Formation of California's Salton Sea in 1905–07 was not "accidental"

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Abstract—It is widely thought that the Salton Sea was created accidentally in 1905–07 because of engineering negligence in the diversion of Colorado River water for agricultural use in California's Imperial Valley. This is a misconception. Scientific data and historical records establish that formation of the Salton Sea was not accidental. The lake formed during 1905–07 in the same manner that numerous other large Salton Basin lakes did for at least tens of thousands of years from the Late Pleistocene through the late 19th century: as a result of the lower Colorado River's natural hydrodynamic regime, floodplain morphodynamics, and established avulsion style in combination with changes in streamflow attributable to regional hydroclimate. A large body of scientific and historical evidence indicates the 1905–07 Colorado River flooding into the Salton Basin and the creation of a large lake there would have occurred regardless of man-made modifications to the river's natural levee and distributary channels. In fact, the flooding would likely have been even worse in the absence of human intervention.

Introduction—the creation flood

For over 100 years it has been widely accepted that the Salton Sea, California's largest lake, was created accidentally in 1905–07 within an otherwise desiccated desert basin (e.g., Nijhuis, 2000; Barringer, 2014) as the result of engineering negligence by the California Development Company (CDC) as it struggled to keep irrigation water flowing from the lower Colorado River into the fledgling agricultural community of the Imperial Valley within the Salton Basin (Figure 1). The first diversion point for moving Colorado River water into the Imperial Valley ("Heading No. 1" on Figure 2) was constructed beginning in 1900 about 500 m north of the US–Mexico border. The opening from the lower Colorado River into the company's diversion canal was cut out of the river's natural western levee at an oblique angle, and flow into the main course of the canal was controlled by a wooden headgate placed a few hundred feet from the river bank down the canal (Grunsky, 1907). Below the headgate the canal connected to one of the Colorado River's natural delta distributary channels, the Alamo River, which was then dry. Diversion of water began in June 1901, and soon the river's heavy load of silt began to repeatedly obstruct the headgate and canal. As a consequence, water shortages in the Imperial Valley agricultural area began occurring in 1902 and continued through 1903 and into 1904, putting tremendous pressure on the CDC to fix the problems. Eventually, in the fall of 1904, the company resorted to making two unprotected cuts into the river's natural levee farther south in an attempt to achieve reliable diversion of river water into the canal and onward into the Imperial

Figure 1. Overview map. (1) Colorado River; (2) Gila River; (3) Yuma, AZ; (4) approximate path of the modern, controlled Colorado River's channel through the lower delta (where the channel is mostly dry today); (5) lower delta region below the crest; (6) Imperial Valley in the Salton Basin; (7) Salton Sea.

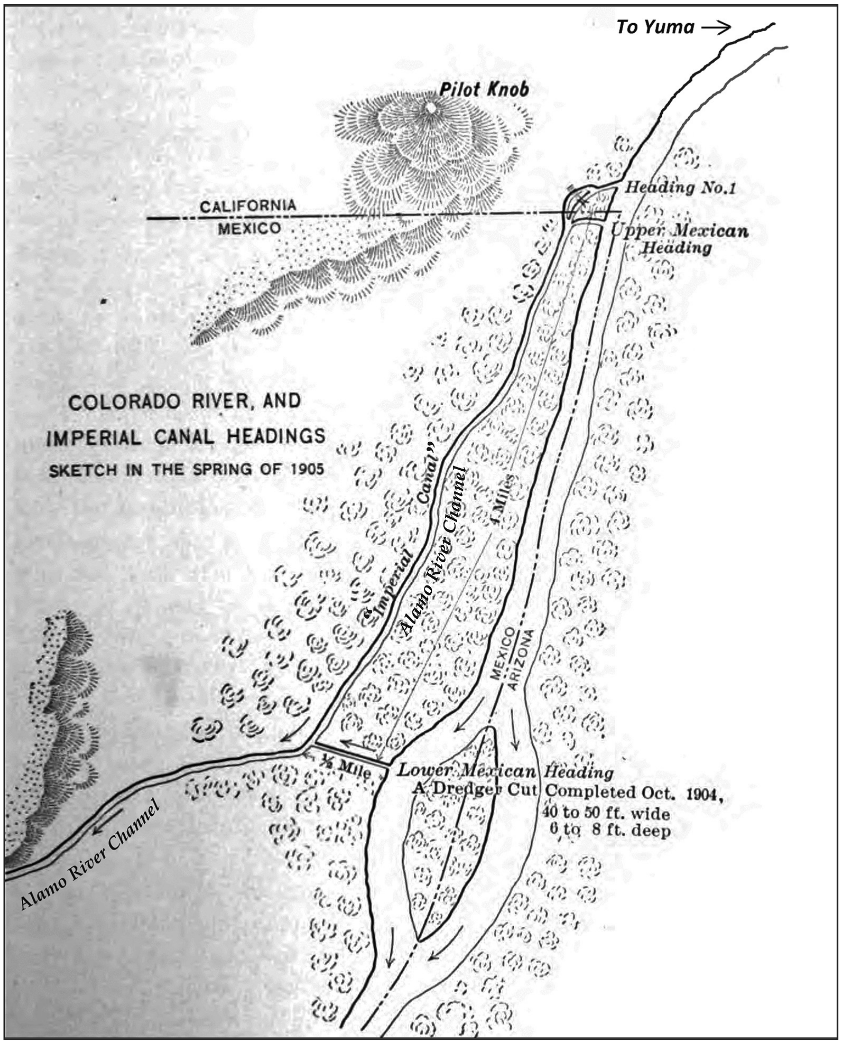

Figure 2. Sketch map of the lower Colorado River below Yuma, and the California Development Company's diversion headings below Pilot Knob. (Modified from Grunsky (1907), Fig. 2., to specify the location of Yuma and designate the Alamo River channel.)

Valley via the Alamo River (Grunsky, 1907; Cory, 1915; Kennan, 1917; Brown, 1923).

The first additional cut, known as the Upper Mexican Heading, was made just below the US–Mexico border. It quickly showed a pronounced tendency to silt up. The CDC eventually decided to close the first cut and try again slightly farther south. The second cut, known as the Lower Mexican Heading, was made about 4 miles (~6.4 km) below the international border. It was a simple cut with a dredger, made about 40 to 50 feet (~12-15 m) wide and 6 to 8 feet (~2-2.5 m) deep. It was connected to the CDC canal, which in turn connected to the Alamo River channel. There was no headgate. Through this cut there was sufficient fall from the river to the canal for the water to achieve scouring velocity, so silt did not accumulate. Instead, natural erosion of the unprotected cut began immediately. In the CDC's haste to reinitiate the flow of irrigation water into the valley, the company failed to add a control structure at the new diversion point, although they intended to do so eventually. The company's engineers perceived no urgency in adding that structure because the primary problem they had experienced up until that time was too little flow from the river into the valley rather than too much (Grunsky, 1907; Cory, 1915; Kennan, 1917; Brown, 1923).

