POST-DAM SEDIMENT DYNAMICS AND PROCESSES IN THE COLORADO RIVER ESTUARY AND ITS IMPLICATIONS FOR HABITAT RESTORATION.

by

Hector A. Zamora

A Prepublication Manuscript Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

In the Graduate College
THE UNIVERSITY OF ARIZONA
2013
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Abstract

River-sea connectivity is essential for restoring ecosystem services in the Colorado River delta. The mixing of river water and seawater sustains biodiversity and provides brackish-water nursery grounds for both commercially important and endangered marine species. The Colorado River no longer reaches the sea except during particularly high tides and anomalously wet years. The river’s relict channel is now obstructed by an accumulation of sediments deposited during flood tides; ebb flows are not strong enough to keep the channel open. Landsat 5-TM and Landsat-7 scenes from the Colorado River delta and tide prediction tables were used to reconstruct river-sea connectivity and geomorphic processes after 50 years of extensive human manipulation of the Colorado River. Historical documentation, previous topographic surveys and sediment cores were used to estimate sedimentation rates in the lower river channel. Satellite images and tide charts show that currently the river reaches the sea or the sea reaches the river about 12 days per year, unlike 10 years ago when a year-round connection existed. Reduction in connectivity results from the evolution of a tidal sandbar located within the bedload convergence zone, about 35 kilometers upstream from the river’s mouth. Historical documentation and sediment core analyses suggest sedimentation rates in the range of 10-21 cm per year. With the current conditions prevailing, active management -dredging- is required and needs to occur once every 5-10 years to reconnect the remaining riparian wetlands in the Colorado River to the Gulf of California.
Introduction

The Colorado River is the most important river in the southwestern United States and it allowed for the extensive agricultural and urban development in the southwestern U.S. and northwestern Mexico. Progress in the region came at a significant environmental cost to the river’s delta and estuary sections. Prior to large-scale river diversions, the 800,000 hectares of the delta received 18 billion cubic meters of freshwater discharge annually, forming an enormous estuary and serving as home for a diverse number of bird and fish species (Calderon-Aguilera and Flessa, 2009). During the last century, the Colorado River became one of the most managed and diverted rivers in the world (Figure 1). Dam building projects and water management practices were implemented to provide water to more than 27 million people and more than 1.2 million hectares of farmland in the rapidly developing southwest U.S and northwestern Mexico (Barnett and Pierce, 2009). The 1944 treaty that allocated water to Mexico and the United States did not account for the water needs of the wetland and estuary ecosystems. Water consumption for human uses led to a massive decrease in the biodiversity and ecosystem services downriver on the Mexican part of the delta. At present, less than 1% of the river’s water reaches the delta and the area formerly occupied by wetlands has been reduced to less than 5% of its original extent (Zamora-Arroyo and Flessa, 2009). Furthermore, the river no longer reaches the sea except during extremely wet years and during very high spring tides. Spring-season floods no longer maintain a connection to the Gulf of California by clearing away material accumulated in the river’s lowermost channel restricting nursery grounds for endangered and economically valuable species (Rowell et. al., 2005; Rowell et al., 2008).

The river’s relict lowermost channel is plugged by sediment accumulated during flood tides. Ebb flows are not strong enough to keep the river channel open. Spring-season floods, which used to deliver 60 percent of the river’s flow in only three months (USGS, 1954; Harding et al., 1995), no longer reach and
maintain the channel. Under these circumstances, active river management - dredging - is needed to reconnect the river and the Gulf of California. This research seeks to understand current sedimentological processes and quantify sedimentation rates in the river’s lowermost channel section in order to develop a feasible plan to manage sedimentation and water flux. A healthy river-ocean interface can help restore nutrient cycling processes, improve nursery grounds for commercially valuable fish and shrimp, provide habitat for biodiversity, and flush the estuary from accumulated salts and contaminants.

Study Area

The Colorado River delta begins near Yuma, Arizona, and extends into the states of Sonora and Baja California in Mexico south to the Gulf of California (Figure 2). The southern delta portion and the upper Gulf of California were declared protected land under the UNESCO Biosphere Reserve program in 1993 by the Mexican government. Located between 31.5N and 32.0N, it is one of the warmest and driest regions in North America: average temperatures reach 40°C during the summer and annual precipitation averages about 6.5 centimeters (Zamora-Arroyo et al., 2001). Two important agricultural districts are located in the region, the Imperial Valley (USA) and the Mexicali Valley (Mexico); they are both fed by water retained in Lake Mead and Lake Powell (Graf, 1985). Little in-channel flows reached the delta after Glen Canyon Dam’s completion in 1964 (Glenn et al., 2001) and prevailing drought conditions in the Colorado River Basin since 2000 have further restricted flow releases into the Delta (IBWC, 2011). Downstream of the U.S. - Mexico border and Morelos Dam, the Colorado River is joined by the Hardy River, a former Colorado River channel, discharging agricultural waste-water from the Mexicali Valley, and treated wastewater from the recently artificially created Arenitas wetlands (Daesslé et al. 2009; Valdes-Casillas et al. 1998). This water has helped to partially restore and sustain the few, but still
important wetlands and riparian corridors that remain in the area.

