Minute 319
Colorado River Limitrophe and Delta Environmental Flows Monitoring Final Report

November 28, 2018

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 final 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:
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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Acknowledgments

This report was compiled and edited for the Environmental Work Group (previously called Environmental Flows Team) of the International Boundary and Water Commission by Dr. Karl Flessa (University of Arizona), Dr. Eloise Kendy (The Nature Conservancy), Dra. Jesús Eliana Rodríguez Burgueño (Universidad Autónoma de Baja California) and Karen Schlatter (Sonoran Institute) on behalf of all the people and organizations engaged in monitoring in the Colorado River Delta under Minute 319.

These efforts represent a collaboration among 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: Osvel Hinojosa-Huerta, Pronatura Noroeste. Morelos Dam and the Colorado River, looking north, during the first days of the pulse flow, March, 2014.

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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." "The 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.

Ecological and hydrologic 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 continued through 2017.

This Final Report summarizes activities and results through December 31, 2017. Previously, the "Minute 319 Colorado River Delta Environmental Flows Monitoring Initial Progress Report, December 4, 2014" reported results observed 90 days after the cessation of the pulse flow. The

"Minute 319 Colorado River Limitrophe and Delta Environmental Flows Monitoring Interim Report May 19, 2016" reported results observed through December, 2015. Both reports are available at the IBWC website https://cila.sre.gob.mx/cilanorte and https://www.ibwc.gov/home.html.

Contributors to this report are listed in Table 1-3.

Table 1-1. Representatives of the binational Minute 319 Environmental Work Group

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

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*indicates former affiliation

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

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*indicates former affiliation

We take special note of the contributions of Edward P. Glenn (1947-2017) of the University of Arizona. Professor Glenn's vision and scientific contributions inspired and convinced citizens on both sides of the border that restoration of the Colorado River Delta is possible.

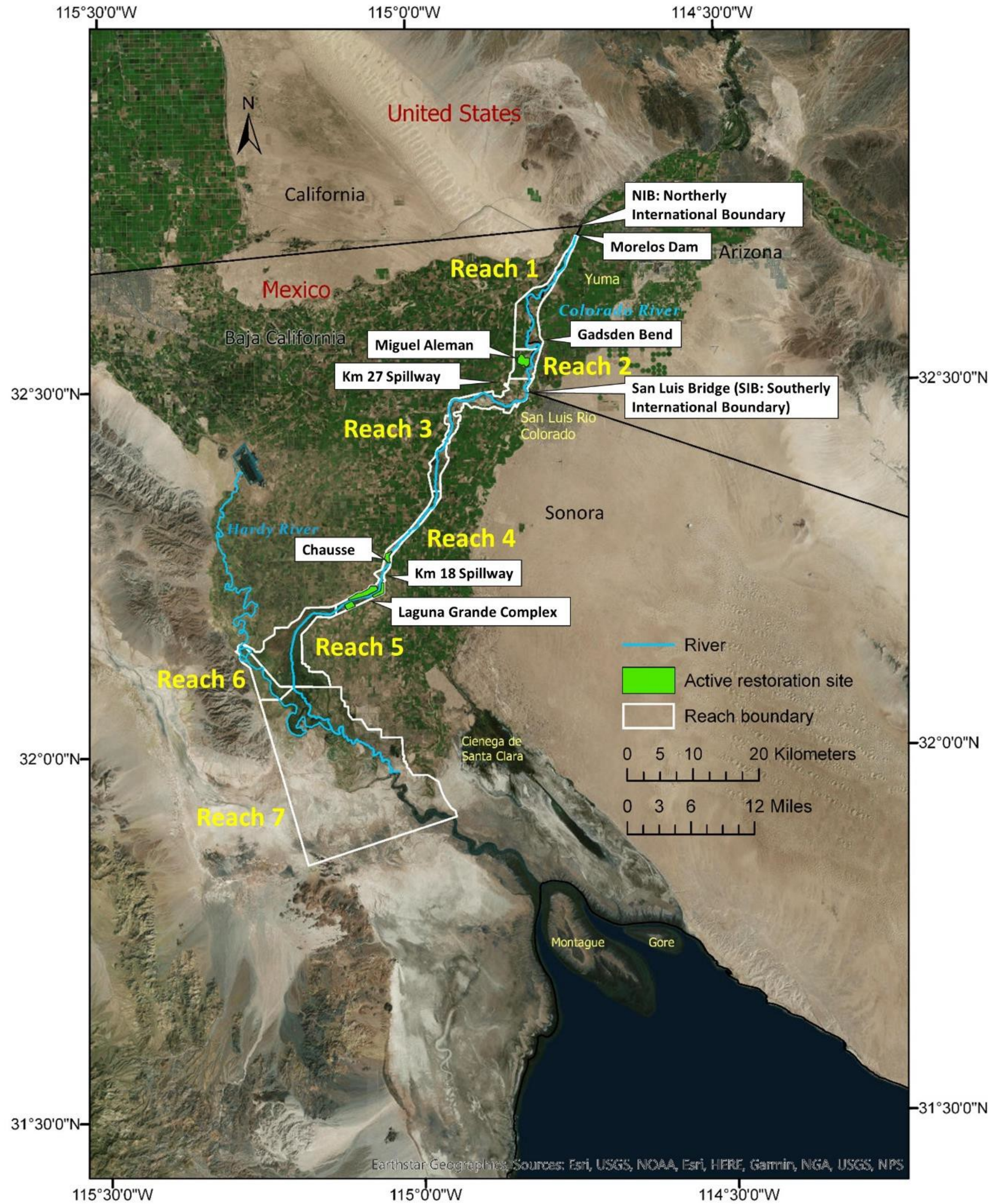

Figure 1-1. Colorado River Limitrophe and Delta Reaches and locations mentioned in this report.

Executive summary

As provided in Section III.6.e.i of Minute 319 to the U.S.-Mexico Water Treaty of 1944, a pulse flow of approximately 130 million cubic meters (mcm) (105,392 acre-feet), implemented by the U.S. and Mexican governments, 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 57,621 acre-feet (71.074 mcm) were delivered to Miguel Aleman, El Chausse, and Laguna Grande restoration areas and to the Colorado River channel in Mexico during the term of Minute 319 through December 31, 2017. This total exceeds the volume pledged by the non-governmental organizations by approximately 4,924 acre-feet (6.074 mcm). Base flow volumes delivered by year in each reach are reported in the Hydrology Section below.

Methods

The following activities were conducted during the term of Minute 319 to evaluate the ecosystem response, including the hydrological response and the biological response to the environmental flows.

- Baseline (pre-pulse flow) conditions from published reports and from field observations were summarized.
- Surface-water discharge was measured during the pulse flow at 15 sites.
- Groundwater levels in the riparian corridor and restoration site were measured by piezometers before, during and after the pulse flow.
- Geophysical techniques were used in the Limitrophe section of the study area (i.e., Reaches 1 and 2) to determine the hydraulic properties of the aquifer and the areal changes in groundwater levels.
- Surface and groundwater salinity were measured.
- 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 pulse 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 in 2014 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 establishment of new vegetation to 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. Seed dispersal, soil salinity and texture, and vegetation cover along the 21 transects were monitored before and after the pulse flow; vegetation cover was monitored annually through 2017.
- Detailed surveys of new vegetation, groundwater conditions, soil conditions, and bird populations were conducted at restoration sites.
- Satellite-based remote sensing was used to assess vegetation health (NDVI, or “greenness”) annually (begun in 2000).
- Photographic images of fixed locations within the riparian corridor shortly before, during, six months, 12 months and 30 months after the pulse flow were assembled. (See Appendix F in https://www.ibwc.gov/Files/Minutes%20319/Delta_Monitoring_Interm_Appendices_March2016_1.pdf page 139).
- 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 and were conducted annually from 2013-2017.
- Fish populations, groundwater levels, and surface water parameters were monitored in the lowermost river reaches and estuary to document changes in connectivity between the river and the Gulf of California.

Geography of the study area

The area that was monitored extends downstream from where the pulse flow and base flows were delivered and consists of the Colorado River channel and its floodplain extending from Morelos Dam approximately 160 river km (≈100 river miles) to the Upper Gulf of California. The 680 km^2 (263 mi^2) study area is defined by drivable levees and highways that confine the channel. Detailed maps of the Colorado River Delta’s riparian corridor are shown in Figures 1-2A-D. The maps show the locations of transects, discharge measuring stations (DMS), restoration areas and other places referred to in this report. Groundwater monitoring sites (piezometers) are shown in Appendix B. Bird monitoring sites are shown in Appendix C.

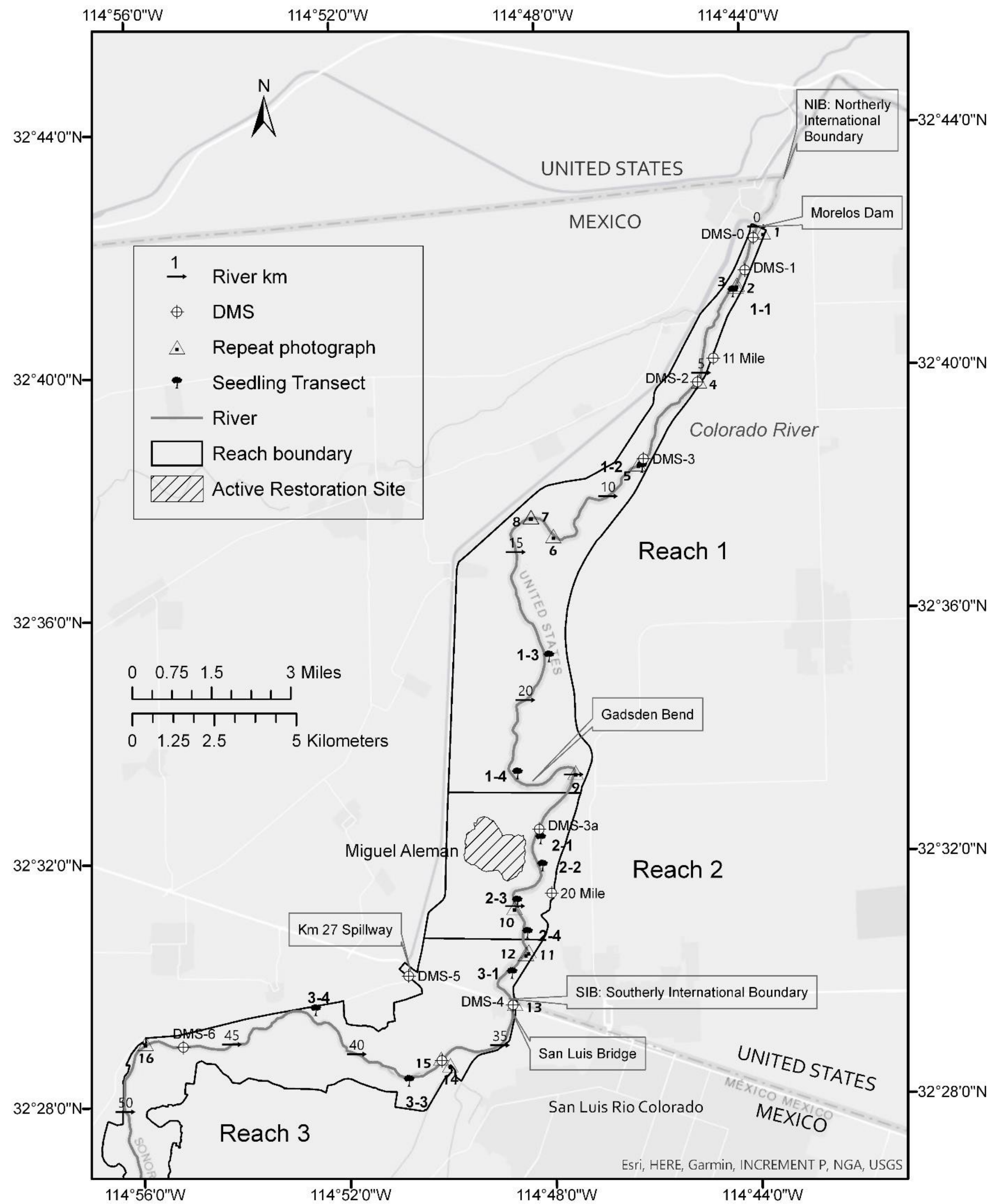

Figure 1-2A. Study area. Reaches 1, Reach 2 and part of Reach 3. River km (in 5 km increments) is river distance from Morelos Dam.

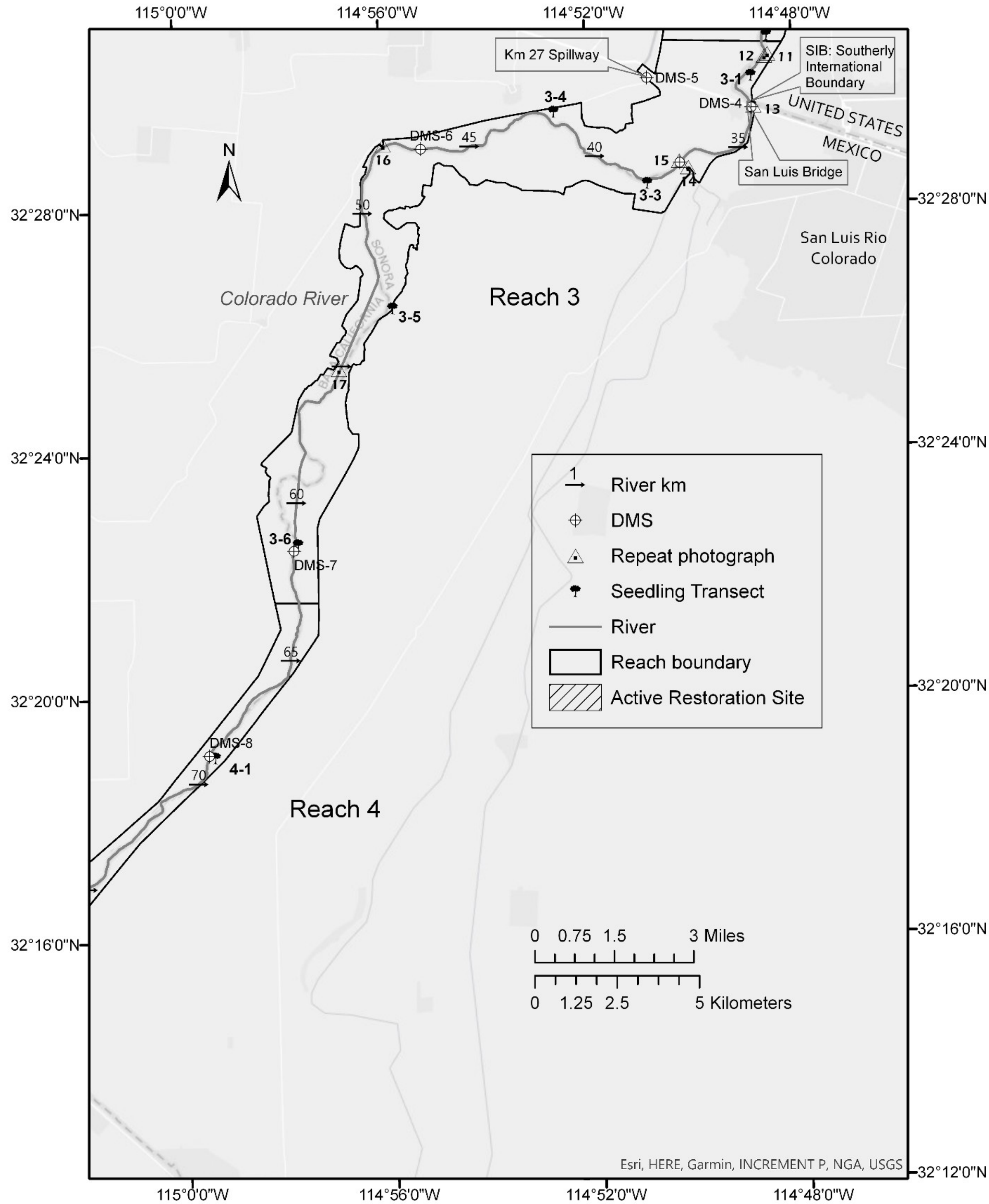

Figure 1-2B. Study area. Reach 3 and northern part of Reach 4. River km (in 5 km increments) is river distance from Morelos Dam.

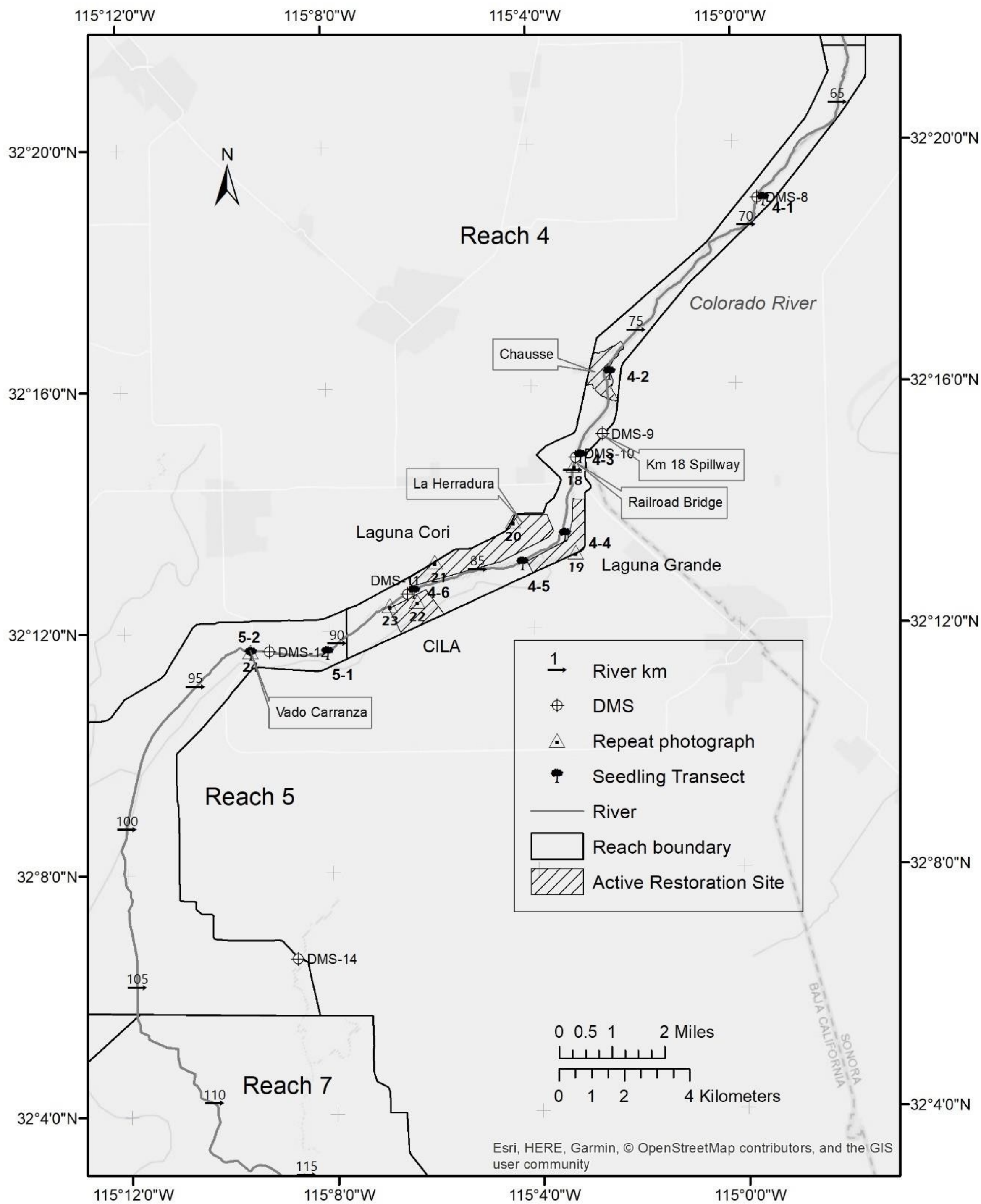

Figure 1-2C. Study area. Reach 4 and eastern part of Reach 5. River km (in 5 km increments) is river distance from Morelos Dam.

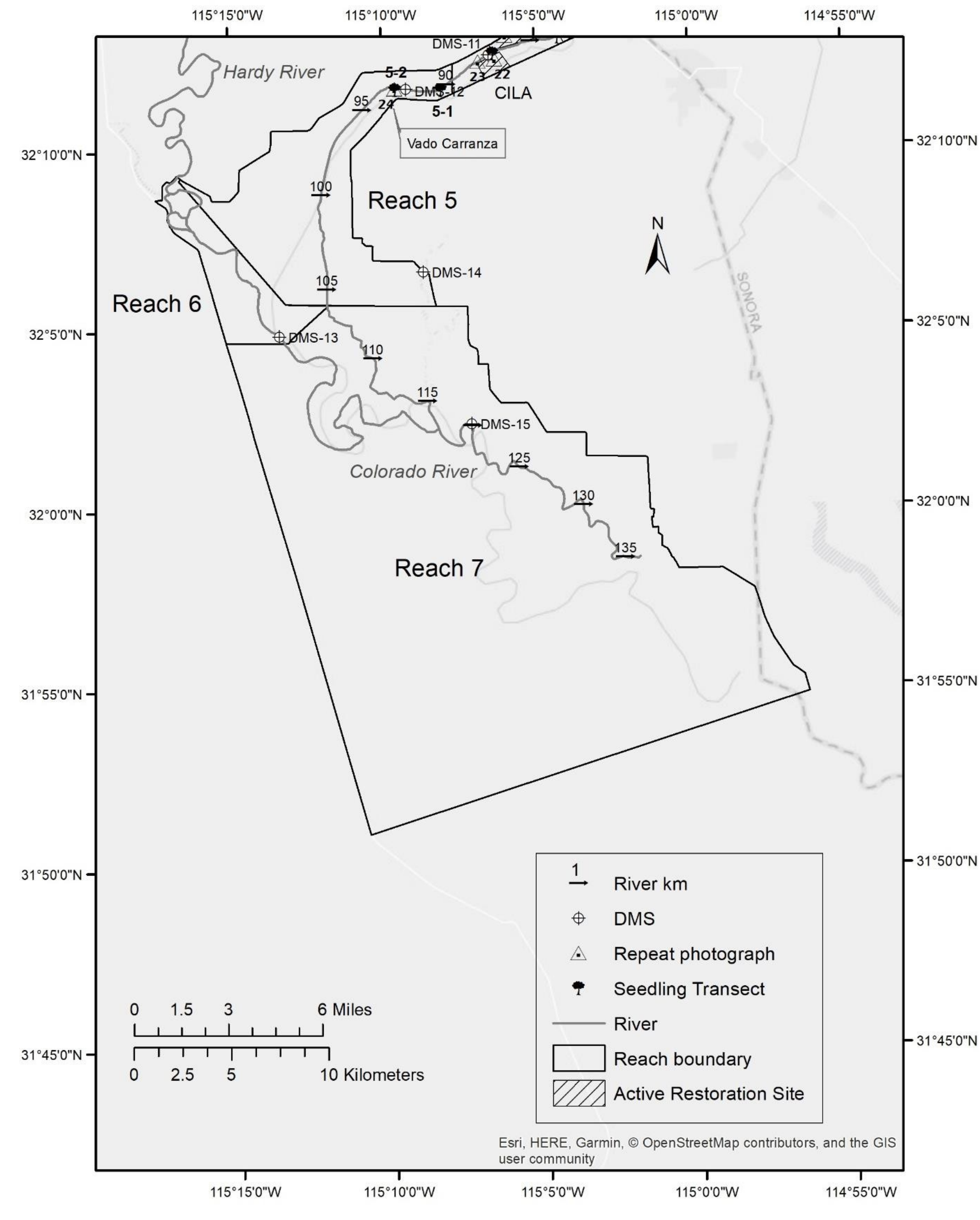

Figure 1-2D. Study area. Reaches 5, 6 and 7. River km (in 5 km increments) is river distance from Morelos Dam.

Summary of observations and analyses made through December 31, 2017

Detailed presentation and discussion of these results with supporting data are in the subsequent sections and appendices of this report, in the Initial Progress Report (December 4, 2014), in the Interim Report (May 19, 2016), and in ScienceBase https://www.sciencebase.gov/catalog/items?q=Minute%20319.

1. The 2014 pulse flow of approximately 130 mcm (105,392 acre-feet) inundated approximately 1,600 ha (4,000 acres) of the main channel and adjacent terraces of the Colorado River Delta, achieving lateral and longitudinal connectivity along the entire river from Morelos Dam to the estuary for the first time since 2001[1].
2. Pulse flow discharge was not sufficient to widen the channel, or to scour or bury significant amounts of existing vegetation. Geomorphic changes within Reaches 1-3 during the pulse flow were limited to local 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. The pulse flow's discharge and volume decreased downstream, primarily as a result of infiltration. Ninety-one percent of the pulse flow infiltrated within the first 61 km of the river channel below Morelos Dam. Infiltration in dry reaches can be minimized by clearing the channel of vegetation and other obstacles, pre-wetting the channel, and maintaining low water levels to preclude overflowing out of the channel.
4. Within two months of the conclusion of the pulse flow, approximately 122 mcm (99,000 acre-feet), or about 94% of the pulse flow infiltrated. About 1.6 mcm (1,300 acre-feet), or about 1% of the pulse flow, reached the upper estuary as surface flow.
5. 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.
6. Base flow releases from Morelos Dam and three irrigation canals totaled 71.07 mcm (57,620.9 acre-feet) during the term of Minute 319.
7. Releases from downstream irrigation spillways were essential for connecting the river to the sea during the pulse flow.
8. The Mexicali Valley irrigation system provides a practical means for delivering water directly to restoration sites. This routing avoids dry channel reaches where infiltration rates are high, and incurs delivery fees.
9. Delivery of water to restoration sites via the main channel of the Colorado River recharges groundwater more than deliveries via lined canals. Deliveries via the main channel can provide recreational benefits.

[1] The date has been updated from 1997, which was reported in the Minute 319 Colorado River Limitrophe and Delta Environmental Flows Monitoring Interim Report, to 2001 based on analysis of remotely sensed data.

10. The pulse flow resulted in a 17% increase in NDVI ("greenness") throughout the riparian corridor in 2014. From 2016-2017 NDVI decreased steadily, with most reaches falling to below 2013 levels in the riparian corridor.
11. The most favorable areas for recruitment of native plant species were in Reaches 1 and 4, where stands of mature cottonwoods and willows provided a seed source and groundwater levels are shallow. Removal of exotic vegetation and land grading increased seedling survival.
12. Recruitment and persistence of seedlings was most successful in Reach 4 restoration sites (Laguna Grande; LG), where groundwater conditions are favorable, base flows were delivered, channels were reconnected and graded, and nonnative species were removed.
13. Patterns of vegetation cover are greatly affected by hydrological conditions present before Minute 319 flows. Vegetation cover is greatest in perennial reaches with a high water table. Vegetation cover was affected to a lesser degree by the pulse flow and base flow deliveries. At the local level, vegetation cover changed in response to depth to groundwater, availability of bare ground, and fires.
14. Mortality of seedlings established during the pulse flow resulted from competition, decreasing groundwater levels, fire, and herbivory.
15. Three active restoration sites were established or expanded as a result of Minute 319 and private funding, with water supplied from the pulse flow or subsequent base flows[2]:
    a. Miguel Aleman (Reach 2; 101 hectares (248 acres); Pronatura Noroeste
    b. Chausse (Reach 4; 63 ha (155 acres); Restuaremos el Colorado
    c. Laguna Grande (Reach 4; 207 ha (512 acres); Sonoran Institute
16. Restored habitat types included open water/marsh (25 ha/ 62 acres), cottonwood-willow (161 ha/398 acres, mesquite bosque (162 ha/401 acres), and upland (22 ha/54 acres).
17. Active restoration prior to Minute 319 (CILA site) totaled 17 ha (41 acres).
18. In addition to the active restoration sites, 59 ha (145 acres) were passively restored (i.e., without any intervention other than the incidental delivery of water).
19. As of the end of Minute 319 (December 31, 2017) a total of 446 ha (1,102 acres) of riparian vegetation have been restored (Minute 319 active [371ha/916acres] + Minute 319 passive [59 ha/145 acres] + pre-Minute 319 [17 ha/41 acres]).).
20. Of the 275,000 trees that were planted, year-to-year survival rates ranged from 75% to 95%.
21. Measurements on the time, duration and volume of base flows by delivery point were not available; therefore, the effects of baseflows were not directly analyzed.
22. The abundance (+20%) and diversity (+42%) of birds in the riparian corridor increased in 2014 after the pulse flow. Abundance and diversity declined after 2014 in each reach, but 2017 levels still exceed those observed in 2013.
23. The abundance (+80%) and diversity (+27%) of birds continues to be greater in restoration sites than in non-restored areas in the riparian corridor.

