GEOMORPHIC CHANGE IN THE LIMITROPHE REACH OF THE COLORADO RIVER IN RESPONSE TO THE 2014 DELTA PULSE FLOW, UNITED STATES AND MEXICO

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Abstract A pulse of water was released from Morelos Dam into the dry streambed of the Colorado River in its former delta on March 23, 2014. Although small in relation to delta floods of a century ago, this was the first flow to reach the sea in nearly two decades. The pulse flow was significant in that it resulted from an international agreement, Minute 319, which allowed Colorado River water to be used for environmental restoration. Here we present a historical perspective of channel change and the results of geomorphic and sediment transport monitoring during the pulse flow between Yuma, Arizona and San Luis Rio Colorado, Sonora. This reach is known as the Limitrophe, because the river channel is the legal border between the United States and Mexico. Peak discharge of the pulse flow was 120 m^3/s at Morelos Dam, but decreased to 71 m^3/s at the southern border because of infiltration losses to the dry streambed. In contrast, flood flows in the 1980s and 1990s peaked above 600 m^3/s at the southern border, and high flows above 200 m^3/s were common. The sustained high flows in the 1980s caused widening and reworking of the river channel downstream through the delta. In the Limitrophe, flooding in 1993 from the Gila River basin dissected the 1980s flood surfaces, and smaller floods in the late 1990s incised the modern “active” channel within these higher surfaces. Field observations show that most geomorphic change during the pulse flow was confined to this pre-pulse, active channel. Relatively little bank erosion was evident, particularly in upstream reaches where vegetation is most dense, but new sandbars formed in areas of flow expansion. Farther downstream, localized bed scour and deposition ranged from 10s of centimeters to more than a meter, and fluvial dunes aggraded the bed in several locations. Measurable suspended-sediment transport occurred throughout the Limitrophe. Sediment concentrations peaked during the rising limb, and suspended sand concentrations suggest deposition in the lower 7 km of the Limitrophe as the channel gradient decreases by an order of magnitude. The pulse flow was small compared to historic floods, and flood magnitudes greater than the 2014 pulse flow are therefore necessary to significantly rework stable geomorphic surfaces or induce channel widening.

INTRODUCTION

The Colorado River delta is a completely transformed landscape. The Colorado River in much of its former delta is now an intermittent stream and includes long segments that are persistently dry. Historically, the delta extended from a point approximately 21 km upstream from the Gila River confluence near Yuma, Arizona, downstream to the Gulf of California, and includes the closed basins of the Salton Sink in the United States and Laguna Salada in Mexico. Sykes (1937) estimated the delta covered approximately 8600 km^2. Prior to the construction of large dams and diversions, the flow of the Colorado River in its delta fluctuated annually with high flows from snowmelt in the Rocky Mountains and periodic widespread rain or rain-on-snow events in the lower basin. Discharge recorded at the Yuma stream gage exceeded 5000 m^3/s several times in the early 20th century, and, occasionally, during periods of extended low flow, no water reached the estuary in the pre-dam period (Sykes, 1937). In its natural state, the Colorado River delta was characterized by shifting channels and high sand, silt, and clay loads. Meade et al. (1980) estimated that the Colorado River delivered more than 10^8 tons of sediment per year to the delta prior to significant human activity in the watershed. The completion of diversions to the Imperial and Mexicali valleys in the early 1900s initiated the period of major regulation of streamflow and sediment to the delta, which became increasingly dramatic following the construction of large dams such as Hoover Dam (1935) and Glen Canyon Dam (1963). Today, the Colorado River is normally dry throughout the year along large segments of its former delta in the United States and Mexico and essentially no sediment reaches the Gulf of California.

High flows of the 1980s and 1990s rejuvenated portions of the riparian and wetland ecosystems of the delta that had been lost during the filling of upstream reservoirs. The ecological impact of these flows created significant bi-national interest in using intentional flow releases to rehabilitate parts of the delta ecosystem (Tiegs et al., 2005; Glenn et al., 2008; Flessa et al., 2013). Following more than a decade of international negotiations, Minute 319 of the International Boundary and Water Commission (IBWC) established the political foundation for one experimental flow release. The release of intentional flows into the delta is extremely controversial in a fully utilized river system faced with protracted drought. Thus, the science that underlies this pulse flow and the monitoring of its consequences is crucial to deciding if future environmental flows will occur. Here we present an overview of historical geomorphic change and effects of the spring 2014 pulse flow release in the Limitrophe. The Limitrophe, or border, reach of the river lies between Morelos Dam, the last dam on the river, and the Southern International Boundary (SIB) (Fig. 1). The Limitrophe is a critical segment of the Colorado River in the delta because it is the only segment that is a shared border of the U.S. and Mexico, it is relatively rich in native riparian and marsh habitat in its upstream half (Glenn et al., 2008), and it is almost always dry in its downstream half. This zone was potentially an area of significant loss of flow into the bed and ground water system, and the losses here may greatly decrease the magnitude of flows in Mexico where the potential for rehabilitation is greater.