**Colorado River Estuary**

The Colorado River estuary is now limited to the southern section of the delta (Figure 3). Near the river’s mouth, it is characterized by a funnel-shaped channel 45 km in length with two elongated, linear tidal ridges, Montague and Pelican Islands (Carriquiry et al., 2011). This estuarine morphology is often found in macrotidal or tide-dominated settings (see, e.g., Wright, 1977). The gentle gradient in the estuarine channel (16 cm/km) above the tidal islands (Thompson, 1968), combined with the extreme tides characteristic of the Northern Gulf of California (up to 10 m) result in tidal waters reaching far upstream from the river’s mouth (Payne et al., 1992).

The estuary is described as a hypersynchronous estuary, where tidal-induced currents reach maximum speeds in the upper sections due to the tidal wave convergence into a smaller cross-sectional area; these currents are ultimately dissipated by friction near the tidal limit (Allen, 1980; Wells, 1995). Three different energy regions receiving active river flow are found in such settings: marine-dominated, mixed energy and river dominated (Dalrymple and Choi, 2007). Prior to massive dam operations, the Colorado River deposited large amounts of sediment, actively prograding its delta. During strong river-flow conditions the bedload convergence zone, where tidal and fluvial bedload meet, was located seaward of the river’s mouth creating the characteristic tidal ridges present at the mouth (Dalrymple and Choi, 2007). Dalrymple and Choi (2007) suggest that in a tidally dominated estuary with low river influence, the bedload convergence zone will be located inland from the mouth, resulting in active transport of sediment inland from the mouth into the convergence zone. The effect of the hypersynchronous estuary coupled with the fact that in the northern Gulf, the highest tides follow the lowest tides (Thompson, 1968), generates currents strong enough to entrain and deposit bedload within the mixed
energy zone during high water slacks between the higher high and lower low tides.

Tidal conditions promote bedload transport from the Gulf into the lower channel, and appear important for sandbank formation and the maintenance of Montague Island and Pelicano Island despite the lack of fluvial sedimentation (Montaño and Carbajal, 2008). Carriquiry et al., (2011) suggest a net sediment export (up to 7 tons per tidal cycle) and a delta erosion phase based on their measurements of suspended sediment loads during dominating neap tide ebb-flow stages (stronger and faster than flood flow) at the river mouth. Although their study provides important information about sediment dynamics south from the mouth of the river, their estimates are based only on neap tide conditions and may overestimate sediment export values during the stronger spring tide conditions (Montaño and Carbajal, 2008). In any event, their observations do not explain the channel siltation observed in the estuarine lower channel, where strong flood currents seem to dominate during spring tides. This flood-current dominance upstream from the river’s mouth during spring tide conditions is explained by the tidal wave asymmetry resulting as the tidal wave interacts with the estuarine geometry and becomes distorted while it moves upstream (Figure 4). During these particular events, flood-flows will be shorter in duration, but higher in magnitude resulting on stronger currents. The subsequent ebb-flows will be longer in duration but lower in magnitude with currents not as strong as during flood flows. In terms of sediment transport, this suggests that while there will be an import and export during both flood and ebb tides, a net import of sediment into the estuary will result from the stronger currents generated during flood events. The resulting sediment accumulation in other similar settings has been observed to occur in the bedload convergence zone where the tightest bends in the channel occur, within a “low-high-low” channel sinuosity pattern (Dalrymple et al., 2012). This observation holds true for our study area as the focus of sediment accumulation in the channel seem to be localized in this particular position (Figure 5). With the lack of fluvial in channel flows reaching the delta, we suggest the
previously described mechanisms of sediment transport to be dominating in the area carrying sediment upriver into the estuary particularly during spring-tide conditions.

Materials

Landsat Archive and Historical Data

In order to reconstruct the history of river-gulf connectivity and geomorphic changes in the estuary during the last decades, RGB Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM+) scenes from the 1972-2010 period were acquired from the United States Geological Survey EarthExplorer website (http://earthexplorer.usgs.gov/) and interpreted using ArcGIS® software package. Landsat MSS color composite scenes were displayed using bands 5(2) (red, 0.6-0.7 μm), 6(3) (NIR, 0.7-0.8 μm), and 7(4) (0.8-1.1 μm). Landsat TM and ETM+ were displayed using bands 1 (blue, 0.45-0.52 μm), 4(NIR, 0.52-0.60 μm), and 5 (SWIR, 1.55-1.75 μm). These bands were selected in order to enhance visibility of water covered or wet surfaces (Nelson et. al, 2012). By combining the imagery from the different sensors, up to four images per month could be obtained. These images were used to estimate the tidal height needed for marine water to reach the river and the frequency of such connection. A topographic study of the estuary of the area from 2010 (Zamora-Arroyo, 2012; Appendix A) and a longitudinal section map of the estuary made by the Mexican Agriculture and Hydraulics Service (MAHS) in 1972 (USACE, 1982; Appendix B) were also used to assess sediment accumulation and geomorphic evolution during the last four decades.

