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# The Siltcatcher: A Sediment-Capture System for Wetland Creation and Coastal Protection in Western Lake Pontchartrain

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# THE SILTCATCHER: A SEDIMENT-CAPTURE SYSTEM FOR WETLAND CREATION AND COASTAL PROTECTION IN WESTERN LAKE PONTCHARTRAIN

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**Dedicated to James Howard Taylor, Jr.**
**1928 – 2019**

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Finally, this thesis is dedicated to my grandfather, Dr. James Taylor, Jr., who loved numbers, music, his family, and the Gulf Coast, and who passed away when this project was in its nascent stages. May this project be worthy of his memory.

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## ABSTRACT

The West Lake Pontchartrain region faces a number of long-term environmental challenges due to anthropogenic climate disturbance and landscape modification, including sea level rise, increased storm surge risk, shoreline erosion, and wetland degradation. In response, this thesis applies recent research in the fields of landscape architecture and civil engineering to propose a dynamic, natural-systems solution for wetland creation and shoreline protection. The project envisions a series of breakwater-like structures in western Lake Pontchartrain positioned to slow water released from the nearby Bonnet Carré Spillway, causing suspended sediment to settle and create self-building and self-sustaining wetlands capable of keeping pace with future sea level rise. This hybrid grey-green system would reduce erosion of the western Lake Pontchartrain shoreline, provide storm protection for the communities of St. James and St. John the Baptist Parishes, create valuable wildlife habitat, and provide ecosystem services and cultural opportunities for local residents. This proposal seeks to contribute to the ongoing discourse regarding "Engineering with Nature"[1] principles and explore the interdisciplinary potential suggested by their adoption.

The project's design methodology embraces a wide range of tools used by both landscape architecture and engineering including field work, mapping, drawing, image-making, and model making. The research identifies physical and numerical hydrodynamic modeling as key tools for the design of coastal infrastructure and integrates their use into a recursive, non-linear design process typical of architectural practice. In doing so, it seeks to expand the range of tools typically used by landscape architects for design ideation and visualization and posit alternative interdisciplinary workflows for the conceptualization and design of large-scale infrastructure.


1. "Engineering with Nature" is a US. Army Corps of Engineers initiative defined as "the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaborative processes." For examples of projects which exemplify this concept, see Todd Bridges, *Engineering With Nature: An Atlas*, ed. Holly Kuzmitski (Vicksburg: US Army Engineer Research and Development Center, 2018), https://ewn.el.erdc.dren.mil/img/atlas/ERDC-EL_SR-18-8_Ebook_file.pdf.

The resulting proposal complements the already-planned West Shore Lake Pontchartrain Hurricane Protection Levee and Maurepas River Reintroduction projects, providing a forward buffer in keeping with the "Multiple Lines of Defense" strategy promulgated by the Lake Pontchartrain Basin Foundation.[2] In contrast with conventional mono-functional infrastructure, the system proposed in this research offers multiple co-benefits for both human and non-human constituencies. Finally, the design strategies derived from this research represent a novel form of coastal infrastructure with potential applicability to a broad range of sites and scales along the Louisiana coast.

2. John A. Lopez, "The Multiple Lines of Defense Strategy to Sustain Coastal Louisiana," *Journal of Coastal Research* 10054 (November 2009): 186–97, https://doi.org/10.2112/SI54-020.1. The West Shore Lake Pontchartrain Levee is a planned 18.27-mile long hurricane risk reduction levee designed to protect communities in St. Charles, St. John the Baptist, and St. James Parish. The Maurepas River Reintroduction Project is a freshwater diversion canal that will siphon water from the Mississippi River into the Maurepas Swamp in an attempt to reverse the swamp's decline in recent decades.

# INTRODUCTION

In recent decades, landscape architects have identified infrastructure as an emerging area of importance and growth for the profession, especially coastal infrastructure. Save for a few noteworthy exceptions, the discipline's ambition in this area remains largely unfulfilled, however. This research hypothesizes that landscape architecture's lack of progress in this arena rests in large part on its failure to expand its methods and frameworks of design and communication. Landscape architects are accustomed to communicating ideas, proposals, and research through the means of architectural representation, namely diagrams, plans, sections, *maquettes*, presentation models, and rendered perspective illustrations. These tools of representation, many of them primarily qualitative in nature, give landscape architects immense power to communicate directly with diverse constituencies and shape the public imagination, but often lack the quantitative or empirical rigor required to speak to the concerns of policy makers, let alone sway government agencies tightly bound to narrow mandates. Conversely, civil and coastal engineers make extensive use of physical and numerical modeling to arrive at and support design conclusions. These quantitative tools and modes of communication carry great value for policy makers, giving engineers authority and sway in the planning and development of coastal infrastructure. These divergent methodologies stand as a barrier to collaborative discourse between landscape architects and civil engineers, limiting landscape architects' ability to more meaningfully engage in the conceptualization, design, and implementation of civic infrastructure.

This thesis bridges this gap with a "yes, and" approach, embracing a wide variety of design, research, and representation methods commonly used by landscape architects and engineers to craft a proposal grounded in the architectural tradition of speculative design but guided by modeling, testing, and empirical rigor. It applies these methods in pursuit of three main research goals. First, it develops and demonstrates the feasibility of redirecting and capturing sediment from the Bonnet Carré Spillway to create new self-building wetland habitat for coastal protection in western Lake Pontchartrain (the "Siltcatcher"). Second, it employs

numerical and physical hydrodynamic modeling in a non-linear, recursive design process, demonstrating the usefulness and feasibility of hydrodynamic modeling as conceptual design tool thanks widely available digital tools and resources. Finally, it explores the interdisciplinary potential suggested by living shorelines, natural and nature-based features, and "Engineering with Nature" approaches to coastal infrastructure. The pursuit of these goals is informed and inspired by the designers and researchers who have contributed to this emerging area of practice, such as SCAPE Landscape Architecture, the US Army Corps of Engineers Engineering with Nature initiative, the Dredge Research Collaborative, and Catherine Seavitt Nordenson and the Structures of Coastal Resilience design initiative.

As this project pursues multiple avenues of research, there are multiple audiences for whom it may be of interest. For policy makers and the general public, it illustrates the potential and opportunity presented by the next generation of coastal infrastructure, as well as the and challenges and uncertainties posed by rising sea levels and shifting coastlines. For civil and coastal engineers, this project provides an example of the value that landscape architects can bring to the process of planning and designing coastal infrastructure. Finally, for landscape architects, this research charts a course to greater involvement with the design and conceptualization of large-scale infrastructure through the adoption of tools and methods primarily used by engineers.

## I. Context: Physiography, Ecology, and History of The West Lake Pontchartrain Region

### The Study Area

The West Lake Pontchartrain region lies between New Orleans and Baton Rouge along Interstate 10 in Southeast Louisiana's Lake Pontchartrain Basin. It is bordered by Lake Maurepas to the north, Lake Pontchartrain to the northeast, Jefferson Parish to the east, the Mississippi River to the south, and St. James Parish to the west, encompassing 400,000 acres [Fig. 1]. Its population center is the city of La Place in St. John the Baptist Parish, home to approximately 30,000 residents.[3] For many residents of southeast Louisiana, this area is more likely to be thought of as passing scenery along I-10 than as a place in its own right.[4] This overlooked

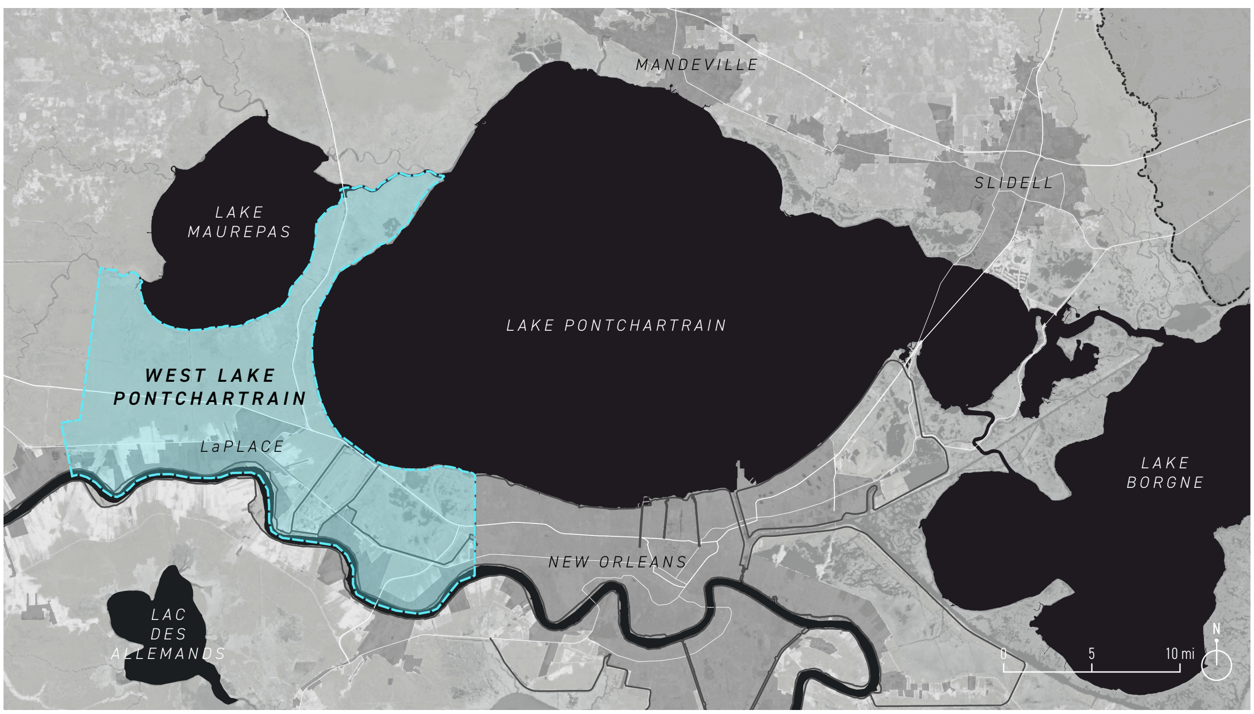


Figure 1. The West Lake Pontchartrain Region.

3. United States Census Bureau, 2010 Census of Population and Housing, generated by author using QuickFacts, https://www.census.gov/quickfacts/fact/table/US/PST045219?

4. I-10 carries approximately 40,000 vehicles per day, nearly twice as many vehicles as the total population of St. James Parish. For traffic statistics, see Louisiana Department of Transportation and Development, *Average Daily Traffic Counts, St. James Parish*, 2012. http://wwwapps.dotd.la.gov/engineering/tatv/. Population data retrieved from St. James Parish, "Demographics." https://www.stjamesla.com/239/Demographics.

area along the highway is crucial for the economy, infrastructure, and ecology of southeast Louisiana, however.

**Geomorphological History and Current Physiography**

On a geological timescale, the West Lake Pontchartrain region is young, formed through the interplay of Holocene sea level rise and the deltaic depositional processes of the Mississippi River. The region was once a site of the mouth of the Mississippi, and developed through the deltaic processes of sediment deposition, shoreline progradation, and subsidence.

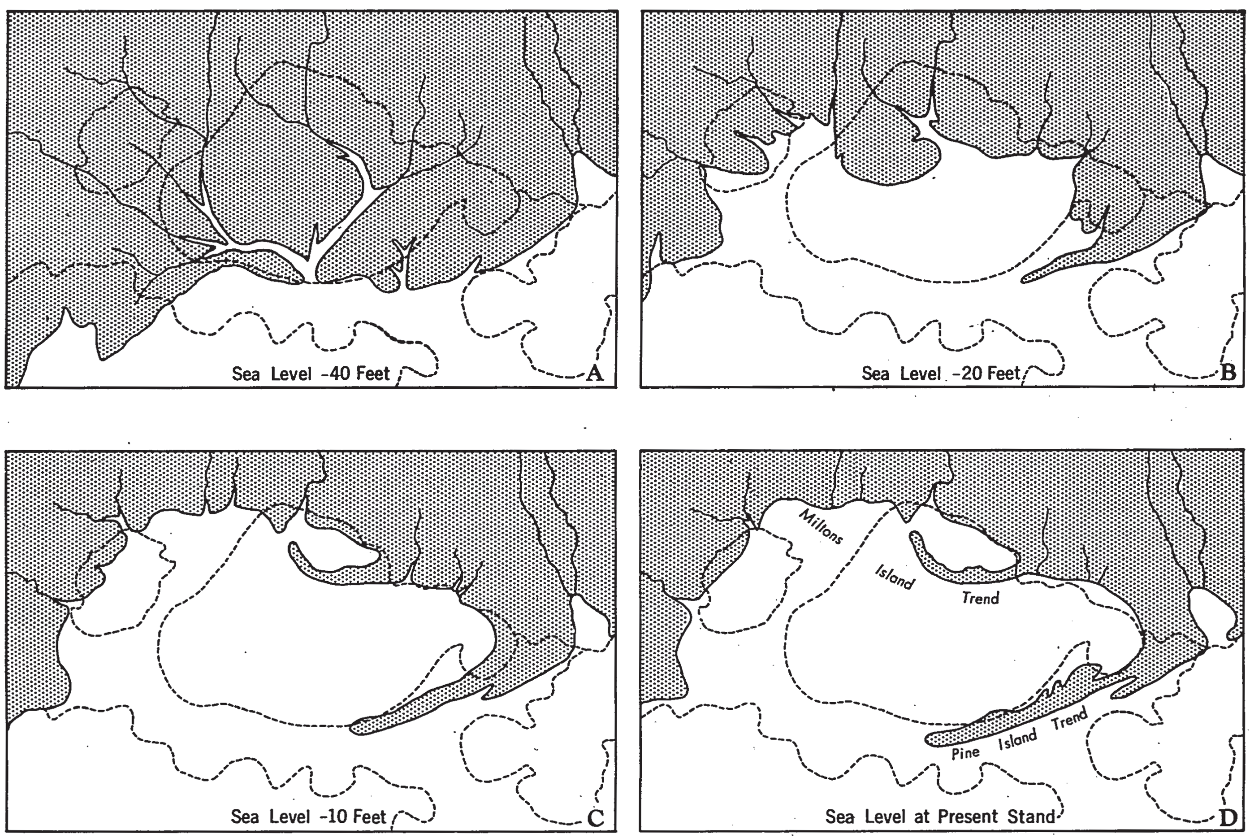



Figure 2. The Pontchartrain Embayment. *Source*: Roger Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 84.

The body of water that would become Lake Pontchartrain began as an embayment formed by the inland advance of Holocene sea level rise [Fig. 2]. The shoreline of this embayment reached its northernmost extent approximately 5,000 years ago, as sea level rise slowed. This shoreline generally followed the same east-west course as present-day Interstate 12,

which roughly marks the transition between low-lying wetlands of Lake Pontchartrain and the upland Pleistocene terraces that characterize the Florida Parishes.[5] The Pontchartrain embayment was partially separated from the Gulf of Mexico by the Pine Island barrier spit, a long, sandy peninsula which stretched from present-day Slidell to New Orleans, creating a brackish estuarine environment on the protected bay side. This peninsula was formed by sediments from Pearl River, which were carried west by long-shore currents. Evidence of this formation can be found in sandy deposits beneath portions of New Orleans.[6] [Fig. 3]

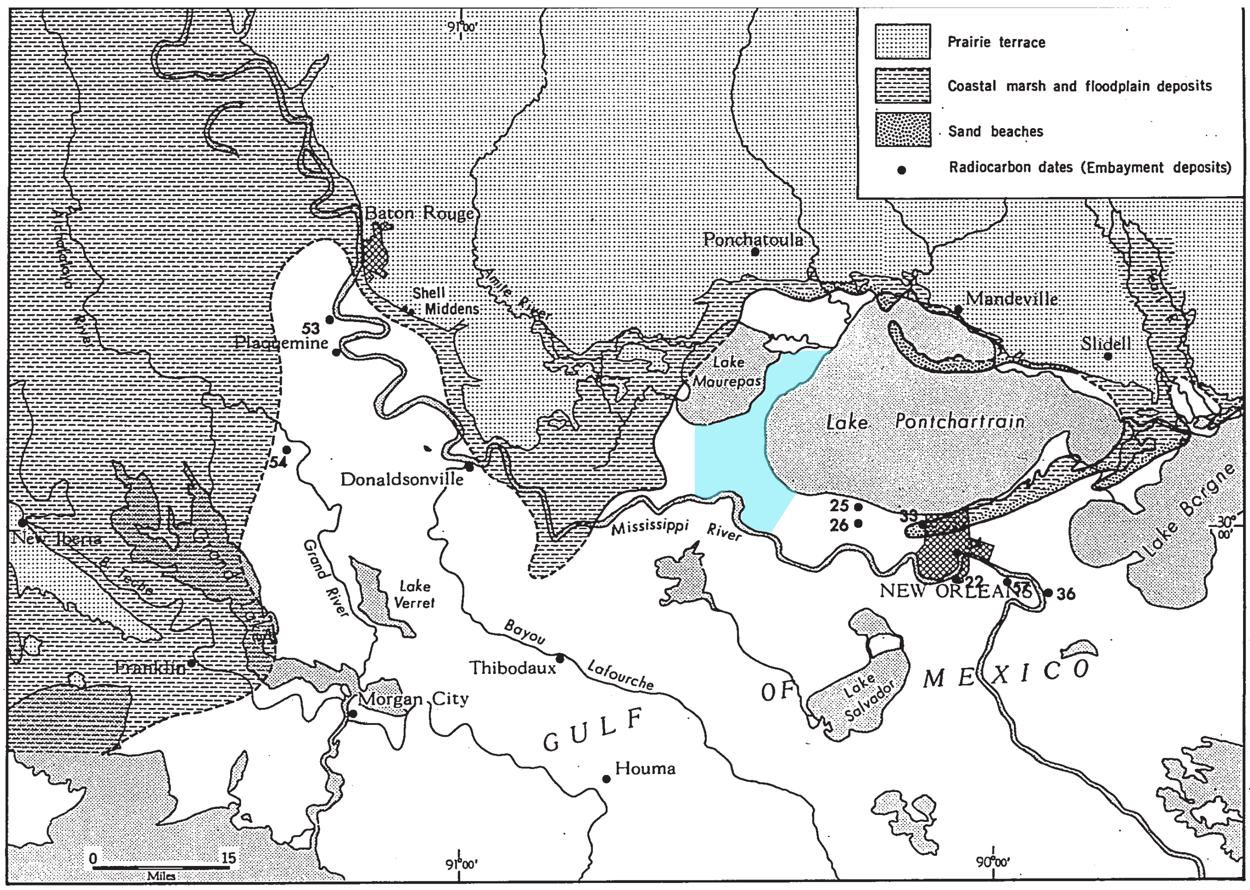



Fig. 15. Postulated maximum extent and shoreline features of the Pontchartrain Embayment.

Figure 3. The West Lake Pontchartrain Region in the context of the Pontchartrain Embayment. *Source*: Roger Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 72. Annotation by author.

5. Roger Thomas Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," (Dissertation, Louisiana State University, 1968), 71-77. This section is heavily informed by Saucier's dissertation, which entailed the use of approximately 5,000 soil borings to construct a geological history of the region. His work remains a key reference for study of the geology and geomorphology of the Lake Pontchartrain Basin.

6. Ibid., 80-83.

About 4,500 years ago, as sea levels stabilized, the Mississippi River began to build a new delta at its mouth south of present-day Baton Rouge, eventually creating the present-day West Lake Pontchartrain region.[7] As this deltaic landmass (the so-called Cocodrie Delta[8]) grew, it connected with the western end of the Pine Island spit, separating the Pontchartrain embayment from the Gulf. [Fig. 4] This created a brackish lacustrine environment influenced by freshwater inputs from the Mississippi River to the west and surface drainage from the upland Pleistocene terrace to the north.[9] The present-day configuration of the Lake Pontchartrain Basin formed approximately 1,800 to 2,600 years ago from the progradation of the St. Bernard Delta, the landmass that today is home to eastern New Orleans.[10] With this development, large quantities of sediment no longer flowed into Lake Pontchartrain, leading to subsidence and shoreline retreat.[11] From radiocarbon dating of peat deposits, Roger Saucier calculated an average subsidence rate of 0.39 feet per century in the Pontchartrain Basin over the last 4,400 years, or approximately 1.2 mm/year.[12]

Today, the Lake Pontchartrain Basin encompasses 4,700 square miles of southern Mississippi and southeastern Louisiana and includes the cities of Baton Rouge and New Orleans and populated areas to the north and west of Lake Pontchartrain.[13] The lake itself is oblong, approximately 40 miles across from east to west and 25 miles from north to south, covering an area of 630 square miles.[14] [Fig. 5] It is shallow, with a maximum depth of 16 feet; the

7. Ibid., 86.

8. Ibid., 98-101. There is some debate as to whether the Cocodrie formation constitutes a distinct delta complex from the St. Bernard. See also James M Coleman, Harry H Roberts, and Gregory W Stone, "Mississippi River Delta: An Overview," *Journal of Coastal Research* 14, no. 3 (1998): 698–716, and T. E. Tornqvist et al., "A Revised Chronology for Mississippi River Subdeltas," *Science* 273, no. 5282 (September 20, 1996): 1693–96.

9. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 93.

10. Ibid., xiv and 105-110.

11. Ibid., 124-125.

12. Ibid., 23.

13. Carlton Dufrechou, "Preface" in *Environmental Atlas of the Lake Pontchartrain Basin*, United States Geological Survey Open File Report 02-206, https://pubs.usgs.gov/of/2002/of02-206/intro/preface.html.

14. Ibid.

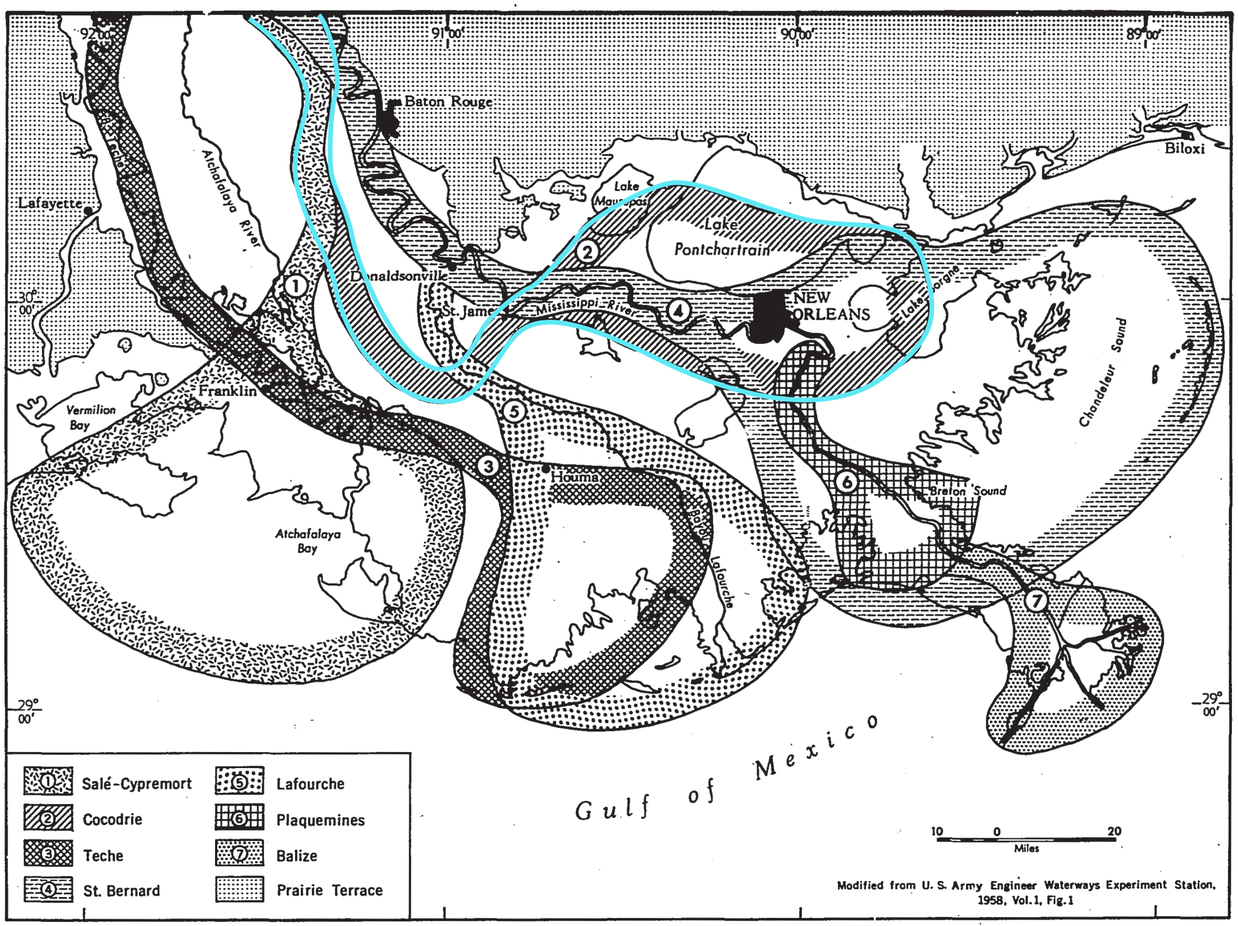



**Fig. 24. Deltas of the Mississippi River.**

Figure 4. The Cocodrie Delta and other historic delta lobes of the Mississippi River. *Source*: Roger Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 100. Annotation by author.

majority of the lake is no deeper than 10 feet.[15,16] In the Western Lake Pontchartrain region, development and industry clusters around the "high" ground of the natural levees created by the deposition of the heaviest sediments closest to the Mississippi River.[17] Further from the Mississippi, these natural levees gradually transition to low-lying marsh and swamp before ultimately giving way to the open waters of Lakes Pontchartrain and Maurepas. [Fig. 6]

15. Saucier, 13-14.

16. Lopez et al. note that the ratio of the lake's depth to its diameter is "roughly the ratio of a sheet of paper." See John Lopez et al., "The Dynamics of Storm Surge in the Pontchartrain and Maurepas Region" (Lake Pontchartrain Basin Foundation, May 2016).

17. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 30-33. This pattern of development follows historic land-use patterns, in which the natural levees were used for intensive, industrial-scale agriculture powered by enslaved laborers.

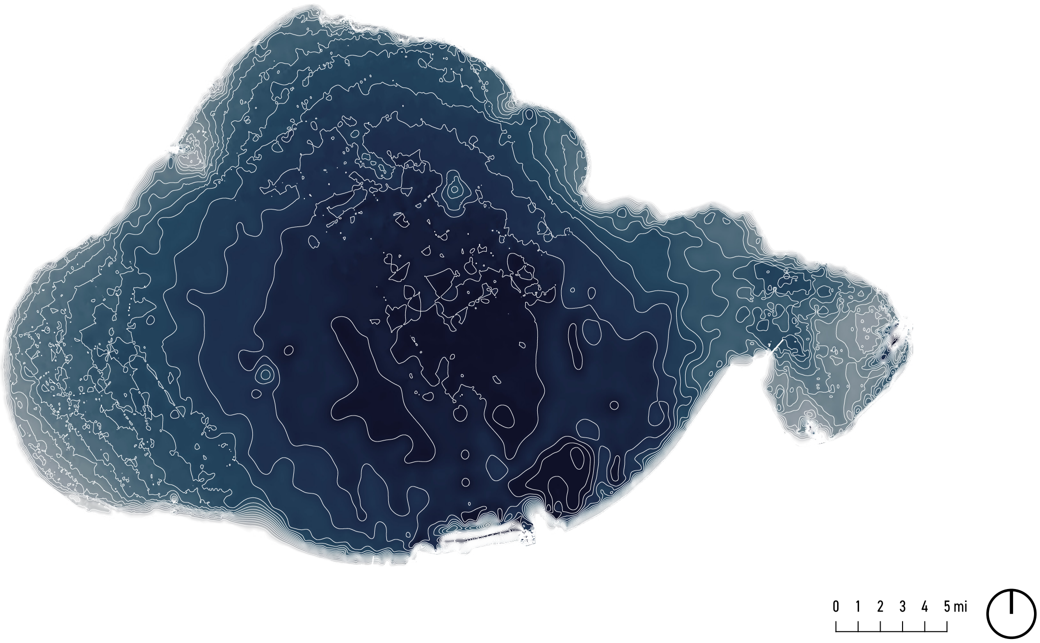


Figure 5. Lake Pontchartrain Bathymetry.

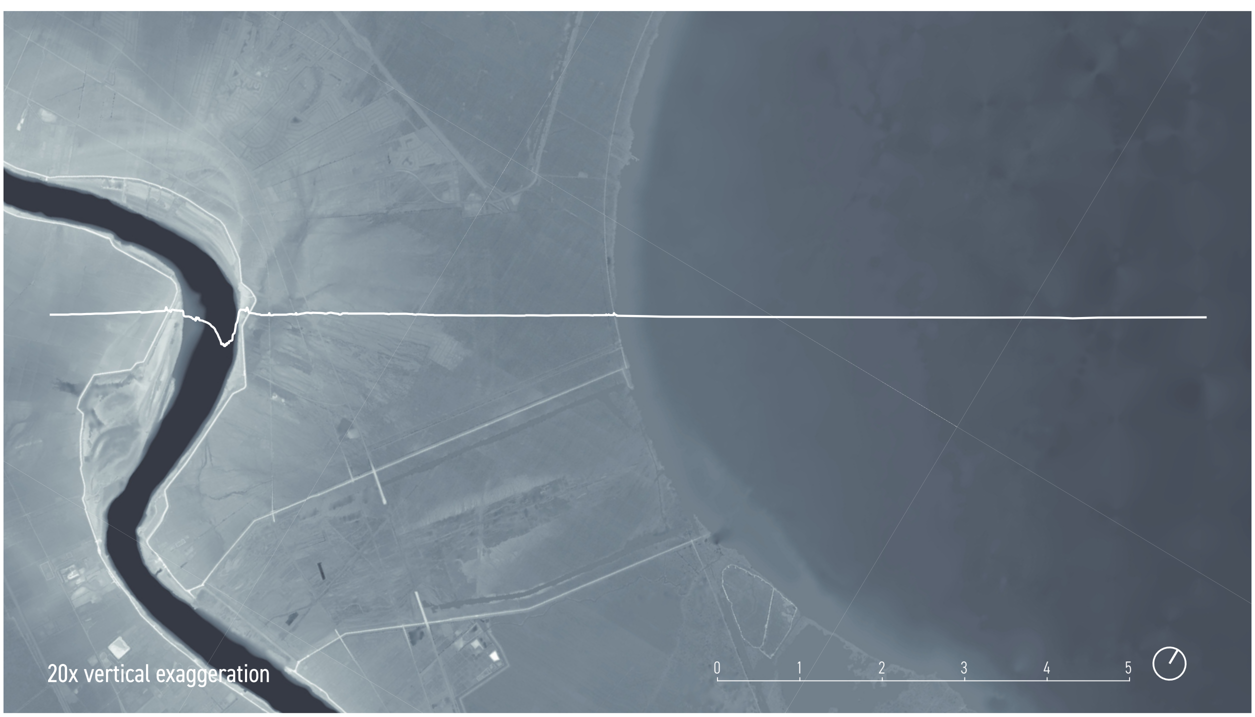


Figure 6. Elevation profile at LaPlace.

**Ecology**

Lake Pontchartrain and its associated wetlands constitute a coastal estuary whose ecology is predominantly influenced by the balance of riverine freshwater, marine saltwater, the salinity gradient formed by their interaction, and the impacts of tides and winds on the resulting gradient. This interface, combined with the region's flat topography, supports extensive wetlands, especially along the lake's undeveloped eastern and western shores.[18] These wetlands make the area a rich and productive ecosystem that provides essential ecosystem services such as provisioning, protection, carbon dioxide sequestration, and recreation.[19]

The ecological character of Lake Pontchartrain and its surrounding wetlands is heavily influenced by the dynamic hydrologic conditions that characterize the lake. The lake is considered oligohaline, or brackish, with average salinities ranging from <0.5 to 6 parts per thousand (ppt).[20] The western end of the lake tends to be fresher due to the influence of the Amite, Tangipahoa, and Tickfaw Rivers, as well as large periodic influxes of freshwater from the Bonnet Carré Spillway. The eastern end of the lake, which interacts with the Gulf of Mexico through Lake Borgne, the Rigolets, and Chef Menteur Pass, tends to be saltier. This balance is not static, however: the interface between these fresh and brackish influences forms a salinity gradient which is constantly moving based on tides, winds, currents, and the volume of freshwater input from mainland sources.[21] [Fig. 7]

Diurnal tidal ranges in Lake Pontchartrain are limited to approximately six inches from mean high water (MHW) to mean low water (MLW).[22] More dramatic changes in water level oc-

18. According to Saucier, these low-lying wetlands constitute at least 40% of the immediate Lake Pontchartrain Basin. See Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 9.

19. Gary Shaffer et al., "Decline of the Maurepas Swamp, Pontchartrain Basin, Louisiana, and Approaches to Restoration," *Water* 8, no. 3 (March 15, 2016): 2, https://doi.org/10.3390/w8030101.

20. J. Alex McCorquodale et al., "Salinity, Nutrient, and Sediment Dynamics in the Pontchartrain Estuary," *Journal of Coastal Research* 10054 (November 2009): 71–87, https://doi.org/10.2112/SI54-000.1.

21. The Lake Pontchartrain Basin Foundation publishes bi-weekly salinity maps which illustrate this phenomenon. See "Hydrocoast Maps - Salinity," Lake Pontchartrain Basin Foundation, https://saveourlake.org/lpbf-programs/coastal/hydrocoast-maps/salinity/.

22. National Oceanic and Atmospheric Association, "Datums for 8762483, I-10 Bonnet Carre Floodway LA," NOAA Tides & Currents, January 14, 2016, https://tidesandcurrents.noaa.gov/datums.html?id=8762483&name=I-10%20Bonnet%20Carre%20Floodway&state=LA.

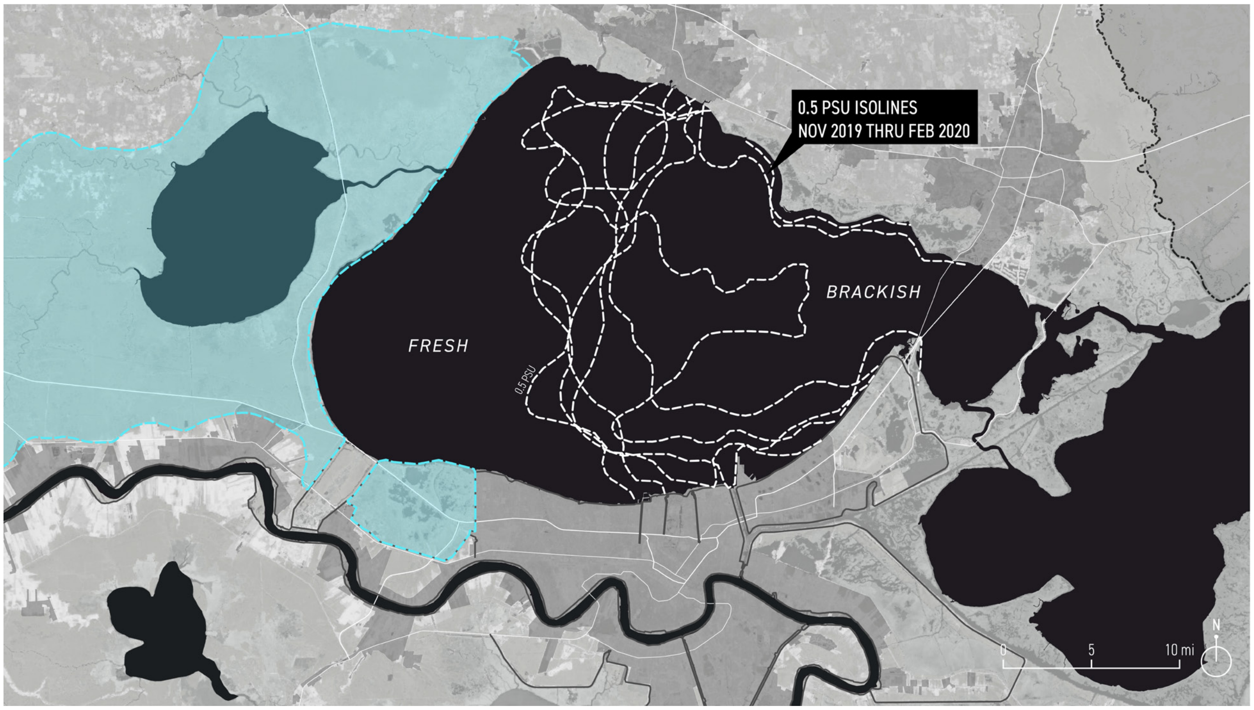


Figure 7. Movement of 0.5 PSU isoline, November 2019 through February 2020.

cur in the lake on a non-periodic basis due to the effects of wind and the lake's shallow depth. In the winter months, persistent winds from the north and northwest can have the effect of pushing water out of the Lake and into the Gulf of Mexico through The Rigolets, causing the water's surface to drop by as much as two feet relative to summer water levels.[23] The effects from extreme wind events can be even more dramatic, and can cause water levels on one side of the lake to vary from those on other side by magnitude of feet.[24]

Wind also plays a decisive role in the lake's currents. As might be expected, water near the lake's surface flows in the same direction as the prevailing winds. In deeper areas near the lake's center, however, water beneath the surface flows in the opposite direction. When these flows are depth-averaged, a two-gyre pattern emerges, with shallow water near the lake's edge flowing in the same direction as current-driving winds and deeper areas toward the center of the lake flowing in the opposite direction. [25] On average, the gentlest currents appear

23. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 15.

24. For a comprehensive discussion of the impacts of hurricanes and storm driven winds on the lake's currents and water levels, see Lopez et al., "The Dynamics of Storm Surge in the Pontchartrain and Maurepas Region."

25. Kindinger et al., "Physical Environments – Circulation" in *Environmental Atlas of the Lake Pontchartrain Basin,* United States Geological Survey Open File Report 02-206, https://pubs.usgs.gov/of/2002/of02-206/phy-environ-

toward the center of the lake, whereas the fastest occur near The Rigolets to the east, the relatively narrow channel through which water is exchanged with the Gulf of Mexico.[26]

Aside from the natural levees which line the Mississippi River, the area west of Lake Pontchartrain region is characterized by extensive wetlands. [Fig. 8] The most significant of these is the Maurepas Swamp, a 200,000-acre freshwater forested wetland and one of the largest coastal forests in Louisiana, second only to the Atchafalaya Swamp.[27] The swamp is characterized by stands of *Taxodium distichum* (Baldcypress) and *Nyssa sylvatica* (Water Tupelo), while understory vegetation includes *Fraxinus caroliniana* (Swamp ash), *Cephalanthus occidentalis* (Buttonbush), *Morella cerifera* (Wax myrtle), and *Sabal minor* (Dwarf palmetto).[28] The area was logged extensively in the late 19th to early 20th century, meaning the vast major-

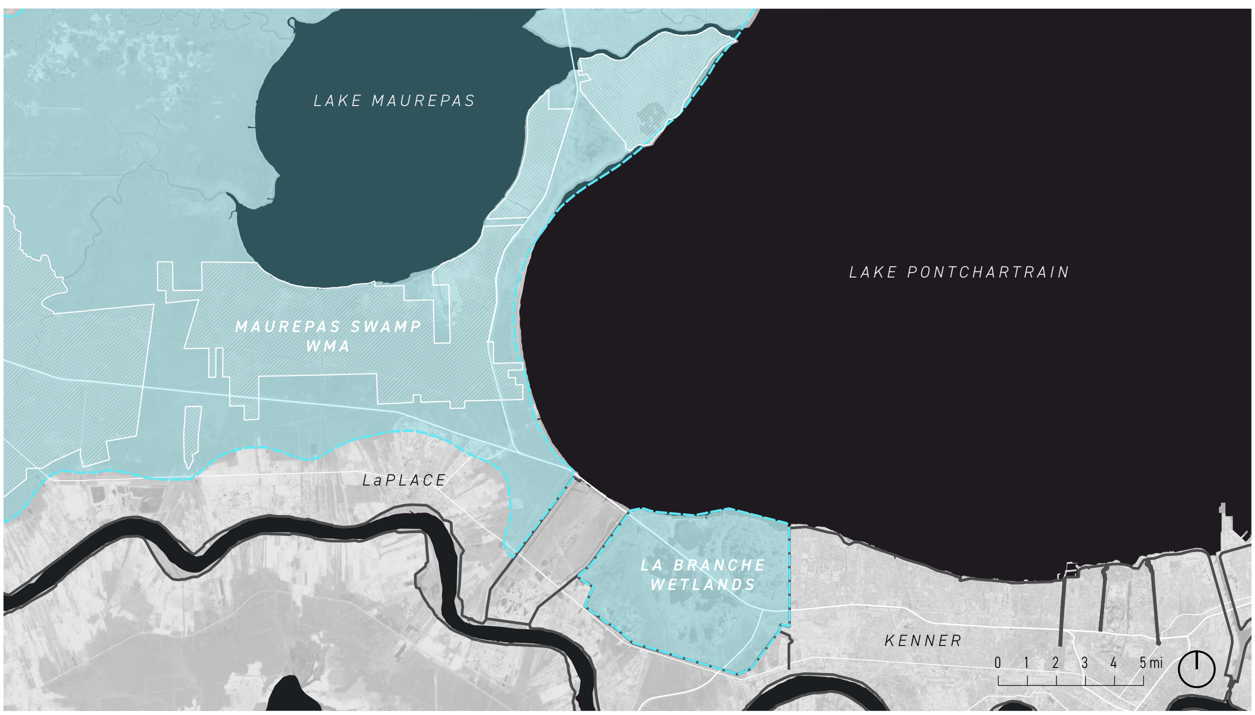


Figure 8. The Wetlands of the West Lake Pontchartrain Region.

ment/circulation.htm.

26. Ibid.

27. P.A. Keddy et al., "The Wetlands of Lakes Pontchartrain and Maurepas: Past, Present and Future," *Environmental Reviews* 15, no. NA (December 2007): 44, https://doi.org/10.1139/a06-008

28. Louisiana Coastal Protection and Restoration Authority (CPRA), "Coastal Information Management System (CIMS) - Forested Swamp Vegetation," accessed January 6, 2019, https://cims.coastal.louisiana.gov/DataDownload/DataDownload.aspx?type=forestveg.

ity of the present-day Maurepas Swamp is second-growth.[29] The effects of logging and subsequent alteration of the landscape have led to a dramatic decline in the health of the Maurepas Swamp, large parts of which have converted or are in the process of converting to freshwater marsh.[30] These areas are characterized by freshwater species such as *Sagittaria*, *Eleocharis*, *Zizania*, as well as patches of *Phragmites australis*.[31]

Southeast of the Maurepas Swamp, the LaBranche wetlands represent the other major wetland system of West Lake Pontchartrain region. Covering approximately 20,000 acres between Jefferson Parish and the Bonnet Carré Spillway, the LaBranche wetlands consist of freshwater cypress-tupelo swamp at the wetland's southernmost reaches to brackish and saline marsh at the edges of Lake Pontchartrain. The LaBranche wetlands as a whole are heavily degraded as a result of more than a century of alterations to the landscape, including levees, canals, and other impoundments. These features have drastically altered the area's hydrology, accelerating subsidence, shoreline retreat, and land loss.[32] In a sense, the LaBranche wetlands offer a preview of what the Maurepas Swamp could become without large-scale restoration efforts.

These wetland systems were historically extremely productive and served as important habitat for a large number of species. Common bird species include egrets, herons, wood ducks, osprey,  hawks, and eagles. [Fig. 9] The American Alligator (*Alligator mississippiensis*) is the area's apex predator.[33] The West Lake Pontchartrain wetlands are also home to large numbers of invasive nutria, a large rodent which eats all parts of wetland plants. The Maurepas Swamp has historically been a popular location for deer and duck hunting, however the

29. Susanne Sigrid Hoeppner, "Swamp Ecology in a Dynamic Coastal Landscape: An Investigation through Field Study and Simulation Modeling" (Dissertation, Louisiana State University, 2008): 10-11.

30. Gary P. Shaffer et al., "Decline of the Maurepas Swamp, Pontchartrain Basin, Louisiana, and Approaches to Restoration," 15-16.

31. Personal observations, November 2019.

32. John Day et al., "Ecological Response of Forested Wetlands with and without Large-Scale Mississippi River Input: Implications for Management," *Ecological Engineering* 46 (September 2012): 59. https://doi.org/10.1016/j.ecoleng.2012.04.037.

33. Keddy et al., "The Wetlands of Lakes Pontchartrain and Maurepas: Past, Present and Future," 43. Keddy suggests that a return of Louisiana alligators to their historic populations could restore balance to the coastal food chain and help reduce the herbivory threat posed by Nutria.

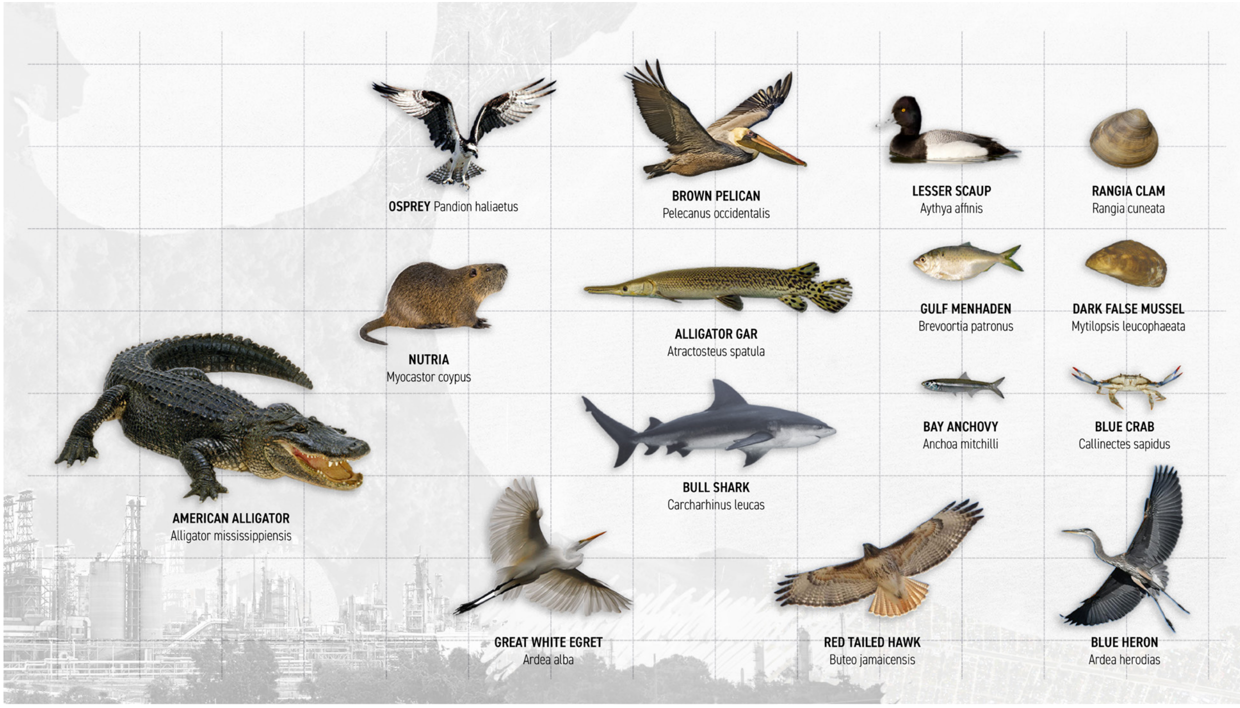


Figure 9. Fauna of western Lake Pontchartrain.

swamp's decline and introduction of exotic invasive species such as *Salvinia* and Water Hyacinth have negatively impacted habitat conditions for native fauna.[34]

The dynamic hydrologic conditions within the lake itself mean that most wildlife endemic to Lake Pontchartrain is migratory, with just a few species with permanent populations.[35] These include *Rangia cuneata*, a clam native to the northern Gulf Coast, and *Mytilopsis leucophaeata*, the dark false mussel. Both are important winter food sources for the Lesser Scaup (*Aythyna affinis*), a diving duck that regularly winters in the Lake Pontchartrain region.[36] *R. cuneata* were a major food source for early inhabitants of the region, who left large rubbish mounds of spent shells along the shores of Lake Pontchartrain called *middens*.[37] *R. cuneata*

34. "Maurepas Swamp WMA," Louisiana Wildlife and Fisheries, n.d., http://www.wlf.louisiana.gov/wma/2791.

35. Rezneat M. Darnell, "Ecological History of Lake Pontchartrain, an Estuarine Community," *American Midland Naturalist* 68, no. 2 (October 1962): 434, https://doi.org/10.2307/2422749.

36. Clay M. Stroud et al., "Diet of Lesser Scaup Wintering on Lake Pontchartrain, Louisiana," *Journal of Fish and Wildlife Management* 10, no. 2 (December 2019): 567–74, https://doi.org/10.3996/052019-JFWM-036.

37. Paleogeologists are able to make inferences about historic coastal conditions and formations by analyzing the presence and number of different bivalve shells in archaic middens: the presence of *Rangia* shells in middens also indicates the historic presence of brackish water, whereas *Crassostera* (oyster) shells indicate more marine conditions. From radiocarbon dating, we are able to understand when the Pontchartrain Basin shifted from a protected marine embayment to a fully enclosed brackish estuary. See Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 59-60.

also provide important ecosystem services such as water filtration and nutrient cycling; at their maximum population densities, they are capable of filtering the volume of water in Lake Pontchartrain in just 2-3 days.[38] From 1933 to 1990, *Rangia* shells were dredged from Lake Pontchartrain for use as an aggregate material in the construction industry, leading to reduced clam density, increased water turbidity, and decreased sediment stability.[39] This in turn contributed to die-offs of seagrasses and submerged aquatic vegetation (SAV) such as *Vallisnaria americana* and *Ruppia maritima*.[40] These aquatic flora provide important ecosystem services in their own right, including sediment stabilization, wave mitigation, carbon sequestration, and habitat and food provision for marine wildlife.[41]

*Rangia* and SAV populations rebounded after commercial shell dredging activities ceased in 1990, but successive disturbances such as droughts, hurricanes, saltwater intrusion, hypoxic conditions, and influxes of Mississippi River water from the Bonnet Carré Spillway have limited the extent of their recovery.[42] Without active restoration efforts, disturbances due to climate change will likely continue this trend.[43]

**Early Inhabitants**

The first human occupants of the West Lake Pontchartrain region likely arrived in the area shortly after its formation from the deposition of deltaic sediments approximately

38. Michael A. Poirrier, Claire E. Caputo, and Carol D. Franze, "Biogeography of Submerged Aquatic Vegetation (SAV) in the Pontchartrain Basin: Species Salinity Zonation and 1953–2016 Lake Pontchartrain Trends," *Southeastern Geographer* 57, no. 3 (2017): 273–93, https://doi.org/10.1353/sgo.2017.0025.

39. Elizabeth Spalding, Ashley Ferguson, and Michael Poirrier, "Restoration of 100 Square Miles of Shellfish Habitat in Lake Pontchartrain, Louisiana" (Environmental Protection Agency, October 2006), 1.

