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Geomorphic change and sediment transport during a small artificial flood in a transformed post-dam delta: The Colorado River delta, United States and Mexico

Erich R. Mueller[a,*], John C. Schmidt[b], David J. Topping[a], Patrick B. Shafroth[c], Jesús Eliana Rodríguez-Burgueño[d], Jorge Ramírez-Hernández[d], Paul E. Grams[a]

[a] U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, AZ, USA
[b] Utah State University, Department of Watershed Sciences, Logan, UT, USA
[c] U.S. Geological Survey, Fort Collins Science Center, Fort Collins, CO, USA
[d] Universidad Autónoma de Baja California, Instituto de Ingeniería, Mexicali, Baja California, México

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ABSTRACT

The Colorado River delta is a dramatically transformed landscape. Major changes to river hydrology and morpho-dynamics began following completion of Hoover Dam in 1936. Today, the Colorado River has an intermittent and/or ephemeral channel in much of its former delta. Initial incision of the river channel in the upstream ~50 km of the delta occurred in the early 1940s in response to spillway releases from Hoover Dam under conditions of drastically reduced sediment supply. A period of relative quiescence followed, until the filling of upstream reservoirs precipitated a resurgence of flows to the delta in the 1980s and 1990s. Flow releases during extreme upper basin snowmelt in the 1980s, flood flows from the Gila River basin in 1993, and a series of ever-decreasing peak flows in the late 1990s and early 2000s further incised the upstream channel and caused considerable channel migration throughout the river corridor. These variable magnitude post-dam floods shaped the modern river geomorphology. In 2014, an experimental pulse-flow release aimed at rejuvenating the riparian ecosystem and understanding hydrologic dynamics flowed more than 100 km through the length of the delta's river corridor. This small artificial flood caused localized meter-scale scour and fill of the streambed, but did not cause further incision or significant bank erosion because of its small magnitude. Suspended-sand-transport rates were initially relatively high immediately downstream from the Morelos Dam release point, but decreasing discharge from infiltration losses combined with channel widening downstream caused a rapid downstream reduction in suspended-sand-transport rates. A zone of enhanced transport occurred downstream from the southern U.S.-Mexico border where gradient increased, but effectively no geomorphic change occurred beyond a point 65 km downstream from Morelos Dam. Thus, while the pulse flow connected with the modern estuary, deltaic sedimentary processes were not restored, and relatively few new open surfaces were created for establishment of native riparian vegetation. Because water in the Colorado River basin is completely allocated, exceptional floods from the Gila River basin are the most likely mechanism for major changes to delta geomorphology for the foreseeable future.

1. Introduction

Dewatering and damming of large rivers has caused dramatic alteration to many delta ecosystems (Giosan et al., 2014). In extreme cases, stream flow no longer enters the sea for significant periods, such as in the Rio Grande (Pearce, 2006), Yellow River (Yang et al., 1998), and Indus River (Syvitski et al., 2013). In other cases, trapping of sediment in upstream reservoirs has greatly reduced the amount of sediment reaching deltas and caused erosion of delta shorelines (Carriquiry et al., 2001; Syvitski et al., 2009, 2013; Rao et al., 2010). Relatively few studies have described changes to the geomorphology of the riverine part of deltas in the zone where the upstream river enters its delta. Yang et al. (2011) documented incision of the Yangtze River into its delta following construction of Three Gorges Dam. Incision of the Rhone River in its delta has been attributed to a combination of early 20th century climate change and to engineering works and water developments that have reduced sediment supply (Arnaud-Fassetta,

* Corresponding author.
E-mail address: emueller@usgs.gov (E.R. Mueller).

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2003; Antonelli et al., 2004). Up to 10 m of incision in the delta of the Pearl River was caused by sediment depletion from upstream sand mining (Lu et al., 2007). Recently, Anthony et al. (2015) documented sediment evacuation along much of the length of the Mekong River in its delta, which they attributed to upstream sand and gravel mining.

Sykes (1937) estimated that the areal extent of the Colorado River delta was approximately 8600 km^2. Historically, the head of the delta was where the Colorado River emerges from a narrow valley approximately 21 km upstream from the confluence of the Gila and Colorado rivers near the Laguna Diversion Dam (Fig. 1). The distal part of the delta is tide-dominated, and delta sediments deposited near the head of the Gulf of California partially fill a funnel-shaped estuary that has a large tidal range (Wright, 1982). In other parts of the delta, Colorado River sediments fill basins that are part of the Mexicali seismic zone. This zone is the southernmost part of the San Andreas fault system and includes the sub-sea-level Salton Sink in the United States and the Laguna Salada in Mexico (Fig. 1). As described below, the Colorado River avulsed into these basins and filled them with delta sediment during periods when virtually no water or sediment was delivered to the Gulf of California estuary. The pre-dam delta of the Colorado River was comprised of a complex series of channels, sloughs, and lakes with limited human habitation (Sykes, 1937).

The modern Colorado River delta is one of the most transformed deltas in the world (Pitt, 2001; Schmidt, 2007; Glenn et al., 2013). The construction of large dams and diversions throughout the basin in the 20th century completely dewatered the formerly navigable maze of channels. Today, no flow reaches the Gulf in most years. Much of the channel is intermittent or ephemeral, and there are long segments that are persistently dry. Much of the channel in the former upstream part of the delta is now confined by levees, and more than 90% of the former delta has been converted to farm fields (Luecke et al., 1999).