Sediment Cores

Four sediment cores measuring 75-107 cm were obtained from the Colorado River delta, including two samples from the estuary (CRE1 and CRE2, Figure 3) and two samples from the Hardy River (HR1 and HR2, Figure 3) during late July-early August 2011. The sediment cores were acquired using an Aquatic
Research Instruments universal percussion corer lined with acid-washed, polycarbonate core barrels (68mm x 71mm x 120cm). Cores were retrieved at strategic sites where tidal influence had been observed, and where an open channel was present during the last 4 decades according to the Landsat archive and historical documents. After collection, excess water was drained from the core. Transportation in upright position was maintained to prevent disturbing the core’s natural structure. For the present study, the two cores from the estuary, CRE1 (not shown) and CRE2 (Figure 3), and the two cores from the river HR1 (Figure 3) and HR2 (not shown), were sliced transversely, photographed, described, and subsampled in 1.0 cm intervals for different analyzes. The remaining cores and core fractions were stored at 35 °F in a cold room at the University of Arizona.

**Analytical Methods**

Channel Connectivity

Tidal heights in the area were predicted using the MARV10 tide predictor program created by the Center for Scientific Research and Higher Education at Ensenada, Baja California (CICESE, http://www.cicese.edu.mx) for San Felipe, Baja California because no tidal height prediction stations exist in the estuary. A process was needed to reconstruct river-sea connectivity because Landsat temporal resolution did not allow scene collection for every single day and every important tidal event. Starting in 2000 until 2010, images within each year were scrutinized; those showing a clear river-gulf connection during high tides were identified and marked, and the predicted tide height for each particular event was recorded. The lowest high-tide among these events was assumed to be the minimum tidal height needed to maintain connectivity. For example, during 2009, the minimum tide needed to maintain a connection was 5.42 m. Using the CISESE tide predictor, each day having a 5.42 m tide or higher was counted as a day having connectivity and was ratified by the satellite images if the image for that date was available. This same approach was followed for every year from 2000-2009.
Grain Size Analysis

Grain size distribution was obtained using a Malvern Mastersizer 2000 laser-diffraction particle size analyzer. Core CRE2 was sub-sampled at 1-cm intervals and approximately 0.5 cm$^3$ of sediment taken from each interval. These sub-samples were treated for 24 hours with 10% HCl in centrifuge tubes and placed inside a heating block at low heat to remove carbonate material. Supernatant was decanted after centrifugation at 3500 RPM for 3 minutes. The process was repeated twice and followed by washing with DI water, centrifugation, and decanting twice as well. The entire process was repeated using 30% H$_2$O$_2$ to remove organic material, and 1M NaOH to remove biogenic silica. Prior to analysis in the Malvern Mastersizer 2000, 10 ml of dispersant (25 g sodium hexametaphosphate dissolved in 500 ml DI water) was added to the samples followed by reciprocating shaking. Five different measurements were made for each sample and an average was obtained from the results.

$^{210}$Pb Geochronology

The radioactivity of $^{210}$Pb and the anthropogenically produced $^{137}$Cs were measured on 16 homogenized, oven-dried subsamples from core CRE2. These samples were analyzed using a gamma-ray spectrometer with a well-type germanium detector (EG&G ORTEC Co. Ltd.) corrected for self- absorption effects at the Shimane University in Japan. Obtained activities were used to determine sedimentation rates in the study area using the $^{210}$Pb method originally developed by Appleby and Oldfield (1978). Water content was calculated in the samples by weighting the wet samples, drying them in an oven and reweighting them. This was followed by storage in gas-sealed containers for 4 weeks to attain secular equilibrium between $^{226}$Ra and $^{222}$Rn. Supported $^{210}$Pb was established using $^{214}$Pb (352 keV), the short-lived daughter of $^{226}$Ra (Joshi, 1987; Daesslé et al., 2009). To estimate the excess $^{210}$Pb, the $^{210}$Pb supported fraction was subtracted from the total $^{210}$Pb (46.5 keV) exhibited at the different sediment intervals.
Sediment Core Description

