Sediment and nutrient deposition over a reconnected floodplain during large-scale river diversions, the Bonnet Carré spillway in 2011, 2016, and 2019.

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Measurement units

Teragram (Tg) = 1,000,000,000 kg
Gigagram (Gg) = 1,000,000 kg
Megagram (Mg) = 1,000 kg
milligram (mg) = 0.001 kg
cubic kilometer (km^3) = 1,000,000,000 m^3
cubic meter per second (m^3/sec) = 35.3 ft^3/sec
millimeter (mm) = 0.00328 ft
Tg = 1.102 x 10^6 US tons
cubic feet per second (ft^3/sec) = 0.0283 m^3/sec

Introduction

In hopes of reversing or slowing the decline of the river delta, water diversions have been built and planned, and natural diversions have formed and been allowed to develop along the lower Mississippi River. In addition to the possibility of building land, these diversions allow for the storage of nutrients within the deposited sediments and provide a buffer from coastal storm surge flooding. Deposition from diversions reduces nutrient loading to the receiving waterbodies. Along the Mississippi River delta in Louisiana, modern planned diversions after 2017 (CPRA 2017) seek to bring sediment-laden water from the river to a receiving area that may once have been part of the historic delta floodplain. Many of the existing diversions discharge directly into open-water bays of the subaqueous delta, however some flood diversions outflow to the subaerial floodplain (Kroes et al. 2015). The effects of diversion outflows to bays are difficult to physically analyze and quantify due to the complex hydrodynamics of subaqueous sites, such as storm-driven resuspension, and tidal currents that mobilize deposited fine sediments downcoast or off the continental shelf. In contrast, flood diversions that outflow to subaerial floodplains offer clear and numerous sediment deposition measurement opportunities and clearly identifiable material to analyze. Flood diversions, while similar, may not exhibit identical depositional environments due to hydraulic gradient and vegetation differences. Because flood diversions draw water from the river at a greater height above the riverbed, they may entrain less bed sediment than non-flood diversions (Karmaker et al. 2010). Previous studies indicate that the large discharges through flood diversion control structures deposit large masses of sediment (Nittrouer et al. 2012) and nutrients and can provide depositional curves that may be extrapolated to other diversions (Kroes et al. 2015).

Study Area

In this study we examine a large flood diversion, the Bonnet Carré Spillway (hereafter the Spillway). The Spillway was constructed in 1931 on the footprint of four naturally forming crevasses that formed from 1849 to 1882 between the Mississippi River and Lake Pontchartrain. This Spillway is part of a comprehensive flood control plan designated in the 1928 Flood Control Act of May 15, 1928 (17th Congress, ch. 569, 45 Stat. 534), which authorized the implementation of the Jadwin Plan, which later evolved into the Mississippi River and Tributaries (MR&T) Project. Chief Engineer General Edgar Jadwin’s plan differed from the "levees only" approach of flood risk management that had previously been used in the Mississippi River valley in three major respects, as it included: 1) the incorporation of floodways to divert peak flows and reduce stages in the main channel; 2) backwater areas to divert peak flows from the river and store a portion of the flood waters near the peak of the flood resulting in reduced downstream stages; and 3) designing all works on the basis of a project design flood (Jadwin 1928; USACE 2023).

