado River Basin States
The Nature Conservancy
University of Arizona
U.S. Department of the Interior, Bureau of Reclamation
U.S. Geological Survey

For Mexico:
El Colegio de la Frontera Norte
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Comisión Nacional del Agua
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These efforts represent a collaborative effort of many entities who directly and indirectly participated in all phases of this study promoting a binational partnership among federal agencies, universities, and non-governmental organizations.

*Cover photo credit, Repeat photography, Laguna Grande restoration area before, during and six months after the Minute 319 pulse flow. Dale Turner, The Nature Conservancy

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Section 1: Introduction and Executive Summary

Introduction

Minute No. 319 (Minute 319), Interim International Cooperative Measures in the Colorado River Basin Through 2017 and Extension of Minute 318 Cooperative Measures to Address the Continued Effects of the April 2010 Earthquake in the Mexicali Valley, Baja California, was signed by the two Sections of the International Boundary and Water Commission (IBWC) on November 20, 2012. A component of Minute 319 is Section III.6, Water for the Environment and ICMA/ICS Exchange Pilot Program (ICMA – Intentionally Created Mexican Allocation; ICS – Intentionally Created Surplus), which outlines that the "pilot program will arrange for the means to create 158,088 acre-feet (195 mcm) of water for base flow and pulse flow for the Colorado River Limitrophe and its delta by means of the participation of the United States, Mexico, and non-governmental organizations." "Implementation of this Minute will provide a mechanism to deliver both base flow and pulse flow"…"tentatively during 2014 but no later than 2016." "[T]he information developed through implementation of this Minute will be used to inform future decisions regarding binational cooperative efforts to address proactive actions in the Colorado River Delta." "To provide for the delivery of the base flow and pulse flow for environmental purposes under this Minute, the Commissioners [of both Sections of the IBWC] will direct the Consultative Council and the Environmental Work Group to prepare a Delivery Plan, which will include a schedule of monthly flows, delivery points and volumes in an amount of approximately 105,392 acre-feet (130 mcm) for pulse flow and 52,696 acre-feet (65 mcm) for base flow." A portion of the funds provided in Section III.6.d by the United States will provide funding for projects in Mexico which will generate 50% of this pulse flow. The sources of water to implement this flow shall be from ICMA created or water deferred by Mexico under Section III.1. The Consultative Council and Environmental Work Group formed and tasked a binational Environmental Flows Team (Table 1-1) to develop the Delivery Plan (membership included representatives of U.S. and Mexican Federal and State agencies and non-governmental organizations).

As part of the pilot program, Minute 319 required that "resources for a joint investigation of the different aspects of the pilot program should be obtained. The resources for this investigation should be provided by the United States and Mexico." Environmental flows were one of the items to be investigated through an evaluation of the "the ecosystem response, most importantly the hydrological response, and secondarily, the biological response." To achieve this goal, the binational Environmental Flows Team worked with scientists and experts to develop plans for ecosystem response monitoring.

Ecosystem monitoring was conducted before, during, and after the March 23 to May 18, 2014 pulse flow. Monitoring activities were conducted in the riparian corridor of the Colorado River Delta (Fig. 1-1) by binational teams (Table 1-2) and these activities will continue through 2017. This Interim Report summarizes activities and preliminary results through December 1, 2015. Contributors to this report are listed in Table 1-3. Additional reporting will follow with the preparation of a Final Report by June 2018.

Table 1-1. Representatives of the binational Minute 319 Environmental Flows Team.

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Jennifer Pitt, National Audubon Society

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Table 1-2. Representatives of binational teams responsible for monitoring the ecosystem response of the pulse flow and base flow.

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Karen Schlatter, Sonoran Institute
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Eduardo Soto, Comisión Nacional de Áreas Naturales Protegidas

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Steve Nelson, Independent scientist
Jeff Milliken, Bureau of Reclamation
Francisco Zamora-Arroyo, Sonoran Institute

Table 1-3. Science and monitoring team members who contributed to this report.

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Karen Schlatter, Sonoran Institute
Patrick Shafroth, United States Geological Survey
Dale Turner, The Nature Conservancy
Francisco Zamora-Arroyo, Sonoran Institute

Figure 1-1. Colorado River delta study reaches for Minute 319 monitoring activities.

Executive summary

As provided in Minute 319 of the U.S.-Mexico Water Treaty of 1944, a pulse flow of approximately 130 million cubic meters (105,392 acre-feet) was released to the riparian corridor of the Colorado River Delta from Morelos Dam at the U.S.-Mexico border, Km 27 spillway and Km 18 spillway. The water was delivered over an eight-week period that began on March 23, 2014 and ended on May 18, 2014. Peak flows were released early in this period to simulate a spring flood. Some pulse flow water was released to the riparian corridor via Mexicali Valley irrigation spillway canals.

Base flow volumes totaling 65 mcm (52,696 acre-feet) are being delivered to the Miguel Aleman and Laguna Grande restoration areas and to the channel below Morelos Dam during the term of Minute 319 through December 31, 2017. Base flow volumes by delivery point are known for 2014; further details on base flow deliveries in 2014 and 2015 will be provided after the information becomes available.

Methods

The following list describes the general monitoring activities that have been conducted before, during, and after the pulse flow.

- Baseline (pre-pulse flow) conditions from published reports and from field observations were summarized.
- Surface-water discharge, groundwater behavior, and water salinity were measured during the pulse flow. Geophysical techniques were used in the Limitrophe section of the study area (i.e., Reach 1 and 2) to further understand the immediate groundwater response to the pulse flow.
- Post-pulse flow groundwater monitoring is on-going.
- Pulse flow arrival times were tracked on the ground using direct observations and temperature sensors.
- Scour chains, topographic surveys, digital elevation models, grain-size analyses, and suspended sediment samples were used to estimate erosion and deposition.
- The areal extent of inundation was documented as the flow progressed, using direct observations and aerial and satellite (Landsat, WorldView) images and river stage measurements coupled with hydrologic (HEC-RAS) modeling.
- Light Detection and Ranging (LiDAR) data were acquired before and after the pulse flow to document topographic changes resulting from the pulse flow and to help map the distribution, composition, and structure of vegetation.
- Topography was surveyed along 21 transects perpendicular to the channel in order to relate the germination, growth, and survival of new vegetation to changes in channel and floodplain topography.
- Recruitment of native and non-native vegetation was surveyed along 21 transects co-located with topographic survey transects and groundwater monitoring sites. The influx of seeds, changes in soil salinity and texture, and vegetation cover along the 21 transects were monitored before and after the pulse flow and at the end of the first and second growing seasons.
- In the Laguna Grande area, 130 hectares (320 acres) of non-native vegetation in the Laguna Grande area were cleared and graded to promote regeneration of native vegetation. Portions of the site were hydro-seeded with native vegetation and 55 hectares (136.5 acres) of the site were planted with native trees. Detailed surveys of new vegetation, groundwater conditions, soil conditions, and bird populations are ongoing.
- In the Miguel Aleman restoration site, 63 hectares (156 acres) were cleared and graded and of these, 38 hectares (93 acres) site were planted with native trees.

- Vegetation health ("greenness") assessments that began in 2000 using satellite-based remote-sensing data are on-going.
- Photographic images of fixed locations within the riparian corridor shortly before, during and six months after the pulse flow were assembled.
- Baseline vegetation and riparian bird surveys (begun in 2002) and marsh bird surveys (begun in 2004) were expanded to include additional areas in the Limitrophe, restoration sites and elsewhere.
- Zooplankton, fish and water quality continue to be monitored in the lowermost river reaches and estuary in order to document changes in connectivity between the river and the Gulf of California.

Geography of the study area

Detailed maps of the Colorado River Delta's riparian corridor are shown in Figures 1-2A-D. These maps show the location of transects, discharge measuring stations, restoration areas and places referred to in this report.

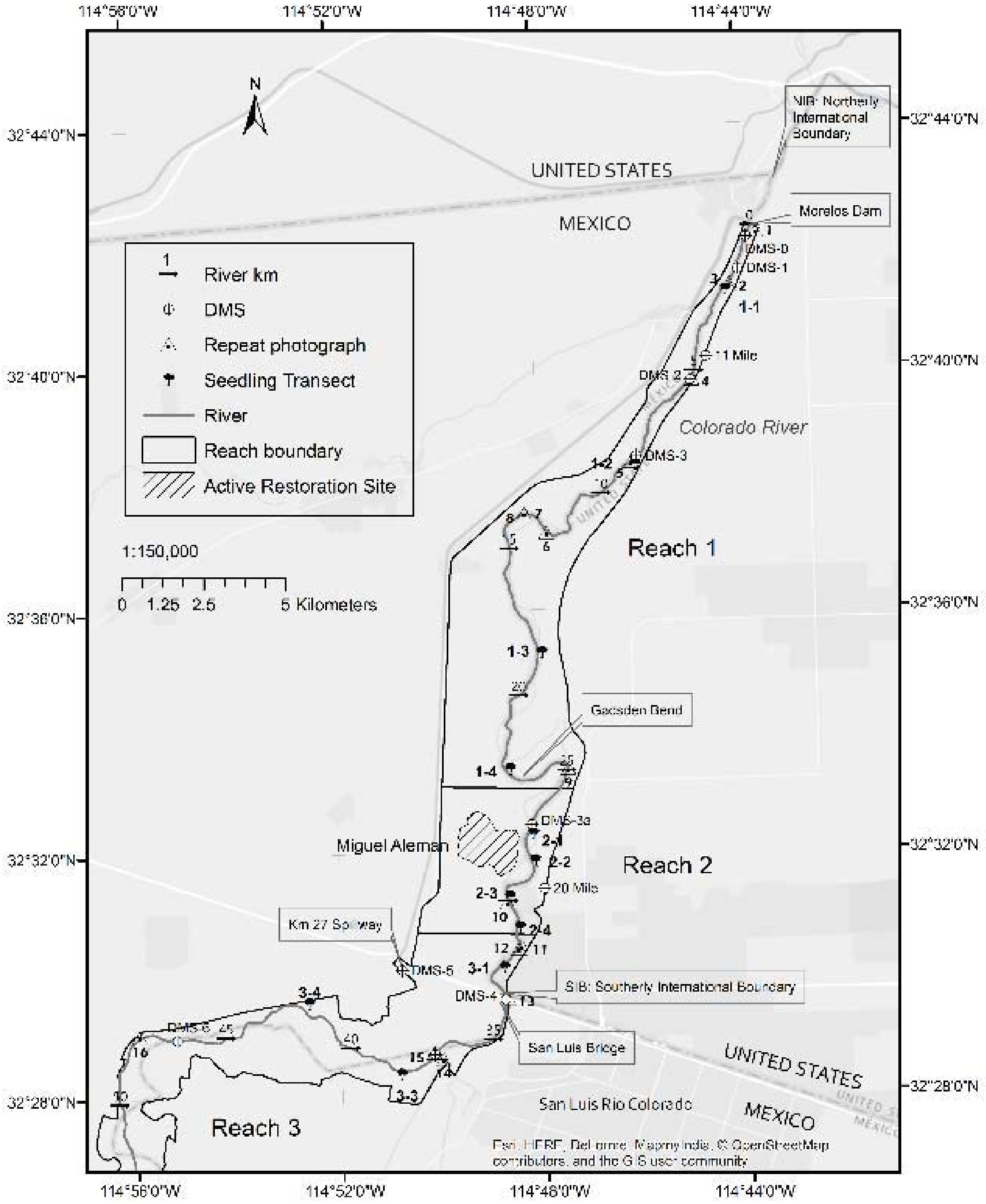

Figure 1-2A. Study area. Reaches 1, Reach 2 and part of Reach 3. River km (in 5 km increments) is river distance from Morelos Dam.

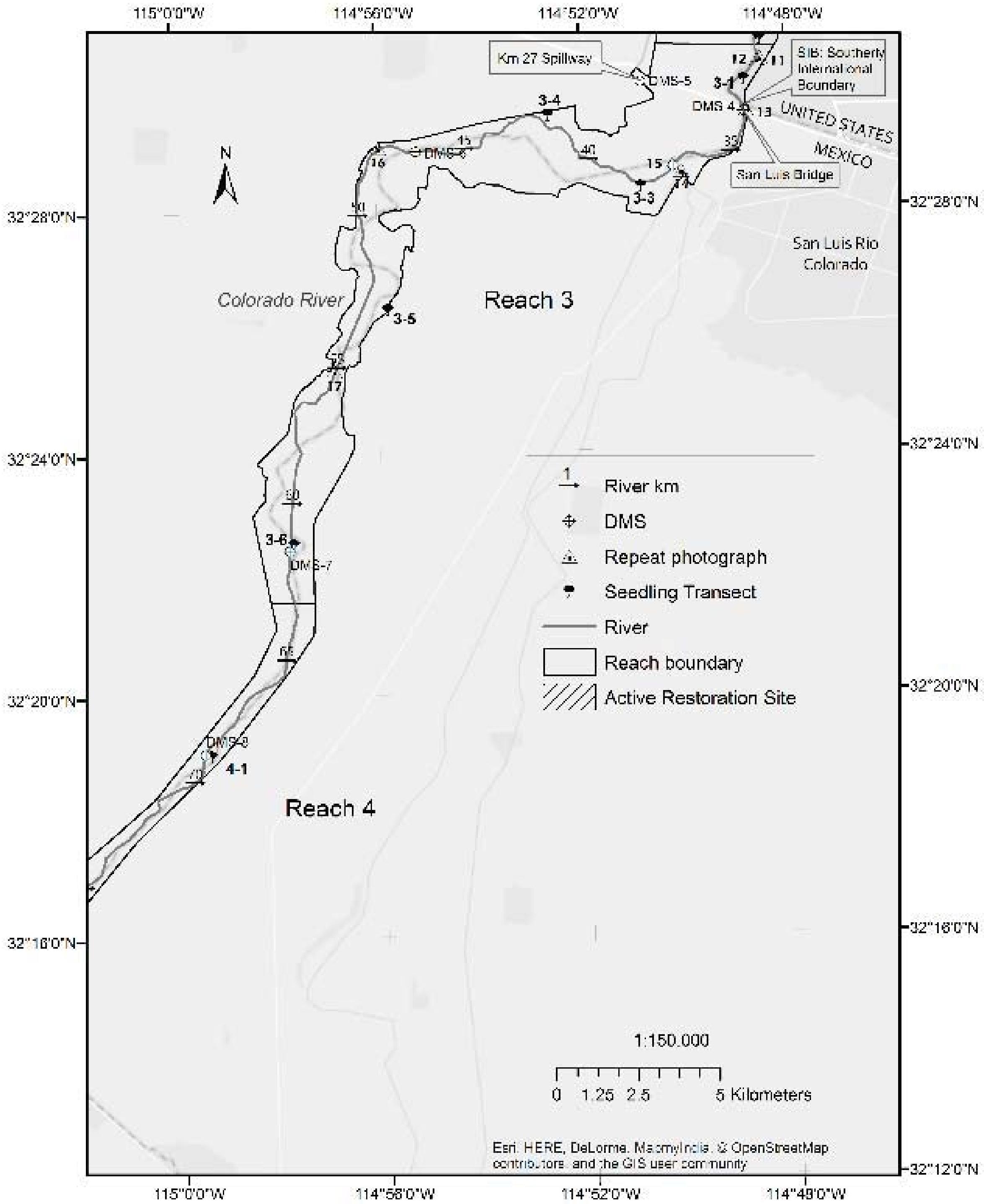

Figure 1-2B. Study area. Reach 3 and northern part of Reach 4. River km (in 5 km increments) is river distance from Morelos Dam.

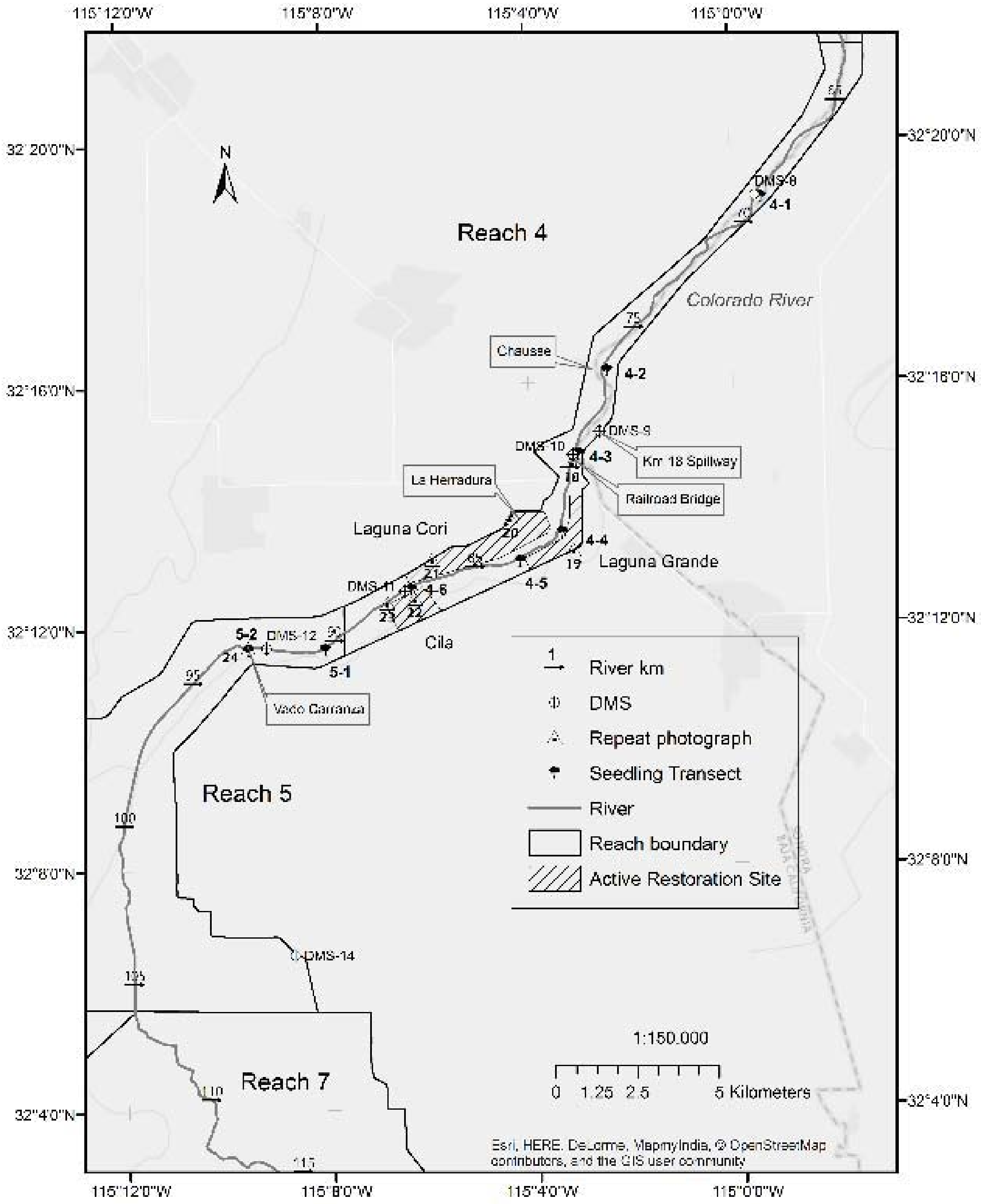

Figure 1-2C. Study area. Reach 4 and northern part of Reach 5. River km (in 5 km increments) is river distance from Morelos Dam.

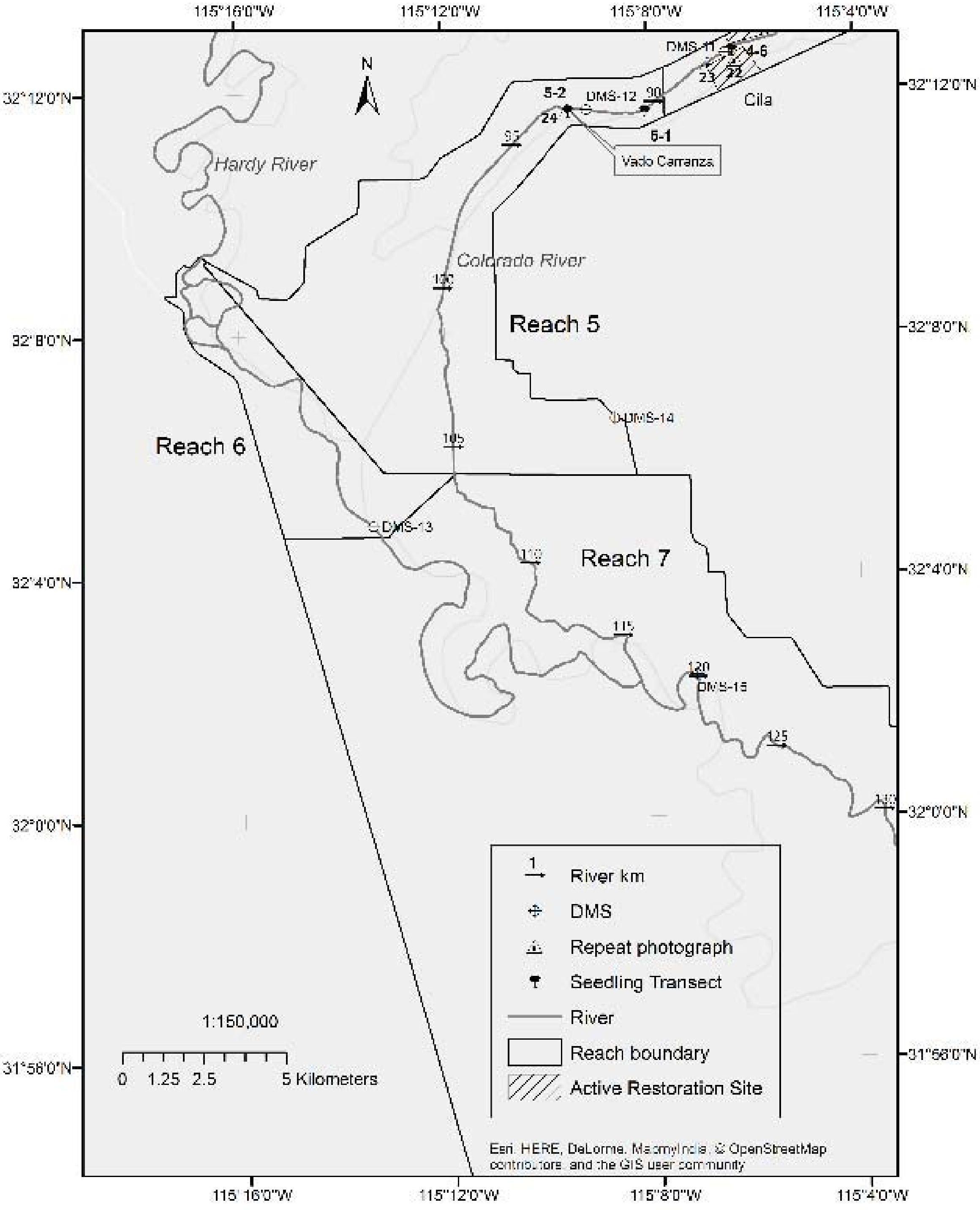

Figure 1-2D. Study area. Reaches 5, 6 and 7. River km (in 5 km increments) is river distance from Morelos Dam.

Summary of observations and analyses made through December 4, 2015

Detailed presentation and discussion of these results - and supporting data, are in the subsequent sections and appendices of this report and in ScienceBase.

1. The 2014 pulse flow inundated approximately 1,600 ha (4,000 acres) of the main channel and adjacent terraces, achieving lateral and longitudinal connectivity along the entire river from Morelos Dam to the estuary for the first time since 1997.
2. Surface water flow rates and volumes decreased downstream, primarily as a result of infiltration. Infiltration volumes were highest in Sectors 4 and 5 (Reach 3; km 34-61), where surface water filled isolated depressions from which water could not return to the main channel after the peak flow had passed.
3. If a pilot channel through the dry reach had been able to convey the entire pulse flow, an additional 60 Mm^3 (50,000 acre-ft) might have flowed downstream rather than recharging the local aquifer from the off-channel depressions.
4. Monitoring of the 2014 pulse flow greatly improved understanding of river hydraulics in the Limitrophe and delta under prevailing conditions.
5. Approximately 122 Mm^3 (99,000 af) of water from the pulse flow recharged the underlying regional aquifers. This additional groundwater influx was superimposed on the complex flow patterns defined by regional recharge and discharge
6. Vertical connectivity between the river and groundwater was achieved in all reaches. During the pulse flow, the water table rose as much as 9 m (30 ft) locally, with impacts decreasing away from the river channel. Water-table elevations returned largely to pre-pulse levels within 6 months, as the mound created by the pulse flow dissipated into the regional aquifer.
7. Although the pulse flow raised the groundwater level less than 2 meters in Reach 4 where the water table was already high, this increase is important for establishing vegetation.
8. The highest measured suspended sediment transport rates were in the upper limitrophe and in an approximately 10 km (6.2 mi) distance downstream from the Southerly International Boundary (SIB).
9. Although 156,000 ± 81,000 cubic meters (5.5 million ± 2.8 million cubic feet) of sediment were mobilized, changes within Reaches 1-3 during the pulse flow were limited to localized reworking of the channel bed, scour and fill on the order of 1 m (3 ft) or less within the active channel, and minor bank erosion.
10. Pulse flow discharge was not sufficient to widen the channel, or to scour or bury significant amounts of existing vegetation.
11. Most requirements for recruitment of woody, native riparian species were met in Reaches 1 and 4 unprepared areas due to high seed availability, continued soil moisture, and tolerable levels of soil salinity. However, dense, existing vegetation in these unprepared areas reduced the availability of bare ground necessary for seed germination in the most hydrologically favorable sites.
12. All seedling establishment requirements were met at the majority of prepared restoration areas in Reach 4 due to management actions. Prior to the pulse flow, site managers removed tamarisk and arrowweed and excavated and graded meanders; base flows were delivered in the first and second growing seasons.
13. Native, woody riparian species established with highest frequencies and densities in Reach 4 prepared areas (except LG1) and Reach 1 unprepared areas.

14. More extensive recruitment of woody, native riparian species in unprepared sites with favorable hydrological conditions (Reaches 1 and 4) will require active management such as the removal of existing vegetation, delivery of base flows, and control of nonnative species.
15. Reach 4 has elevated surface soil salinity compared to other river reaches due to the presence of a shallow groundwater table and lack of regular surface flows. Environmental flows are critical for soil salinity management in areas such as Reach 4 that support existing and restored native riparian habitat.
16. Riparian plant species were successfully established in the actively managed Miguel Aleman and Laguna Grande sites through removal of tamarisk and arrowweed, planting/seeding of native species and irrigation.
17. The Minute 319 Pulse Flow produced a 16% increase in Normalized Difference Vegetation Index (NDVI, or "greenness") throughout the riparian reaches in 2014.
18. Increases in NDVI in 2014 occurred in the zone inundated by the pulse flow as well as in the non-inundated outer parts of the riparian floodplain, where groundwater supports existing vegetation. In 2015, NDVI decreased to 2013 levels.
19. The abundance and diversity of birds increased in the floodplain of the Colorado River in Mexico after the 2014 pulse flow. The response was maintained in 2015. Migratory waterbirds, nesting waterbirds and nesting riparian birds all increased in abundance.
20. The combined abundance of 19 species of conservation interest increased 49% from 2013 to 2015, including Gila Woodpecker, Brown-headed Cowbird, Ash-throated Flycatcher, Yellow-breasted Chat and Song Sparrow.
21. The restoration sites had a greater abundance, higher number of species and greater diversity index per point of birds than in the rest of the floodplain.
22. The combined abundance of the 19 species of conservation interest was 43% higher at the restoration sites than in the rest of the floodplain. Hooded Oriole, Yellow-breasted Chat, Vermillion Flycatcher, Gila Woodpecker and Cactus Wren all increased in abundance.
23. Approximately 10 percent of the pulse flow water reached the top of Reach 5; the water inundated and infiltrated portions of Reaches 5 and 7, supporting the vegetation there.
24. A small amount of Colorado River water mixed with Gulf of California water.
25. Gulf of California water mixes with Hardy River water during spring high tides, but a sand bar restricts the return of the mixture to the Gulf. Connectivity is largely one-way.
26. The pulse flow had little to no impact on the zooplankton or fish fauna of the upper estuary.
27. In order to enhance habitat and benefit marine species in the upper estuary, a larger amount of freshwater would be required *in addition to* improved tidal connectivity above the sand bar. Additional research, including modeling and experimental flow deliveries, is needed to estimate the amount and timing of flows required for estuary enhancement.