Unanticipated high streamflow on the lower Colorado River arrived in early 1905, and floodwaters soon rapidly eroded the unreinforced cut and rushed through it. The river's high flows avulsed across the delta and streamed north primarily through the Alamo River channel and another previously dry but well-established natural distributary channel of the Colorado, the New River, that headed into the Salton Basin. Continuing to widen the breach in the Colorado River's natural levee and erode and overtop the river's distributary channels, the floodwaters coursed across the delta in sheetflow, rampaged through recently-developed farm fields in the Imperial Valley, poured into the central Salton Basin, flooded the Southern Pacific Company's railroad tracks, and began creating an enormous lake dubbed the "Salton Sea." The CDC, Southern Pacific, and hundreds of workers made many desperate attempts to block the breach in the river's levee. Each time the efforts ultimately failed as numerous large floods raced down the lower Colorado River below Yuma during 1905. By August 1905, the entire flow of the Colorado River was rushing through the breach, into the river's distributary channels, across the Imperial Valley, and into the growing Salton Sea. Extremely high streamflow continued on the lower Colorado River in 1906 and washed away every structure the CDC attempted to use to block the breach. In November 1906, the river finally appeared to be thwarted and human control achieved. But on December 5, 1906 another huge flood roared down the Colorado past Yuma. New breaks occurred in the repaired levee, and soon the river was once again flowing uncontrollably through the Imperial Valley and onward into the central Salton Basin. After many additional efforts, in January 1907 the Southern Pacific Company was finally able to block the floodwaters and turn the river toward the Gulf of California by using millions of tons of quarried rock dumped into the breach (Grunsky, 1907; Cory, 1915; Kennan, 1917; Brown, 1923).

The story of the epic two-year battle to stanch the raging flow of the wild Colorado River and redirect the river toward the Gulf of California is a well-known tale of man against nature described fully in many historical accounts (e.g., Cory, 1915). The saga of this "Creation Flood" that formed the Salton Sea, crippled the nascent Imperial Valley, and led ultimately to the damming and complete control of the Colorado River for human purposes (e.g., LaRue 1916, 1925) is engaging and highly memorable. At the time the events unfolded, they "were so spectacular as to result in world-wide notoriety." (Cory, 1915.) For the pioneers of the region who toiled to create what they hoped would be an agricultural Eden in the desert, as well as for others who followed in developing the Imperial Valley into an extraordinarily productive agricultural region, the story served as an inspirational saga demonstrating the power of persistence and human ingenuity to succeed despite seemingly insurmountable odds. The tale vividly demonstrated the capacity of mankind to triumph over and control wild nature (e.g., Larkin, 1907; Howe & Hall, 1910; Farr, 1918; Sperry, 1975). But the memorable story and its appealing allegorical aspects led to the widespread adoption of a fundamental misconception that has colored opinions of the Salton Sea ever since: namely, the misimpression that the 1905–07 flooding into the Salton Basin would not have occurred, and the Salton Sea would not have been created, were it not for the infamous series of incautious decisions made by the California Development Company. The Creation Flood story has resulted in the ingrained but mistaken view that the Salton Sea is accidental and unnatural, a man-made lake in a parched desert where such an expanse of water should not be.

But historical records and scientific data of various types indicate that formation of the Salton Sea in 1905–07 was not an accident, and engineering negligence was not the cause. The lake formed in the same manner that lakes had been forming in the Salton Basin, sustained by Colorado River water, for at least tens of thousands of years from the Late Pleistocene through the late 19th century: as a result of the Colorado River's natural hydrodynamic regime, floodplain morphodynamics, and established avulsion style in combination with changes in streamflow attributable to regional hydroclimate. A large body of scientific and historical evidence indicates the 1905–07 Colorado River flooding into the Salton Basin and the creation of a large lake there would have occurred regardless of man-made modifications to the river's natural levee and distributary channels. In fact, the flooding would likely have been even worse in the absence of human intervention.

Geologic and geographic context

The Colorado River arrived at the proto-Gulf of California approximately 4.8 Ma (Crow *et al*., 2019; Dorsey, 2012), and began building a vast delta at the boundary of the Pacific and North American tectonic plates. The Salton Trough, the northwest landward extension of the Gulf of California Shear Zone, was originally part of the proto-Gulf and began accumulating Colorado River sediments during the early Pliocene (Dibblee, 1954; Muffler and Doe, 1968; Winker and Kidwell, 1996). The northern Salton Trough likely became cut off from marine waters of the Gulf by latest Pliocene time, as the result of aggradation of delta sediments and net plate movement to the northwest along the San Andreas fault (Winker and Kidwell, 1986; Winker, 1987; Winker and Kidwell, 1996; Dorsey, *et al*., 2011); but marine incursions northward may have occurred during periods of very elevated sea level (Ross *et al*., 2020, this volume). The Salton Basin is a below-sea-level, fault-bounded rift valley lying within the northern Salton Trough north of the U.S.-Mexico border and straddling the plate boundary (Figure 1). The lowest elevation in the central Salton Basin was determined by the Southern Pacific Company in 1891 to be 280.2 feet (85.4 m) below sea level (McGlashan and Dean, 1913); in 1903 it was found to be -286 feet (-87 m) (MacDougal, 1907); and in 1907 it was measured at -278 feet (-84.7 m) (Grunsky, 1907).

The Salton Basin was part of the Colorado River's delta and shifting floodplain, and received part or all of the river's flow at various times as a result of avulsion and channel switching that delivered water to the north. Affected by tectonic, sedimentary, hydrologic, and climatic factors, the Colorado River adjusted its flow sometimes into the Salton Basin, sometimes into the Gulf, and sometimes to both regions (Cecil-Stephens, 1891; Blake, 1914; MacDougal, 1915; Brown, 1923; Kniffen, 1932). When the Colorado River flowed into the Salton Basin, large lakes were often created and sometimes sustained for long periods (Blake 1854, 1858; LeConte 1855; Sykes 1914, 1937; Kniffen, 1932; Li *et al*., 2008a,b; Rockwell *et al*., 2018). Thick lacustrine and fluvial-deltaic sedimentary deposits with a Colorado River provenance that accumulated in the Salton Basin from the Pleistocene through the Holocene have a total thickness of several thousand meters and include the Borrego Formation (Tarbet, 1951), the Brawley Formation (Dibblee, 1954), and the Lake Cahuilla beds (Blake, 1907).

Throughout the Late Pleistocene and Holocene, the path of the lower Colorado River through its floodplain and delta was extremely variable. Until the river was dammed and controlled in the mid-20th century, the entire delta region was a maze of constantly shifting distributary channels transporting heavily silt-laden water. According to Ives (1861):

> "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. . ."