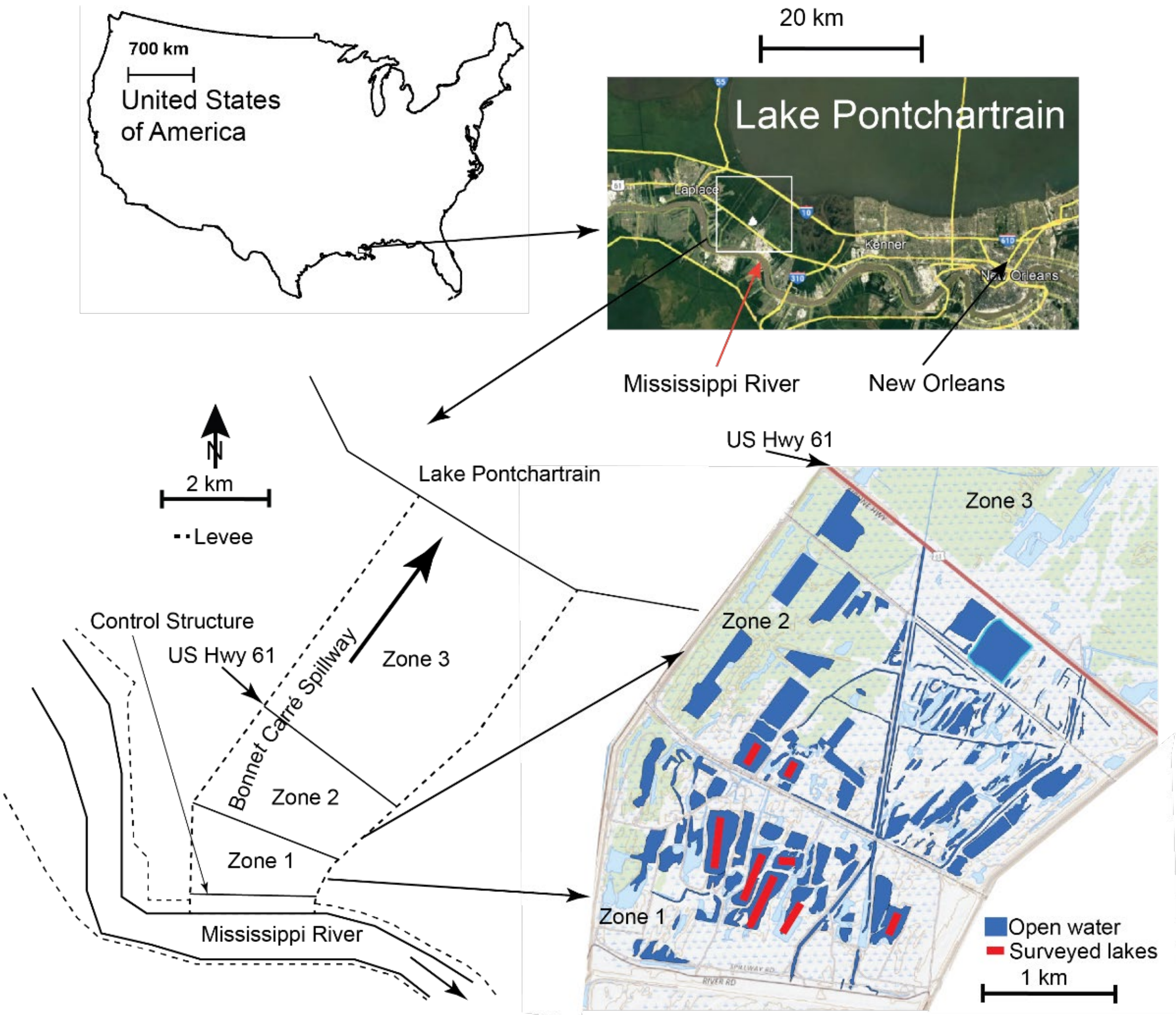

Figure 1. The Bonnet Carré Spillway study area is approximately 51 km upstream of New Orleans along the Mississippi River and is located between the river and Lake Pontchartrain. The Spillway was separated into three deposition zones. Zones 1 and 2 had many open water bodies, some of these lakes were surveyed before and after the 2016 opening. Base maps modified from Kroes and Brinson (2004), Google Earth (2022), and Esri (2022).

The Spillway redirects flows that exceed the design capacity of the downstream levee system. This design capacity of the levee system below the Spillway is 35,000 m^3/sec, which includes the levees and floodwalls through the City of New Orleans. The Spillway is the most frequently used spillway of the MR&T System located 51 km upstream of New Orleans along the Mississippi River (Figure 1). Its design discharge capacity is 7,080 m^3/sec and flows across an area of 28 km^2 before draining into Lake Pontchartrain (USACE 2014); however, during the 2011 flood operation, discharge through the Spillway was observed to be approximately 8,900 m^3/sec and was open 42 days. During the 2016 (23 d) and 2019 (122 d) flood operations, the Spillway passed a maximum discharge of 6,000 m^3/sec (USACE 2014; USGS 2023).

Following operation, sand deposits are mined and removed from the Spillway to preserve the ability to continue to meet its design flow capacity and reduce sediment transport to Lake Pontchartrain. The Spillway also acts as a source site for levee building and construction materials. Because of this mining there are hundreds of small open water bodies that are in various stages of filling or excavation (Figure 1, USACE 2010, Google Earth 2022).