[2] The implementation of the restoration projects established under Minute 319 was extended in accordance with the Joint Report of the Principal Engineers dated September 5, 2017. The total number of restored acres reported will be complete by the end of 2018.

24. A small amount of pulse flow water mixed with Gulf of California water. However, hydrologic and ecological effects of the pulse flow were not detected in the estuary.
25. Dredging of the main river-tidal channel in the upper estuary in 2016 increased freshwater-tidal-water exchange, resulting in decreased surface water salinity (at one station, from 60 parts per thousand (ppt) to approximately 20 ppt in spring months and from 100 ppt to 45 ppt in winter months).
26. Dredging of the tidal channel enabled freshwater from the Hardy River and Ayala Drain to flow to the upper estuary and sea when agricultural return flows were high (January –June).

Section 2: Hydrologic Response: Surface Water and Groundwater Response

Key findings

1. The 2014 pulse flow temporarily achieved connectivity of the Colorado River from Morelos Dam to the Sea of Cortez.
2. Ninety-one percent of the pulse flow infiltrated within the first 61 km of the total 130 river km below Morelos Dam. Infiltration in dry reaches can be minimized by clearing the channel of vegetation and other obstacles, pre-wetting the channel, and maintaining low water levels to preclude overflowing out of the channel.
3. The Mexicali Valley irrigation system provides a practical means for delivering water directly to the restoration sites. This routing avoids dry channel reaches where infiltration rates are high. Releases from irrigation spillways were essential for connecting the river to the sea during the pulse flow.
4. The area where groundwater is too deep to support riparian vegetation is extending downstream from Reach 3 toward Reach 4 and upstream into Reach 1.
5. Shallow groundwater levels in the Reach 4 restoration areas are maintained primarily by irrigation return flows from February through May and by base flows from June through October, after irrigation ceases.
6. Groundwater levels indicate that base flows were delivered to the river channel at least 7 times from Morelos Dam to the Limitrophe, 10 times from Canal Alimentador del Sur to Chausse, and one time from Canal Barrote lower Reach 4. 2016 deliveries to lower Reach 4 reached the upper estuary.
7. Hydrologic monitoring during Minute 319 suggests several water delivery strategies, depending on the management objectives.
    - To reduce infiltration into dry reaches, maintain flow volumes below the capacity of the channel, clear the channel of obstructions, and, if possible, pre-wet the channel to convey surface water swiftly downstream.
    - To maximize duration of flows at San Luis Rio Colorado for recreation benefits, deliver water as close as possible upstream of San Luis Rio Colorado.
    - To maximize ecological benefits to native riparian habitat, a combination of irrigation and in-channel deliveries may be needed. Water control structures in Reach 4 enable management of inundation extents and recession rates. Coordinated monitoring of water delivery and management with soil salinity and ecological responses can enhance ecological benefits by adjusting the frequency, duration, locations, and volumes of water applications.
    - To maximize flows to the estuary from Reach 4, deliver water in large (at least 2 m^3/s), steady flows and remove sediment and invasive vegetation from the last 2 km of river channel to improve connectivity. Coordinated monitoring of water deliveries and hydrologic responses can inform the volume and duration of flow releases needed to achieve inundation and salinity goals.

Introduction

Under the auspices of Minute 319, approximately 195 mcm (158,000 acre-feet) of water were released into the Colorado River Delta for environmental flow purposes. Of this volume, approximately 130 mcm (105,392 acre-feet) were delivered as a pulse flow from Morelos Dam and the Kilometer 27 and Kilometer 18 spillways (Figure 2-1) from March 23 through May 18, 2014, and 71.07 mcm (57,620 acre-feet) were released from various delivery points as base flows throughout the period of the Minute (through 2017).

The pulse flow was designed to move sediment and nutrients, enhance longitudinal connectivity, reduce soil salinity, and disperse and germinate native riparian plant seeds (Pitt and Kendy, 2017). Base flows were intended to enhance open-water habitats and provide sufficient soil moisture and shallow groundwater conditions to support native riparian and upland habitats.

Minute 319 Section III.6.c.iv requires evaluation of the hydrologic responses to these environmental water deliveries. The Binational Science team performed this evaluation. Appendix B inventories groundwater and surface-water data obtained during Minute 319.

Pulse Flow

To benefit habitat restoration, in-channel flow deliveries need to reach sites that have shallow groundwater, which are located primarily in Reach 4. Prior scientific knowledge and modeling results (Ramirez-Hernandez et al., 2013; Tetra Tech, 1999) indicated that some of the pulse flow would be retained in off-channel depressions, some would infiltrate laterally into soil or vertically into the underlying vadose zone and into the aquifer as recharge, and some would evaporate.

Infiltration above Reach 4 was of particular concern. 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 (Freeze and Cherry, 1979).

Significant infiltration was expected to occur in the lower portion of Reach 1 and in Reaches 2 and 3, collectively termed the dry reaches, where more than 16 m (52 ft) of unsaturated sediments underlie the dry, sandy riverbed. To minimize infiltration and enhance longitudinal river connectivity, Km 27 and Km 18 spillways of the Mexicali Valley irrigation canal system (Figure 2-1) supplemented pulse flow deliveries from Morelos Dam. The available capacity of these canals and spillways was utilized to divert water around the dry reaches toward sites with greater potential for restoration.

The pulse flow achieved lateral and longitudinal connectivity along the entire river from Morelos Dam to the estuary for the first time since 2001. Landsat imagery showed that about 1,600 hectares (4,000 acres) of the main river channel and adjacent terraces were inundated (Nelson et al., 2007). Flessa et al. (2014, 2016), Kennedy et al. (2017), and Ramírez-Hernández et al. (2017) described in detail the hydrologic response to the 2014 pulse flow.

About 91% of the pulse flow that was delivered above the Km 18 spillway infiltrated into the first 61 km of the total 130 river km below Morelos Dam (Ramírez-Hernández et al., 2017; Figure 2-1). Within two months of the conclusion of the pulse flow, approximately 122 mcm (99,000 acre-feet), or about 94% of the pulse flow infiltrated. Infiltration volumes were largest in the normally dry Reach 3 (river km 34-61), where water overflowed from the main channel into abandoned meanders and other dry depressions that lacked flow paths back to the main channel. This isolated water filled empty voids in the aquifer below, as indicated by groundwater levels measured in piezometers. Conversely, little infiltration occurred in places with shallow groundwater (Kennedy et al., 2017; Ramírez-Hernández et al., 2017; Rodriguez-Burgueño et al., 2017; Schlatter et al., 2017a).

Channel wetness also affected the advance of the wetting front. Infiltration rates in the dry reaches were highest during the initial days of both the pulse flow and a September 2014 base flow delivery from Morelos Dam, declining only after the substrate was thoroughly wetted (Rodríguez-Burgueño *et al.*, 2017). Thus, pre-wetting the channel below the Km 27 spillway may reduce conveyance loss in the dry reaches. Reach 5, where groundwater is shallow, conveyed water from Reach 4 to Reach 7 with minimal infiltration losses (Nelson et al., 2017; Schlatter et al., 2017b).

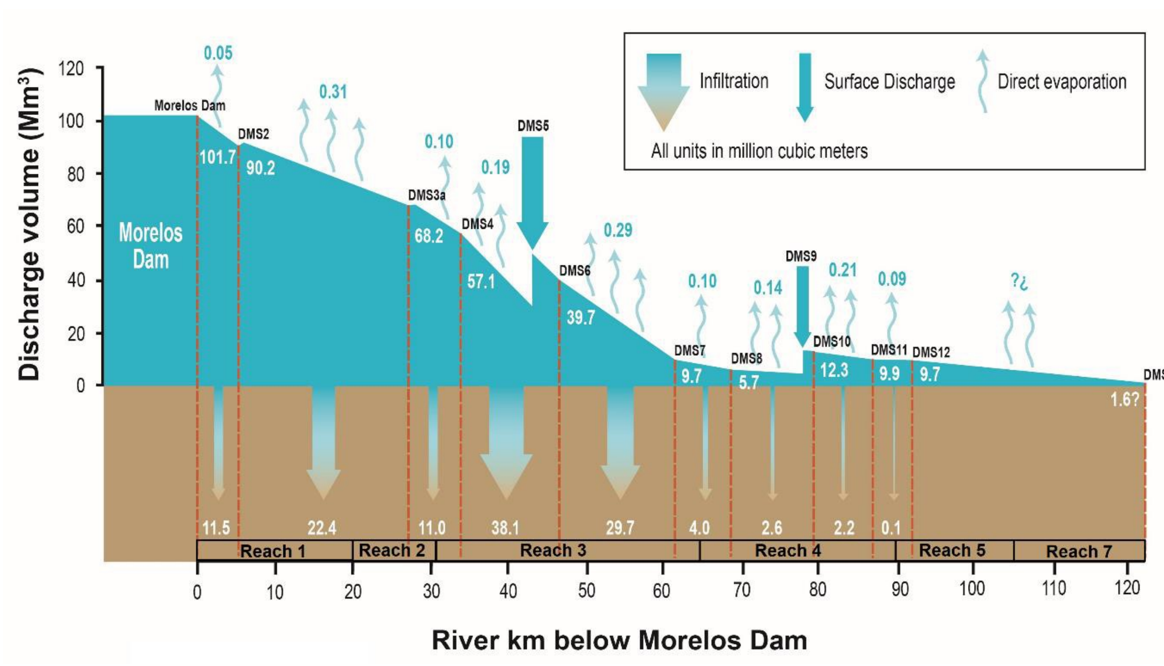

Figure 2-1. Water balance of the 2014 pulse flow. Arrow widths are proportional to flow volumes. DMS indicates Discharge Measuring Station; DMS5 is the Km 27 spillway and DMS9 is the Km 18 spillway (Ramírez-Hernández et al., 2017).

The wetting front advanced at rates ranging from 0.04 to 8.20 kilometers per hour (Nelson et al., 2017). The slowest advance occurred in Reaches 2 and 3, which had the highest infiltration rates and the largest infiltration volumes (Flessa et al., 2016). Eighty-three percent of the infiltration volume occurred in the dry reaches, and infiltration volume into off-channel meanders and other depressions exceeded infiltration volume into the main river channel (Alarcón Gómez, 2015). Obstructions along the main channel, diversions into abandoned river meanders, and the highly permeable nature of the sandy riverbed and terrace sediments all contributed to high infiltration volumes (Kennedy et al., 2017; Ramirez-Hernandez et al., 2017).

Infiltration from future flow releases could be minimized by maintaining flow volumes below the 10-20 m^3/s capacity of the pilot channel 3.5 km (2.2 mi) south of the Southerly International Border and extends for approximately 106 river km (65.9 river mi). This would keep water from entering off-channel depressions. Clearing the channel of obstruction or lining the pilot channel would further reduce infiltration.

Rodriguez-Burgueño (2017) applied a coupled groundwater (MODFLOW) and surface water (diffusion wave, or DFW) model to a natural ephemeral stream for the first time. This application further illuminated the pulse flow infiltration process. The model was calibrated to the wetting front, surface water data, and groundwater data from the pulse flow event, using hydraulic characteristics obtained from gravity measurements (Kennedy et al, 2017a) and electromagnetic induction (Kennedy et al., 2017b). Results indicate that during the first 11 days of the pulse flow, 125,000 m^3 (100 acre-feet) recharged the aquifer compared to 320,000m^3 (250 acre-feet) that was retained in surficial meanders and channels; the highest infiltration rates (0.2 to 1.2 m^3/s) occurred at river km 22, 27-30, and 37-40 (Rodriguez-Burgueño, 2017).

As the pulse advanced downstream, its flow rate decreased from a peak of 120 cubic meters per second (m^3/s) at Morelos Dam (Flessa et al., 2016). About halfway down Reach 3 (river km 46.5), deliveries from the Km 27 spillway boosted the declining flow to 36 m^3/s (DMS5, Figure 2-1), which then rapidly decreased as the pulse flow traversed the remaining dry reaches. Of the three delivery points, the Km 18 spillway was most effective in delivering water to the restoration sites in Reach 4 because the canal system delivering the water bypasses the dry reaches.

The pulse flow tested whether approximately 130.5 mcm (105,392 acre-feet), the volume of water available for a pulse flow under Minute 319, could scour river channels and terraces, deposit fresh sediment, reduce soil salinity, soak seeds, and maintain soil moisture for growing seedlings. These consequences of floods enhance recruitment of native riparian plants. However, no significant morphological changes to the river channel or terraces resulted from the pulse flow (Mueller et al., 2017). This is likely because the pulse flow's peak magnitude was very small (120 m^3/s; 4,200 f^3/s) compared to historical flood peaks (2,300 m^3/s; 81,000 f^3/s) in the Delta (Figure 2-2). Only localized, meter-scale scour and fill of the stream channel occurred, without any deposition or erosion on the banks or terraces. No geomorphological changes were detected below river km 65 (Mueller et al., 2017).

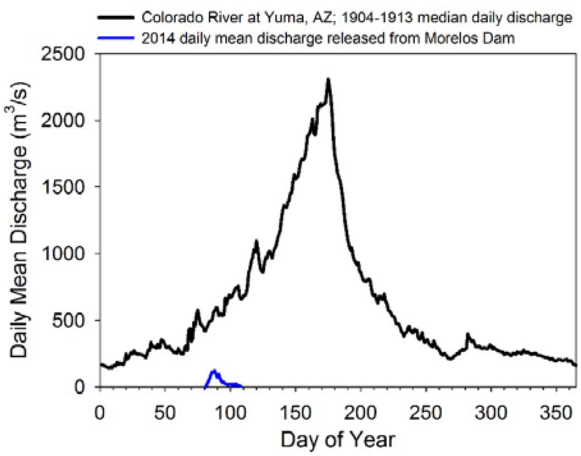

Figure 2-2. Comparison between median daily mean discharge for the Colorado River at Yuma, Arizona, for the period 1904-1913 and daily mean discharge released from Morelos Dam during the 2014 pulse flow (Mueller et al., 2017).

Other hydrologic effects of the pulse flow were similarly subdued. When the water arrived at restoration areas in Reach 4, the depleted flow inundated a smaller area than anticipated. Fortunately, flow releases from the Km 18 spillway, retained by downstream dams, successfully inundated the floodplain and germinated willows and cottonwoods in mechanically cleared areas (Flessa et al., 2016). Soil salinity measurably decreased in inundated areas, benefiting existing vegetation (Schlatter et al., 2017b). However, the inability of the pulse flow to mimic natural recession rates (Nelson et al., 2017) inhibited new plant recruitment. In Reach 5 at river km 94, the water filled an approximately 2.5-km^2 floodplain dominated by saltcedar, thereby reducing and delaying flow downstream to the estuary (Nelson et al., 2017). Even so, increases in chlorophyll-a concentrations in riverine and estuarine waters indicate a possible pulse flow effect on the coastal environment (Daesslé et al. 2017).

Glenn et al. (2017) compared the Minute 319 2014 pulse flow to environmental pulse flows in other rivers and noted that expectations need to match the amount of water available for the environment, which is frequently less than natural flows. Mueller *et al.* (2017) suggested that given the uses of water in the Colorado River Basin and the physical infrastructure on the Colorado River, exceptional natural floods from the Gila River basin would be the most likely mechanism for major changes to the Delta's geomorphology.

Base Flows

The binational science team was tasked with assessing the hydrologic impacts of 71.07 mcm (57,620 acre-feet) of base flows delivered to the riparian corridor (Table 2-1). All base flows were delivered either from Morelos Dam to benefit the Limitrophe or from Mexicali Valley's irrigation system to benefit designated restoration sites. Measurements on the time, duration and volume of base flows by delivery point were not available; therefore, the effects of baseflows were not directly analyzed. Here, we infer approximate delivery dates based on groundwater responses measured in piezometers

(Figure 2-3), and then examine how those deliveries affected local hydrology.

Table 2-1a. Baseflow deliveries (m^3) by canal and delivery point through December 31, 2017*. Water years begin on October 1. Source: Official data.

Water Delivery Point by Canal/Module[3] (Units in m^3)	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018[4]	Total by canal
Reforma Canal/ Module 7	0	538,360	1,425,082	808,704	1,024,324	194,400	3,990,870
Barrote Canal / Module 22	693,219	3,383,423	7,460,554	10,981,354	2,626,818	362,016	25,507,383
Canal Alimentador del Sur / Module 8	0	3,513,987	3,302,498	4,550,688	6,776,438	472,781	18,616,392
Morelos Dam - CONAGUA	0	5,157,389	17,802,202	0	0	0	22,959,591
Total Deliveries	**693,219**	**12,593,159**	**29,990,335**	**16,340,746**	**10,427,580**	**1,029,197**	**71,074,236**

Table 2-1b. Baseflow deliveries (acre-feet) by canal and delivery point through December 31, 2017*. Water years begin on October 1. Source: Official data.

Water Delivery Point by Canal/Module[4] (Units in acre-feet)	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018[5]	Total by canal
Reforma Canal/ Module 7	0	436	1,155	656	830	158	3,235
Barrote Canal / Module 22	562	2,743	6,048	8,903	2,130	293	20,679
Canal Alimentador del Sur / Module 8	0	2,849	2,677	3,689	5,494	383	15,092
Morelos Dam - CONAGUA	0	4,181	14,432	0	0	0	18,614
Total Deliveries	**562**	**10,209**	**24,313**	**13,248**	**8,454**	**834**	**57,621**

[3] Modules are a subdivision of Irrigation District 014 in the Mexicali Valley.
[4] This data is through December 31, 2017.

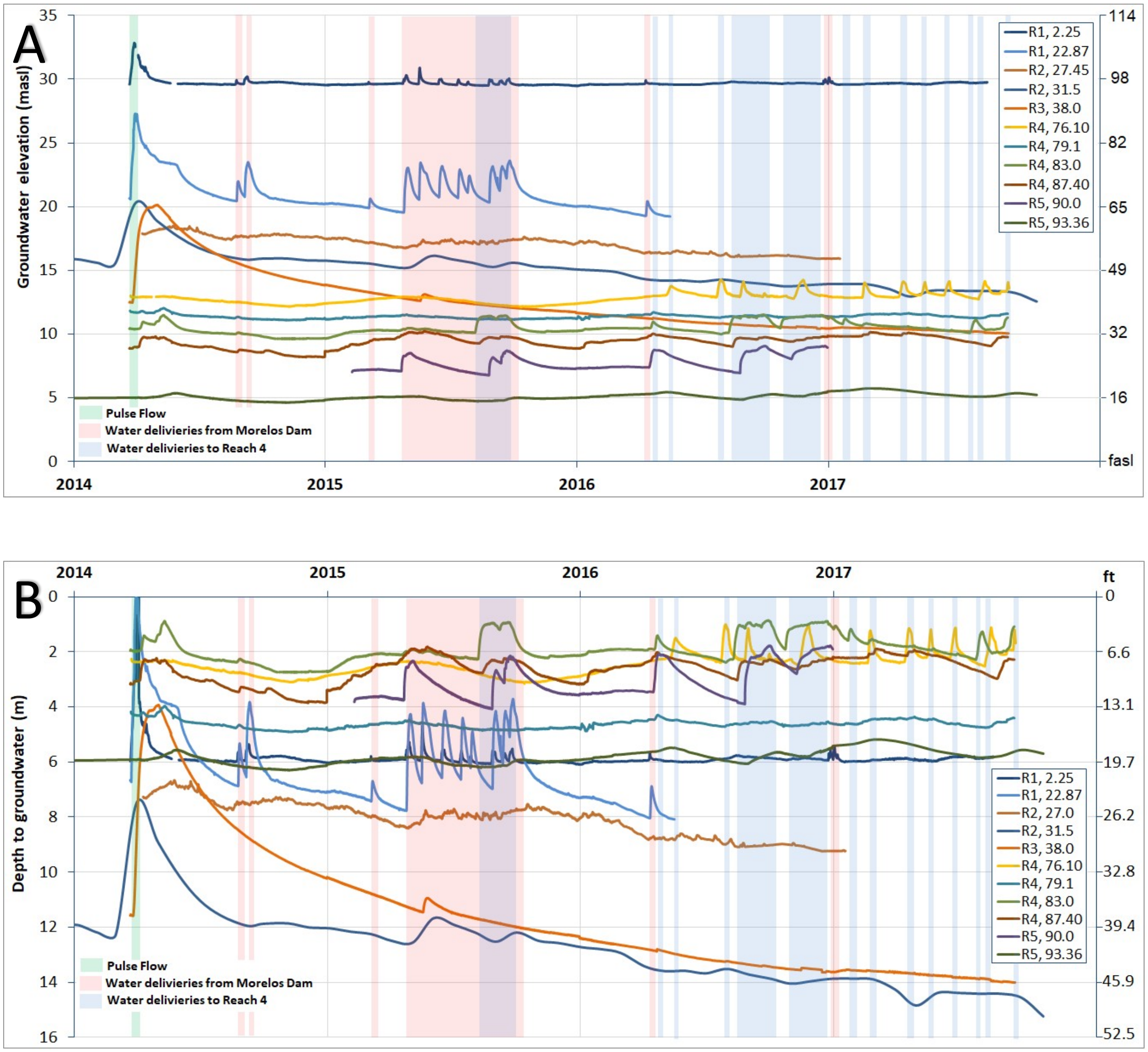

Figure 2-3. Groundwater elevation (A) and depth to groundwater (B) records at piezometers along the riparian corridor, showing effects of in-channel base flow deliveries in 2014-2017. Reach number (R) and downstream distance (km from Morelos Dam) are indicated for each piezometer. Piezometer locations are shown in Figure 2-4.

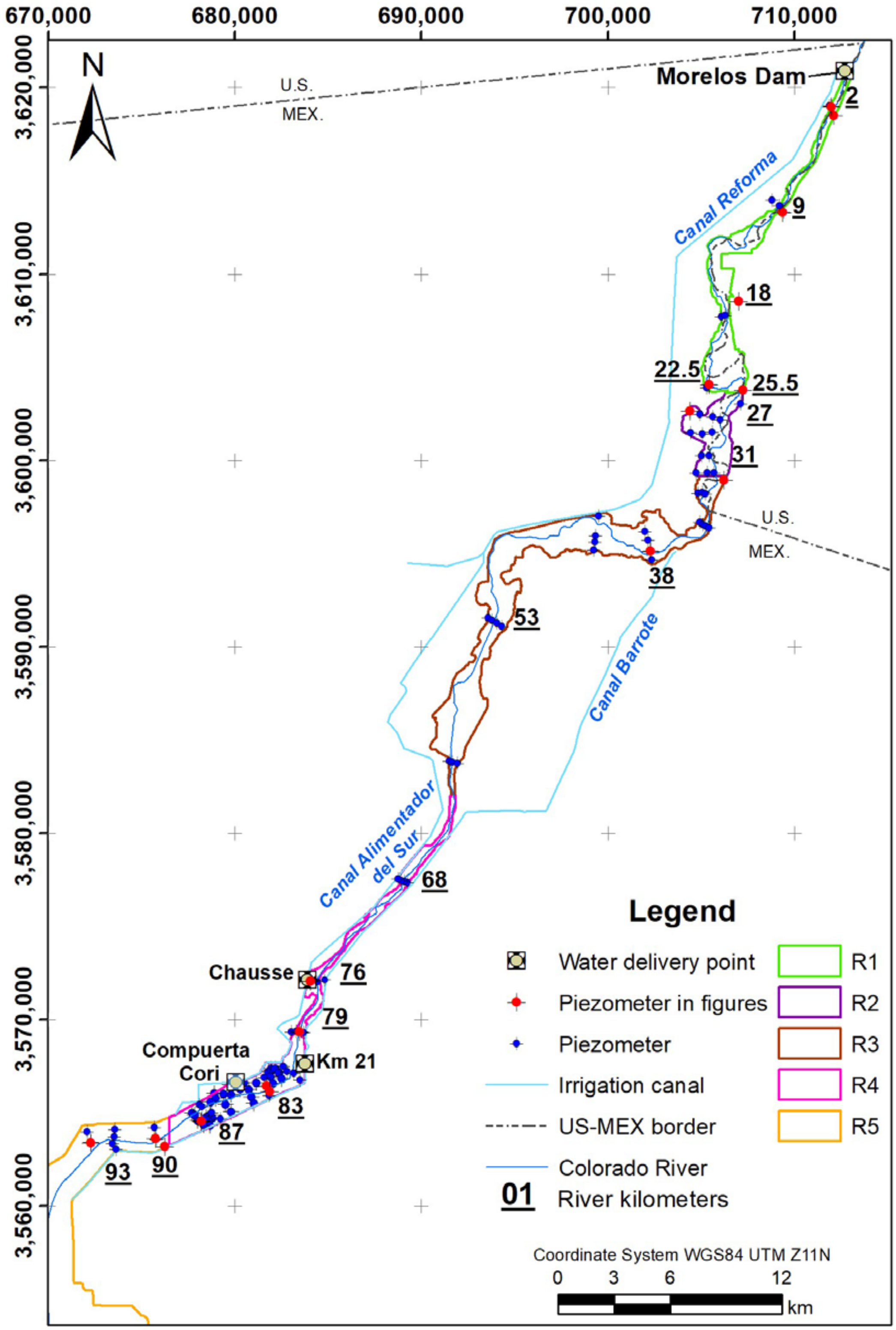

Figure 2-4. Locations of piezometers monitored under Minute 319. See Appendix B for construction data.

Morelos Dam delivered water to the river channel during September 2014 and at least six times during 2015, based on groundwater responses depicted in Figure 2-3. For the first few km below the dam, irrigation return flows and seepage from the dam normally maintain shallow water levels (less than 1 m); there, the deliveries did little to raise the water table. Impacts on groundwater are more evident downstream (e.g., Figure 2-3, R1 km 22.87), where the water table is deeper (10-12 m). Slight effects (about 1-m rise) were observed in piezometers as far as 31.5 km downstream.

The September 2014 delivery from Morelos Dam lasted five days and ranged from five to 13 m^3/s (Rodríguez-Burgueño et al., 2017). Surface flow inundated the river channel well into the dry reaches. Rodríguez-Burgueño et al. (2017) compared lateral infiltration processes between this base flow and the 2014 pulse flow, using two methods: (1) heat as a tracer in discrete points along the dry river channel and (2) saturated/unsaturated numerical modeling along a dry river channel cross section located approximately 30 km downstream from Morelos Dam. Results indicate that the lateral infiltration rate was highest during the initial days of both flow events and remained high so long as unsaturated conditions prevailed. The authors concluded that to maximize the advance of surface water across dry river reaches, base flow rates should begin small to saturate the surface, and then increase to move water downstream. As previously noted, water levels should stay low enough to prevent water from overflowing the main channel into adjacent, isolated depressions, where the water could only evaporate or infiltrate (Rodríguez-Burgueño et al., 2017).