40. Kindinger et al., "Environmental Overview - Regional Description of the Lake Pontchartrain Basin" in *Environmental Atlas of the Lake Pontchartrain Basin,* United States Geological Survey Open File Report 02-206, https://pubs.usgs.gov/of/2002/of02-206/env-overview/vegetation.html.

41. Poirrier, Caputo, and Franze, "Biogeography of Submerged Aquatic Vegetation (SAV) in the Pontchartrain Basin."

42. Michael A. Poirrier, Elizabeth A. Spalding, and Carol D. Franze, "Lessons Learned from a Decade of Assessment and Restoration Studies of Benthic Invertebrates and Submersed Aquatic Vegetation in Lake Pontchartrain," *Journal of Coastal Research* 10054 (November 2009): 88–100, https://doi.org/10.2112/SI54-005.1.

43. Michael A. Poirrier and Claire E. Caputo, "Rangia Cuneata Clam Decline in Lake Pontchartrain from 2001 to 2014 Due to an El Niño Southern Oscillation Shift Coupled with a Period of High Hurricane Intensity and Frequency," *Gulf and Caribbean Research*, 2015, https://doi.org/10.18785/gcr.2601.04.

4,000-5000 years ago.[44] These early inhabitants left middens of oyster and clam shells, pottery shards, and other waste items along the shores of Lake Pontchartrain and the bayous that flow into it. [Fig. 10] One such site was discovered at Bayou Jasmine in St. John the Baptist Parish in 1973 during the construction of Interstate 55. There, archaeologists discovered a midden dating to 1300 – 1500 B.C. Artifacts from the site were found in excellent condition, preserved by the oxygen-poor peat soil in which they were buried.[45] Middens could rise as high as 20 feet, and were often used as elevated, flood-resistant foundations for structures, providing an early model of adaptive reuse and design responding to local environmental conditions.[46]

The earliest European account of the region and its inhabitants was recorded by Pierre Le Moyne, Sieur d'Iberville, on his 1699 expedition up the Mississippi River.[47] By then, southeast Louisiana was occupied by small, independent tribes, including the Bayougoula, Houma, Acolapissa, Mugulasha, Okelousa, Quinapisa, and Tangipahoa peoples, who collectively are known as the Muskogeans.[48] With assistance from the Bayougoula, Iberville successfully located the mouth of the Mississippi River and from there conducted an expedition upriver. On the return trip south, Iberville traveled via a shortcut which the Bayougoula referred to as "Bayuk Imashaka" (known today as Bayou Manchac).[49] This route led Iberville back to the expedition's sailing vessels by way of two large lakes, which he named in honor of Louis de Phélypeaux,

44. Saucier dates their arrival at 1800 B.C. (Saucier, 47). The earliest presence of Native Americans in Louisiana at large coincides with the late Pleistocene/early Holocene era, approximately 10,000-12,000 years ago. See Fred B. Kniffen, Gregory F. Hiram, and George A. Stokes, *The Historic Indian Tribes of Louisiana From 1542 to Present* (Baton Rouge: Louisiana State University Press, 1987), 28.

45. Gerald J. Keller, Lisa Keller-Watson, and Darroch Watson, *Precious Gems from Faded Memories*, 2008.

46. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana,"120.

47. Kniffen, Gregory and Stokes describe Spanish explorer Hernando DeSoto's 1542 "discovery" of the Mississippi River as "like a flash of lightning–spectacular, but providing little illumination," whereas Iberville and the French explorers were "literate men who had come to stay and who recorded much of what they saw and did." (Kniffen, Hiram, and Stokes, *The Historic Indian Tribes of Louisiana From 1542 to Present,* 44)

48. Ibid., 49-52.

49. Mary Sternberg, *Winding Through Time: The Forgotten History and Present-Day Peril of Bayou Manchac* (Baton Rouge: LSU Press, 2007), 24-25.

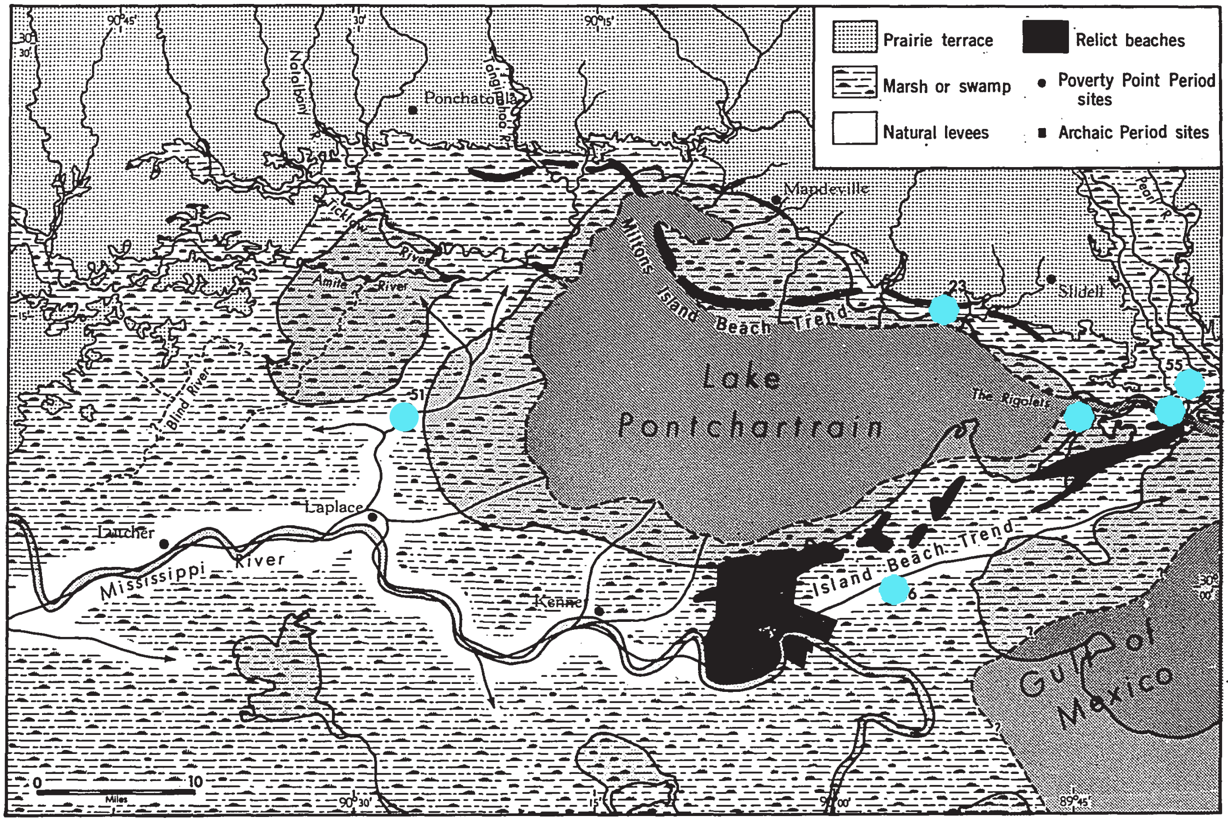



Fig. 23. Paleogeography of the Pontchartrain Basin, about 3500 to 4000 years before present, showing maximum extent of the Cocodrie Delta and locations of Poverty Point and Archaic period sites.

Figure 10. Indigenous sites in the Pontchartrain Basin, approx. 4,000 ybp. *Source*: Roger Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 94. Annotations by author.

Comte de Pontchartrain, the royal Minister of Marine who had commissioned Iberville's expedition, and his son, Jérôme de Phélypeaux, Comte de Maurepas.[50]

European settlement of the West Lake Pontchartrain region began in earnest not long after Iberville's first expedition. As early as 1721, German and Alsatian immigrants began to settle along the Mississippi upstream from New Orleans, a region that became known as the German Coast.[51] As it had throughout the American continent, European exploration and settlement brought disease, violence, and dislocation to Native American populations.[52] While the

50. W. Adolphe Roberts, *Lake Pontchartrain*, The American Lakes Series (Indianapolis: The Bobbs-Merrill Company, 1946), 21-23.

51. Glenn R. Conrad, *Abstracts of the Civil Records of St. Charles Parish, 1770-1803* (Lafayette: University of Southwestern Louisiana, 1974), ix.

52. Kniffen, Hiram, and Stokes, *The Historic Indian Tribes of Louisiana From 1542 to Present*, 62-66.

first Europeans settled the fertile floodplain of the Mississippi, the small independent tribes that occupied the Western Lake Pontchartrain region dwindled in number and assimilated with the nearby Houma.[53]

**Industrial Economies**

The history of the West Lake Pontchartrain Region since initial European settlement is defined by large-scale industrial economies. By the time of the Louisiana purchase in 1803, European families and growers along the German Coast had been in place for eighty years, establishing plantations powered by enslaved African laborers. Around the same time, advances in sugar refining led to a sugar boom, increasing both national demand and local production of refined sugar.[54] By the mid 19th-century, sugar was "a merciless industry in which cane farming and mechanized sugar production fused on industrial-scale plantations" which made use of "steam-powered sugar mills, drilled gang work, modern assembly-line techniques, and disciplined clock-ordered management."[55] [Fig. 11] None of this would have been possible without the generations of enslaved laborers who endured the backbreaking work of planting, harvesting, and processing sugarcane. As Richard Follet observes in his essential history of Louisiana's antebellum sugar industry, "steam power profoundly shaped the sugar industry, but its economic success rested primarily on the mass importation of African American bondspeople to Louisiana."[56] In 1795, there were 2,797 enslaved workers on German Coast plantations. By 1860, there were 8,776.[57]

Plantation agriculture and chattel slavery remained the operative economic system of the Western Lake Pontchartrain region until the end of the American Civil War in 1865. With the abolition of slavery, plantation economics gave way to sharecropping, and capital-intensive

53. Ibid., 78.

54. Richard Follett, *The Sugar Masters: Planters and Slaves in Louisiana's Cane World, 1820-1860* (Baton Rouge: Louisiana State University Press, 2005), 17-21

55. Ibid., 3-4.

56. Ibid., 24.

57. "Slavery In Louisiana," Whitney Plantation, https://www.whitneyplantation.org/education/louisiana-history/slavery-in-louisiana/.

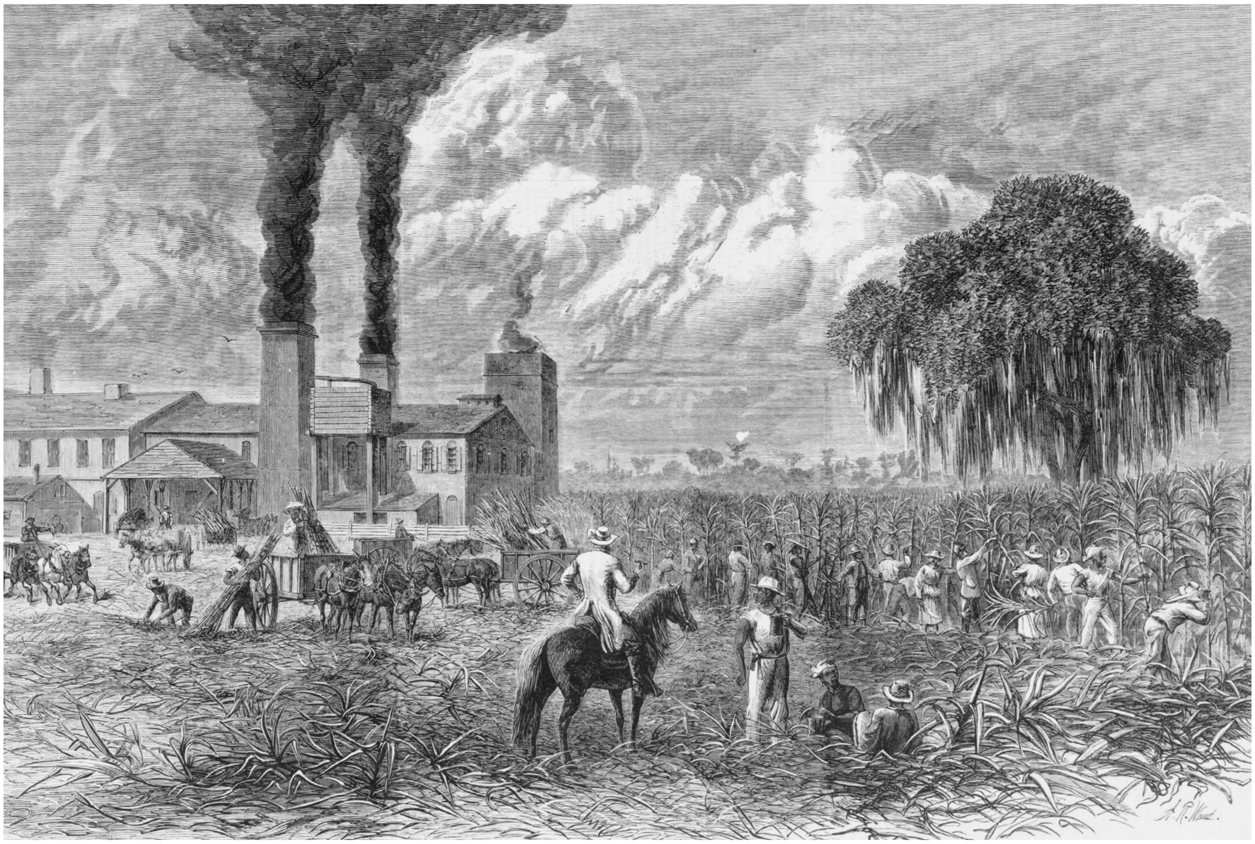


Figure 11. A.R. Waud, "The Sugar Harvest in Louisiana," *Harper's Bazaar*, October 30, 1875.

business ventures found new investment opportunities in natural resource extraction. The late 19th century saw a local timber boom as federal policies opened up vast tracts of cypress forest to logging for the first time.[58] Would-be timber barons were aided in their efforts by the invention of the steam-powered pullboat system, which enabled the harvest of previously inaccessible stands of cypress deep in Louisiana's coastal swamps.[59] By the early 20th century, the timber industry surpassed agriculture as the primary source of economic activity in

58. Rachel Edna Norgress, in her 1947 history of cypress logging in Louisiana, provides an explicit link between the origins of the Louisiana timber industry, emancipation, and the decline of the plantation system: "At the close of the Civil War, in order to procure homesteads for the Negro freedmen, Congress passed the Homestead Act of the 21st of June, 1866, providing that in Alabama, Mississippi, Louisiana, Arkansas, and Florida lands should be disposed of only under provisions of the Homestead Act. This law, of course, affected the gigantic cypress timber of Louisiana, since the swamp land was wholly unfit for cultivation–and therefore could not be taken up under the Homestead Act. Of course, *such a provision could not long withstand the demands of the Louisiana pioneers, impoverished by the 'Lost Cause'."* (Emphasis by Norgress). Ten years later, congress passed the Timber Act of 1876, which authorized the sale of vast swaths of cypress forest for $1.25 per acre. For more, see Rachel Edna Norgress, "The History of the Cypress Lumber Industry in Louisiana," *The Louisiana Historical Quarterly* 30, no. 3 (July 1947).

59. Paul A. Keddy, Water, Earth, Fire: Louisiana's Natural Heritage, 2008, 121.


Figure 12. Cypress logging in the swamps near Pontchatoula circa 1946. *Source*: University of Louisville Archives & Special Collections via the Louisiana Digital Library.

the region.[60] The logging frenzy continued until the 1920s, by which point the state's cypress reserves were exhausted. By 1934, more than 98% of Louisiana's cypress forests had been cleared – some 1.6 million acres.[61] [Fig. 12]

As logging activity declined, the nascent petrochemical industry took hold in the region, lured by proximity to Louisiana's vast coastal oil reserves, access to the Mississippi River, and a favorable business environment. A key factor in attracting investment to the West Lake Pontchartrain Region were "the large-scale tracts of land that were customary features of the old plantations–and families willing to sell."[62] In 1911, the New Orleans Refining Company – NORCO – purchased the Good Hope Plantation in St. Charles Parish, constructing a massive, eponymous refinery facility in its place.[63] The adjacent town of Sellers was renamed to Norco in 1934.[64] DuPont arrived in 1957, constructing a plant on the former site of Belle Point Planta-

60. Sternberg, *Winding Through Time*, 115.

61. Norgress, "The History of the Cypress Lumber Industry in Louisiana," 71.

62. Keller, Keller-Watson, and Watson, *Precious Gems from Faded Memories,* 97.

63. Steve Lerner, *Diamond: A Struggle for Environmental Justice in Louisiana's Chemical Corridor* (Cambridge: MIT Press, 2006), 24.

64. Mary Ann Sternberg, *Along the River Road: Past and Present on Louisiana's Historic Byway* (Baton Rouge: Louisiana State University Press, 2013), 123-125.

tion in St. John the Baptist Parish.[65] The Marathon Oil Refinery–one of the largest oil refineries in the nation–was constructed beginning in 1973 on the site of the San Francisco Plantation, also in St. John the Baptist Parish.[66, 67] [Fig. 13] These and other industrial facilities in the area are supported by the Port of South Louisiana, a collection of frontages and docks that line the Mississippi River in St. James, St. John the Baptist, and St. Charles Parishes for 54 miles. Together, these disparate shipping facilities constitute the largest port in the Western Hemisphere by tonnage.[68]


Figure 13. The Marathon Oil Refinery and San Francisco Plantation.

This concentration of industrial petrochemical facilities along the Mississippi River between Baton Rouge and New Orleans has raised local concerns over risks to the health and

65. Ibid., 98.

66. Keller, Keller-Watson, and Watson, *Precious Gems from Faded Memories*, 100.

67. According to the U.S. Energy Information Administration, the capacity of the Marathon Refinery in Garyville is 594,000 barrels per stream day, making it the fourth-largest refinery in the nation by capacity. See "Refinery Capacity Data by Individual Refinery (xls)" (U.S. Energy Information Administration, August 9, 2019), https://www.eia.gov/tools/faqs/faq.php?id=607&t=6.

68. "Port of South Louisiana," http://portsl.com.

safety of neighboring communities, giving rise to grim nickname "Cancer Alley."[69] Residents living in close proximity to industrial facilities have reported foul odors, strange illnesses, skin problems, cancers, and early deaths.[70] According to the EPA Toxic Release Inventory, Louisiana has the highest concentration of toxic air emissions per square mile in the nation, with St. Charles, St. James, and St. John the Baptist Parishes among the worst affected areas.[71] In many cases, the communities nearest to industrial facilities, and therefore most impacted by pollution and toxic releases, are largely black and poor.[72] Many African American communities in the region are directly descended from communities of formerly enslaved laborers, underscoring the links between today's environmental inequity and the injustices of the past.[73]

Today, the Western Lake Pontchartrain region is home to approximately 70,000 residents, primarily in the towns of LaPlace (29,147), Destrehan (10,933), Reserve (9,280), and St. Rose (7,665).[74] LaPlace, the region's largest population center, is 50.5% African American and 45.3% white. Residents of Destrehan and Norco are predominately white, older, and have higher median incomes than neighboring communities such as Reserve, Garyville, and New Sarpy, which are majority African American. These communities have lower rates of education-

69. Kate Orff and Richard Misrach's collaborative atlas *Petrochemical America* is a seminal study of the region, its history, and its relationship to the petrochemical industry. See Richard Misrach and Kate Orff, *Petrochemical America* (New York: Aperture, 2014).

70. Trymaine Lee, "Cancer Alley: Big Industry, Big Problems," MSNBC, August 10, 2015, http://www.msnbc.com/interactives/geography-of-poverty/se.html.

71. Environmental Protection Agency, "TRI National Analysis Supporting Tables: Where You Live," *TRI 2018 National Analysis*, https://www.epa.gov/trinationalanalysis/supporting-data-files-tri-national-analysis. The EPA cautions that "this information does not indicate whether (or to what degree) the public has been exposed to toxic chemicals," and "no conclusions on potential risks can be made based solely on this information (including any ranking information)." However, the concentration of industrial chemical facilities in the region, combined with Louisiana's high cancer rate and anecdotal evidence collected by reporters and advocates on the subject in recent decades, suggest that these areas pose a number of environmental health risks to their residents.

72. Studies have found that African American Louisianans suffer from cancers at a significantly higher rate than their white counterparts. See Merrill Singer, "Down Cancer Alley: The Lived Experience of Health and Environmental Suffering in Louisiana's Chemical Corridor," *Medical Anthropology Quarterly* 25, no. 2 (June 2011): 147, https://doi.org/10.1111/j.1548-1387.2011.01154.x.

73. See Tristan Baurick, Younes Lylla, and Joan Meiners, "Welcome to 'Cancer Alley,' Where Toxic Air Is About to Get Worse," ProPublica, October 30, 2019, https://www.propublica.org/article/welcome-to-cancer-alley-where-toxic-air-is-about-to-get-worse, for the story of one such community (St Gabriel, Iberville Parish) and their attempts to push back against industrial expansion.

74. All data presented in this paragraph are sourced from U.S. Census Bureau American Community Survey 5-Year Estimates, generated via data.cesus.gov.

al attainment and employment and larger percentages of residents living in poverty, reflecting nationwide trends as well as the region's history of race-based enslavement, segregation, and institutional discrimination. These communities are also home to some of the area's largest industrial and petrochemical facilities, including Noranda Aluminum, Nalco, and Marathon Oil (Garyville); Dupont and Cargill (Reserve), and Valero (New Sarpy). Other facilities in the region include Shell (Norco), IMTT (St. Rose), Entergy (Montz), and Bayou Steel and Continental Cement (LaPlace).

### Infrastructure: The Bonnet Carré Spillway

Infrastructure is a defining feature of the West Lake Pontchartrain region. Roads, canals, railways, oil and gas pipelines, high-tension power lines, and levees crisscross the landscape. [Fig. 14] One of the largest works of infrastructure in the area, and the most significant for the purposes of this research, is the Bonnet Carré Spillway, a U.S. Army Corps of Engineers operated flood-control structure of regional and national importance.[75]


Figure 14. The infrastructure of the West Lake Pontchartrain Region.

75. In addition to its flood-protection value, the Spillway also represents a milestone in modern civil engineering and is listed on the National Register of Historic Places. See "Bonnet Carré Spillway" (US Army Corps of Engi-

Named for the nearby Bonnet Carré Crevasse, the Bonnet Carré Spillway was developed as a means of controlling the level of the Mississippi River downriver to reduce strain on the New Orleans levee system. It does so by diverting a large volume of water from the Mississippi River into a broad, flat floodway which empties into Lake Pontchartrain, thereby lowering downriver discharge and crest height. It is, in essence, "an artificial and controllable crevasse."[76] [Fig. 15]

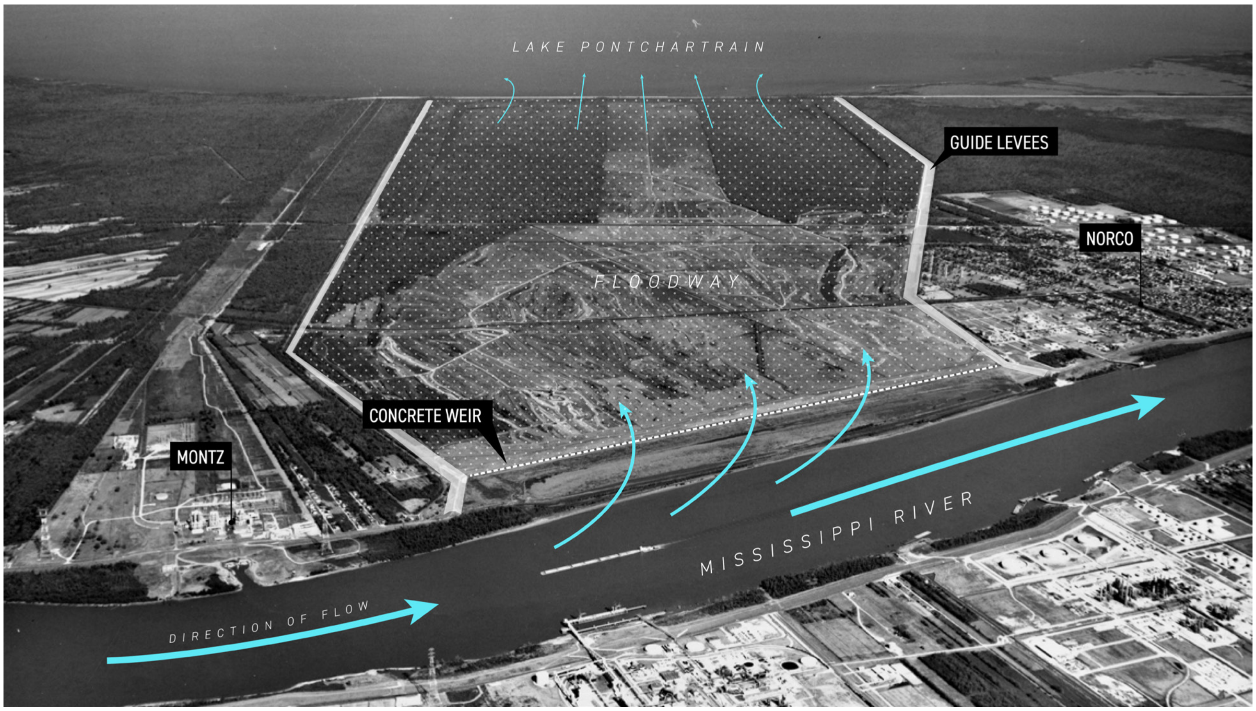



Figure 15. The Bonnet Carré Spillway. *Source*: The Historic New Orleans Collection via Antigravity Magazine. Annotations by author

The Flood Control Act of 1928 authorized construction of the Spillway, which was completed in 1931 at a cost of $14.2 million, or approximately $212 million in 2020 dollars.[77] The spillway control structure consists of a 7,000-foot long concrete weir located along the east-

neers, New Orleans District, December 2018), MVN PAM 360-1-5, https://www.mvn.usace.army.mil/Portals/56/docs/Recreation/BCS/Brochures/BC%20spillway%20booklet%20Dec%202018%20.pdf.

76. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 143.

77. U.S. Army Corps of Engineers, "Draft Bonnet Carré Spillway Master Plan" (U.S. Army Corps of Engineers New Orleans District, May 2009), 2-1. Adjustment for inflation calculated using the U.S. Bureau of Labor Statistics CPI Calculator, https://data.bls.gov/cgi-bin/cpicalc.pl.

ern levee of the Mississippi River, downriver of LaPlace and just upriver of Norco. The weir is divided into 350 bays which allow water from the Mississippi River to pass through when opened. Half of the bays have a weir crest height of 15.00 NGVD, while the remainder are set at 17.00 NGVD. When fully opened, the Spillway is capable of discharging water into the adjacent floodway at a rate of 250,000 cubic feet per second (cfs). When not in operation, the spillway is kept closed by timber "pins," which retain river water above the weir crest height. These pins are not watertight; they allow a small amount of river water to pass through the structure when river levels surpass the weir crest height but are not high enough to merit an official opening of the structure.[78] The weir is held in place by thousands of timber pilings driven into the ground below the structure.[79] Beneath the weir outfall, concrete revetments prevent scour. [Fig 16]

Figure 16. The Bonnet Carré Spillway control structure. Photograph by author, April 13, 2019.

78. Ibid., 2.3.1.

79. U.S. Army Corps of Engineers New Orleans District, "Bonnet Carré Spillway."

River water passing through the spillway then enters a 7,600 acre, 5.7-mile long floodway that eventually empties into Lake Pontchartrain. Two guide levees keep water within the floodway, while channels within the floodway direct flow.[80] The floodway is crossed by multiple roads and rail lines on elevated structures, including U.S. Highway 61 and Interstate 10. Surface elevations at the southern end of the spillway (near the control structure) range from approximately +7 to +12 feet NAVD88 and gently slope toward +0 to +3 NAVD88 at Lake Pontchartrain.[81] When the spillway is not in use, the floodway serves as a public recreation area for activities such as boating, fishing, and hunting.[82]

The construction of the Spillway required the purchase of large tracts of agricultural land and former plantation property. In the aftermath of the 1975 opening, human remains were discovered in the southern portion of the floodway. While initially thought to be related to criminal activity, a 1985 cultural resource study uncovered the presence of two historic cemeteries within the floodway. These cemeteries were connected to the former Kenner and Kugler plantations and were active burial sites up until the purchase of the land by the Federal government in 1928, serving as the final resting place for upwards of 300 enslaved African laborers and their descendants. Despite their history and active use, early maps of the Spillway did not document the presence of the cemeteries. After their re-discovery by the USACE in 1985, the cemeteries were placed on the National Register of Historic Places, and the Corps developed plans for their preservation and memorialization, soliciting input from local residents and descendants of those interred in the cemeteries.[83] Despite their efforts, this exercise demonstrated the Corps' institutional blind spots, as the plans received negative feedback

80. U.S. Army Corps of Engineers, "Draft Bonnet Carré Spillway Master Plan," 2.3.2

81. OCM Partners, 2019: Topobathymetric Model of the Northern Gulf of Mexico, 1888 to 2013 from 2010-06-15 to 2010-08-15. NOAA National Centers for Environmental Information, https://inport.nmfs.noaa.gov/inport/item/49465.

82. U.S. Army Corps of Engineers, "Draft Bonnet Carré Spillway Master Plan," 2.3.2

83. Chris Brantley and Rachel Rodi, "Public Meeting Summary: Long Term Management of the Bonnet Carré Spillway Historic Cemeteries" (U.S. Army Corps of Engineers New Orleans District, February 8, 2012), https://www.mvn.usace.army.mil/Portals/56/docs/MRT/Feb82012BCScempubmtg.pdf, 2-3. The ability to conduct interviews and work with living descendants of those buried at the Kenner and Kugler cemeteries testifies that their history was never forgotten–it was simply ignored.

from local residents and descendants concerning the nature and tone of the proposed memorial elements.[84] Today, the cemeteries remained unmarked, their exact locations kept confidential.[85]

During openings, the river deposits large volumes of sediment into the floodway, although the exact quantity deposited varies depending on the specifics of a given opening. The 1950 opening deposited five million cubic yards of sediment in the floodway, representing approximately 63 percent of the total sediment which passed through the spillway.[86] Between 1936 and 1969, surface elevations at the outfall of the control structure increased by as much as ten feet.[87] The 1973 opening resulted in the deposition of approximately 12 million cubic yards of sand and clay within the floodway.[88] This sediment represents both a significant resource and a significant liability, as accretion in the floodway could negatively impact the ability of the spillway to operate as designed. The USACE has historically mitigated this risk by allowing commercial interests to extract deposited sand and clay from the floodway between the spillway control structure and U.S. Highway 61 at no cost.[89]

Because of the regular disturbance of the Spillway openings and the influx of sediment and nutrients they bring, the floodway represents a dynamic novel ecosystem. [Figs. 17-19] In the southern end of the floodway, closest to the Mississippi River and the spillway structure,

84. Robin McDowell, in her overview of the saga of the Kenner and Kugler Cemeteries for *Antigravity Magazine*, reports that "the information along the [proposed] interpretive trail contained few details and featured a flat, generalized narrative of the Black experience in Southeast Louisiana," referred to enslaved persons as "workers and residents," and made no mention of slavery. One public comment in response to the proposed memorial elements read. "It feels like a war is still being fought over the right to exist." Robin McDowell, "Sacred Ground: Unearthing Buried History at the Bonnet Carré Spillway," *Antigravity Magazine*, May 6, 2019, http://antigravitymagazine.com/feature/sacred-ground-unearthing-buried-history-at-the-bonnet-carre-spillway/.

85. Anna Thibodeaux, "Slave Cemeteries Remain Unmarked, Underwater in the Spillway," *The St. Charles Herald-Guide*, March 25, 2019, https://www.heraldguide.com/news/slave-cemeteries-remain-unmarked-underwater-in-the-spillway/. The Corps' desire to keep the exact locations of the cemeteries out of the public sphere is apparently due to fears of vandalism. See U.S. Army Corps of Engineers, "Draft Bonnet Carré Spillway Master Plan," 5.2.1.

86. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana,"144.

87. Day et al., "Ecological Response of Forested Wetlands with and without Large-Scale Mississippi River Input," 64.

88. U.S. Army Corps of Engineers, "Draft Bonnet Carré Spillway Master Plan," 5.1.1.

89. Ibid., 2.6.

significant deposition of the heaviest sediments occurs, creating undulating ridge and swale patterns. Due to mowing and the impact of spillway openings, vegetation in this zone consists of ruderal, early successional riparian species such as *Panicum repens* (Torpedo grass), *Salix nigra* (Black willow), *Xanthium strumarium* (Rough cocklebur), and *Cyperus* sp. (flatsedges). North of U.S. Highway 61, trees and shrubs dominate. The central portion of the floodway in this area is dominated by a dense forested wetland consisting almost entirely of *Salix nigra.* At the edges of this area, closer to the guide levees, cypress and tupelo dominate.[90] Wildlife within the spillway include alligators, crawfish, the bald eagle (*Haliaeetus leucocephalus*), white-tailed deer *(Odocoileus virginiana*), ducks, egrets, herons, hawks, and a large variety of turtles, snakes, frogs, and other amphibians.[91]

Figure 17. The Bonnet Carré floodway. Photo by author, October 17, 2019.

90. Observations by author, October and November 2019. A comprehensive survey of flora within the spillway can be found in the previously cited 2009 USACE Master Plan.

91. U.S. Army Corps of Engineers, "Draft Bonnet Carré Spillway Master Plan," 3.1.6.

Figure 18. The swamps and bottomland forests of the Bonnet Carré floodway. Photo by author via UAV, November 9, 2019.

Figure 19. The outfall of the Bonnet Carré floodway into Lake Pontchartrain. Photo by author via UAV, November 9, 2019.

In the 20th century, the Spillway was opened eight times, or every eight years on average.[92] That pace has increased dramatically in the 21st century, with openings in 2008, 2011, 2016, 2018, and 2019, when the Spillway was opened twice in the same year for the first time in its history.[93] As a result of this increased pace, 43 percent of all spillway openings have taken place in the last 11 years. [Fig. 21] Extreme high-water events, prolonged flood fights, and more frequent Spillway openings are projected to continue through the 21st century, as changing weather patterns contribute to warmer atmospheric temperatures and increased precipitation in the Mississippi River watershed.[94]

92. U.S. Army Corps of Engineers New Orleans District, "Bonnet Carré Spillway."

93. Jeff Adelson, "Bonnet Carre Spillway Opens along Mississippi River for Third Time in Four Years," The Advocate, February 27, 2019, https://www.theadvocate.com/new_orleans/news/article_7c3777d2-3aa0-11e9-b0ea-fb9909be0c5f.html.

94. Claire Taylor, "Why Mississippi River and Atchafalaya River Flooding Is Likely to Happen More Often, Experts Say," The Advocate, June 1, 2019, https://www.theadvocate.com/acadiana/news/article_f6ef23cc-82f2-11e9-96d2-576c3fafa0a7.html.

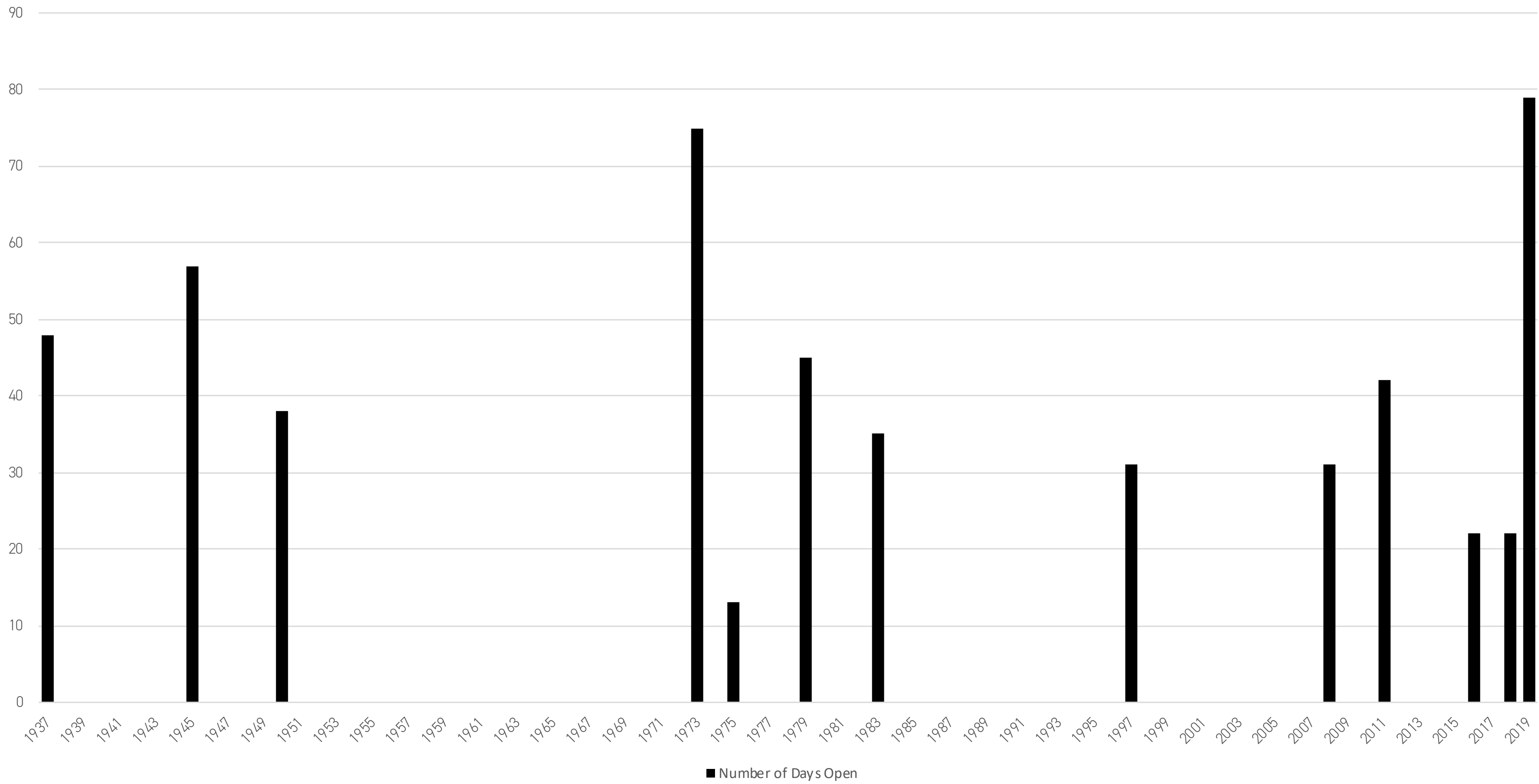



Figure 20. Chart of Bonnet Carré Spillway openings.

## II. The West Lake Pontchartrain Region's Long-Term Environmental Challenges

The West Lake Pontchartrain Region faces a number of long-term environmental challenges due to both natural processes and anthropogenic modifications to the landscape. These include dramatic shoreline erosion, wetland degradation, inland flooding, and impaired water quality in Lake Pontchartrain, all of which will be made more severe in coming decades due to the effects of a warming climate. These issues are the direct and indirect results of the region's deltaic physiography, estuarine ecology, and history of extractive industrial economies. [Fig. 22]

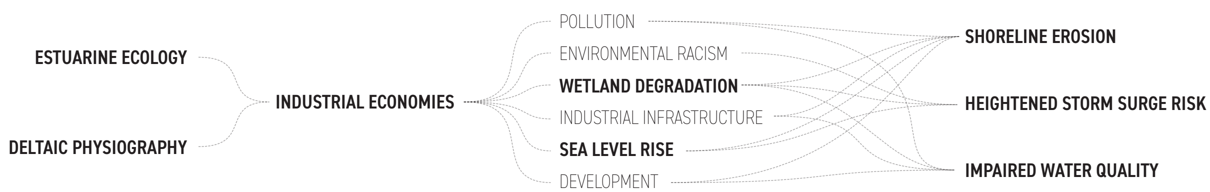



Figure 22. Conceptual diagram linking the region's physiography, ecology, and economic history with present-day environmental challenges.

### Shoreline erosion

Because it was formed by deltaic processes, the West Lake Pontchartrain region is ultimately subject to the same dynamics of sedimentation and erosion which characterize the rest of the Louisiana coastline. Between 1930 and 1990, the Lake Pontchartrain basin lost more than 188,000 acres of land in total.[95] The pace of this erosion can be seen by comparing historic maps and aerial imagery. [Fig. 23]

The U.S.G.S attributes this erosion to "a complex interaction between natural and human activities," including the construction of canals, resource extraction, population growth,

95. Jack Kindinger, "Environmental Issues – Shoreline Change and Shoreline Change Rates" in *Environmental Atlas of the Lake Pontchartrain Basin*, United States Geological Survey Open File Report 02-206, https://pubs.usgs.gov/of/2002/of02-206/env-issues/shoreline-intro.html.

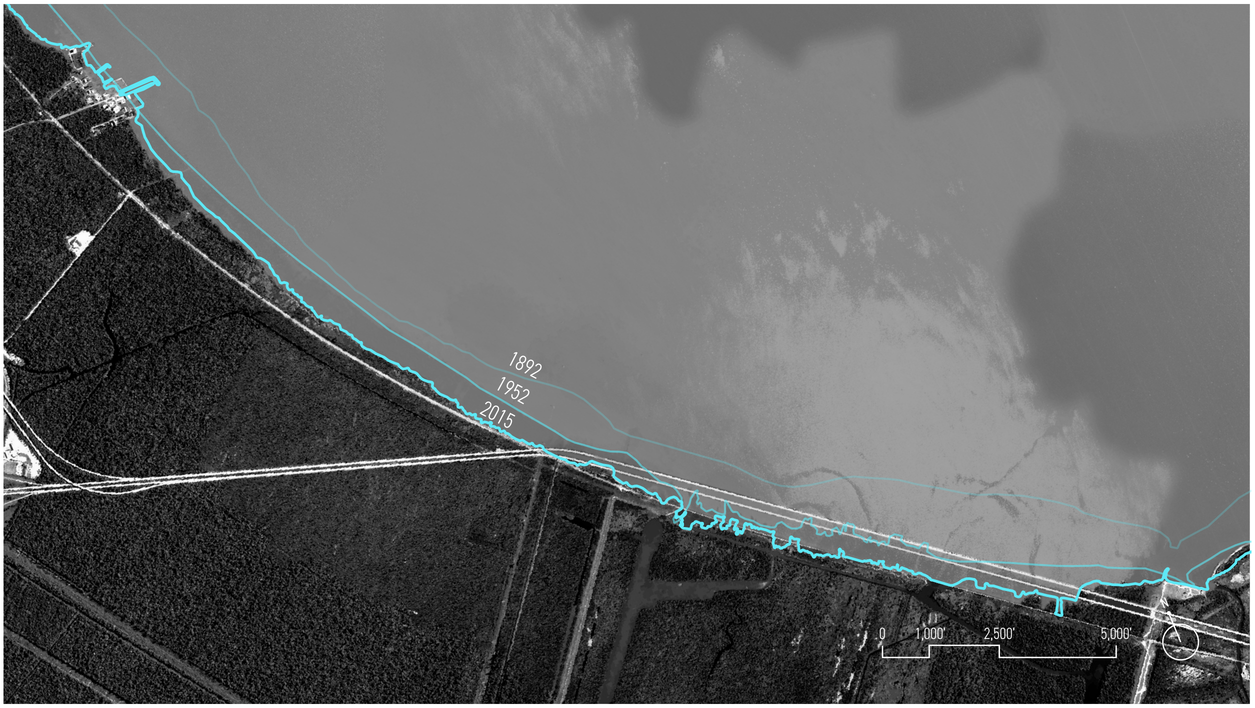


Figure 23. Historic shorelines of the West Lake Pontchartrain Region.

pollution, land development, and naturally occurring subsidence and wave action.[96] A key contributing factor is the construction of the federal Mississippi River levee system, which disconnected the region's wetlands from a regular supply of freshwater, sediment, and nutrients during spring high water events. As a result, Lake Maurepas and Pontchartrain "have been steadily enlarging at the expense of marsh and swamp areas."[97] This is, in effect, no different from conditions downriver of New Orleans, where deltaic wetlands, starved of riverine input, have steadily disappeared into the Gulf of Mexico.

**Wetland Degradation**

Closely related to shoreline erosion, the degradation of Western Lake Pontchartrain's wetlands is extensive and severe. Compared to shoreline erosion, however, the decline of West Lake Pontchartrain's wetlands is more acute and the causes more readily identifiable.

96. Kindinger, "Environmental Issues – Shoreline Change and Shoreline Change Rates" and Jeff Williams, Jack Kindinger, et al., "Shoreline/Wetland Changes" in *Geologic Framework and Processes of the Lake Pontchartrain Basin*, (United States Geological Survey, December 5, 2016), https://archive.usgs.gov/archive/sites/coastal.er.usgs.gov/pontchartrain/.

97. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," xv.

This is especially true in the case of the Maurepas Swamp, the 125,000 acre freshwater bottomland swamp to the north of LaPlace.

The Maurepas Swamp of 2020 is dramatically different from that of 150 years ago, and the story of that transformation can be closely tied to specific moments in history. The first major anthropogenic shocks to the Maurepas Swamp came with the passage of The Timber Act of 1876, and subsequent logging boom, which fundamentally altered the character of the wetlands along the western shore of Lake Pontchartrain (see Chapter II). The landscape left in the wake of this logging frenzy was not simply stripped of trees: the steam-powered pullboat system used by late 19th and early 20th century lumbermen left a pockmarked network of canals and ditches in the swamp's soft alluvial soils. Pullboats were used to drag freshly felled cypress logs across the otherwise impassable swamp landscape from as far as 5,000 feet away.[98] The pullboats were often kept in a central location, allowing timbermen to systematically harvest logs in a circular pattern, using radial "runs" along which logs were dragged. This technique left distinctive cuts and scrapes in the swamp landscape which are still clearly visible in aerial orthoimagery. [Fig. 24]

These ditches and canals left by pullboats dramatically altered the swamp's micro-topography and hydrology, limiting the ability of cypress and tupelo trees to recover.[99] In some of the most heavily logged areas along the Manchac Landbridge, the forest never returned, and instead has converted into open freshwater marsh. "Pullboat logging, therefore, not only removed the forest," writes Paul Keddy, "but permanently changed the physical nature of the landscape. It was nothing short of a disaster for the coastal wetlands of Louisiana."[100] The mass deforestation also interrupted land-building processes, removing a primary source of new soil in the form of leaf litter and woody debris and exposing the underlying soils and organic matter to oxidation and decomposition. This inhibits the swamp's ability to counter-

98. Keddy, *Water, Earth, Fire: Louisiana's Natural Heritage*, 120-126.
99. Ibid., 125-126.
100. Ibid., 126.

Figure 24. Radial ditches and canals left by pullboat logging as seen in orthoimagery. *Source*: Google Earth.

act subsidence and sea level rise, leading to increased inundation.[101] Cypress and tupelo are adapted to prolonged periods of inundation, but require periods of low water levels and relatively dry soils for seedlings to germinate. Today, portions of the Maurepas Swamp are flooded twice as often as they were in the 1950s.[102]

These impacts were compounded by the development of the federal Mississippi River Levee system in the aftermath of the Flood of 1927. Historically, the Maurepas Swamp would have received freshwater inputs from distributaries of the Mississippi such as Bayou Manchac, as well as from periodic overtopping of the natural levees during seasonal flooding events. These multiple points of connectivity to the Mississippi, along with surface runoff from the upland Pleistocene-era terraces to the north, facilitated a broad distribution of freshwater, sediments, and nutrients across the entirety of the swamp. While the levees protect human settlements along the river from seasonal flooding, they do so by interrupting these processes

101. Ibid., 126.

102. Gary P. Shaffer et al., "Degradation of Baldcypress–Water Tupelo Swamp to Marsh and Open Water in Southeastern Louisiana, U.S.A.: An Irreversible Trajectory?," *Journal of Coastal Research* 10054 (November 2009): 159, https://doi.org/10.2112/SI54-006.1.

and therefore are "incompatible with the long-term survival of deltaic wetlands."[103] Ironically, fees generated by the sale of timber leases in the late 19th century were used to construct and maintain the state's levees, which were the precursor to the modern federal system.[104]

Forty years after the region's last lumber mills ceased operations, the canals cut by lumbermen impacted the swamp in a new way. In the 1960s, the USACE constructed the Mississippi River to the Gulf Outlet, also known as MRGO, to shorten shipping travel times from New Orleans to the Gulf of Mexico. While it accomplished this goal, MRGO had the unintended side-effect of introducing large amounts of saltwater from the Gulf of Mexico into Lake Pontchartrain, altering the lake's sensitive and dynamic salinity regime. This increasingly salty water eventually began to find its way into the Maurepas Swamp by way of canals first cut for the logging industry nearly 100 years prior. Cypress and tupelo trees are highly sensitive to saltwater, which limits their ability to transport water and nutrients and can lead to tree mortality. Research indicates that cypress productivity begins to decline with exposure to salinities as low as 0.7 psu.[105] The cumulative influences of sea level rise, subsidence, and saltwater intrusion can lead to salinities as high as 10 psu in the Maurepas Swamp during droughts.[106] In one instance documented by Dr. Gary Shaffer of Southeastern Louisiana University, high salinities in the Maurepas Swamp in 1999 and 2000 led to cypress seedling mortality rates in excess of 97%.[107] Other studies have found similar impacts on mature trees.[108] Over time, this saltwater

103. Keddy et al., "The Wetlands of Lakes Pontchartrain and Maurepas: Past, Present and Future," 70.

104. Sternberg, *Winding Through Time*, 114-115.

105. Ken W. Krauss et al., "Performance Measures for a Mississippi River Reintroduction Into the Forested Wetlands of Maurepas Swamp," Scientific Investigations Report (Reston, Virginia: U.S. Geological Survey, 2017), 13, https://www.lacoast.gov/reports/project/Krauss_et_al_2017_sir20175036.pdf.

106. Gary P. Shaffer et al., "Decline of the Maurepas Swamp, Pontchartrain Basin, Louisiana, and Approaches to Restoration," 3.

107. Lee Wilson & Associates, Inc. et al., "Diversion to the Maurepas Swamps: A Complex Project under the Coastal Wetlands Planning, Protection, and Restoration Act," 1-5, June 2001, https://lacoast.gov/reports/project/3891453~1.pdf.

108. A 1993 study of a cypress forest in South Carolina found that hurricane driven storm surge and saltwater intrusion led to the loss of 50-65% of mature canopy specimens. See William H. Conner, "Artificial Regeneration of Baldcypress In Three South Carolina Forested Wetland Areas After Hurricane Hugo," in *Proceedings of the Seventh Biennial Southern Silvicultural Research Conference* (Seventh Biennial Southern Silvicultural Research Conference, Mobile, AL: Southern Forest Experiment Station, United States Forest Service, 1992), 185–88, https://www.srs.fs.usda.gov/pubs/gtr/gtr_so093.pdf.