POST-DAM HYDROLOGY OF THE COLORADO RIVER DELTA The construction of Hoover and Glen Canyon Dams, and the subsequent filling of the reservoirs they impound, resulted in progressively decreasing flows and drastically reduced sediment loads to the lower Colorado River. Stream gaging at SIB serves as a measure of flows to the Mexican portion of the delta from 1950 to the present, and represents the minimum discharge in the Limitrophe because of infiltration losses to the streambed in the downstream half of the Limitrophe. We present the following hydrologic analysis based solely on this stream gage. From 1950 to 1963, Hoover Dam modulated flood flows from the upper Colorado River basin, but the river often flowed to the

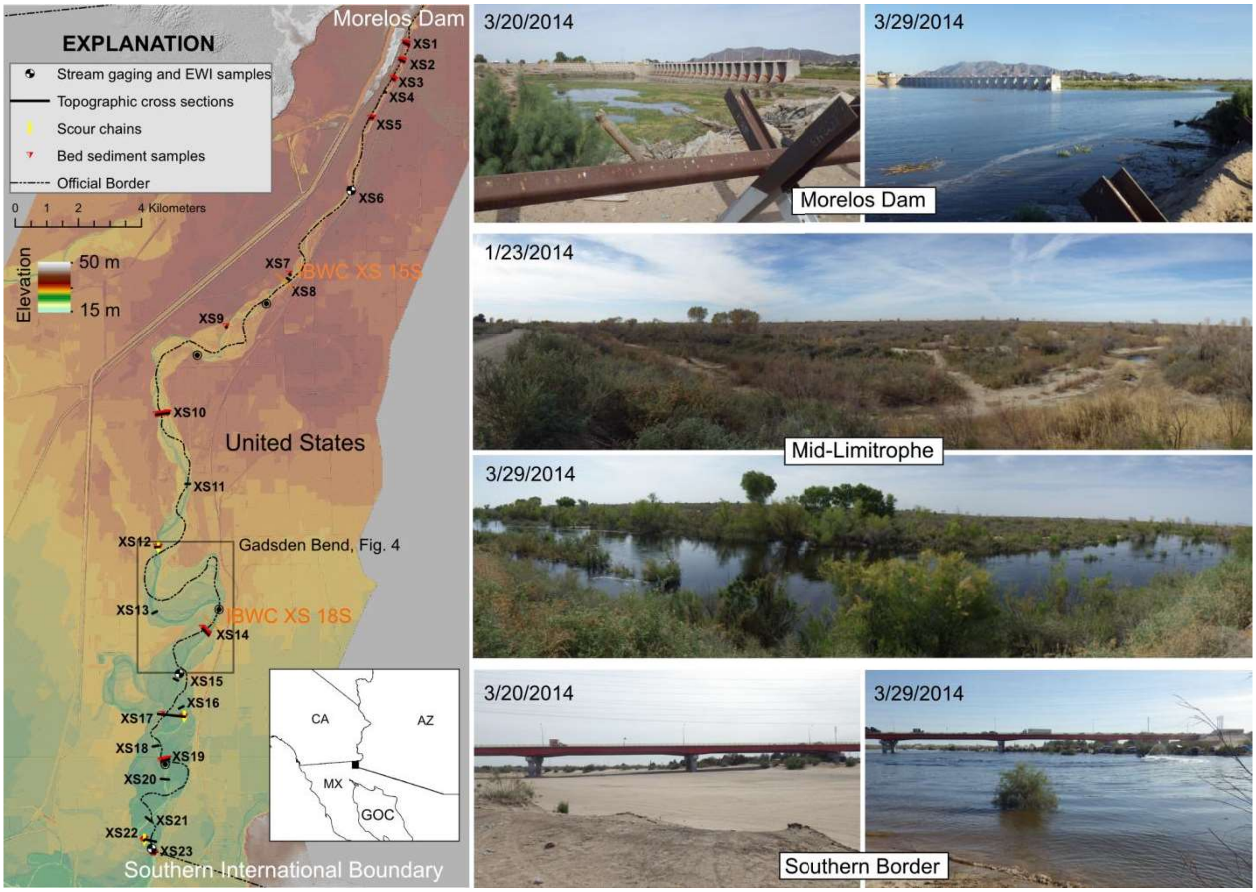

Figure 1 The Limitrophe reach study area (left); inset map shows the location of the Limitrophe as a black square; GOC: Gulf of California. Photos before and during the pulse flow (right).

Gulf of California. During that time the peak daily discharge was 581 m^3/s, the average daily discharge was 93 m^3/s, and zero flow was recorded on only 14 days. From 1963 to 1981, the filling of Lake Powell upstream from Glen Canyon Dam and other reservoirs in the upper basin greatly reduced flows; the peak daily discharge was 268 m^3/s, the average daily discharge was 15 m^3/s, and no flow was recorded 18 percent of the time.