Groundwater levels beneath the **Miguel Aleman** restoration site (Figure 2-3, R2 km 27) responded more to surface water deliveries from Morelos Dam than from base flow deliveries directly to the restoration site. The 2015 Morelos Dam deliveries to the main river channel generated maximum and average groundwater rises of 0.68 m (2.2 ft) and 0.60 m (2 ft), respectively, at Miguel Aleman. Conversely, groundwater levels declined about 0.4 m (1.3 ft) per year during subsequent years, when no water was delivered from Morelos Dam. In contrast, only small groundwater peaks (0.10 m; 0.33 ft) result from irrigating Miguel Aleman directly because irrigation water (base flows delivered via a pipeline from Canal Reforma) is carefully timed and applied in only small amounts.

El Chausse is part of the network of restoration sites along the riparian corridor benefitting from environmental water and funding from Minute 319. The observed groundwater rises of 1-1.5 m (Figure 2-3, R4 km 76.1) were used to infer that the Chausse restoration site received at least 10 in-channel water deliveries in 2016-2017. The maximum flow delivery rate possible at this site is 2 m^3/s. The site design calls for 5 ha-m/ha (17 acre-feet/acre) of water deliveries annually. These base flows create open-water habitat by filling a 1.8-km abandoned meander. Control structures allow site managers to retain water in the meander and then slowly release it to the main river channel. Groundwater levels along transect 4-3 (Figure 2-3, R4 km 79.1), located 3 km downstream from Chausse, did not rise in response to the flow releases, likely because the water table there was already high. Accordingly, NDVI data indicate no increase in greenness (Section 3) and vegetation surveys indicate no increase in vegetation cover (Section 4) along the transect. This is consistent with Shanafield et al.'s (2017) observation that environmental flows delivered to the river channel did not affect evapotranspiration from restoration sites in Reach 4, where groundwater levels were already sufficiently shallow to support riparian vegetation. Other potential benefits, such as salinity reduction, long-term drought resilience, and open-water habitat in the river channel, were not evaluated.

Laguna Grande restoration area receives base flows as irrigation and as in-channel deliveries. Prior to Minute 319, agricultural return flows maintained shallow groundwater levels during the February – May irrigation season only (Figure 2-5, R5 89.5). During Minute 319, piezometer data indicate that April – October environmental water deliveries maintained these shallow levels throughout the growing season (Figure 2-5, R4 and R5 hydrographs) (Ramirez-Hernandez et al., 2015), creating adequate conditions for the establishment and survival of native riparian vegetation (Glenn et al., 2001; Hinojosa-Huerta et al., 2013).

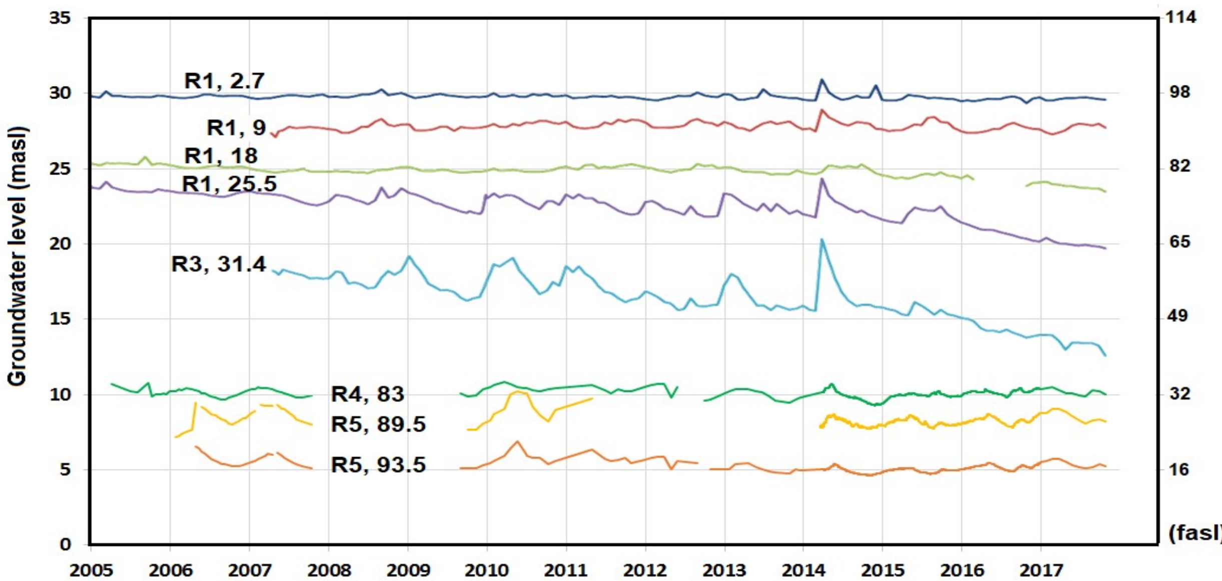

Figure 2-5. Long-term groundwater hydrographs, indicating the reach number (R) and river kilometer (downstream distance from Morelos Dam) of the piezometer for which each hydrograph was recorded. Units: masl = meters above sea level; fasl = feet above sea level. Data published in Kennedy et al. 2017a and updated through monitoring completed during Minute 319.

The **estuary** does not receive direct base flow deliveries although in-channel deliveries to Reach 4 can potentially flow to the estuary. In August through December 2016, approximately 5.1 mcm (4,200 acre-feet) of water was released at varying rates to the Colorado River channel in Reach 4 from the Km 21 and Compuerta Cori Spillways. This base flow was designed to (1) ecologically benefit riparian habitat in Reach 4, (2) test whether water delivered to Reach 4 could flow to the estuary, and (3) assess groundwater impacts (Schlatter et al., 2017a). The experimental design aimed to maintain flows at 2 m^3/s for 30 days in August through September. Although flow delivery measurements are not available, it was inferred from downstream hydrologic measurements and Landsat images that discharge rates actually ranged from about 0 – 1.5 m^3/s (0-53 ft^3/s) (Schlatter et al, 2017a). The flow rate decreased as the water advanced downstream. For example, on September 12-13, 2016, the delivery rate was estimated to be approximately 0.7 m^3/s. By about 5.5 and 15 km downstream from the spillways, discharge had decreased to 0.6 m^3/s and 0 m^3/s, respectively (Schlatter et al., 2017a).

In response to this base flow, groundwater levels generally rose less than 1 m (Figure 2-3, R5 93.36), possibly contributing to a slight NDVI increase observed in Reaches 4, 5, and 7 between October and November 2016. In contrast, NDVI decreased in other reaches over the same period (Schlatter et al., 2017a).

Despite the low flow delivery rates, satellite imagery shows that the surface flow advanced into the upper estuary (Reach 7) in October 2016 (Figure 2-6). Reach 5, which is usually dry, conveyed water from Reach 4 to Reach 7 with minimal infiltration losses (Nelson et al., 2017; Schlatter et al., 2017b) because the water table was shallow.

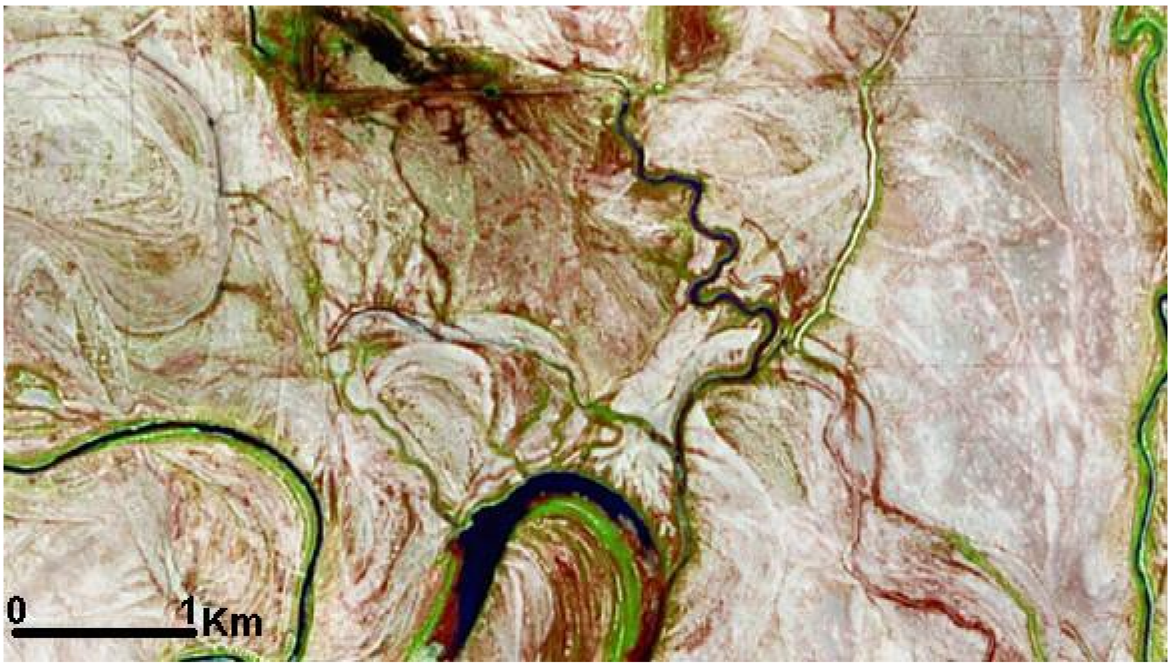

Figure 2-6. October 3, 2016 Sentinel 2a image (10-m resolution) showing surface water in the upper estuary (bottom, center) despite ponding at the end of the Reach 5 channel (top, center-left).

However, no measurable impacts to surface water discharge, salinity, or groundwater elevation were observed in the estuary. Nevertheless, the fact that flow reached the estuary despite channel blockages and low, fluctuating discharge rates suggests that in-channel deliveries to Reach 4 could provide benefits to the estuary. Higher, steadier flow rates (together, Km 21 and Km 37 spillways and Ayala Drain are physically capable of delivering more than double the highest rate delivered during this experiment) and sediment and vegetation removal from the last 2 km of river channel would improve connectivity with the upper estuary (Schlatter *et al.*, 2017a).

Groundwater

In 2014, the binational science team began monitoring groundwater levels in a network of 123 piezometers along the riparian corridor and upper estuary (Appendix B), including those that detected base flow deliveries, described above. By December 2017, only 85 of the original piezometers remained functioning after 31 went dry and 7 were destroyed. Only three piezometers remain active in Reach 3, where groundwater levels are lowest. An additional five piezometers monitored by the U.S. Bureau of Reclamation provide water-level data for the Yuma area.

The riparian corridor overlies a regional, binational alluvial aquifer. Water management activities such as pumping and irrigation on both sides of the border affect its groundwater flow directions, water-level fluctuations, and connectivity between surface water and groundwater. For example, in upper Reach 1, irrigation return flows and canal leakage maintain steady, shallow groundwater levels (Figure 2-5).

In contrast, near the Southerly International Boundary, pumping wells create a subsurface zone of aquifer depletion characterized by depressed water levels that leave the river channel dry for 42 km, from lower Reach 1 to the top of Reach 4. Historically, groundwater flowed in a southerly to southwesterly direction beneath the riparian corridor; now, it flows toward this depression from all directions within the depletion zone.

The depth and lateral extent of the groundwater depletion zone are increasing. From 2005 to 2017, groundwater levels beneath lower Reach 1, Reach 2 (inferred) and Reach 3 declined about 2 to 5 m, respectively (Figure 2-5). NDVI data delineate the edges of the zone as locations where greenness has most rapidly decreased (Section 3, Figures 3-5 and 3-6, insets A and D), as the water table dropped below the roots of riparian vegetation. This water table drop may have caused the decrease in vegetation cover observed in Transect 1-3 (Section 4 Figure 4-1b).

In-channel flow deliveries to the Delta were expected to raise the groundwater table and thus improve water availability for riparian vegetation. Indeed, in response to the 122 mcm (98,500 acre-feet) of water that infiltrated into the aquifer during the pulse flow, groundwater levels rose in Reaches 1-5 (Figure 2-5) and the river reconnected with the aquifer along the entire riparian corridor. However, these responses largely dissipated within six months, as the recharged water joined the regional flow system (Kennedy et al., 2017; Flessa et al., 2016). Likewise, recharge from much smaller in-channel base flow deliveries rapidly dissipated (Figure 2-3). In contrast, as mentioned previously, delivering water directly onto restoration sites effectively extends the shallow groundwater period beyond the irrigation season, well into October.

Recommendations for future environmental flows

Intensive monitoring of the Minute 319 pulse flow greatly improved the understanding of how water moves through the Colorado River Delta, and has already informed the design of future flow releases. However, the lack of base flow delivery data limited what could be learned about the small, in-channel and irrigation deliveries that will likely dominate future restoration efforts. Therefore, these recommendations pertain to both water management and monitoring to improve restoration outcomes.

The health of riparian and estuarine vegetation depends upon the presence of shallow groundwater or surface water deliveries. Water levels beneath the riparian corridor are deepening and the affected area is increasing (Figure 2-5). Consequently, the dry river reach is extending northward into Reach 1 and southward towards Reach 4. Continued groundwater monitoring can track declining groundwater levels and signal when restoration strategies need to adapt.

Based on hydrologic monitoring during Minute 319, several water delivery strategies have emerged, depending on the management objectives.

- To reduce infiltration into dry reaches, maintain flow volumes below the capacity of the channel, clear the channel of obstructions, and, if possible, pre-wet the channel to convey surface water swiftly downstream.
- To maximize duration of flows at San Luis Rio Colorado for recreation benefits, deliver water as close as possible upstream of San Luis Rio Colorado.
- To maximize ecological benefits to native riparian habitat, a combination of irrigation and in-channel deliveries may be needed. Water control structures in Reach 4 enable management of inundation extents and recession rates. Coordinated monitoring of water delivery and management with soil salinity and ecological responses can enhance ecological benefits by adjusting the frequency, duration, locations, and volumes of water applications.
- To maximize flows to the estuary from Reach 4, deliver water in large (at least 2 m^3/s), steady flows and remove sediment and invasive vegetation from the last 2 km of river channel to improve connectivity. Coordinated monitoring of water deliveries and hydrologic responses can inform the volume and duration of flow releases needed to achieve inundation and salinity goals.

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Section 3: Vegetation Response: Remote Sensing of the Riparian Corridor

Key findings

1. The Minute 319 pulse flow resulted in a 17% increase in NDVI (“greenness”) throughout the riparian corridor in 2014 (Jarchow et al., 2017 – in Appendix A).
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 supported existing vegetation.
3. From 2016-2017 NDVI decreased steadily, most reaches falling to levels below 2013 levels in the riparian corridor.

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) was used for this analysis. 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 published performance comparisons made in riparian ecosystems (Nagler, et al., 2005).

Response to Minute 319 Environmental Flows

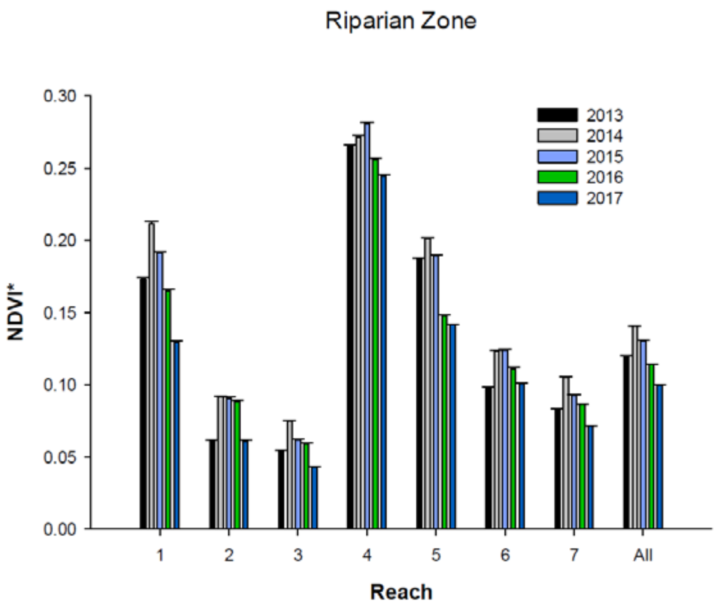
Landsat NDVI was averaged across the growing season (May-Oct.) from 2013-2017 for each river reach and all reaches combined (Fig. 3-1).

NDVI is greatest in Reaches 1, 4 and 5, where shallow groundwater and surface water supports vegetation. Reaches 2 and 3 are within the “dry reach” where the water table is deep and vegetation is sparse. Reach 6 is dominated by the Río Hardy drainage and was largely unaffected by the pulse flow and subsequent base flow. Reach 7 includes the upper estuary and received a small amount of surface water from the pulse flow in 2014 and more regular flows from the Río Hardy and agricultural drains. Groundwater is shallow in Reach 7.

NDVI was higher in 2014 than in 2013 for all reaches. The overall NDVI increase from 2013 to 2014 was 17% ($P < 0.001$). The most intense greening in 2014 took place in the zone of inundation by the pulse flow 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.

The overall peak NDVI values occurred in Reach 4 in 2015, perhaps reflecting the effects of planting and vegetation growth in the Laguna Grande restoration site.

For Reaches 1, 4, 5, and all combined, NDVI decreased steadily from 2016-2017, falling below 2013 levels. The rapid decrease in NDVI values in Reach 1, and the 2017 drop in the Reach 2 may be consequences of declining groundwater levels as noted in Section 2 of this report.



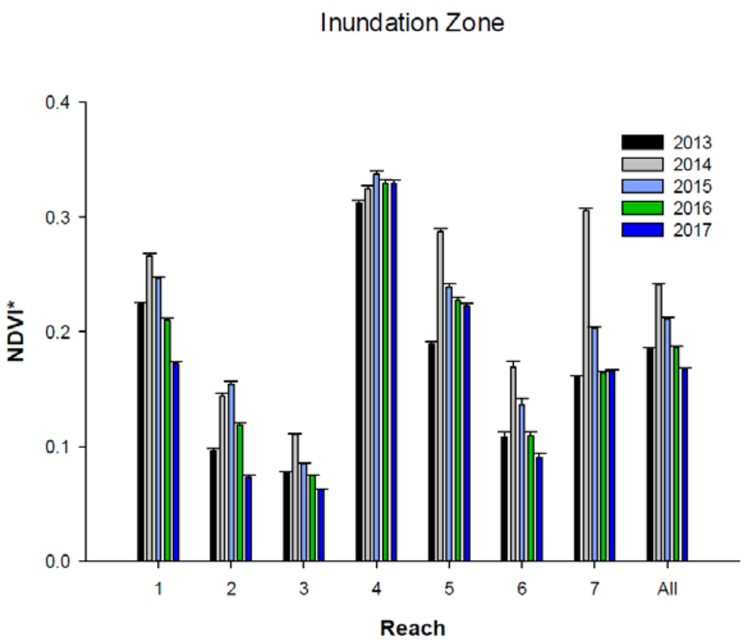


Figure 3-1. (Top). NDVI in the entire riparian zone, by river reach, from 2013-2017. (Bottom) NDVI in the inundation zone, by river reach, from 2013-2017. 2013-2015 NDVI data derived from Jarchow et al. (2017).

In the inundation zone (Fig. 3-1), NDVI in 2015 was higher than 2013 levels in all reaches.

By 2017, NDVI values in the Reaches 2 and 3 – the dry reaches- and Reaches 6 (Río Hardy) and 7 (the upper estuary) fell to values similar to or slightly lower than those observed in 2013. Restoration activities at the Miguel Aleman site appear to have been at too small a scale to sustain overall NDVI values in Reach 2.

The Reach 4 average NDVI values did not fall as much after 2014 as in other reaches, perhaps as a consequence of base flow deliveries to the two restoration sites in this reach, the persistent high water table in this reach, or, most likely, both factors.

Figure 3-2 shows areas inundated during the pulse flow and differences in NDVI between 2013 (pre-pulse) and 2014 (post-pulse), with selected enlarged portions of the riparian corridor. A greener color indicates that NDVI was higher in 2014 than in 2013. There was extensive green-up in all areas, except for the portion in the lower part of Reach 4 (Figure 3-2C), where extensive land-clearing took place prior to the pulse flow. Much of the land cleared was not inundated during the pulse flow.

Figure 3-3 shows areas inundated during the pulse flow and differences in NDVI between 2014 and 2015. A greener color indicates that NDVI was higher in 2015 than in 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 were greener than in the post-pulse growing season of 2014 (Figure 3-3A and C), other parts of the riparian corridor were not as green as in the previous year – see especially enlarged part of Reach 7 (Figure 3-3A, 3-3E).

Figure 3-4 shows areas inundated during the pulse flow and differences in NDVI between 2013 (pre-pulse) and 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 were less green than under pre-pulse conditions.

Figure 3-5 shows areas inundated during the pulse flow and differences in NDVI between 2015 and 2016. Note that the overall trend was a decrease in greenness, but some localized areas (such as in Reach 7 and Reach 3; Figure 3-6E and D, respectively) displayed a slight increase in greenness.

Figure 3-6 shows areas inundated during the pulse flow and differences in NDVI between 2016 and 2017. Note that the overall trend was a decrease in greenness in 2017, but the area corresponding to the inundation zone in Reach 7 (Figure 3-6E) saw a slight increase in greenness.

Conclusions

The Minute 319 Pulse Flow produced a 17% increase in NDVI ("greenness") throughout the riparian corridor in 2014, compared to 2013. 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 supported existing vegetation.

From 2015-2017, vegetation greenness steadily declined, eventually falling to or below 2013 (pre-pulse) levels in most Reaches.

In Reaches 1, 2, 3, and 7, the pulse flow and subsequent base flows did not – at the scale of reaches, and at 30 m satellite image resolution – produce effects on vegetation greenness in the riparian zone that persisted to the end of the 2017 growing season. In Reaches 4 and 5, greenness was maintained at a higher level than the 2013 level through 2017. In Reach 4, greenness may have been sustained because of restoration activities, including base flow.

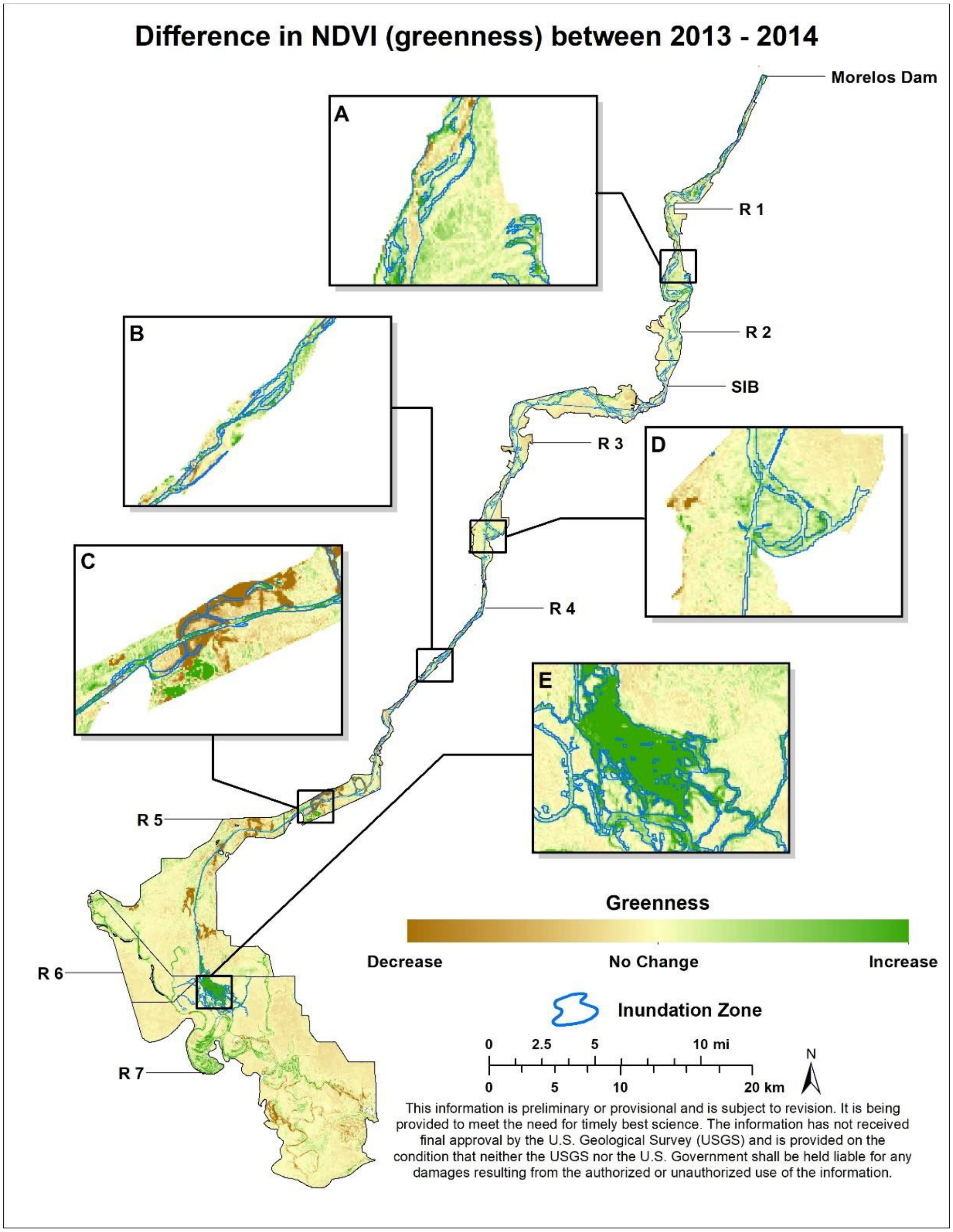


Figure 3-2. 2014 pulse flow inundation zone and the difference in NDVI from 2013 and 2014. Greener color indicates higher NDVI than in previous year; browner color indicates lower NDVI than in previous year. Image from Jarchow et al. (2017).

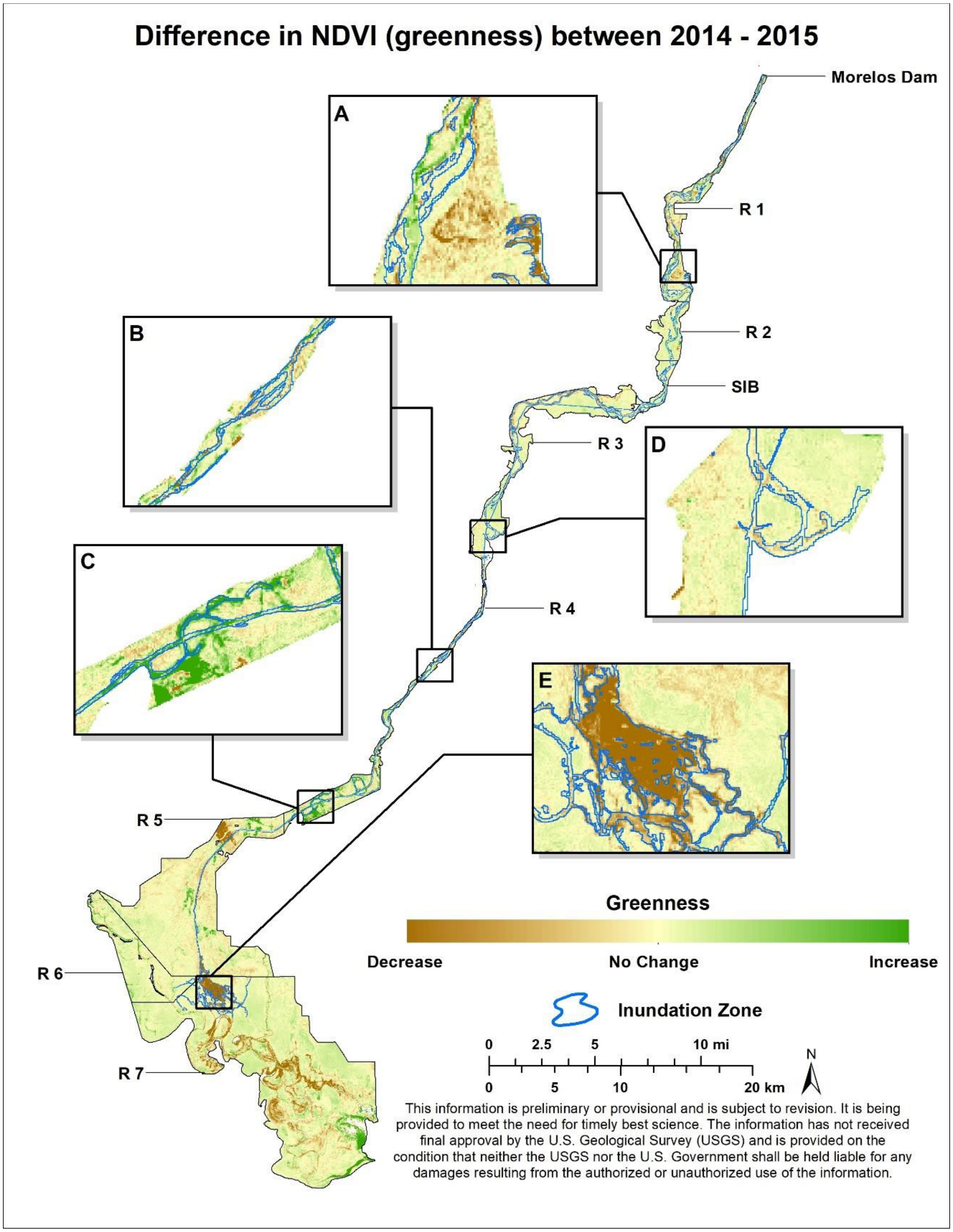


Figure 3-3. 2014 pulse flow inundation zone and the difference in NDVI from 2014 and 2015. Greener color indicates higher NDV than in previous year; browner color indicates lower NDVI than in previous year.