Estuary

Core CRE2 from the estuarine section of the Colorado River delta had a length of 96 cm, and it was characterized by heterolithic deposits containing very fine silts, fine sands, and minor amounts of clay-sized particles (Figure 6). The upper 3-4 centimeters of the core and CRE2 contained a light-brown (7.5 YR 6/4 Munsell Color Scale), wavy, very fine silt that coarsened into fine silty-sands up to about a depth of 21.5 cm. Between the silty-sands, a black (10 YR 2/1), organic rich section, characteristic of reducing conditions is present. At 21.5 cm in depth, CRE2 shows a sharp contact and a down-core transition from the fine-silty sands into a brown (7.5 YR 5/4) very fine silt suggesting a sudden change in energy and sediment dynamics. This portion is distinguished by thin, 0.1-0.7 cm very fine clayey-silt wavy laminae intercalated with very thin 0.1-0.2 cm very fine sandy-silt laminations down to a 40 cm depth. At 40 cm and down to the bottom of the core, there is a marked increase in the number of laminae present and the thickness of sandy material. These sands are fine, oxidized reddish-brown (5 YR 4/4) in color, with layers ranging from 1-5 cm in thickness and intercalated with grayish brown (10 RY 3/2), wavy to straight, 0.3-0.6 cm fine silt laminae. A conspicuous 5-cm thick layer is present at about 68-73 cm suggesting a high energy event of some kind. In general, there seems to be an increased sand concentration in the deeper core sections, especially below 40 cm in depth. These sand layers suggest frequent high energy episodes capable of transporting coarser-grained material into the mid-estuary section. Core CRE1 measures ~75 cm, but part of the surface portion of sediments was lost during its collection. In this core, the sharp contact present in core CRE2 at 21 cm is also present at 10 cm in depth. Below the sharp contact this sediment column shows overall the same heterolitic characteristics and structures as CRE2 since it was collected only a few meters away. However, sand layers thickness varies by a few centimeters from core CRE2, possibly due to terrain differences. The correlation between these two cores suggests that they were exposed to the same environment of depositional
conditions.

Hardy River

Cores HR1 (Figure 6) and HR2 had a recovery length of about 107 cm. Both cores are composed of very fine silts and clay sized particles with no visible sand layers as those observed in cores from the estuary. Unlike the cores from the estuarine section of the Colorado River delta, these cores do not show as much variability in terms of sedimentary structures. In fact, the upper 55-60 cm of the cores section shows 3-6 cm thick layers, without any other depositional structure, but they are capped by a 0.5-3 cm black organic-rich layer. Besides the observed black organic layers capping the described sections of the core, no other small scale structure is observed in the upper 55-60 cm of the column. Below the 55-60 cm section, not much variation is observed except for the thinning of the layers going from 3-6 cm to 1 cm or less. The visible absence of sandy material in this section of the river (before reaching the estuary) suggests that it is not a source of this grain fraction for the estuarine area of the Colorado River delta. Cores HR1 and HR2 are located about 15 km northwest from cores CRE1 and CRE2, and about 45 km northwest from the mouth of the Colorado River. The distance is enough to keep cores HR1 and HR2 isolated from current tidal processes rather reflecting fluvial environment characteristics similar to those cores described by Daessle et al. (2009), upriver from the El Tapon Dam (about 8 km upriver from our HR cores), which show zero to low (max 21%) sand fractions with estimated sedimentation rates of 0.5-2.0 cm a⁻¹ based on stratigraphic markers.
Results

Channel Connectivity

Landsat scene analysis show a clear reduction in channel connectivity after the year 2000. Particularly after 2003, the number of days having a connection decreased from an almost full-year connection to about only 12 days per year in 2009 (Figure 7). This number is close to the 10-12 days observed in 2011 by Nelson et al., 2012 using pressure-based logger data in the estuary. As the number of days of connectivity decreased, the tide height needed for marine water to reach and connect with the river channel increased. The emergent crest of a tidal sandbar in the mid-estuary section, 23 km north of Montague Island, is evident by 2006 in Landsat images. By the year 2009, a tidal height of 5.42 meters was needed to keep a connection, unlike 2003 and before, when a 4.37 m tide could reach the area now occupied by the tidal sandbar. It is important to remember that because we are using the tide prediction at San Felipe and the tidal wave is further deformed as it travels into the estuary, these tidal heights needed to keep connectivity are relative heights and do not necessarily represent the height of the sandbar.

Sedimentation Rates

Field Survey and Historical Documentation

In 1972 the MAHS reported a tidal sandbar occurrence along 29 kilometers of the channel in the estuary (USACE, 1982). In that report, the sandbar rose to 1.7 meters above the normal channel bottom (3.5 above mean sea level, ASL), and it can be clearly observed in 1970’s Landsat imagery (see Nelson et al., 2012). The tidal sandbar started to accumulate after Glenn Canyon dam started operations in 1964. The filling of Lake Powell behind Glen Canyon Dam caused a sharp reduction in the flow of water across the US-Mexico border. At that time, tidal processes became dominant over fluvial processes. The MAHS report (Appendix B) indicates a tidal sandbar height increase from a base of 3.5 m ASL to 5.2 m
ASL from 1964 to 1972; this implies average sedimentation rates of up to 21 cm a\(^{-1}\) at the tidal sandbar crest to accumulate 1.7 meters of sediment during this time lapse.

A similar phenomenon was observed in the early 2000’s after the last excess flows were delivered to the delta in 1999. The 2010 topographic survey (Zamora-Arroyo, 2012; Appendix A) indicates a 4.5 m ASL elevation at the site where cores CRE1 and CRE2 were taken. For this estimate, we assume the channel was scoured to a depth of 3.5 m ASL during 1980’s and 1990’s excess flows releases. With tidal processes dominating in the estuary after that time, tides started to import and accumulate sediments in the lower channel. The 1 meter difference from 2000 to 2010 at this core site would then be the result of sediment accumulation at an average rate of 10 cm a\(^{-1}\). It is important to mention that the topographic survey shows the terrain after the El Mayor-Cucapah 7.2M earthquake. While much of the bedload was deposited at the tidal sandbar before this event, post-earthquake sedimentation rates at the sandbar may have been affected due to landscape deformation (Nelson et al., 2012). Particularly, lower sedimentation rates than during previous years would be expected since bedload deposition is not constricted to a single pre-earthquake channel anymore, but it now affects a much larger area (Nelson et al., 2012).