POST-DAM DELTA FLOODS In the 1980s, successive years of extremely high snowmelt runoff from the upper Colorado River basin resulted in a period of high flow releases from Glen Canyon and Hoover Dams (Fig. 2). As a result, flood flows in the delta region were the greatest since the completion of Hoover Dam and caused considerable channel adjustment (McCleary, 1986; Tiegs and Pohl, 2005). Peak daily discharge at SIB reached 934 m^3/s on August 20, 1983, andremained above 500 m^3/s for more than 250 consecutive days. From 1983 to 1987, mean daily discharge remained above 150 m^3/s for nearly four consecutive years. Since that time, flows with magnitudes of 150 m^3/s have occurred less than 3% of the time (Fig. 2). Following the 1980s floods, periods of zero discharge at SIB became increasingly common. From 1989 to 1992, there was no flow recorded at SIB 92% of the time. This dry period was punctuated by flood flows from the Gila River in 1993 that peaked at 646 m^3/s on March 7th and 8th (Fig. 2). The 1993 flooding was caused by a series of winter storms that produced widespread rain and rain-on- snow in the upper Gila River watershed (House and Hirschboeck, 1997). Discharge at SIB remained relatively high throughout much of 1993 because of continued upstream water releases from reservoirs on the Gila River. Following extended periods of zero discharge in the middle 1990s, a series of moderately high flows occurred in the late 1990s. These high flows peaked above 200 m^3/s and followed releases from Hoover Dam that resulted in over-deliveries to Mexico. Progressively decreasing flows have been recorded at SIB since 2000 (Fig. 2).

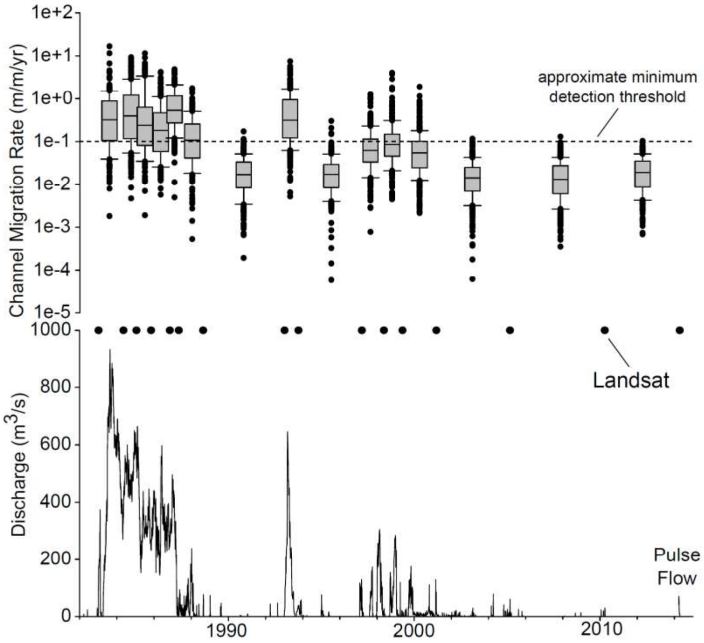

Figure 2 Box plots (top) showing channel migration rates of the Colorado River in the 50 km reach downstream from Morelos Dam; rates are bracketed by the Landsat imagery dates shown. Boxes represent the 25th, 50th, and 75th percentiles; whiskers represent the 5th and 95th percentiles, with outliers as dots. Daily mean discharge (bottom) recorded at SIB, 1980 to present.

THE PULSE FLOW The periodic floods of the 1980s and 1990s created bare sediment surfaces for native seedling recruitment, and made water more available to maturing trees during subsequent periods of low or no flow. But since 2000, drought conditions in much of the Colorado River basin have greatly reduced flows past Morelos Dam. Typically, the upstream half of the Limitrophe has some baseflow because of a higher water table and irrigation return flows. Periods of no flow at SIB have occurred more than 60% of the time since 2000, and the channel bed is usually dry in most of the downstream half of the Limitrophe where the groundwater table is meters below the streambed. This contributed to losses of native riparian vegetation, such as cottonwood and willow, which had established in the prior two decades. The maximum daily discharge measured at SIB since 2000 was 129 m^3/s (on March 1st, 2001). The last measured discharge at SIB prior to the pulse flow peaked at 30.5 m^3/s (in April, 2010) following several winter and spring storms in the lower basin (Ramírez-Hernández et al., 2013).

On March 23rd, 2014, an experimental pulse of water bypassed Morelos Dam and flowed into the dry river channel. The maximum peak discharge released past Morelos Dam was 120 m^3/s on March 29th, which decreased to 71 m^3/s at SIB (Fig. 2) because of infiltration losses to the dry streambed (discussed further in the results). The peak release occurred during a three-day period, and the flow was reduced to zero during a period of approximately three weeks after which flow from Morelos Dam ceased. Additional water was supplied to the river from irrigation canals downstream from SIB in order to supplement the losing flow of the river. The pulse flow reached the Gulf of California on May 15th, by which time the discharge was approximately 0.6 m^3/s.