Figure 25. A "ghost forest" in the LaBranche Wetlands. *Source*: John Hazlett, "Down on the Bayou," *Hakai Magazine*, November 12, 2015.

intrusion, combined with the lack of seasonal freshwater inundation from the Mississippi, has created "ghost forests" of dead cypress in the wetlands west of Lake Pontchartrain. [Fig. 25]

A final factor limiting the health and regeneration of the region's wetlands is herbivory from the exotic aquatic rodent *Myocastor coypus*, commonly known as the nutria. Native to South America, nutria were introduced to Louisiana for fur farming in the 1930s. Before long, nutria had escaped captivity. Their populations increased rapidly, reaching an estimated 20 million within 20 years.[109] This population explosion wreaked havoc on Louisiana's already-fragile wetlands due to rampant herbivory.[110] In the case of the Maurepas Swamp, nutria herbivory severely limits tree regeneration and sapling survival, with some trials resulting in 100% mortality of unprotected saplings.[111]

109. John Baroch et al., "Nutria (Myocastor Coypus) in Louisiana" (Prepared for Louisiana Department of Wildlife and Fisheries, March 31, 2002), https://digitalcommons.unl.edu/icwdmother/46.

110. Nutria eat all parts of plants, including roots, and also uproot and damage plants that they do not eat. Each nutria eats an estimated 2.5-3.5 pounds of vegetation per day. See Keddy, *Water, Earth, Fire: Louisiana's Natural Heritage*, 150.

111. Keddy et al., "The Wetlands of Lakes Pontchartrain and Maurepas," 65.

Figure 26. Reforestation efforts on the Manchac Landbridge. Photo by author, November 2, 2019.

The cumulative effect of these overlapping and compounding factors is that large portions of the Maurepas Swamp are at risk of disappearing forever. According to a 2016 study led by Dr. Gary Shaffer, "if current trends continue, most of the forested wetlands in the Maurepas sub-basin will  have transitioned to emergent wetlands or open water by mid-century."[112] [Fig. 26]

### Water Quality

While the Mississippi River levee system has disrupted hydrologic connections to coastal wetlands in the West Lake Pontchartrain Region, the river is not entirely disconnected from the Lake itself. Indeed, Lake Pontchartrain receives large influxes of Mississippi River water on a semi-regular basis through the Bonnet Carré Spillway. Mississippi River water of today is not the same as that of the 19th century, however. Today, development and industrial agriculture in the Mississippi watershed contribute to high levels of pollutants, particular-

112. Shaffer et al., "Decline of the Maurepas Swamp, Pontchartrain Basin, Louisiana, and Approaches to Restoration," 3.

Figure 27. Algae in Lake Pontchartrain following the 2019 opening of the Bonnet Carré Spillway. *Source*: Fox 8 Local News, New Orleans, LA.

ly excess nutrients from agricultural runoff. This concentration of nutrients has created the infamous "dead zone" in the Gulf of Mexico, where nitrogen-fueled algae blooms lead to anoxic conditions unable to support marine life.

A similar process plays out in Lake Pontchartrain following openings of the Bonnet Carré Spillway. As the spillway is closed and suspended sediment settles out of the water column, more light is able to penetrate deeper into the water column, catalyzing large algae blooms.[113] Following the historic spillway openings of 2019, a massive bloom of potentially toxic blue-green algae blanketed the late, causing recreational beaches along the Pontchartrain lakefront to shut down and forcing the state of Louisiana to issue a public warning that remained effect for more than two months.[114] [Fig. 27] As the Bonnet Carré Spillway is opened

113. Xiaobo Chao, Yafei Jia, and A. K. M. Azad Hossain, "Numerical Modeling of Sediment Transport and Its Effect on Algal Biomass Distribution in Lake Pontchartrain Due to Flood Release from Bonnet Carré Spillway," *Journal of Geoscience and Environment Protection* 04, no. 09 (2016): 64–79, https://doi.org/10.4236/gep.2016.49006.

114. For a summary of the far-reaching environmental impacts of extended openings of the Bonnet Carré Spillway, including dramatically increased dolphin mortality rates in the Mississippi Sound, see Emily Woodruff, "'Blind' swarms, algae blooms in Louisiana's 'uncharted' territory: Inside true costs of Bonnet Carre," Nola.com, July 1, 2019, https://www.nola.com/news/environment/article_5ed1a994-9c32-11e9-9695-bb42b9b7a073.html?23434.

with increasing frequency in the future, these large, disruptive algae blooms will likely become more common.

**Flooding**

For much of the recent history of the West Lake Pontchartrain region, the primary flood risk was from the seasonal swelling of the Mississippi River. Persistent high-water levels would lead to levee failure, or *crevasses*, where fast moving river water would burst through the levee and inundate the low-lying areas behind them, connecting the river to Lake Pontchartrain. The construction of artificial levees beginning in the 18th century made these events far more destructive by raising the river's flood crest height, increasing the elevation gradient between the river and the surrounding floodplain.[115] [Fig. 28] *Crevasse* events at Bonnet Carré occurred at least five times in the 19th century, creating levee breaches up to one mile wide. One such breach, formed in 1871, remained open for nine years until funding could be secured for its ultimate repair.[116]

While the flood risk from the Mississippi River was substantially reduced with the construction of the modern levee system, the threat of flooding from Lake Pontchartrain has emerged as a key concern. In August 2012, Category 1 Hurricane Isaac struck southeast Louisiana, dropping up to 19 inches of rain in some locations.[117] In LaPlace, the rainfall combined with an 8.4 foot storm surge from Lake Pontchartrain to cause unprecedented flooding which impacted more than 7,000 homes, rendered Interstates 10 and 55 impassable,[118] forced the closure of the Port of South Louisiana, and disrupted the national energy supply.[119] [Fig. 29] The

115. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 138.

116. Sternberg, *Along the River Road: Past and Present on Louisiana's Historic Byway*, 131-132.

117. Jennifer Sparenberg et al., "Hurricane Isaac in Louisiana: Building Performance Observations, Recommendations, and Technical Guidance," Mitigation Assessment Team Report (U.S. Department of Homeland Security Federal Emergency Management Agency (FEMA), March 2013), https://www.fema.gov/media-library-data/20130726-1908-25045-0581/fema_p_938_isaac_mat.pdf

118. "St. John the Baptist Parish, Louisiana Community Recovery Strategy: One Parish, One Future: Building Back Better and Stronger" (St. John the Baptist Parish, May 2013), http://www.sjbparish.com/SJBRecoveryStrategy.pdf.

119. U.S. Army Corps of Engineers, "West Shore Lake Pontchartrain Hurricane and Storm Damage Risk Reduction Study: Final Integrated Feasibility Report and Environmental Impact Statement" (New Orleans: U.S. Army Corps

Figure 28. "Louisiana - the Bursting of the Crevasse at Bonnet Carre, on Missippi River." *Source*: *Frank Leslie's Illustrated Newspaper*, May 13, 1871, Library of Congress Prints and Photographs Division.

flooding from Hurricane Isaac demonstrated the vulnerability of the West Lake Pontchartrain region, and contributed to a renewed interest in and support for the construction of a hurricane protection levee for the communities of St. James and St. John the Baptist Parishes, an idea first raised in the 1970s.

The West Lake Pontchartrain region is especially prone to storm surge flooding because of the geometry of Lake Pontchartrain and the trajectory of most storms that impact the region. As hurricanes and tropical storms approach from the south, the counter-clockwise rotation of their circulation imparts strong easterly winds, pushing the shallow waters of Lake Pontchartrain into the lake's western half, a phenomenon referred to by the Lake Pontchartrain Basin Foundation as "surge focusing."[120] While Hurricane Issac was only a Category 1

of Engineers, New Orleans District, November 2014), https://www.mvn.usace.army.mil/Portals/56/docs/PD/Projects/WSLP/Final/01_FINAL_WSLP_REPORT_2nd_CWRB.pdf.

120. Lopez et al., "The Dynamics of Storm Surge in the Pontchartrain and Maurepas Region."

Figure 29. Storm surge flooding from Hurricane Isaac, 2012. *Source*: Chris Graythen for Getty Images.

storm, a LPBF analysis estimates a 500-year storm event would produce a storm surge as high as 18 feet at Frenier Landing.[121] As atmospheric warming, sea level rise, and regional subsidence continue into the 21st century, the chances of such extreme surge events rise.[122]

**Sea Level Rise**

All of the aforementioned issues–shoreline erosion, water quality, flooding, and wetland degradation–stand to be exacerbated by a warming climate and associated sea level rise. [Fig. 30] A warming climate causes eustatic sea level rise due to thermal expansion of the water in the earth's oceans and an increase in total water body mass due to inputs from terrestrial glaciers and ice sheets. Eustatic sea level rise refers to the change in sea levels independent of vertical movement of the earth's surface, whereas relative sea level rise (RSLR) takes into

121. Ibid., 27.

122. It is worth noting that flooding is a naturally occurring process in this area and, unlike wetland loss, is not indicative of any sort of underlying ecosystem failure. Rather, flooding is only an issue to the extent that it intersects with areas of human habitation and encounters an unprepared and unprotected population. In this respect, flooding can be understood as both and environmental and a social challenge.

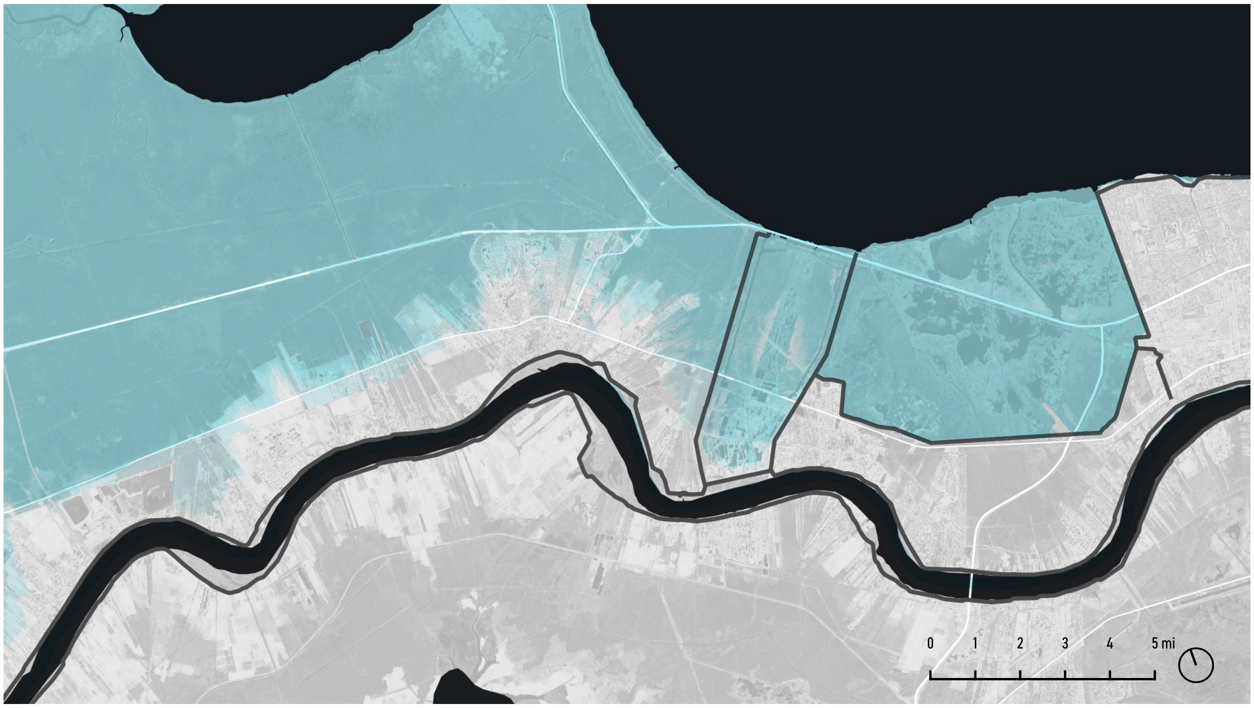


Figure 30. Sea level rise (RSLR) in the West Lake Pontchartrain region.

consideration changes in land surface elevation due to subsidence, sedimentation, and/or tectonic uplift.

Future rates of global mean sea level rise (GMSLR) remain highly uncertain, as GMSLR rates depend on factors that are either unknowable (i.e., the extent and success of efforts to reduce greenhouse gas emissions) or poorly understood (i.e., warming feedback loops, ice sheet behavior, etc.). Because of this uncertainty, official sea level rise estimates display a wide range of variance among agencies. [Table 1] "Scientists expect that GMSLR will continue to rise throughout the 21$^{st}$ century and beyond because of global warming that has already occurred and warmed that is yet to occur due to the still-uncertain level of future emissions," however. "GMSLR rise is a certain impact of climate change; the questions are *when,* and *how much,* rather than *if.* There is also a long-term commitment (present trend); even if society sharply reduces emissions in coming decades, sea level will most likely continue to rise for centuries."[123]

123. W.V. Sweet et al., "Ch. 12: Sea Level Rise. Climate Science Special Report: Fourth National Climate Assessment, Volume I" (U.S. Global Change Research Program, 2017), https://doi.org/10.7930/J0VM49F2, 1.

Table 1. Working Eustatic Sea Level Rise Projections (2100)

| Source | IPCC (GMSLR)[124] | NOAA (GMSLR)[125] | CPRA (Regional)[126] |
|---|---|---|---|
| **Low End Estimate (m/ft)** | 0.43 m / 1.41 ft | 0.3 m / 0.98 ft | 0.31 m / 1.02 ft |
| **High End Estimate (m/ft)** | 0.84 m / 2.76 ft | 2.5 m / 8.2 ft | 1.98 m / 6.50 ft |

While sea level rise can be measured and predicted at the global scale, its impacts vary locally due to the effects of ocean currents, winds, tides, and local geological conditions. Due to its deltaic geology, the Louisiana coastline is experiencing the highest rates of relative sea level rise in the United States, at a rate of 8-10 mm/year. This is due to subsidence, a result of the steady compaction of deltaic sediments, as well as anthropogenic groundwater and gas extraction.[127] CPRA estimates spatially variable future rates of subsidence along the Louisiana coastline, with the Lake Pontchartrain basin experiencing subsidence at rates of 2.6 – 3.5 mm/year.[128]

In recent years, as modeling capabilities have increased and political commitment to climate mitigation has faltered, future sea level rise estimates have begun to increase significantly above previous estimates. As summarized in a 2017 report from NOAA, "the projections and results presented in several peer-reviewed publications provide evidence to support a physically plausible GMSL rise in the range of 2.0 to 2.7 meters, and recent results regarding Antarctic ice-sheet instability indicate that such outcomes may be more likely than previously thought."[129] In 2019, the Intergovernmental Panel on Climate Change (IPCC) warned "Sea level rise has accelerated (*extremely likely*) due to the combined increased ice loss from the Green-

124. M. Oppenheimer et al., "Sea Level Rise and Implications for Low-Lying Islands, Coasts, and Communities," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, ed. H.-O. Pörtner et al., 2019, 327.

125. William V. Sweet et al., "Global and Regional Sea Level Rise Scenarios for the United States," NOAA Technical Report (Silver Spring, Maryland: National Oceanic and Atmospheric Association, January 2017). The report's authors note rates of relative sea level rise will be greater than GMSL for areas along the Atlantic and Gulf Coasts of the United States.

126. James Pahl, "2017 Coastal Master Plan Attachment C2-1: Eustatic Sea Level Rise" (Coastal Protection and Restoration Authority, April 2017).

127. Ibid., 9.

128. Denise Reed and Brendan Yuill, "2017 Coastal Master Plan Attachment C2-2: Subsidence" (Coastal Protection and Restoration Authority, April 2017).

129. Sweet et al., "Global and Regional Sea Level Rise Scenarios for the United States," vi.

land and Antarctic ice sheets (*very high confidence*). Mass lass from the Antarctic sheet over the period 2007-2017 tripled relative to 1997-2006."[130] Summarizing the report for *The Atlantic,* Robinson Meyer wrote: "The headline finding of this report is that sea level rise could be worse than we thought. The report's projection of worst-case sea-level rise by 2100 is about 10 percent higher than the IPCC predicted five years ago. The IPCC has been steadily ratcheting up its sea-level-rise projections since its 2001 report, and it is likely to increase the numbers further in the 2021 report, when the IPCC runs a new round of global climate models."[131] If accurate, these higher sea level rise projections could undermine the efficacy of coastal projects designed under previous lower estimates.

**Responses to Environmental Challenges**

The West Lake Pontchartrain Region's concentration of residents, cultural and ecological resources, critical infrastructure, and environmental challenges has made it a focus of coastal planning in recent decades. As a result of these efforts, two large infrastructure projects representing nearly $1 billion in investment have been funded for construction and are in final planning and design stages. The $200 million Maurepas Swamp River Reintroduction Project, led by the CPRA, will restore historic hydrologic connectivity between the Mississippi River and the Maurepas Swamp in an attempt to reverse the swamp's dramatic decline in recent decades.[132] The $790 million West Shore Lake Pontchartrain Project, led by the U.S. Army Corps of Engineers, will provide hurricane risk-reduction to the population centers of LaPlace, Reserve, and Garyville, as well as Interstate 10 and nearby industrial facilities. [Fig. 31]

130. IPCC, "Summary for Policymakers," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, ed. H.O. Pörtner et al. (IPCC, 2019), 10.

131. Robinson Meyer, "The Oceans We Know Won't Survive Climate Change," *The Atlantic*, September 25, 2019, https://www.theatlantic.com/science/archive/2019/09/ipcc-sea-level-rise-report/598765/.

132. "River Reintroduction into Maurepas Swamp: Project Overview" (Louisiana Coastal Protection and Restoration Authority, March 2018), https://www.lacoast.gov/reports/project/PO-0029_Project_Overview_20180326.pdf.

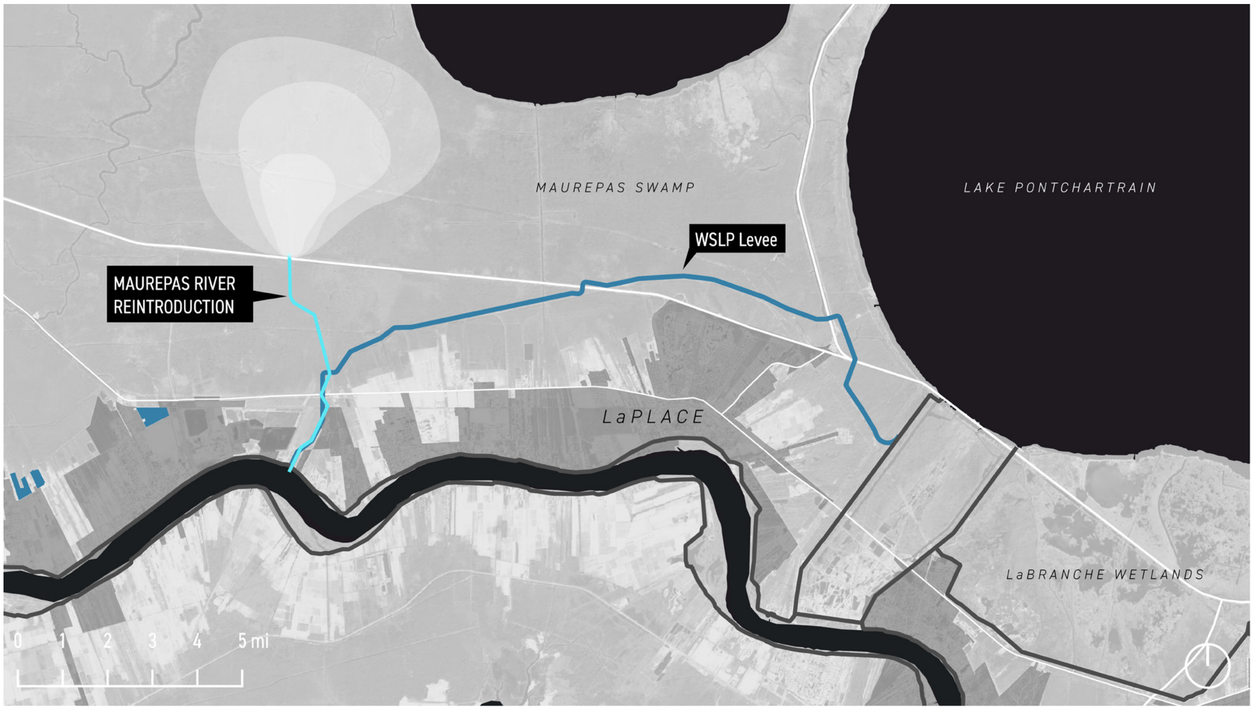



Figure 31. The planned West Shore Lake Pontchartrain (WSLP) Levee and Maurepas River Reintroduction projects.

### Maurepas Swamp River Reintroduction Project

The decline and restoration of the Maurepas Swamp has been a focus of study since the passage of the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) in 1990.[133] The 1993 Louisiana Coastal Wetlands Restoration Plan identified restoration of historic hydrologic patterns between the Mississippi River and the swamps and marshes of the Pontchartrain Basin as critical for the long-term protection of the region, and proposed a freshwater diversion into the Maurepas Swamp near Donaldsonville. This influx of fresh river water into the swamp would mitigate the effects of saltwater intrusion, as well as provide nutrients and small volumes of fine-grain sediment.[134] A subsequent study in 2001 identified a tie-in to the Hope Canal at Garyville as an ideal location for such a diversion to maximize benefits to

133. Also known as "The Breaux Act" in reflection of the bill's sponsor, Louisiana Senator John Breaux, CWPPRA created the first mechanism for federal and state coordination and regular funding of Louisiana coastal restoration projects. See John Snell, "Nearly 30 Years after Its Passage, the Breaux Act Pumps Millions into Louisiana Coastal Projects," Fox 8 Local News, December 18, 2019, https://www.fox8live.com/2019/12/19/nearly-years-after-its-passage-breaux-act-pumps-millions-into-louisiana-coastal-projects/

134. "Louisiana Coastal Wetlands Restoration Plan: Main Report and Environmental Impact Statement" (Louisiana Coastal Wetlands Conservation and Restoration Task Force, November 1993), https://lacoast.gov/reports/cwcrp/1993/1993lcwrp-all.pdf.

the swamp.[135] Engineering and design work followed, and the project was included in both the 2012 and 2017 Louisiana Coastal Master Plans.[136] In 2020, the project received $130 million in funding for construction funding through the Gulf Ecosystem Restoration (RESTORE) Council, which oversees the distribution of penalty funds collected in the aftermath of the Deepwater Horizon oil spill.[137]

The Maurepas River Reintroduction project will siphon as much as 2,000 cubic feet per second (cfs) of freshwater from the Mississippi River into a 5.5-mile long conveyance channel, ultimately connecting to the swamp north of Interstate 10. South of the primary outfall into the swamp, four lateral release valves will allow for small volumes of water (125 cfs) to be diverted into swamp area adjacent to the conveyance channel south of Interstate 10.[138] The system will be operated to achieve specific performance measures designed to mimic historic hydrologic patterns and support the long-term sustainability of the Maurepas Swamp, including periodic water level drawdowns to encourage baldcypress and water tupelo germination.[139] In all, the diversion is estimated to benefit 45,000 acres of swamp by providing oxygenated freshwater, nutrients, and sediment.[140]

### The West Shore Lake Pontchartrain Levee Project

In the aftermath of the flooding caused by Hurricane Isaac in 2012, political pressure mounted for the construction of a hurricane protection levee system for LaPlace and other

135. Wilson & Associates, Inc. et al., "Diversion to the Maurepas Swamps: A Complex Project under the Coastal Wetlands Planning, Protection, and Restoration Act."

136. K. LaCour-Conant, K. Ramsey, and K. Bollfrass, "PO-0029 River Reintroduction into Maurepas Swamp: Swamp Community Wetland Value Assessment" (Baton Rouge: Coastal Protection and Restoration Authority, June 2019).

137. "Gulf Coast Ecosystem Restoration Council Funded Priorities List 3a" (Gulf Coast Ecosystem Restoration Council, February 12, 2020), https://www.restorethegulf.gov/sites/default/files/Final_FPL%203a_Final_Perdido_EC_508_3_2_2020.pdf.

138. Honora Buras et al., "River Reintroduction into Maurepas Swamp Project (PO-0029) Preliminary Operations, Maintenance, Monitoring, and Adaptive Management Plan" (Coastal Protection and Restoration Authority, October 16, 2018), https://www.lacoast.gov/reports/project/Preliminary_Maurepas_OMMAM_Plan_10-16-18.pdf.

139. Ibid., 16.

140. Ibid., 6.

urbanized areas of St. John the Baptist Parish,[141] an idea that dates back to the 1970s.[142] In 2014, the U.S. Army Corps of Engineers issued their final recommendations on the matter.[143] The Corps' recommended plan consists of an 18.27 mile-long levee and flood-wall system encircling the populations centers of LaPlace, Reserve, and Garyville, stretching from the upper (west) guide levee of the Bonnet Carré Spillway to the Mississippi River levee system east of the Sunshine Bridge. The proposal also includes "localized storm surge risk reduction measures," primarily consisting of small ring levees (or "polders") encircling at-risk structures in St. James Parish outside of the main levee, as well elevating and flood proofing a small number of residential and commercial structures.[144] According to the Corps, the project would provide storm surge risk reduction for 7,000 structures and 4 miles of Interstate 10. The Corps proposal calls for the levee to be designed to a 1% (100 year) storm probability and 2020 intermediate RSLR condition, resulting in initial levee heights ranging from 8.5' to 15' NAVD 88.[145] The plan also calls for the levee to be elevated with additional lifts in order to maintain 100-year storm protection in the face of RSLR. These lifts would be carried out in 2030, 2045, and 2060, and would result in total levee heights up to 19.5' NAVD 88.[146]

Because the proposed levee alignment runs through the Maurepas Swamp, impacts on the region's wetlands are considerable. The construction of the levee would eliminate 1,198 acres of swamp and bottomland hardwood forest and enclose another 8,432 acres of

141. John Schwartz and Campbell Robertson, "New Orleans Levees Hold, and Outsiders Want In," *The New York Times,* September 6, 2012, https://www.nytimes.com/2012/09/07/us/new-orleans-levees-hold-and-outsiders-want-in.html.