The Salton Basin is topographically separated from the Gulf of California by a region of aggraded deltaic sediments where today the city of Mexicali, Mexico and the Mexicali Valley agricultural area are located (Brown, 1923). The highest elevation portion of that region, the crest of the Colorado River delta, is a broad linear zone beginning east of the Sierra de Los Cucapah and Cerro Prieto at Volcano Lake, and trending northeast across the delta toward the mainstem of the Colorado River (Kniffen, 1932; Muffler and Doe, 1968). There is a pronounced asymmetry in the slopes directing drainage in opposite directions on either side of the delta crest—toward the Gulf of California in the south and toward the Salton Basin in the north (Grunsky, 1907; Brown, 1923; Kniffen, 1932). Kniffen (1932) explained, "South of the crest the slope is quite uniform to the gulf, with a gradient of less than two feet to the mile. North of the crest the slope to the Salton Sea is much greater." At its east end, the delta crest meets the course of the Colorado River's mainstem where, prior to damming and course modification, the river turned sharply south-southwest near Pilot Knob after flowing due west from its junction with the Gila River (Emory, 1848; Kniffen, 1932; Muffler and Doe, 1968). The low point of the delta crest in the west, where it reaches Volcano Lake, was approximately 13 m when measured in the mid-twentieth century, but is now lower as the result of tectonic and anthropogenic subsidence (Arnal, 1961; Sarychikhina *et al.*, 2011).

The Imperial Valley agricultural region is located within the Salton Basin and extends north from the US–Mexico border to the southern and southeastern shores of the Salton Sea. The current elevation of the Imperial Valley along its southern border with Mexico ranges from approximately sea level in the west to approximately 13 m above sea level in the east, excluding the area farther east covered by the Algodones Dunes. The Salton Sea, which is currently receding from water-deprivation, is located in the central Salton Basin and presently has a surface elevation of approximately 72.4 m below sea level (USGS, 2020). The lake has been sustained primarily by irrigation drainwater from the Imperial Valley since the Colorado River was dammed and controlled in the mid-twentieth century and prevented from flowing into the Salton Basin.

Delta distributaries and floodplain morphodynamics

Just as it had for millions of years, in the 19th and early 20th centuries the lower Colorado River flowed at will through an extensive and complex network of distributary

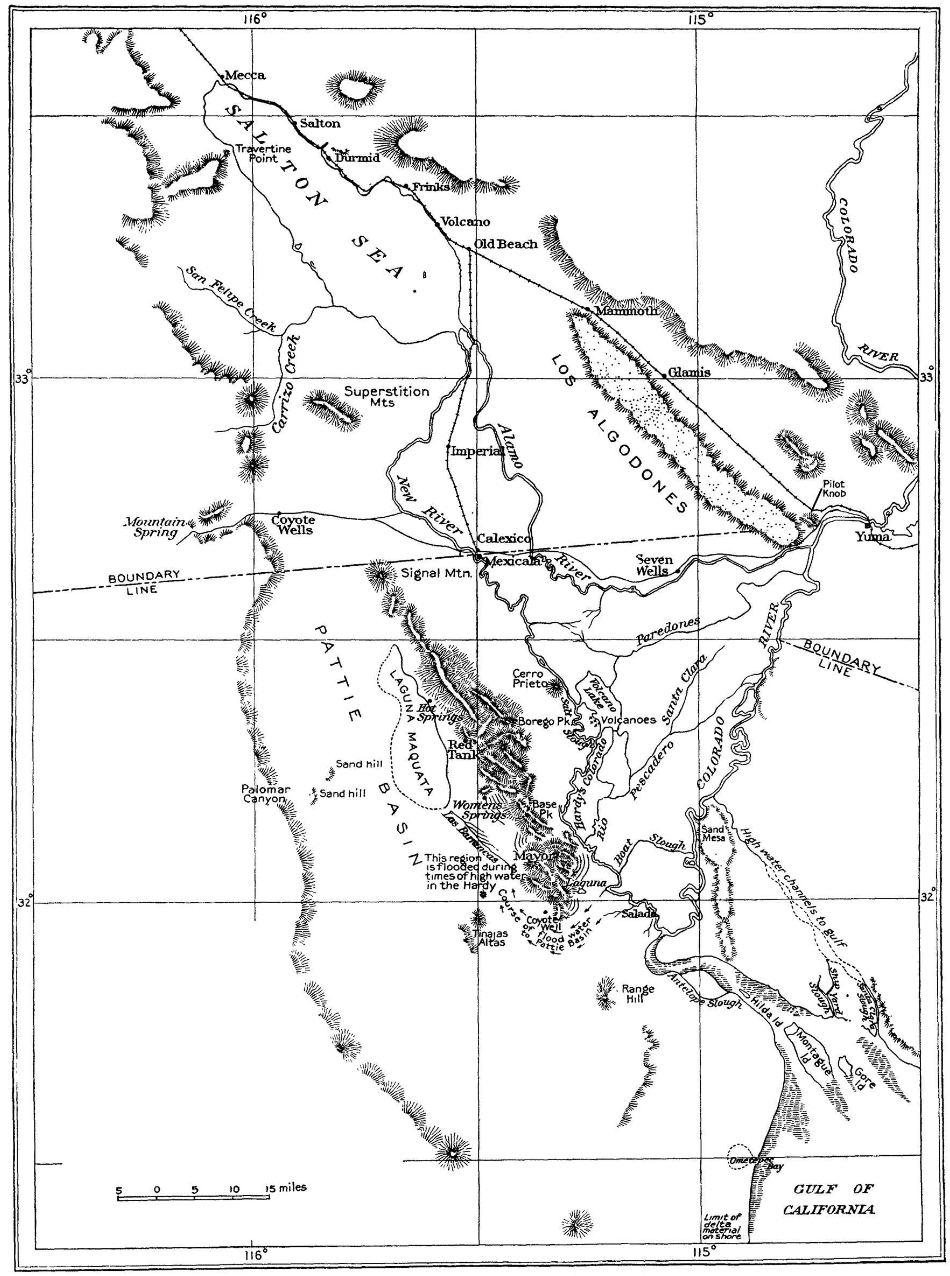

Figure 3. Sketch map of the Colorado River delta and Salton Basin showing distributary channels. (Modified from Fig. 1 in MacDougal (1907), drawn by Godfrey Sykes, to clarify the label for Pilot Knob.)

channels, sloughs, and lagoons in a delta and floodplain covering thousands of square kilometers, including the Salton Basin. Sykes (1937) estimated that the areal extent of the Colorado River delta was approximately 8600 km^2 in the early 20th century. The dynamic and capricious course of the river in its lower reaches was described by C.K. Clark in 1913: "The lower Colorado has no fixed channel, because of the character of the soil, which is a deposit of silt, easily eroded. The current swings back and forth, cutting the banks and changing the meander line…." (Cory, 1913).