Section 2: Hydrology: Surface water response

Key Observations:

1. **The 2014 pulse flow inundated 1,600 ha (4,000 acres) of the main channel and adjacent terraces, achieving lateral and longitudinal connectivity along the entire river from Morelos Dam to the estuary for the first time since 1997.**
2. **Surface water flow rates and volumes decreased downstream, primarily as a result of infiltration. Infiltration volumes were highest in Sectors 4 and 5 (Reach 3; km 34-61), where surface water filled isolated depressions from which water could not return to the main channel after the peak flow had passed.**
3. **If a pilot channel through the dry reach had been able to convey the entire pulse flow, an additional 60 Mm^3 (50,000 af) might have flowed downstream rather than recharging the local aquifer from the off-channel depressions.**
4. **Monitoring of the 2014 pulse flow greatly improved understanding of river hydraulics in the Delta under prevailing conditions.**

Introduction

Below Morelos Dam, the 33-km (21-mile) Limitrophe section of the Colorado River begins as a sluggish stream fed by shallow groundwater and leakage from the dam, transitioning to a dry channel around Km 19 (mile 12). From there, the dry riverbed winds south past the Southerly International Boundary (SIB) as a sandy channel flanked by a tamarisk-choked floodplain, confined between levees. Fed by shallow groundwater and agricultural drains, the River re-emerges around Km 61 (mile 38) as a series of shallow pools, growing to a wide, slow-moving stream where the Río Hardy (Km 114, mile 71) contributes agricultural drainage and treated municipal wastewater. For the next 20 kilometers or so, the River is choked with tamarisk, supported by a high, saline water table. Downstream, vegetation gives way to vast expanses of mud and salt flats, which meet the tidal channels of the Gulf of California.

This condition has existed essentially since Lake Powell began filling in 1963, with notable exceptions during isolated wet years when flood waters released from Morelos Dam flowed to the Gulf (Glenn et al., 1996). For example, in January 1993, January 1997, and January 2001, an estimated 92, 88, and 147 million cubic meters (Mm^3) (75,000, 71,000 and 119,000 acre-feet (af)), respectively, flowed past SIB, the most reliable historical measurement site[1]. By comparison, 59 Mm^3 (48,000 af) flowed past SIB during the 2014 pulse flow. Figure 2-1 compares the 2014 pulse flow to the median hydrograph prior to completion of Hoover Dam.

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[1] Historical streamflow volumes are estimates based on mean daily flow rates measured at Southerly International Boundary. Source: IBWC gage data.

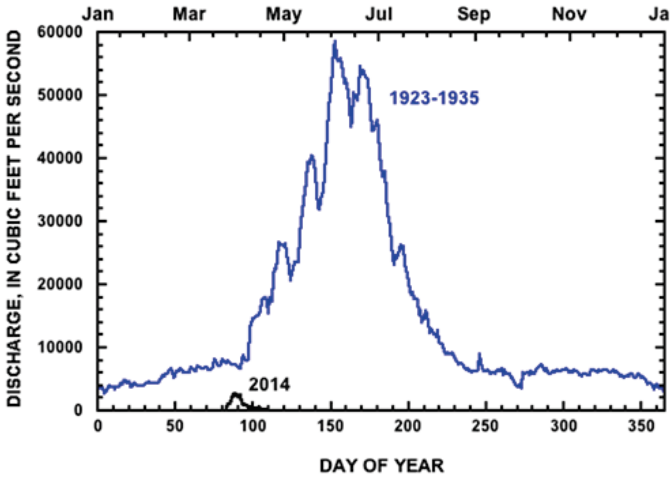

Figure 2-1. *Comparison of the 2014 pulse flow hydrograph (black line) and the median hydrograph of Colorado River discharge in the delta prior to completion of Hoover Dam (blue line, 1923-1935) (Schmidt 2014).*

The pulse flow

To ensure accuracy of analyses in this section, we consider "Sectors", as defined in Table 2-1 and delineated in Figure 2-2. In contrast to Reaches, upper and lower Sector boundaries correspond precisely with discharge measurement stations.

At its maximum extent, the pulse flow inundated about 1,600 hectares (4,000 acres) (Table 2-1) with surface water depths (stages) as great as 6.5 meters (21 ft). For the first time since 1997, the pulse flow achieved lateral and longitudinal connectivity among the main channel, isolated and connected meanders, and floodplains from Morelos Dam to the estuary.

Table 2-1. Maximum inundation by sector (see Figure 2-2 for Sector locations). *Inundation of Sectors 1-9 calculated from continuous river stage data and LiDAR-based topography, using GIS software. Inundation of Sector 10 (Reaches 5 and 7) obtained from Landsat images taken on May 11, within 4-5 days of peak inundation. (dry) indicates normally dry conditions.*

Sector	**1**	**2 (dry)**	**3 (dry)**	**4 (dry)**	**5 (dry)**	**6**	**7**	**8**	**9**	**10**
DMS	Dam-2	2-3a	3a-4	4-6	6-7	7-8	8-10	10-11	11-12	12-15
Reach	1	1-2	2-3	3	3	3-4	4	4	4-5	5-7
Hectares	64	641	164	184	242	66	70	91	37	42
Acres	160	1,580	405	455	598	163	173	225	91	104

Several methods were employed to collect surface-water and related data. Comisión Internacional de Límites y Aguas (CILA) and their US counterpart, International Boundary and Water Comission (IBWC), reported water deliveries from Morelos Dam, Km 27 (DMS 5), and Km 18 (DMS 9), as well as 11-mile and 21-mile spillways, which contributed additional water to the channel during the pulse flow. The monitoring team measured surface water discharge at 18 discharge measuring stations (DMS) from Morelos Dam to the lower channel in Reach 7 (Figure 1-2). Flow volumes at DMS2, 3a, 4, 6, 8, 10, and 12 were determined from continuous stage and daily discharge data. Flow volumes at DMS7, DMS11, and DMS15, where stage was not recorded, were estimated from daily discharge data. Where both discharge and stage were used, flow volumes agreed within 0.02 to 6 percent. Flow measurements at DMS11 were affected by pooling water. Flow measurements at DMS15 were affected by wind blowing the water across the wide, shallow, braided channel. Open-water evaporation was determined by applying the standardized reference equation (ASCE-EWRI 2005) to daily inundated areas, using data from the AZMET Yuma South station and an albedo of 0.06. GIS software was used to determine daily inundated areas from LiDAR data and continuous river stage data recorded in transducers.

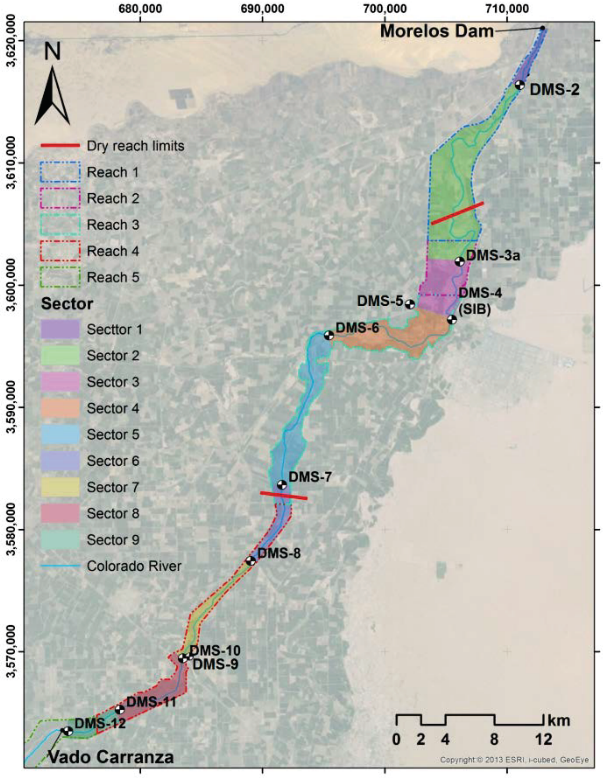

Figure 2-2. *Discharge Measuring Stations (DMS), Reaches, and Sectors from Morelos Dam to Vado Carranza (top of Reach 5). Sectors refer to portions of the riparian corridor between discharge measuring stations. DMS 0, 1, 3, 13, 14, and 15 are not shown.*

From March 23 through May 18, 2014, the pulse flow delivered a total of 132 Mm^3 (107,000 af) to the riparian corridor of the Colorado River Delta, including 102 Mm^3 (77%) from Morelos Dam, 21 Mm^3 (16%) from the Km 27 spillway of Canal Reforma (river km 37; river mile 23), and 9 Mm^3 (7%) from the Km 18 spillway of Canal Barrote (river km 79; river mile 49). An additional 0.8 Mm^3 (650 af) entered the river from 11-mile and 21-mile spillways as operational surplus.

Figure 2-3 shows discharge *rates* measured during the pulse flow as it progressed downstream over time. Figure 2-4 shows the total flow *volume* that passed each gaging site. Both flow rates and volumes decreased downstream.

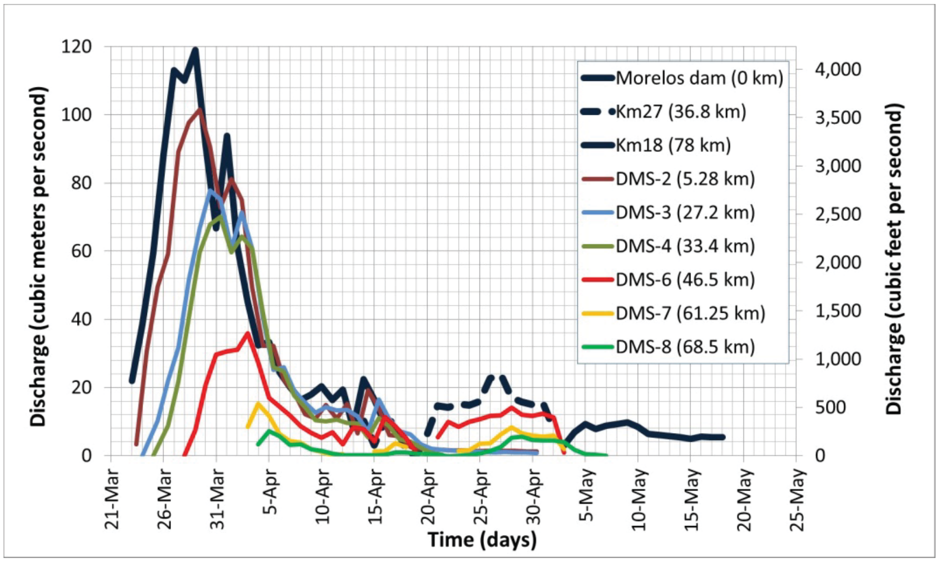

Figure 2-3. *Pulse flow discharge rates measured at nine gaging stations along the Colorado River, showing delays and attenuation as the pulse flowed downstream. Water was delivered at Morelos Dam, Km 27, and Km 18. (DMS4 is SIB).*

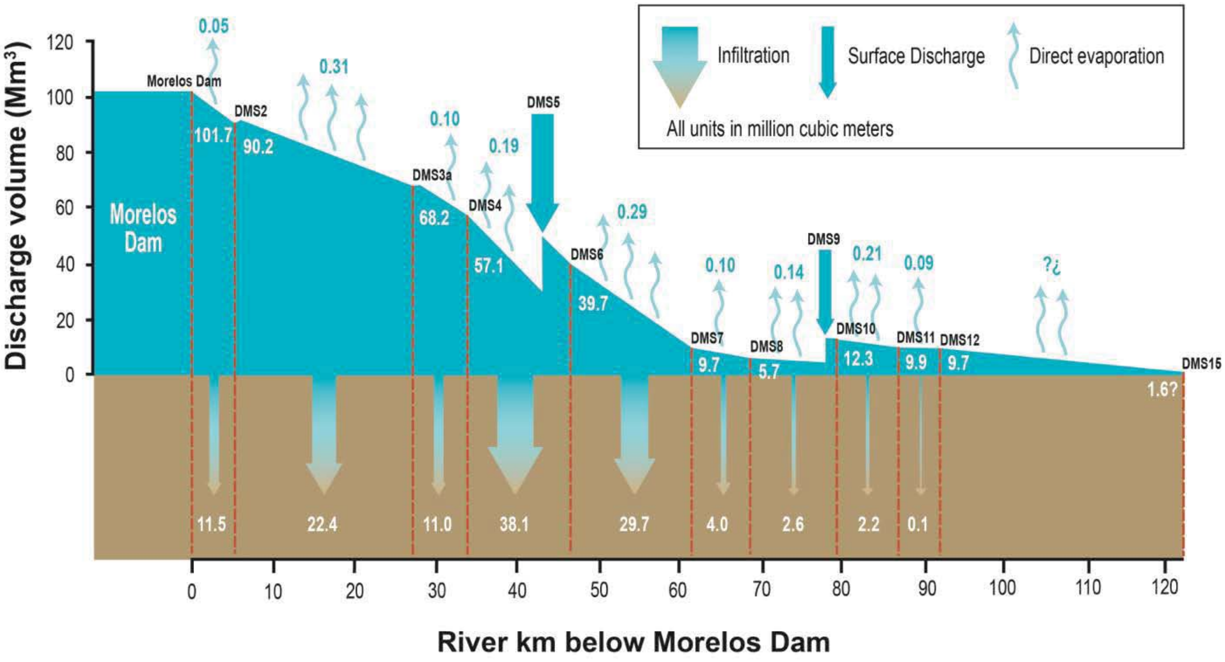

Figure 2-4. *Surface water budget as the pulse flow progressed downstream, showing volumes of water delivered, water in the channel, evaporation from open water, and infiltration, March 23-May 22, 2014. Arrow widths are proportional to water volumes. DMS5 and DMS9 are Km 27 and Km 18 spillways, respectively.*

The majority of pulse flow water infiltrated into the stream channel and floodplain (Figure 2-4). Evaporation from open water consumed about 1 percent of the pulse flow. About 92 percent (122 Mm^3, or 99,000 af) of the pulse flow infiltrated into the ground. Some of the infiltrated water was later captured by groundwater pumping and evapotranspiration (ET), which we address in the groundwater section of this report. The remaining 8 percent (10 Mm^3, or 8,000 af) flowed downstream from DMS12. As far as we know, no other surface water was withdrawn from the river during the pulse flow.

Table 2-2. *Infiltration volumes by Sector. The methods used to distinguish main-channel from off-channel infiltration (Appendix A; Alarcón Gómez 2015) required collecting and analyzing riverbed sediment, which was only accessible in the dry reach (Sectors 2-5).*

Sector	**Infiltration (Mm^3)**	**Infiltration (m^3/m^2)**	**Infiltration (percent of inflow to sector)**	**Infiltration into main channel (Mm^3)**	**Infiltration off-channel (Mm^3)**
1 (Dam-DMS 2)	11.5	3.5	11		
2 (DMS 2-3a)	22.4	0.5	25	9.5	12.9
3 (DMS 3a-4)	11.0	0.7	16	4.8	6.2
4 (DMS 4+5-6)	38.1	1.7	49	16.5	21.6
5 (DMS 6-7)	29.7	1.4	75	8.8	20.8
6 (DMS 7-8)	4.0	0.5	41		
7 (DMS 8+9-10)	2.6	0.2	17		
8 (DMS 10-11)	2.2	0.3	18		
9 (DMS 11-12)	0.1	0.0	1		
TOTAL	**121.5**			**39.7**	**61.5**

Three different methods were used to calculate infiltration rates and volumes for each river sector within the dry river reach; the results are mutually consistent (Appendix A; Alarcón Gómez 2015). Eighty-three percent of the infiltration occurred in the dry reach (Sectors 2-5). Infiltration into off-channel meanders and other depressions exceeded infiltration into the main river channel in every dry-reach Sector (Table 2-2).

The aim of delivering water via Km 27 and Km 18 spillways was to minimize infiltration in non-restoration areas by routing the pulse flow around the dry reaches. The volumetric increase that was evident at DMS10 (Fig. 2-4) and persisted through the Laguna Grande restoration complex (Sector 9) suggests that this strategy succeeded at Km 18. The relatively small amount of water that infiltrated below DMS10 was available to promote restoration. In contrast, little of the surface water that was delivered via Km 27 remained in Sectors 7 and 8 (Reach 4) (Figs. 2-3 and 2-4).

Off-channel infiltration volumes and rates were particularly high in Sectors 4 and 5 (Table 2-2). An aerial view of Sector 4 during the pulse flow (Figure 2-5) illustrates the extent of inundation of off-channel depressions. As the peak flow receded, the depressions became isolated from the main channel, allowing the remaining water to infiltrate and evaporate (Figure 2-6, bottom). Inundated areas in other Sectors generally remained connected to the main channel, allowing water to continue flowing downstream (Figure 2-6, top).

Of course, off-channel inundation is a natural hydrological response to pulse flows. However, had a "pilot" channel been able to contain the entire pulse flow through the dry reach (Sectors 2-5) without leaking, then, according to Table 2-2, total infiltration during the 2014 pulse flow might have been reduced by as much as 61.5 Mm^3 (50,000 acre-ft). Currently, the pilot channel's carrying capacity is about 10-20 m^3/s (350-700 cfs), compared to peak pulse flows of about 70 and 36 m^3/s (2,500 and 1,300 cfs) at DMS4 (SIB) and DMS5, respectively. Therefore, preventing all of this off-channel infiltration would have required building and lining a much larger pilot channel, and extending it into the Limitrophe.

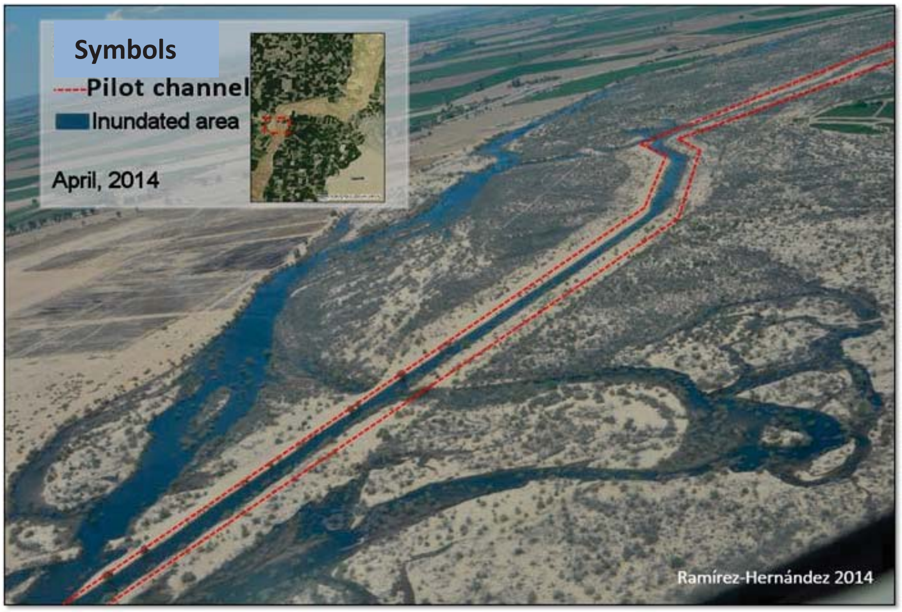

Figure 2-5. *Oblique aerial view of a typical portion of Sector 4 during the pulse flow, showing the extent of inundation of the pilot channel and off-channel depressions.*

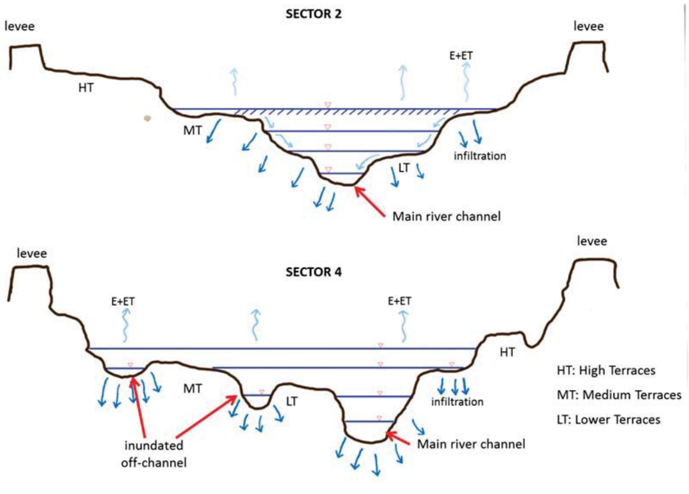

Figure 2-6. *Conceptual cross sections comparing Sector 2 (top), where inundated off-channel areas drained back into the main channel as the pulse flow passed, to Sector 4 (bottom), where inundated off-channel areas became isolated and thus continued infiltrating after the peak pulse flow had passed. E+ET = evaporation plus evapotranspiration. HT, MT, and LT = high, middle, and low terrace, respectively.*

While the 2014 pulse flow greatly improved our understanding of river hydraulics in the Delta, it is an incomplete predictor of the outcomes of future pulse flows, when prevailing conditions could differ. The areas of inundation and the water balance volumes reported here resulted from many factors, including, but not limited to, the pulse flow design. Infiltration is controlled by the magnitude and duration of flow, depth and extent of inundation, hydraulic characteristics of the substrate, depth to groundwater, antecedent moisture content, and whether the substrate was wetting or drying prior to the flow. Flow depth, extent, and duration are affected by channel roughness, which in turn is affected by vegetation and other obstructions. Clearly, tamarisks in the path of the pulse flow impeded downstream flow, which increased both the inundated area and the infiltration volume.

Monitoring the pulse flow provided ample data to build and calibrate a 1-dimensional, steady-state HEC-RAS model, which simulates the hydraulic response of the river to different discharge rates under the prevailing conditions (Salcedo-Peredia 2016). This simulation of water levels and inundation extents at specific cross sections informs analyses of both hydrologic and ecological responses to the pulse flow.

Additional flows: May, 2015

Because flows in addition to those released during the pulse flow may have affected the hydrology and ecology of the Limitrophe and delta, we report here, for informational purposes, that approximately 28.2 Mm^3 (22,900 af) were released from Morelos Dam from May 16-19, 2015. These flows reached the SIB.

Base flows

In addition to the 132 Mm^3 (107,000 af) pulse flow, 12.3 Mm^3 (9,970 af) of base flow was delivered in water year 2014 (October 2013 – September 2014). Of this volume, 5.1 Mm^3 (4,100 af, or 41%) was delivered to the main channel via Morelos Dam on Sept 5-9, 2014; 0.5 Mm^3 (400 af, or 4%) was delivered to the Miguel Aleman restoration site; and 6.7 Mm^3 (5,400 af or 55%) was delivered via Km 18 spillway to the main channel and the Laguna Grande restoration site. Information on base flows during the 2015 water year (October 2014-September, 2015) will be provided after the information becomes available.

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Section 3: Hydrology: Groundwater response

Key Observations:

1. **Approximately 122 Mm^3 (98,500 af) of water from the pulse flow recharged the underlying regional aquifers. This additional groundwater influx was superimposed on the complex flow patterns defined by regional recharge and discharge.**
2. **Vertical connectivity between the river and groundwater was achieved in all reaches. During the pulse flow, the water table rose as much as 9 m (30 ft) locally, with impacts decreasing away from the river channel. Water-table elevations returned largely to pre-pulse levels within 6 months, as the groundwater mound created by the pulse flow dissipated into the regional aquifer.**
3. **Although the pulse flow raised the groundwater level less than 2 meters in Reach 4 where the water table was already high, this increase is important for establishing vegetation.**

Introduction

The project area overlies the regional Mexicali Valley, San Luis Valley, and Yuma alluvial aquifers. Groundwater flow in these aquifers is controlled by regional recharge and discharge. According to government sources, approximately 760 Mm^3 (620,000 acre-ft) of water recharges the Mexicali and San Luis aquifers annually (Diario Oficial de la Federacion (DOF), 2015) as underflow from Arizona, California, and Sonora; seepage from irrigation canals, cropland, and domestic wastewater; and episodic recharge from the river (Ariel, 1968). About 900 Mm^3 (730,000 acre-ft) of water discharges from the aquifers to pumping wells (Distrito de Riego Río Colorado 2014), and additional water discharges as underflow to the Gulf of California (DOF 2015). The volume of water stored in the aquifers is decreasing by an estimated 463 Mm^3 (375,000 acre-ft) annually (DOF 2015). Distinguishing the spatial and temporal distribution of regional recharge and discharge and their effects on flows in the river is beyond the scope of this report.

Groundwater generally flowed from northeast to southwest, at least into the 1980s (Fig 3-1, left). By 2006, groundwater management had altered this flow pattern. Recharge in the Yuma area pushed groundwater west across the Limitrophe reach, while pumping pulled groundwater into the Mesa Arenosa, and Minute 242 well fields east of the Southerly International Border (SIB) and into the Old Mexicali well field to the west, as evidenced by depressed water levels (Fig. 3-1, right). In both 1984 and 2006, the water table was nearly flat along Reach 4 and lower Reach 3, indicating relatively low-velocity groundwater flow. Projections indicate that the lining of the All-American Canal will reduce underflow from California to Baja California, further altering flow in the aquifer (USBR 2006; Coes *et. al*. 2015). Regional water level data in Mexico is required in order to delineate the regional flow patterns. Moreover, as can be seen in Fig. 3-1 (see also Appendix B), a larger number of piezometers are required south of the railroad bridge to deduce flow directions downstream in Reaches 4, 5, 6, and 7.

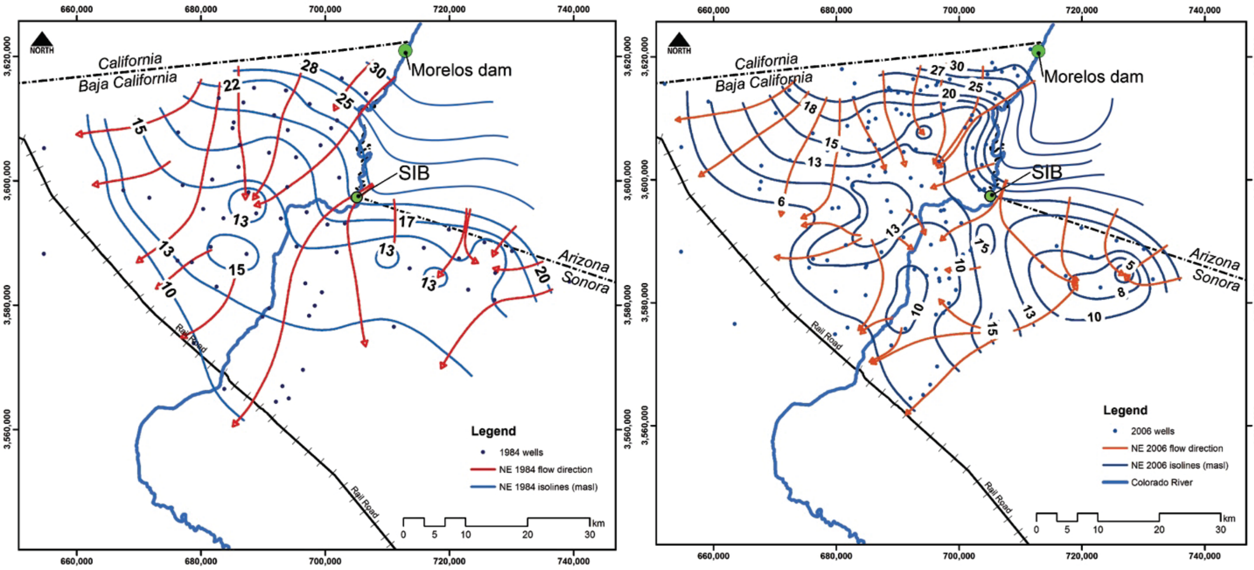

Figure 3-1. Water-table elevations and groundwater flow directions in the Mexicali Valley/San Luis Valley/Yuma aquifer in 1984 (left) and 2006 (right). Groundwater flows from higher to lower water levels. Sources of water-level contours: Lesser 2006; Overby 1992; U.S. Bureau of Reclamation 2015.