142. Della Hasselle, "Long awaited $744 million hurricane levee for River Parishes authorized in bill signed by Obama," *The New Orleans Advocate,* January 1, 2017, https://www.theadvocate.com/new_orleans/news/environment/article_94294fb6-cc64-11e6-a919-4b459677d4e4.html (accessed December 4, 2108).

143. "U.S. Army Corps of Engineers, "West Shore Lake Pontchartrain Hurricane and Storm Damage Risk Reduction Study: Final Integrated Feasibility Report and Environmental Impact Statement."

144. Draft proposals called for up to $300 million in buyouts and structure elevations, but these plans were revised after initial public comments revealed "this type of program would likely receive very little public participation if the program were voluntary due to the number of structures potentially removed from the community." Ibid., 3.9.1.

145. Ibid., Table 2-2. The Intermediate RSLR scenario used by the Corps estimates 0.34' of RSLR by 2020 and 2.32' of RSLR by 2070.

146. Ibid., 5.1.

swamp.[147] The enclosure of this large portion of swamp will in essence divide the swamp in two and interrupt surface groundwater patterns. The Corps acknowledged "decrease in tidal interchange between the interior (protected side) and the exterior (unprotected side) areas of the proposed levee alignment" as "major indirect impacts of the [proposed] structural measures." In an attempt to mitigate these impacts, the proposed levee includes a series of drainage structures, canals, and pumps to manage surface runoff and tidal exchange. The Corps claims that these structures will maintain hydrologic connectivity between wetland areas, a conclusion supported by studies conducted using one-dimensional hydraulic models in HEC-RAS. However, "the limitation of the 1D HEC-RAS model is that it averages water surface across an area."[148] Given the spatial complexity of tidal exchange and surface runoff and the specific hydrologic conditions required by many wetland plant species, it is almost certain that the hydrologic regime established by the WSLP levee system and its associated drainage structures will not be directly equivalent to the regime currently in place.

President Obama authorized funding for the project in 2016,[149] and in 2018 Congress allocated $760 million for the design and construction of the system.[150] At the time of writing, the project is in initial stages of construction.[151]

147. Ibid., Table 3-9.

148. Ibid., Page 4-2.

149. "President Obama Signs Water Bill Into Law" (St. John the Baptist Parish, December 19, 2016), http://www.sjbparish.com/news_details.php?id=2260.

150. "West Shore Lake Pontchartrain," US Army Corps of Engineers New Orleans District, https://www.mvn.usace.army.mil/About/Projects/BBA-2018/West-Shore-Lake-Pontchartrain/.

151. West Shore Lake Pontchartrain – New Orleans,USACE (@WestShoreLakePontchartrain), "The WSLP project site is being toured as part of the Mississippi Valley Division (US Army Corps of Engineers) governance week," Facebook, January 22, 2020, https://www.facebook.com/WestShoreLakePontchartrain/posts/486812415569454.

## III. The Siltcatcher Concept

### The Problem

The Lake Pontchartrain Basin Foundation has proposed and promoted a "Multiple Lines of Defense" strategy for coastal protection in southeast Louisiana, in which coastal communities are protected from hurricane-driven storm surge and flooding by layers of ecological and engineered systems such as coastal marshes and swamps, levees, and floodwalls.[152] [Fig 32] The planned Maurepas Swamp River Reintroduction and West Shore Lake Pontchartrain Levee projects are in keeping with this strategy, providing a new line of coastal defenses (the levee) and rehabilitating an existing one (the swamp).

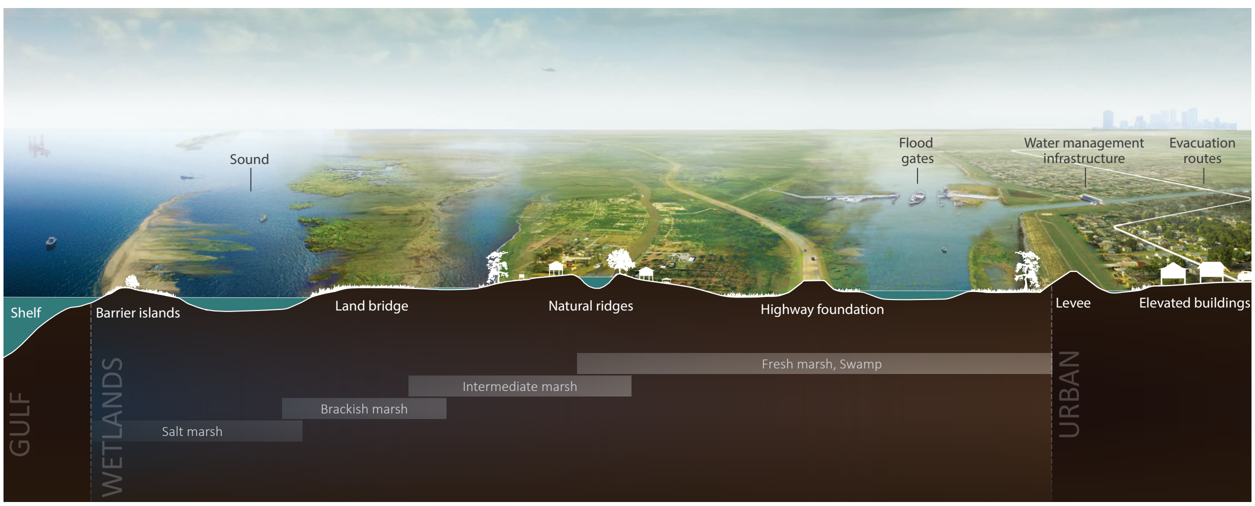


Figure 32. The Multiple Lines of Defense Strategy. *Source*: LSU Coastal Sustainability Studio.

Rising sea levels will undermine the efficacy of these projects, however. While the U.S. Army Corps incorporated relative sea level rise into its design for the WSLP, it nonetheless acknowledged "uncertainty about how much SLR change would occur in the region," cautioning that "future RSLR could impact the benefits achieved by the Recommended Plan."[153] Similarly, the CPRA has acknowledged "the largest single environmental uncertainty in planning and im-

152. John A. Lopez, "The Multiple Lines of Defense Strategy to Sustain Coastal Louisiana," *Journal of Coastal Research* 10054 (November 2009): 186–97, https://doi.org/10.2112/SI54-020.1.

153. U.S. Army Corps of Engineers, "West Shore Lake Pontchartrain Hurricane and Storm Damage Risk Reduction Study: Final Integrated Feasibility Report and Environmental Impact Statement," 5.8.2.

plementing restoration projects in south Louisiana is accounting for the potentially high, and highly variable, rates of relative sea level rise. [...] Underestimation of RSLR during planning and design could result in greater than anticipated deepening of the receiving basin regardless of biological benefits of the freshwater and nutrient deliveries to the vegetation."[154]

These statements, when considered in light of the upward trend of sea level rise estimates in recent years (see Chapter II), suggest the currently planned projects may be less effective than initially envisioned, in which case additional strategies may be warranted in order to safeguard the future of the West Lake Pontchartrain Region. [Fig 33] This research proposes one such strategy.

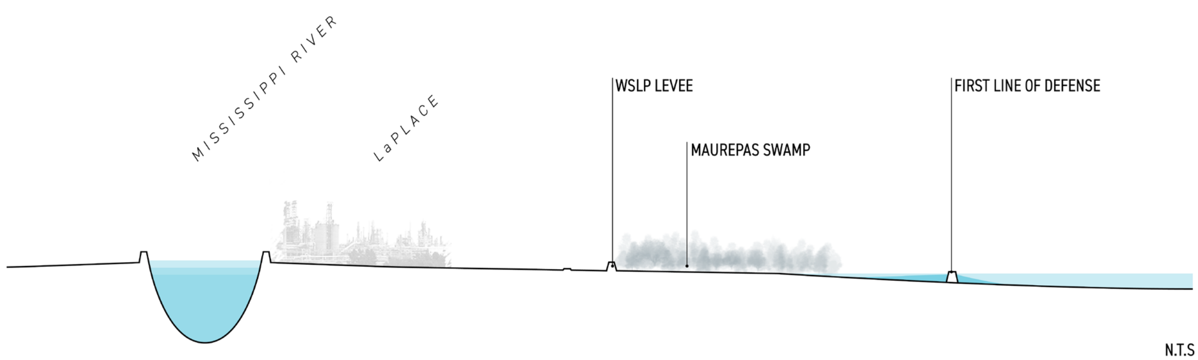



Figure 33. Conceptual Section of the West Lake Pontchartrain Region.

## The Concept

The "Siltcatcher" proposes the utilization of existing infrastructure, flows, and processes to address community and ecosystem needs in the West Lake Pontchartrain region. The concept envisions a series of offshore breakwater-like structures and associated features in western Lake Pontchartrain positioned to slow water released from the nearby Bonnet Carré Spillway, causing suspended sediment to settle and creating self-building and self-sustaining wetlands capable of keeping pace with future sea level rise. [Fig. 34a] This hybrid grey-green

154. "Mississippi River Reintroduction into Maurepas Swamp RESTORE Proposal" (Baton Rouge: Coastal Protection & Restoration Authority, 2014), https://www.restorethegulf.gov/sites/default/files/Mississippi%20River%20Reintroduction%20into%20Maurepas%20Swamp.pdf, 3.

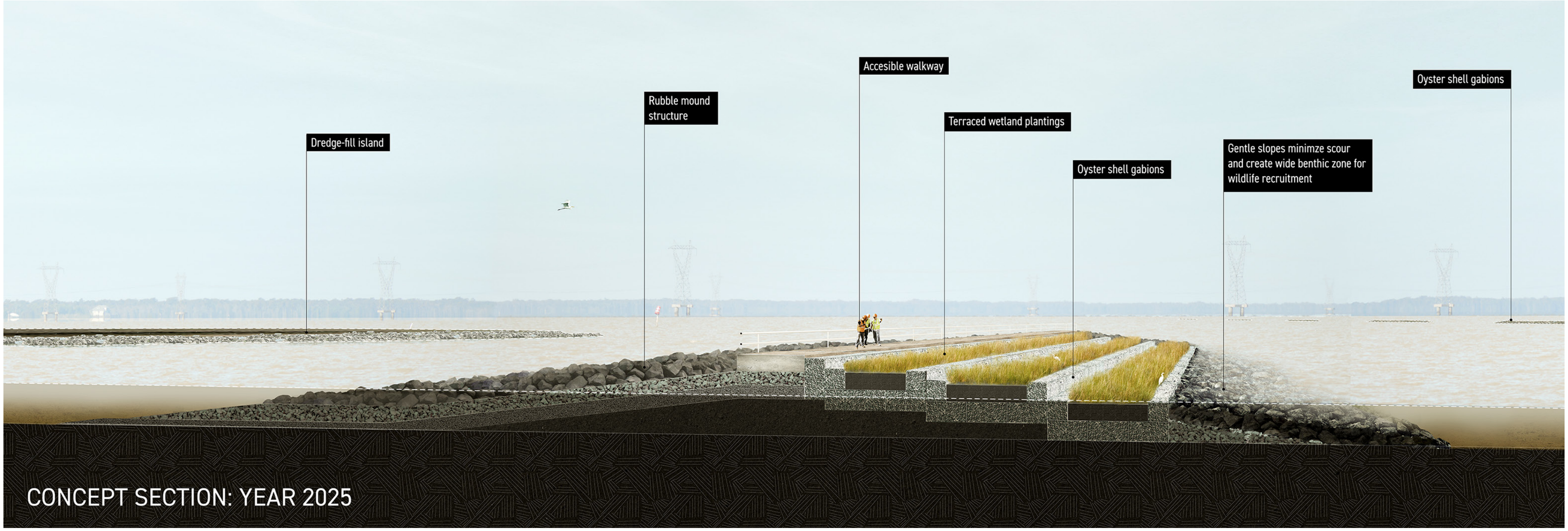



Figure 34a. Conceptual section/perspective of the proposed Siltcatcher system, 2025.

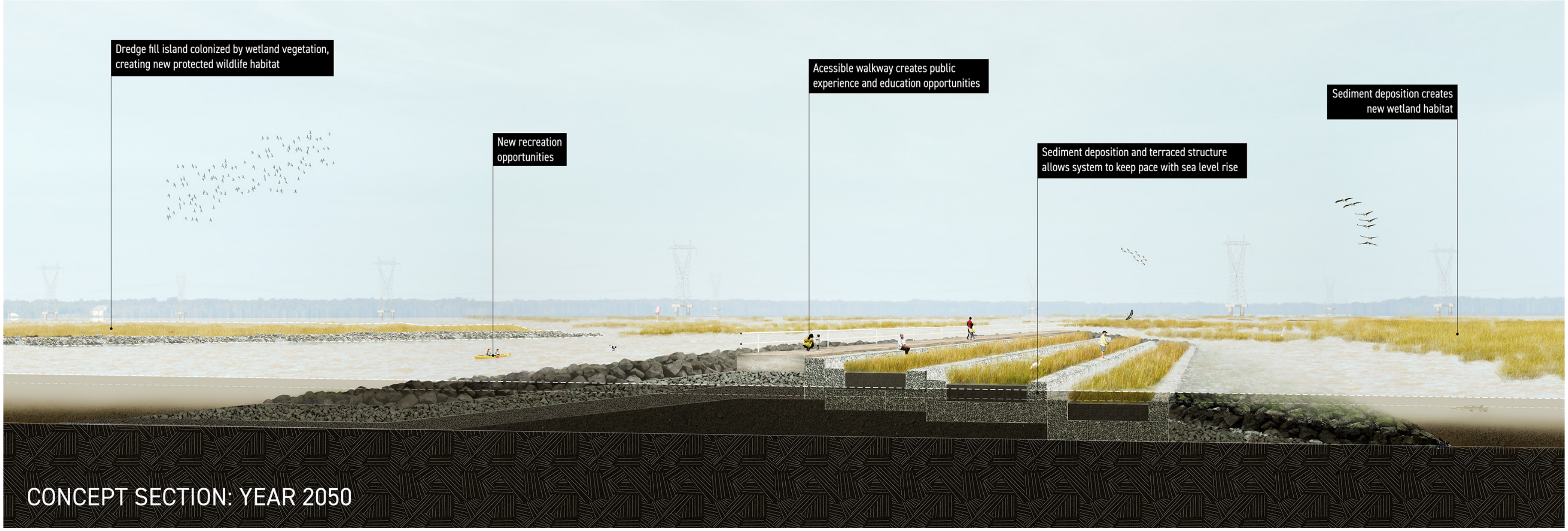



Figure 34b. Conceptual section/perspective of the proposed Siltcatcher system, 2050.

system would provide both wetland creation and storm protection, providing a forward line of defense while generating multiple additional benefits in the process, including water quality mitigation, recreational and educational opportunities, and responsiveness to the anticipated effects of a warming climate. [Fig 34b]

**Benefits of Proposed System**

- **Shoreline and Storm Protection:** Breakwaters are a standard coastal engineering tool for storm protection and shoreline stabilization. They are generally long berms located some distance offshore, parallel to the shoreline, and constructed of exterior armoring and layers of progressively graded rubble, with the finest aggregate at the core of the structure. They create a calm area on their leeward (shoreward) side, reducing the erosive impact of large, storm driven waves on the protected shoreline.[155] The Siltcatcher system would consist of a series of modified rubble-mound breakwater structures, protecting the rapidly-eroding western Lake Pontchartrain shoreline and a providing a forward line of storm protection for inland communities in keeping with the "Multiple Lines of Defense" strategy. Over time, the growth of adjacent wetlands from openings of the Bonnet Carré Spillway would add additional wave and storm protection capacity to the system.[156]
- **Land Building and Wetland Creation:** The Bonnet Carré Spillway presents an opportunity for land building and wetland creation through the enormous amounts of sediment that it siphons from the Mississippi River when in use. [Fig. 35] Past events have demonstrated this potential. The nearby Bonnet Carré Crevasse left deposits up to sev-

155. Robert M. Sorensen, *Basic Coastal Engineering* (New York: Chapman & Hall, 1997), 202-206.

156. Wetland vegetation is known to reduce the impacts of storm surge. While observed surge reduction rates have varied in different studies, a commonly quoted rule of thumb states that 2.7 miles of wetland equates to 1 foot of storm surge reduction. More recent research suggests that wetlands and soft shorelines may in fact be ***more*** effective than hard engineered structures when it comes to mitigating storm impacts. See Ty V. Wamsley et al., "The Potential of Wetlands in Reducing Storm Surge," *Ocean Engineering* 37, no. 1 (January 2010): 59–68, https://doi.org/10.1016/j.oceaneng.2009.07.018, and Rowan Jacobsen, "Rebuilt Wetlands Can Protect Shorelines Better Than Walls," Scientific American, accessed March 19, 2019, doi:10.1038/scientificamerican0419-32.


Figure 35. False-color infrared image of Lake Pontchartrain captured by Landsat 8 on March 6, 2019.

en feet thick in western Lake Pontchartrain in the mid-19th century.[157] Openings of the Spillway in the 20th century have left as much as 11.5 million cubic meters of silt and sand in the floodway itself, which does not include the smaller particles which would have escaped into the lake.[158] Sediment that does reach the lake–approximately 40% of the total flow according to a 1953 study–appears to either settle out in an "underwater delta fan" at the mouth of the spillway or remain suspended in the water column.[159] More recently, Jeffrey Fabre confirmed this pattern in his research of the 2011 opening, which he estimated deposited anywhere from 1-4 megatonnes of sediment into the lake itself.[160] Still, despite these immense volumes of sediment entering Lake Pontchartrain from the Bonnet Carré Spillway, past spillway openings have not generated ac-

157. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 139-142.

158. Day et al., "Ecological Response of Forested Wetlands with and without Large-Scale Mississippi River Input," 59.

159. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 144.

160. Jeffrey Bryant Fabre, "Sediment Flux & Fate for a Large-Scale Diversion: The 2011 Mississippi River Flood, the Bonnet Carré Spillway, and the Implications for Coastal Restoration in South Louisiana" (Master's Thesis, Baton Rouge, LA, Louisiana State University, 2012), 16-19 and 26. Fabre also found that the majority of this sediment remained within the lake and settled into lake-bed deposits, rather than being carried into the Gulf of Mexico.

cretion greater than two feet. Saucier argues this was likely due to the relatively brief duration of Spillway openings when compared to the 19th crevasses, which in some cases were left open for years.[161] The increasing frequency and duration of Spillway openings in recent years and predictions of similar conditions in the future suggest that the potential for land-building will increase, however. The Siltcatcher structures would take advantage of this increased sediment supply, altering flow and deposition patterns to create zones of enhanced deposition and accretion which would develop into mudflats and emergent marsh over time.[162] In addition to the rubble-mound structures, deposition could be bolstered by sediment-trapping Christmas tree fences, connecting the system to a popular, long-running community-based coastal restoration program.[163] At the project's outset and during periods with no spillway openings, sediment could be manually introduced to the system through thin-layer placement of dredged material. Together, these efforts would allow the network of wetlands to grow and evolve with sea level rise, providing dynamic, sustainable, and resilient habitat and turning back the clock on subsidence and erosion in western Lake Pontchartrain.[164]

- **Improved water quality:** Once established, the Siltcatcher wetlands would help mitigate the effects of Spillway-induced algae blooms by absorbing nitrogen and phosphorous from the water column. The ability of wetlands to take up excess nutrients from

161. Saucier, "Recent Geomorphic History of the Pontchartrain Basin, Louisiana," 145.

162. In concept, this is similar to marsh terracing, in which earthen berms are created in degraded marshes to reduce fetch and create marsh-edge conditions for emergent vegetation recruitment and sediment trapping. Marsh terracing has been used extensively in coastal Louisiana, especially in the western half of the state, due to its low cost and ease of implementation. For more, see Michael G Brasher, "Review of the Benefits of Marsh Terraces in the Northern Gulf of Mexico" (Lafayette: Ducks Unlimited, Inc.).

163. Roelof M.J Boumans et al., "The Effect of Intertidal Sediment Fences on Wetland Surface Elevation, Wave Energy and Vegetation Establishment in Two Louisiana Coastal Marshes," *Ecological Engineering* 9, no. 1–2 (September 1997): 37–50, https://doi.org/10.1016/S0925-8574(97)00028-1.

164. Jeffery Fabre, concluding his thesis, underscores the land-building potential of the Bonnet Carré Spillway: "The results presented here indicate that even a large scale man-made diversion not designed for coastal restoration purposes *can deliver sediment fluxes on the order of existing large diversions and natural subdeltas in the Mississippi Delta* if operated on a regular basis during high-flows when both sediment concentration and discharge are highest. In addition, results herein demonstrate that *receiving basin geometry and boundaries are important factors in maximizing the land building potential of an engineered diversion,* due to the abundance of finer grained sediment in the river and the variability of trapping efficiencies throughout the delta plain." (Emphasis added.)

riverine inputs has been well researched and documented. A 2019 review of studies on the effects of Mississippi River sediment diversions into deltaic wetlands in southern Louisiana confirms that "wetlands have long been recognized for their importance in sequestering and transforming land-based nutrients prior to reaching coastal waters."[165] By intercepting and sequestering nutrients, the Siltcatcher wetlands would reduce the overall nutrient budget available for suspended algae growth in other parts of the lake, potentially mitigating one of the more negative short-term impacts of increasingly frequent Spillway openings in Lake Pontchartrain.

- **Recreational and educational opportunities:** The Siltcatcher would create valuable recreation and education opportunities for residents of southeast Louisiana. The calm, protected area created on the leeward side of The Siltcatcher system would provide ideal conditions for canoeing and kayaking. The nearby wetlands would serve as nurseries and habitat, creating a haven for recreational fishing. The breakwaters could be designed at a size and scale to allow for access to structures via a complementary boardwalk system, providing the unique opportunity to see and experience a growing wetland up close. These accessible wetlands would also likely become excellent locations for birding and duck hunting. Access to the structures could be via boat from Frenier Landing, where increased visitor traffic would provide a boost to local business owners, or from Wetland Watchers Park, a park on Lake Pontchartrain at the end of the lower Bonnet Carré Spillway guide levee. The proposed system also presents value as a tool for education and public awareness. Due to its highly visible location near some of the most densely populated areas in the state, the Siltcatcher would be a flagship project for coastal restoration efforts in Louisiana, serving as a living demonstration laboratory for the deltaic land-building processes that built and sustained coastal Louisiana and the novel engineering approaches now being used to protect it. The

165. T. Elsey-Quirk et al., "Mississippi River Sediment Diversions and Coastal Wetland Sustainability: Synthesis of Responses to Freshwater, Sediment, and Nutrient Inputs," *Estuarine, Coastal and Shelf Science* 221 (May 31, 2019): 170–83, https://doi.org/10.1016/j.ecss.2019.03.002.

opportunities for research in and around the structures would be immense, driving collaboration between local universities, nonprofits, and stakeholder agencies. Similarly, stakeholder partnerships and education programs with local primary and secondary schools would help strengthen ties between local populations and coastal restoration efforts.

- **Responsive to climate change:** Openings of the Bonnet Carré Spillway are predicted to increase in frequency in a warming climate due to increased precipitation in the Mississippi watershed.[166] These more frequent openings will in turn provide larger volumes of sediment into Lake Pontchartrain than experienced in the 20th century. The Siltcatcher takes advantage of this phenomenon, converting a local byproduct of climate change into an asset. Assuming the relationship between the frequency of Bonnet Carré Spillway openings and a warming atmosphere remains constant, sediment inputs to the system would increase over time, allowing the system to be self-sustaining and self-organizing in the face of accelerating sea level rise.
- **Cost effectiveness:** A detailed cost analysis is outside of the scope of the present research. However, because rubble mound breakwaters are constructed of basic materials and generally rely on relatively simple and imprecise construction methods, their construction costs are relatively low. Furthermore, because the system is designed to grow over time, the cumulative value passively produced over decades would likely exceed initial construction costs. Over a long enough timescale, the primary building material for the project is a resource that is already present, freely available in large quantities, and assembles itself passively: sediment.

### Risks and Uncertainties

While the Siltcatcher concept offer many potential benefits, it is also subject to risks and uncertainties. Chief among these is the unpredictability of future Bonnet Carré Spillway openings. Without regular spillway openings and influxes of sediment, it is likely that not

166. Taylor, "Why Mississippi River and Atchafalaya River Flooding Is Likely to Happen More Often, Experts Say."

enough land-building would occur for wetlands to materialize. Alternative contingency plans could be made to prepare for this risk, such as thin-layer placement of dredge material, but because the concept ultimately depends on the spillway for large volumes of sediment, the uncertainty is essentially unavoidable. In this scenario, the structures would continue to provide shoreline stabilization and protection, however.

Another risk is the uncertainty of deposition and accretion patterns. Simply put, even with an ample supply of sediment from the spillway, the structures could fail to induce the desired sediment deposition if not properly designed. This research is intended to explore this uncertainty and provide suggestions as to how the system might be designed to maximize deposition. Sediment hydraulics and dynamics are extremely complicated and challenging to model with accuracy, however. Were this concept to be developed further, more rigorous qualitative modeling and design iteration would be needed to ensure adequate sediment capture and accretion. A related risk is the possibility that offshore structures may interfere with the operation and efficacy of the Bonnet Carré Spillway. As with the question of sediment deposition, this risk can be mitigated through judicious design and modeling of proposed alternatives.

There are also environmental risks associated with a project of this scale. Depending on the design and extent of the system, it could exert an influence on the exchange of fresh and brackish water and nutrients between the eastern and western ends of the lake, with the potential for both positive and negative impacts on nearby wetlands and sub-aquatic ecosystems. On one hand, if the system serves to reinforce the fresh-brackish west-east gradient, it could support restoration efforts in the Maurepas Swamp. On the other hand, if it impedes exchange of fresh and brackish water, it could lead to increased salinities in the western end of the lake, with negative repercussions for local flora and fauna. As with the previously mentioned risks, this uncertainty can be mitigated with both judicious design and with robust modeling and analysis of the proposed design.