Grain Size Analysis

Prior to upstream dams and reservoirs, the river delivered 135 million metric tons of sediment to the delta each year (Milliman and Meade, 1983). This original river sediment load consisted of about 80% red silts and clays and 20% sand (Thompson, 1968). Such sediment is no longer delivered from upstream sources. Grain size analysis of the CRE2 core shows that modern sediments in the estuary contain alternating silt-rich layers (up to 99%) and sandy (up to 55%) sediments with very low (1%) clay content (Figure 8). Increases in silt percentage come associated with a decrease in the sand fraction along the vertical profile. The abrupt change at 21.5 cm from silt (99%) to sand (45%) suggests a drastic,
sudden shift in dynamics. This horizon likely represents the 7.2 magnitude El Mayor Cucapah Earthquake that struck the area 4\textsuperscript{th} April, 2010. This particular horizon shows different characteristics from other sand deposits discussed below: a sharp contact with very different grain-size compositions and also a different coloration in the material deposited suggesting a different source (upstream). The black organic-rich and coarser material observed above the contact likely came from the agricultural fields upstream from breaks in irrigation canals and sand boils caused by ground liquefaction during the earthquake. If this horizon marks the earthquake event, as we are assuming, then 21.5 centimeters of sediment accumulated during 16 months (~1.3 years) from April 2010 to August 2011 (date of core collection) at an approximate rate of 16.5 cm a\textsuperscript{1}.

Extreme Tide Events

Figures 8 and Figure 9 show a marked increase in the sand fraction at 71 cm depth where it climbs up to 55\% relative to silt and clay, suggesting a high-energy event that could transport coarser material into the area. This incident, as well as other spikes in sand fractions, may be linked to unusually strong spring-tide conditions occurring in the estuary. Prior to the event at 21 cm, there is a silt accumulation period that was preceded by different sand deposition events as observed in the many sand spikes obtained by the grain size analysis. There seems to be a general increase in sand fraction moving down the vertical profile, in comparison to the 20-40 cm interval in the core, indicating not only the regular occurrence of these events but also their relative magnitude (Figure 8). The wavy bedding observed in the sediment core is characteristic of high-energy tidal environments, where individual sand ripples are filled by mud during low-energy periods (Martin, 2000).

Evidence from Landsat imagery and grain size analysis suggests these sediments started to accumulate after the last excess flows reached the delta in 1999. The unusually high presence of sand in the core
implies the dominance of a process other than simple downstream transport because present-day downstream flows are too weak to entrain and transport sand. Extreme spring tides can explain the spikes in the sand fraction in the sediment column. The CICESE tide prediction data allows a particular date to be assigned to each sand spike (Figure 9) because lamina thickness relates positively and directly to tidal current strength and the tidal range magnitude (Kvale, 2012). The sand spike at 72 cm could represent October 8th, 2006 perhaps because of the succession of very high tides during September, October and November of that year (~5.76 m or higher). Based on the impact generated by the tide on the estuary, as depicted in the Landsat images, dates were assigned to the different sand deposits within the core and used as time markers. By relating the amount of sediment accumulated since the incidence date of every event (Figure 9) and core collection date (August 2011), sedimentation rates ranging from 13-20 cm a⁻¹ with an average of 15.65 cm a⁻¹ were obtained (Table 1). Further, by using the dates of these time markers and the amount of sediment accumulated between two successive tidal events, an average sedimentation rate of 10.61 cm a⁻¹ was obtained (Table 1).

Discussion

The relatively high concentration of sand in core CRE2 (Figures 8 and 9) is a striking feature. Historically, the Colorado River has not been known to carry or deposit this particular grain fraction in the amounts found in CRE cores even when a full river discharge existed (Thompson, 1968). In recent times, the river simply does not flow at a sufficient rate to entrain and transport sand into the estuary from upstream sources. Upstream reservoirs would also trap this size fraction. Important sand-fraction percentages are not present in any of the cores collected at the Hardy River location and are also limited in cores collected in other studies at the river (Daessle et. al, 2009). Additionally, the lack of excess flows and the construction of El Tapon dam would prevent any sand from upriver El Tapon to reach the estuarine lower section of the channel during the last decade. Nevertheless, local fishermen have reported and
complained about the rapid sediment accumulation in the channel (CRE cores location) since the last excess discharge events in the delta (see Nelson et al. 2012). Field observations corroborate and associate this phenomenon with the tidal sandbar development. Even though Carriquiry et al. (2011) suggests a net sediment export to the gulf at the river mouth due to stronger ebb than flood flows during neap tides, this study suggests tidal forcing during spring tides results in stronger flood flows in the channels and a net import of sand in the estuary’s lower channel. The sand source could be the eroding Sonoran coast and adjacent areas or the sand winnowed away from previously-deposited sediment on the delta front.