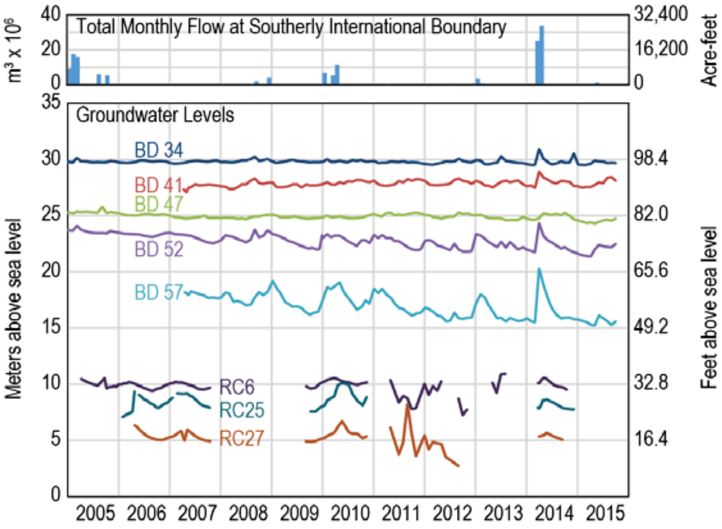

Figure 3-2. Groundwater elevations along the river corridor juxtaposed to monthly flow at Southerly International Boundary (SIB), 2005-2015. For piezometer locations, please see Appendices A and C

Limited historical groundwater data provide water level trends in the riparian corridor (Figure 3-2). In the upper Reach 1 and in Reach 4, water levels have remained relatively stable for a decade. In contrast, water levels in the dry reach (BD52 and BD57) are declining.

Evapotranspiration (ET) from riparian vegetation was quantified from remotely-sensed MODIS enhanced vegetation index (MODIS-EVI) data using the method developed by Nagler *et. al.* (2013). Our analysis indicates that in 2000-2013, riparian vegetation evapotranspired an annual average of 160 Mm^3 (130,000 af), with rates decreasing over time. By comparison, an average of 46 Mm^3 (37,000 af) of surface water flowed passed SIB annually, according to IBWC gage data.

The pulse flow

Groundwater levels were measured before, during and after the pulse flow. One hundred sixteen piezometers[2] were utilized along the channels and adjacent floodplain and terraces to record changes in the elevation of the water table (Appendix D). Geophysical techniques were used in the Limitrophe section of the study area (Reaches 1 and 2) to further understand the immediate groundwater response to the pulse flow.

Locally along the river corridor, piezometers recorded pre-pulse flow groundwater depths ranging from zero where the water table intersects the river channel, to more than 14 m (46 ft) near San Luis Río Colorado (piezometer P15). During the pulse flow, the water table rose as much as 9 m (30 ft) in the lower Limitrophe (piezometer MA15), with impacts decreasing away from the river channel.

Figures 3-3 – 3-5 show how water levels changed as a result of the pulse flow at representative sites along the river. The most significant changes occurred in the dry reach (Reaches 2 and 3), where pre-pulse groundwater levels were the deepest. In the Reach 4 restoration areas, the groundwater elevation changed little because little recharge occurred from the relatively small volume of water delivered to Reach 4 and because the pre-pulse water table was already near the land surface.

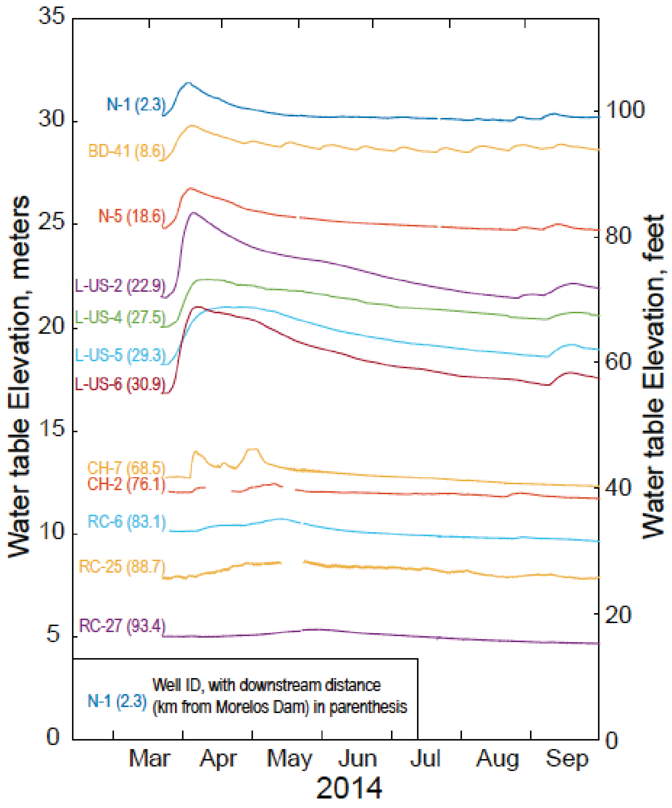

Figure 3-3. Hydrographs recorded at representative piezometers along the river corridor, showing how the pulse flow response varied downstream and attenuated with time. River kilometers from Morelos Dam to each piezometer are shown in parentheses.

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[2] Seventy-nine Universidad Autónoma de Baja California (UABC) and 37 U.S. Geological Survey (USGS), Bureau of Reclamation (USBR), and International Boundary and Water Commission (IBWC).

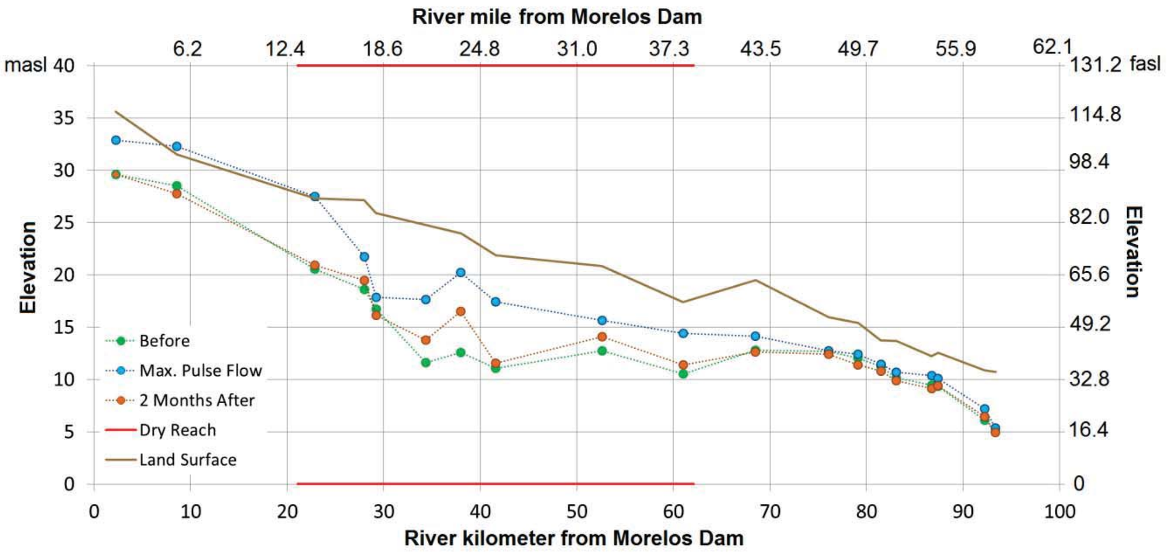

Figure 3-4. Groundwater level changes along the river corridor, showing groundwater elevations relative to the floodplain surface (at piezometer locations) before (March 2014), during, and two months after the pulse flow peak passed each location.

In all reaches, the pulse flow established a vertical connection between the river and groundwater (Fig 3-5). However, hydraulic effects on the groundwater flow system were relatively short-lived and localized.

In the Limitrophe reach (Fig. 3-5, top), groundwater flowed laterally into the river from the surrounding aquifer prior to the pulse flow; that is, groundwater discharged into the river, as previously observed by Ramírez-Hernández et al. (2013). For a short period during the pulse flow, the flow direction reversed, and the river recharged the aquifer. Within two months, the water table had returned to nearly its pre-pulse level, and groundwater resumed flowing into the river. By October, all groundwater levels in the Limitrophe reach had returned to within 2 m (7 ft) of their pre-pulse levels.

In the dry reach (Fig. 3-5, center), groundwater flowed west to east beneath the river toward the Mesa Arenosa and Minute 242 well fields prior to the pulse flow. Recharge from the pulse flow raised the water table more than 9 meters (30 ft) in the immediate vicinity of the river. By October, all groundwater levels beneath the dry reach had returned to within 2 m (7 ft) of their pre-pulse levels.

Groundwater levels in the Reach 4 restoration areas closely correlate with irrigation of adjacent farmland (Ramírez-Hernández et al. 2015). Therefore, in Reach 4 (Fig 3-5, bottom), relatively little recharge to a pre-existing high water table caused the groundwater response, like the surface-water response, to be modest. However, although the water table rose less than 2 meters, this increase was sufficient to reach target germination sites on the lower terrace.

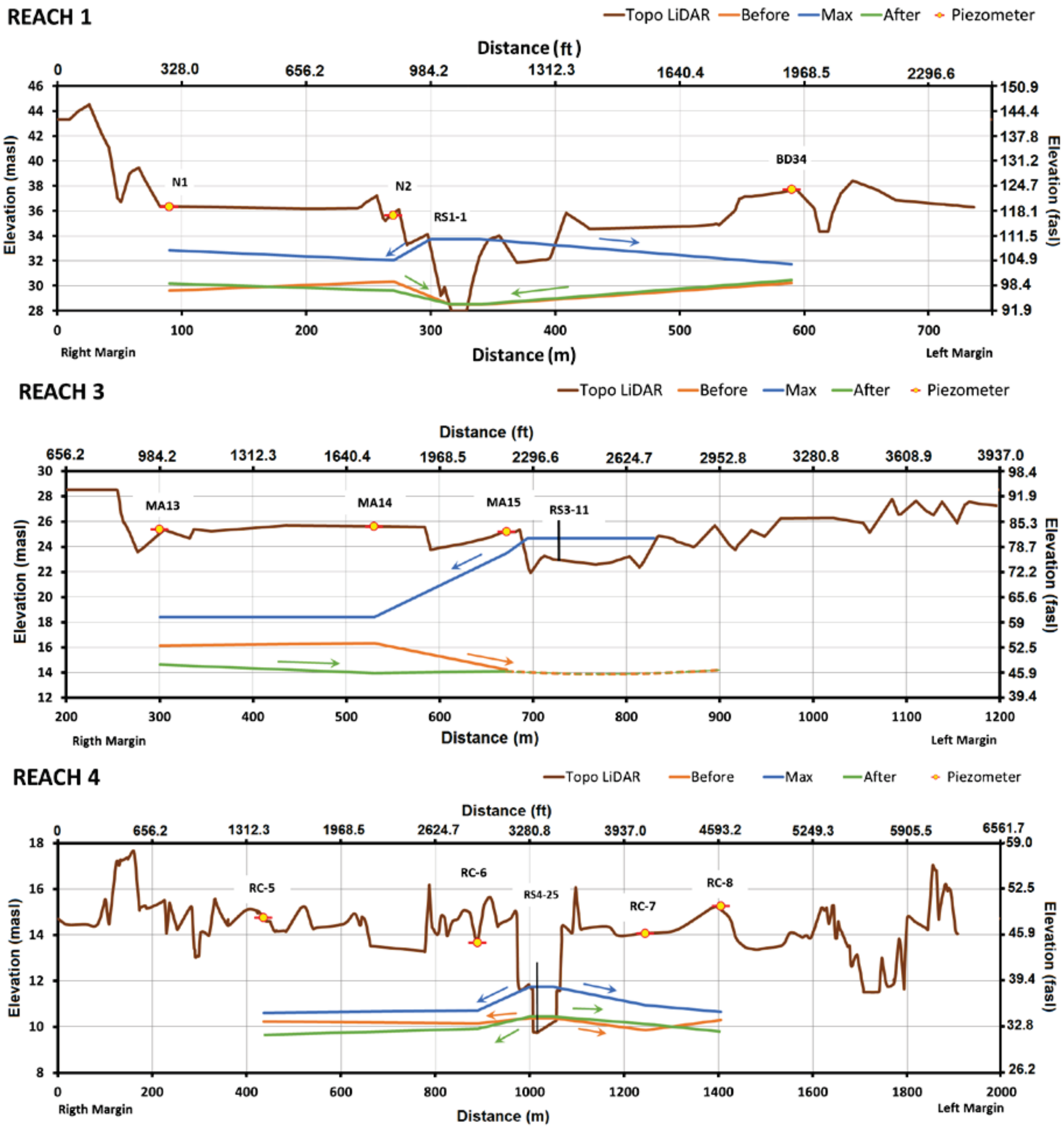

Figure 3-5. Cross sections showing how the pulse flow affected the component of groundwater flow perpendicular to the river channel before (orange), during (blue), and 2 months after (green) the pulse flow peak passed each location**.** Dashed line indicates inferred water level beneath piezometer RS3-11, which was dry. Note that vertical scale varies between figures. RS indicates river stage gage.

As mentioned previously, annual ET from groundwater generally has been decreasing since 2000. In 2014, this trend temporarily reversed, perhaps in response to the pulse flow (figure 3-6, left). The 2014 pulse flow did not increase ET to the magnitude predicted by the regression equation in Figure 3-6 (right), perhaps due to the deteriorated condition of the vegetation. The 2015 response likely reflects greenness of existing vegetation; newly germinated vegetation would have been too small in 2015 to be detected by MODIS. Because the existing vegetation was in a deteriorated condition, it might have had little capacity to recover following a single pulse flow. It should also be noted that ET captures water from numerous sources. Surface water measured at SIB may be a proxy for water infiltrating into the ground and used by plants farther downstream.

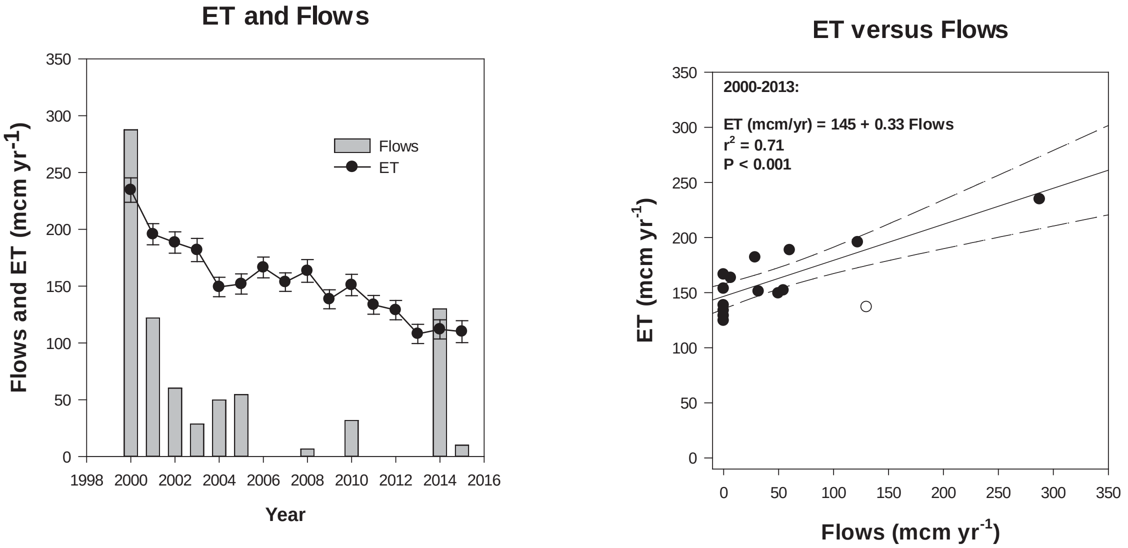

Figure 3-6. Left: Annual ET from the riparian corridor and surface flows at SIB, 2000-2015. Right: regression of ET against surface flows, 2000-2013. The 2014 ET (open circle) fell outside the 95% confidence interval of the regression (dashed line) and was omitted from the analysis.

Table 3-1 compares infiltration from the pulse flow to evapotranspiration (ET) from the aquifer underlying the river corridor (between the levees) by sector during the 2014 growing season (March-October). Infiltration is the pulse flow water that recharged the aquifer, as described in the Surface Water section. The method used to quantify ET (Nagler et al 2013) does not distinguish between ET derived from water from above versus below the water table. Assuming vegetation consumed water primarily from the saturated zone, we included the entire volume in Table 3-1. In each sector, the difference between infiltration and ET is the volume of infiltrated pulse flow water that was withdrawn by pumping wells or flowed laterally into or out of the sector as groundwater.

Table 3-1. Groundwater flow components between the levees, excluding underflow and pumping, March-October 2014, in million cubic meters (Mm^3), with a 5-10% error margin. Note that the pulse flow generated all of the infiltration, but not all of the ET, which, according to MODIS-EVI data, did not differ appreciably between 2013, 2014, and 2015. Infiltration from 12.3 Mm^3 base flow deliveries in water year 2014 is not included. ND = not determined.

Sector or Reach	Infiltration	ET
Sector 1 (DMS 1-2)	11.5	1.1
Sector 2 (DMS 2-3)	22.4	7.5
Sector 3 (DMS 3a-4)	11	2.3
Sector 4 (DMS 4-6)	38.1	4.0
Sector 5 (DMS 6-7)	29.7	3.9
Sector 6 (DMS 7-8)	4.0	1.1
Sector 7 (DMS 8-10)	2.6	4.2
Sector 8 (DMS 10-11)	2.2	1.9
Sector 9 (DMS 11-12)	0.1	2.5
Reach 5	ND	26.4
Reach 6	ND	5.8
Reach 7	ND	25.1
TOTAL	122	85.7

Groundwater salinity

Groundwater salinity affects the type and distribution of vegetation in the Limitrophe and delta. Specific electrical conductance (a proxy for salinity) of groundwater was measured periodically in selected piezometers in 2014 (Appendix D). Salinity concentrations generally increased downstream (Figure 3-7), as expected in a system with limited freshwater inflows and high evapotranspiration rates. Our data show no consistent temporal pattern of groundwater salinity changes during the pulse flow.

The measured concentrations are considerably lower than the 3-10 g/L typical of saltcedar stands that depend on seepage from the Lower Colorado River, as at Cibola (Glenn et al., 2013) and Havasu (Guay, 2001) National Wildlife Refuges. The Delta's riparian zone, therefore, is unusual in the Lower Colorado River floodplain because it has relatively low-salinity groundwater that can support native trees (Nagler *et al.*, 2005).

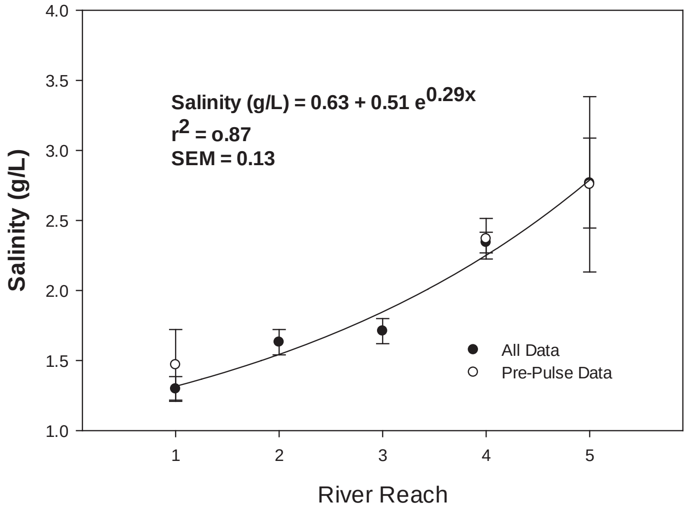

Figure 3-7. Groundwater salinity measured in 69 piezometers along the riparian corridor from March to May 2014, measured as specific conductance (dS/m) and converted to salinity (g/L) using a factor of 0.62 (based on groundwater analyses reported in Dickenson et al. 2006). Vigorous growth of cottonwood and willow trees requires a salinity concentration of less than 2.5 g/L (4 dS/m), although the trees can tolerate up to 5 g/L (8 dS/m) (Shafroth et al., 2008; Glenn et al., 1998).

Base flows

In addition to the 132 Mm^3 (107,000 acre-ft) pulse flow, 12.3 Mm^3 (9,970 af) of base flow was delivered in water year 2014 (October 2013 – September 2014). Of this volume, 5.1 Mm^3 (4,100 af, or 41%) was delivered to the main channel via Morelos Dam on Sept 5-9, 2014; 0.5 Mm^3 (400 af, or 4%) was delivered to the Miguel Aleman restoration site; and 6.7 Mm^3 (5,400 af or 55%) was delivered via Km 18 spillway to the main channel and the Laguna Grande restoration site. Detailed information on the timing of the 2014 and 2015 base flows will be provided after the information becomes available. Similarly, the effects of base flows on groundwater will be evaluated after the information becomes available.

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Section 4: Geomorphic response

Key observations:

1. **The highest measured suspended sediment transport rates were in the upper limitrophe and in an approximately 10 km (6.2 mi) reach downstream from SIB.**
2. **Although 156,000 ± 81,000 cubic meters (5.5 million ± 2.8 million cubic feet) of sediment were mobilized, changes within Reaches 1-3 during the pulse flow were limited to localized reworking of the channel bed, scour and fill on the order of 1 m (3 ft) or less within the active channel, and minor bank erosion.**
3. **Pulse flow discharge was not sufficient to widen the channel, or to scour or bury significant amounts of existing vegetation.**

Introduction

Historical flood conditions shape riparian geomorphology. Following completion of Hoover Dam in 1935, the annual streamflow and sediment supplies to the Colorado River were drastically reduced, but moderate flood peaks still occurred most years. Delta floods largely ceased following completion of Glen Canyon Dam in 1963, and no flow occurred nearly 20% of the time as recorded at the Southerly International Boundary (SIB). After filling of Lake Powell, large floods in the 1980s followed successive years of extremely high snowmelt runoff from the upper Colorado River basin and a peak flow of 934 m^3/s (33,000 cfs) was recorded at SIB in 1983. These floods were long duration and caused considerable channel adjustment (McCleary, 1986; Tiegs and Pohl, 2005). From 1989 to 1992, there was no flow recorded at SIB 92% of the time. This dry period was punctuated by flood flows in 1993 from the Gila River, which peaked at 646 m^3/s (22,800 cfs) at SIB. Following extended periods of zero discharge in the middle 1990s, a series of moderately high flows occurred in the late 1990s. Progressively decreasing flows have been recorded at SIB since 2000, except in 2001.

The river channel in the limitrophe reach is relatively natural, in that it has not been significantly modified by human activity except for levees. The upstream segment (Reach 1) is more confined within levees, and leakage from Morelos Dam and irrigation return flow results in a wetted channel with dense bank vegetation. In the downstream segment (Reach 2), the river channel is dry, bank vegetation is less dense, and the channel is less confined by levees. The width of the alluvial corridor between the levees ranges from approximately 0.5 km (0.3 mi) immediately downstream from Morelos Dam, to more than 4 km (2.5 mi) in parts of Reach 2. Downstream of the SIB, the channel remains dry for approximately 35 km (22 mi) (Reach 3). Here, much of the river corridor maintains a semi-natural form, but is bisected by a pilot channel intended to convey flow downstream. Approximately 30 km (20 miles) downstream from the limitrophe, the river corridor is fully channelized, and eventually becomes wetted from groundwater inflow (Reaches 4 and 5). The river channel in much of Reach 3 and 4 follows the path of the Vacanora Canal constructed in 1929 (Sykes, 1939), and, downstream from the railroad bridge in Reach 4, the river follows a course established in 1942 following spillway test releases from Hoover Dam.

The Pulse flow

Pre-existing surveys, maps and photographs document historic channel changes from 1939 to 2014 in the limitrophe reach, which established conditions for surface water flow and sediment transport during the pulse flow. Satellite imagery, aerial photography, and LiDAR (acquired early March, 2014 and August, 2014) digital elevation models document geomorphologic change and sediment transport in the entire river corridor during the pulse flow. Additionally, repeat cross-sections, scour chains, and suspended sediment transport measurements at several locations provide more detailed field-based observations of geomorphologic response to the pulse flow. Twenty-three cross-sections within the limitrophe, spaced 1 to 4 km (0.6 to 2.5 mi) apart, focused on areas likely to be inundated by the flood. An additional 13 cross-sections were surveyed downstream from the limitrophe. Equal width increment (EWI) suspended sediment samples were collected on six occasions at three sites in the limitrophe during the pulse flow, and single-vertical suspended sediment samples were collected during the flow peak at an additional six sites, including two sites downstream from SIB, to quantify magnitudes of sediment transport during the pulse flow.

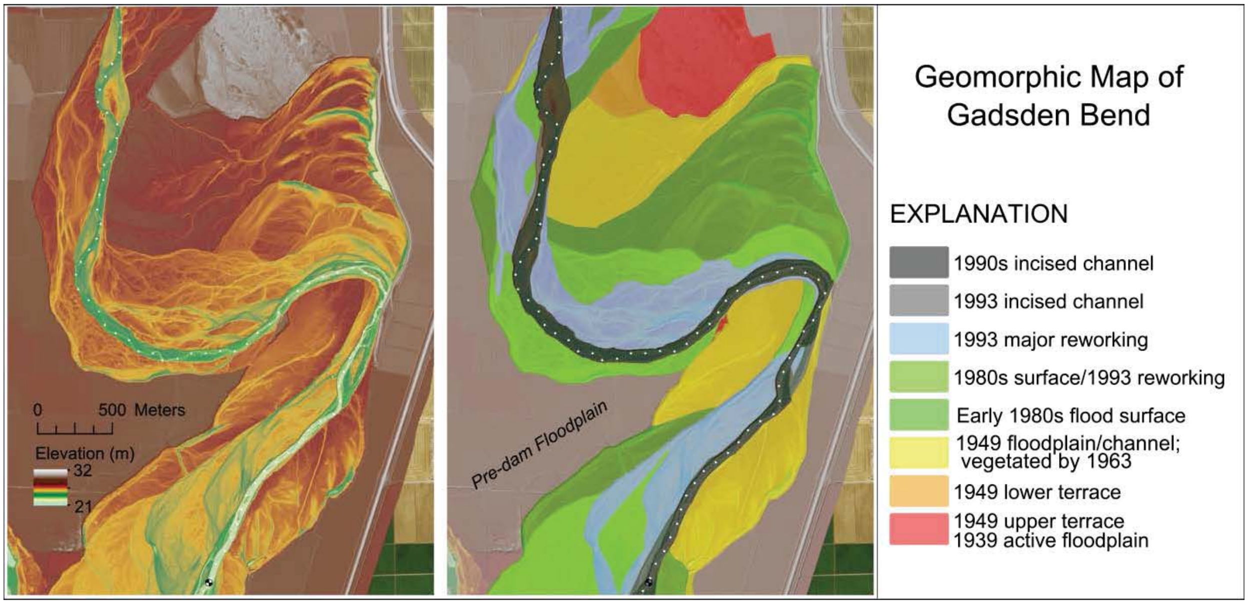

Figure 4-1. Example of river channel and geomorphic surfaces at Gadsden Bend within the limitrophe. Pre-pulse flow LiDAR (left) and geomorphic surfaces showing time of most recent occupation and reworking (center); modern channel (dots) follows recent "active" channel incised in the 1990s.

Aerial photography and historic IBWC cross-sections and reports suggest that the most significant post-dam channel changes occurred in the early 1940s when there was roughly 2 m (7 ft) of bed degradation, and during the long-duration floods of the mid-1980s (Fig. 4-1, inset). The 1980s floods caused significant lateral migration and channel change between 1982 and 1989, but deep bed incision in 1983 mostly recovered by the late 1980s (Fig. 4-1, inset) (IBWC unpublished data; Tetra Tech, 2004; NCD/FPC 2006). The 1980s floods also resulted in considerable channel migration, flooding, and bed reworking along the river corridor downstream from the SIB in Mexico. The Gila River floods of 1993 resulted in further channel migration and bed reworking, but most geomorphic change was confined to the part of the channel affected by the 1980s floods, rather than eroding older and higher terraces. The floods in the late 1990s mostly modified this channel, which became further incised, and forms the modern "active" channel (Fig. 4-1). By 1999, the deepest part of the channel had incised below the 1989 level, and the 2014 LiDAR indicates that the channel configuration is similar to that observed in 1999. The degree of channel incision below the floodplain surface decreases downstream in Mexico.