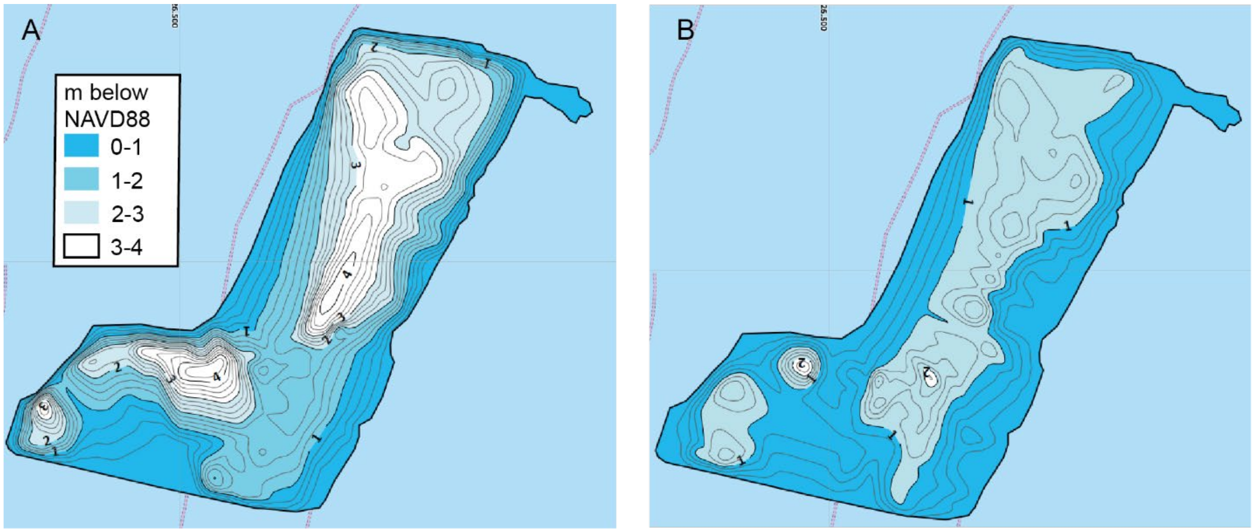

Figure 2. An example of bathymetric outputs from Bonnet Carré Spillway lake surveys before (A) and after (B) the 2016 Mississippi River flood. Maps created in Reefmaster (2019). Contour lines indicate depth (m) below NAVD88.

Methods

Sediment deposition during the 2011 flood was partially calculated by Nittrouer et al. (2012) from field measurements in zones 1, 2, and a small portion of 3. Before the 2016 operation, we performed bathymetric surveys on several of the lakes across the Spillway. In 2016 and 2019, before Spillway opening, we established several artificial marker horizons to measure sediment accretion. These artificial markers included feldspar clay pads and plastic tiles (Figures 2 and 3). We measured the height above sediment surface of several PVC pipes, steel pipes, and concrete footings. Discharge into the Spillway during each flood was calculated using a weir calculation by the U.S. Army Corps of Engineers for all studied floods and verified by discharge measurements in the Mississippi River upstream and downstream of the Spillway. During the 2011, 2016, and 2019 openings, nutrient concentration samples were collected along the US Highway 61 (Hwy 61) crossing, midway down the Spillway at U.S. Geological Survey (USGS) site no. 300115090245000 (USGS 2022) and analyzed for total nitrogen (TN) and total phosphorus (TP). During the 2011 diversion, suspended-sediment concentrations (SSC) at the Hwy 61 were measured daily and were used to calculate a daily suspended-sediment load. During the 2016 and 2019 diversions, SSCs were calculated based on a regression of all available measurements of Hwy 61 SSC as correlated with the Mississippi River at Baton Rouge SSC (n=79, USGS site no.07374000, USGS 2022) using **Equation 1**.

$$\text{Hwy61 SSC} = 0.6324(\text{Baton Rouge SSC}) + 37.3,\ R^2 = 0.704 \quad (1)$$

Sediment and nutrient loads were calculated as the product of the daily volume of water passing into the Spillway and the concentration of suspended sediment, TN, or TP. If days were not sampled, a linear interpolation was used between sampled dates.

After the Spillway drained in 2016 and 2019, accretion was measured above the artificial horizons and a variety of natural horizons (grass roots, leaf pack, willow roots, Figure 3). Samples of new deposition were collected and analyzed for bulk density, mass, particle size, total carbon, nitrogen, and phosphorous concentrations. Lakes surveyed for bathymetry before opening were resurveyed after closure in 2016 (Figure 2). Depositional volume was calculated for those lakes and a ratio was developed for lake deposition relative to the surrounding spillway deposition. Sediment and nutrient concentrations in the Mississippi River were determined from samples taken by USGS during the floods at Belle Chase, Louisiana (USGS site no. 07374525, USGS 2022) and compared with the sediment load during the studied openings. A one end-member mixing model (Phillips and Koch 2002) was developed to determine the percentage of bed load material and suspended sediment in the deposited sediments. This model used total nitrogen concentrations (mg-N/g) of previously collected bed material at the Baton Rouge site (USGS site no. 302800091114800, USGS 2022) and the total nitrogen concentration of suspended load during the 2016 and 2019 operation.