Because it consists of large, heavily armored offshore structures, the Siltcatcher system would likely have temporary negative impacts on benthic ecosystems disturbed by construction. The long history of human activity in the lake, including significant dredging and excavation, somewhat mitigates this concern, however. Furthermore, any losses would likely be offset by new benthic and wetland habitat created by the system, especially if constructed using ecologically-friendly materials such as oyster shells, reef balls, and non-traditional cement mixes.

A final but not insignificant risk is the fact that this project, if successful, would transform a large portion of Lake Pontchartrain into emergent wetland, which may be a difficult or unacceptable proposition for some stakeholders. Community engagement is outside of the scope of this research, but its absence here should be construed as reflective of its importance. To the contrary: it is vital. Any project of this scale should only be constructed and implemented with extensive community involvement, support, and buy-in.

**Conclusion**

The Siltcatcher concept represents a novel approach to coastal restoration and wetland creation in southeast Louisiana which responds to the breadth of environmental issues facing the region, with multiple co-benefits. It is forward looking, taking into account future relative sea level rise and its implications for the region. It is informed by its history and context, making use of the same processes of deposition and accretion which led to the creation of the region 5,000 ago. Rather than starting from scratch, the proposal retrofits an existing piece of infrastructure (the Bonnet Carré Spillway) with a secondary intervention, amending its functional reach and capabilities for a new time and environmental context.

## V. Methods and Process: Hydrodynamic Modeling as Interdisciplinary Design Methodology

Early in the design process, hydrodynamic modeling was identified as an important tool for development of the Siltcatcher concept and for understanding and predicting the complicated flow scenarios it might induce.[167] Models–especially physical models–are also attractive as they can be powerful tools for communicating complex concepts to other disciplines, stakeholders, and the general public.[168] The Siltcatcher project presented an opportunity to explore the interdisciplinary potential of hydrodynamic modeling by incorporating its use into an iterative, non-linear design process typical of landscape architecture. [Fig. 36]

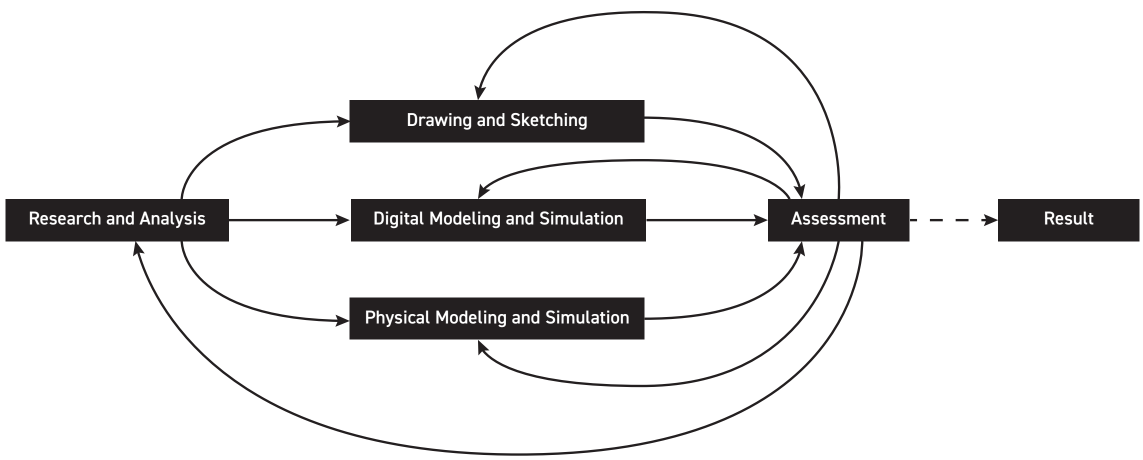



Figure 36. Conceptual diagram of the design process used to develop the Siltcatcher concept.

In the broadest sense, modeling can be described as the process of abstracting and simplifying some phenomenon or system for the purposes of making predictions and drawing inferences about that system. This notion is expressed and understood in different ways by dif-

167. Waldron, Ryan L. "Physical Modeling of Flow and Sediment Transport Using Distorted Scale Modeling." Master's Thesis, Louisiana State University, 2008, 4.

168. Physical models in particular "have a way of making complex phenomena clear to everyone from specialist researchers to community members, including regulating and managing organizations such as the EPA and USACE." See Sean Burkholder and Brian Davis, "Port Futures: Revaluing Rivermouths in the Great Lakes Basin," in *Fresh Water: Design Research for Inland Water Territories*, ed. Mary Pat McGuire and Jessica M. Henson (San Francisco: Applied Design + Research Publishing, 2019), 110.

ferent professions, but conceptually remains fundamentally the same across disciplines. Landscape architecture has inherited the study model tradition of architecture, and the production of *maquettes*, concept models, and presentation models remains a hallmark of the landscape architecture education process.[169] These models are primarily static and formalistic, used to explore, understand, and communicate design ideas in three-dimensional space (as opposed to a two-dimensional representation on paper). In recent decades, the adoption of programs such as SketchUp and Rhinoceros 3D have allowed designers to translate this process to three-dimensional digital models, while parametric tools such as Grasshopper have opened new possibilities for creating dynamic, algorithmically generated models and forms. Generally speaking, modeling techniques favored by landscape architects are primarily qualitative in nature and do not model dynamic properties of a site, such as vegetation growth, fluid flows, or sediment flux. Geospatial modeling using open-source GIS platforms such as GRASS GIS and QGIS can be used to fill these gaps, but their adoption among landscape architects remains low, likely due to lack of familiarity with the technology and its capabilities.[170]

Civil and coastal engineering methods, on the other hand, are deeply concerned with the dynamic properties of a system, and engage a range of modeling techniques to address this concern. Most basic among these are numerous equations and formulas that have been developed to quantitatively describe the physical behaviors of water, sediment, wind, heat, and pressure, among other materials and phenomena. These equations have been compiled into advanced computer-driven numerical modeling platforms such as HEC-RAS, ADCIRC, and Delft3D, which are used to simulate a wide range of coastal and riverine processes. These models offer quantitative precision, and are often inexpensive, as many platforms are open-source and freely available to download.[171]

169. See Nadia Amoroso, ed., *Representing Landscapes: Analogue* (Abingdon: Routledge, 2019), for examples. While some studios and firms are known for their use of process and presentation models, for the most part the academic emphasis on physical modeling does not carry over to the world of professional practice.

170. A 2019 survey of landscape architecture practices found that only 40% utilized GIS tools in their design process. See Benjamin H George and Peter Summerlin, "Get With the Program: Software and Technology Trends in Landscape Architecture," *Landscape Architecture Magazine*, November 2019.

171. Waldron, "Physical Modeling of Flow and Sediment Transport Using Distorted Scale Modeling," 3.

Despite their benefits, numerical models are not without limitations. User error, boundary effects, the quality of input data, and limitations on computing power can all reduce their effectiveness. For these reasons, scaled physical models are often used to model large, complicated systems.[172] In addition to the costs of design, construction, maintenance, and model operation, a key limitation to physical modeling is distortion introduced by scaling effects. It is often not possible to fully satisfy the complete range of requirements to achieve total similitude of every variable of a given system, meaning results and inferences derived from physical models are generally understood to be qualitative or semi-quantitative in nature, depending on the degree of similarity to the prototype system. Despite this limitation, physical models remain crucial to the simulation and study of complex systems. Because of the limitations of each approach, physical and numerical models are often used in tandem.[173]

As landscape architects have increasingly turned their attention to coastal infrastructure in recent years, some have begun to explore and embrace these tools which have conventionally been limited to engineering practice. SCAPE, in developing and implementing the Living Breakwaters project off the coast of Staten Island, embarked on an extensive modeling process using both digital and physical hydrodynamic models.[174] In 2017, researchers at MIT's Leventhal Center for Advanced Urbanism and Nepf Hydraulics Lab collaborated on an extensive study on the impact of wetland topography on the phytoremediation performance of urban stormwater wetlands, conducting flume and tracer dye tests of CNC routed models to better understand the relationship between residence time and basin topography.[175] Dredge Research Collaborative members Sean Burkholder and Brian Davis have employed physical modeling as both a

172. The Expanded Scale Physical Model of the Lower Mississippi River at the LSU Center for River Studies is an example of this approach.

173. Waldron, "Physical Modeling of Flow and Sediment Transport Using Distorted Scale Modeling," 3-4.

174. See SCAPE Team, "Living Breakwaters & Tottenville Shoreline Protection Project Elements," https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/Living%20Breakwaters%20Display.pdf, and Scott Baker et al., "Design and Physical Model Studies of Innovative Living Breakwaters," Coastal Engineering Proceedings, no. 36 (December 30, 2018): 59, https://doi.org/10.9753/icce.v36.papers.59.

175. Celina Balderas Guzmán, Heidi Nepf, and Alan M. Berger, "Design Guidelines for Urban Stormwater Wetlands" (Cambridge, MA: MIT, 2018), http://lcau.mit.edu/sites/lcau.mit.edu/files/attachments/project/Design%20Guidelines_Web%20Version.pdf.

design and communication tool in their work in the Great Lakes region.[176] Designers Guy Nordensen, Catherine Seavitt Nordenson, and Adam Yarinksy have used small-scale hydrodynamic models as "strategic and performative design tools" in the exploration of coastal resilience strategies, observing that "coastal resilience projects often dissolve the disciplinary boundaries between engineering, ecology, architecture, and landscape architecture."[177]

These examples demonstrate landscape architecture's growing interest in moving beyond conventional static architectural models in order to more rigorously engage with flows and change as design media. This is a necessary consequence of landscape architecture's embrace of coastal zones, water systems, and climate adaptation as areas of professional concern. Rivers, deltas, and shorelines are inherently dynamic; landscape architecture's conventional tools of modeling and representation are not. Dynamic modeling techniques transcend this limitation, allowing landscape architects to engage with these environments holistically and to participate in projects and addressing challenges that have historically been managed by engineers alone.

There are barriers to hydrodynamic modeling for landscape architects, however. Chief among these is the technical knowledge required for their use. Both numerical and physical modeling require an understanding of fluid mechanics and physics that most landscape architects do not possess. Physical models have the added limitations of cost and scale. To minimize scaling effects, physical hydrodynamic models are often constructed at very large scales, often requiring dedicated facilities and custom equipment for their storage and operation. As a result, constructing models at this scale is extremely costly and labor intensive.

In light of these limitations, modeling methods employed for the development of the Siltcatcher concept occupy a middle ground between small-scale architectural study models,

176. "Physical models have a way of making complex phenomena clear to everyone from specialist researchers to community members," they write. See Sean Burkholder and Brian Davis, "Port Futures: Revaluing Rivermouths in the Great Lakes Basin," in *Fresh Water: Design Research for Inland Water Territories*, ed. Mary Pat McGuire and Jessica M. Henson (San Francisco: Applied Design + Research Publishing, 2019), 106–15.

177. Catherine Seavitt Nordenson, Guy Nordenson, and Julia Chapman, *Structures of Coastal Resilience* (Washington: Island Press, 2018), 70-72.

technical numerical models, and large-scale physical hydrodynamic modeling. This approach employed sketching, parametric modeling, and open-source GIS tools for initial form finding and flow modeling. Physical hydrodynamic modeling was conducted using the Expanded Scale Physical Model (ESPM) of the lower Mississippi River at the LSU Center for River Studies, [Fig. 37] as well as a small-scale, "DIY" physical hydrodynamic model of the study area constructed specifically for this project. These modeling approaches were integrated into a recursive, non-linear design process that also employed conventional tools of landscape architectural practice such as field work, sketching, mapping, and image-making. This methodology demonstrates one way landscape architects might integrate hydrodynamic modeling into the design process, empowering them to engage with new sites, systems, and strategies in coastal environments.

Figure 37. The Expanded Scale Physical Model (ESPM) of the Mississippi River delta at the LSU Center for River Studies. Photograph by author.

**Sketching for Design Ideation and Development**

Sketching and drawing are fundamental tools for all design disciplines. Sketches were used throughout the Siltcatcher design process to quickly explore different design ideas and strategies, often serving as "first drafts" of ideas for later exploration, development, or modeling. This occurred prior to, during, and after the use of the other design tools described in this chapter. A collection of sketches produced at various points in the design process are included below. [Figs. 38-40]

**Physical Model Testing at the LSU Center for River Studies**

Initial hydrodynamic modeling took place concurrent with the development and digital modeling of parametric breakwater forms. On September 27 and October 2, 2019, a set of initial flow studies were conducted using the Expanded Scale Physical Model (ESPM) of the Mississippi River housed at the LSU Center for River Studies. The ESPM is a large physical hydrodynamic model built to study the impact of planned and proposed sediment diversions under different future sea level rise scenarios. The model encompasses a substantial portion of southeast Louisiana, including Lake Pontchartrain and the Bonnet Carré Spillway. It is constructed from panels of high-density foam which are carved individually with a CNC-router and then glued together. The model's horizontal scale factor is 1:6000, and its vertical scale factor is 1:400.[178]

The ESPM was designed to accurately model sediment flux within the Mississippi River channel. For this reason, scaling and model physics cannot be assumed to accurately reflect real world conditions once water escapes the main river channel. However, both the Bonnet Carré Spillway and Lake Pontchartrain are modeled with a high degree of accuracy from the same high-resolution LIDAR data used throughout the model. Given the model's scale, extents, frequency of operation, and accuracy, the ESPM served as an excellent tool for preliminary flow studies.

178. BCG Engineering & Consulting, Inc. "Expanded Scale Physical Model Design Memorandum." The State of Louisiana Coastal Protection and Restoration Authority, February 2017.

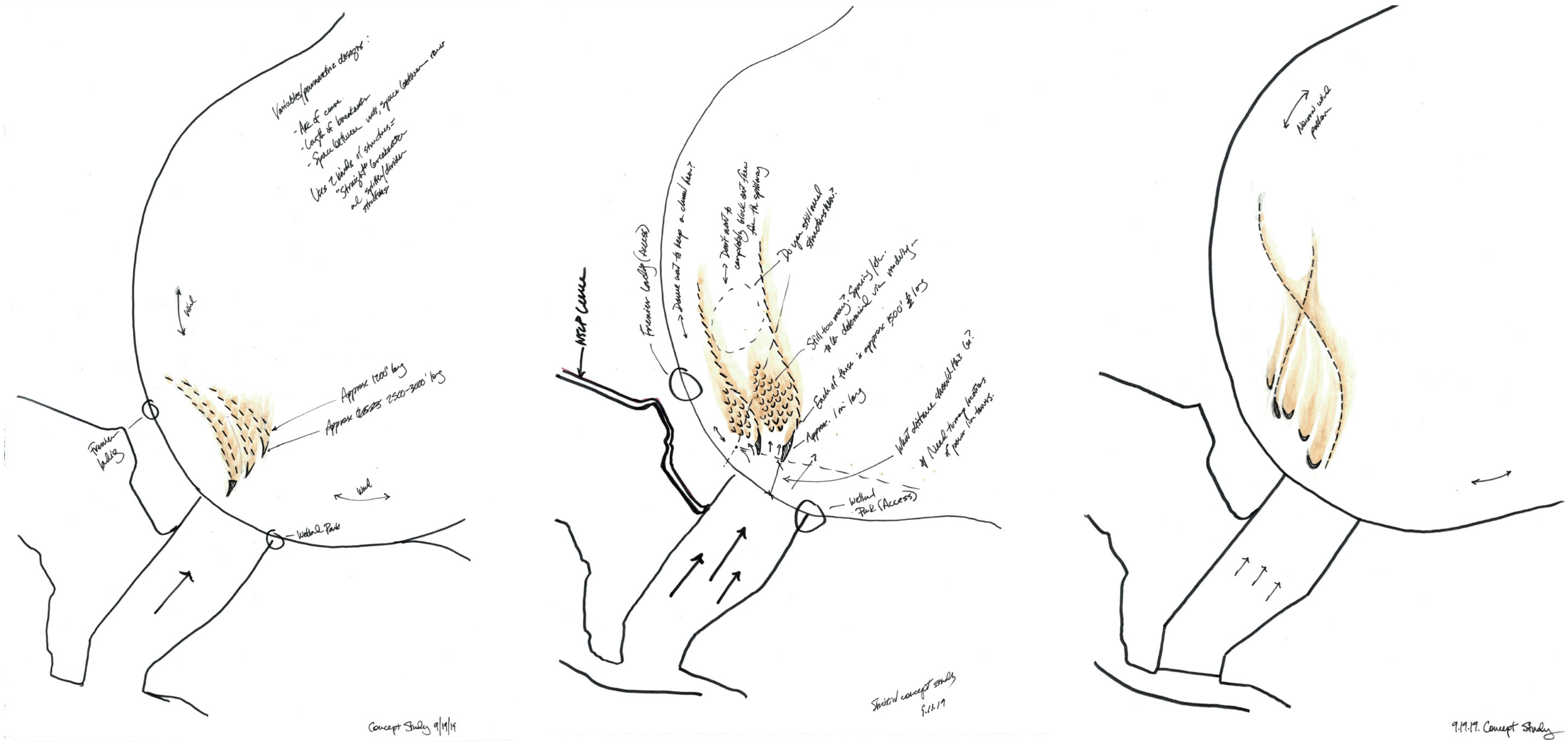



Figure 38. Initial planimetric Siltcatcher concept studies Felt tip markers on tracing paper.

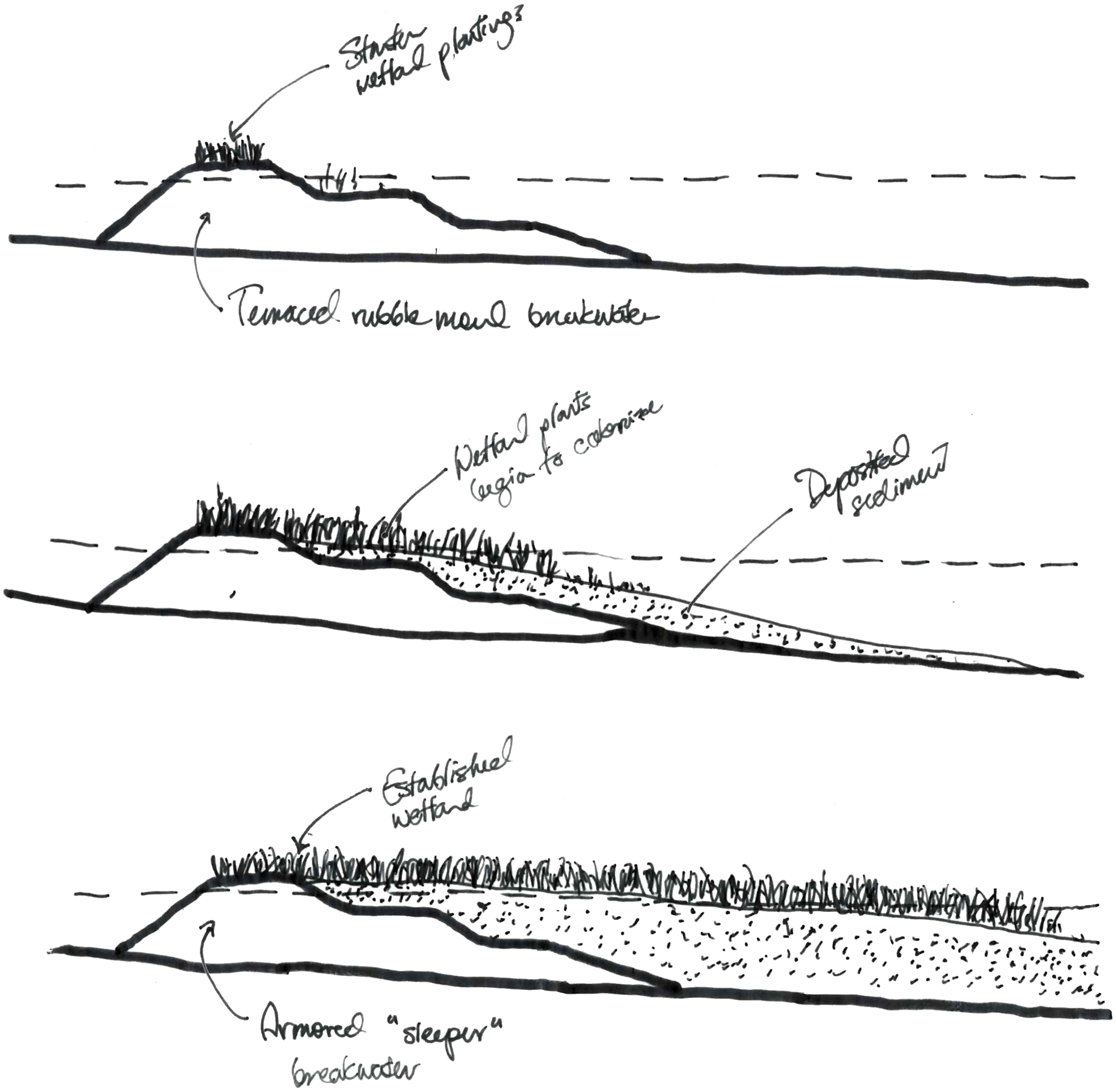



Figure 39. Initial study sections. Felt tip marker on tracing paper.

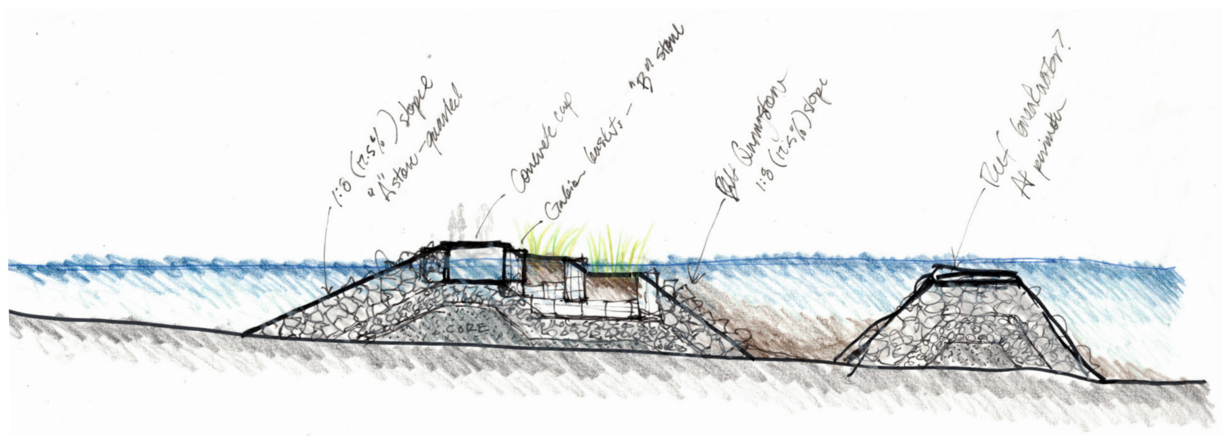


Figure 40. Study section. Colored pencil and felt tip marker on tracing paper.

The first visit to the CRS took place during a simulation of river year 2011, in which the Bonnet Carré Spillway was opened from May 9 to June 20.[179] Studies carried out on this visit were informal and used to develop a better understanding of model flow through the Spillway and flow interactions with in-lake structures. Model breakwaters were loosely modeled with clay and placed near the outfall of the Spillway to explore how different shapes and locations would interact with flow. These informal experiments were recorded to video using an iPhone.

The second visit on October 2 took place during model runs of river years 2018 and 2019, over which time Bonnet Carré Spillway was opened three times. The 2018 opening was recorded in its entirety using a tripod-mounted digital single-lens reflex (DSLR) camera as a "control," to capture model flow conditions into Lake Pontchartrain without any intervening structures. For the 2019 openings, a series of loosely modeled clay structures were placed into the lake. The shape and placement of these structures were one of multiple initial ideas previously sketched in planimetric view. The 2019 spillway openings and the resulting flow patterns were recorded using the same tripod-mounted DSLR and camera location used for the 2018 opening. [Fig. 41]

Initial flow studies on the ESPM yielded a number of findings that informed subsequent design research. First, study of flow through the Bonnet Carré Spillway revealed that flow velocities entering Lake Pontchartrain are higher in some locations than others due to topographic variations within the floodway. This heterogeneous flow pattern has important implications for the placement and orientation of potential flow-diverting structures. Second, these studies demonstrated the feasibility of diverting and redirecting the flow of water as it exits the spillway and enters Lake Pontchartrain through the strategic placement of offshore structures. The flow pattern created by the placement of structures during the 2019 model run demonstrated a clear "bending" and deceleration as the spillway outfall interacted with the structures. This confirmed that flow exiting the spillway and the resulting depositional

179. "Bonnet Carré Spillway" (US Army Corps of Engineers, New Orleans District, December 2018), MVN PAM 360-1-5, https://www.mvn.usace.army.mil/Portals/56/docs/Recreation/BCS/Brochures/BC%20spillway%20booklet%20Dec%202018%20.pdf.

Figure 41. Preliminary modeling at the LSU Center for River Studies Expanded Scale Physical Model (ESPM).

patterns can be manipulated and redirected to satisfy specific design goals. Third, the visits demonstrated the value of tangible physical modeling as a design tool and underscored the importance of constructing a scaled-down hydrodynamic model for more rapid, iterative testing of design ideas and configurations, a process that began shortly after these initial tests at the Center for River Studies.