The maximum pulse flow discharges of 120 m^3/s (4,200 cfs) at Morelos Dam and 71 m^3/s (2,500 cfs) at SIB (Figure 2-3) were much less than the post-dam floods described above. The hydrograph of daily flow from Morelos Dam shows a 3-day period of maximum releases, a second discharge spike three days after the peak, and several other fluctuations during the falling limb (Fig. 4-2).

Suspended sediment concentrations decreased through time (Fig. 4-2, right). Relatively high suspended sand concentrations were isolated to the 11-mile gage site (DMS-2) approximately 5 km (3.1 mi) downstream from Morelos Dam, and the majority of the 4000 tons (4410 U.S. tons) of suspended sand that passed this gage was deposited within the limitrophe (Fig. 4-2, right). Downstream, as the river corridor widens, suspended sediment transport decreased rapidly, and most geomorphic change was limited to local sediment scour and deposition in the recently active channel (Fig. 4-3). In the 10-km (6-mile) reach downstream from SIB, sediment concentrations were somewhat higher than in the downstream part of the limitrophe (Fig. 4-3). This area of enhanced geomorphic change was somewhat unexpected because of the reduced discharge in this reach, but channel change remained confined to the active channel bed and pilot channel with limited bank erosion. Except for isolated segments, sediment transport likely diminished rapidly as discharge decreased below 15 m^3/s (530 cfs) further downstream in Reaches 4 and 5.

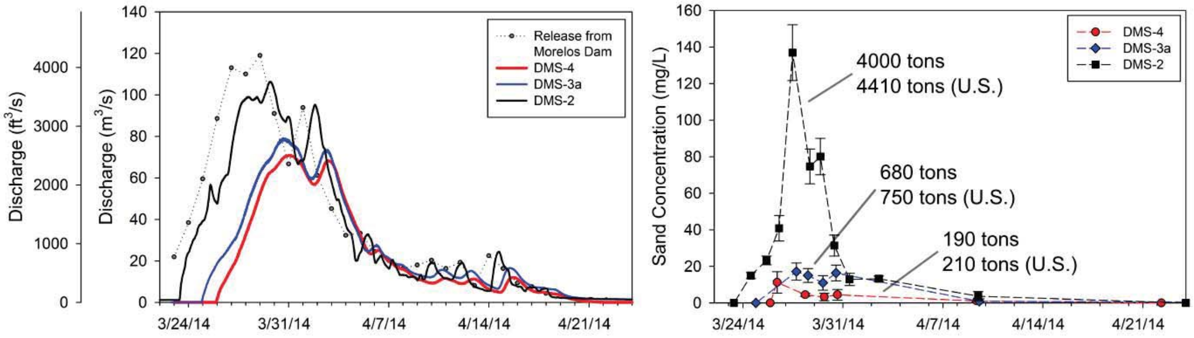

Figure 4-2 Continuous discharge hydrographs for suspended sediment sampling sites in the limitrophe reach (left), and associated sand concentrations with total suspended sand loads indicated (right).

Geomorphic changes in stream bed topography along the Colorado River during the pulse flow were concentrated in the recent active channel where flow depths were greatest; further downstream, there was also considerable sediment transport in places where the pilot channel intersects the natural river course formed during the 1980s floods and where earthen dams were overtopped (Fig. 4-4 – channelized meanders and breached dams). Maximum erosion and deposition along the channel bed was generally in the range of ± 1 m (3 ft) with no net longitudinal trend (Fig. 4-4). Repeat LiDAR indicates approximately 156,000 ± 81,000 m^3 (5,509,000 ± 2,860,000 ft^3) of sediment were involved in bed reworking (erosion and deposition processes) in the dry channel (Reaches 2 and 3), but there was no statistically significant net change in sediment storage for the reach within uncertainty.

Low-velocity flow did inundate some higher surfaces in the 50-km (30-mile) segment downstream from Morelos Dam, but there was no noticeable geomorphic change on those surfaces. Significant bank erosion did not occur along most of the channel, but sandbars locally buried vegetation and the main channel bed was reworked along much of the river corridor in the limitrophe. Only two scour chains showed evidence of significant scour (>0.1 m, or 0.3 ft) prior to deposition, whereas most showed relatively short-lived and localized sediment transport. Thus, the pulse flow resulted in meter-scale topographic changes focused on the bed of the recent active channel and pilot channel, but did not cause further channel incision or significant bank erosion because of its relatively small magnitude and short duration.

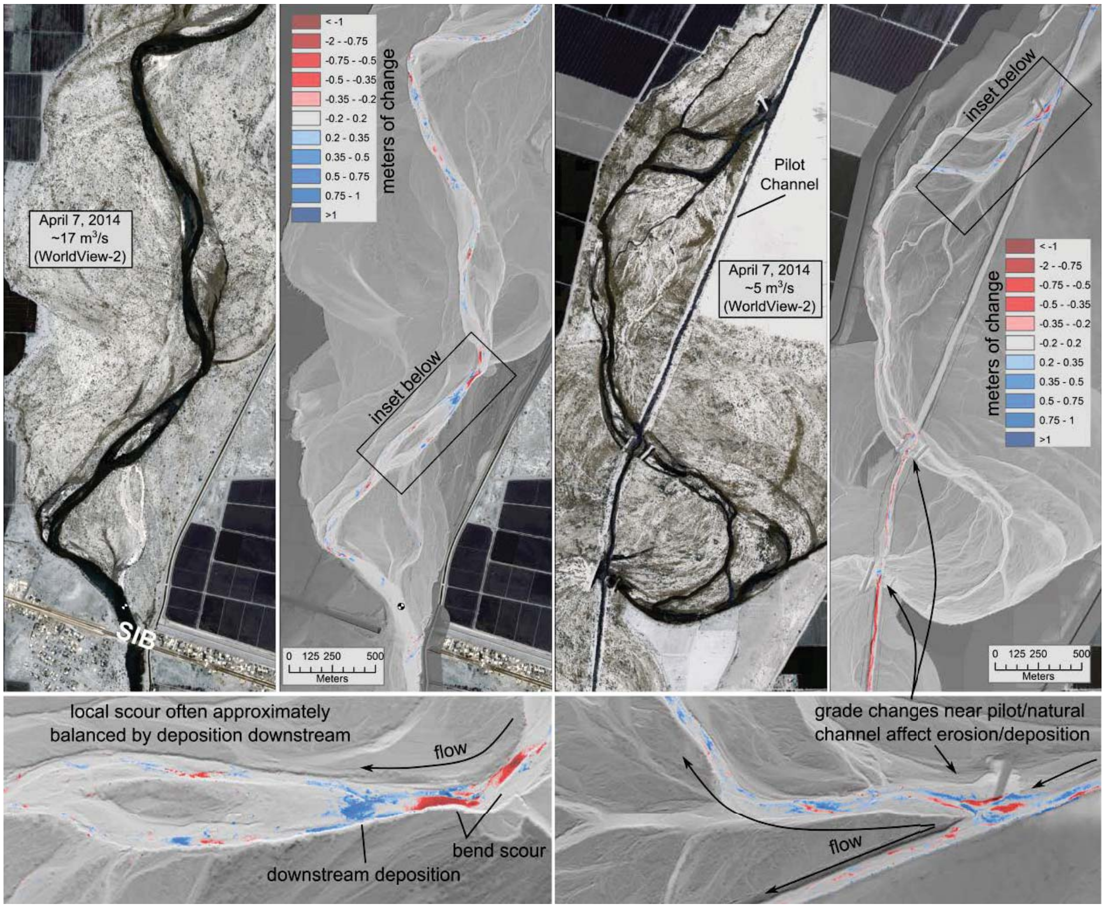

Figure 4-3. Worldview imagery from 4/7/2014 showing active channel inundated several days after the peak discharge and LiDAR DEM (Digital Elevation Model) of difference showing examples of channel change. Sites are located just upstream from SIB (left) and in the downstream part of Reach 3 (right).

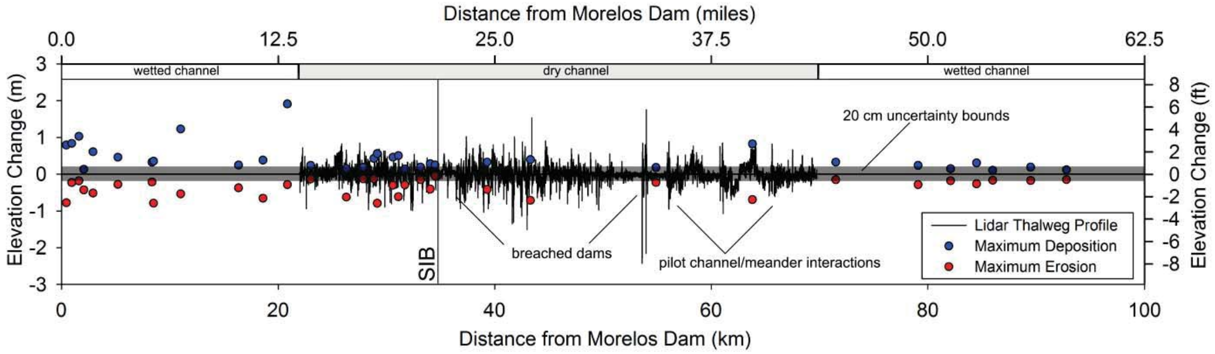

Figure 4-4. Downstream trend in maximum aggradation and degradation from surveyed cross-sections (dots), and LiDAR DEM of difference for the thalweg profile (lines) along the river corridor.

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Section 5: Vegetation response using ground survey techniques

Key Observations

1. **Most requirements for woody, native riparian species recruitment (cottonwood, willow, and baccharis) were met in Reaches 1 and 4 unprepared areas due to high seed availability, continued soil moisture, and tolerable levels of soil salinity. However, dense, existing vegetation in these unprepared areas reduced the availability of bare ground necessary for seed germination in the most hydrologically favorable sites.**
2. **All seedling establishment requirements were met at the majority of prepared restoration areas in Reach 4 due to management actions. Prior to the pulse flow, site managers removed tamarisk and arrowweed and excavated and graded meanders; base flows were delivered in the first and second growing seasons.**
3. **Native, woody riparian species established with highest frequencies and densities in Reach 4 prepared areas (except LG1) and Reach 1 unprepared areas.**
4. **More extensive recruitment of woody, native riparian species in unprepared sites with favorable hydrological conditions (Reaches 1 and 4) will require active management such as the removal of existing vegetation, delivery of base flows, and control of nonnative species.**
5. **Reach 4 has elevated surface soil salinity compared to other river reaches due to the presence of a shallow groundwater table and lack of regular surface flows. Environmental flows are critical for soil salinity management in areas such as Reach 4 that support existing and restored native riparian habitat.**
6. **Riparian plant species were successfully established in the actively managed Miguel Aleman and Laguna Grande sites through removal of tamarisk and arrowweed, planting/seeding of native species, and irrigation.**

Introduction

Understanding the seedling establishment requirements of riparian plants is critical to interpret vegetation responses to the Minute 319 environmental flow releases. Several factors affect the recruitment success of pioneer riparian trees and shrubs along western North American rivers, including the Colorado River and its delta (Fig. 5-1; Harper et al. 2011; Mahoney and Rood 1998; Shafroth et al. 1998). These include: 1) seed availability; 2) bare substrate availability; 3) exposure to secondary flooding; 4) surface and groundwater levels and rates of decline; 5) soil salinity and texture; and 6) competition and herbivory. If conditions are not met at various stages in the life cycle of the seedling, then seedling mortality is likely. Active management can improve the probability of recruitment by overcoming limiting factors (Fig. 5-1). For this report, we assess how well each recruitment requirement was met in Reaches 1-4 in the context of Minute 319 environmental flow releases, including both prepared sites (i.e., in restoration areas) and unprepared sites (i.e., seedling transects).

The following key plant taxa are referred to in the text and figures as follows:

- Fremont cottonwood (*Populus fremontii*; species code: POFR; hereafter referred to as cottonwood);
- Goodding's willow (*Salix gooddingii*; SAGO; hereafter referred to as willow);
- Seep-willow and Emory's baccharis (*Baccharis* species; BASP; hereafter referred to as baccharis);
- Arrowweed (*Pluchea sericea*; PLSE; hereafter referred to as arrowweed);
- Tamarisk (*Tamarix* species; TASP; hereafter referred to as tamarisk).

Cottonwood, willow, baccharis, and arrowweed are all native riparian species. Tamarisk is the dominant nonnative species along much of the river corridor and is considered to be of lower habitat quality than native tree species (Hinojosa-Huerta et al. 2008).

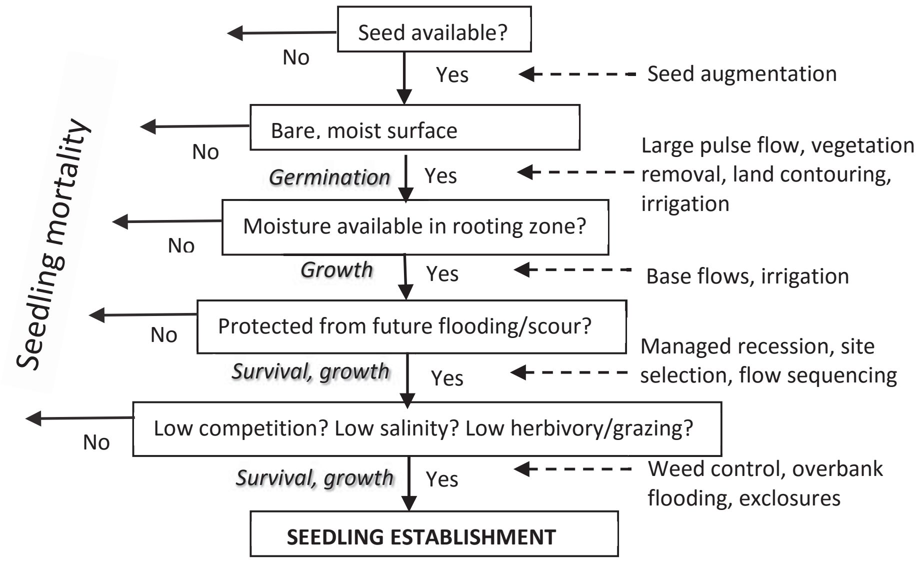

Figure 5-1. Key requirements for germination and establishment of pioneer riparian trees and shrubs. Requirements are described inside the boxes in the form of questions and are presented sequentially. If a requirement is met (“yes”), then germination, survival, or growth occurs and the next requirement is examined (downward facing arrows). If a requirement is not met (“no”), then seedling mortality is likely (solid arrows facing left). Management actions are indicated on the right side of the figure, with dashed arrows pointing to the condition or requirement addressed by the management action.

Methods

The Minute 319 vegetation monitoring team used field-based methods to assess the effects of the pulse flow on riparian vegetation along the Colorado River corridor in areas with varying levels of active management. We use four sub-headings to organize our presentation of material related to vegetation response: 1) *seedling transects* (unprepared areas), 2) *Laguna Grande transects* (prepared areas), 3) *comparison* between unprepared and prepared areas, and 4) *managed, planted restoration areas* in Laguna Grande and Miguel Aleman. Detailed discussion of sampling methods and locations can be found in Appendix E

In addition, repeat photography was used to document various sites shortly before, during, and six months after the pulse flow. See Appendix F for methods used in repeat photography.

Seedling transects (unprepared areas)

No management actions were taken prior to environmental flow releases in unprepared sites in the Colorado River floodplain where seedling transects were established. Woody seedling establishment and environmental factors were monitored in Reaches 1-5 along 21 belt transects oriented perpendicular to the main channel (hereafter “seedling transects”). Transects were monitored before (March) and after (May) the 2014 pulse flow and again in June and October 2015. In addition, 34 “long-term" monitoring plots were established in October 2014 along transects where seedlings were present and were surveyed again in May and October 2015.

Laguna Grande transects (prepared areas)

To help meet seedling requirements, such as bare, moist surfaces with little competition from existing vegetation, the Sonoran Institute prepared sites in the Laguna Grande Restoration Area (Laguna Grande) prior to the pulse flow release. Site preparation occurred in areas that were projected to be inundated by the pulse flow based on a one-dimensional, steady-state hydraulic model (HEC-RAS; Hydrologic Engineering Center, Davis, CA, USA). Management actions included: 1) removal of tamarisk and arrowweed from 129 hectares (ha) (320 acres); 2) excavation to reconnect three former channel meanders (hereafter, "meanders") with the Colorado River mainstem; 3) excavation to connect portions of six former channel meanders with each other; and 4) land grading and leveling.

In the Laguna Grande prepared sites, 32 belt transects perpendicular to meander channels were established along five cleared meanders to assess plant species recruitment and survival following the pulse flow. Transects were monitored in August and October 2014 and in May and October 2015. Results are grouped into different restoration areas within Laguna Grande: Herradura (LG1), Cori (LG2), and CILA (LG3) (Fig. 5-2).

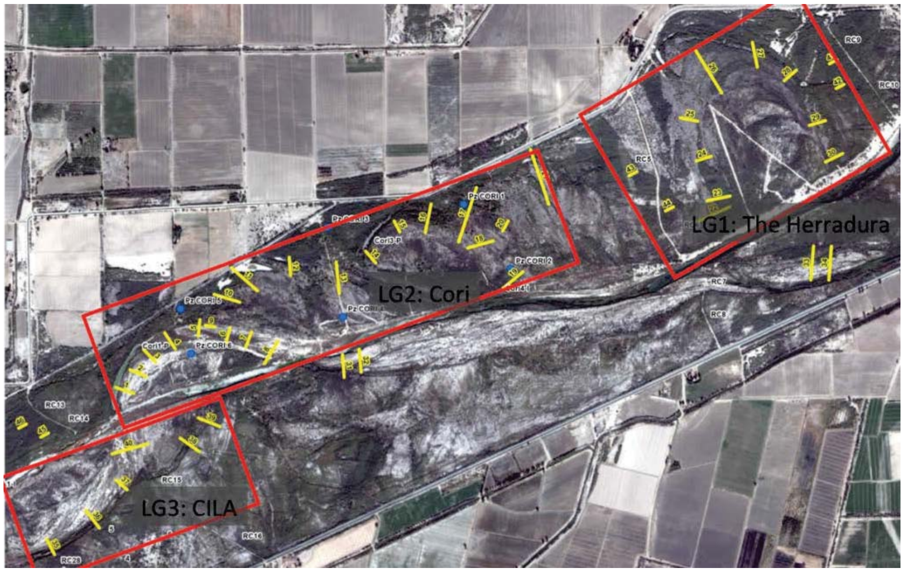

Figure 5-2. Location of transects in prepared restoration areas in the Laguna Grande Restoration Area: Herradura (LG1), Cori (LG2), and CILA (LG3).

Managed, planted restoration areas (Laguna Grande and Miguel Aleman)

Native species were planted in managed restoration areas that were regularly irrigated and weeded. Preparation in Laguna Grande managed restoration sites included clearing of tamarisk and arrowweed, leveling of the site, and creation of furrows (or installation of drip irrigation systems) prior to planting/seeding. Preparation in the Miguel Aleman managed restoration site included the clearing of 80 hectares (198 acres) of tamarisk, the installation of a 4.8-kilometer (km) (3-mile) pipe to bring irrigation water from Canal Reforma, and the grading and leveling of 63 ha (156 acres) prior to planting. Vegetation monitoring in managed, planted restoration areas included estimates of average tree density, survival, and growth of planted trees.

Results

Ground surveys

This report provides an update on field-based monitoring conducted in 2014-2015 and preliminary results from those efforts. We emphasize that these are draft, preliminary, provisional results. See Appendix E for detailed results.

1. Conditions before and after the pulse flow:

a. Creation of bare substrates:

Seedling transects (unprepared areas):

Reaches 2 and 3, where a wide, dry sandy channel predominates, had the highest percentage of bare substrate along transects before and after the pulse flow (Fig. 5-3a). The average percent of transects where bare substrate was present changed very little as a result of the pulse flow, and declined slightly in four of five reaches (Fig. 5-3a), although pre- vs. post-pulse differences were not statistically significant. Small differences may result from a combination of changes due to erosion and deposition associated with the pulse flow, growth of existing and newly established vegetation between March and May, presence of inundated areas after the pulse flow, and sampling error (see Appendix E for methods of bare ground estimation).

Laguna Grande transects (prepared areas):

The average percent of bare substrate along transects exceeded 90% in all Laguna Grande sites: Herradura (LG1), Cori (LG2), and CILA (LG3) (Fig. 5-3b). These sites were cleared of some or all of the pre-existing vegetation (desirable native species were not cleared).

Comparison of bare surfaces:

The prepared restoration sites had a much higher percentage of bare substrate cover than the unprepared sites both before and after the pulse flow. This is due to the clearing of tamarisk and arrowweed along the meander channels prior to the pulse flow release.

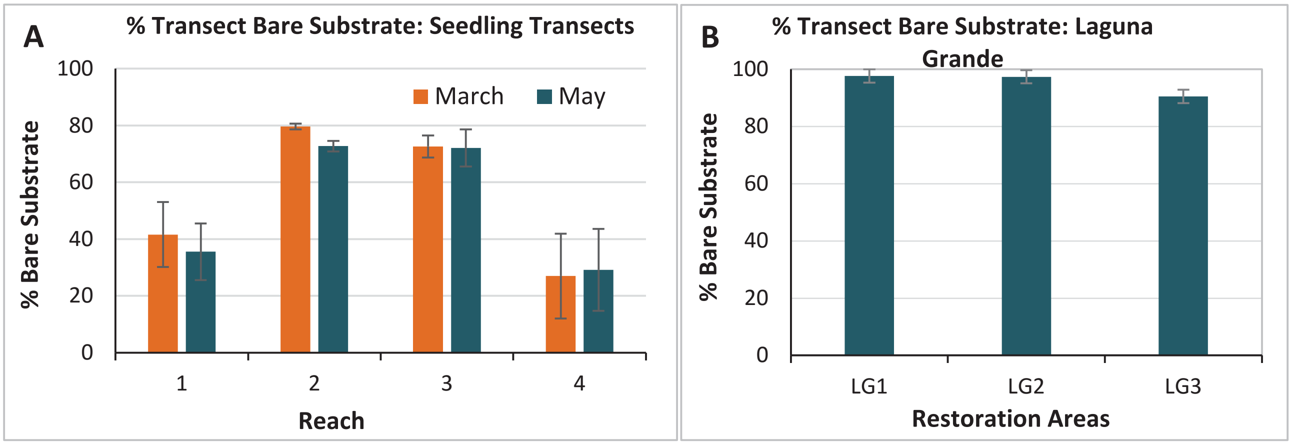

Figure 5-3 A. Average percent of transect with bare soil before (March) and after (May) the 2014 pulse flow along the unprepared seedling transect sites. **B.** Average percent of transect with bare soil cover in prepared sites (extracted from May 2015 data, and assumed to be representative of bare soil cover in March 2014 after clearing).

b. Soil Salinity

Seedling transects (unprepared areas):
Soil salinity can limit native woody riparian species germination and growth; we use 8 dS/m as a general upper tolerance limit for mesic riparian species based on previous studies (Shafroth et al., 2008; Glenn and Nagler, 2005). In all four reaches, 75-100% of March (pre-pulse flow) soil samples had salinity values within the suitable range for riparian species (Fig. 5-4a). However, surface soil salinity was highly variable in Reaches 1 and 4 and may have been a limiting factor in some areas within these reaches. All May (post-pulse flow) soil samples had salinity values below the 8 dS/m threshold, and almost all were below 4 dS/m. For Reaches 1 and 4, the decrease in soil salinity following the pulse flow was not significant due to high variability of salinity levels. The increase in surface soil salinity in Reaches 2 and 3 was significant, but likely not to levels that would limit cottonwood and willow growth.

Unfortunately no soil samples were collected from cottonwood or willow seedling plots (there was only one plot, and no samples were taken). Soil salinity in *tamarisk and baccharis* seedling plots was highest in Reach 4 (Fig. 5-4b). In general, soil salinity in seedling plots may be higher than samples taken earlier along transects due to the fact that the seedling plot samples were collected in October when plots were established; evaporation over the growing season may have led to elevated soil salinity. Soil texture in areas where seedlings established may also cause elevated soil salinity in seedling plots.

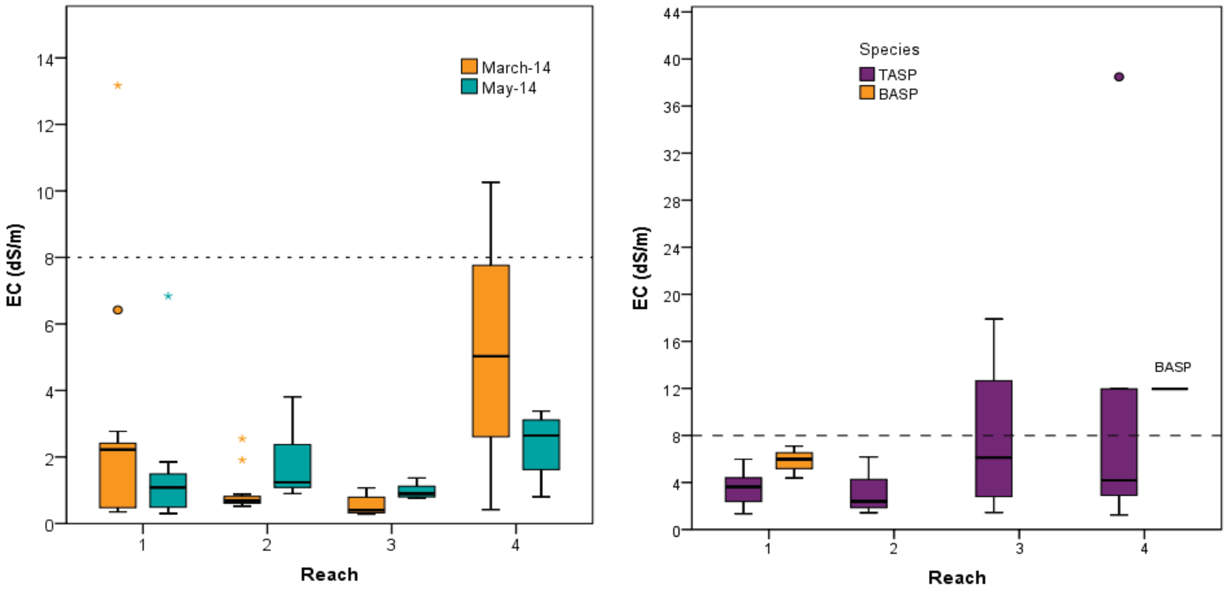

Figure 5-4a (left). Boxplot of surface soil salinity in Reaches 1-4 before and after the pulse flow (March and May 2014). The box represents 25-75% of soil salinity values for each reach, the black line is the median, points represent outliers, and asterisks are extreme outliers (values more than 3 times higher than the height of the box). Whiskers show the lowest and highest sample values and the dashed line indicates the salinity tolerance limit for riparian trees and shrubs.
Figure 5-4b (right). October 2014 surface soil salinity in long-term seedling plots (n=31) in reaches 1-4. Note: figure only contains samples from seedling plots with tamarisk and baccharis (i.e., no cottonwood or willow).

Laguna Grande transects (prepared areas):

Soil salinity results from Laguna Grande are limited by the small number of repeat surface soil samples taken before (March 2014) and after (October 2014) the pulse flow from inundated areas. Additionally, samples were not taken along the seedling transects, which makes it difficult to determine how seedling recruitment was directly affected by soil salinity. In general, surface soils across the restoration sites were highly variable (Fig. 5-5), which means that suitable areas for seedling recruitment varied greatly from place to place. The Herradura site (LG1) appears to have the highest surface soil salinity of all the restoration areas, which may have inhibited seed germination there. The limited number of samples suggests that in most areas soil salinity decreased from March to October 2014, consistent with flushing of salts that could have resulted from pulse and base flow deliveries to the restoration areas. It should be noted as well that native and nonnative seedling establishment was observed in areas that had known high surface soil salinities prior to the pulse and base flow deliveries (salt visible on surface); this suggests that 1) flows reduced salinity and 2) seedlings may have established in areas with salinity above the tolerance level provided in the literature (8 dS/m). Many existing (remnant) cottonwood and willow trees in the restoration sites currently survive in areas with known high surface soil salinity.