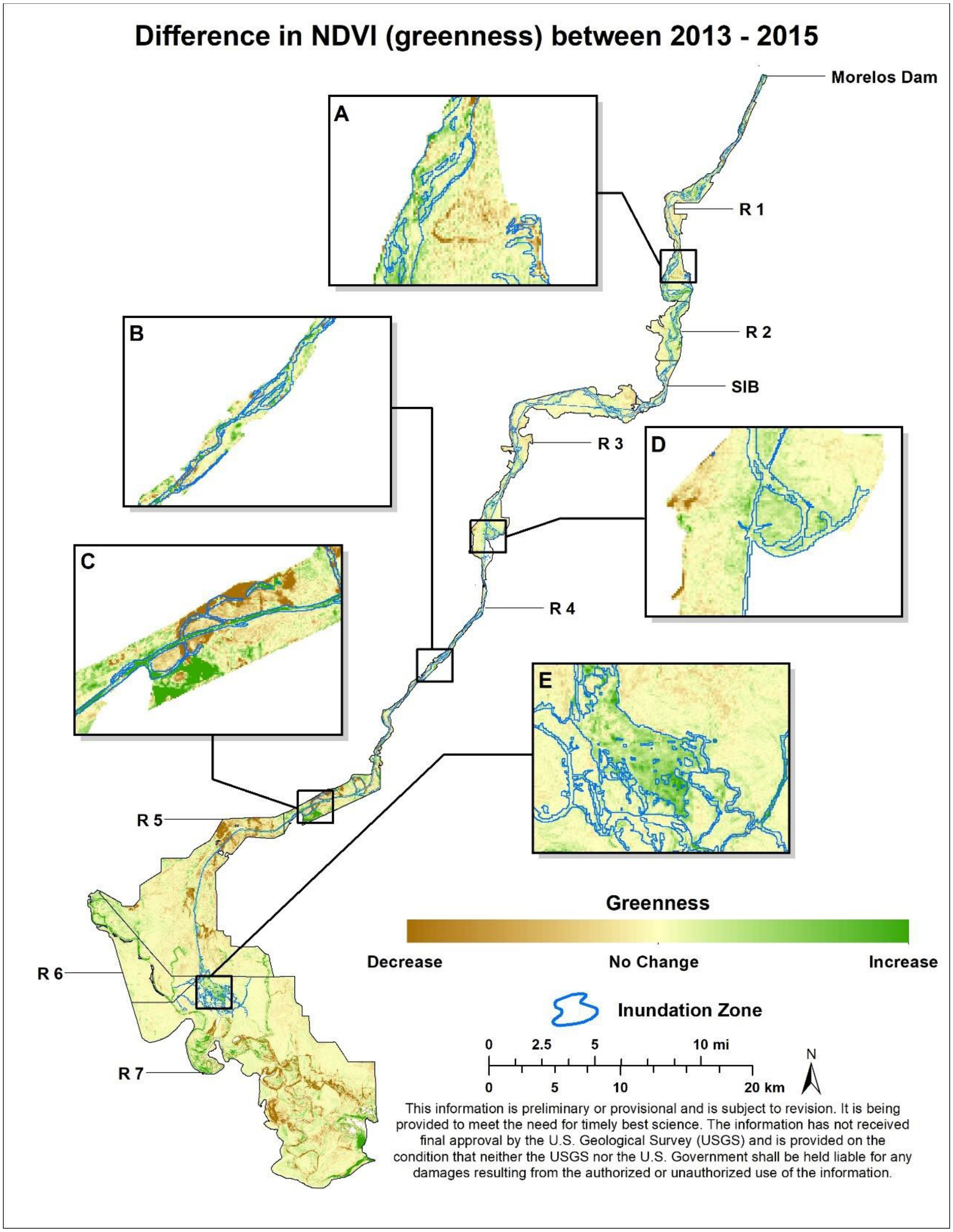


Figure 3-4. 2014 pulse flow inundation zone and the difference in NDVI from 2013 and 2015. Greener color indicates higher NDVI than in earlier year; browner color indicates lower NDVI than in earlier year.

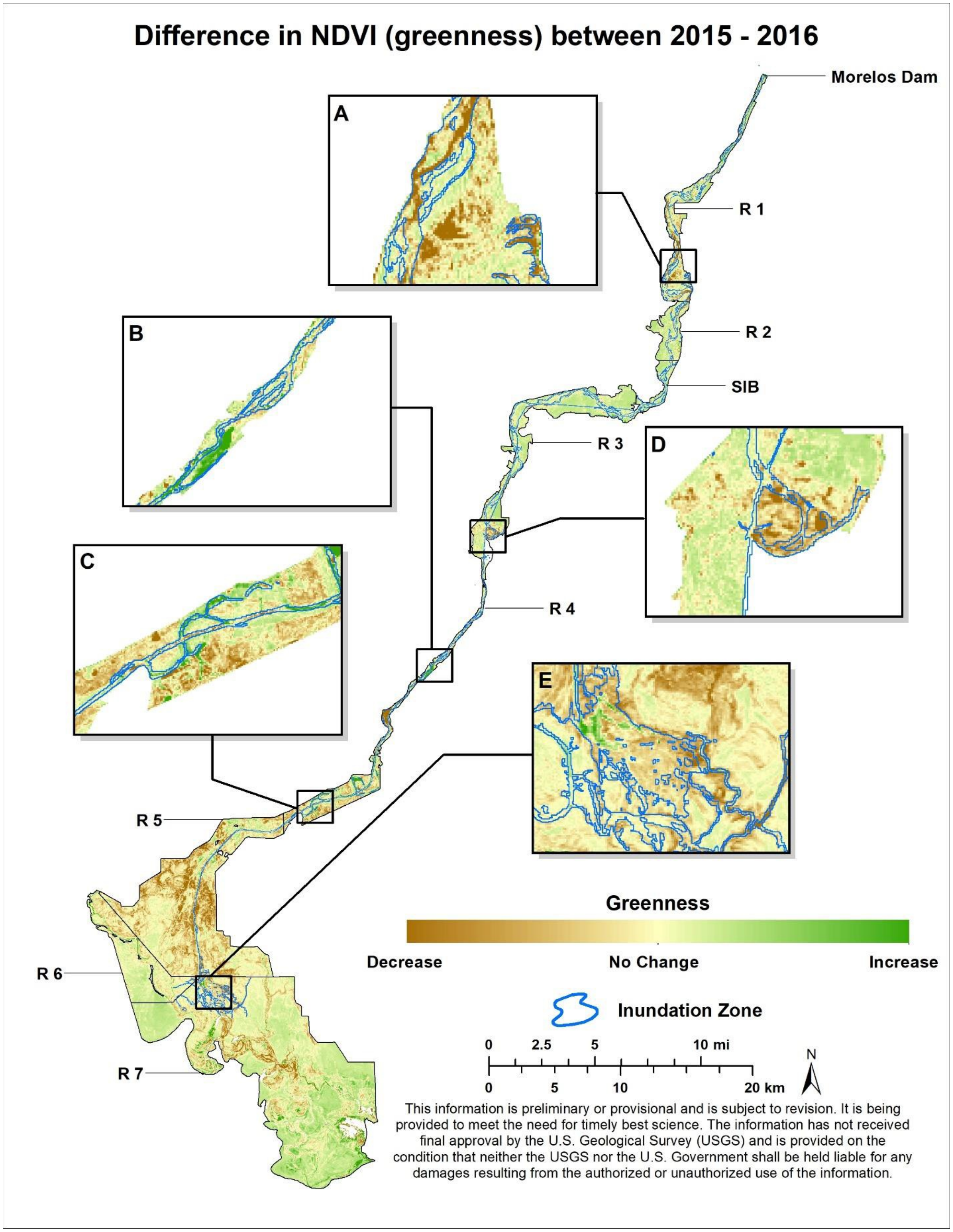


Figure 3-5. 2014 pulse flow inundation zone and the difference in NDVI from 2015 and 2016. Greener color indicates higher NDVI than in previous year; browner color indicates lower NDVI than in previous year.

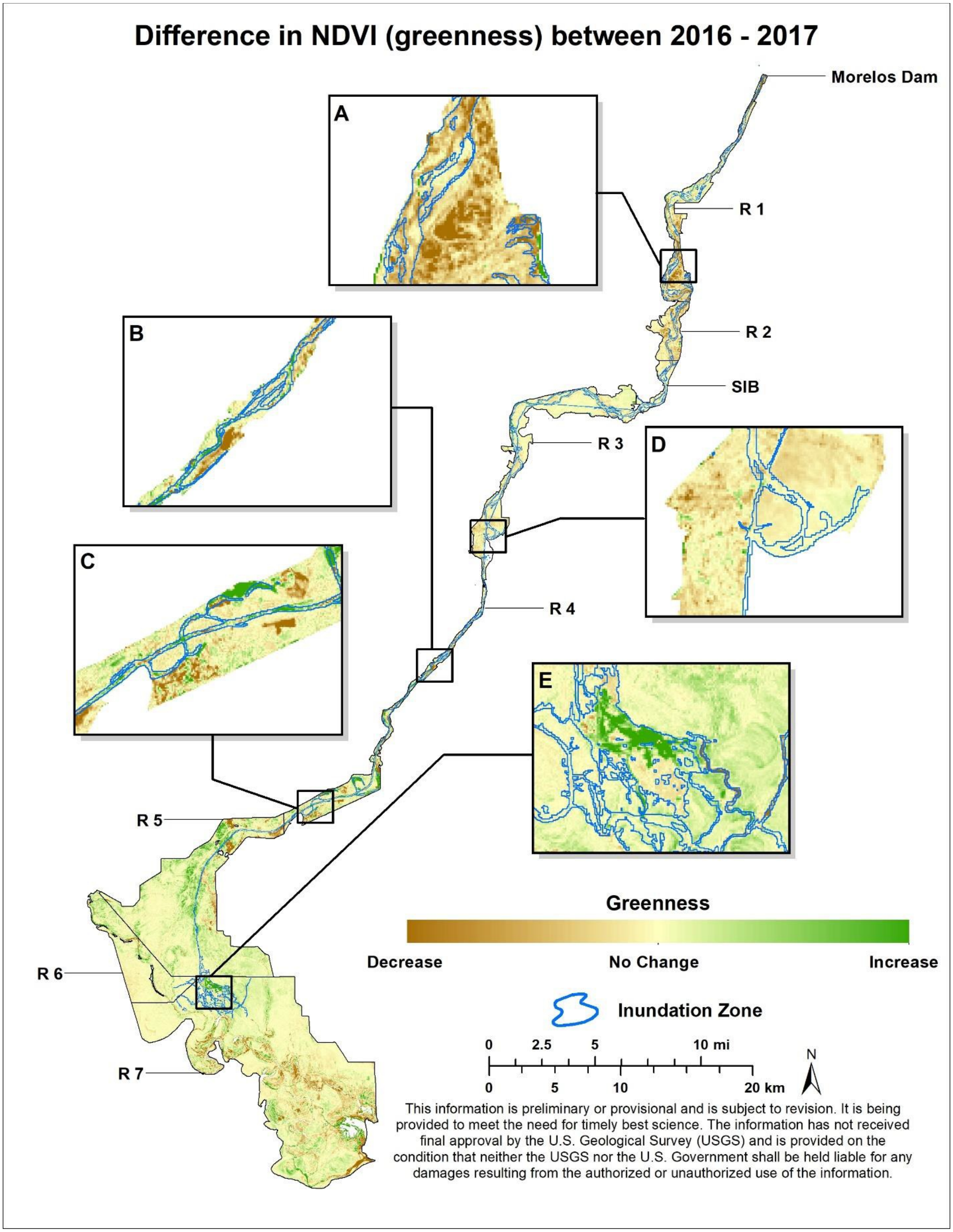


Figure 3-6. 2014 pulse flow inundation zone and the difference in NDVI from 2016 and 2017. Greener color indicates higher NDVI than in previous year; browner color indicates lower NDVI than in previous year.

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Section 4: Vegetation Response: Recruitment in the Riparian Corridor

Key findings

1. The most favorable areas for recruitment of native plant species were in Reaches 1 and 4, where stands of mature cottonwoods and willows provided a seed source and groundwater levels are shallow. Removal of exotic vegetation and land grading increased seedling survival.
2. Recruitment and persistence of seedlings were most successful in Reach 4 restoration sites (Laguna Grande; LG), where groundwater conditions are favorable, base flows were delivered, channels were reconnected and graded, and nonnative species were removed.
3. Patterns of vegetation cover are greatly affected by hydrological conditions present before Minute 319 flows. Vegetation cover is greatest in perennial reaches with a high water table. Vegetation cover was affected to a lesser degree by the pulse flow and base flow deliveries. At the local level, vegetation cover changed in response to depth to groundwater, availability of bare ground, and fires.
4. Mortality of seedlings established during the pulse flow resulted from competition, decreasing groundwater levels, fire, and herbivory.

Introduction

This section summarizes vegetation responses along the Colorado River riparian corridor from 2014-2017 following the Minute 319 pulse flow release in 2014. We present results on seedling establishment of trees and shrubs in riparian corridor transects inundated by the pulse flow and in transects where pulse and base flow deliveries were applied to prepared sites in the Laguna Grande restoration site. We also present data on changes in vegetation cover (including that of seedlings and mature vegetation) because changes in vegetation structure and composition are key to evaluating ecosystem responses to restoration treatments or changes in streamflow (Auble et al., 1994; Friedman et al., 1996; Stevens et al., 2001).

As Flessa et al. (2015) and Shafroth et al. (2017) report, the principal factors that affected the recruitment success of riparian woody plant species, principally cottonwood (*Populus fremontii*) and willow (*Salix gooddingii*), in this system were: 1) limited availability of bare, moist ground that provides conditions required for seed germination; 2) low or lack of seed availability; 3) insufficient soil moisture as a result of deep groundwater or lack of base flows, and 4) competition with other plant species. Survivorship of seedlings could also be affected by factors such as exposure to secondary flooding, soil texture and salinity, and herbivory (Mahoney and Rood, 1991; Shafroth et al., 1998; Schlatter et al., 2017). 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 likelihood of recruitment by providing missing requirements.

Methods

We surveyed vegetation in 21 transects (with no restoration activities) distributed along a 90 km (56 mile) stretch of the Colorado River riparian corridor and along 33 transects (with restoration activities) located in the Laguna Grande Restoration Area (LG) in Reach 4, including the Herradura (LG1), Cori (LG2), and CILA (LG3) restoration sites (see 2015 Interim Report for map of transects). The LG sites had the following restoration activities before the pulse flow: 1) removal of saltcedar (*Tamarix* spp.) and arrowweed (*Pluchea sericea*) from 129 hectares (ha) (319 acres); 2) excavation to reconnect former channel meanders with the Colorado River main stem and each other; and 3) land grading and leveling.

Vegetation surveys documented the response of four key riparian woody plant species/groups of interest: Baccharis (*Baccharis salicina, B. salicifolia*), cottonwood (*Populus fremontii*), willow (*Salix gooddingii*) and saltcedar (*Tamarix* spp.). We conducted surveys at the end of the growing season in October 2014, 2015, 2016 and 2017.

We analyzed the changes in vegetation cover (percent of transect with canopy cover) for all species along the riparian corridor transects. We used three metrics to document riparian tree and shrub seedling recruitment and sustained presence over time: 1) frequency of seedling presence: percentage of transects in each reach with seedlings present; 2) seedling occupancy: percent of transect length with seedlings present; and 3) seedling density: number of plants per square meter in plots where seedlings were found following the pulse flow release.

Results

Trends in Vegetation Cover

The variability of vegetation cover along the riparian corridor is associated with variability in surface and groundwater hydrology. Vegetation cover is greatest in Reach 1 and Reach 4, where surface flows are perennial, and the groundwater table is 0 to 3 m below the surface. Cover is lowest in the “dry reaches” (the lowermost portion of Reach 1 and Reaches 2 and 3), where flows are ephemeral and depth to groundwater is 3 to 15 m (Kennedy et al., 2017; Ramirez-Hernandez et al., 2013).

Table 4-1 shows that average vegetation cover across all riparian corridor transects increased from 34.0% in 2014 to 48% in 2015, likely as a result of pulse flow and base flow deliveries. On average, vegetation cover was 36% in 2016 and 36.3% in 2017. In areas where base flows were provided (transects from Reach 1, Reach 2 and Reach 4) in 2014 and 2015, vegetation cover continued to increase in 2015. In 2017, cover increased mostly in transects near the Laguna Grande restoration area (4-4, 4-5 and 4-6). Cover was greater than in areas that did not receive base flows. However, variation among transects is high and it is difficult to determine if the response is directly related to the Minute 319 flow deliveries, or if it reflects natural variation of the system (Fig. 4-1a). For instance, we did not detect increases in vegetation cover in transects 4-2 and 4-3 located at the Chausse restoration site and downstream respectively, even though that section of river received in-channel water deliveries in 2016 and 2017.

At the transect level, variations in groundwater levels, surface water flows, and fires caused changes in vegetation cover in some years. In Reach 1, transect 1-3 experienced a 73% drop in vegetation cover in 2016 compared to 2015 (Fig. 4-1b).

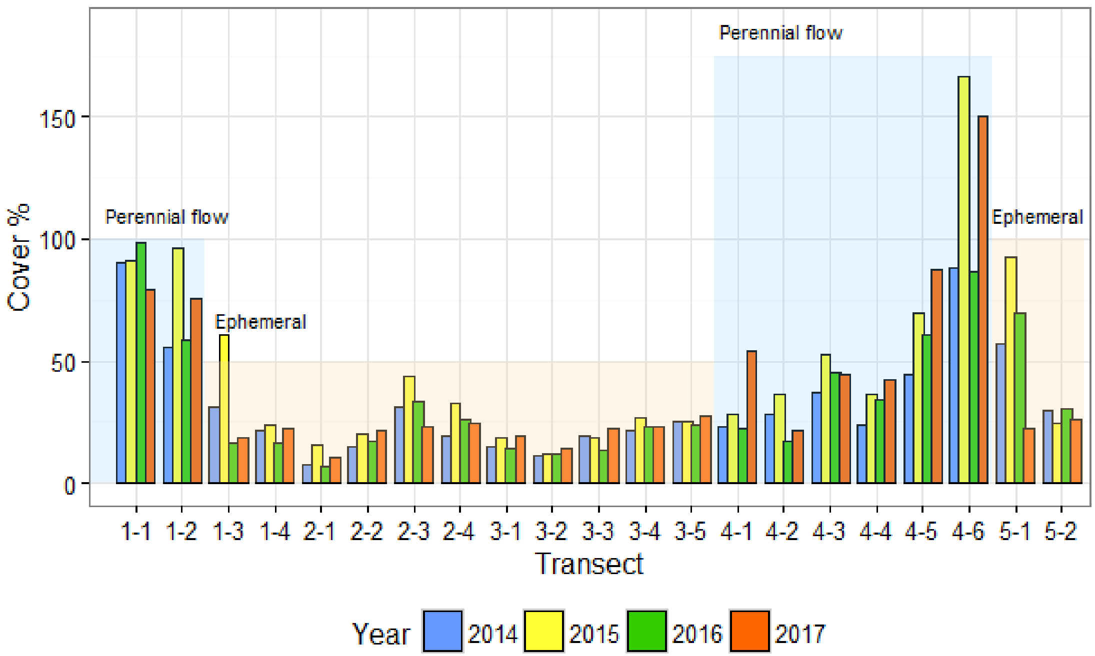
In Reaches 1 (transect 1-1) and 5 (transect 5-1), vegetation cover decreases of about 19% and 67% from 2016 to 2017, respectively, were associated with fires before and during the growing season.

Along transect 4-1, vegetation cover increased by more than 100% from 2016 to 2017. Based on field observations, the increase was caused by a decline in surface water levels that created exposed bare ground, which was subsequently colonized by giant cane (*Arundo donax*) and arrowweed (*Pluchea sericea*) (Fig. 4-1a).

Table 4-1. Percent vegetation cover in transects, reaches and riparian corridor, 2014-2017. Standard deviation shown in parenthesis.

Transect	**2014**	**2015**	**2016**	**2017**
1-1	90.5	91.3	98.2	79.4
1-2	55.3	96.4	58.3	75.3
1-3	31.5	61.0	16.6	18.8
1-4	21.3	24.0	16.4	22.5
Reach 1 average	49.7 (30.7)	68.2 (33.3)	47.4 (39.2)	49.0 (32.8)
2-1	7.2	15.9	6.5	10.3
2-2	14.6	19.8	16.8	21.8
2-3	31.0	43.8	33.7	23.1
2-4	19.5	32.4	26.4	24.7
Reach 2 average	18.0 (10.0)	28.0 (12.7)	20.9 (11.8)	20.0 (6.6)
3-1	14.6	18.6	14.3	19.6
3-2	10.9	11.7	12.0	14.2
3-3	19.5	18.7	13.4	22.4
3-4	21.7	26.7	23.1	23.0
3-5	25.2	25.2	24.0	27.8
Reach 3 average	18.4 (5.7)	20.2 (6.0)	17.4 (5.7)	21.4 (5.0)
4-1	22.9	28.3	22.1	53.8
4-2	28.6	36.2	17.2	21.7
4-3	37.1	52.7	45.6	44.2
4-4	23.8	36.7	34.3	42.7
4-5	44.7	69.5	60.9	87.1
4-6	88.1	166.2	86.3	150.0
Reach 4 average	40.9 (24.6)	64.9 (51.7)	44.4 (26.0)	66.6 (46.1)
5-1	56.9	92.7	69.7	22.4
5-2	29.8	24.6	30.5	26.2
Reach 5 average	43.4 (19.2)	58.7 (48.2)	50.1 (27.7)	24.3 (2.7)
Corridor average	34.0 (14.8)	48.0 (22.3)	36.0 (15.6)	36.3 (20.7)

a)



b)

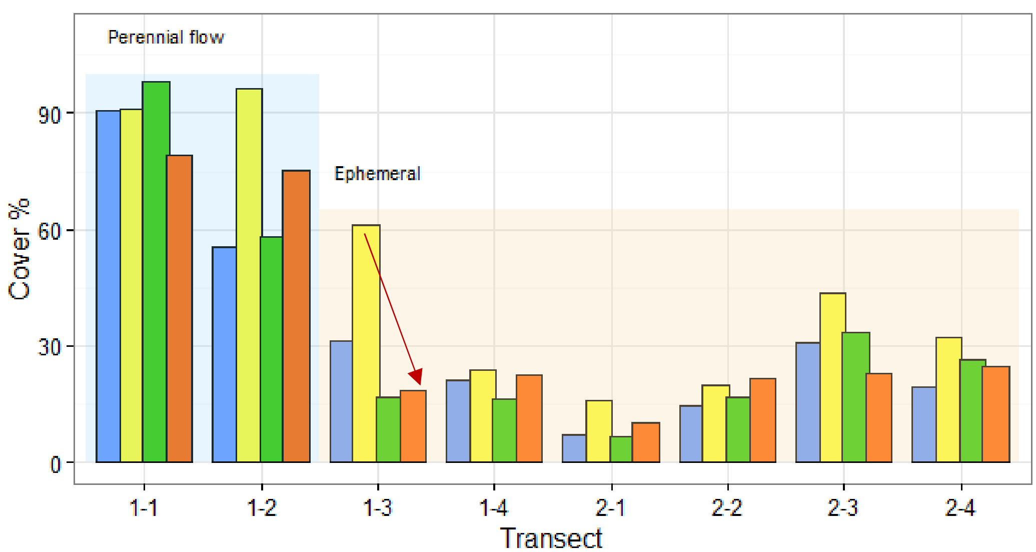


Figure 4-1. (a) Percent vegetation cover of all species along 21 monitoring transects, including woody and herbaceous species. Cover values can exceed 100% when different species have overlapping cover. The first number of transect codes indicates the reach. (b) Vegetation cover along Reach 1 and 2 transects, red arrow highlights a decrease of percent cover in Transect 1-3 from 2015 to 2016.

Seedling Recruitment and Persistence

1. *Baccharis*

Baccharis germinated and established in Reach 1, Reach 4, LG2 and LG3 after the pulse flow in 2014 (Fig. 4-2a). The frequency of seedling presence was initially low in 2014 (1-25% of transects), increased in LG2 and LG3 sites from 2014-2017, and fluctuated in Reach 1, Reach 4 and LG1 from 2014-2017. Baccharis transect occupancy (Fig. 4-2b) was low with less than 1% cover in Reaches 1 and 4. Baccharis density (Fig. 4-3) declined from 1 individual (ind/m^2) to 0.2 ind/m^2 in Reach 1 and 1 ind/m^2 to 0 ind/m^2 in Reach 4. In LG sites, baccharis maintained densities in the range of 0.02 to 0.25 ind/m^2 (200 to 2,500 ind/ha; 81 to 1,012 ind/acre), a density similar to that of cottonwood and willow seedlings.

Recruitment of baccharis (*Baccharis salicina* in most cases) in years subsequent to the pulse flow in Reaches 4 and 5 is likely associated with base flows delivered to the Laguna Grande restoration sites, presence of surface water, and favorable groundwater conditions in these reaches. Following the 2014 pulse flow release, baccharis establishment occurred in areas with groundwater depth <2.3 m in the Colorado River Delta riparian corridor (Shafroth et al., 2017). During 2014, depth to groundwater in Reach 4 was less than 2.5m in piezometers located near the transects (Kennedy et al., 2017; Ramírez-Hernández et al., 2017; Shafroth et al., 2017), suggesting that groundwater requirements for establishment and survival were met in both Reaches 4 and 5.