Analysis of Landsat imagery shows tidally-driven sediment deposition occurs after major excess freshwater flows. The increase in the minimum tide height needed to maintain a connection and the decrease in the number of days of tidal connection over time imply a vertical accretion of the tidal sandbar. In other words, after major freshwater releases reached the estuary (Figure 1), sediment began to fill up the channel (upriver shift of bedload convergence zone) restricting the flow of river water into the gulf. As the sand bar continued to accrete, the tide height needed to allow seawater to flow upriver had to increase. In time, the tidal sandbar reached an elevation that only particularly high spring tides could breach, hence, reducing the days with tidal connection each year. These same dynamics explain the tidal sandbar’s appearance in the 1970’s and during the 2000’s. Both the MAHS survey in 1972 and the topographic survey in 2010 demonstrate sediment accumulation in the lower channel despite the lack of fluvial sedimentation. The core length (98 cm) along with the consistent sand fraction present in the lower section implies this vertical column is not older than 10 years assuming sedimentation rates in the 10-21 cm a⁻¹ range.

The core’s sedimentary sequence reveals several steps in the evolution of the tidal sandbar. Starting at
the bottom of the core, bed load and suspended load were carried by strong tidal currents. Coarser sediments were carried as bed load during dominating flood flows with finer material capping them after settling from slack water deposits left behind as the tide retreated. This process explains the alternating silt and sand layers and the continuously aggrading tidal sandbar. At about 38 cm the sand fraction decreased considerably. It is possible that at this depth, the tidal sandbar reached an elevation where tidal exchange was restricted and bed load sedimentation was severely diminished. Finer-sized particles settling from slack water pool deposits seem to dominate up to 21 cm. Then, the El Mayor-Cucapah 7.2 magnitude earthquake struck the area breaking irrigation canals and draining water downstream into the estuary. Sand boils due to ground liquefaction delivered sand to the surface. Thus, the earthquake may have produce both a source of sand and the means for its transport into the lower channel in the estuary.

The low $^{210}$Pb activities in the sediment profile (Table 2) do not allow a reliable geochronology using this method and dating by means of this method was not further pursued. The absence of a normal decay curve suggests variable sedimentation rates, low atmospheric $^{210}$Pb fluxes, and possibly different sediment sources. Earlier studies in the area show low atmospheric $^{210}$Pb fluxes in the southern Colorado River Basin and Gulf of California (Rama et al., 1961). Daesslé et al. (2009) measured 0.0001Bq/g to 0.065 Bq/g excess $^{210}$Pb activities in cores located about 8 km upstream from the cores presented in this study and Ruiz-Fernandez et al (2007) measured .001-.028 Bq/g in sediments from the Culiacan River estuary. Neither of those studies was able to detect anthropogenic $^{137}$Cs activity in the sediment profiles. Because $^{210}$Pb deposition is affected by rainfall, it is very likely that the low annual precipitation in the area (6.5 cm a$^{-1}$) constitutes one factor for the low $^{210}$Pb activities in the region. Additional factors affecting the $^{210}$Pb also include $^{210}$Pb-depleted Colorado River water reaching the delta, the influence of $^{210}$Pb-diminished oceanic air water masses as well as sediment mixing and
redeposition from geological older strata along the Colorado River basin (Daesslé et al., 2009). The rapid sedimentation rates resulting from tidal processes will most likely influence $^{210}$Pb activities by diluting the isotopic signal. The absence of a decay curve can be attributed to the lack of time for the radioactive isotope to decay into its daughter product.

Management Implications

Dredging the currently blocked channel, or ones like it, would improve the riparian and intertidal habitats and provide habitat and nursery grounds for migratory birds, endangered species, and economically important species in the area. The estimated sedimentation rates suggest that in order to restore a full-year connectivity between the lowermost Colorado River and the Gulf, the channel within the bedload convergence zone needs to be dredged to a depth of 1m (3.5 m ASL) and a length of about 10 km at least once every 5 to 10 years, assuming sedimentation rates of $10-21$ cm a$^{-1}$ (Table 3). After dredging, due to the lack of high magnitude spring season flows, tidal processes will continue to dominate in the area, and will keep importing sediments. As the tidal sandbar builds up over time, connectivity will decrease and the tide height needed to overtop the tidal sandbar will consequently increase. The cost and need for dredging could be reduced if high magnitude pulse flows destined for conservation were released from upriver sources. These flows would mimic pre-dam spring flows and would help to scour and flush sediments accumulated within the channel. Table 4 shows a simulation tidal sandbar development and connectivity after dredging based on the Landsat observations from 1999-2009. These estimates assume a normal channel depth (3.5 m ASL) and a sedimentation rate of 10 cm a$^{-1}$. 
Conclusions