The purpose of this paper is to describe sediment transport and the geomorphic effects of a short-duration pulse flow that was released from Morelos Dam (Fig. 1) into the delta in spring 2014. We provide context for our analysis of the effects of the pulse flow by describing the large-scale equilibrium processes and characteristics of the delta when it was most recently active in the late 1800s and early 1900s. We also describe the transient processes typical of the mid- and late 1900s when the delta changed greatly in response to upstream dam construction and operation of reservoirs and diversions. Analysis of sediment transport and scour and fill caused by the pulse flow addresses concerns expressed when the flow release was planned that sediment transport and associated scour and fill would adversely impact near-channel land use in Mexico. Our results also provide context for evaluating the central ecological objective of the 2014 pulse flow – to rejuvenate the riparian ecosystem along the river corridor, and our data may be helpful in designing future pulse flows. Here, we use a combination of aerial photography, Landsat satellite imagery, historical survey data, conventional field surveys, scour chains, light detection and ranging (lidar) surveys, and longitudinal measurements of suspended and bed sediment to describe geomorphic changes throughout the former delta's river corridor, with a focus on the 65-km river segment immediately downstream from Morelos Dam.

1.1. Geologic and geomorphic setting of the Colorado River delta

The delta of the Colorado River partially fills a tectonic basin formed by rifting and transform faulting along the San Andreas – Gulf of California part of the North American-Pacific plate boundary (Nelson et al., 2013). Sediment derived from the Colorado River fills the Salton Trough, the landward extension of the Gulf of California tectonic basin, to depths exceeding 5 km (Muffler and Doe, 1968; Dorsey and Umhoefer, 2012). A delta cone comprised of Colorado River sediment blocks northern extension of waters from the Gulf of California into the Salton Sink, the sub-sea-level portion of the Salton Trough. The Colorado River has occasionally drained into the Salton Sink during the last 5 million years (Dorsey et al., 2007). Shorelines of paleo-Lake Cahuilla, created during more recent filling of the Salton Trough, reached a maximum surface elevation of 12 m, the elevation of the delta apex near Volcano Lake at the base of the Cucapah Mountains (Fig. 1) (Waters, 1983). Sedimentologic evidence suggests that the lake filled and dried many times, and the most recent high stand was in the 17th century (Philibosian et al., 2011).

1.2. Transformation of the delta: a navigable waterway to an ephemeral channel

The pre-development delta was a sparsely inhabited maze of distributary channels, and the river's main channel was navigable by some early explorers and, later, as a steam navigation route from the Gulf of California to the inland port at Yuma, Arizona (Sykes, 1937). The main channel primarily occupied the eastern part of the delta from the 1700s until profitable navigation ended in 1877 (Fig. 1) (Sykes, 1937), but the channel had been located further west at other times. Ives (1861) described the delta as an ever-shifting array of secondary and tertiary channels:

> "The channel is circuitous . . . Slues branch in every direction . . . The water is perfectly fresh, of a dark red color, and opaque from the quantity of mud held in suspension. The shifting of the channel, the banks, the islands, the bars is so continual and so rapid that a detailed description, derived from the experiences of one trip, would be found incorrect, not only during the subsequent year, but perhaps in the course of a week, or even a day. . ."

Cory (1913) described progressive rise of the bed at Yuma of approximately 0.9 m between 1878 and 1909, and many observers reported that the channel near Yuma was unstable and difficult to navigate due to shifting bars. Fine sediment delivered to the delta caused occasional progradation into the Gulf of California, and Cory (1913) stated that the delta "has extended out into the Gulf more than 6 miles in the past 40 years."

The existence of a large dry area below sea level relatively near a large river attracted land speculation in the Salton Sink, and diversion of the Colorado River into the Sink was first proposed in the 1850s (Worster, 1985; Stevens, 1990; deBuys, 2001). Part of the Colorado River's flow was first diverted into an abandoned distributary channel – the Alamo River – in 1901, allowing settlement and agricultural development of the Salton Sink and eventual transformation of that area into the Imperial Valley. In 1905, initiated by Gila River flooding that caused the Colorado River to peak at approximately 3200 m^3/s (Fig. 2), the channel avulsed through a poorly-constructed diversion into the newly-completed canal that linked the Colorado River with the Alamo River. This "Great Diversion" caused two years of uncontrolled inflow from the Colorado River to the Salton Sink and created the modern Salton Sea (Fig. 1). Tremendous effort went toward shifting the river toward its former course, which was successful in 1907, and the main channel again flowed along the base of Sonora Mesa on the eastern edge of the delta (Sykes, 1937).

Cory (1913) and Sykes (1937) each argued that the artificial avulsion of the Colorado River to the west and into the Salton Sink would have eventually occurred naturally. In fact, the earliest notice of floodwaters escaping to the Salton Sink was in 1840, and waters also entered the basin in 1842, 1852, 1859, 1862, and 1867 (MacDougal, 1917). A significant diversion of the channel into the Sink occurred in 1890 and 1891 (MacDougal, 1917; Sykes, 1937).