2. *Cottonwoods and willows*

Cottonwoods and willows germinated and established with low frequencies in Reach 1 in response to the 2014 pulse flow (1-25%, Fig. 4-2a). The percent occupancy of cottonwood seedlings along transects in Reach 1 was less than 1% in 2014 and decreased to zero by 2017 (Fig. 4-2b). The percent occupancy of willow seedlings along transects in Reach 1 was less than 1% in 2014 and decreased to zero by 2016 (Fig. 4-2b). Mortality of cottonwood and willow seedlings in 2015-2017 was partly due to competition with non-native grass, giant reed (*Arundo donax*), and cocklebur (*Xanthium strumarium*)—an annual herbaceous species that grew more rapidly and densely than native trees (Shafroth et al., 2017). Herbivory, likely by beavers, reduced the height of native tree seedlings by about 50% to 80% in 2016, which likely also increased the likelihood of mortality (See Fig. 4-4). Groundwater conditions were favorable in Reach 1 considering that establishment of native trees occurred in an area adjacent to perennial streamflow.

The lack of cottonwood and willow recruitment in Reach 4 (outside of Laguna Grande), where groundwater conditions are similarly favorable as in Reach 1, could be related to the absence of inundated bare ground and lack of sufficient seed source (Shafroth et al., 2017; Schlatter et al., 2017). We detected germination of willow (data not shown) at the end of the 2017 growing season in Reach 5 that was probably the result of water releases from Reach 4 before the 2017 survey.

In the three Laguna Grande (LG) sites, seedlings of cottonwood and willow established after the pulse flow (Fig 4-2a). From 2015-2017, cottonwood seedlings persisted in LG2 with frequency of 1-25% of transects, but did not survive in LG1 and LG3. Willow recruitment in 2014 was more successful in the LG sites, with presence along 76-100% of transects in LG3 and 25-50% in LG2. From 2015-2017, willow seedling mortality occurred, but additional recruitment did as well, as is evident from the decreasing and increasing frequencies from year to year. The average density of seedlings of native tree in LG sites (Fig. 4-3) in 2014 ranged from 0.03 ind/m^2 to 0.29 ind/m^2. In 2015 the density decreased slightly (0.02 to 0.19 ind/m^2) and fluctuated in subsequent years indicating new seedling cohorts. These results suggest that active restoration treatments before the pulse flow along with base flow deliveries from 2014 to 2017 can result in increased recruitment and survival of native tree seedlings as compared to areas with no restoration actions and no base flows (Schlatter et al., 2017).

3. Saltcedar

Saltcedar germinated and established in all reaches and LG sites (Fig 4-2a). Frequency of seedling presence declined in Reaches 1-3 and showed increases in some years in Reaches 4-5 (Fig. 4-2a). The frequency of seedling presence in 2017 ranged from 0 to 26-50% along riparian corridor transects. In contrast, saltcedar was present along the majority of transects in LG sites (76-100% frequency) (Fig. 4-2a). Based on observations in the field, there was high saltcedar mortality in the LG sites as well, but moist, bare ground conditions led to new saltcedar establishment from year to year.

Saltcedar seedling occupancy along transects generally declined in Reaches 1 and 2 from 2015-2017, and by 2017 was 0-5% in all reaches (Fig. 4-2b). In Reaches 1 and 2, seedlings that established in 2014 became difficult to distinguish from previously-established saltcedar; this, in addition to mortality, led to decreased occupancy. Saltcedar density declined in all five reaches from 2014 with densities of < 0.1 ind/m^2 by 2017 (Fig. 4 -3). In LG sites, saltcedar showed the highest densities (1.1 to 7 ind/m^2) during the four-year period, but generally declined from an average density of 4.7 ind/m^2 in 2014 to 1.4ind/m^2 in 2017 (Fig. 4-3).

The establishment of new saltcedar that occurred in Reach 4 could be associated with the favorable soil moisture and groundwater conditions, as in the case of baccharis, and to declines in the surface water level that occurred in the upper portion of this reach thus exposing bare ground for new seedlings. Cottonwood and willow establishment was limited in this section of the river by seed availability (Shafroth et al., 2017). Seedlings of saltcedar in Reach 5 were killed by a fire that occurred in 2017 in transect 5-1, whereas new seedlings were observed in transect 5-2, likely as a result of upstream base flow releases at the end of the growing season.

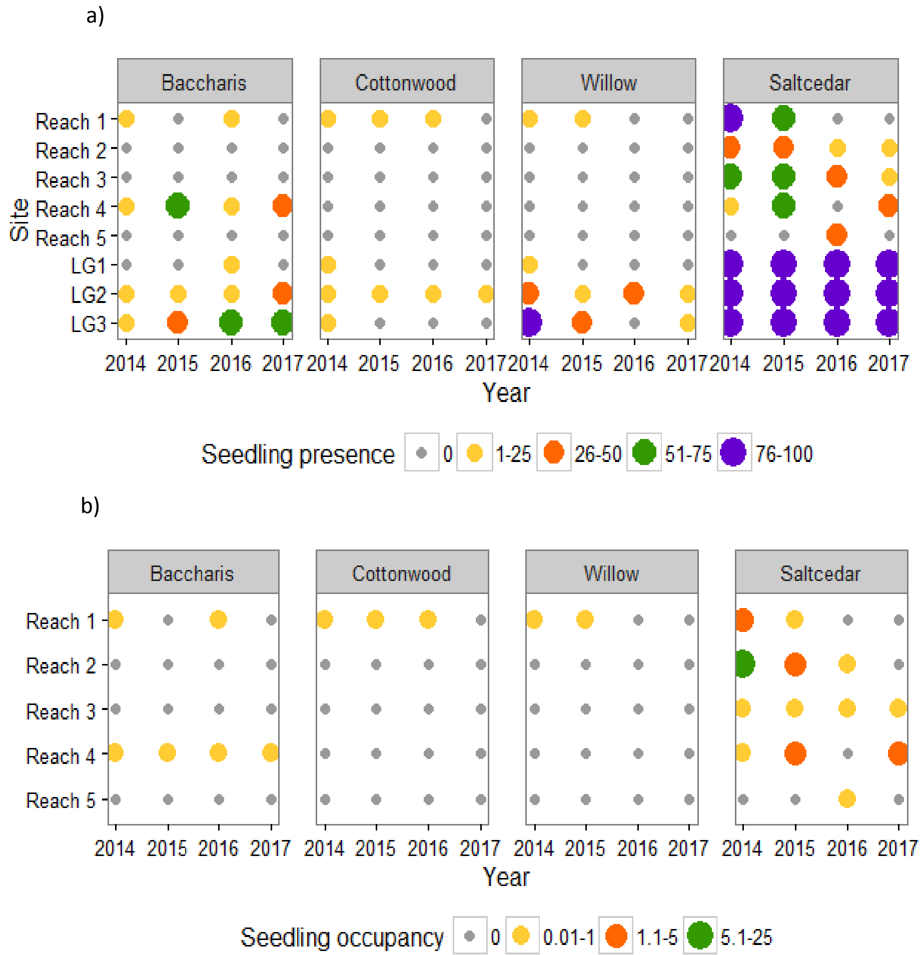


Figure 4-2. (a) Frequency of seedling presence by reach (1-5) and by restoration site area (LG1-LG3) and (b) seedling occupancy along riparian corridor transects by reach.

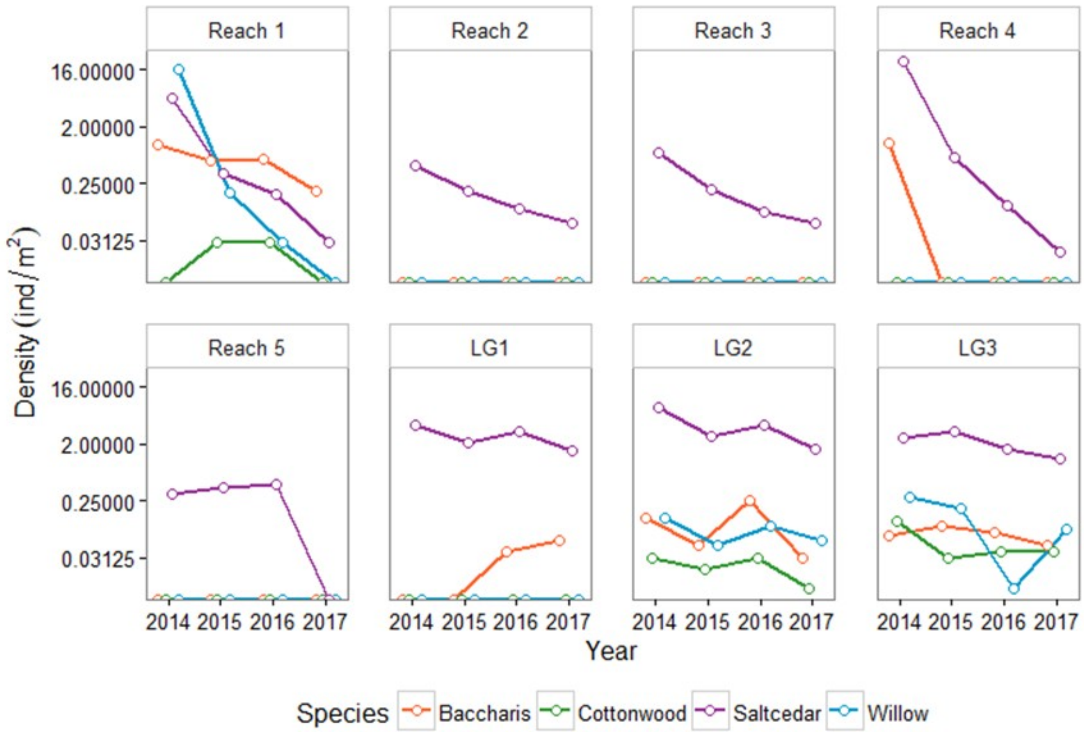


Figure 4-3. Seedling density (individuals/m^2) by reach and Laguna Grande site (LG). Note the y axis is a logarithmic scale. Data were collected in October or November in each year.

Figure 4-4. Cottonwood (left) and willow (right) seedlings in 2016 found in Reach 1, showing signs of herbivory. Diameter of cottonwood stump is approximately 3.2 cm; willow stump is approximately 2.3 cm diameter.

Summary

The most favorable areas for recruitment of native species were in Reaches 1 and 4 where stands of mature cottonwoods and willows provided a seed source and groundwater levels are shallow.

Persistence and new recruitment of native seedlings in 2015-2017 was limited to Laguna Grande (LG) sites where groundwater conditions are favorable, base flows were delivered, and land grading and creation of bare ground improved recruitment conditions and subsequent persistence.

Trends in vegetation cover are greatly affected by hydrological conditions present before Minute 319 flows (high water table in perennial reaches vs. low in the ephemeral) and likely to a lesser degree by the pulse flow and base flow deliveries. At the transect level, vegetation cover can change in response to depth to groundwater, availability of bare ground, and fires.

Seedling mortality was a consequence of competition, rate of decrease of groundwater levels, fire, and herbivory.

Groundwater levels in Reaches 1, 2 and 3 should be monitored in order to detect changes that could affect vegetation and to prepare management strategies such as types of vegetation planted at restoration sites and water delivery regimes.

Future research on the response of mature stands of native trees to current and past river flows would improve our understanding potential benefits to existing vegetation that can be achieved by environmental flow deliveries.

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Section 5: Vegetation Response: Active Riparian Restoration Sites

Key findings

1. Three active restoration sites were established or expanded as a result of Minute 319 funding contributions and private funding, with water supplied from the pulse and base flows:
    a. Miguel Aleman (Reach 2; 100 hectares (247 acres); Pronatura Noroeste
    b. Chausse (Reach 4; 63 ha (155 acres); Restauremos el Colorado
    c. Laguna Grande (Reach 4; 207 ha (512 acres); Sonoran Institute
2. Restored habitat types included open water/marsh (25 ha/62 acres), cottonwood-willow (161 ha/398 acres, mesquite bosque (162 ha/401 acres, and upland 22 ha/54 acres).
3. Recruitment and persistence of seedlings was most successful in Reach 4 restoration sites (Laguna Grande), where groundwater conditions are favorable, base flows were delivered, channels were reconnected and graded, and nonnative species were removed.
4. Irrigation techniques included flood irrigation in plots or furrows, flooding through use of water control structures, drip irrigation, sprinkler systems, and direct delivery to river meanders.
5. More than 275,000 trees were planted, and year-to-year survival rates ranged from 75% to 95%.
6. Active restoration with flood or drip irrigation from base flow deliveries via irrigation canals is an effective use of water to create or maintain riparian habitat.
7. Hydro-seeding native tree, shrub, and herbaceous species' seed was a successful re-vegetation method for creating species-diverse and genetically-diverse native habitat.

Summary

From 2013-2018, a total of 370 ha (914 acres) of riparian habitat was actively restored by Sonoran Institute, Pronatura Noroeste, and Restauremos el Colorado using Minute 319 funding contributions and private funding. From 2010-2012, Sonoran Institute actively restored 17 ha (41 acres) of cottonwood-willow habitat in the CILA restoration site. The total of all actively restored riparian habitat in the Delta is 387 ha (957 acres).

Active restoration includes the following activities: removal of non-native vegetation, land grading to either improve irrigation efficiency or maximize slope of meanders for native habitat, channel excavation to reconnect meanders to the mainstem, installation of irrigation infrastructure, planting of native vegetation, irrigation, and maintenance/weeding. The Sonoran Institute, Pronatura Noroeste, and Restauremos el Colorado restored marsh, cottonwood-willow, mesquite bosque, and upland habitat at three different restoration sites: Miguel Aleman, Chausse, and Laguna Grande.

Table 5-1. Area of riparian habitat actively restored by habitat type and restoration site.

	Pre-Minute 319		During Minute 319						Total	
Habitat Type	Laguna Grande		Laguna Grande		Miguel Aleman		Chausse			
	Ha	Acres	Ha	Acres	Ha	Acres	Ha	Acres	Ha	Acres
Open water/marsh	-	-	15	37	-	-	10	25	25	62
Cottonwood Willow	17	41	121	299	15	36	26	64	178	439
Mesquite Bosque		-	72	176	64	158	27	66	162	401
Upland	-	-	-	-	22	54	-	-	22	54
TOTAL	**17**	**41**	**207**	**512**	**101**	**248**	**63**	**155**	**387**	**957**

An additional 59 ha (145 acres) of riparian habitat were “passively” restored in the Laguna Grande restoration site along the river channel and in meanders through environmental flow deliveries for an estimated total of 446 ha (1,102 acres) of restored habitat. “Passive” restoration is delivery of environmental flows to enhance existing habitat and/or create new habitat, without clearing, grading, planting or subsequent irrigation and maintenance.

Base flow deliveries were primarily targeted to the three restoration sites for habitat creation and maintenance.

See Schlatter et al. (2017) (Appendix A) for a description of how restoration site management actions improve native riparian species establishment with environmental flow deliveries, and Shafroth et al. (2017) (Appendix A) for a review of the vegetation response to the pulse flow along the Colorado River riparian corridor in Mexico. Other descriptions of the vegetation response to the pulse flow are in Flessa et al. (2014, 2016).

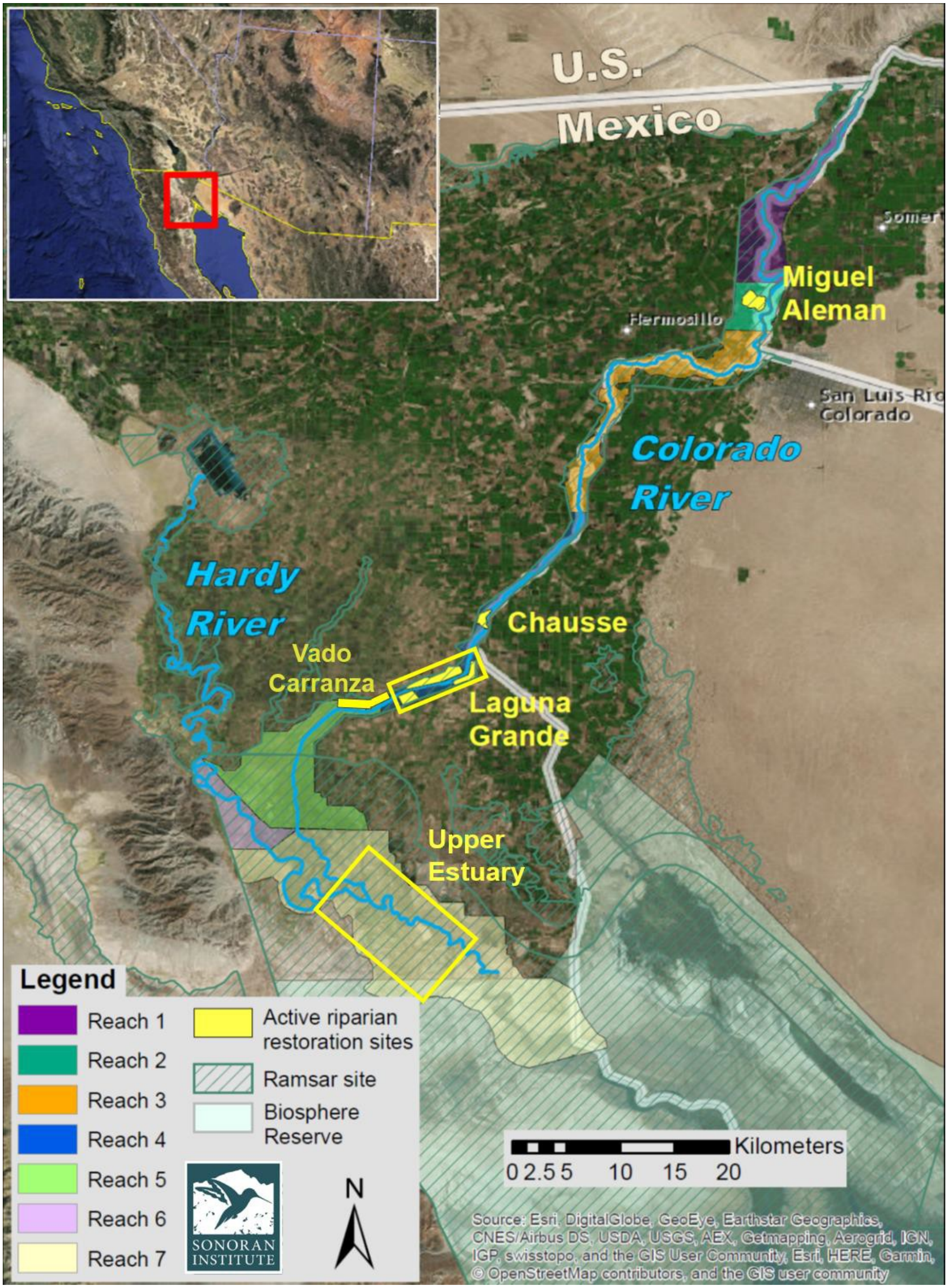

Figure 5-1. Active restoration sites along the Colorado River riparian corridor in Mexico.

Miguel Aleman

The total Miguel Aleman land concession area is 200 hectares (494 acres), which was granted to Pronatura Noroeste from the Mexican federal government in 2010. A total of 100.5 hectares (ha) (248 acres) of habitat was restored in four phases (time intervals) (Figure 5-2) with funding from Minute 319 and private sources. Water for the site is delivered from Canal Reforma, under water rights that are within Irrigation Module 7. Of the 100.5 ha (248 acres), 14% vegetative cover is cottonwood-willow habitat, 64% cover is mesquite terrace, and 22% is upland habitat (Table 5-2).

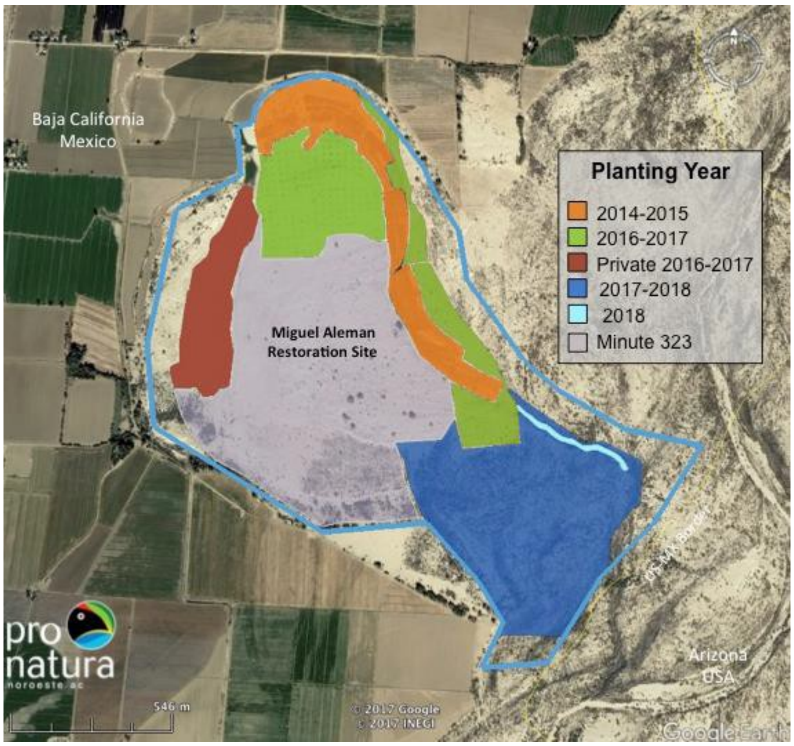

Figure 5-2. The Miguel Aleman restoration site located in Reach 2.

Table 5-2. Total hectares, acres, and percent cover by habitat type at the Miguel Aleman restoration site.

Habitat Type	Ha	Acres	% Cover
Open water/marsh	0	0	0
Cottonwood Willow	15	36	14
Mesquite Terrace	64	158	64
Upland	22	54	22
Total	**100.5**	**248**	**100**

A total of 73,055 native trees was planted at Miguel Aleman over the four phases, with an average tree density of 727 trees per ha (296 trees/acre) (Table 5-3). The survival of trees has been increasing over the years as water management, maintenance, and restoration designs and methods have improved. Trees planted in Phase I had a survival rate of 74%. For the most recent tree plantings, year-to-year survival has been more than 96% (Figure 5-3). The average survival rate during the four years was 90.6%.

Table 5-3. Tree density by habitat type and total trees planted at the four different phases of the Miguel Aleman restoration site.

Phase	Number of Trees	Tree Density by Habitat Type (# of trees/hectare)		
		Riparian	Mesquite	Upland
1	22,805	1,800	650	250
2	7,800	NA	650	NA
3	15,700	1,800	700	NA
4	26,750	1,500	650	NA
	Total: 73,055	**Avg: 1,700**	**Avg: 662.5**	**Avg: 250**

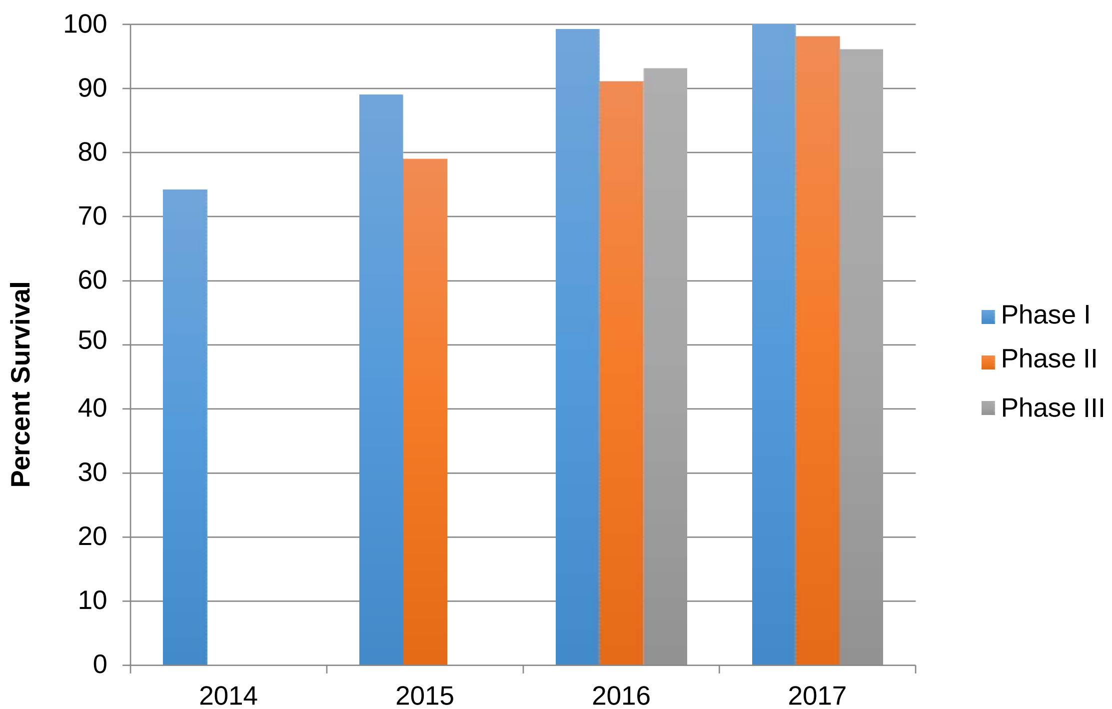

Figure 5-3. Tree survival at the different phases in the Miguel Aleman restoration site from 2014 to 2017. Height of bar indicates percent survival from initial planting or from the previous year.

Planted trees were irrigated using flooded furrows, drip irrigation, and sprinkler systems. The Miguel Aleman restoration site uses an average of 0.99 mcm (800 acre-feet) per year. For the 2016-2017 water cycle, a total of 1.04 mcm (843 acre-feet) were delivered, with highest deliveries between June and September. For the 2017-2018 water cycle, 1.23 mcm (988 acre-feet) of water is planned for delivery, as the project area has expanded with the completion of planting in Phase IV.

Chausse

The Chausse site is a remnant oxbow of the river located in Reach 4, upstream of the Laguna Grande site. The site was cleared of non-native vegetation, graded/excavated, water control structures were installed, and trees were planted. Lower elevation cottonwood-willow and mesquite areas are irrigated through a flood, hold, and release water program. Chausse is part of the network of restoration sites along the riparian corridor benefitting from environmental water and funding from Minute 319. Restoration at the Chausse site was initiated in 2017; therefore, ecological monitoring data were not evaluated for this report.

In the 2016-2017 water cycle, approximately 3.07 mcm (2,485 acre-feet) were scheduled for delivery. In the 2017-2018 water cycle, approximately 3.3 mcm (2,704 acre-feet) are scheduled for delivery. Site managers report that approximately 84% of the water used for flood irrigation is released into the main channel.

In 2017-2018 Restauremos el Colorado will complete restoration of 63 ha (155 acres) at the Chausse restoration site in two phases (Figure 5-4, Table 5-4) with support from Minute 319 and private funding and using water from Minute 319 base flow deliveries.