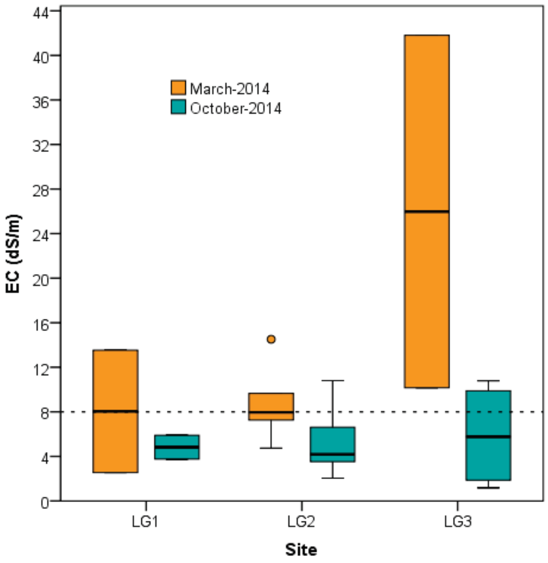

Figure 5-5. Surface soil salinity in prepared restoration areas: LG1 (Herradura), LG2 (Cori), and LG3 (CILA).

Comparison of soil salinity:

Surface soil salinity in Reach 4 prepared areas was similar to that of the unprepared areas, which overall was much higher than soil salinity in Reaches 1-3. The high surface soil salinity in Reach 4 unprepared and prepared areas is likely due to the perennial presence of stagnant, saline water (from groundwater seepage) in some meanders and much of the Reach 4 river channel. Unlike the Reach 1 channel, the Reach 4 channel and meanders were rarely flushed with low saline water prior to environmental flow deliveries, whereas Reach 1 receives incidental flows from Morelos Dam more regularly. In addition, due to the shallow groundwater table in Reach 4, salts move towards the soil surface through capillary rise, evaporate on the surface, and persist in the absence of freshwater inputs. These factors likely cause elevated surface soil salinity across much of the Reach 4 floodplain; environmental flows are critical for soil salinity management to support existing and restored native riparian habitat in this area.

In both the prepared and unprepared sites, surface soil salinity in some cases increased following the environmental flows, which could have been due to the rising of the groundwater table and movement of salts toward the soil surface through capillary rise and evaporation. In other cases, surface soil salinity decreased (but not significantly), as in Reaches 1 and 4 and in the restoration surface soil samples. Differences in March and May surface soil salinity could be a function of 1) the pre-pulse flow salinity level (if initial salinity levels are extremely high, they are more likely to decrease), and 2) the proximity of the sample to the zone of inundation. If the sample location was inundated, then surface soil salinity may have decreased; if it was not inundated, but was wetted from the rising of groundwater to the surface, then surface soil salinity may have increased. The resolution of the inundation zone is in many cases not fine enough to assess if the samples were in the surface-water inundation zone or the groundwater wetted zone.

c. Seed Availability

Seedling transects (unprepared areas):
Cottonwood had a notably shorter seed dispersal window than that observed for willow; cottonwood seed dispersal ended around the beginning of June 2014, whereas willow seed dispersal was observed through August 2014 (although our official monitoring period ended June 18th) (Fig. 5-6). Due to the absence of mature cottonwood and willow trees in much of Reaches 2 and 3, seed dispersal was either absent or observed for a shorter time period for these species and areas. Similar to willow, baccharis species dispersed seed throughout the monitoring period. Tamarisk actively dispersed abundant seed throughout our monitoring period in all reaches, a characteristic that contributed to a high rate of establishment throughout the study area.

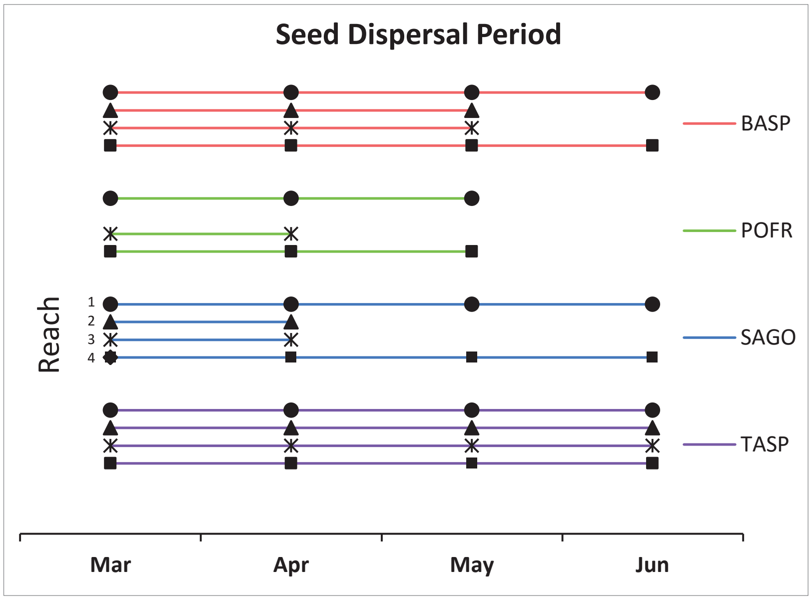

Fig. 5-6. Seed dispersal period by species and reach (over duration of monitoring period). Reach 1 is represented by circles; Reach 2 triangles; Reach 3 asterisks; and Reach 4 squares. POFR = cottonwood (*Populus fremontii*); SAGO = willow (*Salix gooddingii*); TASP = tamarisk (*Tamarix* species); BASP = baccharis (*Baccharis* species). R1-5 = Reaches 1-5. Restoration sites: LG1 = Herradura; LG2 = Cori; LG3 = CILA. Note different scale on y-axis between 2014 and 2015.

Laguna Grande transects (prepared areas):
In general, cottonwood, willow, and baccharis seed were abundant in the Laguna Grande prepared areas due to the presence of existing (remnant) mature trees/shrubs as well as planted mature trees/shrubs. CILA had the highest seed availability for native woody species (it is the most developed restoration site), followed by Cori, followed by Herradura (LG1). The Herradura site has a small number of existing willows in the meander areas, and a handful of cottonwood, willow, and baccharis along the river channel itself; the limited seed source may have limited native species establishment in this area. Tamarisk seed was highly available in all sites during the entire growing season.

d. Groundwater Levels

Unprepared areas
The maximum depth to groundwater from March to October 2014 provides an estimation of the most limiting groundwater conditions during the growing season for existing and newly established vegetation. For this assessment, we used groundwater measurements from piezometers that were no more than 200 meters from the seedling transect. We are working on estimating groundwater levels at exact seedling transect locations, but these estimates were not available at the time of writing this report. Thus, groundwater levels summarized below (Fig. 5-7) do not provide an accurate assessment of groundwater levels in the area of seedling establishment due to the distance from the transect to piezometers. Groundwater levels at the seedling transects are likely shallower than levels presented due to closer proximity to the river channel than the piezometer locations. However, the relative comparison of depth to groundwater from reach to reach is likely more meaningful. In the first growing season (May-October 2014), Reach 3 had the deepest maximum groundwater level out of all reaches (with high variability among transects), followed by Reach 2 (Fig. 5-7). Reach 4 had overall the shallowest maximum depth to groundwater (median value of 4m), while Reach 1 had median value of 5m.

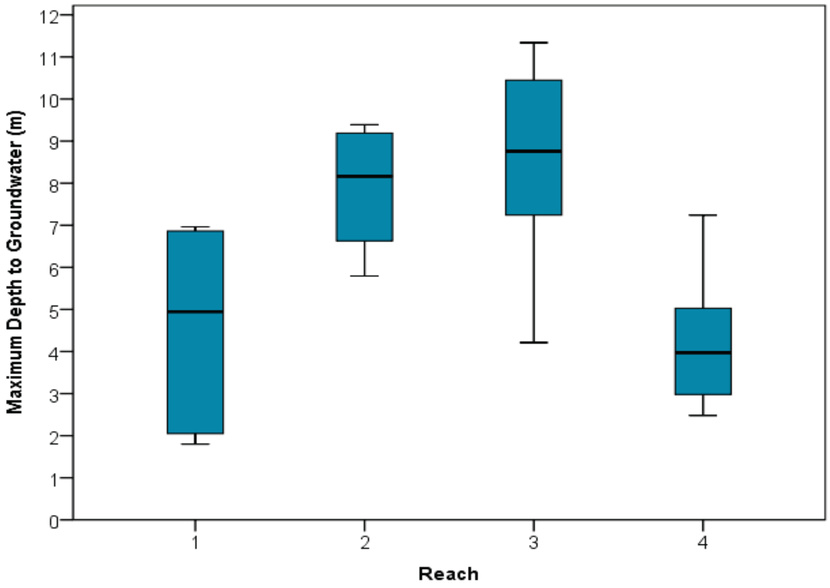

Figure 5-7 (left). Boxplot of maximum depth to groundwater from March to October 2014 in piezometers located 200m or less from the seedling transect in Reaches 1-4. The box represents 25-75% of groundwater depth values for each reach, the black line is the median, and whiskers show the lowest and highest sample values.

Prepared areas
In general, base flows appeared to be beneficial in the restoration areas (Laguna Grande and Miguel Aleman). The benefits of the base flows in Reach 4 areas outside of the Laguna Grande area cannot be assessed without more detail on their timing and delivery points. Benefits of base flows in Reach 1 cannot be determined without detailed information on their timing, amounts, and delivery points.

e. Overall comparison of conditions

The most favorable area for native recruitment was in *Reach 4 prepared sites*, where seedling establishment requirements were met in the majority of sites due to management actions implemented before, during, and after the pulse flow (including the provision of base flows). The most favorable *unprepared* areas for native recruitment occurred in Reaches 1 and 4. Reach 3 had the most unfavorable conditions, followed by Reach 2 (Table 5-1).

Table 5-1. Qualitative estimates of how well requirements for recruitment of native riparian vegetation were met in each reach and with different management actions in Reach 4 following the pulse flow.

Component	**Reach 1**	**Reach 2**	**Reach 3**	**Reach 4 (unprepared)**	**Reach 4 (prepared)**
Seed Availability	good	fair	poor	good	excellent
Bare Substrate	fair	good	good	poor	excellent
Continued Moisture	good	poor	poor	good	good
Low competition	poor	good	good	poor	good
Low soil salinity	good	good	fair	poor - fair	poor - fair
Lack of herbivory/grazing	good	good	good	good	good

2. Recruitment of Woody Seedlings After 1st and 2nd Growing Seasons

Seedling transects (unprepared areas):
At the end of the 2014 growing season (October), a low density of cottonwood and high density of willow seedlings were present in Reach 1 (Fig. 5-8a; Table A-1 in Appendix E). Baccharis seedlings were fairly dense in both Reaches 1 and 4, and tamarisk density was also highest in Reaches 1 and 4. There was no native species establishment in Reaches 2, 3, or 5. The distribution of seedlings was very patchy along transects.

Changes in seedling density between Oct. 2014 and Oct. 2015 (Table 5-2) were highly variable by plot and by species. By the end of the second growing season in October 2015, seedling density of all sampled species was less than 1 individual/m^2 in all reaches (Fig. 5-8b; Table A-2 in Appendix E). Cottonwood seedling density remained the same from 2014 to 2015 in Reach 1 (Table 5-2). The low survival rate of willow from 2014 to 2015 (1%) may have resulted from willow seedlings being outcompeted by the invasive grasses *Arundo donax* and *Phragmites australis,* and other herbaceous species. New baccharis and tamarisk seedlings germinated in 2015, which meant that although 2014 seedlings' survival rate was likely low, new seedlings may have elevated density numbers in 2015. In Reach 4, baccharis seedlings did not survive through the end of the second growing season, likely due to a lack of moisture and/or competition from other species. Tamarisk densities decreased in all reaches with the greatest density reductions in Reaches 1 and 4. In Reach 2, some new tamarisk seedlings established in 2015, which lessened the reduction in density between the two years, as we did not distinguish first-year from second-year seedlings during seedling transect surveys. In Reach 3, tamarisk had low establishment in 2014 but a higher survival rate than other reaches from year 1 to year 2.

Table 5-2. Seedling density comparison from seedling plots between Oct. 2014 and Oct. 2015 (seedlings in 2015/seedlings in 2014*100). *Note, this table shows data just from seedling plots (low N) and does not account for transects without seedlings. Densities provided in figures 5-6a and b are averages across all transects within a reach, which includes transects with zero seedling plots (which lowers overall density).

	Reach			
Species	1	2	3	4
Baccharis spp.	100%, N=3			0%, N=2
Populus fremontii	100%, N=1			
Salix gooddingii	1%, N=1			
Tamarix spp.	18%, N=9	37%, N=8	43%, N=10	19%, N=5

Laguna Grande transects (prepared areas):
Seedling establishment varied across prepared restoration areas in the first growing season (Fig. 5-8a; Tables A-3 in Appendix E). In particular, native species establishment was low in the Herradura site (LG1). Although this site was cleared of tamarisk and arrowweed prior to the pulse flow, it was not inundated during base flow deliveries. In addition, few nearby seed sources (i.e., mature trees or shrubs) existed, especially for cottonwood and baccharis, and soil salinity levels were high at the site, which could have further inhibited establishment of native species establishment. The highest establishment of native species in restoration sites was along CILA meanders (LG3), likely due to a high number of mature native riparian trees dispersing seed from the adjacent active restoration areas, relatively low soil salinity, and ongoing deliveries of base flows to the area.

Similar to the river corridor transects, seedling density decreased from 2014 to 2015 along Laguna Grande transects due to seedling mortality (Fig. 5-6b; Table A-4 in Appendix E). Survival rates were 29%, 30%, 15%, and 31% for cottonwood, willow, baccharis, and tamarisk seedlings, respectively, from October 2014 to 2015 (survival rates were able to be determined because we distinguished between 2014 and 2015 germinants in Laguna Grande transect surveys). Total seedling zone area was reduced by 11% from 2014 to 2015 in the Laguna Grande prepared areas.

Comparison of seedling establishment in prepared vs. unprepared sites:
We compare frequency of seedlings in 2014 and 2015 between prepared and unprepared sites to assess effectiveness of land preparation and base flow deliveries in promoting native seedling recruitment. Direct comparisons of density between Laguna Grande transects and river corridor seedling transects are limited due to differences in monitoring methods. Specifically, density of plants in the Laguna Grande prepared areas are likely underestimated (see Appendix E for explanation of estimation methods); however, in most cases seedling density in Laguna Grande prepared areas is still higher than unprepared areas.

Frequency of seedling presence along transects is a directly comparable metric between the prepared and the unprepared sites. In October 2014, there was a high frequency of native species (cottonwood, willow, and baccharis) in Reach 1 unprepared areas and the Laguna Grande prepared sites (Fig. 5-9a). The low frequency of tamarisk, cottonwood, and willow seedlings in unprepared Reach 4 transects is likely due to the high density of giant cane (*Arundo donax*), common reed (*Phragmites australis*), tamarisk, and arrowweed along much of the channel. Although the baccharis that was established in Reach 4 in 2014 did not survive, there was new recruitment in 2015, likely as a result of variation in soil moisture, small gaps in existing vegetation, or disturbance events such as fire and new roads that created bare soil. Thus, the frequency of tamarisk and baccharis increased in Reach 4 unprepared sites during the second year (2015) (Fig. 5-9b). Effects of fire in Reach 4 were not extensive; one out of six transects had new seedling establishment in 2015 seemingly as a result of bare soil created from fire.

In the Laguna Grande prepared areas, willow establishment was particularly prevalent in October 2014 (Fig. 5-9a). This may be due to the late timing of base flow recession (June-August 2014), which actually caused higher inundation levels than the pulse flow in Laguna Grande. Mature willow trees were still dispersing seed through August 2014, while cottonwood trees stopped seeding in late May, which was prior to significant base flow inundations. Frequency of native species mostly decreased from 2014 to 2015 in prepared areas, with 2015 frequency ranging from 0-40% (Fig. 5-9b). Tamarisk was present in a majority of Laguna Grande transects, with high frequencies maintained in 2015.

Discussion

Combined cottonwood-willow 2014 and 2015 densities (Figures 5-8a and 5-8b) suggest that Minute 319 environmental flows contributed to the successful establishment of native riparian seedlings in Reach 1 unprepared and Reach 4 prepared areas. Observed seedling densities and survival rates of cottonwood, willow, and tamarisk along seedling transects and restoration sites are comparable to those reported in studies of seedling establishment conducted along other rivers in the Western United States (Cooper et al., 1999; Cooper and Andersen, 2012); densities are typically low for cottonwood and willow species after the first year of growth, and seedling mortality from year to year is typically greater than 50%. Additionally, it is important to provide context on relative sizes and competitive interactions between native and nonnative pioneer species. Although cottonwood and willow established in lower densities than nonnative tamarisk across the river corridor and in prepared restoration areas, after 1-2 years of growth, native riparian tree species can often outcompete the high-density tamarisk through rapid growth in height and canopy (Sher et al. 2002). Furthermore, riparian habitat composition with relatively low native vegetative cover (20-40%) mixed with nonnative species cover is considered to be high quality habitat for many avian species (Van Riper et al. 2008).

Seedling frequency and density results support the qualitative estimates derived from the seedling recruitment model (Figure 5-1; Table 5-1): native riparian plant species established with highest frequencies and densities in Reach 1 unprepared areas and in Reach 4 prepared restoration areas (with the exception of LG1, the Herradura). This is not a surprising result given the lack of seed availability and deep groundwater levels in much of Reaches 2 and 3. Management actions, including clearing of some existing vegetation and provision of base flows to Reach 4 restoration areas, were successful in promoting native species establishment, compared to unmanaged areas.

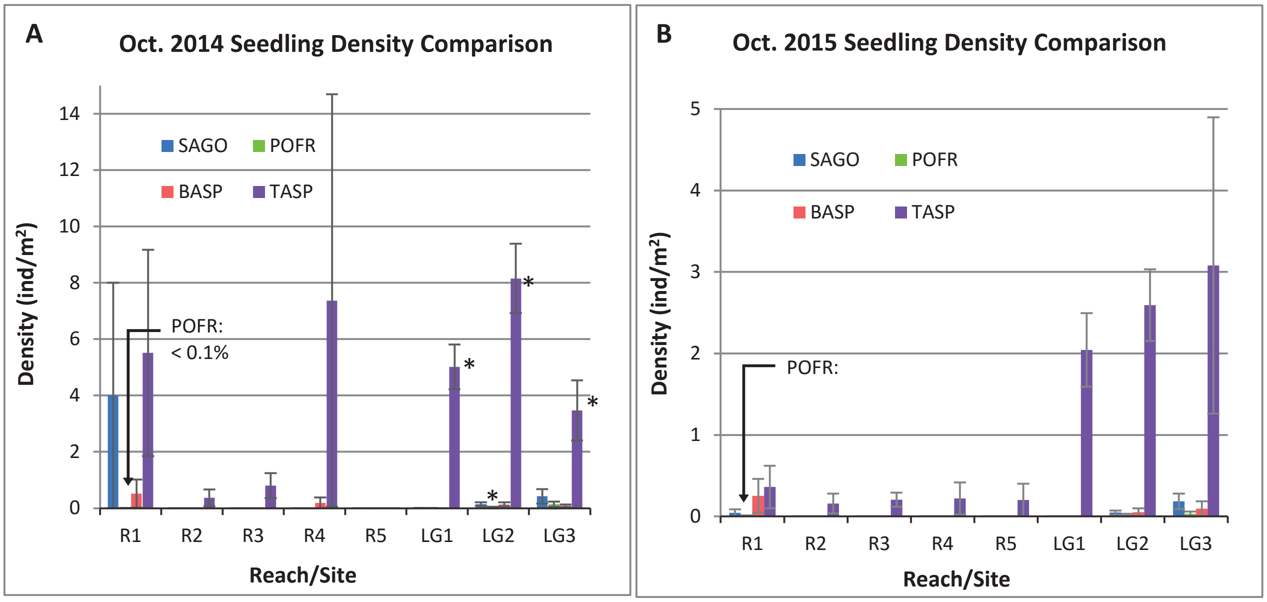

Figure 5-8a and 5-8b. Seedling density in long-term seedling plots in Reaches 1-5 and 4x5-meter plots in restoration sites LG1-3 in October 2014 (left) and 2015 (right). POFR = cottonwood (*Populus fremontii*); SAGO = willow (*Salix gooddingii*); TASP = tamarisk (*Tamarix* species); BASP = baccharis (*Baccharis* species). R1-5 = Reaches 1-5. Restoration sites: LG1 = Herradura; LG2 = Cori; LG3 = CILA. Note different scale on y-axis between 2014 and 2015.

* indicates "greater than" because there was a category of greater than 100 in the count per patch for transect monitoring in Laguna Grande. This occurred for TASP in all three restoration areas, and for BASP in LG2 in 2014.

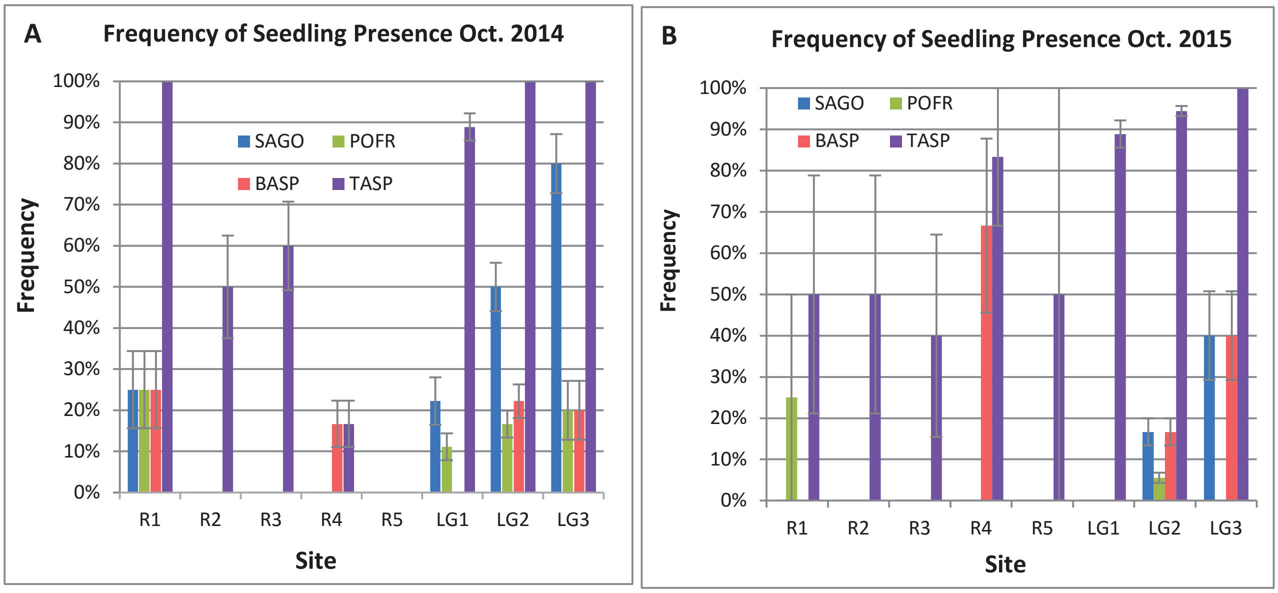

Figure 5-9a and 5-9b. Frequency of seedling occurrence in 1-meter belt transects in river reaches (R1-R5) and Laguna Grande prepared areas (LG1-LG3) in October 2014 (left) and 2015 (right). POFR = cottonwood (*Populus fremontii*); SAGO = willow (*Salix gooddingii*); TASP = tamarisk (*Tamarix* species); BASP = baccharis (*Baccharis* species). R1-5 = Reaches 1-5. Restoration sites: LG1 = Herradura; LG2 = Cori; LG3 = CILA.

Density and Survival in ***Planted*** *Restoration Areas in Laguna Grande and Miguel Aleman:*

Laguna Grande:
In 2013, 25,167 trees were planted in 14 ha (35 acres) of cleared land in the CILA polygon. In 2014, 59,177 trees were planted in 24.5 ha (60.5 acres) of prepared land in the CILA polygon. As of November 2015, 24,176 trees were planted in 15.9 ha (39.3 acres) of prepared land in the Cori polygon at the Herradura site. Species planted from 2013-2015 included cottonwood, willow, coyote willow, and screwbean and honey mesquite trees. Additional acreage was hydroseeded with cottonwood, willow, and diverse native plant species in Laguna Grande from 2013-2015. Planted and hydroseeded sites were irrigated using flood irrigation in furrows or drip irrigation, and they were weeded 1-2 times per year. From 2013-2015, average tree density was 1995/ha (805/acre), and average survival was 89% (Table 5-3).

Table 5-3. Summary of area planted in the Laguna Grande Restoration Area from 2013-2015.
*After 1 year of growth. Additional open water habitat not counted in planted area total.

Year Planted	Location (polygon)	# of Ha	# of Acres	Avg. Density (trees/ha; trees/acre)	% Survival*	Species Planted
2013	CILA	14	35	1798/ha; 719/acre	96%	*Cottonwood, Willow, Coyote Willow, Honey Mesquite, Screwbean Mesquite*
2014	CILA	24.5	60.5	2415/ha; 978/acre	85%	
2015	Cori/CILA	15.9	39.3	1520/ha; 615/acre	85-90%	
Total / Average		54.4	134.8	1995/ha; 805/acre	89%	

Miguel Aleman
Planting began in the Miguel Aleman site in 2014, with a total of 16,092 trees planted in 7.5 ha (18.6 acres). In 2015, 24,591 trees were planted in 30 ha (74.1 acres). Species planted included cottonwood, willow, screwbean and honey mesquite, and palo verde. From 2014-2015, average planted tree density was 1083/ha (439/acre) and average survival was 76% (Table 5-4).

Table 5-4. Summary of area planted in the Miguel Aleman Restoration Site from 2014-2015.
*After 1 year of growth. Additional open water habitat not counted in planted area total.

Year Planted	# of Ha	# of Acres	Avg. Density (trees/ha; trees/acre)	% Survival*	Species Planted
2014	7.5	18.6	2146/ha; 865/acre	71	*Cottonwood, Willow, Honey Mesquite, Screwbean Mesquite, Palo Verde*
2015	30	74.1	820/ha; 332/acre	81	
Total/ Average	**37.5**	**92.6**	**1083/ha; 439/acre**	**76**	

Repeat photographs (see Appendix F)

Visible effects from the pulse flow were strongly influenced by pre-existing conditions of vegetation and water. Areas with standing water before the pulse, which were mechanically prepared (parts of Reach 4) had sparse vegetation pre-pulse as a result of clearing activities. Six months after the pulse, those areas showed significant recruitment of new riparian vegetation, primarily of native species, in a band approximately 2 m wide along the standing water that remained. Those areas also showed increases in height and volume of pre-existing plants.

Areas which had standing or flowing water before the pulse and no mechanical preparation (Reach 1, parts of Reach 4) also had abundant pre-pulse riparian vegetation comprised of native and nonnative species. After the pulse there was little or no change in the composition or density of vegetation, but some individual plants had greater height and foliage volume. Areas where the channel was dry before the pulse (Reaches 2 and 3) had sparse riparian vegetation dominated by nonnative species, and after the pulse showed small increases in height and volume of pre-existing plants.

There were no visible changes to channel morphology except at photo point 12. That site, at the upstream end of Reach 3, showed approximately 1 m of scour at a sharp bend in the channel. That local scour was also noted in analysis of geomorphic response (Appendix F, Figure 4.3, left images).

Effects of base flows

Detailed information on the timing, amounts and delivery points of base flows delivered in water years 2014 and 2015 will be provided after the information becomes available. We will provide a detailed evaluation on the effects of base flows on the vegetation in the study area after the information becomes available.