GEOMORPHOLOGY In the Limitrophe, the Colorado River follows approximately the same path as reported in some of the earliest accounts of river navigation (Sykes, 1937). The river delta was essentially natural until 1900, when large-scale diversions and levees began to be constructed. The period 1900-1930 saw the river channel avulse several times in the delta, with most of the sediment load deposited internally downstream from the Limitrophe, but not flowing to the sea (Sykes, 1937). Closure of Hoover Dam muted flood peaks and greatly decreased the sediment load. Nevertheless, aerial photographs from 1949 show the Colorado River as a dynamic meandering channel with many active bars and bounded by floodplains and terraces that show evidence of recent occupation (Fig. 3). Olmstead and others (1973) report that the Colorado River incised from 3-6 meters from north of Yuma to SIB following the construction of Hoover Dam, but they provide no supporting data. Cross-sections surveyed by the IBWC, spaced approximately 2-3 km apart in the Limitrophe, show 2 to 3 m of bed incision during high flows in the early 1940s. Following this degradation, the bed remained vertically stable or aggraded slightly until the early 1980s (IBWC data, unpublished). There was significant channel widening in the 1980s (Tiegs and Pohl, 2005), and bed elevations in 1989 remained similar to those in 1982, but were still lower than those observed in the early 1940s (Tetra Tech, 2004; NCD/FPC, 2006). The flood of 1993 reworked much of the river corridor that was inundated in the 1980s, and dissected finer channel threads into the 1980s deposits (Tiegs and Pohl, 2005). By 1999, vegetation encroachment, dominated by tamarisk, had created a narrower channel (Tiegs and Pohl, 2005; Tiegs et al., 2005), and the thalweg of most of the IBWC cross-sections reached their minimum elevations (Tetra Tech, 2004; NCD/FPC, 2006).

THE MODERN COLORADO RIVER IN THE LIMITROPHE The Limitrophe can be divided into two major geomorphic segments that have a gradational boundary. The river channel in the upstream segment is more confined within levees, and irrigation return flow results in a wetted channel with dense bank vegetation. In the downstream segment, the river channel is dry, bank vegetation is less dense, and the channel is less confined by levees (Fig. 1). The width of the alluvial corridor between the levees ranges from approximately 0.5 km immediately downstream from Morelos Dam, to more than 4 km in the downstream part of the Limitrophe. The average channel gradient is 0.00022 m/m along the modern thalweg, but reach-scale (5-10 km) gradient ranges from 0.000044 to 0.00040. Sediments range in grain size from silt and clay to gravel, with the active channel composed dominantly of fine to medium sand and finer sediments on higher abandoned surfaces.

METHODS

In this paper, we present results from two related elements to characterize the geomorphic response of the Colorado River in the Limitrophe to the 2014 pulse flow. First, we build on the analysis of historic channel changes from 1983 to 2014 that shaped the configuration of the pre-pulse channel and set the boundary conditions for surface water flow and sediment transport during the pulse. Second, we report results from geomorphologic and sediment transport monitoring of the pulse flow.

CHANGES IN CHANNEL MORPHOLOGY, 1983-2014 We used 30 m Landsat imagery to map changes in the channel thalweg or centerline using 16 image sets that bracketed major flow events. We purposefully chose periods of relatively low flow to more accurately digitize the channel thalweg. During the periods of sustained high discharge in the 1980s, flows were often too high to define the thalweg, and we used the channel centerline instead. After digitizing the channel thalweg/centerline, we used the Planform Statistics Toolbox from the National Center for Earth Surface Dynamics (Lauer, 2006) to calculate channel migration in 100-300 m segments. The exact length of individual segments depended on the degree of channel sinuosity, and thus point spacing, in the digitizing process. In order to account for different segment distances and time intervals, we report the results in meters of lateral change per meter of streamwise distance per year. We approximate the error in thalweg location as plus or minus 30 m, or one pixel width, as a conservative estimate of a minimum detection threshold. Our analysis builds on that of Tiegs and Pohl (2005), extending it through 2014, and establishes the magnitude of those flows that are sufficient to cause significant lateral channel migration.

We also developed a geomorphic base map of portions of the Limitrophe reach to better understand the spatial and temporal evolution of geomorphic change. We used high-resolution aerial photography and a 1-m bare earth lidar digital elevation model acquired from an airborne scanner in March 2014 prior to the pulse flow. Aerial photography dating back to 1949 was available for the entire Limitrophe reach (earthexplorer.usgs.gov). Imagery from 1949 and 1963 is sub-meter resolution, imagery from 1976, 1981, and 1989 has a resolution ranging from 5 to 6 m per pixel, and data sets from 1992 to present (1992, 1996, 2003, 2007, and 2013) are 1-m resolution. These aerial photo dates include images of the river corridor prior to construction of Glen Canyon Dam, which caused major reductions in flow as discussed above. These photo dates also bracket the major floods of the 1980s and 1990s, allowing for documentation of channel change in response to these events. In addition to these aerial photos, we compared historic IBWC cross-sections to the pre-pulse flow lidar to document changes since 1999, and to provide a quantification of changes in bed elevation. Here we present data for two IBWC cross-sections that we could most reliably match to the lidar data (Fig 1).