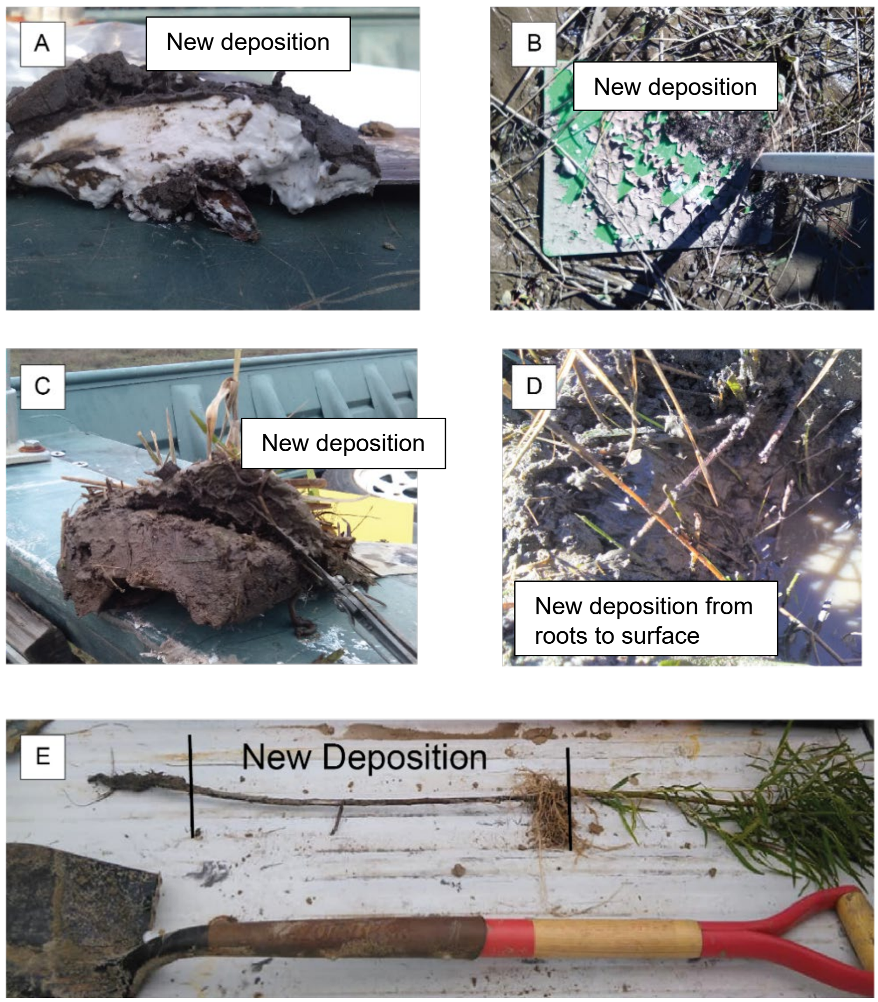

Figure 3. Sediment accretion was measured over a variety of artificial and natural markers; (A) feldspar clay, (B) plastic tiles, (C) buried grass layers, (D) buried herbaceous stems, (E) buried willow saplings. Photos taken by Daniel Kroes, USGS.

Results

During the 2011, 2016, and 2019 Spillway operations, large volumes of river water (21.5 km^3, 2.91 km^3, and 38.0 km^3, respectively) and masses of sediment flowed through the Spillway from suspended Mississippi River load (3.48 teragrams (Tg), 1.95 Tg, and 5.35 Tg, respectively; Figure 4). However, sediment deposition onto the Spillway exceeded the suspended load in 2011 (6.41 Tg using 2019 bulk density) and 2019 (5.95 Tg), whereas 2016 deposition was 1.17 Tg.

Mean depth of accretion on the Spillway ranged from 28.5 mm in 2016 to 286 mm in 2011 (Figure 5).