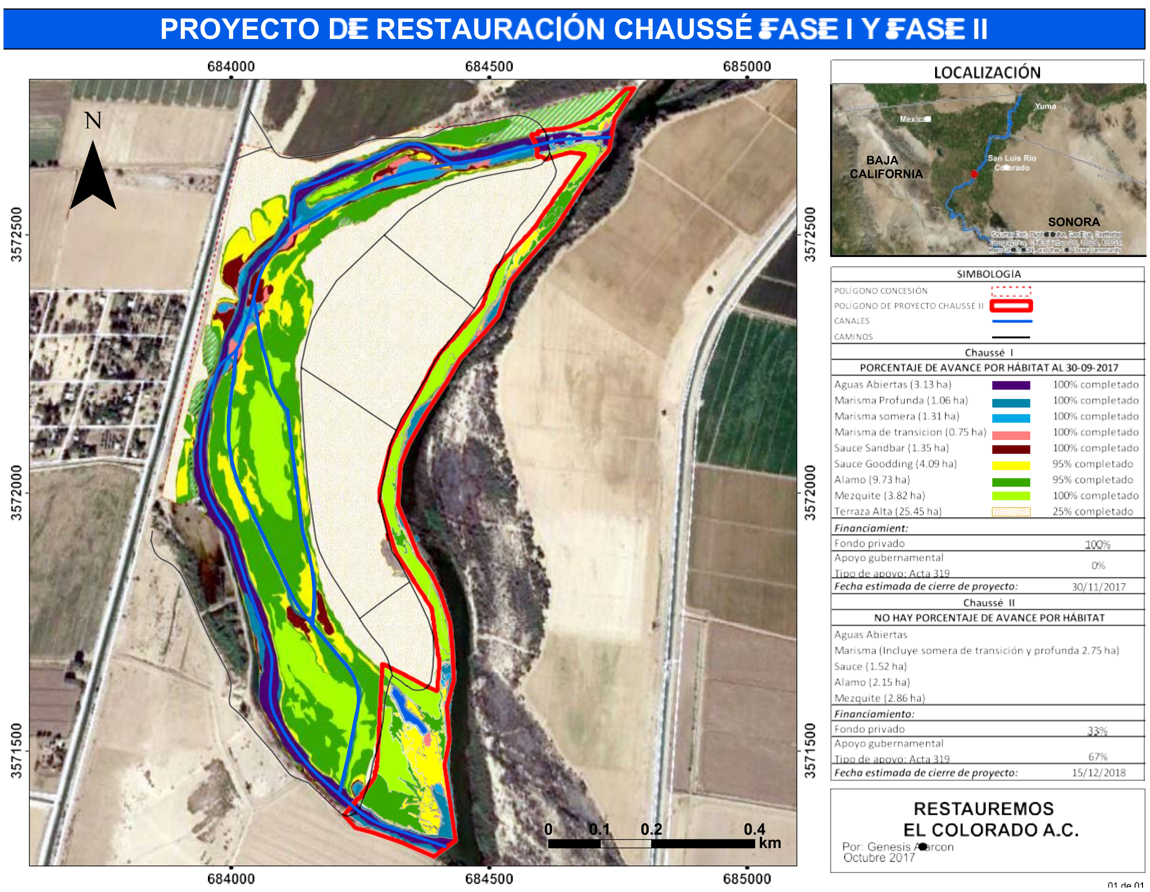

Figure 5-4. Restoration design for the Chausse phase I and II areas.

Table 5-4. Area by habitat type to be restored at the Chausse restoration site by the end of 2018.

Habitat Types	Restored by Dec. 2017		Planned in 2018		Total	
	Ha	Acres	Ha	Acres	Ha	Acres
Open water/marsh	7	17	3.2	8	10	25
Cottonwood Willow	20	51	5.3	13	26	64
Mesquite Bosque	25	63	1.2	3	27	66
Total	**53**	**131**	**9.8**	**24**	**63**	**155**

Laguna Grande

From 2013-2018, Sonoran Institute will have restored a total of 207 ha (512 acres) of riparian habitat at the Laguna Grande Restoration Site in Reach 4 (Table 5-5). Funding was provided by Minute 319 and private sources and water was supplied by the pulse flow and subsequent base flows. Restoration was implemented at three land concession areas within Laguna Grande: CILA, Cori, and Laguna Larga (Figure 5-5). Species planted from 2013-2018 included cottonwood, willow, coyote willow, and screwbean and honey mesquite trees. Additional areas were hydro-seeded and planted with diverse native herbaceous and grass species. Hydro-seeding native tree, shrub, and herbaceous species' seed was a successful re-vegetation method for creating species-diverse and genetically-diverse native habitat, particularly when applied in irrigated plots.

Table 5-5. Area by habitat type to be restored at the Laguna Grande restoration site from 2013-2018.

Habitat Types	Restored by Dec. 2017		Planned in 2018		Total	
	Ha	Acres	Ha	Acres	Ha	Acres
Open water/marsh	10	25	5	12	15	37
Cottonwood Willow	94	232	27	65	121	298
Mesquite Bosque	24	59	48	117	67	164
Total	**128**	**316**	**79**	**195**	**207**	**512**

By the end of 2018, an estimated 201,950 trees will have been planted at Laguna Grande, with an average planting density of 976 trees/ha (394 trees/acre). From 2013-2017, the average tree survival rate was 91.5%. Planted and hydro-seeded sites were irrigated using flood irrigation in furrows or plots, water deliveries to meanders (indirect irrigation), or drip irrigation. Sites were weeded 2-3 times per year. In the 2016-2017 water cycle, 4.04 mcm (3,278 acre-feet) were scheduled for delivery. In the 2017-2018 water cycle, 4.7 mcm (3,810 acre-feet) are scheduled for delivery to restoration sites in Laguna Grande.

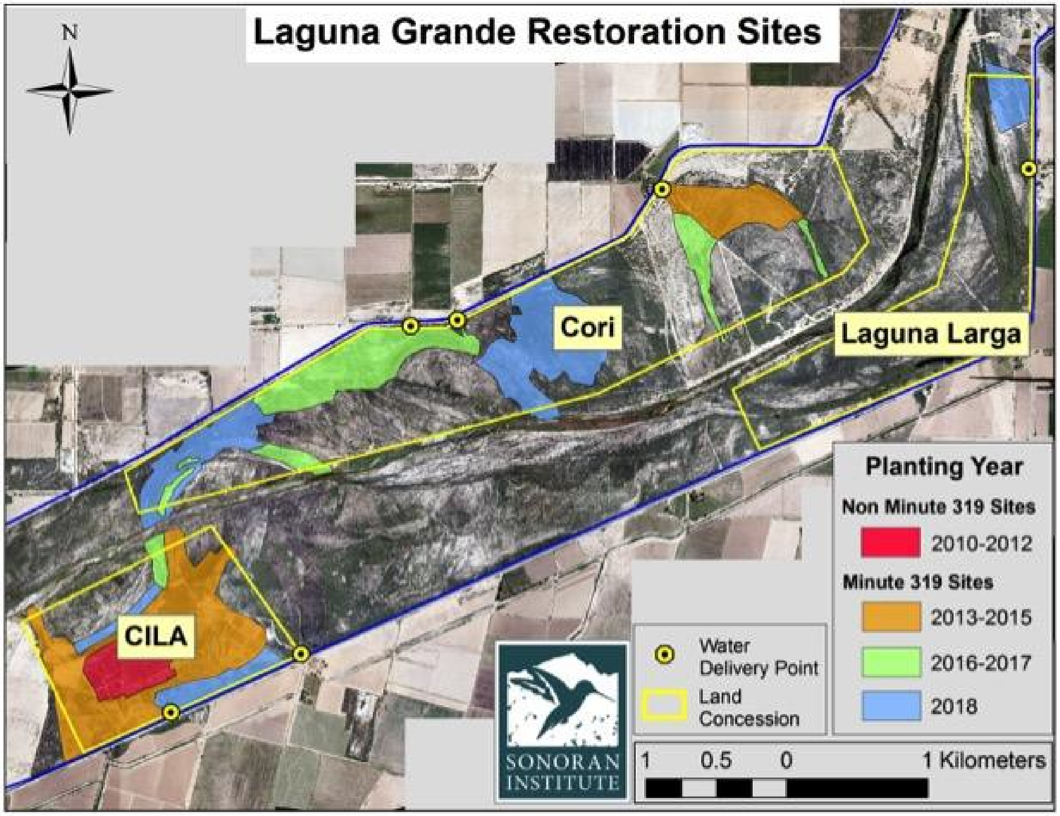

Figure 5-5. Restored areas at the Laguna Grande restoration site.

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Section 6: Integrated Data and Modeling of Hydrologic and Ecological Responses to Future Conditions

Key findings

1. Coordinated monitoring and analysis of future flow deliveries and their responses can provide the information needed to refine water delivery strategies and to determine the most efficient uses of the limited water available for the environment, including long-term maintenance needs.
2. Preliminary interdisciplinary models, based on the limited data obtained during Minute 319, demonstrate the predictive power of integrating diverse data and models to understand system dynamics and evaluate management strategies.

Prior to Minute 319, little was known about how water moves through the riparian corridor and how vegetation and wildlife would respond. Early attempts at understanding this system were based on historic observations and on greenhouse experiments and did lead to some valuable predictions (e.g., Ramírez-Hernández et al., 2013; Zamora-Arroyo et al., 2001; Vandersande et al., 2001; Rodríguez-Burgueño, 2012). Nevertheless, few quantitative tools were available to support the pulse flow design (Pitt and Kendy, 2017). During Minute 319 (2012-2017), scientists from multiple disciplines collected data under the new conditions. By integrating those data, the intersecting dynamics of environmental water delivery and habitat restoration in the Delta are better understood. This enables new, predictive tools to be built to support future restoration efforts. Preliminary models demonstrate the potential for such tools.

Integration of Data and Models (IDM) in the Limitrophe

Prior to the 2014 pulse flow, the science team used an existing HEC-RAS hydraulic model to predict the extent to which the flow would inundate land surfaces. The model's imprecision reflected the lack of data available to parameterize it. After the pulse flow, Salcedo-Peredia (2016) refined the model, using newly acquired LiDAR and hydrologic data. This recalibrated model is the foundation of the Integrated Data and Models (IDM), a new tool that predicts not only the extent of inundation, but also the rate of infiltration, extent of open water areas, and recruitment of native plants resulting from different environmental water delivery hydrographs. The U.S. Department of the Interior, Bureau of Reclamation (through its Desert Landscape Conservation Collaborative) and diverse Minute 319 stakeholders and scientists helped shape the tool, based on their interests and findings from the 2014 pulse flow (Hydros Consulting and Sonoran Institute, 2017).

The Integrated Data and Models (IDM) tool is modular, so it can link different existing and future models to simulate hydrologic processes and ecological responses along the entire riparian corridor. Hydrologic processes are simulated by a transient HEC-RAS model of the Limitrophe, and a diffusion-wave (DFW) model of the dry reach (Rodríguez Burgueño, 2017). Ecological processes are simulated using multi-criteria evaluation in a GIS platform (Hydros Consulting and Sonoran Institute, 2017).

Preliminary model runs (using infiltration curves from temperature modeling) informed binational negotiations for Minute 323. The Environmental Work Group asked the team to use the IDM to predict areas of new habitat and volumes of aquifer recharge that would result from two flow delivery scenarios from Morelos Dam – 10 m^3/s for 8 days and 30 m^3/s for 10 days (Hydros Consulting and Sonoran Institute, 2017).

Subsequently, the team also modeled responses to 20- and 30-m^3/s peak flow releases from Morelos Dam, with different rise and fall rates. The exercise revealed that in the upper Limitrophe, where the channel is steep and narrow, rapid flow recession rates limit cottonwood and seedling recruitment because Morelos Dam is not able to reduce flows in increments of less than 5 m^3/s. In the lower Limitrophe, where the water table is depressed, depth to groundwater is the limiting factor. In both the upper and lower Limitrophe, a lack of bare ground limits seedling establishment (Hydros Consulting and Sonoran Institute, 2017).

The IDM was calibrated to the pulse flow, which peaked at 120 m^3/s. Therefore, its predicted responses to 20- and 30-m^3/s peak flow releases are only approximations. Recalibration to hydrologic data collected during smaller flow releases in the future will yield more reliable results.

Impacts to Riparian Habitat from Changes in Climate and Agricultural Water Practices in Reach 4

A shallow water table is essential to the survival of riparian vegetation in the Limitrophe and Delta. Currently, subsurface inflows from upstream in the basin, along with local irrigation return flows, maintain a water table shallow enough to support restored habitat in Reach 4. In the future, however, climate change and water transactions could drive a shift toward more efficient irrigation, adoption of lower water use crops, and fallowing, which would reduce return flows and therefore lower the water table (Schlatter *et al*., 2017b).

An interdisciplinary team examined the extent of riparian habitat in Reach 4 that groundwater can support under altered future conditions. First, the team determined groundwater depth thresholds of 0.0 m for open water and marsh, 2.5 m for cottonwood-willow forest, and 4.0 m for mesquite bosque in the Delta, based on historic and current groundwater conditions and informed by scientific literature (e.g., Stromberg, 2013; Merritt and Bateman, 2012; Lite and Stromberg, 2005; Horton *et al*., 2001, 2003; Glenn and Nagler, 2005; Hultine et al., 2010; Caplan et al., 2013). The team then used a groundwater flow model (MODFLOW; Rodriguez-Burgueño, 2012) to simulate groundwater-level changes in Reach 4 due to changes in environmental flows, agricultural return flows, upstream subsurface inflows, and evapotranspiration. The combined results of the groundwater threshold analysis and the groundwater flow model yielded maps depicting the extent of each riparian habitat type that would be supported by groundwater under different scenarios (Schlatter *et al.,* 2017b).

The results indicate that (1) agricultural return flows are currently the major control on groundwater depths, and thus on riparian habitat potential in Reach 4 and (2) sustained agricultural return flows and irrigation water directly applied to restoration sites have longer-term impacts on groundwater levels than higher volume, shorter duration deliveries to the mainstem (Schlatter *et al*., 2017b). This is consistent with the findings reported in Section 2 (Hydrology), Figures 2-3 and 2-5.

According to the model, increased environmental flow deliveries can reduce impacts of groundwater declines and habitat loss if agricultural return flows to Reach 4 are reduced. Monitoring can determine how future groundwater changes affect habitat condition, and how best to manage the restoration sites.

In the future, coordinated monitoring and analysis of future flow deliveries and their responses can provide the information needed to refine these strategies. Preliminary interdisciplinary models, based on the limited data obtained during Minute 319, demonstrate the potential of predictive tools to determine the most efficient uses of environmental water to maximize ecological benefits.

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Section 7: Response of the Avian Community to Minute 319 Environmental Flow Releases and Restoration Actions in the Colorado River Delta

Key findings

1. The abundance and diversity of birds in the riparian corridor increased 20% and 42% respectively after the 2014 pulse flow.
2. This abundance increase was significant especially in Nesting and Migratory Waterbirds and Nesting Riparian Landbirds.
3. Abundance and diversity declined after 2014 in each reach, but the 2017 level still exceed those observed in 2013.
4. Diversity (27%) and abundance (80%) are consistently greater within restoration sites than in other sample locations in the riparian corridor.

Introduction

From 2000 to 2012, the avian populations in the riparian corridor were monitored to assess the changes in the avian community in relation to decreasing flows and other habitat changes (Hinojosa-Huerta et al., 2008, 2013). The same monitoring design was continued in the period of Minute 319 (2012-2017), with some modifications, to assess the response of birds to the flow releases and the restoration efforts in the area.

The primary questions of this avian component of the binational monitoring effort were:

1- What are the changes in abundance, diversity and composition of the riparian avian community along the floodplain of the Colorado River in Mexico in response to the environmental flows of Minute 319?

2- How are these changes related to restoration activities?

In this report, we concentrate on the results of the bird community and its changes before and after the pulse flow, as well as the differences between the restoration sites and the floodplain.

Methods

The study area is located within the floodplain of the Colorado River in Baja California and Sonora, Mexico, from Morelos Dam downstream to the confluence of the Colorado with the Hardy River. The floodplain traverses the Mexicali Valley as the river flows toward the Gulf of California and is confined by flood control levees on both banks. This study area includes the main stem of the Colorado, secondary streams, and backwater lagoons, as well as the dry sections of the floodplain, covering 17,630 ha (43,565 acres) and extending for 95 river kilometers (59 river miles). Survey points are shown in Appendix C.

We monitored birds at 160 sites in the floodplain (grouped in 20 transects) following a variable distance point count methodology, four times per year (once per season, following Hinojosa-Huerta et al. 2008). Transects were run by teams of two persons, mainly for security reasons, starting at sunrise and continuing until no later than 4 hours after sunrise. At each point we counted all birds heard or seen within a 5-minute period, recording the distance from the observer to the bird and the time at which it was detected. Sixteen of these transects, all located downstream from the Southerly International Boundary, have been surveyed since 2002. These transects were randomly selected, at least 2 km (1.24 miles) apart, along the 146 km (90.7 miles) of levees within the study area. Each transect is composed of 8 points, 200 m (656 ft) apart, and extends for 1.6 km (1 mi) from the levee toward the main channel of the river. In 2014 we added 4 transects (32 points) along the Limitrophe section of the river, on the Mexican side, and since 2013, we have been adding survey points at the restoration sites, as these continue to expand. In 2017, we surveyed 31 points in three restoration sites (Miguel Alemán in Reach 2, and Herradura and CILA sites in Reach 4).

During 2017, we concentrated on evaluating the avian responses at the restoration sites in contrast with the rest of the floodplain, and conducted the surveys at the same sites, but with three visits during the breeding season, to increase the statistical power to detect differences in bird abundance and diversity (Hinojosa-Huerta and Hernández-Morlán 2016). Due to the change in survey methodology, data from 2017 was not compared to previous years' data.

To evaluate changes in bird abundance and diversity, we used the average number of individuals and species per point at each transect. We conducted the analysis for different guilds (resident and migratory birds) and for 15 indicator species, which were selected for their close association with the quality of the riparian habitat (see Appendix C for the lists of species).

For the diversity analysis, we used Hill's N_2 index, because it is less sensitive to rare occurrences than other diversity metrics, allowing for a more cohesive comparison of diversity across sites and years (Magurran 2004).

Results

Bird abundance in the floodplain decreased an average of 3.3% per year between 2002 and 2013, 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). During 2014, the trend was reversed: abundance increased 20% from 2013 (up to 138 birds per transect) and was maintained in 2015 (134 birds per transect) and 2016 (142 birds per transect) (Figure 7-1). The major changes occurred in Reach 3, where the increase in 2014 and 2015 in relation to 2013 was 51 and 47% respectively. In the Limitrophe we observed a spike during the summer of 2014, with a nearly four-fold increase in abundance of birds (an increase from an average of 281 birds per transect to 1,100 birds per transect).

The diversity index for birds (N_2) also had a downward trend since 2003 (an average reduction of 0.17 units per year), with 2013 having the lowest number since 2003 (3.58 in 2013 vs 5.96 in 2003). The diversity index increased 42% from 2013 to 2014 (N_2 = 5.09) and decreased from 2014 to 2015 (N_2 = 4.62) and 2016 (N_2 = 4.57) but still was 29% higher than in 2013 (Figure 1) (Figure 7-1). 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.

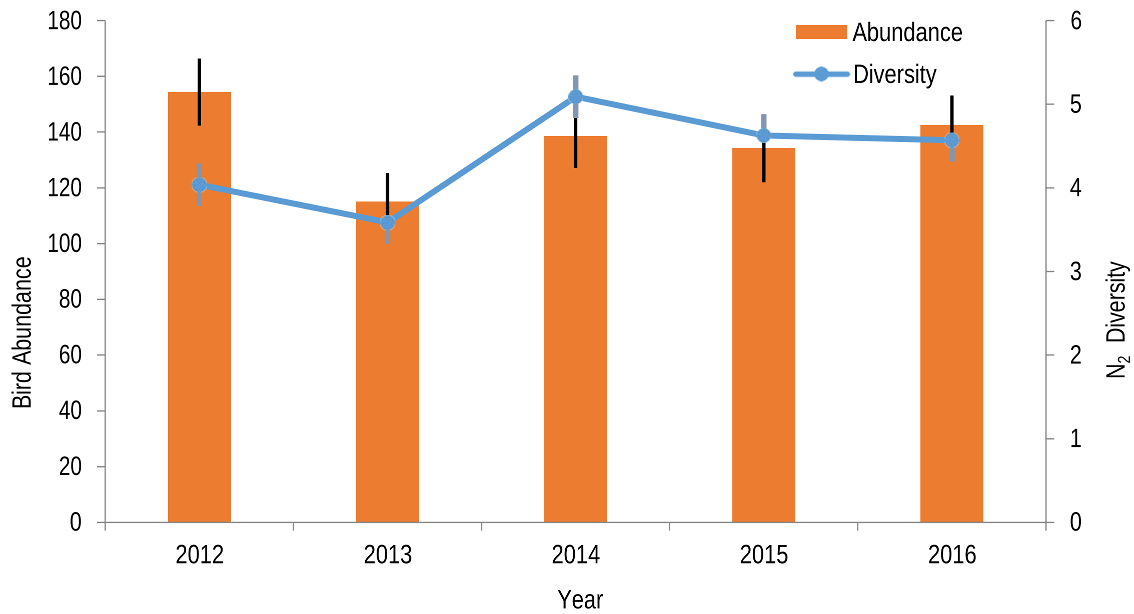

Figure 7-1. Bird abundance (average per transect) and Hill's N_2 diversity (per point) in the floodplain of the Colorado River in Mexico from 2012 to 2016. Error bars represent 95% confidence interval.

Looking at specific bird groups, the Nesting Riparian Landbirds, which includes species of landbirds closely related with the native riparian vegetation and that are resident or breeding visitors in the Delta, showed a significant increase of 22% (one-way ANOVA $p < 0.001$) from 2013 (average abundance per transect = 52.15, 95% CI 46.64 - 57.6) to 2014 (average abundance per transect = 63.86, 95% CI 58.38 – 69.35). Their abundance decreased from 2014 to 2015 and 2016, but was still 12.3% higher than 2013 (Figure 7-2).

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, also showed a significant increase (81% one-way ANOVA $p < 0.001$) from 2013 (average abundance per transect = 7.58, 95% CI 5.95 – 9.25)to 2014 (average abundance per transect = 13.76 95% CI 12.11 – 15.42). Their numbers decreased from 2014 to 2015 and 2016, but their abundance was still 11% higher than in 2013 (Figure 7-2).

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). Their abundance increased fourfold from 2013 to 2014 (one-way ANOVA $p < 0.001$, Figure 7-2). 2014 was the year with the highest abundance of this group recorded since we started the study in 2002, with an average of 109 birds per transect, or an estimated abundance in the floodplain (Reach 1 to Reach 5) of 53,680 (95% CI 46,350 – 61,010, distance sampling, GOF Chi-p = 0.71) migratory waterbirds during the pulse flow. In 2015 and 2016, the abundance of migratory waterbirds decreased to an average of 47 birds per transect, but this number is still 75% greater than the abundance of this group during 2013. Almost all records occurred in Reach 1 and Reach 4. We did not detect any major changes in the numbers of other guilds in the floodplain between 2012 and 2016 (agricultural related, raptors, migratory landbirds, or desert birds).

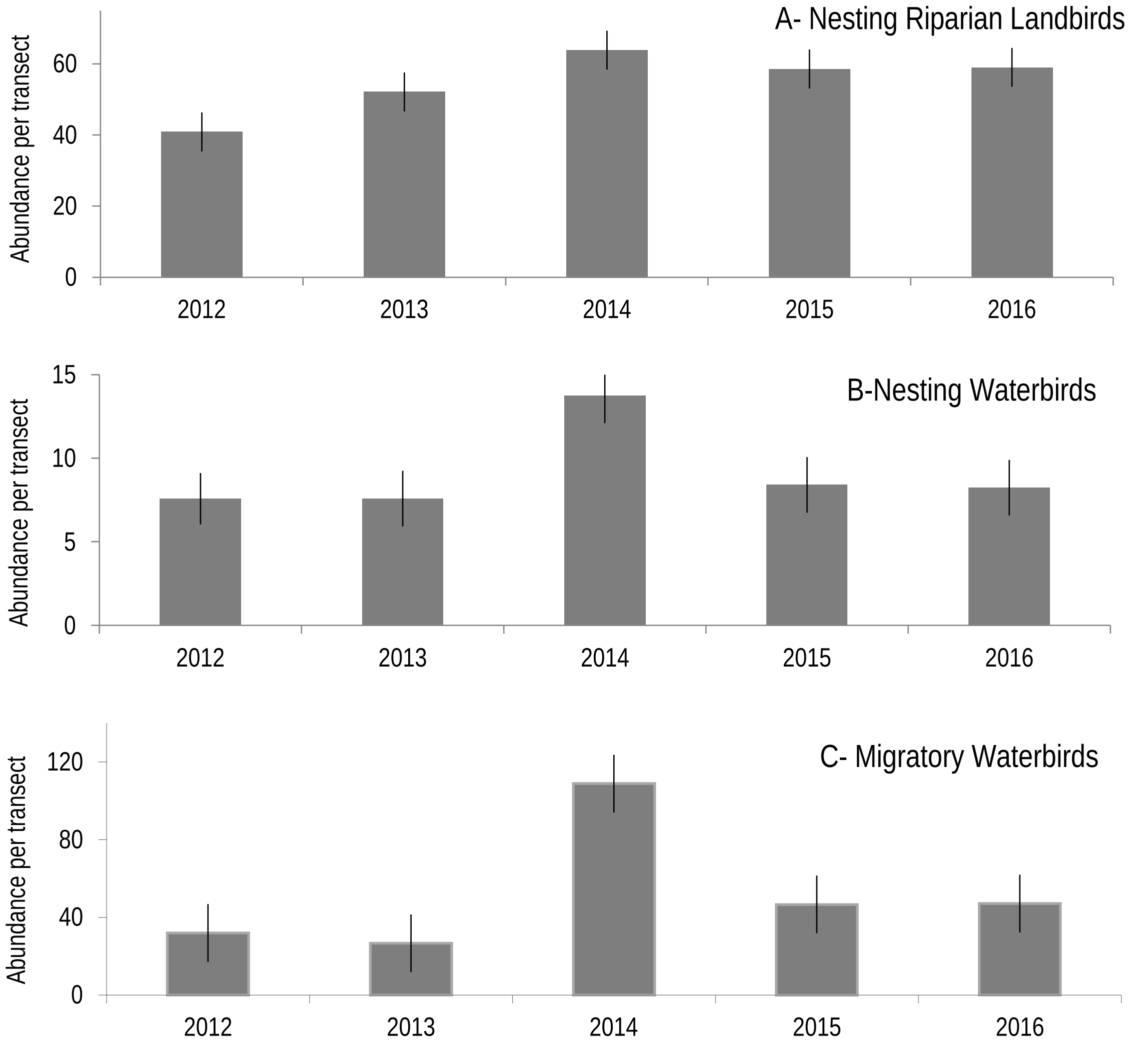

Figure 7-2. Average abundance per transect of nesting riparian landbirds (A), nesting waterbirds (B) and migratory waterbirds (C) in the floodplain of the Colorado River from 2012 to 2016. Error bars represent 95% confidence interval.

During the breeding season of 2017, the average bird diversity per point was 27% higher (two-tailed t-test, $p = 0.014$), and the average abundance per point of the 15 indicator species was 80% greater (two-tailed t-test, $p < 0.001$) at the restoration sites (Miguel Alemán, CILA and Herradura) than in the rest of the floodplain (Reach 1 to Reach 5). The highest diversity was detected at the Herradura site ($N_2 = 8.41$), while the highest abundance was detected at the CILA site (6.42 birds per point), both sites within the Laguna Grande restoration site in Reach 4. The lowest diversity ($N_2 = 3.79$) and abundance (1.79 birds per point) was detected in Reach 3 survey points (Figure 7-3).

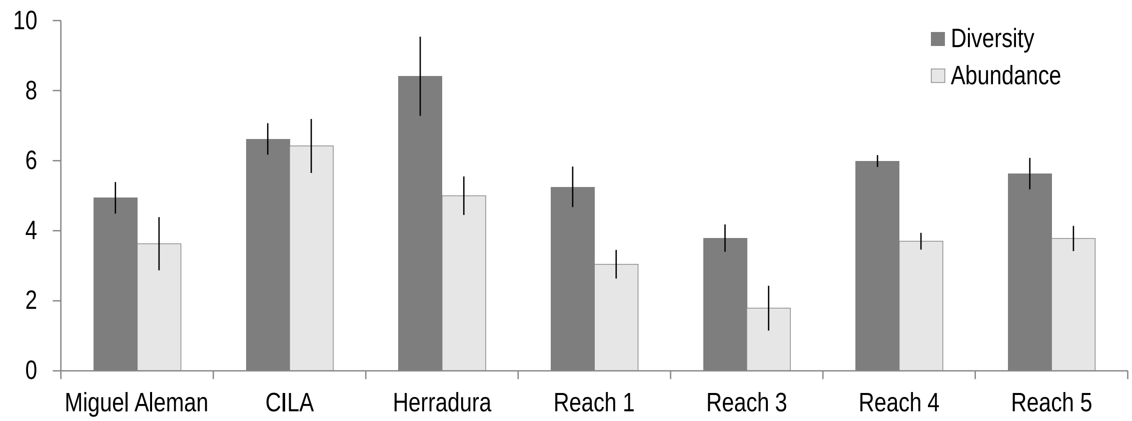

Figure 7-3. Abundance of indicator species (birds per point) and bird diversity for all species (N_2 per point) at the restoration sites and the reaches of the Colorado River during the breeding season of 2017. Error bars represent 95% confidence interval.