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Section 6: Vegetation response using remote-sensing techniques

Key observations

1. **The 319 Pulse Flow produced a 16% increase in NDVI (“greenness”) throughout the riparian reaches in 2014.**
2. **Increases in NDVI in 2014 occurred in the zone inundated by the pulse flow as well as in the non-inundated outer parts of the riparian floodplain, where groundwater supports existing vegetation. In 2015, NDVI decreased to 2013 levels.**

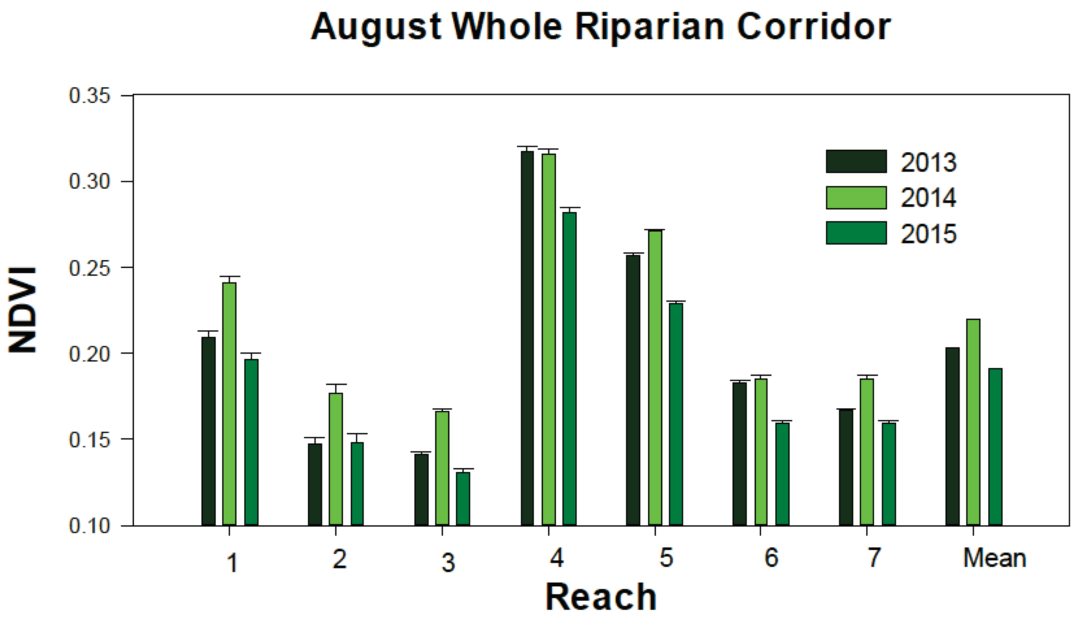
Introduction

This section documents the changes in green foliage density (greenness) associated with the Minute 319 pulse and base flows.

Landsat imagery (30 m (98 ft) resolution, 16-day return time) and Moderate Resolution Imaging Spectrometer (MODIS) imagery (250 m (820 ft) resolution, daily return time) were used for the analyses. The analyses used vegetation indices, which are ratios of different optical bands that provide a measure of canopy "greenness". The Normalized Difference Vegetation Index (NDVI) was used for Landsat images. These indices were chosen based on previous performance comparisons made in riparian ecosystems (Nagler, et al., 2005a).

Response to Minute 319 Environmental Flows

Landsat NDVI was compared for each river reach in August of 2013, 2014, and 2015 (Fig. 6-2). The month of August was selected for comparisons, as it is a time of near-maximum greenness. NDVI of the riparian corridor (both inundated and non-inundated zones) was higher in 2014 than in 2013 for all reaches except Reach 4 (Fig. 6-2a), where tamarisk and arrowweed had been cleared in restoration sites in advance of the pulse flow, and additional clearing of land occurred in the floodplain for agricultural use. The overall NDVI increase from 2013 to 2014 was 16% ($P < 0.001$). The most intense greening in 2014 took place in the zone of inundation, but increases in NDVI also occurred outside the zone of inundation, indicating that the pulse flow likely enhanced groundwater conditions in those areas as well. Riparian corridor NDVI (inundated and non-inundated zones) returned to lower levels in 2015, and in most reaches 2015 values were lower than those observed in 2013.



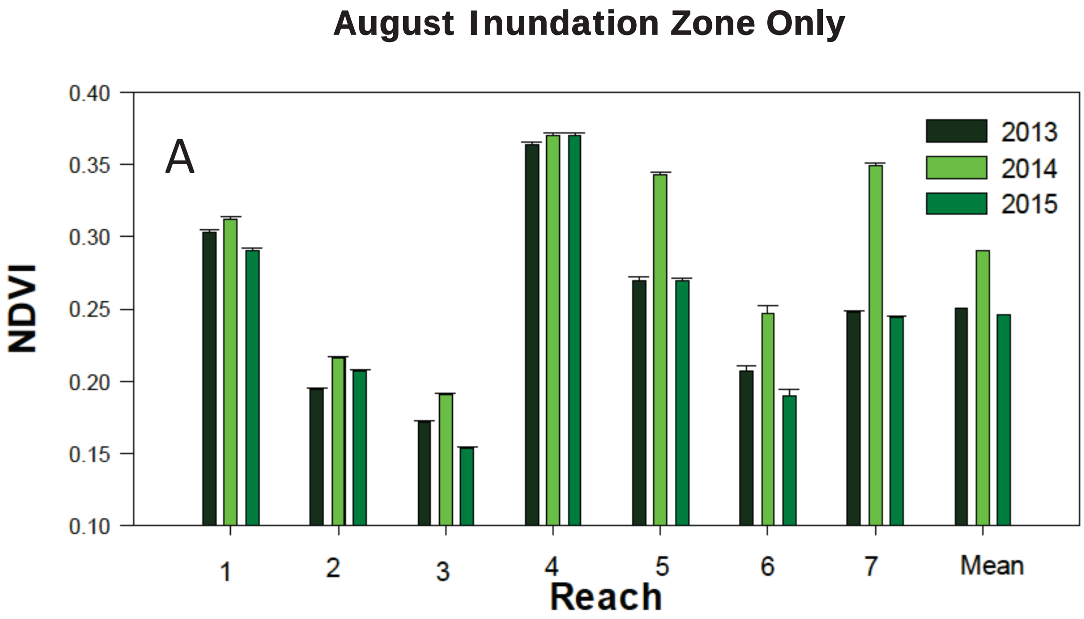


Figure 6-2a (top). NDVI in entire riparian zone, by river reach, in August of 2013, 2014, and 2015.
6-2b (bottom). NDVI in inundation zone, by river reach, in August of 2013, 2014, and 2015.

In the inundation zone, (Fig 6-2b), NDVI in 2015 returned to approximately 2013 levels in all reaches except for Reach 2 and Reach 4. In Reach 2, 2015 values were lower than in 2014, but higher than in 2013. In Reach 4, values were equal in 2014 and 2015, which were higher than 2013 values.

Figure 6-3 shows areas inundated during the pulse flow and differences in NDVI between August 2013 (pre-pulse) and August 2014 (post-pulse), with selected enlarged portions of the riparian corridor. A greener color indicates that NDVI was higher in August 2014 than in August 2013. There was extensive green-up in all areas, except for the portion in the lower part of Reach 4 (enlarged), where extensive land-clearing took place prior to the pulse flow. Much of the land cleared was not inundated during the pulse flow.

Figure 6-4 shows areas inundated during the pulse flow and differences in NDVI between August 2014 and August 2015. A greener color indicates that NDVI was higher in August 2015 than in August 2014. A browner color indicates a reduction in greenness (not necessarily the result of brown vegetation) from 2014 to 2015. Note that while some areas are greener than in the post-pulse summer of 2014 (see enlargements of Reach 1 and of lower part of Reach 4), other parts of the riparian corridor are not as green as in the previous year – see especially enlarged part of Reach 7.

Figure 6-5 shows areas inundated during the pulse flow and differences in NDVI between August 2013 (pre-pulse) and August 2015 (two growing seasons after the pulse flow). Some areas continued to increase in greenness from 2013 to 2015 (lower Reach 1 and Reach 7), while other areas show little change, or are less green than under pre-pulse conditions.

Conclusions

The 319 Pulse Flow produced a 16% increase in NDVI ("greenness") throughout the riparian reaches in 2014, compared to 2013. In 2015, NDVI returned to 2013 levels. Increases in NDVI in 2014 occurred in the zone inundated by the pulse flow as well as in the non-inundated outer parts of the riparian floodplain, where groundwater supports existing vegetation.

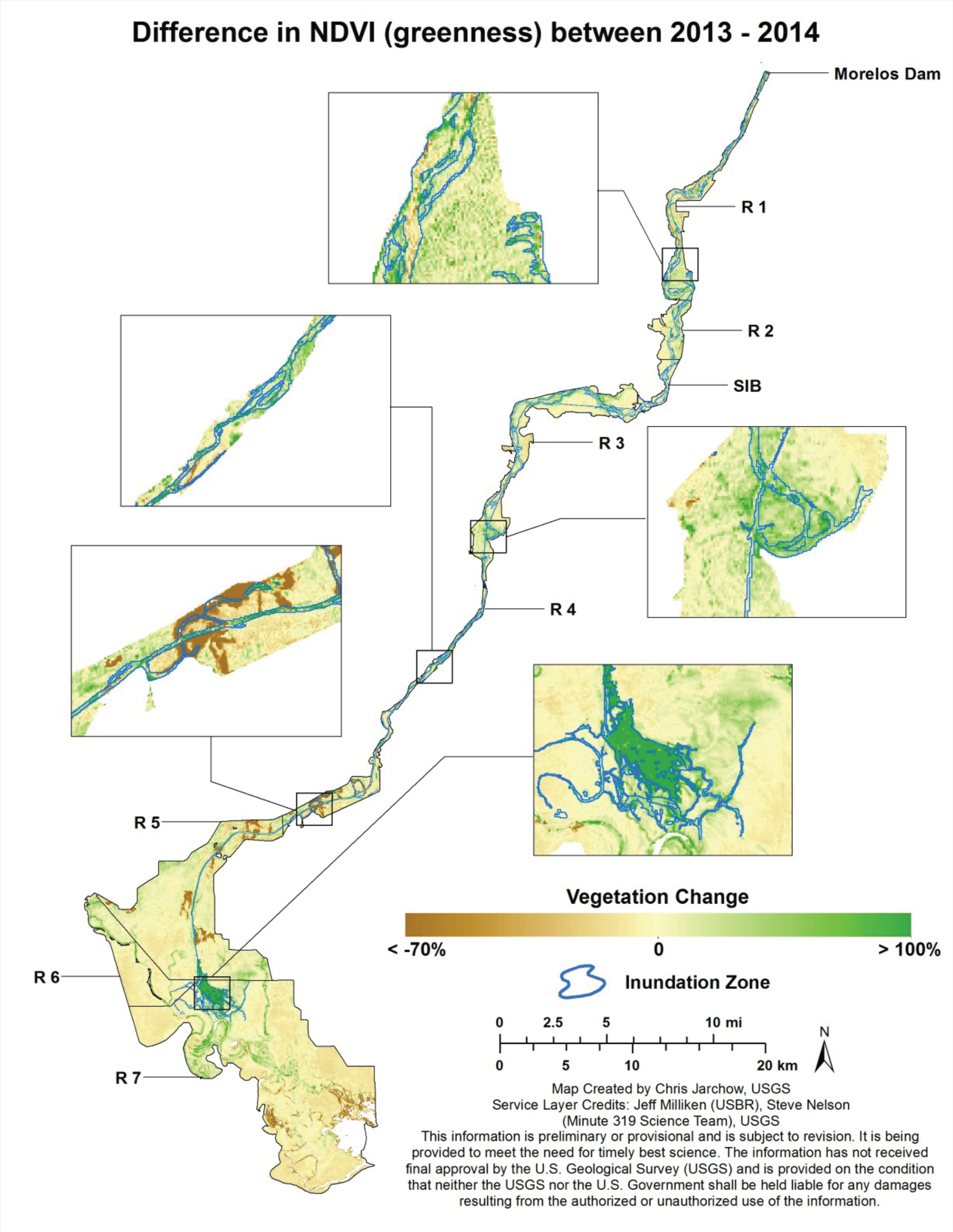


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Figure 6-3. 2014 pulse flow inundation zone and the difference in NDVI from August 2013 and August 2014. Greener color indicates higher NDVI than in previous year; browner color indicates lower NDVI than in previous year.

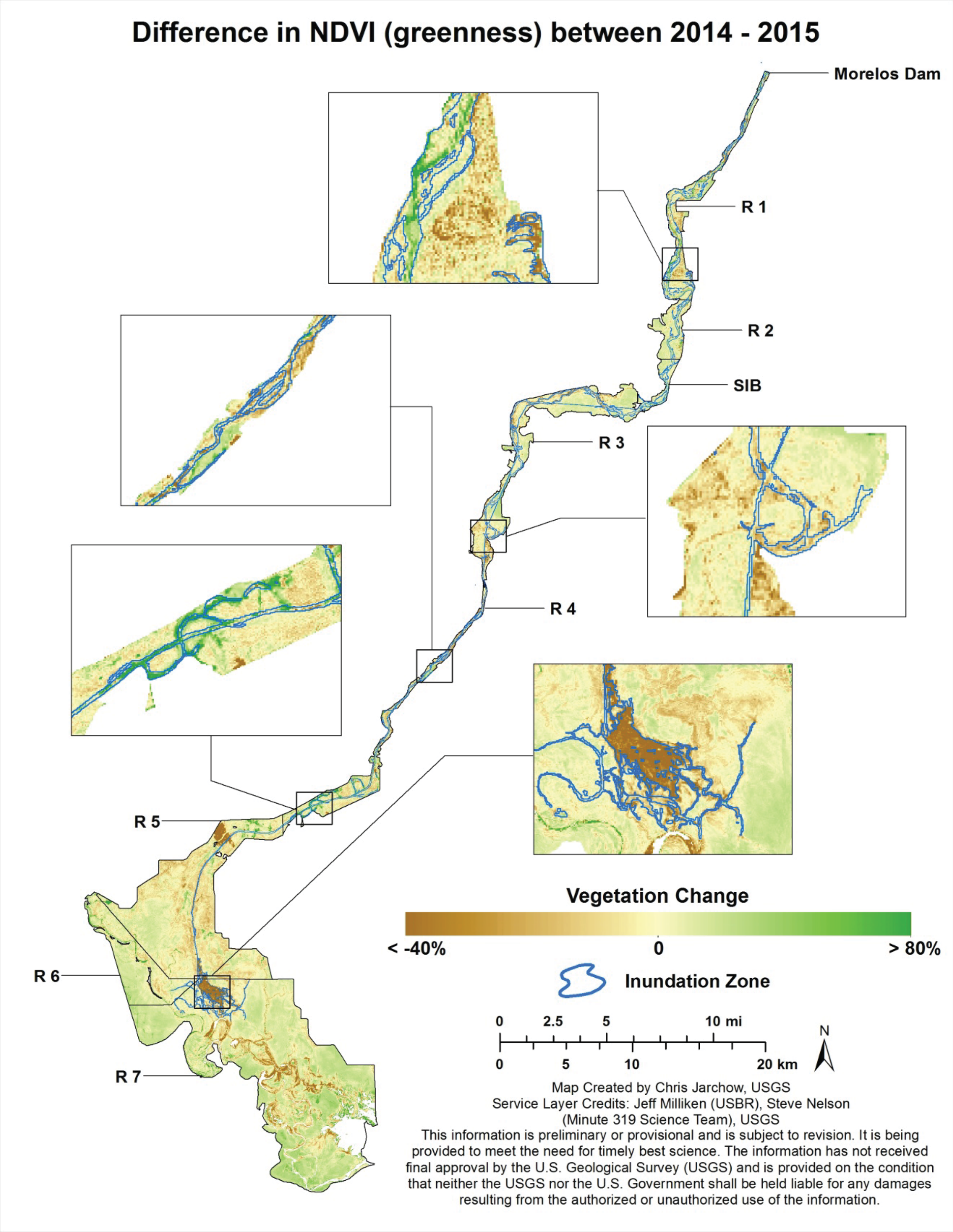
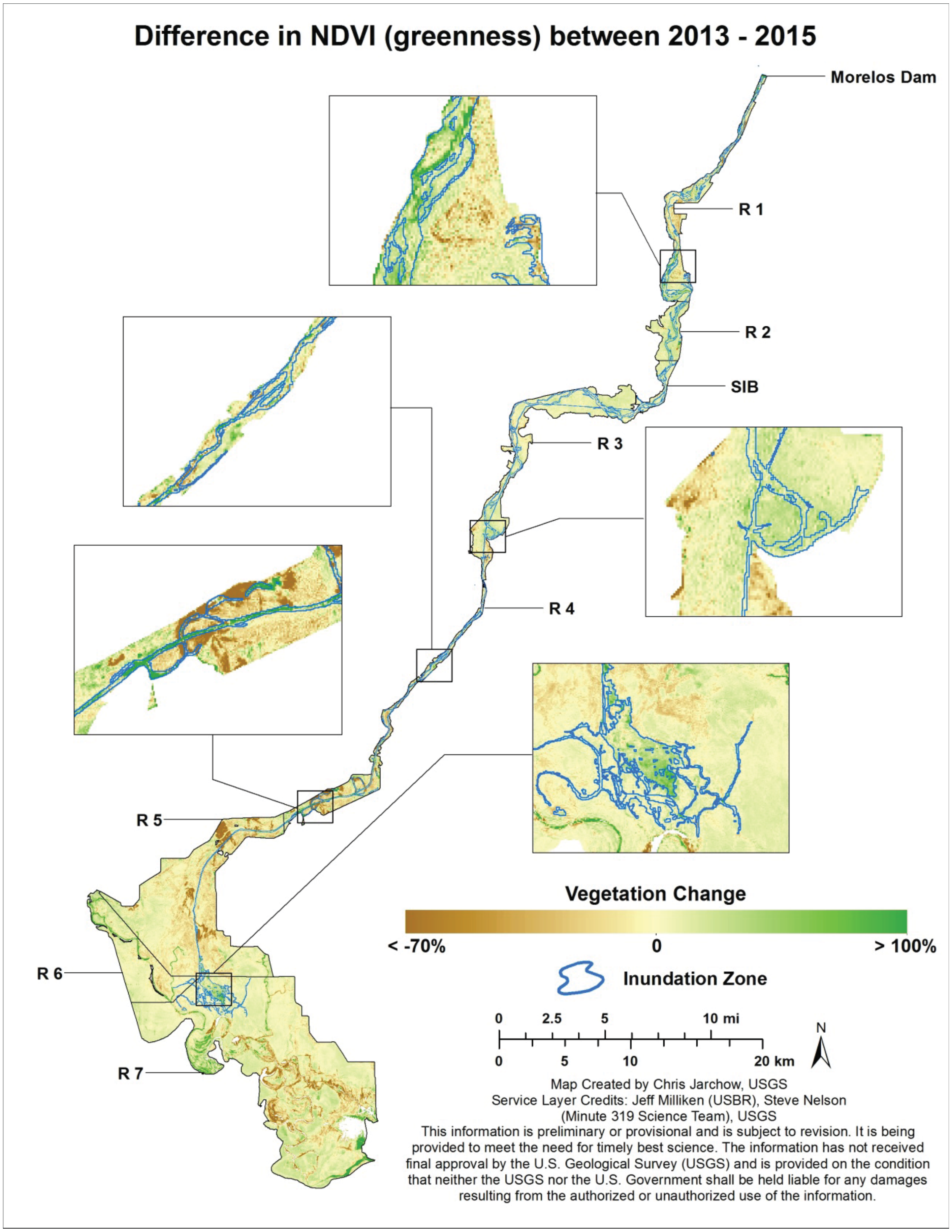


Figure 6-4. 2014 pulse flow inundation zone and the difference in NDVI from August 2014 and August 2015. Greener color indicates higher NDV than in previous year; browner color indicates lower NDVI than in previous year.


Difference in NDVI (greenness) between 2013 - 2015

Map Created by Chris Jarchow, USGS
Service Layer Credits: Jeff Milliken (USBR), Steve Nelson (Minute 319 Science Team), USGS
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Figure 6-5. 2014 pulse flow inundation zone and the difference in NDVI from August 2013 and August 2015. Greener color indicates higher NDVI than in 2013; browner color indicates lower NDVI than in 2013.

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Section 7: Wildlife (Bird) response

Key observations:

1. **The abundance and diversity of birds increased in the floodplain of the Colorado River in Mexico after the 2014 pulse flow. The response was maintained in 2015. Migratory waterbirds, nesting waterbirds and nesting riparian birds all increased in abundance**
2. **The combined abundance of 19 species of conservation interest increased 49% from 2013 to 2015, including Gila Woodpecker, Brown-headed Cowbird, Ash-throated Flycatcher, Yellow-breasted Chat and Song Sparrow.**
3. **The restoration sites had a greater abundance, higher number of species and greater diversity index per point of birds than in the rest of the floodplain.**
4. **The combined abundance of the 19 species of conservation interest was 43% higher at the restoration sites than in the rest of the floodplain. Hooded Oriole, Yellow-breasted Chat, Vermillion Flycatcher, Gila Woodpecker and Cactus Wren all increased in abundance.**

Introduction

Bird surveys followed the protocol described in Hinojosa-Huerta et al. (2008, 2013). Birds are monitored at 200 sites (grouped in 25 transects, with 8 points each). Seventeen transects, all located downstream from the Southerly International Boundary, have been surveyed since 2002. Four transects were added in the restoration sites to document changes in the avifauna related to the reforestation efforts in the Miguel Aleman, Laguna Grande and CILA sites. These surveys started in 2011. For this effort, four transects were added in the Limitrophe region of the river, which were surveyed for the first time during the Spring of 2014.

In the analysis of abundance changes, detections of fly-over birds and counts of the four most abundant species (Mourning Dove, Red-winged Blackbird, White-faced Ibis and Yellow-headed Blackbird), were not included because they are influenced mostly by changes in the agricultural area. These species were included in the analysis of community structure, diversity, and guilds.

Results

The Bird Community of the Floodplain

Different bird species use the habitat in the floodplain of the Colorado River in Mexico in different ways. 192 bird species have been detected between 2002 and 2015; this includes migratory landbirds that either spend the winter there or use the area as stopover site, as well as migratory waterbirds. The variation in abundance of these species in the floodplain depends on many factors which could affect their presence in the delta, including the habitat quality along the river as well as changes in their breeding grounds and yearly fluctuations in migration patterns outside of the delta region.

Table 7-1. Abundance per point per visit (average and standard error) for 19 species of conservation interest at the floodplain of the Colorado River and restoration sites in Mexico, for 2013 and 2015.

	2013		**2015**		**Rest 2013**		**Rest 2015**	
Species	**Avg**	**SE**	**Avg**	**SE**	**Avg**	**SE**	**Avg**	**SE**
Abert's Towhee	0.53	0.07	0.81	0.12	0.91	0.12	1.01	0.24
Ash-throated Flycatcher	0.09	0.03	0.22	0.06	0.19	0.05	0.22	0.09
Brown-headed Cowbird	0.19	0.06	0.71	0.14	0.56	0.11	0.74	0.37
Blue Grosbeak	0.08	0.03	0.10	0.05	0.18	0.04	0.31	0.12
Black Phoebe	0.10	0.04	0.17	0.10	0.18	0.03	0.19	0.10
Black-tailed Gnatcatcher	0.25	0.05	0.49	0.08	0.35	0.07	0.58	0.22
Cactus Wren	0.02	0.01	0.02	0.02	0.01	0.01	0.06	0.06
Common Yellowthroat	0.18	0.06	0.28	0.09	0.39	0.07	0.38	0.19
Crissal Thrasher	0.16	0.04	0.18	0.05	0.22	0.04	0.17	0.10
Gila Woodpecker	0.01	0.01	0.02	0.01	0.01	0.01	0.08	0.08
Hooded Oriole	0.01	0.01	0.01	0.01	0.13	0.04	0.08	0.06
Ladder-backed Woodpecker	0.06	0.02	0.10	0.03	0.16	0.04	0.26	0.11
Marsh Wren	0.41	0.14	0.30	0.12	0.13	0.05	0.07	0.11
Song Sparrow	0.09	0.03	0.21	0.07	0.22	0.06	0.29	0.14
Vermillion Flycatcher	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.03
Verdin	0.64	0.09	0.71	0.11	1.22	0.09	1.19	0.25
Western Kingbird	0.08	0.04	0.18	0.07	0.23	0.07	0.54	0.22
White-winged Dove	0.45	0.13	0.51	0.11	4.00	1.07	0.79	0.28
Yellow-breasted Chat	0.01	0.01	0.02	0.01	0.15	0.05	0.18	0.14
Overall	**3.38**	**0.89**	**5.03**	**1.26**	**9.22**	**2.04**	**7.17**	**2.90**

The floodplain also provides habitat for resident or breeding species. Their numbers are more closely related to the habitat quality in the area. In this study, particular attention is paid to 19 species of conservation interest, due to their close relationship with the quality of the local riparian habitat (Table 7-1).

The floodplain is also inhabited by species that use and depend on the agricultural resources of the Mexicali Valley. The four most common species in this group (Mourning Dove, White-faced Ibis, Red-winged Blackbird and Yellow-headed Blackbird) represent together 75% of all the detected individual birds in the floodplain. The variation in the populations of these species is more closely related to the fluctuation in resource availability in the agricultural areas than to the habitat changes in the floodplain.

The abundance and diversity of birds is different along the different reaches of the floodplain, with higher abundance along Reach 1, followed by Reach 4, Reach 3 and Reach 5 (Fig.7-1). In Reach 3 and 4, the patterns are similar on the left and right margins of the floodplain, but in Reach 5 the average bird abundance is 1.6 times higher on the left margin than on the right margin.

Diversity follows a different pattern, with a higher diversity index in Reach 4, followed by Reach 1, Reach 5 and Reach 3 (Fig. 7-1). These differences are not only driven by the higher number of species detected in Reach 4 and Reach 1, but also by a higher evenness in the community structure and less dominance of the most common species in these reaches.

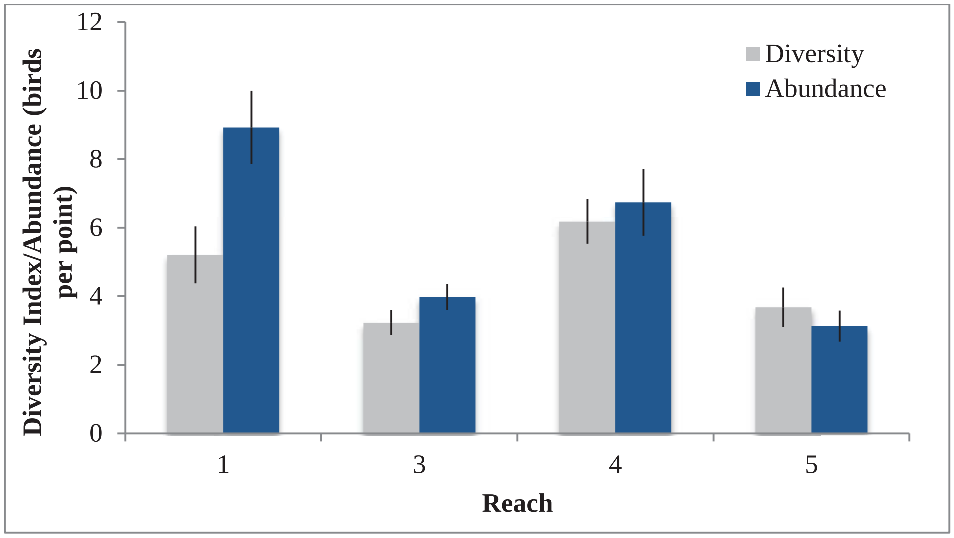

Figure 7-1. Diversity (N2 per point) and abundance (average per point) of birds in the different river reaches of the floodplain of the Colorado River in Mexico.

Changes Related to Minute 319 Environmental Flows

Excluding the detection of fly-over birds and the four most common species, the bird abundance during the breeding season in the floodplain has decreased since 2003 (an average reduction of 3.5% per year), with 2013 being one of the years with the lowest abundance (an average of 115 birds per transect vs 179 birds per transect in 2003; Figure 6-2)).