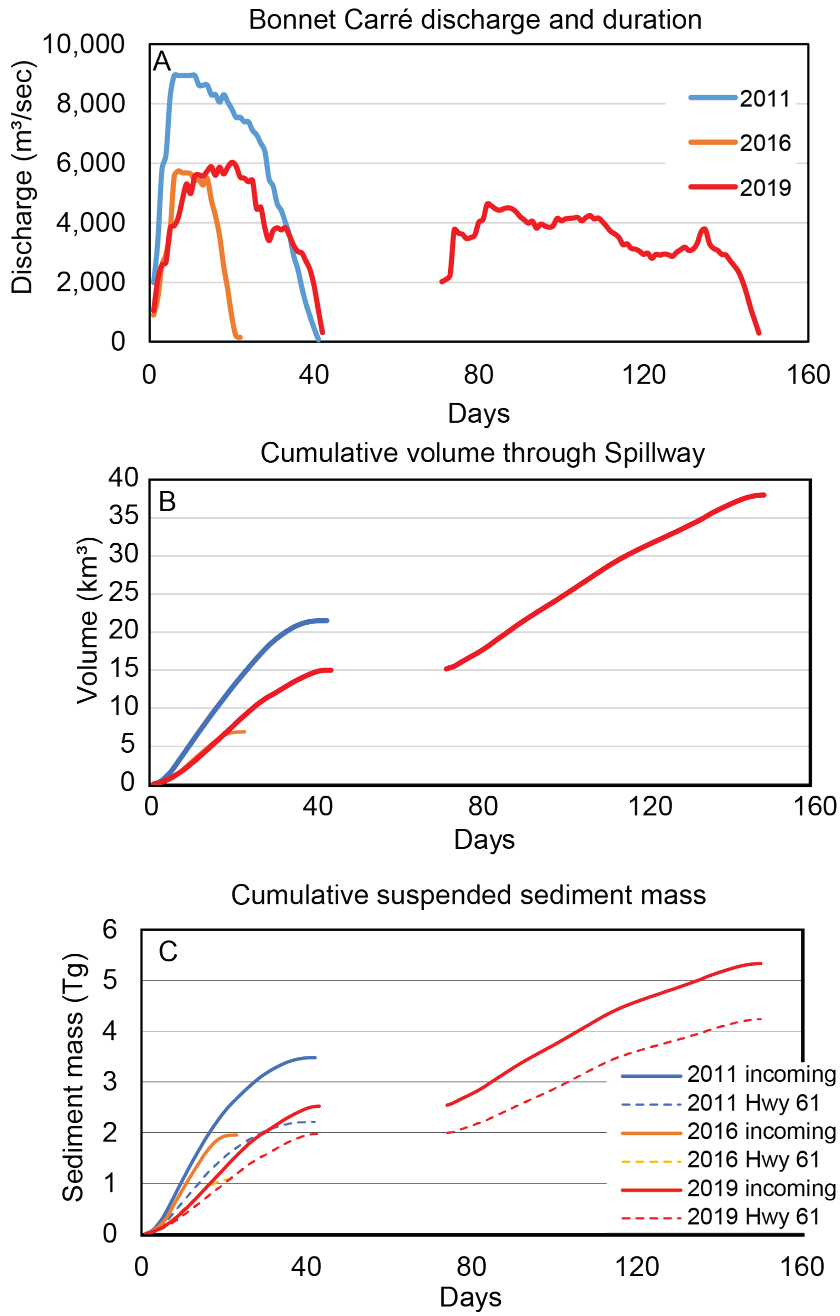

Figure 4. Hydrologic data for the 2011, 2016, and 2019 Bonnet Carré Spillway operation; (A) the discharge (m^3/sec) and hydrograph duration of the openings. During the 2019 flood year the Spillway was open for 42 days, closed for 30 days, and then reopened for 77 days. During the closure, discharge over the Spillway was not calculated. (B) The cumulative water volume through the Spillway (km^3), and (C) the cumulative mass of suspended sediment moving through the Spillway (based on Mississippi River at Belle Chase suspended sediment concentration and the mass passing the Spillway at the Hwy 61 sampling location in teragrams). Gaps in the graphs represent days when no data were collected.