From 2013 to 2017, bird diversity increased in the restoration sites (by 60% in this period overall) and throughout the floodplain (by 40%, Figure 7-4). The combined abundance of the 15 indicator species has also been consistently increasing at the restoration sites (also by 60% in this period overall), although no statistical significance was found. Throughout the floodplain, the abundance increased 32% in 2015 from 2013 and 2014, but then decreased again to similar levels during 2016 and 2017 (Figure 7-5).

Figure 7-6 shows the changes in the abundance of the 15 indicator species among the five reaches and two restoration sites (Miguel Aleman – in Reach 2; CILA – in Reach 4). Note the increasing abundance in the two restoration sites during the study period and the decreasing or fluctuating abundance in the riparian zone outside the restoration sites.

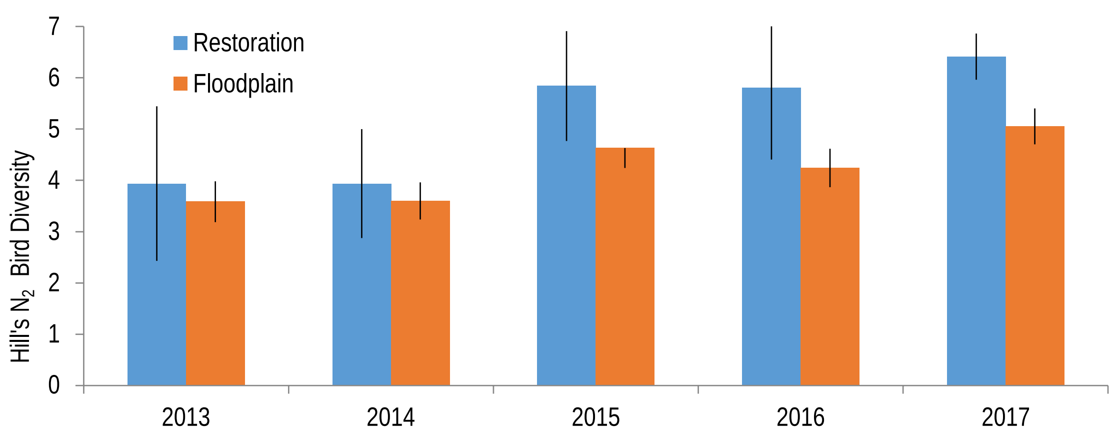

Figure 7-4. Average bird diversity (N_2 per point) at the restoration sites and the floodplain of the Colorado River in Mexico during the breeding season, from 2013 to 2017. Error bars represent 95% confidence interval.

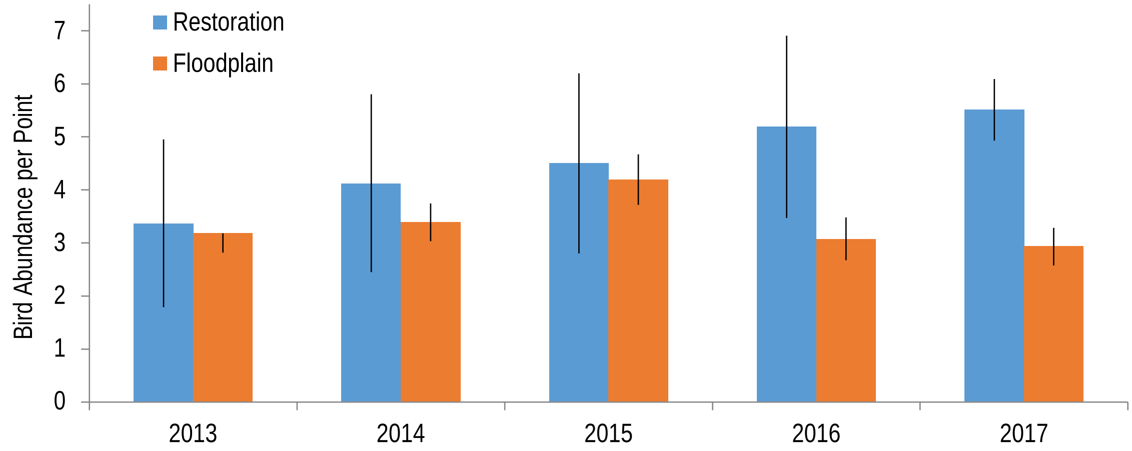

Figure 7-5. Average bird abundance per point of 15 indicator species at the restoration sites and in the floodplain of the Colorado River in Mexico during the breeding season, from 2013 to 2017. Error bars represent 95% confidence interval.

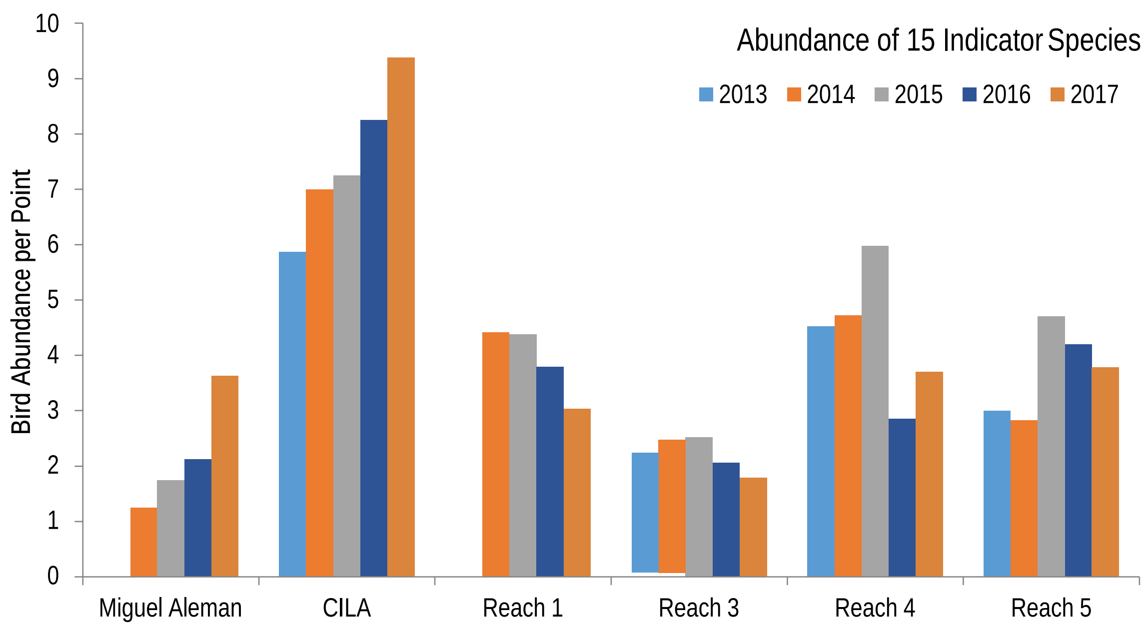

Figure 7-6. Abundance of indicator species in two restoration sites (Miguel Aleman and CILA) and in the five reaches.

Figure 7-7 shows the variation in N2 diversity among the five reaches and two restoration sites (Miguel Aleman – in Reach 1; CILA – in Reach 4). Maximum diversity among all sites is at the CILA restoration site and, with the exception of Reach 4, maximum diversity in each reach is in 2017.

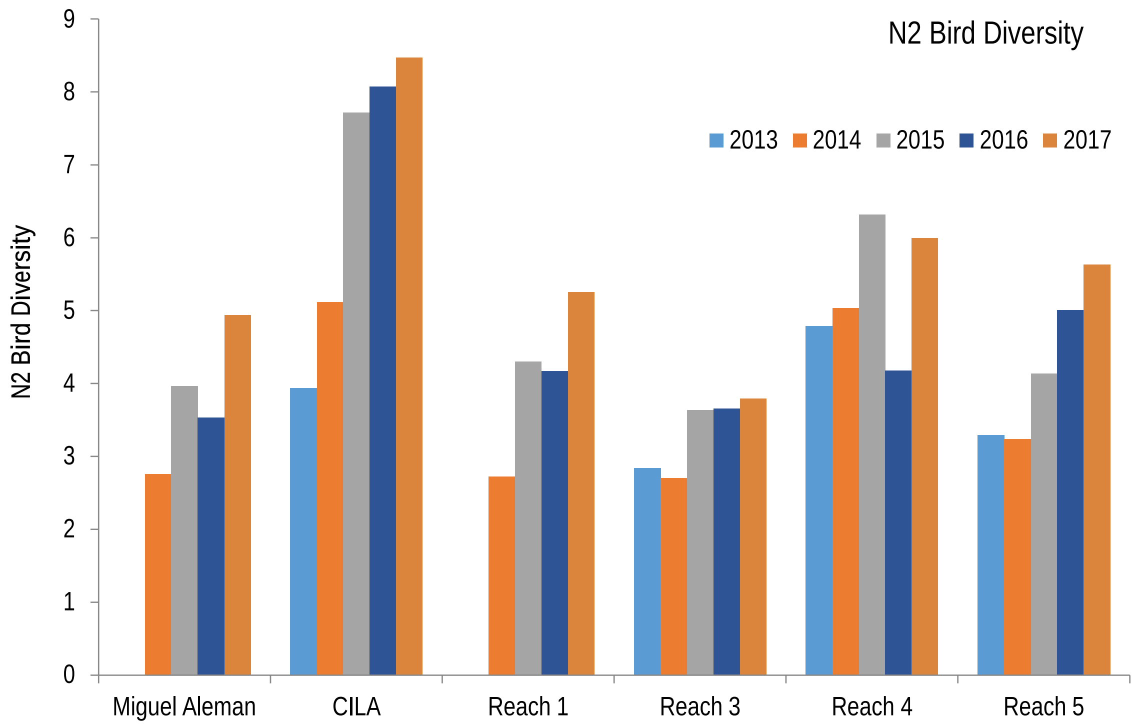

Figure 7-7. Diversity (N2 Hill's Index) of bird species in two restoration sites (Miguel Aleman and CILA) and in the five reaches.

Conclusions

The abundance of birds increased by 20% and bird diversity increased by 42% in the floodplain of the Colorado River in Mexico after the pulse flow. The response was stronger in 2014 but was maintained in 2015 and 2016. The largest change was observed in the migratory waterbirds, with a fourfold increase from 2013 to 2014. Their abundance was reduced in subsequent years, but the numbers were still 75% higher in 2016 than in 2013. At the restoration sites in 2017, bird diversity was 27% higher and the abundance of the 15 indicator species was 80% higher than in the rest of the floodplain.

The pulse flow appears to have improved habitat conditions for birds during 2014, with the strongest effects in that year and in 2015. Other factors, such as the release of base flows into Reaches 1, 4 and 5, may have affected the increase in bird diversity throughout the floodplain. The activities at the restoration sites are related to significant and consistent increases in bird diversity and abundance.

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Section 8: Lower Delta and Estuary

Key findings

1. Dredging of the main river-tidal channel in the upper estuary in 2016 significantly improved river-sea connectivity, resulting in greatly decreased surface water salinity for the area both upstream and downstream of the sandbar (at E3, salinity went from 60 ppt to approximately 20 ppt in spring months and from 100 ppt to 45 ppt in winter months).
2. Post dredging 2016, freshwater (from Hardy River and Ayala Drain) now flows to the upper estuary and sea when agricultural return flows are high (January – June). From July to November, limited freshwater inputs to the Hardy and Ayala Drain result in increased salinity along much of the lower Hardy-Colorado River channel, likely due to evaporation.
3. Environmental flow deliveries to the Hardy River, Ayala Drain, and/or Colorado River mainstem during the months of July-November could complement the spring agricultural return flows and create favorable salinity conditions year-round.
4. Groundwater elevation in the region is strongly influenced by the agricultural irrigation cycle.
5. The most abundant fish species in the lower Delta are the Machete (*Elops affinis*) and flathead grey mullet (*Mugil cephalus*). Both species are native to the Delta region, utilize fresh, brackish and marine habitats, and are abundant in the lower Hardy River (brackish) and upper estuary (brackish to saline), indicating that the system has conditions suitable for entry of juveniles to the upper estuary area.

Introduction

The lower Delta and upper 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 conduct restoration activities and monitor the biologic and hydrologic conditions of the upper portion of the estuary throughout the term of Minute 319. Effects of the 2014 pulse flow release on the upper estuary were reported in the 2016 Interim Monitoring Report (Flessa et al., 2016) and Nelson et al. (2016). This report focuses on the impacts of additional environmental flow releases and dredging of river-tidal channels from 2014-2017.

The lower Delta and upper estuary receive freshwater from the Colorado River, Ayala Drain (agricultural drainage), Hardy River (treated effluent and agricultural drainage), other agricultural drains, and seawater from the Gulf of California (Figure 8-6). Restoration strategies for the upper estuary include increasing freshwater flows to the region and increasing tidal exchange with the Gulf of California. Restoration efforts will improve and create habitat for fish, invertebrates and shorebirds.

The SI monitoring program in the estuary assesses: 1) connectivity between the river and the sea, 2) surface water quality parameters and discharge, 3) groundwater levels, and 4) fish and zooplankton populations (see Figure 8-6 for a map of monitoring points).

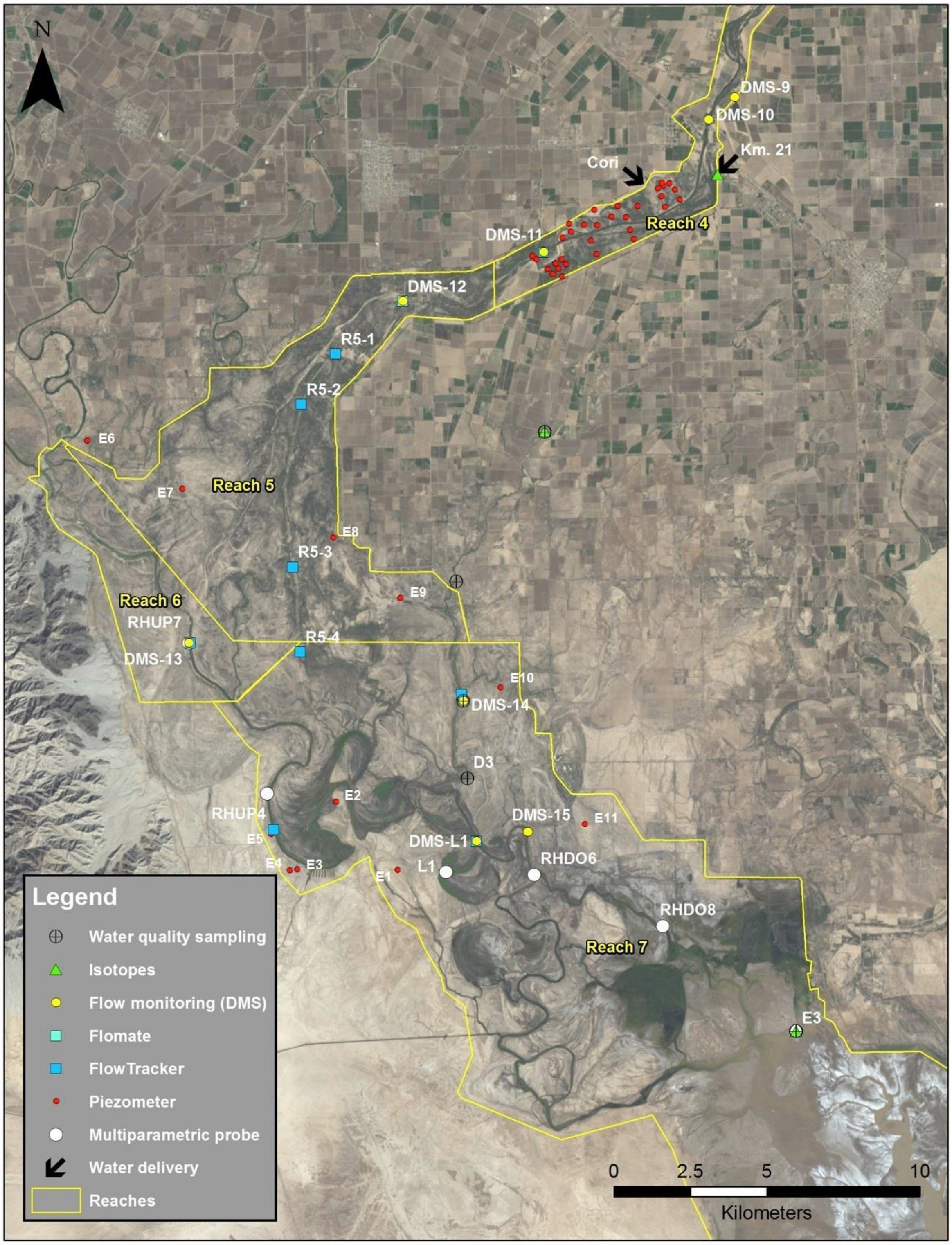

Figure 8-6. Map of monitoring sites in the lower Delta and upper estuary.

Description of restoration activities from 2014-2017:

Upper Estuary Channel

In 2012, sediment was manually removed from a pilot channel through the tidal sandbar barrier (Figure 8-7) in order to increase freshwater influx, tidal flooding and drainage through the highest portion of the sandbar. In 2016, the pilot channel was extended, first through manual digging of a channel, and then by an amphibious excavator (Figure 8-8). Channel dredging location and geometry were determined based on analyses of topographic and hydrologic data. A total of 11.1 km (6.8 mi) of channel was dredged in September-November 2016 (yellow line, Figure 8-2). Additional dredging options for implementation in 2018 are being evaluated using a hydrogeomorphic model developed by Mark Stone of the University of New Mexico with support from The Nature Conservancy (options 1-3, Figure 8-2).

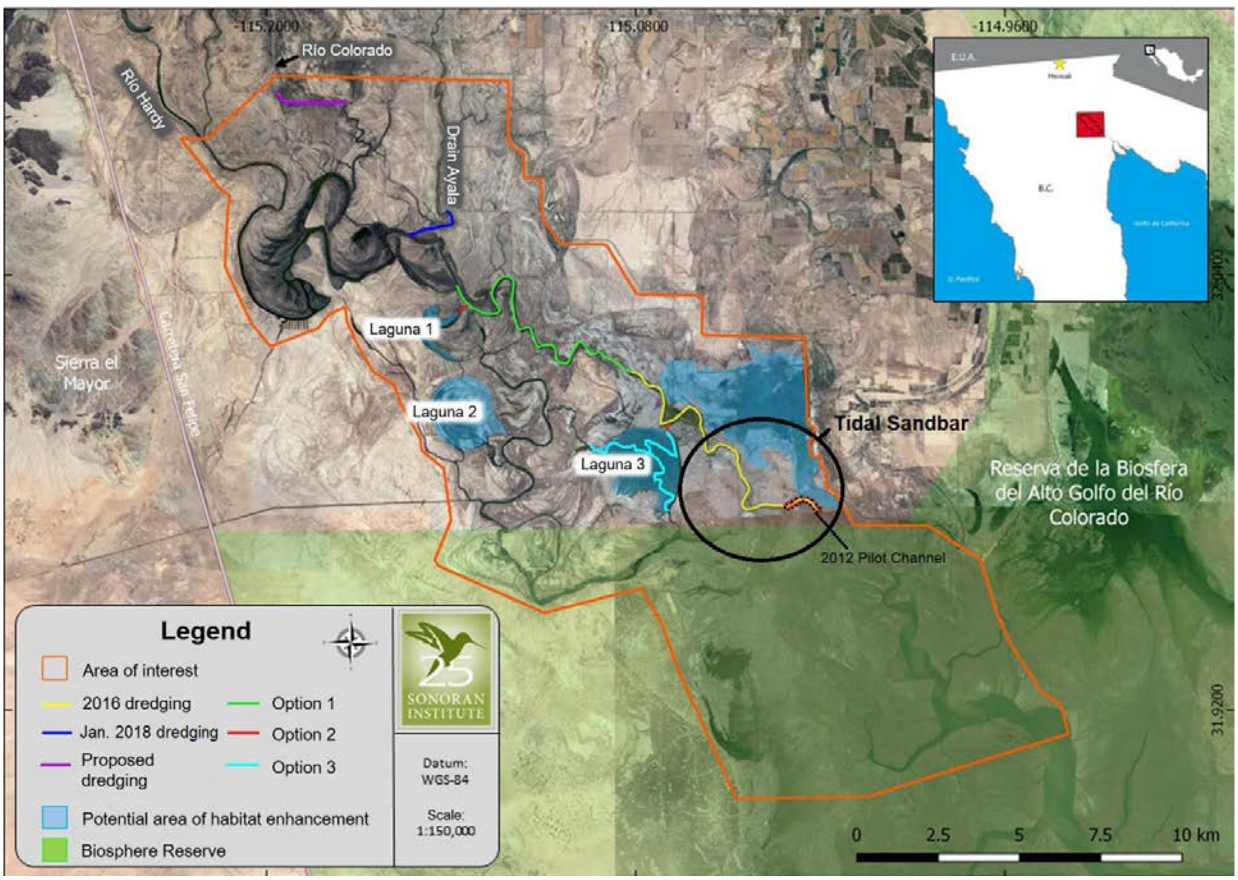

Figure 8-7. Completed, ongoing, and proposed locations for sediment removal along river-tidal channels in the estuary. Blue areas represent potential areas for habitat enhancement.

Figure 8-8. Aerial image of dredged channel, November 2016. Hardy-Colorado River is located top-left, and a tidal channel is located bottom right. Dredged channel connects the two. Yellow line parallels trace of the dredged channel.

Ayala Drain

In August 2015, 0.5 cms (18 cfs) of Colorado River water was delivered to the upper estuary from the Ayala Drain for a total of 30 days (equivalent to 1.3 mcm [1,061 acre-feet]). Minimal salinity responses in the upper estuary indicated that only a small portion of this water reached the upper estuary from the delivery point. The limited delivery was likely a consequence of the shallow, vegetation-choked condition of the drain. As a result, Sonoran Institute improved the Ayala Drain as a delivery option by dredging the lowermost portion of the Drain close to its connection with the Colorado-Hardy River. A total of 1.8 km (1.1 mi) of the channel was dredged in January 2018 (blue line in Figure 8-7), with an estimated 7,098 cubic meters (250,664 cubic feet) removed. Another water delivery to the Ayala Drain is planned for summer of 2018 to test the recently dredged channel. A total of 2.4 mcm (1,934 acre-feet) of permanent and leased water rights have been secured for this purpose.

Colorado River Mainstem

From August 3 – December 24, 2016, approximately 5.1 mcm (4,200 acre-feet)[5] of water was released to the Colorado River mainstem from delivery points located in Laguna Grande (Reach 4), as described in Section 2. The flow delivery was originally planned to be 2 cms (70 cfs) for a total of 30 days. Monitoring results indicate that flows were released from August 3 – October 3, and again from October 22 – December 24, 2016.

Based on results of the release (Schlatter et al. 2017), it was determined that removing sediment and vegetation from a portion of the Colorado River at the top of Reach 7 could increase the percentage of freshwater flows to the mainstem that reach the upper estuary. As such, 2.2 km (1.4 mi) of the lowermost portion of the channel is planned to be dredged in 2018 to improve conveyance of future water deliveries in 2019 (purple line near top of image in Figure 8-7).

Monitoring Program and Results

1. **Hydrology:**

1.1. Surface Water Flows

Flow rates were monitored monthly at five monitoring points (DMS-13, DMS-14, DMS-L1, DMS-15, and Ayala Drain) in the lower Delta and Hardy River region (Figure 8-6) using FlowTracker (SonTec).

Flows in the lower Delta are variable over space and time, with the highest flow rates at DMS-13 (located upstream of the kidney-shaped area on the Hardy River (Figure 8-6)) and DMS-14 (located on the Ayala Drain) and occurring in the late winter/spring, which is when agricultural return flows are greatest (Figure 8-9). These data show that the principal source of freshwater for the lower Delta and upper estuary is the Hardy River, which ranged (at DMS-13) from 0.05 to 1.6 cms (1.8 to 56.5 cfs) during the monitoring period. The Ayala Drain is the second largest source with flow rates ranging 0.3 to 0.22 cms (1.1 to 7.8 cfs) at DMS-14 (mid-point along the drain channel), and 0.01 to 0.18 cms (0.35 to 6.3 cfs) at the end point of the drain. DMS L1 and DMS-15 are downstream of both sources (Figure 8-6).

Precipitation data were obtained from El Mayor (near the Hardy River in Reach 6) meteorological station (CONAGUA, 2017). Rainfall appears to have little impact on flow rates during the period of data collection (Figure 8-9). Limited discharge data in 2017 was available due to staff transition following the dredging activity; therefore, it cannot be determined if dredging affected flow rates in the region.

[5] Data on actual flow release volumes, rates, and dates have not been released; volumes stated here are those that were originally proposed.

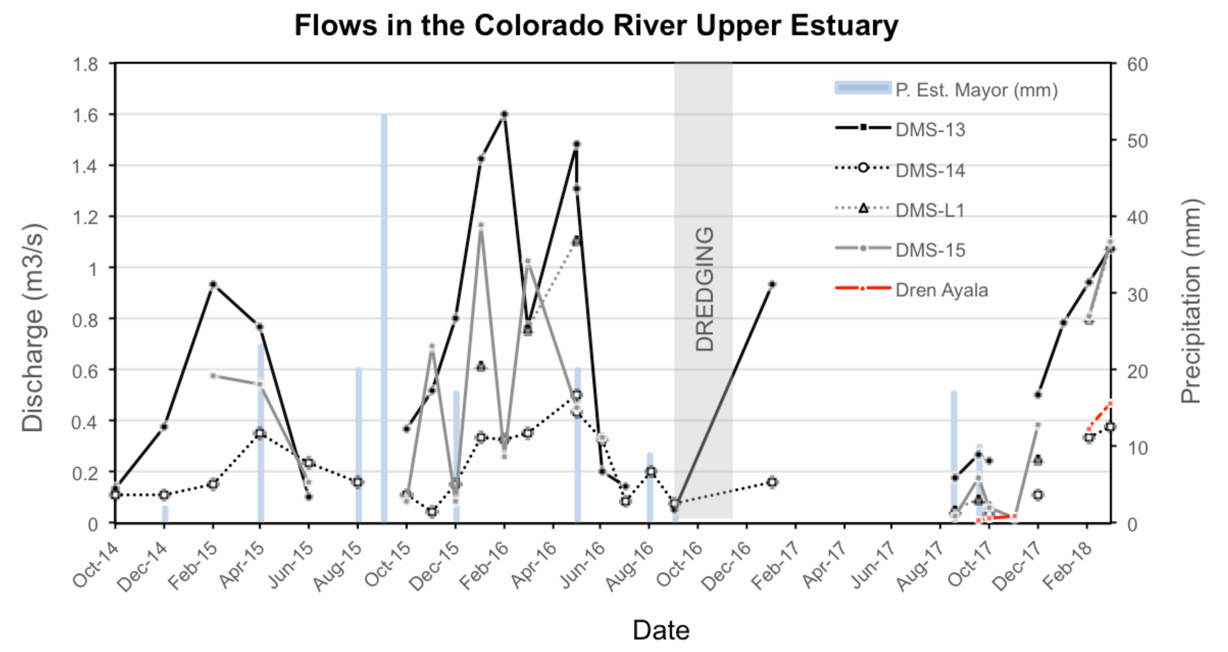

Figure 8-9. Flow measurements at discharge monitoring sites located in the lower Delta region. The light blue bars represent precipitation events and the grey area marked DRAGADO represents the period in which the dredging occurred.