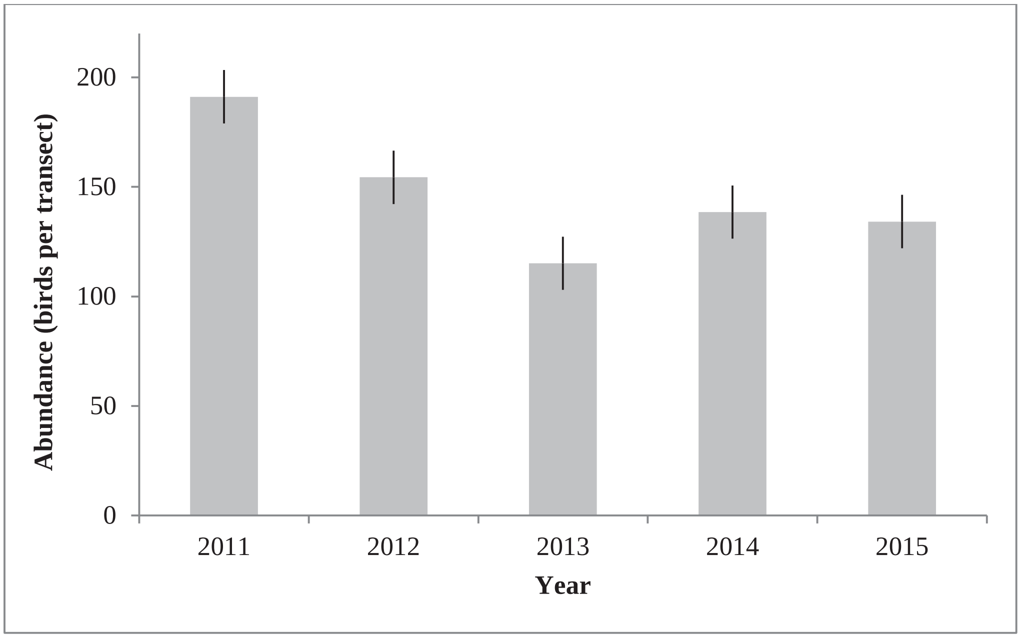

Figure 7-2. Bird abundance (average per transect) in the floodplain of the Colorado River in Mexico from 2011 to 2015.

In 2014, abundance increased relative to 2013 (up to 138 birds per transect), and was similar in 2015 (134 birds per transect). The major changes occurred in Reach 3, where the increase in 2014 and 2015 in relation to 2013 was 51% and 47% respectively. In Reach 4, there was a slight increase of 5% and in Reach 5 there was a small decrease of 4.2%. In the Limitrophe there was a spike during the summer of 2014, with a 3.9 time increase in abundance of birds (an increase from an average of 281 birds per transect to 1,100 birds per transect).

The diversity index (N2) during the breeding season had a downward trend since 2003, with 2013 having the lowest number since 2003 (3.58 in 2013 vs 5.96 in 2003). The diversity index increased during 2014 in comparison with 2013, and decreased in 2015 but still was still higher than in 2013 (Fig. 6-3). The major change occurred in Reach 4, where the diversity index increased 41%, followed by Reach 5, with a 25% increase, and Reach 3 with a 20% increase.

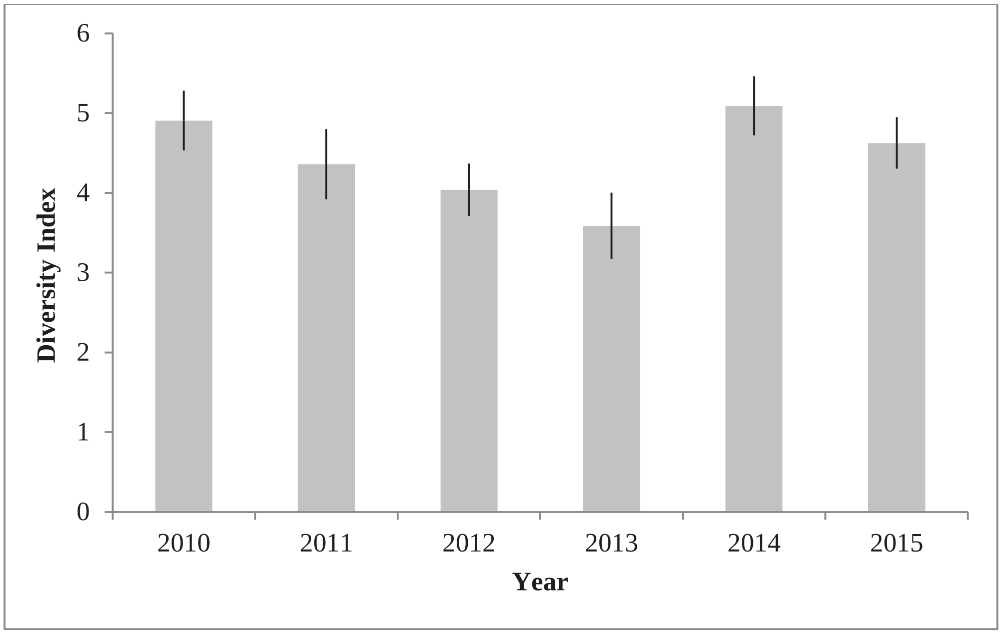

Figure 7-3. Bird diversity (N2 per point) in the floodplain of the Colorado River in Mexico from 2010 to 2015.

The Nesting Riparian Landbirds guild, which includes species of landbirds closely related to the health of the native riparian vegetation and that are resident or breeding visitors in the delta (Appendix G) showed a significant increase of 22% during 2014 in comparison with 2013. Their abundance decreased in 2015, but was still higher than in 2013 (Fig. 6-4).

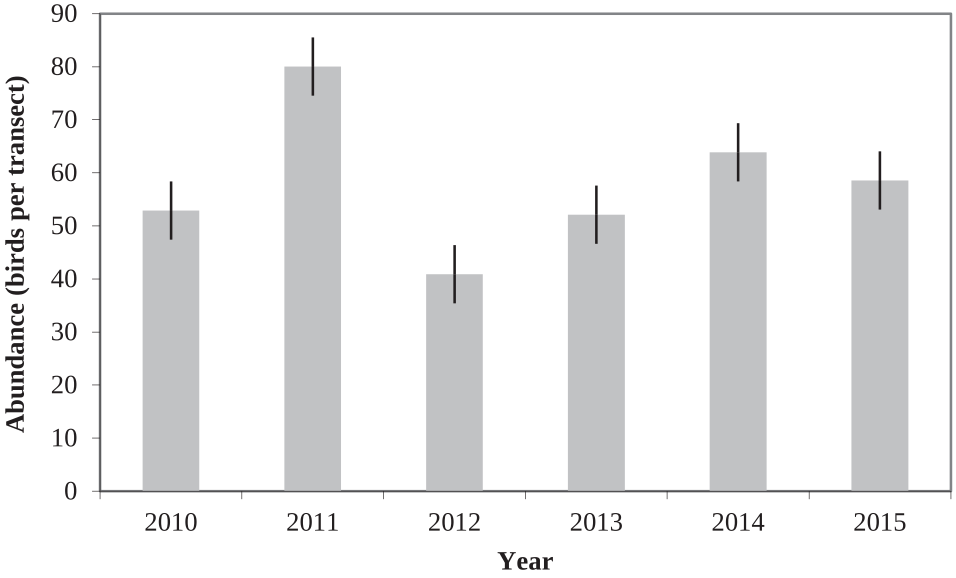

Figure 7-4. Average abundance (birds per transect) of nesting riparian landbirds in the floodplain of the Colorado River in Mexico from 2010 to 2015.

The group of Nesting Waterbirds, which includes species of waterfowl, shorebirds, marshbirds and colonial waterbirds (such as herons and egrets) that are resident or breeding visitors in the delta (Appendix G) also showed a significant increase (81%) in 2014 in comparison with 2013, and their numbers were also reduced in 2015, but their abundance was still 11% higher than in 2013 (Fig. 7-5).

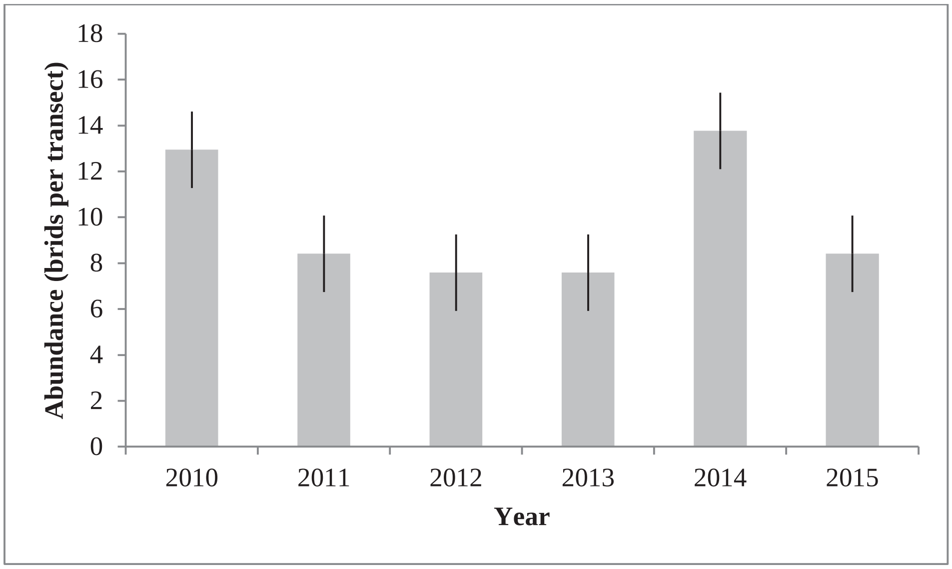

Figure 7-5. Average abundance (birds per transect) of nesting waterbirds in the floodplain of the Colorado River in Mexico from 2010 to 2015.

The strongest response along the floodplain was observed in the Migratory Waterbirds group (shorebirds, marshbirds, waterfowl and other waterbird species that do not breed in the delta, Appendix G). Their abundance increased 4 times in 2014 in comparison to 2013, and this was the year with the highest abundance of this group recorded since the study was started in 2002 (Fig. 7-6), with an average of 109 birds per transect, or an estimated abundance in the floodplain (Reach 1 to Reach 5) of 53,680 (± 7330) migratory waterbirds during the pulse flow. Most of the observations occurred in Reach 1 and Reach 4, but it was interesting to note the temporary presence of migratory waterbirds along Reach 3 during the pulse flow.

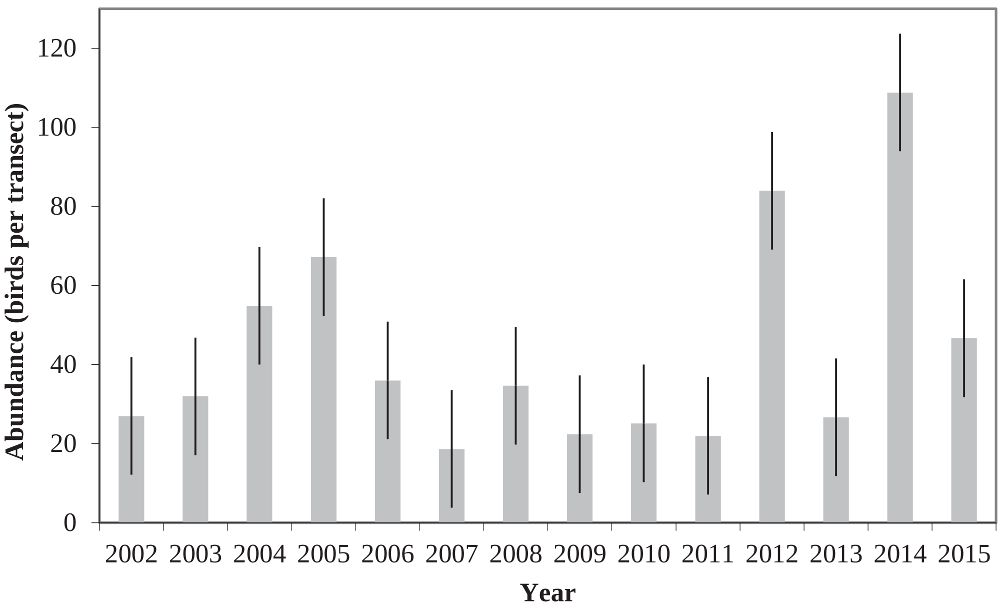

Figure 7-6. Average abundance (birds per transect) of migratory waterbirds in the floodplain of the Colorado River in Mexico from 2003 to 2015

In 2015, the abundance of migratory waterbirds decreased to an average of 47 birds per transect. Almost all records occurred in Reach 1 and Reach 4 – the wet reaches.

Usually the floodplain corridor is not visited by an abundance of migratory waterbirds, and these species tend to visit the Cienega de Santa Clara and the Hardy River instead. However, the available aquatic habitat during the pulse flow was used by many of these species, in particular some species of ducks (Northern Shoveler, Mallard, and Cinnamon Teal), shorebirds (mostly Least Sandpiper, Yellowlegs and American Avocet) and marshbirds (American Coot and Sora).

We did not detect any major changes in the numbers of other guilds in the floodplain (agriculture-related birds, raptors, migratory landbirds, desert birds).

Changes Related to Restoration Sites

During the breeding season of 2015, the abundance at the restoration sites was 50% higher than in the rest of the floodplain, the number of species detected per point was 33% higher, and the diversity index per point was 53% higher (Fig. 7-7).

The combined abundance of 19 species of conservation interest was 43% higher at the restoration sites than at the rest of the floodplain in 2015 (Table 7-1). This group includes species that are closely related to the riparian habitat, for example Blue Grosbeak, Vermillion Flycatcher, Yellow-breasted Chat, Marsh Wren, Western Kingbird and Abert´s Towhee. The species with the highest difference between restoration and floodplain sites were Hooded Oriole (15 times higher abundance at restoration sites), Yellow-Breasted Chat (8.9 times higher), Vermillion Flycatcher (4.3 times higher), Gila Woodpecker (4.2

times higher) and Cactus Wren (2.0 times higher). The Marsh Wren had a 76% decline and the Crissal Thrasher had a 7% decline.

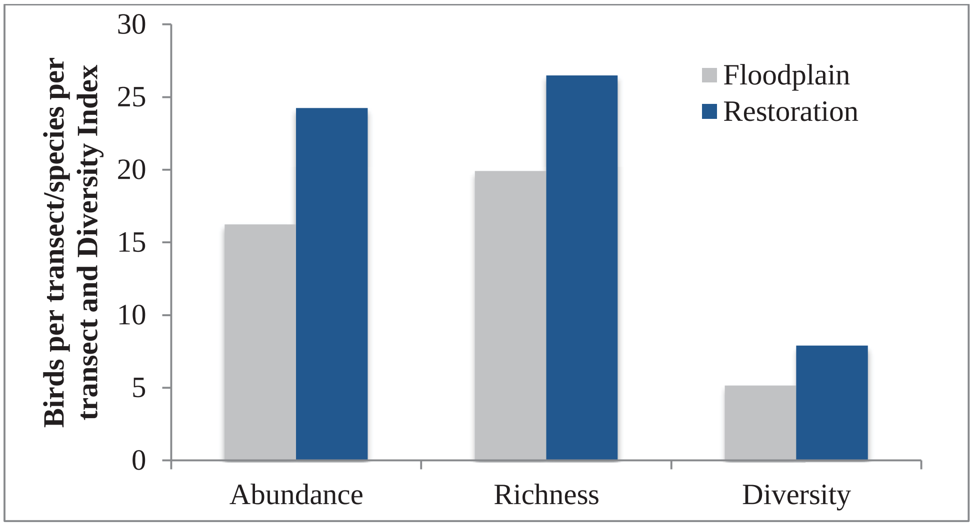

Figure 7-7. Average abundance (birds per transect), species richness (species per transect), and diversity (N2 per point) at the restoration sites and the floodplain of the Colorado River in Mexico.

The combined abundance of these 19 species decreased 28% from 2013 to 2015 at the restoration sites (Table 7-1). However, a large portion of the abundance of 2013 (43%) was contributed by the White-winged Dove, which decreased 80% between 2013 and 2015. The relative abundance of White-winged Dove for this group in 2015 was only 11%. If this species is excluded from the analysis, the overall combined abundance of the other 18 species of interest was 22% higher during 2015.

Thirteen of the species of interest increased their abundance at the restoration sites more than 10%, and four had decreases (White-winged Dove, Marsh Wren, Hooded Oriole, and Crissal Thrasher). The species with largest increases in abundance were Gila Woodpecker, Cactus Wren, Western Kingbird, Blue Grosbeak, and Ladder-backed Woodpecker.

Throughout the floodplain, the abundance of these species of interest increased 49% from 2013 to 2015 (Table 7-1). Fifteen species had greater abundance in 2015, especially Gila Woodpecker, Brown-headed Cowbird, Ash-throated Flycatcher, Yellow-breasted Chat and Song Sparrow. Four species showed a decrease in abundance: Hooded Oriole, Vermillion Flycatcher, Marsh Wren, and Cactus Wren.

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Hinojosa-Huerta, O., Nagler, P.L., Carrillo, Y.K. and Glenn, E.P., 2013. Effects of drought on birds and riparian vegetation in the Colorado River Delta, Mexico. Ecological Engineering 59: 104-110.

Section 8: Lower Channel and Estuary

Key observations:

1. **Approximately 10 percent of the pulse flow water reached the top of Reach 5; the water inundated and infiltrated portions of Reaches 5 and 7, supporting the vegetation there.**
2. **A small amount of pulse flow water mixed with Gulf of California water.**
3. **Gulf of California water mixes with Hardy River water during spring high tides, but a sand bar restricts the return of the mixture to the Gulf. Connectivity is mostly one-way.**
4. **The pulse flow had little to no impact on the zooplankton or fish fauna of the upper estuary.**
5. **In order to enhance habitat and benefit marine species in the upper estuary, a larger amount of freshwater would be required *in addition to* improved tidal connectivity above the sand bar. Additional research, including modeling and experimental flow deliveries, is needed to estimate the amount and timing of flows required for estuary enhancement.**

Introduction

The lower Colorado River channel and estuary region (Reach 7) is outside of the geographic scope for binational monitoring under Minute 319. Sonoran Institute (SI) secured independent support and worked with their partners to monitor the biological and hydrological conditions of the upper portion of the estuary, before, during and after the pulse flow. The main purpose of this monitoring effort was to determine baseline conditions in the estuary and identify changes caused by Minute 319 environmental flow releases and other environmental variables. The SI monitoring program in the estuary assesses: 1) connectivity between the river and the sea, 2) water quality, and 3) ichthyology and zooplankton populations. SI used both on-the-ground surveys and remote sensing techniques (satellite imagery and aerial photography). Sonoran Institute will continue to collect and analyze data for the above components in the upper estuary through June 2016.

Connectivity between the river and the sea

Baseline estuarine conditions:

Connectivity between the river and the Gulf of California is important to many marine species, many of which use the estuary as breeding or nursery grounds, including commercially important species of shrimp and fish (Calderon and Flessa, 2009). Based on historic conditions, a larger estuarine area of freshwater-seawater mixing with frequent connection to the Gulf of California would supply nutrients to the Gulf and provide estuarine nursery grounds, which would support larger populations of several marine species.

The Colorado River lower channel and estuary (Fig. 8-1), located in the lower portion of the Colorado River Delta in Mexico, is the section of the river subject to the influence of extreme tides of the upper Gulf of California (up to 8.5 meters (28 ft) during spring tides) (Thompson, 1968). The intertidal portion of the river extends 56 km (35 mi) upstream from Montague Island at the river's mouth (Payne et al., 1992).

Because of the great range and power of the tides, the deposition of sediments within the intertidal portion of the Delta is subject to a complex balance of fluvial and tidal forces (Dalrymple and Choi, 2007). Tidal forces have dominated during extended periods when the river's fluvial flow is reduced or eliminated. Strong flood tidal currents entrain large quantities of sediment from the bed and banks of the lower estuary channel and carry them upstream where they are deposited in the channel and on adjacent tidal mudflats at the convergence of tidal and fluvial bedload sedimentation (Zamora et al., 2012). This plug of sediments located in the bedload convergence zone is referred to here as the Colorado River tidal sandbar (Fig.8-1, 8-3), the emergent crest of which is located about 35 km (22 mi) upstream from Montague Island (Nelson et al., 2013). This sandbar, when fully developed, can partially or completely obstruct up to 29 km (18 mi) of the estuary channel (ACOE, 1982). The location of the tidal sandbar crest is affected by the relative strength of fluvial and tidal forces. The 2010 El Mayor-Cucapah Earthquake caused subsidence in the lower estuary which increased the strength of tidal flood currents (Nelson et al., 2012). The pre-pulse flow LIDAR suggests that changes in tidal inundation patterns since the earthquake, may have caused the crest of the sandbar to migrate upstream since the 2010 earthquake in response to the increased strength of the tidal flood.

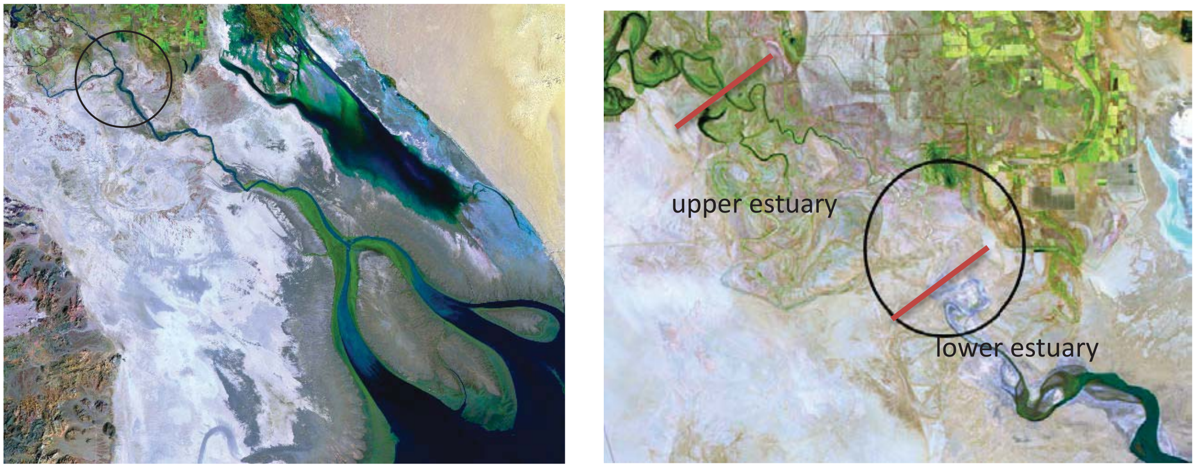

Figure 8-1. Left: Landsat image of the Colorado River estuary in 1987 when a continuous channel connection existed to the Gulf of California. Right: 2006 Landsat image of the tidal sandbar. The crest of the bar is indicated by the red line within the oval, which divides the estuary into upper and lower sections. The ovals in both images represent approximately the same area.

The tidal sandbar effectively cuts the estuary into upper and lower sections, with limited connectivity between them. The tidal sandbar impounds freshwater flowing from the Colorado River, Hardy River and the Ayala Drain and prevents most flows from reaching the lower estuary. While the lower estuary is still subject to the effect of the tides, tidal flow from the Gulf to the upper estuary is limited to the periods of the highest spring tides, when tidal waters can overtop the sandbar. Although tidal water does reach the upper estuary during such events, subsequent downstream (ebb) flow is restricted by the sandbar; most of the tidal water crossing the bar is trapped in the upper estuary.

Conditions before the pulse flow were characterized by approximately 15 years of limited river flow and consequently limited connectivity between the river and the sea. This already-limited connectivity was further reduced by extensive liquefaction associated with the April 4, 2010 Mexicali earthquake. This resulted in further obstruction and effectively obliterated approximately 8 km (5 mi) of the existing river channel in this portion of the estuary (Nelson et al., 2013). In 2012, Sonoran Institute dug a pilot channel through the upper portion of the sand bar to increase connectivity between the upper and lower estuary.

In 2011, Sonoran Institute installed automatic water gauges at several locations in the upper estuary to measure water elevation, temperature and salinity (Fig. 8-2). Sensor E3 was installed at a point near the crest of the sandbar and has the longest data record. Based on previous studies, Sonoran Institute has been using water elevation greater than 3.4 meters above mean sea level measured at E3 to estimate the number of days tides overtop the sandbar. As mentioned previously however, the crest of the sandbar may have since migrated upstream. Studies conducted in 2011 determined that tides reached sensor E1 (6 km upstream from E3) approximately 12-18 times per year (Nelson et al., 2013; Zamora et al., 2012).

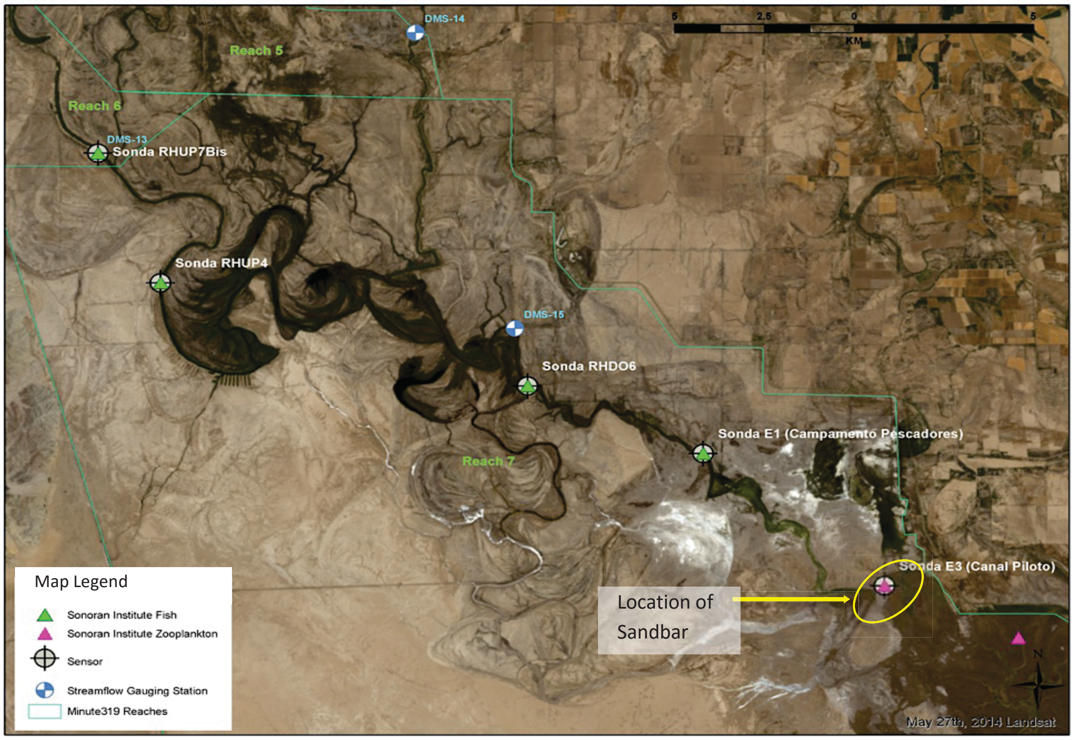

Figure 8-2. Map of Sonoran Institute monitoring locations in the lower Delta region. Green triangles: fish monitoring locations; pink triangles: zooplankton monitoring locations; sonde = sensor locations; blue and white circles: discharge monitoring stations.

Pulse flow impacts on connectivity:

Based on water elevation data from sensor E3, we determined that tidal flows surpassed the sandbar (water elevation >3.4 meters) a total of 39 days between January and December 2014 (Fig. 8-3). It is unclear if the methods used to estimate the number of days of connectivity in the Nelson et al. 2013 publication are the same as methods used currently for sensor E3; therefore a direct comparison of days of connectivity is not possible. However, the number of days of connectivity in 2014 was likely not affected by the pulse flow, as a small amount of pulse flow water reached this area (see next section). As previously mentioned, improving connectivity between the Colorado River and the sea is not only contingent on the amount and flow rate of freshwater to the estuary, but it also depends significantly on the facilitation of tidal flow connectivity through the sandbar.