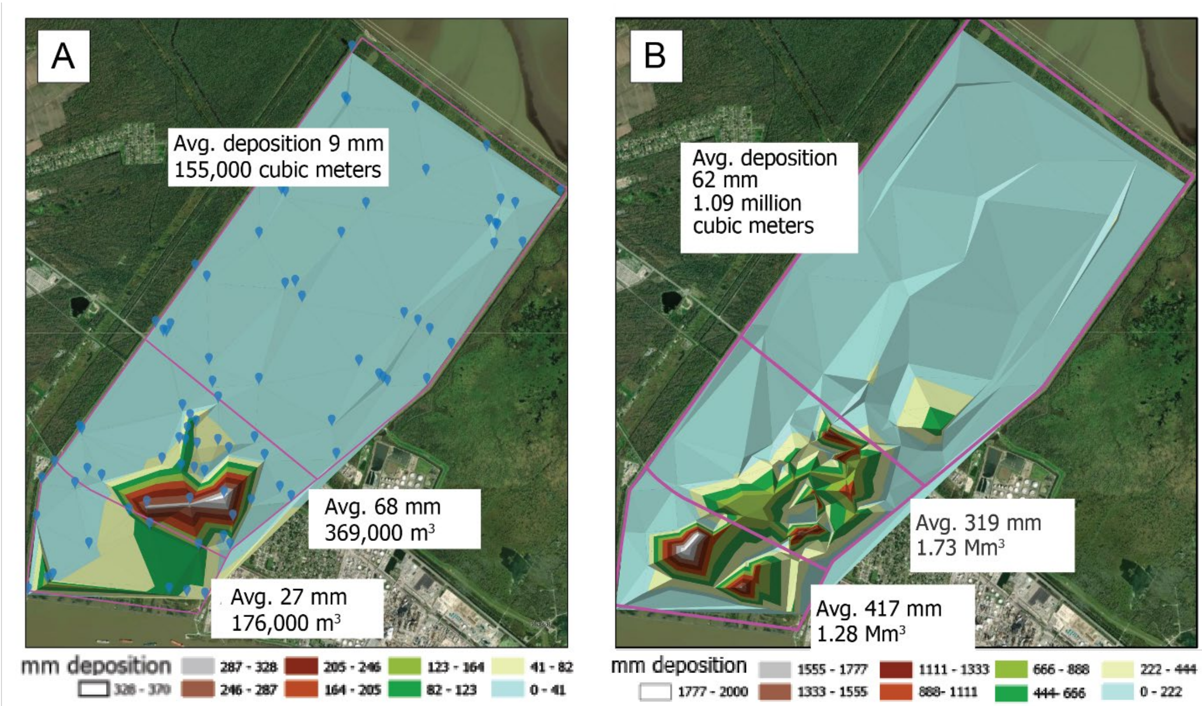

Figure 5. Sediment deposition patterns for the 2016 (A) and 2019 (B) Bonnet Carré Spillway operations. Measurement locations for 2016 are indicated by blue pins on (A) and omitted from (B) because the 90 additional sampling locations obstruct the deposition map. Base map created in ArcPro 3.0 (Esri 2022)

Nutrient deposition on the Spillway was substantial with 0.986 gigagrams (Gg) N, 23.1 Gg C, and 0.662 Gg P in 2016 and 4.90 Gg N, 75.6 Gg C, and 3.42 Gg P in 2019. Longer releases led to an export of particulate nitrogen from zones 1 and 2 during the receding limb of the flood hydrograph (Figures 6 and 7). A substantial portion of the total nutrient deposition occurred beyond the Hwy 61 in zone 3 , with 0.279 Gg N, 3.30 Gg C, and 0.129 Gg P in 2016 and 1.63 Gg N, 23.0 Gg C, and 0.871 Gg P in 2019. However, the timing of that deposition relative to the operation timing was not determined.

The 2011 and 2019 measured deposition plus exported load equated to 248% and 170% of Mississippi River suspended sediment load input, respectively. The total 2016 deposition plus exported load was 104% of the Mississippi River suspended sediment load input. These high trapping rates in combination with the particle size distribution indicated substantial contributions of riverbed material to Spillway sediment load and deposition during the 2011 and 2019 openings (Figure 7). The mass balance for deposition in relation to input and output loads indicated a bedload input of 5.14 Tg, 0.08 Tg, and 3.73 Tg for 2011, 2016, and 2019, respectively. Sediment fingerprinting indicated substantial riverbed load contribution to deposition up to 4 km from the Spillway control structure (Figure 8).