Upstream water diversion in the Colorado River basin drastically changed sediment dynamics in the lower sections of the Colorado River delta. The estuarine section is now a highly dynamic environment deeply influenced by the particularly strong tidal processes dominating the area. Sediment material deposited in the estuarine channel is no longer derived from natural fluvial sources and spring-season floods no longer maintain a connection to the Gulf of California. The sedimentary material filling up the river channel cannot be derived from upstream sources since about 10 years ago the same channel was open and no upstream excess flows capable of transporting sand-sized material have occurred during the same time span. Cores from other studies show very small sand fractions in locations upstream from our cores. Instead, net upriver sediment transportation during spring flood tides derived at the Gulf seems to result in the rapid in-filling of the lowermost river channel within the estuarine section of the delta. Landsat imagery, historical records, and particle size distribution in estuarine cores, suggest non-steady sedimentation rates ranging from 10 to 21 cm a⁻¹. At this rate a year-round connectivity between the river and the Gulf will likely require dredging of the channel to a depth of 1 m at least once every 5-10 years. While some of the methods discussed in this work might be currently speculative, the development of our chronology is a hypothesis consistent with what is known about estuarine sedimentology and actual events and observations from the authors in this region. However, the lack of further constraint in sedimentation rates by a quantitative method such as $^{210}$Pb-method or sediment traps calls for future work to be done in the area. Particularly, it would be helpful to correlate and measure on-site the relationship between sediment laminae thickness being deposited and the tidal current strength for particular events. This would help to demonstrate the presence how particular sand spikes can be formed by specific tidal heights and currents and would also help to obtain a more precise time marker (time/date).
Acknowledgements

This research was supported by a National Science Foundation Graduate Research Fellowship Grant (DGE-1143953) to H.A.Z., NSF research grant EAR 044381 (Research Coordination Network: Colorado River delta) to K.W.F. and Christensen Fund Grant, Community-based restoration and monitoring of the Colorado River estuary, Mexico to K.W.F. We thank Jeanine Ash for her assistance in the field and the Sonoran Institute for their logistical support.
Figure 1. Colorado River Flow at U.S.-Mexico Border from 1878-2009. IBWC 2011.
Figure 2. Study Area: The Colorado River Delta location between the states of Sonora and Baja California, Mexico,
Figure 3. Study Area and surrounding localities. HR: Core locations in the Río Hardy. CRE: Core locations in the estuary. White dotted line marks the approximate extent of tidal influence.
Figure 4. Tidal profile for October 26 and October 27 showing the characteristic tidal wave asymmetry generated during spring tides as the tidal wave interacts with the estuarine geometry. Shorter but higher magnitude currents during flood flows seem to be responsible for the accumulation of sediments in the river channel. La Bocana Fishcamp is located about 20 kilometers upstream from the mouth of the river.

(Based on observations by Steve Nelson 1984-2010)
Figure 5. Sampling sites and approximate location of the bedload convergence zone (white box). Blue dotted line shows the sediment-filled section of the river.
Figure 6. Left: Core CRE2 from the estuarine section. A disturbed section at about 21-22 centimeters can easily be observed. This sharp contact is believed to have been caused by the El Mayor-Cucapah Earthquake. Below 40 cm, this core presents an increased concentration of red oxidized sand layers apparently originated in the Gulf of California. Right: Core HR1 from the fluvial section. Note the different characteristics of this core including a difference in the color of the material, higher concentrations of organic material, more uniform low-energy layering, and the lack of the red, oxidized sand layers.
Figure 7. Channel connectivity reconstruction from Landsat analysis. Minimum tide heights based on predictions at San Felipe, Baja California at mean lower low water using CICESE MARV10 tide prediction program (Bajamar Media Inferior BMI).
Figure 8. Grain size analysis results from core CRE2 showing clay, silt, and sand percentages along the vertical profile.
Figure 9. Grain size analysis and core CRE2. Numbers 1-6 show particularly strong tidal events capable of sand transportation and deposition in the estuary. These events were assigned according to tidal heights predicted by the CICESE MARV10 tide prediction program and the extent of the tide observed in Landsat scenes.
<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Tide Height (m)</th>
<th>Depth (cm)</th>
<th>Rate (cm a(^{-1}))</th>
<th>Rate (cm a(^{-1}))^*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8/20/2009 (23)</td>
<td>5.77</td>
<td>38</td>
<td>19.82</td>
<td>9.23[13]</td>
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<tr>
<td>2</td>
<td>8/1/2008 (36)</td>
<td>5.64</td>
<td>48</td>
<td>16.00</td>
<td>14.66[9]</td>
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<tr>
<td>3</td>
<td>10/26/2007 (45)</td>
<td>5.56</td>
<td>59</td>
<td>15.73</td>
<td>13[12]</td>
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<tr>
<td>5</td>
<td>8/19/2005 (70)</td>
<td>5.75</td>
<td>83</td>
<td>14.23</td>
<td>6[12]</td>
</tr>
<tr>
<td>6</td>
<td>8/29/2004 (82)</td>
<td>5.59</td>
<td>89</td>
<td>13.02</td>
<td></td>
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<tr>
<td>Core</td>
<td>08/2011</td>
<td>Average</td>
<td></td>
<td>15.65</td>
<td>10.61</td>
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Table 1. Sedimentation rates estimates based on tidal events 1-6. Numbers in parenthesis represent the number of months passed from a single event date to core collection date and used to calculate sedimentation rates. *denotes sedimentation rates estimated from intervals between tidal events. Brackets represent the time interval between two tidal events used to calculate sedimentation rates.