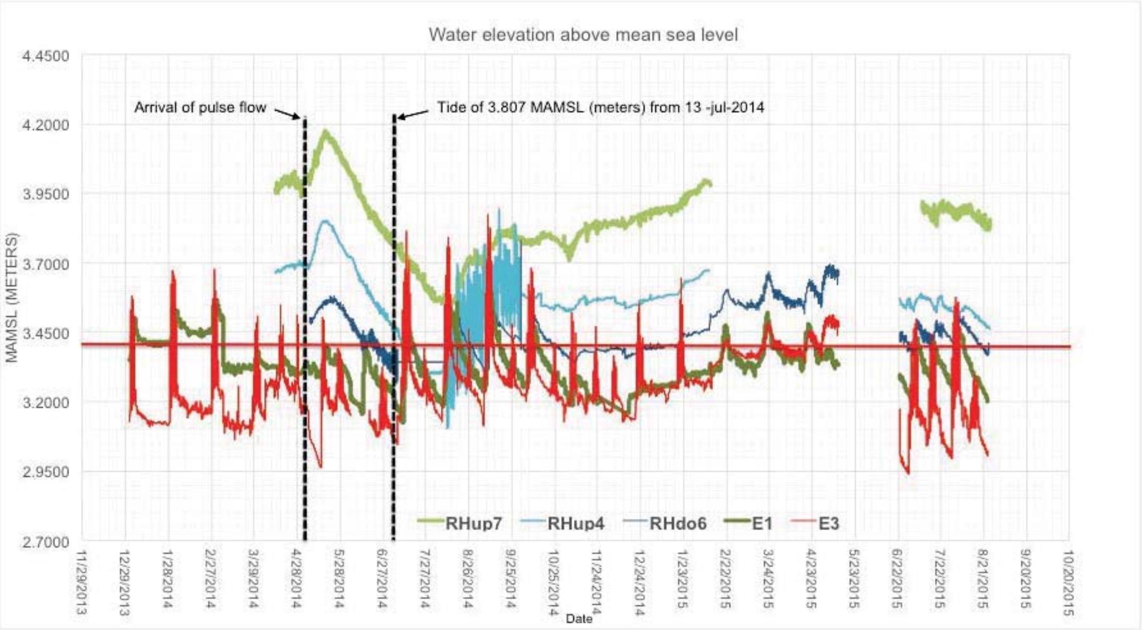

Figure 8-3. Water elevation at sampling locations before, during, and after the pulse flow. Any day when water elevation is greater than 3.4 meters (11.2 ft) above mean sea level (red line) at sensor E3 was counted as a day when connectivity occurred between the lower and upper estuary.

Isotopic analysis:

An isotopic analysis of oxygen and hydrogen ($\delta^{18}O$ and δD) was conducted on water samples taken monthly in 2014 at locations in the upper estuary and lower Hardy River. The analysis provides information on the extent of the mixing of freshwater and sea water, and reveals three distinct groups of samples according to their $\delta^{18}O - \delta D$ values (Fig. 8-4).

The first group (upper trend line) includes samples of seawater and evaporated seawater, for which the majority of samples are located in the southern limit of the upper estuary (E1 is the exception). The second group (lower trend line) includes samples of Hardy River water at increasing degrees of evaporation. The third group (red oval) includes samples of mixtures of seawater, evaporated seawater, and Hardy River water from the upper estuary (RHUP4 and RHDO6). Isotopic results show that freshwater regularly flows into the upper estuary (location RDH06 and E1), but does not reach location E3. The data show that during very high tides seawater is able to reach upstream areas beyond the upper estuary, connecting the upper and lower estuary. The connectivity is largely one-way however; tidal (sea) water reaches the upper estuary, but only a small (unmeasurable) portion of the resulting mixture of seawater and Hardy River water crosses the sandbar obstruction to flow back out to the Gulf during the ebb tide. Much of the trapped mixture of Gulf water and river water then evaporates.

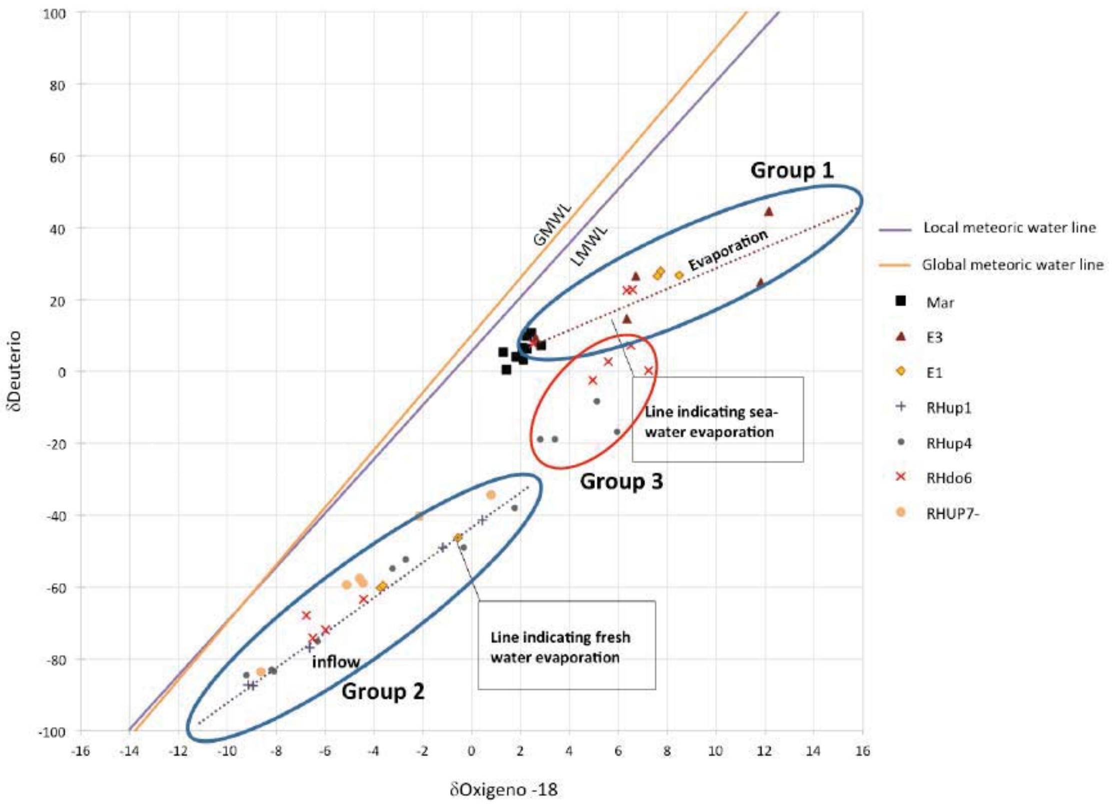

Figure 8-4. $\delta^{18}O$ and δD of water samples taken monthly in 2014 at different locations in the upper estuary and lower Hardy River. GMWL = Global Meteoric Water Line; LMWL = Local Meteoric Water Line.

Pulse flow volume and inundation extent in Reach 7

Reach 7 begins 106 km (66 mi) below Morelos Dam. The Minute 319 science team established one discharge measurement station (DMS-15) in Reach 7, located at river kilometer 120 (river mile 74). Pulse flow arrival at DMS-15 was indicated by increasing discharge and stage height on May 10th, and decreasing specific conductivity (a surrogate measurement of salinity) on May 13th. Discharge and stage height were still elevated on May 25th, when daily monitoring at DMS-15 ceased. Measurements indicate that approximately 1.6 mcm (1,300 af) of pulse flow water reached DMS-15 (see Section 2, Fig. 2-4).

Landsat 8 imagery provides additional information about the pulse flow arrival and extent of inundation in Reach 7. Water originating from the Km 27 Wasteway (Reach 3) arrived at DMS-12 (km 92/mi 57 in upper Reach 5) on April 29th, with a flow rate of $4.7m^3s^{-1}$ (166 cfs) on April 30th. Landsat imagery shows the arrival of this water 48 hours later (May 2nd) at the top of Reach 7 (km106/mi 66, which is 14 km/9 mi downstream of upper Reach 5). Additional pulse flow deliveries from Km 18 caused a peak discharge at DMS 12 of $7.1m^3s^{-1}$ (251 cfs) on May 11th. After May 11th, the area of inundation at the top of Reach 7 expanded substantially, indicating the arrival of Km 18 deliveries. These observations suggest that:
1) the pilot channel in Reach 5 was fairly efficient at transporting flows despite little to no use in the past decade; 2) the infiltration rate in Reach 5 was much lower than that that of Reaches 2 and 3. Thus,

depending on the flow magnitude, it is likely that a portion of water delivered to the bottom of Reach 4/top of Reach 5 will flow to Reach 7 due to low infiltration and high channel efficiency.

Landsat imagery also shows that a portion of pulse flow water was diverted out of the main river channel upstream of DMS-15. The May 27 Landsat image shows increased inundation in the riverside lagoons in the area between km 117 (mi 72) and km 118 (mi 73.5), with the greatest inundation occurring in Lagoon 1 (Fig 8-5). Lagoon 1 is located at a diversion point where high flows are diverted out of the main channel into an older river channel that connects to additional lagoons further south. In addition to the expansion of Lagoon 1, the May 27 image shows inundation of 6.5 km (4 mi) of the former river channel south of Lagoon 1. By June 3rd, an additional 1 km (0.6 mi) of the former channel was inundated. The amount of pulse flow water that inundated the lagoon and former channel was not monitored and is not accounted for in estimates of flow amounts at DMS-15. Thus, the actual volume of water delivered to Reach 7 likely exceeded the 1.6 mcm (1,300 af) estimated from DMS-15 data.

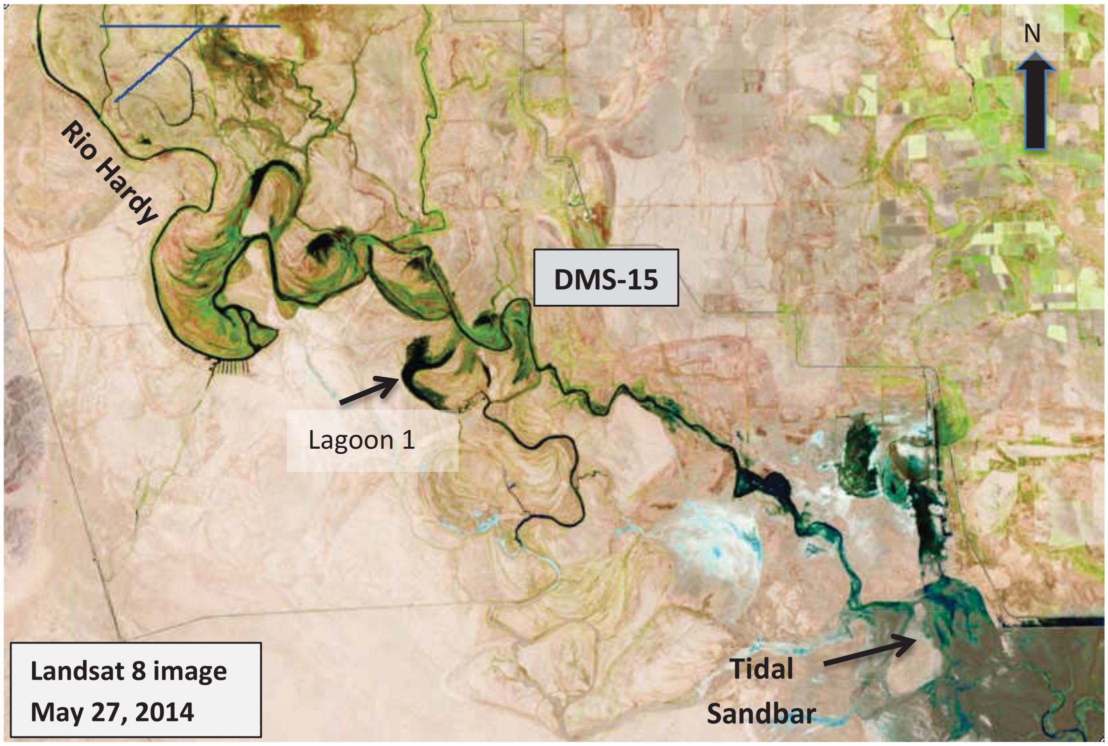

Figure 8-5. Map of lower Colorado River channel and upper estuary. Blue lines in upper left show boundary between Reach 5 (above horizontal line), Reach 6 (to the east (left)) and Reach 7 (to the south and west right and down). DMS = discharge measuring station.

In addition to daily discharge measurements made by the Minute 319 Hydrology Team during the pulse flow release (March – May 2014), SI continued to measure discharge at three locations (DMS 13, 14 and 15; see Fig. 8-2) every other month after the pulse flow through September 2015. Starting in September 2015, SI measured discharge at DMS 13, 14, and 15 on a monthly basis. Based on measurements before (March 24 – May 11, 2014) the pulse flow arrival, the average flow rate at DMS-15 was 0.388 m^3s^{-1} (13.7 cfs); from September 2014 – October 2015, the average flow rate was 0.342 m^3s^{-1} (12.1 cfs).The peak flow rate during the pulse flow at DMS-15 was 0.6 m^3s^{-1} (21.2 cfs) on May 15th. This suggests nearly a doubling of the baseline flow rate at DMS-15 during the pulse flow.

Water Quality

SI monitors water quality parameters at seven locations in the upper estuary and Hardy River; five of these monitoring points are co-located with sensor locations (Fig. 8-2) and the additional two points are located upstream in the Hardy River. The objective of this effort is to determine baseline conditions as well as to detect any changes of physicochemical parameters (temperature, salinity, dissolved oxygen, and pH) and nutrients, bacteria, pesticides, contaminants, and heavy metals over time.

Water salinity decreased at sites RDH06 and E1 (above the sandbar) when the pulse flow arrived at the upper estuary in early May 2014, and returned to higher salinity later in the year (Table 8-1). The pulse flow volume was likely not sufficient to lower high salinity levels at location E3; it is probable that the tidal waters reaching E3 during the high tide caused a decrease (Fig. 8-6).

Concentrations of phosphates, nitrates, and ammonia were higher in mid-May 2014 at both E1 and E2 compared to sampling dates later in the year. However, for ammonia and nitrate, there were only 2 sample dates in 2014; thus, it is difficult to determine a trend over the year and in particular, any changes caused specifically by the pulse flow. Furthermore, changes in concentrations could also be due to influences from Hardy River flows. Concentrations of total coliforms (ΣBC) at both E1 and E3 in May 2014 were similar to concentrations in October and December 2014 (<1.1 MPN/100ml). August concentrations of coliforms were higher than all other sampling dates for both E1 and E3; again, flows from the Hardy River may be influencing these concentrations. Total coliform concentrations in 2014 were well below the limit for direct contact with humans (240 MPN/100ml) established in the Mexican water quality code NOM-003-ECOL-1997 (NOM, 1997).

Concentrations of copper and mercury in May 2014 were higher than concentrations of samples taken in 2010, when concentrations were under the detection limit (Table 8-2). Arsenic levels in May 2014 E1 and E3 water samples were much lower than the 2010 concentration. Mercury and copper concentrations in May 2014 were above the chronic effect concentration (Buchman, 2008), while those for selenium and arsenic were below. As with the nutrient and salinity concentrations, it is difficult to determine if impacts were caused by the pulse flow or other influences. However, similar changes in heavy metal concentrations were observed at both E1 and E3 from 2010 to 2014. This suggests that changes are likely *not* due to the pulse flow because only a small amount of pulse flow water reached E3; E1 and E3 would be affected differently if changes were caused by the pulse flow alone.

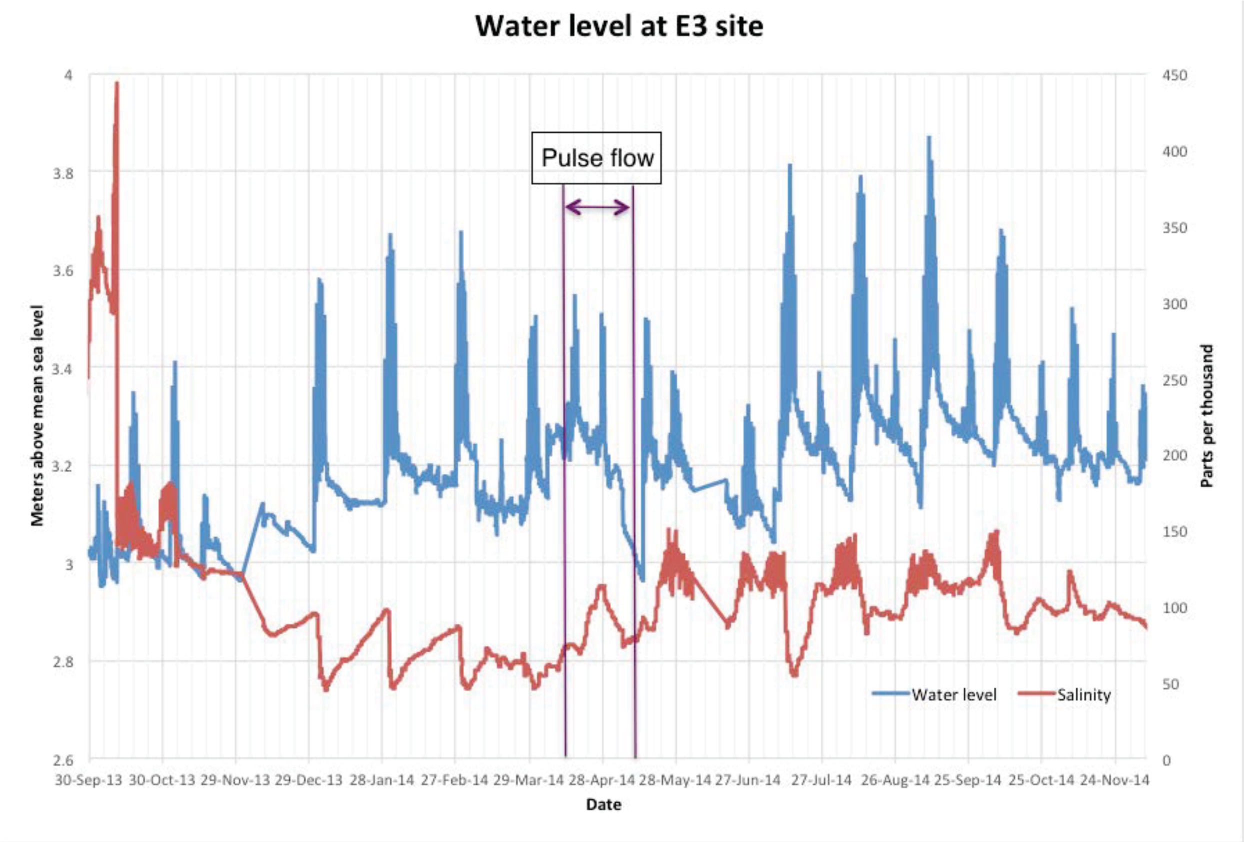

Figure 8-6. Water elevation and salinity at the E3 monitoring site.

Water Quality Parameter	Location	E1				E3			
	Date	5/12/14	8/28/14	10/28/14	12/9/14	5/12/14	8/28/14	10/28/14	12/9/14
Nitrates (ppm)		2.0	1.0	-	-	1.0	0.0	-	-
Nitrites (ppm)		0.029	0.223	0.135	0.032	0.064	0.148	0.114	0.168
Ammonia (ppm)		0.83	-	-	0	0.68	-	-	0
Phosphates (ppm)		0.43	0.12	0.01	0	0.12	0.00	0.03	0
Salinity (ppt)		6.24	99.8	117.55	140.58	94.66	120.66	147.04	56.25
ΣBHC (MPN/100ml)		< 1.1	8	<1.1	<1.1	< 1.1	4.6	<1.1	<1.1

Table 8-1. Concentrations for nutrients, salinity, and coliforms for E1 and E3 sampling sites in the upper estuary.

Heavy Metal (ppm)	2010 Baseline*	May 12, 2014 Sample	
		E1	E3
Selenium	ND	0.000011	0.000678
Arsenic	1.86	0.003266	0.003622
Copper	<DL	0.066667	0.220000
Mercury	<DL	0.001211	0.000478

Table 8-2. Concentrations of heavy metals in 2014 compared to concentrations in 2010 (*Garcia-Hernandez et al. 2010). The 2010 baseline was based on the average concentration from 5 sampling locations in the upper estuary.

<DL signifies under detection limit

Ichthyofauna and zooplankton populations

Sonoran Institute has been monitoring ichthyofauna (fish) and zooplankton species in the upper estuary since 2011. In 2014, fish populations were sampled four times from July-December at six locations, two in the upper estuary and four in the Hardy River. Zooplankton were sampled eight times from March-October 2014 at two locations in the estuary: one upstream and one downstream from sensor E3.

Five fish and two crustacean species were identified during the 2014 fish surveys (Fig. 8-7). *Elops affinis*, a marine-brackish fish species, was the most abundant, while *Micropterus salmoides*, a freshwater fish species, was the least abundant. Two crustaceans, *Procambarus clarkii* and *Callinectes arcuatus* were also captured in the gill-nets during fish surveys.

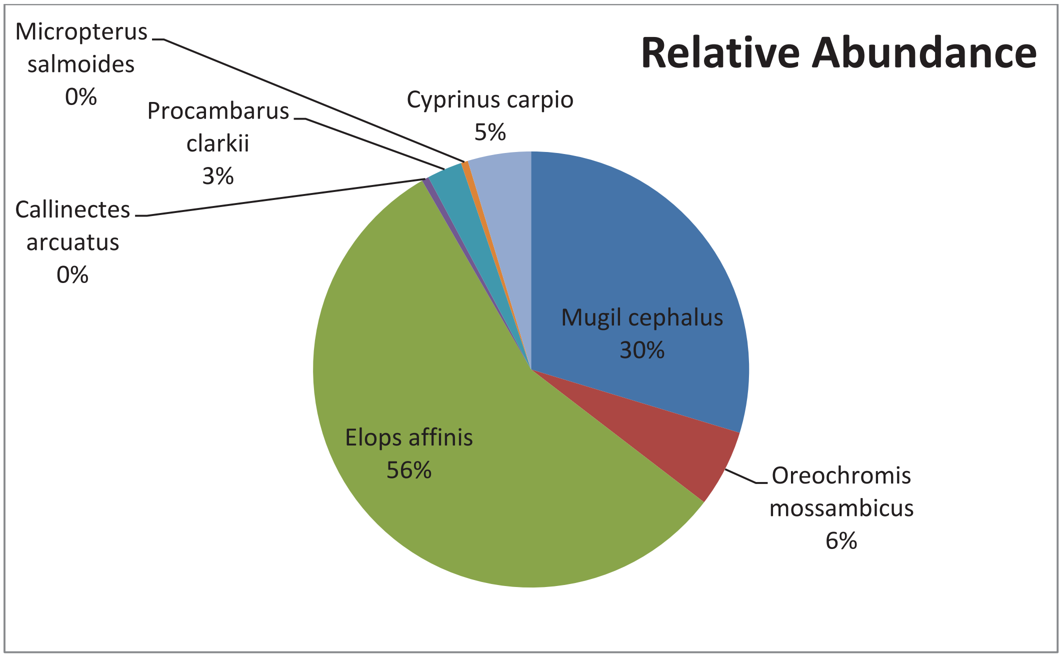

Figure 8-7. Relative abundance of fish and crustacean species identified during fish surveys at six monitoring sites in the upper estuary in 2014.

The analysis of zooplankton surveys previously focused just on shrimp post-larvae, but in 2014, species from other taxonomic groups were identified as well. The shrimp species identified in 2014 include brown shrimp (*Farfantepenaeus californiensis*) and blue shrimp (*Litopenaeus stylirostris*). Only four individuals of these species were found at the location upstream from E3 in May and July (Fig. 8-8), while higher numbers were found at the location downstream from E3 March through October 2014 (Fig. 8-9). This is a biological indicator that connectivity above the sandbar (and the E3 sensor) is limited.

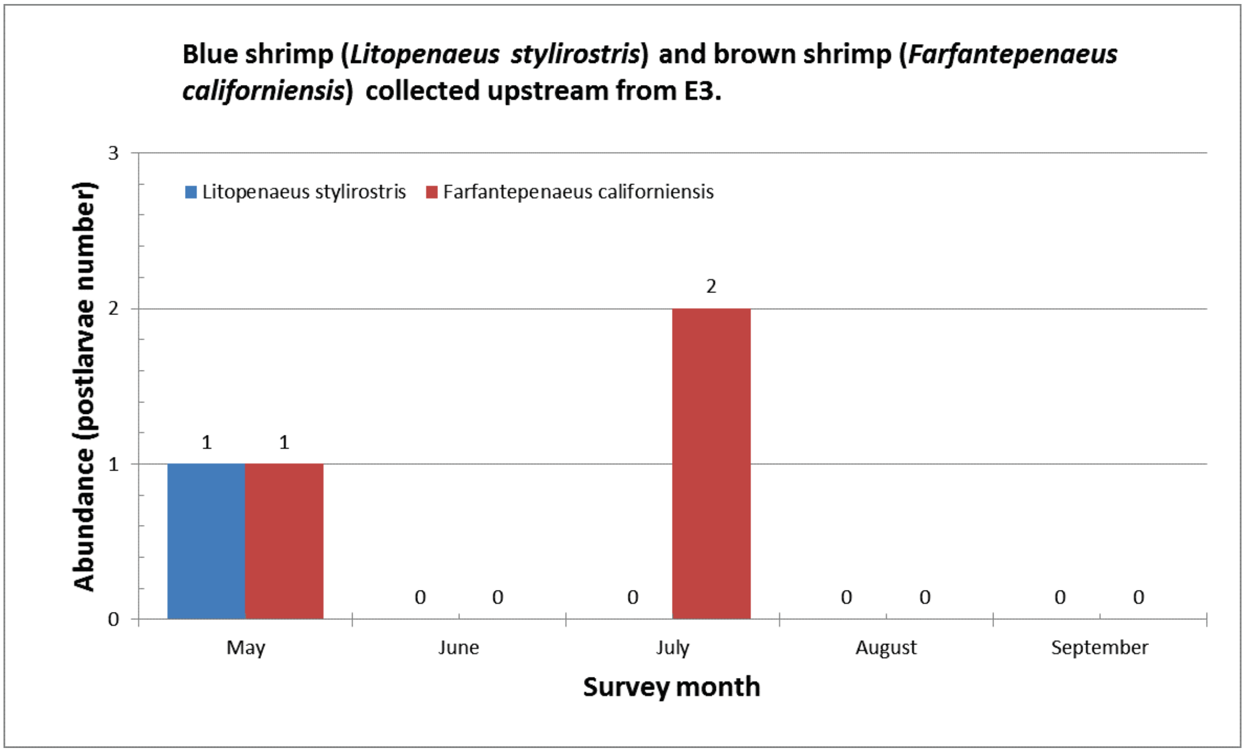

Figure 8-8. Abundance of the two shrimp species found upstream of E3 in the estuary during 2014.

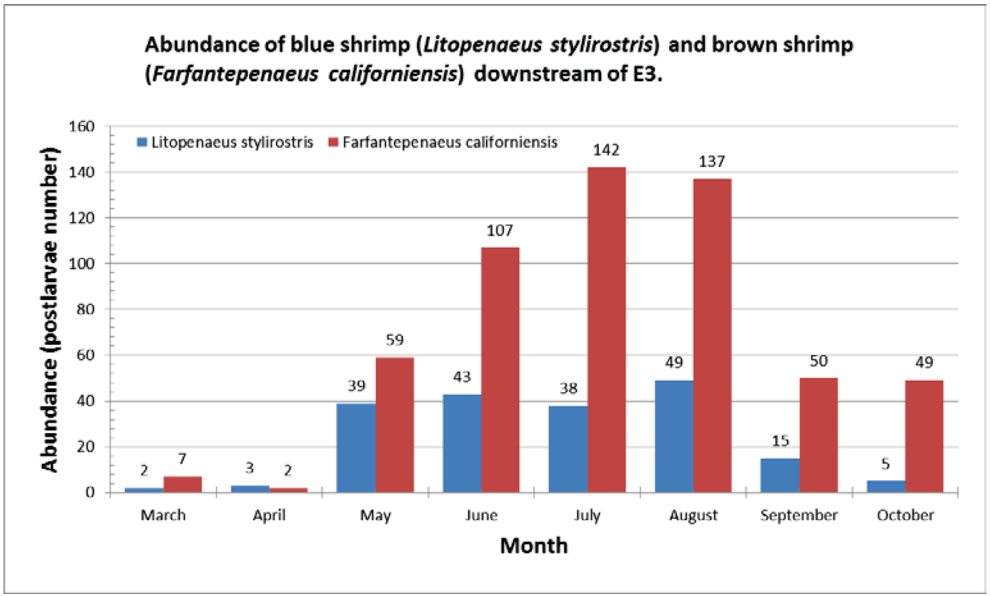

Figure 8-9. Abundance of the two shrimp species found downstream of E3 in the estuary during 2014.

Relevant species from other taxonomic groups, found downstream from E3 include: larvae, juveniles, and adults of the Delta Mudsucker (*Gillichthys detrosus*), a marine fish endemic to the Delta (Swift et al., 2011); larvae and juveniles of *Cynoscion othonopterus* (Gulf Corvina); and eggs of a sciaenid that has not yet been identified but could potentially be *Totoaba macdonaldi* (Totoaba).

Results show no evidence of any impacts of the pulse flow on the fish and zooplankton communities. This is likely due to the small amount and short duration of freshwater brought by the pulse flow into the upper estuary.

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