The Alamo River and the New River are Holocene delta distributary channels of the Colorado River that were established sometime prior to the mid-1800s (Emory, 1848; LeConte, 1855; Blake 1854, 1858). They conveyed flow from the Colorado River into the Salton Basin during high-water periods (LeConte, 1855; Blake 1854, 1858; Kniffen, 1932) until damming and control of the Colorado River in the mid-20th century. Descriptions of the configurations of those streams during the 19th and early 20th centuries make clear their ongoing relationship with the mainstem of the lower Colorado River and with other delta distributary channels (Figure 3). The Alamo River branched off of the Colorado's western levee near where the mainstem turned sharply south-southwest after flowing "perfectly straight" west for approximately 3–4 miles (~4.8–6.4 km) from its junction with the Gila River (Emory, 1848). During periods of high water, the Alamo flowed southwest from the Colorado and then meandered west and north as it followed the topographic contours in the area north of the delta crest (Emory, 1848; Sykes, 1914). When filled, the Alamo flowed through a series of sloughs and lagoons in the northern delta region which sustained the wells of the Alamo Mocho Station, well-known to travelers through the desert (Grunsky, 1907; Jonas, 2009); then it curved northward and flowed into the Salton Basin if it contained sufficient streamflow (Grunsky, 1907; Sykes, 1914). The Rio Paradones, another delta distributary channel of the Colorado River, branched off the west levee of the mainstem south of the Alamo River. The beginning of the Rio Paradones bifurcation channel was situated at a place where the south-southwest flowing mainstem turned briefly toward the east before flowing generally south (Grunsky, 1907). The Paradones flowed west-southwest atop the delta crest and ended at the low point where Volcano Lake was perched adjacent to the beginning of the New River (Grunsky, 1907; Sykes, 1914; Jonas, 2009). During high-water periods, the New River collected Colorado River floodwater that was delivered to it via the Paradones and Volcano Lake. In addition, it received overbank discharge from the Alamo River, and also accumulated water from sheetflow across other portions of the delta (Grunsky, 1907). The New River flowed north from the delta crest and delivered its water into the Salton Basin (LeConte 1855; Sykes, 1914; Kniffen 1932). In 1848, U.S. Army Lieutenant Colonel W. H. Emory described additional arroyos north of the Alamo heading west and then north from the bend of the Colorado River where the mainstem turned sharply to the south-southwest after flowing due west from its junction with the Gila River (Emory, 1848).

Another distributary channel on the south slope of the delta crest, the Rio Hardy, flowed south from the divide at Volcano Lake and ended at the Gulf of California (Hardy 1829; Howe and Hall, 1910; Blake, 1914). During periods of normal flow, Volcano Lake emptied preferentially into the Rio Hardy, but during high flows its waters were distributed both into the Rio Hardy and the New River (MacDougal, 1915; Cory, 1915). When the Rio Hardy overflowed during high-water periods, sheetflow spread west through a gap below the Sierra de Los Cucapah and Sierra El Mayor to fill the shallow below-sea-level basin lying between those mountains and the Peninsular Ranges. The lake formed there, known as Laguna Salada or Laguna Maquata, sometimes achieved a maximum size of approximately 40 miles (~64 km) long by 20 miles (~32 km) wide, depending on available streamflow (Cory, 1915; MacDougal, 1915; Kniffen, 1932).

It was observed by Grunsky (1907) that the fall of the lower Colorado River's mainstem course southward to the Gulf of California along the east side of the delta region was significantly less than the fall of other courses through distributary channels that led into the Salton Basin:

> "The Colorado River flows southerly in a direction in which the general fall of the ground surface is only about 1.5 ft. per mile, which the river in its meanderings cuts down to an effective fall of about 1 ft. per mile. Toward Volcano Lake, southwest from the river, the general surface gradient is 2 ft. or more per mile; and westward, in the direction paralleling Alamo River, it is nearly 3 ft. per mile to a point near Calexico [at the southern edge of the Imperial Valley]. Thence northward into Salton Basin, on lines of greatest slope, the country falls away at the rate of from 4 to 5 ft. per mile."

In the 19th century it was recognized that flow through the Colorado River's distributary channels would bring water into the Salton Basin whenever high-water conditions existed in the mainstem (Blake 1854, 1858; LeConte, 1855; Cecil-Stephens, 1891; Grunsky, 1907; LaRue, 1916; Brown, 1923). LaRue (1916) noted that the geomorphology of the delta region was a crucial factor in this process: "As the slope of the delta is greatest toward the north and west, the river during flood periods is continually seeking a new channel to Salton Sea." It was observed that "overflows" of the river into the Salton Basin would occur at two times of year: in the spring and early summer, as a result of snowmelt in the headwaters of the Colorado River and its tributaries, and in the winter as a result of storms that brought heavy precipitation and caused flash flooding in the lower Colorado River basin, particularly along the Gila River and its tributaries (Cecil-Stephens, 1891; Brown, 1923). During high-water periods the lower Colorado would overflow its banks at many points, particularly below Yuma beginning where the river curved abruptly toward the south-southwest after flowing due west. A relatively low natural levee on the west side of the curve below Pilot Knob was especially vulnerable to over-topping (Emory, 1848; LaRue, 1916). When the river's streamflow was high and overflows were of particularly significant volume, which happened numerous times during the 19th century as described below, large lakes were created in the Salton Basin via overflow and avulsion which shunted the mainstem's water into the Alamo and New Rivers (MacDougal, 1915; Brown, 1923; Kniffen 1932). In 1891, referring to the gage on the lower Colorado River at Yuma, Cecil-Stephens (1891) noted, "Hitherto, New River has always flowed when the Colorado marked 19 feet at Yuma." It was only during periods of drought that distributary channels did not bring Colorado River water into the Salton Basin (LeConte, 1855; Blake 1858; Cecil-Stephens, 1891). Even then, there was a residual vegetated salt marsh in the central basin stretching as much as 25 miles (~40 km) long and 5 miles (~8 km) wide holding Colorado River water that had become saline from evaporation (Farr, 1918).

As is true of all rivers, and particularly those that carry large loads of sediment and form fan deltas, the opening, shifting, blocking, and reopening of the lower Colorado River's distributary channels was affected by varying streamflow and fluctuating quantities of sediment the river carried, deposited, and eroded (Andrews, 1991). A characteristic of dryland rivers generally and the pre-dam Colorado River specifically is the transport of very large quantities of sediment, both as suspended load and as bedload (Andrews, 1991; Tooth, 2000). Kniffen (1932) noted, "As a carrier of silt the Colorado is probably without a peer among the greater streams of the world." He explained that in 1904, during a dry year preceding the 1905–07 flood, a researcher from "the Arizona Experiment Station made a careful study of the river silt. He found that an acre-foot of Colorado River water contained on an average 9.62 tons of silt, and that for the year the river's burden amounted to over 120,000,000 tons—this for a year when the total discharge was considerably under normal. The average annual load passing Yuma is probably around 160,000,000 tons, which translated into terms of volume of dry soil would be approximately 80,000 acre-feet."