GEOMORPHOLOGY AND SEDIMENT TRANSPORT DURING THE PULSE FLOW We used repeat cross-sections, scour chains, and suspended sediment transport measurements at multiple locations to document the geomorphic response to the pulse flow. We established 23 cross-sections within the Limitrophe reach (Fig. 1) to document changes in bed elevation and installed scour chains at three of these cross-sections (12, 17, and 22, Fig. 1) to analyze scour and fill. We spaced cross-sections 1 to 4 km apart and focused on areas likely to be inundated by the flood. Cross-sections were more concentrated immediately downstream from Morelos Dam, and in the dry reach in the downstream portion of the Limitrophe (Fig. 1). We collected 3 to 15 sediment samples on representative surfaces at 14 of the cross-sections before and after the pulse flow. Lidar data were obtained for the entire Colorado River delta in March and August 2014, and will be used to provide a broader spatial picture of channel change resulting from the pulse flow (as of the time of writing, the second lidar data set was still being processed). Suspended sediment measurements were made at three locations in the Limitrophe to provide a record of sand and silt and clay concentrations. Daily equal width increment (EWI) samples were collected on six occasions at three sites during the period of peak discharge of the pulse flow. Here we report results from the two downstream sites located near cross section 15 (Colorado River near Gadsden, Arizona) and at SIB (Colorado River at the Southern International Boundary) (Fig. 1).

RESULTS AND DISCUSSION

CHANGES IN CHANNEL MORPHOLOGY, 1983-2014 Channel migration rates during the three decades since 1983 were greatest during the large floods of the 1980s. Landsat imagery bracketing individual hydrograph peaks during this time shows that between 50 and 75% of the channel had migration rates above the minimum detection threshold, and as much as 25% of the river channel migrated at rates exceeding 1 m/m/yr (Fig. 2). Channel change was particularly pronounced in the downstream portion of the Limitrophe, and substantial portions of higher pre-dam terraces eroded 500 to 1000 m laterally, effectively increasing the size of the lower elevation channel (Fig. 3). There was little channel activity in the late 1980s and early 1990s during a period of very little flow (Fig. 2). The Gila River floods of 1993 caused a similar proportion of the channel to migrate as during floods in the 1980s (Fig. 2). Yet most geomorphic change was confined to the part of the channel affected by the 1980s floods, rather than eroding older and higher terraces (Fig. 3). The 1993 flood dissected much of the 1980s flood surfaces, resulting in a braided appearance on many of these surfaces (Tiegs and Pohl, 2005). Measureable channel migration occurred along approximately 25% of the channel for three periods analyzed during moderately high flows in the late 1990s and early 2000s (Fig. 2). Channel migration rates were 2-10 times less than during the larger 1980s and 1993 floods, and confined to a narrower zone in the river corridor. No measureable channel migration, within the resolution of the Landsat data, has occurred since 2001 (Fig. 2).

Our analysis of aerial photography and the historic IBWC cross-sections suggest that bed incision occurred during high flows in the late 1990s that peaked above 200 m^3/s. While the exact positioning of cross-sections has changed over time, decreasing confidence in smaller scale changes, it is clear that the modern cross-sections derived from lidar are similar to the form measured in 1999 (Fig. 4). The 1980s floods caused significant channel change between 1982 and 1989, but relatively little change in bed elevation (Fig. 4; Tetra Tech, 2004; NCD/FPC 2006). By 1999, the thalweg of the channel had incised below the 1989 thalweg, and the 2014 lidar indicates that the channel configuration is very similar to that observed in 1999. Prior to the 1980s floods, the IBWC data suggest that the most significant channel changes occurred in the early 1940s when there was roughly 2 and 3 m of bed degradation (IBWC unpublished data). The resulting geomorphology of the river corridor in the Limitrophe thus benches down from higher terraces that were active in the pre-dam period, to intermediate terraces representing portions of the active channel and floodplain in 1949 that were largely stable by 1963, and finally to more recent surfaces of the 1980s and 1990s (Fig. 3). Aerial photos and lidar suggest that, in the downstream part of the Limitrophe, the floods of the early 1980s deposited a higher alluvial surface (Fig. 3), and smaller flood peaks in the late 1980s formed an inset channel within this surface (Fig. 3). The 1993 flood reworked this lower 1980s surface considerably, but also caused a more defined thalweg to become incised. The floods in the late 1990s mostly modified this inset channel, which became further incised, and forms the modern “active” channel (Fig. 3). The bed of this inset active channel is 2 to 3 m below those surfaces reworked in 1993, and has a