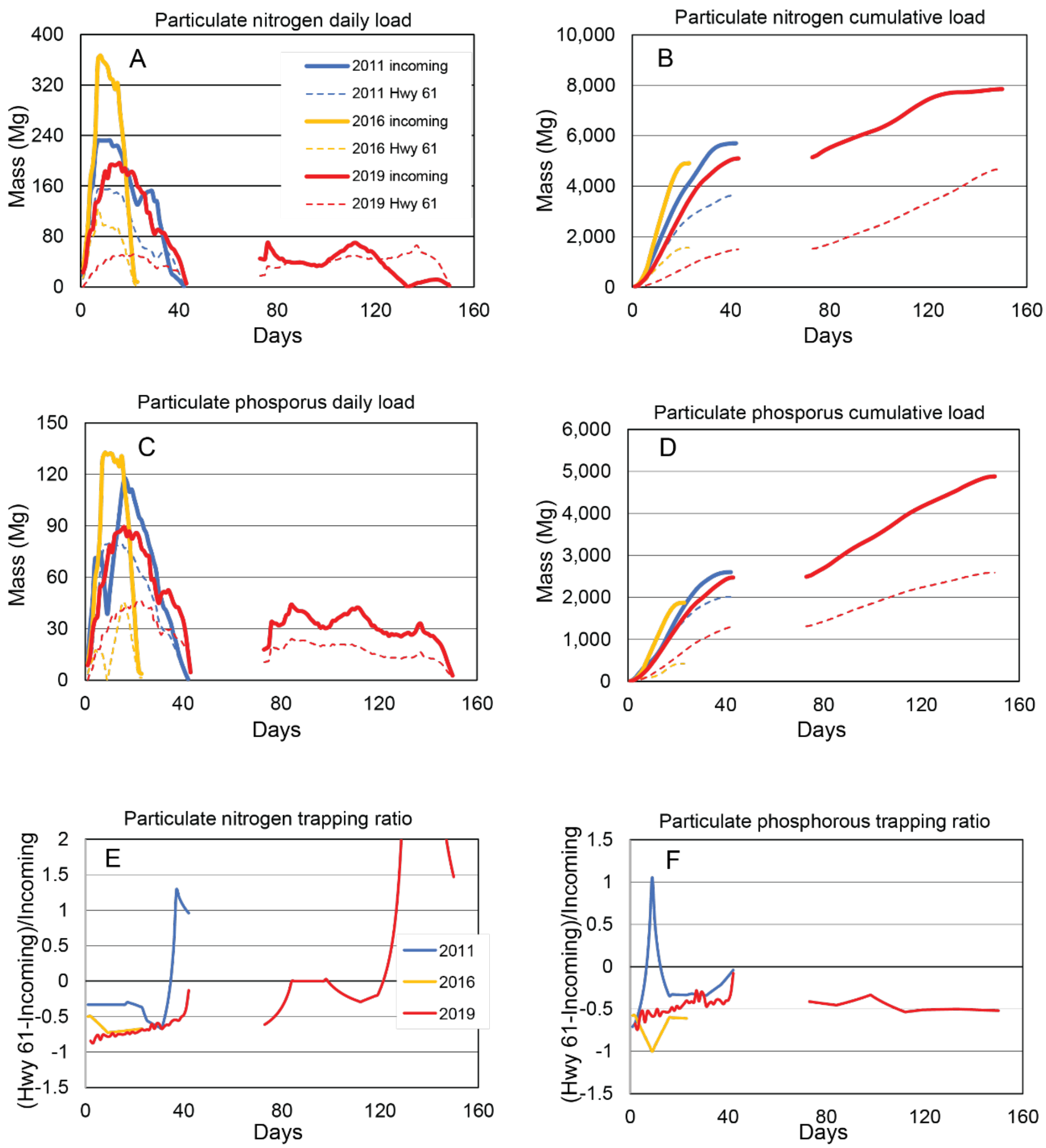

Figure 6. Nutrient loads in megagrams (Mg) and trapping ratios over the operational duration; 2011, 2016, and 2019. (A) The daily incoming particulate nitrogen loads and (B) cumulative mass based on Mississippi River at Belle Chase concentrations and the Hwy 61 sampling point. (C) The incoming particulate phosphorous load and (D) cumulative mass at the incoming and Hwy 61 sampling points. (E) The particulate nitrogen trapping ratios [(Hwy 61-incoming)/incoming] of zones 1 and 2, positive values indicate export to zone 3 (y-axis truncated). (G) The particulate phosphorous trapping ratios [(Hwy 61-incoming)/incoming] of zones 1 and 2. During the 2019 flood year the Spillway was open for 42 days, closed for 30 days, and then reopened for 77 days. During the closure, discharge and load from the spillway were not calculated (represent by gaps in the graphs).