During the portions of the 19th century for which historical records exist, the lake-creating floods from the Colorado River into the Salton Basin were all self-limiting due to silt deposition when streamflow slowed (LaRue, 1916). Extensive sedimentation occurring in the river's distributary channels as floodwaters slackened eventually caused cessation of flow northward into the Salton Basin (LaRue, 1916; Brown, 1923). During periods of drought and chronically slack flow on the lower Colorado River, openings from the mainstem to distributary channels became blocked by deposition of silt, and the courses of distributaries became clogged with sediments and blown sand, and were sometimes overgrown with vegetation (LaRue, 1916; Schyler, 1907). In addition, at those times the sedimentation in the mainstem raised the streambed considerably in relation to the river's floodplain below Yuma. Then, if flash flooding occurred, the elevated streambed of the mainstem could not hold the flow (Schyler, 1907; LaRue, 1916). The river would rapidly overtop its natural levees along the western edge below Yuma. When such flooding ensued, sediment dams in clogged distributary channels would quickly erode—especially if drought had riddled them with mud cracks through which floodwaters could penetrate—and avulsion and bifurcation of the mainstem flow would occur (MacDougal, 1915; LaRue 1916). When streamflow slowed following a period of high water, and sedimentation once again blocked distributaries where they branched off the mainstem, the closures left zones of weakness in the Colorado's natural levees at the former bifurcation points, which encouraged reopening of the distributary channels in the same spots during the next period of high water (LaRue 1916; Andrews, 1991). The portion of the lower Colorado River's mainstem from the curve at Pilot Knob to the Rio Paradones below the US–Mexico border was known to be a stretch particularly vulnerable to avulsion and bifurcation (Grunsky, 1907; Schyler, 1907; MacDougal, 1915; LaRue, 1916; Brown 1923). These early reports of the lower Colorado River's behavior are entirely consistent with the modern understanding of floodplain morphodynamics and processes initiating avulsion and bifurcation (Slingerland and Smith, 1998; Kleinhans *et al*., 2012; Hajek and Edmunds, 2014; Dean *et al*., 2016).

Pleistocene-to-Holocene Salton Basin lakes

Scientific data and historical records establish that many large lakes occurred in the Salton Basin from the Late Pleistocene through the Holocene, sustained by Colorado River water. The most generally well-known among them is Lake Cahuilla, an enormous Late Pleistocene-to-Holocene lake with a highstand overflow path south across the delta crest that filled the Salton Basin to an elevation of approximately 13 m above sea level beginning at least 20.5 kya and continuing intermittently through the 18th century (Blake 1854, 1858, 1907; Brown, 1923; Li *et al*., 2008a,b; Rockwell *et al*., 2018). At various times Lake Cahuilla was closed, through-flowing, or overflowing, depending on climate conditions and the amount of Colorado River streamflow available (Li *et al*., 2008a,b). At its southern end the giant lake was supported by the elevated zone trending northeast across the delta. When the lake's level reached about 13 m above sea level it overflowed at the lowest point of that delta crest, sending a stream to the Gulf of California.

Lake Cahuilla was first described by geologist William Phipps Blake in the mid-19th century, following his participation in the initial survey of the West for possible railroad routes during which he visited the Salton Basin in 1853 (Blake 1854, 1858). He noticed thick layers of calcium carbonate encrusting the east face of the Santa Rosa Mountains and terminating in a line at a consistent elevation on the mountainside, and he realized that this tufa deposit had been formed by an immense lake. He later decided that 'Lake Cahuilla' was an appropriate name for the body of water (Blake 1907), to honor one of the Native American tribes that lived along its shores and exploited its rich natural resources for thousands of years. Blake was also the first scientist to note that the elevation of the Salton Basin extended far below sea level (Blake 1854, 1858). Research conducted a century later concluded there is evidence at various locations in the Salton Trough indicating that even larger lakes, including at least one that reached an elevation of about 46 m above sea level, existed during the late Pleistocene prior to Lake Cahuilla (Thomas, 1963).

Focused scientific studies of the timing of Lake Cahuilla were first conducted in the late 1970s and early 1980s (Wilke 1978; Waters 1983). That research concluded there were at least six lengthy episodes during the past 2000 years when the 13-m lake existed, and its last occurrence was either in the 15th (Wilke, 1978) or 16th (Waters, 1983) century. More recent studies (Li *et al*., 2008a,b) based on stable isotope analysis and serial radiocarbon dating of Lake Cahuilla's thick tufa deposits, determined that the giant lake began depositing tufa on the east face of the Santa Rosa Mountains about 20.5 kya, and there was no hiatus in that deposition through at least 1300 years BP. Li *et al.* (2008a,b) determined that the lake was sustained primarily by flow from the Colorado River, and was either a full closed lake or was overflowing at its delta sill intermittently or continuously as the result of the Colorado River's high streamflow during periods of very wet regional hydroclimate. An additional study by Rockwell *et al.* (2018) used radiocarbon dating, historical records, and modeling of lake filling and evaporation rates to place the timing of the penultimate occurrence of Lake Cahuilla during approximately the first half of the 17th century and the final incarnation of the 13-m lake during approximately the mid-18th century.

Tree-ring based reconstructions of Colorado River streamflow indicate that the last two incarnations of Lake Cahuilla as identified by Rockwell *et al.* (2018) correspond with periods when extremely wet hydroclimate existed in all or a portion of the Colorado River basin—in the upper basin as reflected in reconstructed streamflow for the river at Lees Ferry (Figure 4a; Woodhouse *et al*., 2006; Meko *et al*., 2007), and/or in the lower basin as reflected in reconstructed streamflow for tributaries of the Gila River (Figure 4b; Meko *et al*., 2008). It's important to note that these tree-ring based data may understate very high flow and flash-flooding (Woodhouse *et al*., 2006; Meko *et al*., 2008). Nonetheless, the data indicate: (a) the penultimate occurrence of Lake Cahuilla was during a long period of extremely wet hydroclimate in the 17th century that caused exceptionally high streamflow in both the upper and lower Colorado River basins; and (b) Lake Cahuilla's final occurrence was during a long period of very wet