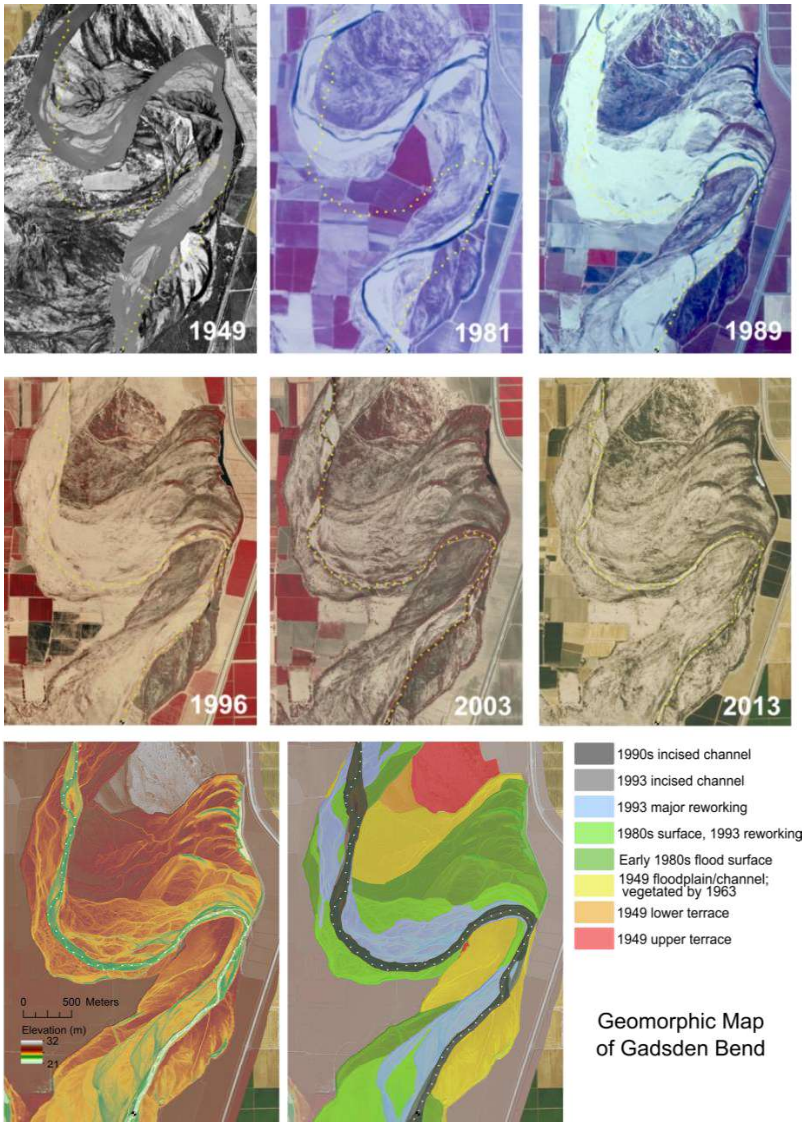

Figure 3 Aerial photos showing geomorphic change for six years from 1949 to 2013; yellow dots indicate modern thalweg. Pre-pulse flow lidar (bottom left) and geomorphic surfaces (bottom center), showing modern thalweg in modern "active" channel incised in the late 1990s.

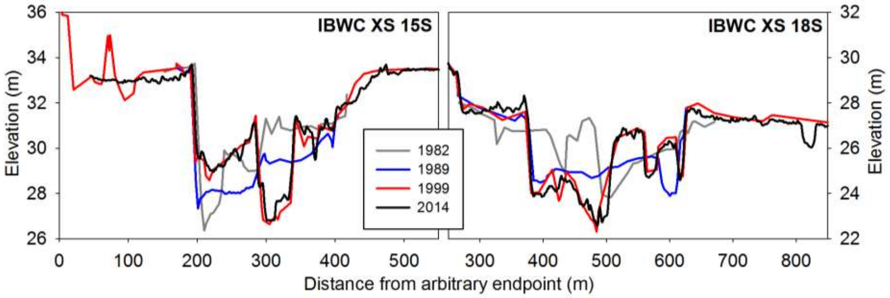

Figure 4 Historic cross-section changes at two locations shown in Figure 1 in the Limitrophe from 1982 to present. 1982, 1989, and 1999 surveys from the U.S. IBWC (data from TetraTech, 2004 and provided by NCD/FPC, 2006), and 2014 data from pre-pulse flow lidar.

typical width of 50-200 m in the Limitrophe. This incised part of the channel contained the majority of the pulse flow, but it did inundate higher surfaces with shallow, low-velocity flow.