1.2. Surface Water Elevation

Surface water elevation is monitored continuously using YSI multi-parameter sensors and is also manually recorded monthly at five monitoring points (RHUP7, RHUP4, RHDO6, RHDO8, E3) in the Hardy River and lower Delta region (Figure 8-6). Surface water elevation at monitoring points located on the upper Hardy River (RHUP7 and RHUP4) has a pattern of higher elevations from January to June across all years, indicating the strong influence of seasonal agricultural irrigation flows (Figure 8-10A). Surface water elevation at monitoring points (RHDO6 and RHDO8) in the lower Hardy River demonstrates influences of both agricultural return flows and tides (Figure 8-10B). During the irrigation period (January-June) water levels are high and relatively stable as compared to the non-irrigation period in summer through late fall. During the fall and winter months, there is greater variability caused by tidal inflow and outflow, which has greater influence on water elevation due to the low baseline river level. At the monitoring point located in the upper estuary (E3), tidal influences are evident year-round with large fluctuations in water elevation due to tidal inflow and outflow (Figure 8-10C).

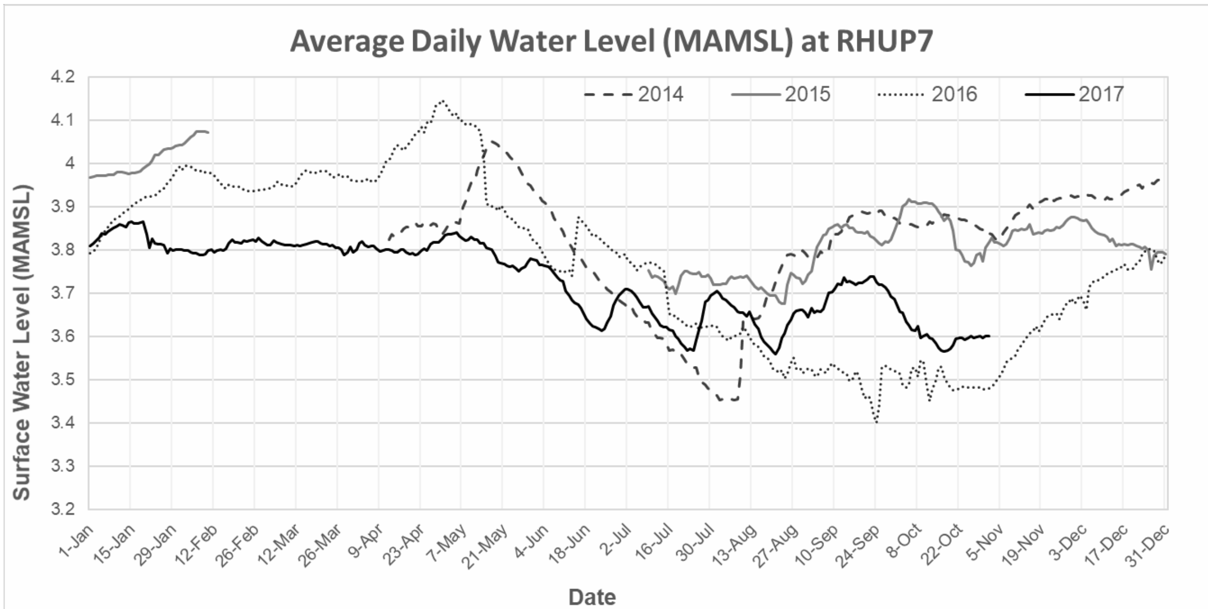

Figure 8-10A. Surface water level from 2014-2017 at RHUP7 (most upstream site; Hardy River). Note: data gap in 2015 was caused by a sensor malfunction.

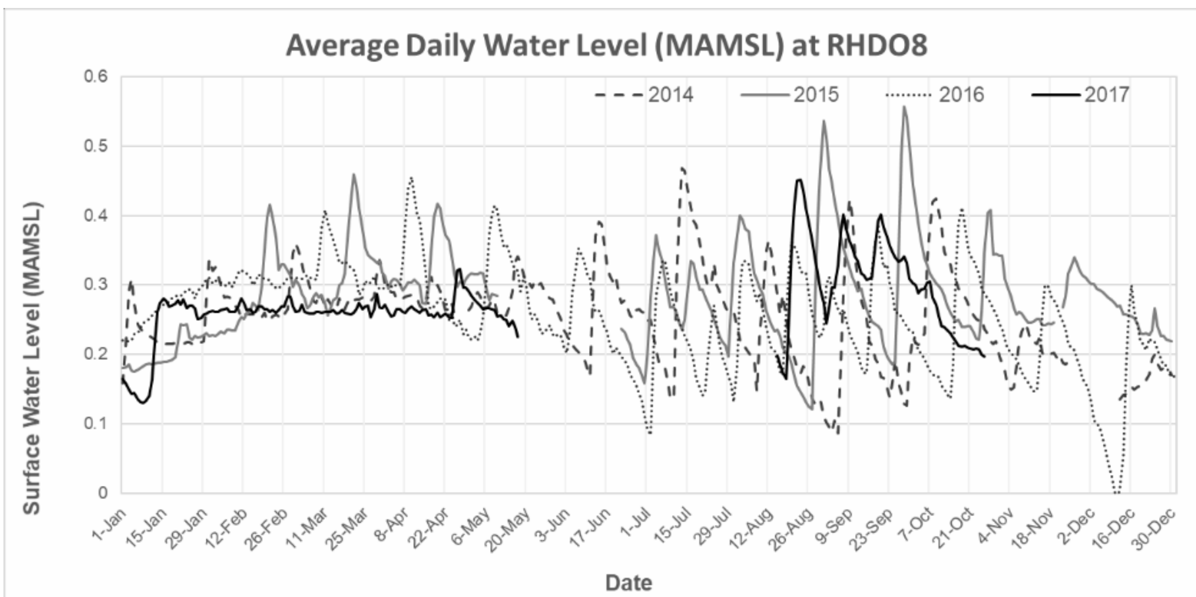

Figure 8- 10B. Surface water level from 2014-2017 at RHD08.

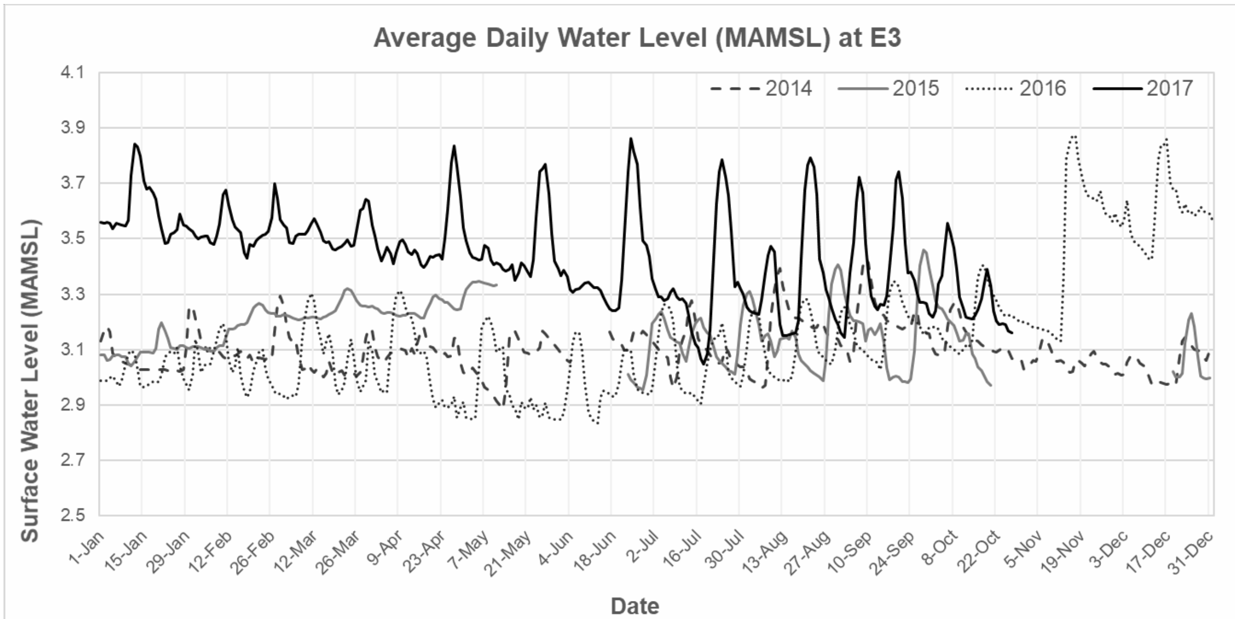

Figure 8-10C. Surface water level from 2014-2017 at E3, the most seaward site.

1.3. Groundwater Elevation

The dataset for groundwater elevation in the estuary is limited to April 2016 (when piezometers were installed) through March 2018, with significant gaps in 2017. Based on the limited available data, groundwater levels appear to be related to seasonal fluctuations of surface water inputs, primarily agricultural return flows (Figure 8-11). During the irrigation season, groundwater levels increase due to the influx of irrigation water. Levels drop slightly in the fall and winter months (September through December), although from August 2017 to March 2018, groundwater levels remained relatively stable. Due to limited data due to transition of monitoring staff, we cannot assess the effects of dredging on groundwater or groundwater inflow to the estuary.

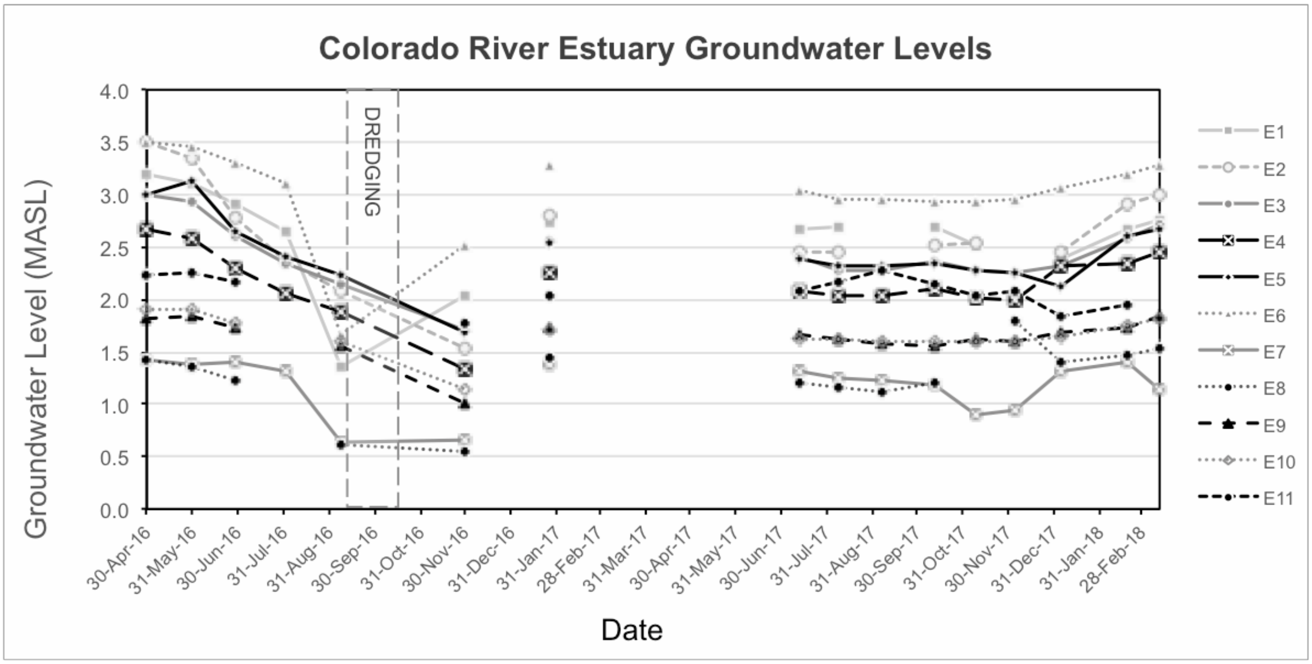

Figure 8-11. Monthly groundwater elevation at piezometers located in the lower Delta region.

2. Surface Water Salinity

Surface water salinity is monitored continuously using YSI multi-parameter sensors at five monitoring points in the lower Hardy, Colorado, and upper estuary (RHUP7, RHUP4, RHDO6, RHDO8, E3) (Figure 8-6). Salinity is an important indicator of estuarine habitat functionality, as it indicates the extent of freshwater-seawater mixing and connectivity between the river and the sea. Historically, salinity in the estuary ranged from near 0 parts per thousand (ppt) at the mouth of the river during the spring flood to 36-38 ppt at the seaward edge of the river-tidal mixing zone.

The upper Hardy River site (RHUP7, located upstream of the kidney area, Figure 8-6) has salinity levels that are typical of freshwater conditions, with low salinity (<2 ppt) from January to June and higher salinities in summer and fall months (August-October), likely due to evaporation and diminished freshwater inputs during that period (Figure 8-12A). The spikes in salinity at RHUP7 in 2017 (60 ppt) and 2015 (40 ppt) in fall months are likely due to a lack of flows in those years, which led to evaporation and accumulation of salts.

Surface water salinity at RHD06 and RHDO8 (Figure 8-12B) indicates two distinct trends. From January to June, freshwater inputs maintain low surface water salinity (<3 ppt), and from July to December, hypersaline conditions are common, with salinities ranging from 60-100 ppt.

At E3 (Figure 8-12C), salinity levels from 2014-2016 were typically greater than seawater salinity of the upper Gulf of California (upper Gulf of California salinity = ~42 ppt, based on SI monitoring in 2017), with extremely hypersaline (90-140 ppt) conditions occurring during the latter half of the year.

Impacts of the 2016 dredging on salinity are evident at points RHDO6, RHDO8, and E3, which are the southernmost three monitoring points located on the lower Hardy River and upper estuary.

At RHDO8, salinities from January to May 2017 range from 7-20 ppt, which indicates a continuous presence of freshwater flows, a trend not observed in 2014-2016. Notably in 2017, the spikes in salinity caused by tidal inflows observed in previous years are absent, which signifies improved flow of freshwater out towards the sea that diminish the influence of incoming higher salinity water of the tides. Salinity at RHDO8 in 2017 for the latter half of the year did not differ significantly from previous years. This suggests that additional freshwater inputs to the Hardy River could be highly important in reducing salinity from July to December.

At E3, salinity levels in 2017 (post-dredging) were significantly reduced throughout the entire year as compared to previous years. Salinity during the first half of 2017 hovered around 40 ppt (close to the salinity of Gulf of California seawater) and dropped to 15 ppt, indicating both freshwater and tidal influences during that time. The only other time salinity went below 40 ppt at E3 was in 2015, when large Hardy River water releases overtopped the sandbar in the upper estuary. No large releases were made in 2017, however, which suggests altered conditions and improved connectivity. Additionally, although salinity in 2017 reached 110 ppt in July, it dropped back down to near 40 ppt in October and November, which demonstrates improved tidal exchange. Unlike in previous years, in 2017, tidal flows passed through the sand bar via the dredged channel and flowed back out, instead of being trapped upstream of the sandbar. Previously, the trapped flows evaporated, causing hypersaline conditions. The average salinity at E3 in 2017 was 59.8 ppt, which is significantly less than in prior years (average in 2012: 134.6 ppt; 2013: 170.6 ppt).

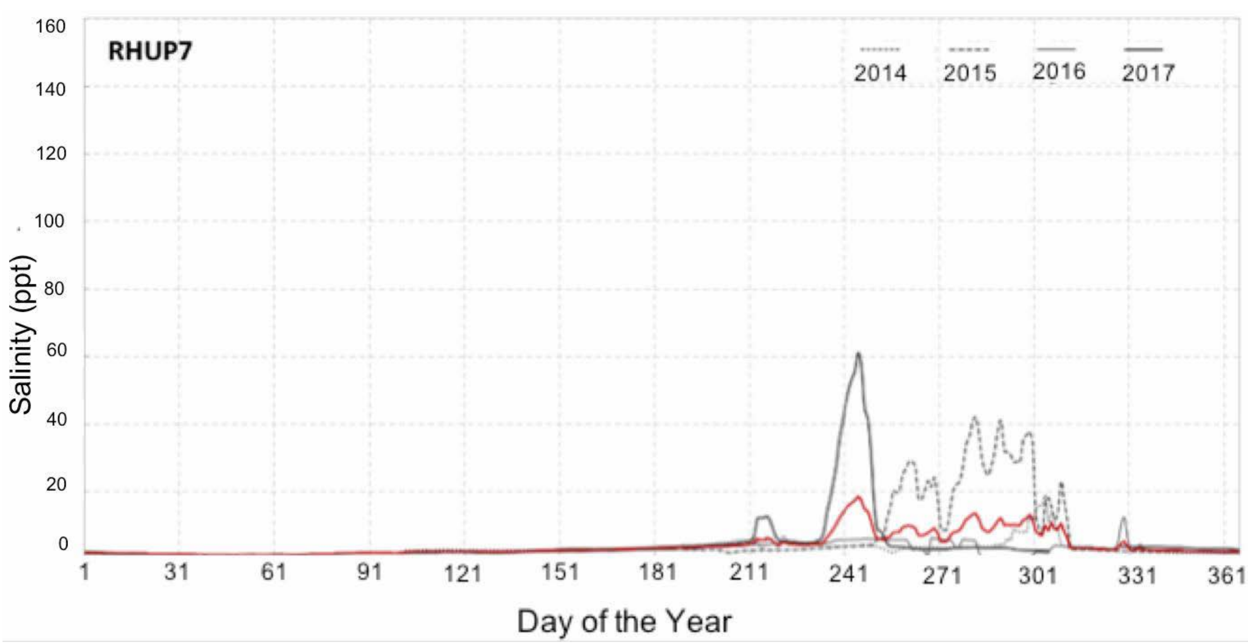

Figure 8-12A. Salinity of surface water from 2014-2017 at RHUP7 (Hardy River site, most upstream). Red line is average across all years.

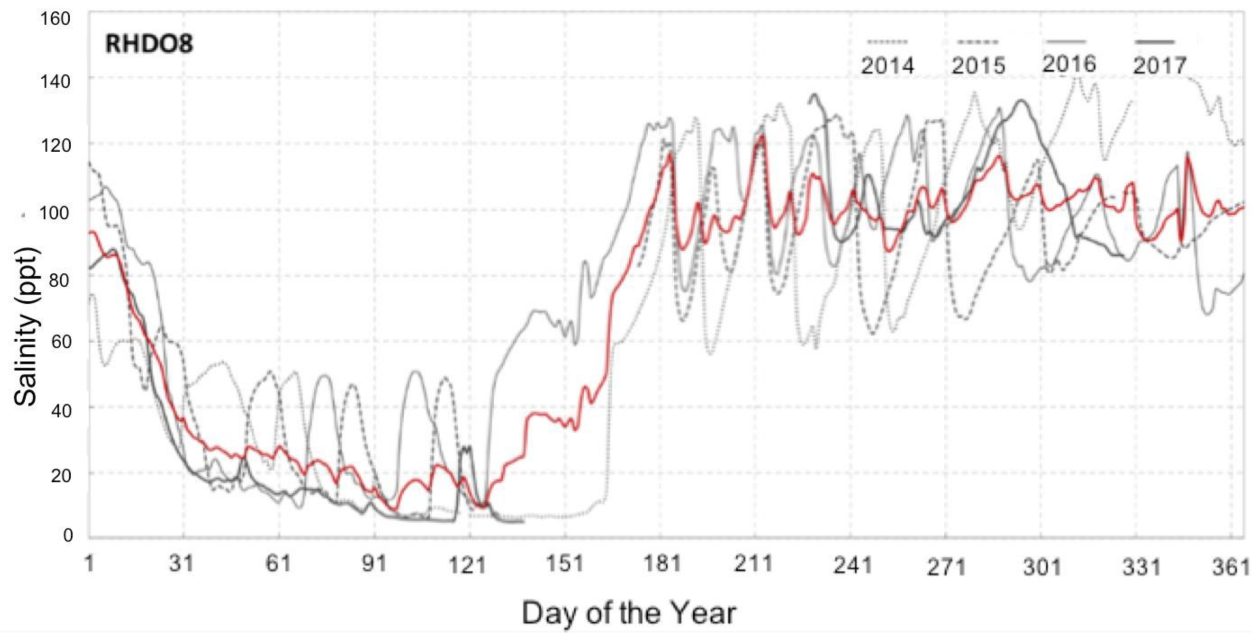

Figure 8-12B. Salinity of surface water from 2014-2017 at RHD08. Red line is average across all years.

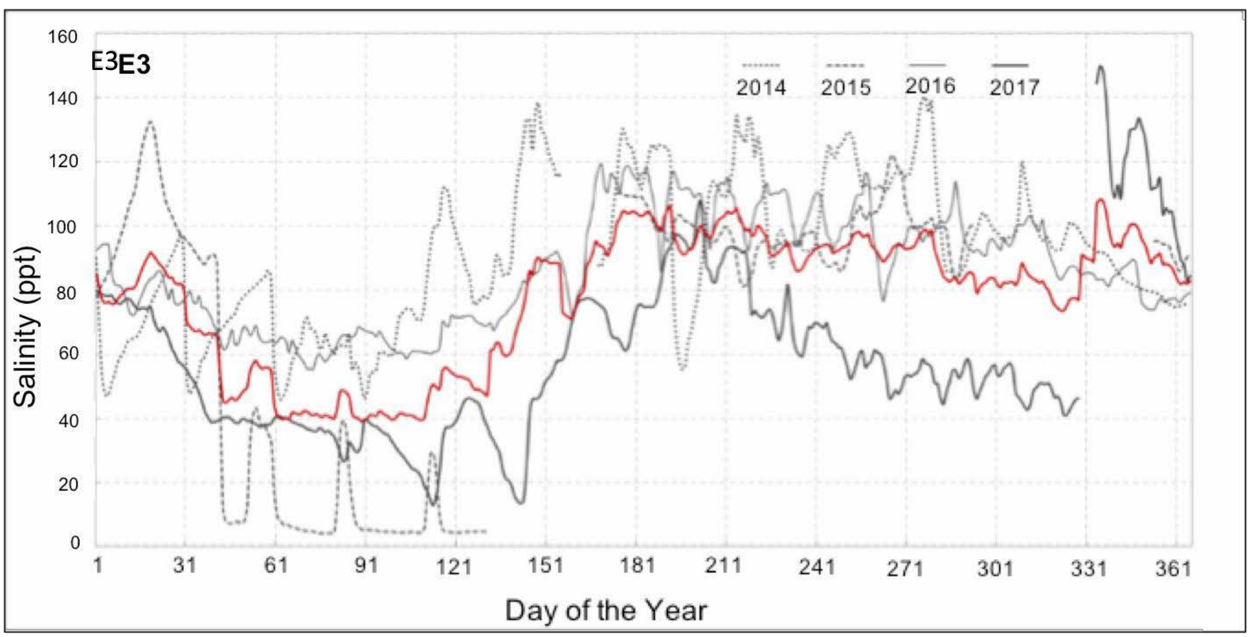

Figure 8-12C. Salinity of surface water from 2014-2017 at E3. Red line is average across all years.

3. Wildlife

3.1. Fish surveys

Fish surveys were conducted three times per year from 2014-2017 at seven points along the Hardy River and upper estuary (Figure 8-13). Surveys used a net designed to capture medium and large-sized fish (see Yáñez-Arancibia (1978) for methods). Prior to 2014, Sonoran Institute conducted surveys once at nine points in 2005, monthly at 21 points from 2009-2010 and monthly at nine points from 2011-2012. Seven of the original survey locations were used in 2014-2017 to maintain a long-term dataset.

To date (including all years of monitoring), a total of 3,782 individuals were collected from 8 orders, 12 families, 8 genera, and 22 species of fish (see Appendix D).

The red crayfish (*Procambarus clarkii*), brown shrimp (*Farfantepenaeus californiensis*), swimming crab (*Callinectes arcuatus*), and the spiny softshell turtle (*Apalone spinifera*) were incidentally caught (not included in the 3,782 individuals).

The most abundant fish species was the Machete (*Elops affinis*) followed by the flathead grey mullet (*Mugil cephalus*). Both species are native to the Colorado River Delta and utilize freshwater, brackish, and marine habitat. These species were collected in the lower Hardy River (brackish) and upper estuary (brackish to saline) indicating that the system has conditions suitable for entry of juveniles to the upper estuary area.

Figure 8-13. Map of fish survey points from 2005-2017. The green points were surveyed in 2014-2017.

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Yáñez-Arancibia, A., 1978. Patrones ecológicos y variación cíclica de la estructura trófica de las comunidades nectónicas en lagunas costeras del Pacífico de México. Revista Biologica Tropical 26, 191-218.

Section 9: Conclusions

The environmental water deliveries made under Minute 319 marked the first-ever scheduled delivery of water by the United States or Mexico to the Colorado River Limitrophe and its associated Delta dedicated to the purpose of improving the riparian ecosystem. Historically, significant volumes of water flowed through this reach of the Colorado River, but without a formal monitoring program in place, limited data was collected about the ecosystem response.

Minute 319 outlines that a joint investigation by the U.S. and Mexico should be conducted to evaluate the ecosystem response to the Minute 319 environmental flows. During the term of Minute 319, numerous government agencies, conservation organizations, and universities collaborated in a binational science and monitoring team, in coordination with the Environmental Work Group, to collect data and perform analyses to meet this requirement in Minute 319. The monitoring and science effort is the product of an effective, collaborative science team based in the United States and Mexico that measured and reported on hydrologic and ecological change in the Colorado River Limitrophe and its associated Delta. This binational collaboration significantly advanced knowledge about how water moves through the Colorado River in this region and how water supports the ecosystem. The results of this binational investigation provided a foundation of data and analysis which will inform future cooperative actions.

Lessons learned through the Minute 319 monitoring efforts include:

- The Minute 319 pulse flow volume, peak flow rate, and duration were sufficient for the binational science and monitoring team to gather data and determine the hydrologic and ecological response.
- The Minute 319 pulse flow volume, peak flow rate, and duration were not sufficient to disturb the river channel and floodplain, create new areas of native vegetation, or result in significant flow downstream from the dry reach where infiltration rates are high.
- The Minute 319 pulse flow temporarily achieved connectivity of the Colorado River from Morelos Dam to the Sea of Cortez.
- During the term of Minute 319, base flows were delivered to support restoration sites. Habitat restoration practitioners employed a variety of management techniques and base flows were essential to habitat restoration.
- The pulse flow produced a 17% increase in greenness throughout the riparian corridor in 2014 compared with 2015. From 2015 to 2017, vegetation greenness steadily declined, eventually falling to or below 2013 levels in most reaches.
- The pulse flow had positive impacts on birds. The abundance of birds increased by 20% and bird diversity increased by 42% in the floodplain of the Colorado River in Mexico after the pulse flow. Their abundance was reduced in subsequent years, but their numbers were still 75% higher in 2016 than in 2013. At the restoration sites, in 2017, bird diversity was 27% higher and the abundance of the 15 indicator species was 80% higher than in the rest of the flood plain.

The Minute 319 pulse flow demonstrated that the Colorado River can connect to the sea, garnered broad community and philanthropic funder support for habitat restoration activities, and created significant (albeit temporary) river-based recreation opportunities.

The Minute 319 monitoring efforts enabled the United States and Mexico to incorporate these lessons learned into Minute 323[6], particularly in planning for environmental water deliveries and habitat restoration.

[6] "Extension of Cooperative Measures and Adoption of a Binational Water Scarcity Contingency Plan in the Colorado River Basin"