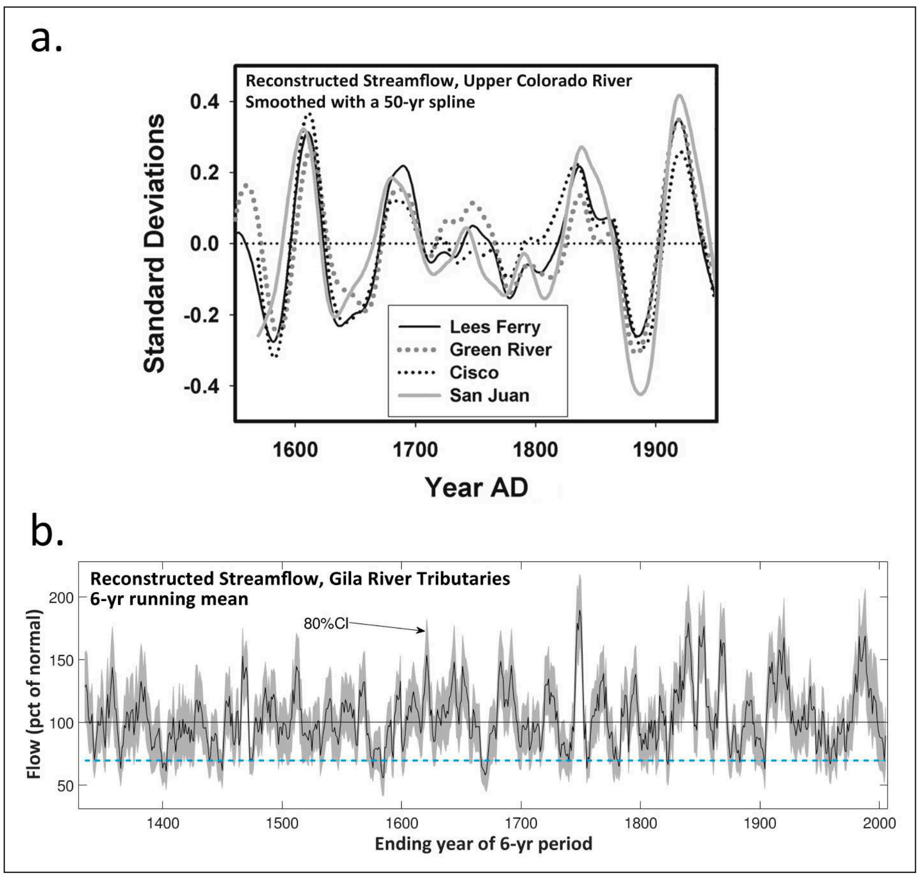

Figure 4. Tree-ring based streamflow reconstructions: (a) Reconstructed streamflow 1550-1950 for three major upper Colorado River tributaries and for the mainstem at Lees Ferry, smoothed with a 50-year spline to highlight low-frequency variability (modified from Woodhouse *et al*. (2006), Fig. 9). (b) Reconstructed streamflow for the Salt + Verde + Tonto Rivers (tributaries of the Gila that are important sources of flow for the lower Colorado River below Yuma), based on a 6-year running mean for 1330-2005. Solid black line represents averaged flows plotted as % of normal, where normal is the median of all 6-year running means. Dashed aqua line is reconstructed 6-year mean for 1999-2004, to serve as a baseline comparison for the entire record. Gray areas define the 80% confidence interval. (Modified from Meko *et al*. (2008), Fig. 13.)

hydroclimate in the 18th century that most affected the lower Colorado River basin and caused particularly high streamflow on the Gila River's tributaries. Notably, the reconstructions also confirm the occurrence of extremely wet hydroclimate in the entire Colorado River basin during the early 20th century, as discussed below.

Additional support for the conclusions of Rockwell *et al.* (2018) regarding the timing of Lake Cahuilla's final occurrence exists in the form of a large detailed map of North America by John Rocque, topographer to England's King George III, published in 1762 (Figure 5). The map shows the Colorado and Gila Rivers pouring their entire flow into a giant lake that is separated from the northern Gulf of California to its south by an expanse of land. According to text on the map within the cartouche, the details shown were "taken from Actual Surveys and Observations Made in the Army employ'd there, From the year 1754, to 1761."

Although for most of the 19th century the Salton Basin was only occasionally visited by people who kept records of what they saw, historical reports indicate that particularly heavy "overflows" from the Colorado River into the Salton Basin via the New and Alamo Rivers were observed to occur and form lakes in the central basin numerous times during the 1800s—in at least 1828, 1840, 1849, 1852, 1859, 1862, 1867, 1884, and 1891 (Grunsky, 1907; Cory 1913; MacDougal, 1914, 1915; Kniffen 1932). At other times there was flow from the Colorado River into the Salton Basin that filled large sloughs and lagoons along the distributary courses, but was insufficient to form a large lake in the central basin (Blake 1854, 1858; LeConte, 1855; Grunsky, 1907). For example, Grunsky (1907) explained:

> "In the mesquite and arrow-weed thicket at the original head of the Alamo, there was an occasional accumulation of so much water, and submersion of so much land, that the locality was called 'The Lagoons' (*Las Lagunas*). Although these lagoons received water at practically every high-water stage of the river, they did not always yield enough to the Alamo River to produce a flow throughout the river's entire length. In other words, there were many years in which the Alamo did not discharge any water into the lowest portion of the Salton Basin. The lagoons, in addition to feeding the Alamo, appear also to have been one of the sources of supply for the Rio Paradones."

Figure 5. A General Map of North America by John Rocque, published in 1762, with superimposed enlargements showing (a) the Colorado and Gila Rivers emptying into a large lake that is separated from the northern end of the Gulf of California and appears to be Lake Cahuilla; and (b) the text in the map's cartouche.

For a long period in the late 19th century there was at least some flow of Colorado River water into the Salton Basin on an annual basis as the result of a recurring breach in the river's natural levee along the stretch below where the mainstem curved sharply toward the south-southwest near Pilot Knob (Brown, 1923; Kniffen, 1932). Kniffen (1932) stated:

> "During the last decades of the nineteenth century there was a minor break in the Colorado near Algodones, occurring annually at the time of the summer flood. A portion of the diverted water went down to the Salton Basin

> in the channel of the Alamo. A greater portion passed through the Paredones to Volcano Lake and was there divided, the larger part passing south through the Hardy, the smaller northward through the New."

In 1850, Dr. J.L. LeConte and U.S. Army Major General S.P. Heintzelman traveled to the Salton Basin seeking mysterious "boiling springs" and volcanic features reported to be at the shore of a salt lake (LeConte 1852, 1855). Accompanied by an Indian guide, they went to the southeast portion of the central Salton Basin where they found several "volcanic mounds" about 100–150 feet (~30.5–45.7 m) high that were near the shore of a large salt lake and "arranged in the arc of a circle." The features LeConte (1855) described are the Salton Buttes, dormant rhyolite domes (Wright *et al*., 2015). When the surface elevation of the Salton Sea was approximately 227–231 feet (~69.2–70.4 m) below sea level from 2005 to 2014 before its more recent decline (Imperial Irrigation District, 2020), the southeast shore of the lake was close to the Salton Buttes (personal observations, 2005–2014). Thus, it is apparent that in 1850 there was a large lake in the Salton Basin that was the size of the modern Salton Sea, roughly 48 km (30 miles) long and 24 km (15 miles) wide.

From December 1861 to January 1862 an extraordinary period of extremely heavy precipitation lasting for approximately 43 days, likely caused by a series of major atmospheric river events (Dettinger and Ingram, 2013), caused a megaflood affecting vast expanses of the western and southwestern U.S., including Oregon, Washington, California, Nevada, Idaho, Utah, Arizona, and New Mexico. The Colorado River delta region was completely inundated, the Army's Fort Yuma at the junction of the Colorado and Gila Rivers was transformed into an island, entire settlements on the lower Gila River and lower Colorado River were washed away, and a large lake estimated to be 60 miles (96 km) long and 30 miles (48 km) wide formed in the Salton Basin (Rigg, E.A., 1862; Wheeler, G.M., 1876). In the vicinity of Lees Ferry, Arizona, between the upper and lower Colorado River basins, the 1862 flood had an extraordinary peak discharge that was estimated to be in excess of 400,000 cubic feet per second (second-feet) (Dickinson, 1944).