GEOMORPHOLOGY AND SEDIMENT TRANSPORT DURING THE PULSE FLOW

The hydrograph of daily flow from Morelos Dam shows a 3-day period of maximum releases, a second discharge spike three days after the peak, and several other fluctuations during the falling limb (Fig. 5). Attributes of the hydrograph observed in the Morelos Dam releases are preserved downstream, but discharge decreased by 30 to 40% because of flood attenuation and, primarily, by infiltration losses to the dry streambed. Further, because of increased groundwater levels during the preceding week, the second peak was of similar magnitude to the first peak in the downstream reaches that were initially dry. The pulse flow tended to inundate a wider area upstream, resulting from a combination of higher discharge upstream and greater channel roughness from dense bank vegetation (Fig. 6).

Suspended sediment concentrations were somewhat greater at the beginning of the pulse and decreased over time, and there is evidence of discharge-concentration hysteresis as measured at our two sampling locations in the downstream part of the Limitrophe (Fig. 5). The decrease in sand concentration at SIB during the pulse may coincide with the formation of dunes that increased drag, because both the grain size and concentration of suspended sand decreased as flow increased. Alternatively, suspended sand coarsened slightly with discharge at our measurement site 7 km upstream (near Gadsden). Sand concentrations were two to three times greater at this upstream site, but silt and clay concentrations were similar between the two sites. Thus, silt and clay likely behaved as wash load and moved downstream to Mexico, whereas sand deposition is likely to have occurred in the downstream 7 km of the reach. Channel gradient is an order of magnitude less between the Gadsden gage and SIB, compared to the reach immediately upstream, and may be a factor in decreasing downstream sand concentrations.

Geomorphic change in response to the pulse flow was limited to the incised active channel that formed during the progressively decreasing flows of the late 1990s and early 2000s. Cross-sections show that the pulse flow inundated most areas to an elevation equal to or slightly greater than the bank top elevation of the previously incised active channel (Fig. 5). In the upstream part of the Limitrophe, thick bank vegetation focused channel change on the narrow, ~20 to 50 m wide, part of the channel that was within, or immediately adjacent to, the wetted portion of the pre-pulse channel. There was little evidence of bank erosion, but sandbars locally buried vegetation and the main channel bed was reworked (Fig. 6, top photo). Because of the negligible upstream sediment contributions and the confined nature of the active channel, we expected that bed incision would occur in these upstream reaches (XS1-XS6, Fig. 1). Instead, our repeat surveys show little evidence of bed incision in these reaches, and, in fact, slight (~0.25 m) aggradation at several cross-sections. A potential sediment source immediately downstream of Morelos Dam was the erosion of dredged material composed of sand and gravel along the Mexican side of the river corridor, but outside of the primary active channel. Much of the channel bed that had been composed of sand overlain by finer sediments bound by an organic mud was composed of sand and gravels following the pulse. Sandbars formed in zones of flow expansion, and the bed of the river developed pool-riffle topography in several locations. Riffles were characterized by coarser bed material and active bed load transport at baseflow discharges (~1-2 m^3/s) following the pulse flow.