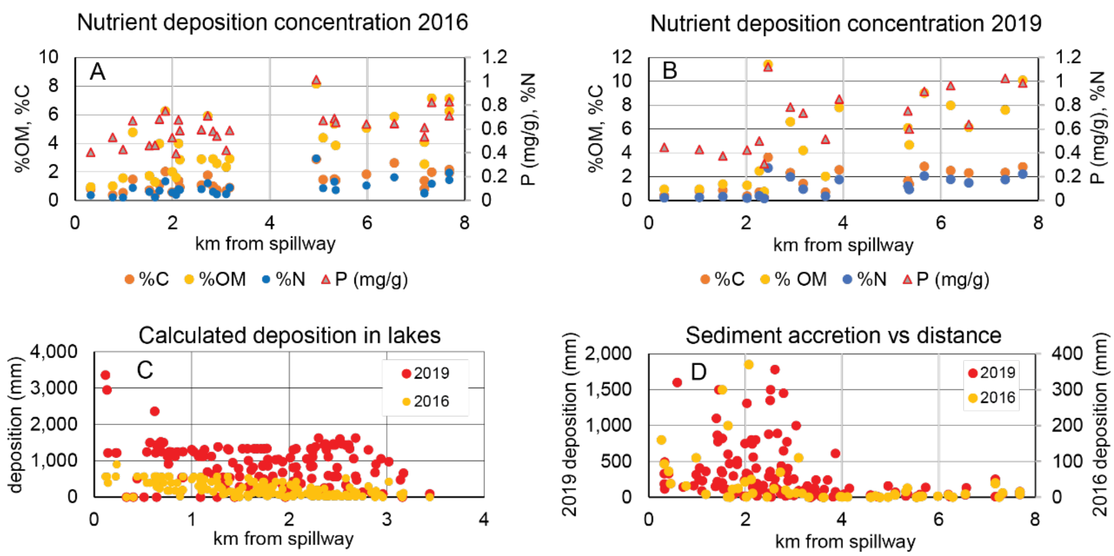

Figure 7. Nutrient concentration of sediment deposited during the 2016 (A) and 2019 (B) floods on the Bonnet Carré Spillway. (C) Calculated depth of accretion in the open water bodies of zones 1 and 2. (D) Measured sediment accretion on the Spillway after the 2016 and 2019 operations. %C = % carbon, %OM = % organic matter, %N = % nitrogen, P (mg/g) = phosphorous (mg/g).

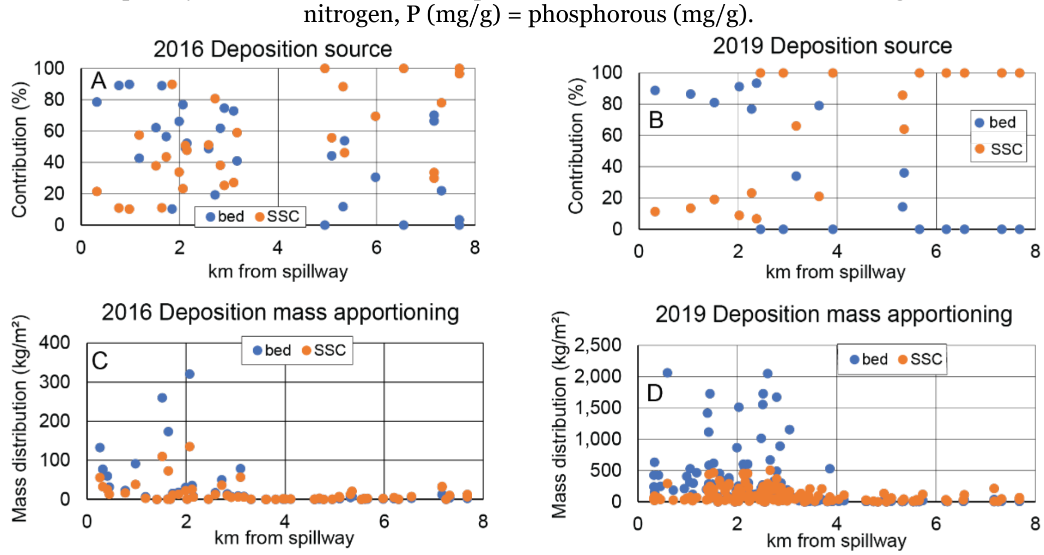

Figure 8. (A and B) The source of deposited material on the Bonnet Carré Spillway, Mississippi River suspended sediment (SSC) or bed material, based on sediment fingerprinting using nitrogen concentrations of the deposition and the two sources. (C and D) The deposited mass of sediment originating from Mississippi River SSC or bed material for the 2016 and 2019 operations.

Conclusions

Floodplain reconnection during large floods moves large masses of sediment and nutrients from the Mississippi River that are mostly deposited on the Spillway during each operation and a portion of those are exported to Lake Pontchartrain. Longer openings with greater deposition and long descending limbs of the hydrograph appear to export particulate nitrogen from zones 1 and 2 during the flood wave recession. These exported nutrients may be trapped in zone 3. Sampling of suspended nutrient and sediment during an opening in zone 3 may clarify this question. These data suggest that both greater discharges through and longer openings of the Spillway are more effective at entraining riverbed sediment through the Spillway structure leading to greater floodplain deposition. These data provide sediment and nutrient depositional properties and curves for the operation of diversions designed to promote land area growth in subsiding deltas for managing floodplain reconnections to improve water quality.

Acknowledgements

Our coauthor, Brian Vosburg, passed away during the writing phase of this study. We wish his surviving two sons the best. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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