In February 1891, the lower Colorado River "rose to an unusually high stage, the water at that time being contributed mainly by the Gila and its tributaries. It overtopped its banks below Yuma, and submerged large areas along the Alamo and New Rivers." (Grunsky, 1907.) During a lengthy dry period preceding the February 1891 flood, those distributary channels became blocked with sediment and thick deposits of blown sand; so in February 1891 the floodwaters pooled rather than flowing onward (Grunsky, 1907; Schuyler 1907; MacDougall, 1915). But later when the usual spring high water caused the Colorado to breach its western levee in the stretch south of Pilot Knob below the U.S.-Mexico border, the already-swollen distributary channels received enough additional flow to fully erode the blockages along their courses, and floodwaters poured into the Salton Basin (Schuyler 1907). The flooding created a large lake in the central basin that was estimated to cover approximately 150-160 square miles (~388-414 km^2) (Schuyler, 1907).

Discussion

Analysis of lower Colorado River hydrodynamics and floodplain morphodynamics

By latest Pleistocene time, the lower Colorado River had developed characteristic hydrodynamics, floodplain morphodynamics, and avulsion style across its delta that were contingent on regional hydroclimate. The unique topography of the region played an important role. The well-established patterns of the river's fluvial-deltaic behavior continued through the Holocene until the river was dammed and controlled in the mid-twentieth century. There were three main patterns in the river's behavior based on different hydroclimate conditions:

(a) Average hydroclimate: During periods of typical spring high water, and sometimes as a result of large winter storms briefly yielding heavy precipitation and flash flooding in the lower Colorado River basin, the river overflowed or occasionally broke through its levee along the stretch below its junction with the Gila River, avulsed moderately, and sent a portion of its flow toward the Salton Basin. When streamflow naturally decreased, channel sedimentation increased, distributaries became blocked, and the river's flow was once again confined within the mainstem.

(b) Temporarily very wet hydroclimate: During periods of extremely high streamflow mediated by short-lived changes in the region's hydroclimate, the lower Colorado River overflowed, avulsed, bifurcated, and moved by sheetflow across its floodplain, reopening established distributary channels and creating new ones. Because of delta topography and exceedingly low base level on the north side of the delta crest, once floodwaters were streaming into the Salton Basin they became temporarily entrenched while wet climate conditions continued. When streamflow subsided significantly with a shift to a drier climate, sedimentation blocked distributaries, and the river's flow was once again limited to its mainstem channel.

(c) Prolonged periods of extremely wet hydroclimate: Lengthy periods of extraordinarily high streamflow lasting for decades, centuries, or millennia caused major, long-lived modifications to the river's floodplain geomorphology and delta. Cutbacks of distributary channels, extreme erosion at points of bifurcation, and long-term entrenchment of the river in courses delivering flow into the Salton Basin resulted in the creation and perpetuation of Lake Cahuilla. Once established, the huge lake was filled to a through-flowing condition (i.e., it was constantly overflowing at its delta sill), or was regularly filled to the point of overflowing, or was simply sustained near its highstand level as a closed lake—depending on the amount of Colorado River streamflow available at any given time, which was in turn dictated by variations in the region's overall extremely wet hydroclimate. When the climate shifted to drier conditions, Lake Cahuilla shrank, became saline from evaporation, and may sometimes have disappeared entirely when very lengthy droughts occurred.

Although the position of the lower Colorado River's mainstem in the region below its current junction with the Gila is not known with precision for much earlier periods, historical documentation indicates that at least for the past several hundred years (until the damming and control of the river) there were four geomorphic factors crucial to the Colorado's floodplain morphodynamics in its lower reaches: (1) the sharp curve to the south-southwest near Pilot Knob made by the mainstem after briefly heading due west from its junction with the Gila; (2) the existence of an unusual elevated zone trending northeast across the central delta, and forming a pronounced drainage divide within that region; (3) the morphology and position of the delta crest in relation to the big curve near Pilot Knob; and (4) extraordinarily low regional base level north of the delta crest. In combination, these factors led with virtual inevitability to overflow, avulsion, and bifurcation of streamflow along the river's western levee at and below the curve, and to flooding into the central Salton Basin during periods of very high flow—such as occurred during 1905-07.

Other workers have suggested that base level and gradient fully determined the issue of whether the river flowed to the Gulf or to the Salton Basin throughout the Holocene. Howard and Lundstrom (2005) state, "In line with evidence that in the late Holocene the huge Salton basin filled several times to overflowing (ancestral Lake Cahuilla), an automatic delta-switching mechanism governed by changing base levels is here proposed. In this model, incised N-directed channels graded to below sea level would tend to capture the river's flow from other delta distributaries until Lake Cahuilla filled to above sea level. When the flow then switched back toward the Gulf, the lake would evaporate and the cycle would renew." Similarly, Howard *et al.* (2007) assert, "We infer that when Lake Cahuilla rose to its spillover level, the feeding distributaries silted in and lowered their grade enough to provide an impetus for the river to switch back to paths down the south side [sic] of the delta to the Sea of Cortez. Shut off from inflow, evaporation of 1.8 m/yr would dry Lake Cahuilla in a few decades, again lowering the base level below sea level and setting the stage for another cycle of northward diversion, downcutting, lake filling, and spillover."

However, this hypothesis is not consistent with the data on Lake Cahuilla developed by Li *et al.* (2008a,b), or with the historical record. Lake Cahuilla existed at its highstand level for millennia, and could not have done so if this cyclical switching model were correct. In addition, there were numerous occasions when lakes much smaller than Lake Cahuilla, with surface elevations very far below sea level, were formed by Colorado River flow into the Salton Basin; and then their filling was truncated when—notwithstanding significantly lower base level in the Salton Basin—the river's course switched back toward the Gulf of California. Thus, while base level and gradient have played important parts in the formation of Salton Basin lakes, those factors have not been fully determinative of the direction of the Colorado River's flow. Climate-related changes in streamflow, erosional capacity, sediment load and sedimentation, along with the unique geomorphology of the floodplain, have all played crucial roles.

Comparison of 1891 versus 1905

In order to understand whether the 1905 formation of the Salton Sea was truly "accidental" and caused by human negligence, or was the result of the lower Colorado River's well-established floodplain morphodynamics and avulsion style combined with regional hydroclimate, it is useful to compare what occurred in 1905 with what happened in 1891 prior to any man-made modification of the river's natural levee and distributary channels below Pilot Knob. The 1891 flood is the event selected for this comparative purpose because it is the only significant lake-creating flood that occurred prior to 1905 for which there is a gaged discharge record of the river at Yuma.

A comparison of the river discharge that resulted in the 1891 flood into the Salton Basin with the discharge that occurred during the 1905 flood shows that the conditions on the lower Colorado River during 1905 were far more hydrologically extreme than during the lake-forming flood of 1891. The extraordinarily wet conditions during 1905, in combination with the nature of the river's well-established floodplain morphodynamics and avulsion style, indicate that flooding into the Salton Basin and initiation of Salton Sea formation would have occurred that year even in the absence of man-made modifications to the river's natural levee and distributary channel.