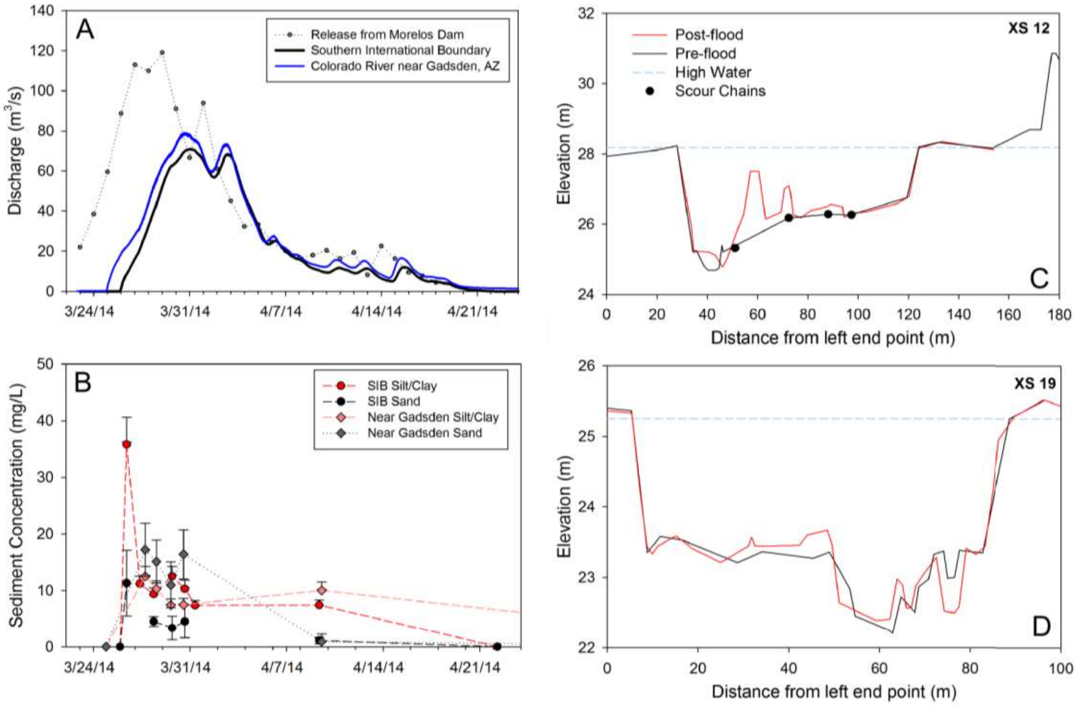

Figure 5 Hydrograph of the pulse flow released at Morelos Dam and measured near Gadsden, Arizona and at SIB (A). Measured sediment concentrations at the Gadsden and SIB gages (B). Two example cross-sections showing topographic change during the pulse flow (C and D).

Downstream where the channel widens, areas of localized bed scour and deposition ranged from tenths of meters to more than a meter and fluvial dunes provided evidence of widespread bed mobilization (Figs. 5 and 6). In the middle portion of the Limitrophe, the main thalweg usually has some baseflow that has allowed dense riparian vegetation to flourish, which protected the stream banks from erosion during the pulse flow. However, there are also remnants of the old 1990s channel that are dry and barren of vegetation. These open sand areas (tens of meters by hundreds of meters) were zones of active dune transport despite relatively shallow flow. The dunes had wavelengths of order 5-15 m, and amplitudes of 0.2 to 0.4 m. Alternatively, the wetted part of the channel in the middle Limitrophe generally showed bedforms associated with topographic steering in a more confined and sinuous channel. Five scour chains placed across the active channel in the mid-Limitrophe show no evidence of bed scour, but as much as a meter of deposition (XS-12, Fig. 5). Immediately upstream from the scour chains there was obvious bed scour and the repeat cross-section shows areas of erosion and deposition in the thalweg.

In the farthest downstream section of the Limitrophe, where the channel was dry and the channel bed was largely devoid of vegetation, evidence of dune migration was obvious throughout the reach. Localized lobate forms (1-10 m) and larger-scale dune fields (>100 m) were common in many places (Fig. 6). Cross-sections in this reach show evidence of both scour and deposition (XS-19, Fig. 5), with little change in grain size. Of our scour chains, and those of our Mexican colleagues, only two locations show evidence of significant scour (>0.1 m) prior to deposition, whereas most show simply scour or deposition. Scour chains at our site just upstream of SIB did show 0.05-0.15 m of scour followed by up to 0.3 m of deposition. Dunes are clearly visible from

Figure 6 Landsat image from 3/31/2014 during the peak of the pulse flow and examples of sediment deposition and bed forms because of the pulse flow. Backpack (circled), 2 m rod in foreground, and person (circled) for scale. Width of channel is approximately 300 m in the Worldview panchromatic image at right.

aerial photos at this site during the waning stage of the pulse flow (Fig. 5). As stated above, the lower 7 km of the Limitrophe was likely a depositional reach, and the short duration of the pulse likely limited downstream transport distances. Any sediment transported past the border must have been deposited on the channel bed far upstream from the estuary as flow rapidly decreased.

Sediment transport and geomorphic change in the Limitrophe during the pulse flow was concentrated in the recent active channel where flow depths were several meters. Higher surfaces were only marginally inundated, and there was no noticeable geomorphic change. Thus, these surfaces served as a pseudo-floodplain for flows similar to the 2014 pulse flow, which flowed through a channel roughly sized to convey that discharge. Ongoing studies will provide quantification of sediment concentrations in the upstream part of the Limitrophe measured at XS-6 (Fig. 1), and allow us to construct sediment budgets between the three gaging stations. We also anticipate that our future analysis of repeat lidar measurements will provide a more spatially robust link between the flux-based sediment budgets and morphologic change, and document the fate of sediment transported to reaches farther downstream in Mexico.

CONCLUSIONS

The Colorado River in its delta is now an intermittent sand-bedded stream for much of its course. Decreasing peak flows during the last two decades shaped the active channel in the Limitrophe reach, and the active channel is sized to convey flows of roughly 100 m^3/s. Terraces formed during the 1980s floods and dissected by the 1993 flood served as a pseudo-floodplain during the 2014 pulse flow. Geomorphic change and sediment redistribution during the pulse flow was limited to reworking of the channel bed and topographic changes of order 1 m or less within the active channel. Channel widening or widespread scouring or burial of vegetation that may affect native vegetation recruitment is only likely to occur with higher discharges. This presents a dilemma for future planning of environmental flows to the delta, because higher river flows correspond to a greater cost in terms of volume of water lost to the subsurface and may cause further channel incision. Furthermore, long-term restoration outcomes will also be contingent on larger floods that will occur periodically from widespread and persistent precipitation in the Gila River basin, and monitoring strategies should consider these unplanned floods.

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