<table>
<thead>
<tr>
<th>Depth(cm)</th>
<th>Pb-210(Bq/g)</th>
<th>Pb-214(Bq/g) at 352KeV</th>
<th>Cs-137(Bq/g)</th>
<th>Pb-210(ex)(Bq/g)</th>
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<tbody>
<tr>
<td>0.00</td>
<td>0.04 ± 0.01</td>
<td>0.02 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.02 ± 0.01</td>
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<tr>
<td>2.00</td>
<td>0.04 ± 0.01</td>
<td>0.02 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>4.00</td>
<td>0.04 ± 0.01</td>
<td>0.02 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.01 ± 0.01</td>
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<tr>
<td>9.00</td>
<td>0.05 ± 0.01</td>
<td>0.03 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>13.00</td>
<td>0.06 ± 0.01</td>
<td>0.04 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.02 ± 0.01</td>
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<td>0.03 ± 0.00</td>
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<tr>
<td>26.00</td>
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<td>0.02 ± 0.00</td>
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<td>30.00</td>
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<td>0.03 ± 0.00</td>
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<td>0.01 ± 0.00</td>
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<td>34.00</td>
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<td>0.01 ± 0.01</td>
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<td>42.00</td>
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<td>0.03 ± 0.00</td>
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<td>0.02 ± 0.01</td>
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<td>46.00</td>
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<td>0.03 ± 0.00</td>
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<td>0.00 ± 0.00</td>
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<td>50.00</td>
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<td>0.01 ± 0.01</td>
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<tr>
<td>54.00</td>
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<td>0.00 ± 0.01</td>
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<tr>
<td>59.00</td>
<td>0.04 ± 0.00</td>
<td>0.03 ± 0.00</td>
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<td>0.01 ± 0.00</td>
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Table 2. \(^{210}\)Pb results obtained from core CRE2
<table>
<thead>
<tr>
<th>Time Period</th>
<th>Sedimentation rate</th>
<th>Source/Marker</th>
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<tr>
<td>1963-1972</td>
<td>21 cm a⁻¹</td>
<td>USACE Survey, 1982</td>
</tr>
<tr>
<td>2000-2010</td>
<td>10 cm a⁻¹</td>
<td>Zamora-Arroyo, 2012</td>
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<tr>
<td>Core</td>
<td>16.5 cm a⁻¹</td>
<td>El Mayor-Cucapah Earthquake</td>
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<tr>
<td>2004-2010</td>
<td>13.02-19.8 cm a⁻¹</td>
<td>Grain size analysis and tidal events</td>
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<tr>
<td>210Pb Chronology</td>
<td>N/A</td>
<td></td>
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</tbody>
</table>

Table 3. Summary sedimentation rates. * denotes average sedimentation rate between tidal events. N/A: not available.

<table>
<thead>
<tr>
<th>Year</th>
<th>Minimum Tide Height</th>
<th>Days connected</th>
<th>Channel Bed Elevation (ASL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredging</td>
<td>3.5</td>
<td>365</td>
<td>3.5</td>
</tr>
<tr>
<td>+1</td>
<td>3.8</td>
<td>248</td>
<td>3.6</td>
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<td>+2</td>
<td>4.03</td>
<td>204</td>
<td>3.7</td>
</tr>
<tr>
<td>+3</td>
<td>4.26</td>
<td>168</td>
<td>3.8</td>
</tr>
<tr>
<td>+4</td>
<td>4.37</td>
<td>140</td>
<td>3.9</td>
</tr>
<tr>
<td>+5</td>
<td>4.72</td>
<td>75</td>
<td>4</td>
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<td>+6</td>
<td>4.97</td>
<td>44</td>
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<td>+7</td>
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<td>+10</td>
<td>5.42</td>
<td>12</td>
<td>4.5</td>
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</table>

Table 4. Expected channel connectivity after dredging assuming sedimentation rate of 10 cm/year and a channel bed elevation of 3.5 m above sea level. Minimum tide heights estimates based on predictions from San Felipe, Baja California at mean lower low water (Bajamar Media Inferior BMI).
Appendix A. 2010 Topographic survey showing the core’s location. Light colors show the lowest elevations and darker colors the higher locations. Zamora-Arroyo, 2012.
Appendix B. 1970’s tidal sandbar profile view along the channel of the lower Colorado River. Modified from Army Corps of Engineers (USACE), 1982.
References


Rowell, K., Flessa, K., Dettman, D., Román, M. J., Gerber, L. R., Findley, L. T. 2008. Diverting the Colorado River leads to a dramatic life history shift in an endangered marine fish. Biological Conservation 141,