- The location where the Colorado River bifurcated in 1905 as a result of the man-made cut in the river's levee was along the same stretch of the lower course below Pilot Knob, just below the US–Mexico border, where the river broke through its natural levee in 1891. In addition, prior to 1891 the river had previously overtopped, avulsed, and bifurcated along that same vulnerable stretch of its levee many times in the absence of any human intervention. Thus, it's reasonable to conclude that the same underlying hydrodynamic forces and characteristic floodplain dynamics were operational in 1905 as in 1891 (and in earlier floods).

- There was a delay between the river overtopping its natural levee during flash flooding in the winter of 1891 and flooding into the central Salton Basin the following spring because the river's distributary channels had previously become clogged with silt and huge deposits of blown sand during a lengthy period of drought preceding the February 1891 high water (Schuyler, 1907). For several months the winter floodwaters soaked into those accumulated sediments and ponded extensively. Then, during the spring high water and levee break, the obstructions in the distributary channels were eroded and the accumulated floodwaters were released into the central Salton Basin. In contrast, in 1905 the river had a clear course through its distributary channels into the central basin because the major blockages in those channels had already been scoured away by previous flooding (Schuyler, 1907). Thus, it's reasonable to conclude that the unblocked conditions of the distributary channels in 1905 made it even more likely that year than in 1891 that floodwaters would make their way into the central Salton Basin.
- In the winter of 1891, there was a seven-day period of extreme high water on the lower Colorado River below Yuma, as the result of major flash flooding on the Gila and its tributaries that occurred from February 23 through March 1 (Murphy, 1906; Schuyler, 1907; McGlashan and Dean, 1913). Later, the spring high water that occurred during two periods in May and June was not in itself remarkable, but it was able to break through the already-weakened western levee below Pilot Knob (Schuyler, 1907; McGlashan and Dean, 1913). In contrast, in 1905, an extraordinary series of seven major back-to-back floods occurred on the Gila River and its tributaries from January 15 to April 30 that pushed the lower Colorado River's discharge below Yuma to extreme levels for prolonged periods (Murphy, 1906; USGS, 1906; McGlashan and Dean, 1913). Following the January–April floods, very high streamflow (over 19,000 second-feet; details in the next paragraph) continued during May and July, and extreme discharge (over 50,000 second-feet; details in the next paragraph) occurred again throughout June and from the end of November to early December (Murphy, 1906; USGS, 1906; McGlashan and Dean, 1913).
- According to Schuyler (1907), as a general matter the stage of the river during which overflow began below Yuma was 22.0 feet above sea level, and at that high-water stage the lower Colorado's discharge was typically about 19,000 second-feet. Using those numbers as a low-threshold indicator for what constitutes 'very high' streamflow, and 50,000 second-feet as a low-threshold indicator for what constitutes 'extreme' streamflow, a comparison of the circumstances in 1891 and 1905 yields the conclusion that stage and discharge of the lower Colorado River below Yuma in 1905 were exceedingly high for much longer than they were in 1891. During the flood from February 23 to March 1, 1891 when gage height ranged from 23.9 to 33.2 feet, discharge significantly exceeded 19,000 second-feet for a total of seven days (McGlashan and Dean, 1913). Discharge above an extreme level of 50,000 second-feet occurred on five of the seven days. During that seven-day period the highest daily discharge achieved was 101,000 second-feet on one day (Schuyler, 1907). In May and June 1891, the gage height slightly exceeded 22.0 feet for a total of 45 days, ranging mostly from 22 to 23 feet on those days but reaching 24 to 25 feet on a total of five days (McGlashan and Dean, 1913). No measurements of the associated discharge are available for that spring high-water period. In contrast, during 1905 the gage height was above 22.0 feet on 151 days, and on 79 of those days it exceeded 25 feet. During the entire month of June it was above 27 feet, and in November it reached a maximum of 31.3 feet (USGS, 1906). Of the 148 days in 1905 for which discharge measurements are available, the river's discharge significantly exceeded 19,000 second-feet during a total of 76 days (USGS, 1906; McGlashan and Dean, 1913). Discharge higher than an extreme level of 50,000 second-feet occurred during a total of 26 days, and extraordinarily high discharge greater than 70,000 second-feet occurred on 15 of those extreme-flow days. During January-April the highest daily discharge achieved was 111,000 second-feet, and two other days had discharges well above 90,000 second-feet (Dickinson, 1944). In addition, another period of extreme streamflow occurred throughout June 1905, with discharge above 50,000 second-feet every day for which measurements are available that month (USGS 1906; McGlashan and Dean, 1913). During June 1905 the highest daily discharges achieved were 94,300 and 92,400 second-feet (Dickinson, 1944). From November 30 to December 5, 1905 another period of flash flooding with very high streamflow occurred with discharge above 19,000 second-feet on each of those days (USGS, 1906; McGlashan and Dean, 1913), and two days had extreme discharges of 103,000 and 77,360 second-feet (Dickinson, 1944).

Inevitability of Salton Basin flooding during high flows

It is important to note that even after the lower Colorado River had been forced to flow toward the Gulf of California in January 1907 by construction of an enormous rock dam across the site of the breach in the western levee, there was ongoing concern about the possibility, and even likelihood, of additional flooding into the Imperial Valley and central Salton Basin. This concern demonstrates an understanding that flooding into the Salton Basin during very high discharge conditions was a characteristic and inevitable feature of the lower Colorado River's hydrodynamic regime and floodplain morphodynamics in the event of sufficiently wet hydroclimate. In fact, this recognition and the desire to prevent the river from flooding into the Imperial Valley and central Salton Basin formed the primary motivation for the construction of Hoover Dam and other control structures built on the upper and lower Colorado River in succeeding decades. LaRue (1925) stated:

> "To protect these lands from floods extensive levee systems have been built and must be maintained… Although millions of dollars have been spent in constructing the levees, these works alone, however well maintained, cannot assure protection from the flood menace. There is grave danger that during periods of high run-off the levees will be breached and the entire flow of the Colorado will find its way into Imperial Valley and the Salton Sea. If these valuable properties on the lower river are to be protected, dangerous stages must be prevented by holding back a part of the flood-making waters. The need for flood control is therefore urgent."

Conclusion

Formation of the Salton Sea in 1905-07 was the result of wet regional hydroclimate and the river's characteristic hydrodynamic regime, floodplain morphodynamics, and avulsion style across its delta. As a result of extremely high flows on the lower Colorado River during that period, the river behaved in exactly the same manner it had since at least the latest Pleistocene when streamflow was high: by overflowing, avulsing, bifurcating, and flooding into the Salton Basin. Formation of the Salton Sea was only "accidental" from the standpoint of the people who were trying very hard to prevent the river from flowing into the basin in the same manner it had for millennia. Were it not for their strenuous and persistent efforts to block the river's flow, the flooding would likely have been far worse.

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