**Parametric Form Finding and Digital Flume Modeling with GRASS GIS**

Conventional breakwaters are generally assumed to be straight, with cross-sectional considerations such as slope and height determined by input parameters such as the design wave height, substrate, and acceptable level of overtopping.[180] For the Siltcatcher concept, form assumes a greater importance, as different shapes and configurations could have dramatically different impacts on scour and deposition patterns. While the conventional breakwater may be perfectly suited to the task of stopping large waves in their tracks, it cannot be assumed to also present the most suitable form for the goal of capturing sediment. In fact, it

180. Robert M. Sorensen, Basic Coastal Engineering (New York: Chapman & Hall, 1997), 206-215

is reasonable to assume that the opposite is true, and there exists an alternate form or set of forms more conducive to sediment deposition.

The study of the complicated interactions between fluid flow and in-channel objects often take places in fluid mechanics laboratories with large-scale recirculating flumes, which allow researchers to simulate a wide variety of generic in-channel conditions in a controlled environment. With the right resources and enough time, such a laboratory would be the ideal venue in which to explore these questions.[181] With no such facility available, however, an alternative process was developed using digital tools commonly used in landscape architecture: parametric modeling and open-source GIS.

Parametric modeling is an approach to digital 3D modeling uniquely suited to the rapid production of a large number of variations of a basic geometry. In parametric modeling, geometry is generated algorithmically from an initial set of input parameters (for example, height or length). These parameters and the form-generating algorithm are then adjusted and manipulated, allowing the designer to quickly create an array of variations based on different parameter input. Open Source GIS refers to a set of freely available geographic information system tools, including QGIS[182] and GRASS GIS[183], which are commonly used for processing, modeling, and visualizing spatial data. In this case, GRASS GIS was used for its unique overland flow and sediment modeling capabilities. These tools allowed for the creation of a rudimentary "digital flume" to gain insights as to what impact different formal variations might have on resulting channel flow patterns. Furthermore, this process enabled the design and testing work to occur within a relatively short time frame.

First, a basic family of forms was developed for testing through hand sketching. [Fig. 42] Simple forms were used so the impact of specific variations and geometries could be bet-

181. For an example of how these tools of fluid mechanics might be used in a landscape architectural context, see Celina Balderas Guzmán, Heidi Nepf, and Alan M. Berger, "Design Guidelines for Urban Stormwater Wetlands" (Cambridge, MA: MIT, 2018).

182. QGIS Development Team, *QGIS Geographic Information System*, version 3.10, macOS (Open Source Geospatial Foundation, 2019), http://qgis.osgeo.org.

183. GRASS Development Team, *Geographic Resources Analysis Support System (GRASS)*, version 7.6, macOS (Open Source Geospatial Foundation, 2019), https://grass.osgeo.org.


Figure 42. Basic forms developed for digital modeling in Grasshopper and GRASS GIS.

ter understood. Three-dimensional models of these breakwaters were then modeled in Rhinoceros 3D (Rhino) [184] using Grasshopper, Rhino's built-in parametric modeling tool. The use of Grasshopper allowed for the rapid generation of variations from these basic forms using multiple variables for each shape. [Table 2] Multiple values were selected for each variable, and each value was modeled in isolation, with the other variables set to a control value, resulting in the creation of a total of seventy-two breakwater variations. A control geometry was created for each base geometry, as was an overall control consisting of a small, circular landform.

Table 2. Digital Breakwater Test Parameters

| Form | Straight | Curved | Chevron | Triangle | Square |
|---|---|---|---|---|---|
| **Variables** | Length | Width | Width | Segment Length | Segment Length |
| | Width | Front Slope | Slope | Slope | Slope |
| | Front Slope | Back Slope | Rotation Angle | Rotation Angle | Rotation Angle |
| | Back Slope | Rotation Angle | Bend Angle Depth | Curve Depth | Curve Depth |
| | Side Slope | Curve Depth | Bend Angle Alignment | | |
| | Rotation Angle | Curve Alignment | | | |
| | | Curve Depth | | | |

A point-cloud was generated in Grasshopper for each modeled breakwater surface, which were then "baked" into Rhino and exported as a .xyz text files. These .xyz files were then used to create raster elevation surfaces in GRASS GIS. Using the GRASS GIS graphical modeling tool, a script was written to import a given .xyz file, place the resulting breakwater on a

184. *Rhinoceros Version 6*, macOS, Robert McNeel and Associates, 2019.

sloped digital surface, and run the flow and erosion models r.sim.water and r.sim.sediment, resulting in two-dimensional flow, depth, erosion/deposition, sediment transport, and sediment flux maps.

Once the simulations were complete, the GRASS GIS univariate statistic module r.univar was used to calculate mean and sum values for the resulting erosion-deposition raster maps. These values were compiled in a spreadsheet and used to identify optimal parameters for each variable tested. These parameters were then used to model an optimal version of each basic geometry. Because this study is comparative, the parameters were also indexed against the mean of all results, as well as against the conventional straight breakwater design.[185]

This process does not provide an exact digital "replica" of a laboratory flume test due to the particularities of the GRASS GIS r.sim.water and r.sim.sediment modules, which were developed to simulate overland flow initiated by precipitation events (that is, rainfall) at a site to landscape scale. Unlike a laboratory flume, with a specified inlet, outlet, depth, and flow velocity, r.sim.water initiates flow by simulating a rainfall event of a user-defined intensity and duration, "flooding" the model surface. Furthermore, because the model is precipitation based, water entering the system is assumed to contain no sediment, and therefore any deposition patterns observed in the model results consist of sediment originating elsewhere on the model surface. This is substantially dissimilar to conditions within Lake Pontchartrain at the outfall of the Bonnet Carré Spillway. Despite these considerable limitations, these models are still helpful for visualizing flow patterns and understanding points of scour resulting from different forms, especially given that the primary modeling objective was to gain comparative insights into the different breakwater forms. However, these considerations do limit the conclusions that can be drawn from this methodology, and warrant the use of additional modeling using other tools and techniques.

185.See Chapter V for the results of this exercise.

### DIY Physical Hydrodynamic Modeling

After initial studies on the Expanded Scale Physical Model at the LSU Center for River Studies, work began on the design and fabrication of a custom physical hydrodynamic model of the Bonnet Carré Spillway and West Lake Pontchartrain Region for rapid design ideation and exploration. The model consists of a 4' x 4' sheet of high-density urethane (HDU) foam milled using a computer numerically controlled (CNC) router to create an accurately scaled topobathymetric model of the study region. The model is supported by a custom-designed table which supports the model at a comfortable working height and allows for the flow of water across its surface.[186] The model surface and the supporting table were constructed using resources available at the LSU College of Art and Design FabLab and Design Shop. [187]

### Model Surface Fabrication

The physical model surface was fabricated over December 10-12, 2019. The router's operable extent is 4' wide by 8' long, placing a limitation on the total size of the model. Model size was also limited by the difficulty of transport, assembly, and operation and the cost of materials. For these reasons, the model surface was scaled to 4' x 4'. This extent dictated horizontal and vertical scale factors, as well as dynamic scale factors. For a detailed explanation of hydrodynamic model scaling using Froude similitude criteria, see Appendix A.

Elevation and bathymetry data for Lake Pontchartrain and the Bonnet Carré Spillway at 3 meter resolution were obtained from NOAA via the NOAA Digital Coast repository.[188] These data were downloaded as two separate tiles which were stitched together using the Merge Raster tool in QGIS 3.8. The resulting raster was imported to GRASS GIS, where a subset of the region was selected for the model surface using the g.region tools. From there, a number of further modifications were made to prepare the surface for fabrication, taking into account

186. Plans and drawings for the model table are included in Appendix X.

187. For those in academia interesting in creating their own small-scale hydrodynamic model, most universities have similar equipment and facilities. These tools are also often available through independent "maker spaces," which require membership.

188. OCM Partners, "Topobathymetric Model of the Northern Gulf of Mexico, 1888 to 2013 | ID: 49465 | InPort," accessed September 24, 2019, https://inport.nmfs.noaa.gov/inport/item/49465.

the effects of vertical distortion, the properties of high-density sign foam, the final resolution achievable by the router, assembly of the model table, and model operations.

- To reduce noise and artifacts from LiDAR acquisition, the model surface was smoothed using the r.neighbors module in GRASS GIS.
- A primary concern was the structural stability of levees, which would be too thin for fabrication with the CNC router if left at their actual dimensions due to the effects of vertical distortion. To address this and ensure their structural stability on the routed model, levee widths on the base surface were exaggerated.[189] To accomplish this, levee centerlines were digitized in QGIS 3.8 using the shapefile creation tools and referencing the base topobathymetry to confirm correct levee alignments. The centerline was then offset twice, once with a distance of 125 feet for the top of the levees (250 foot total width) and 185 feet for the base of the levees (370 foot total width). These offsets were created with the vector buffer tool in QGIS 3.8 with the "dissolve" option selected to create closed offsets. The resulting polygons were imported into GRASS GIS and converted to raster layers using the v.to.rast module, with the top of the levees set to 20 feet and the bottom set to 0 feet. The resulting raster layers were then patched together using r.mapcalc and smoothed using r.neighbors to create the levee side slopes. Finally, the new levees were patched onto the base raster topobathymetry using r.mapcalc.
- A space was delineated for the later addition of a headbox on the river-side of the Bonnet Carré to supply water for the operation of the model. This space was delineated using the vector digitizer in QGIS 3.8. The resulting shapefile was then imported in GRASS GIS, converted to a raster elevation file with a elevation of 13.00 NAVD88[190], and patched into the base topobathymetry raster using the raster calculator, r.mapcalc

189. Modelers made a similar decision in the preparation of LiDAR data for the fabrication of the ESPM. See Draft ESPM Design Memo, BCG Engineering & Consulting, Inc., "Expanded Scale Physical Model Design Memorandum" (The State of Louisiana Coastal Protection and Restoration Authority, February 2017), Chapter 17.

190. This is the same height used for the BCS weir on the ESPM at the LSU Center for River Studies.

module. This area would later be manually removed from the routed model using a coping saw, with the remaining void space used to couple a plexiglass headbox to the model.

- A small portion of the Mississippi River was captured in the subset of the map selected for the study region. Similar to the headbox location, this area was delineated using the vector digitizer in QGIS, imported into GRASS GIS, and merged with the surface using r.mapcalc. This area was set to +0.08 feet above NAVD88, the mean tide elevation of Lake Pontchartrain.[191] This was set as a reference height for the fabrication of a set of plexiglass boundary weirs, which would be used to control water level in the lake. This also had the effect of removing the extremely low elevations at the bottom of the river, which would have extended beyond the depth of the 2" thick blank stock of high-density sign foam.
- Any remaining extreme low or high elevations (less than -50' or greater than +20') were removed using r.mapcalc.

The 3D model surface for CNC routing was generated using Rhinoceros 5 (Rhino) and RhinoTerrain, a 3rd-party plugin for Rhino which specializes in the creation of terrain models. The edited topobathymetry raster layer was exported from GRASS GIS to a GeoTIFF file using the r.out.gdal command at a spatial resolution of 40 feet. This raster was then imported to Rhino using the RhinoTerrain "Import Elevation Raster" tool. The raster was first imported as a mesh, then scaled down to the final model size using the Scale1D and Scale2D commands. Using this mesh a as reference, a 4' x 4' final model region was delineated. This model region was then scaled up to real-world dimensions using Scale2D. The elevation raster was re-imported as a point cloud, which was then clipped using the scaled-up model region boundary and used to generate a triangulated mesh. This clipped mesh was then scaled down to model-scale using the Scale1D and Scale2D commands, resulting in a 4' x 4' terrain mesh at the desired horizontal and vertical scales.

191. "Tidal Elevation," NOAA National Geodetic Survey, https://www.ngs.noaa.gov/Tidal_Elevation/diagram.xhtml?PID=BJ1342&EPOCH=1983-2001.

A small test region was extracted from the full model for test routing. The results of this test confirmed the integrity of the thickened levees, however the time to complete the small test piece was nearly 3 hours. To address the time of fabrication, the full model terrain mesh was smoothed in Rhino using the RhinoTerrain Mesh Denoise command, which removed minor surface noise and reduced the amount of z-axis movement required for the CNC router.

CNC tool paths were generated using RhinoCAM, a 3rd party digital fabrication plugin for Rhino. Two operations were specified for the final model: a parallel roughing cut using a 1/4" ball-end upcut drill bit and a parallel finishing cut using a 1/8" ball-end upcut bit. Due to the size and detail of the model, the 1/8" parallel finishing cut was broken down into 5 separate tool paths. In all, the fabrication of the model surface required approximately 12 hours of cutting time, not including time spent on elevation raster processing and tool path generation. [Fig. 43]

**Model Table Design and Fabrication**

Design for the model table and water circulation system took place concurrent with the preparation and fabrication of the model surface. Designs for the table were sketched and then modeled using Rhino3D. The table consists of a frame constructed from 2" x 4" cedar stock and supported by legs created from 4" x 4" cedar posts.[192] The interior of the 2" x 4" frame features rabbets which support plywood cross members. Together, these components host the model table and the plexiglass weirs which maintain water levels in the model lake. A plywood shelf extends from the southern end of the model surface, providing a working surface as well as supporting the headbox.

Water circulation is managed via a home aquarium pump, aquarium tubing, 15-gallon galvanized metal tubs, and a custom fabricated plexiglass headbox. [Fig. 44] Water is first

192. Cedar was selected for its availability at local hardware stores, its durability and rot-resistance, and its light weight. Weight was an especially important concern given the anticipated need to disassemble and move the model. Lightweight metal such as aluminum have been an ideal material for this purpose, but was ruled out due to the difficulty of fabrication and the author's lack of metalworking experience. Those with such experience and the requisite facilities may find a metal table to be more appropriate for their needs. However, this example demonstrates that it is possible to construct such a system out of wood without an inordinate amount of difficulty.

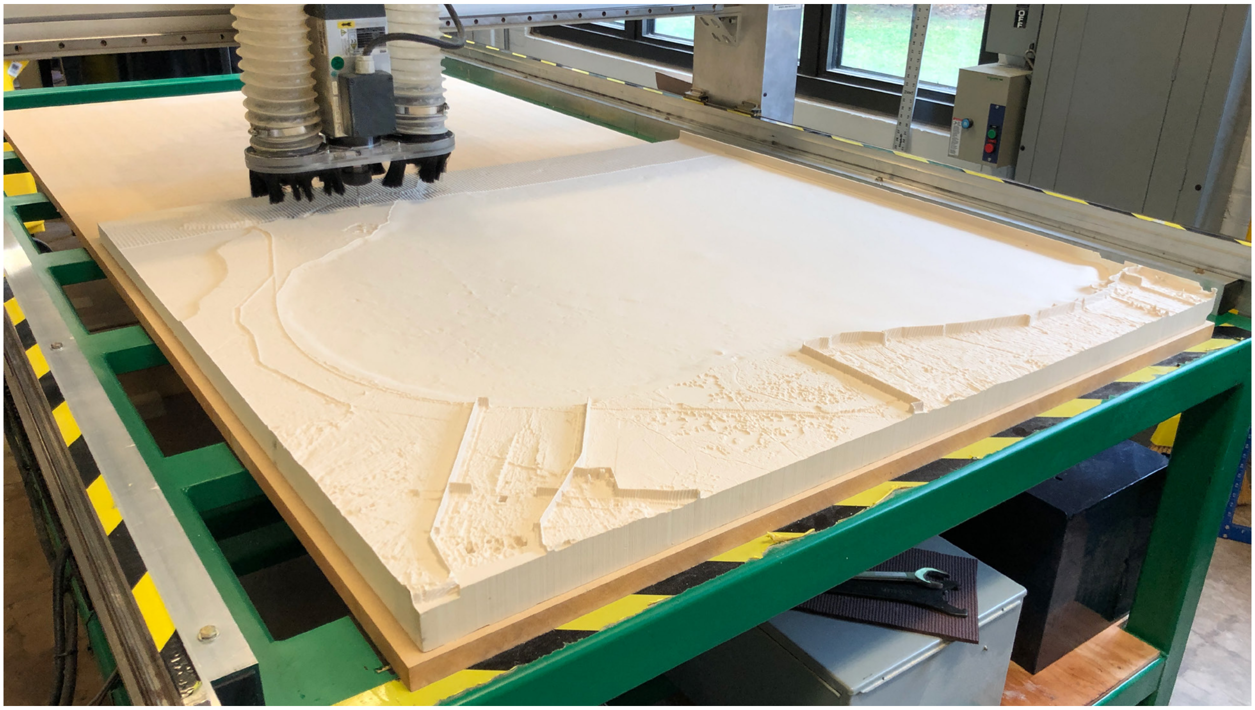


Figure 43. Routing the model surface using the CNC Router in the LSU College of Art and Design Fabrication Factory.

pumped into the headbox from a 15-gallon tub. The headbox is coupled to the model surface at the location of the Bonnet Carré Spillway structure and has an overflow set to the height of the BCS weir at model scale, allowing water to overflow the weir and enter the Bonnet Carré Floodway, ultimately flowing into Lake Pontchartrain. The water level of Lake Pontchartrain is maintained by a plexiglass weir at the edge of the model set to mean tide level. As water enters the lake from the spillway, a corresponding volume overflows these weirs into gutters routed into the top of the table side pieces using a CNC router. The gutters drain to small drainage holes which empty into a receiving 15-gallon tub placed beneath the table.

The total cost of the model table was $358.[193] [Table 3] The most expensive material in the model, high density urethane (HDU) sign foam, was available through the LSU College of Art and Design Fabrication Lab and purchased with Student Technology Fee funds, and therefore was not included in the final budget. With the estimated cost of the HDU foam, the total budget comes to approximately $708 dollars. The model took approximately two months to design and

193. The model was funded in part through generous support from the LSU Faculty Research Grant "Robots in Nature."

construct (from early December 2019 to early February 2020). Construction was delayed by holiday facility closures and unrelated equipment failures. Without those limitations, a quicker fabrication time would likely have been possible.

Table 3. Model Materials List and Costs

| **Material** | **Quantity** | **Cost Per Unit** | **Total Cost** |
|---|---|---|---|
| 48" x 48" x 2" HDU Foam Board | 1 | ($350) | ($350) |
| 4" x 4" x 16' western red cedar stock | 1 | $59 | $59 |
| 2" x 4" x 16' western red cedar stock | 2 | $25.50 | $51 |
| 48" x 96" x 0.4" Luaun Plywood | 1 | $26 | $26 |
| 28" x 48" x ¼" cast acrylic (plexiglass) | 1 | $55 | $55 |
| 12" x 24" x 1/16" cast acrylic (plexiglass) | 1 | $12 | $12 |
| Aquarium Pump | 1 | $9 | $9 |
| 16 gallon galvanized steel tubs | 2 | $36 | $72 |
| Leveling Feet (Set of 4) | 1 | $16 | $16 |
| 1 Quart Spar Urethane Finish | 1 | $18 | $18 |
| Appliance Epoxy (Spray Can) | 5 | $4 | $20 |
| Miscellaneous Hardware | -- | -- | $20 |
| **Total** | | | **$358** |
| Total including HDU Foam Board | | | $708 |

While resource intensive, the model proved to be an invaluable design tool. It provides the unique ability to quickly test and iterate on design ideas, as well as communicate design intent. Thanks to advances in digital fabrication, it is possible to construct such a model on a one-off DIY basis, allowing landscape architects to integrate hydrodynamic modeling into their design process, as opposed to vying for rare opportunities to work with costly, generalized large-scale models maintained by universities and government agencies. As landscape architects increasingly seek to engage with questions relating to coastal infrastructure, sea level rise, and water systems, such small-scale models have the potential to become an important part of the conceptual design process.

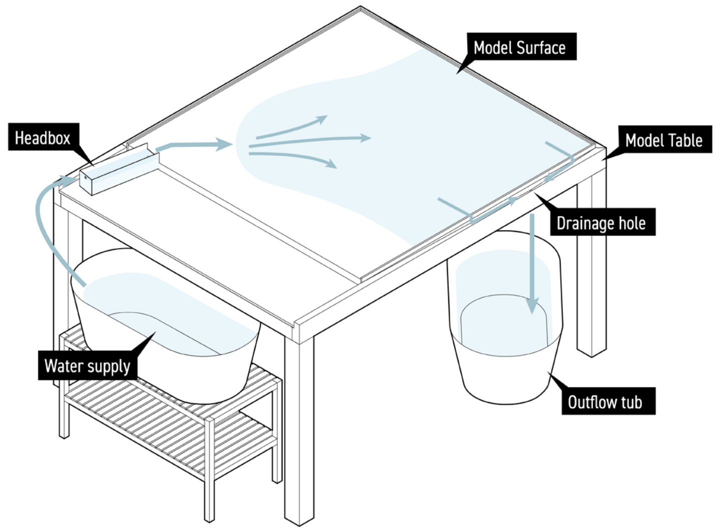



Figure 44. Illustration of the small-scale Siltcatcher model.

**Physical Model Operations**

Physical modeling took place in February and early March of 2020, and was used to quickly explore and test different breakwater configurations and their impact on water flowing from the Bonnet Carré Spillway. Flow was visualized using fluorescent tracer dye, which approximates the behavior of fine-grained sediment and can be used to make inferences about patterns of silt and clay dispersal and deposition.[194] Simulations were recorded using a DSLR camera mounted on a c-stand, providing footage and time-lapse imagery for later analysis.

Modeling began with a control simulation with no structures present in the lake. In subsequent simulations, basic structure configurations developed through sketching were modeled in polymer clay. These configurations were edited and altered from run to run based

194. Models developed by CPRA use a fine-grained plastic particle to model coarse sediment transport and deposition (i.e. sand). However, more than 70% of the sediment transported by the Mississippi River consists of fine silts and clays which cannot accurately be modeled at small scales. Furthermore, the majority of heavy sand particles entrained by the river travel in the "bedload" at the bottom of the channel, whereas the Bonnet Carré Spillway receives water from the uppermost layer of the river. Therefore, the primary materials introduced into Lake Pontchartrain from Spillway openings are fine silts and clays (hence the title of the project). For more on the use of tracer dye to visualize flow and model fine sediment transport, see Brown Cunningham Gannuch, Coastal Restoration Consultants, and Louisiana State University, "Report on Feasibility Of Small Scale Physical Model of the Lower Mississippi River Delta for Testing Water and Sediment Diversion Projects," 2004, 8, and Ashish Mehta, *An Introduction To Hydraulics of Fine Sediment Transport,* vol. 38, Advanced Series on Ocean Engineering (Singapore: World Scientific, 2013): 32.

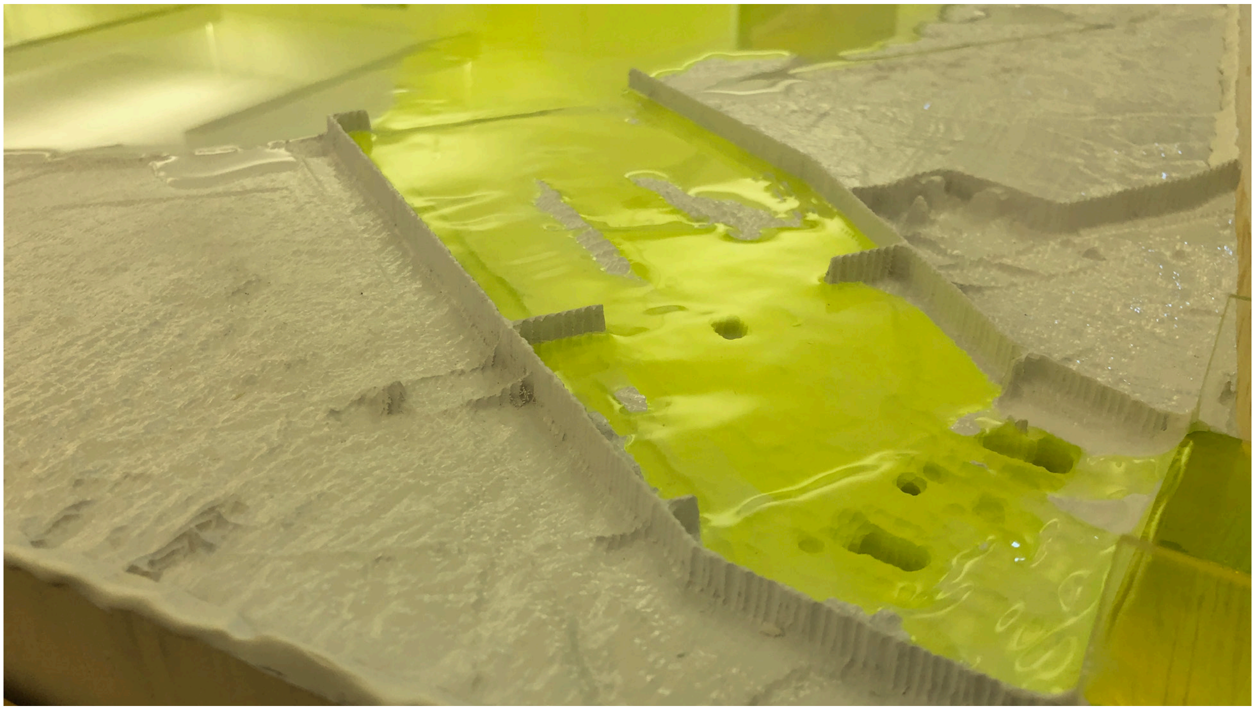


Figure 45. Water with tracer dye flowing over the model floodway and into Lake Pontchartrain.

on visual feedback and observations from previous simulations, resulting in an iterative design process based on real-time feedback provided by the model. A total of seventeen initial configurations and three subsequent composite configurations were modeled. For these tests, flow was introduced into the system at a rate of approximately 1 liter per minute, which corresponds to approximately 200,000 cubic feet per second at real-world scale.[195] [Fig. 45]

195. See Appendix A.

## VI. Results

### Digital Flume Modeling with GRASS GIS

The GRASS GIS modules r.sim.water and r.sim.sediment were used to test flow, scour, and deposition patterns induced by seventy-two breakwater variations derived from five different basic geometries: straight, curved, chevron, triangle, and square. [Fig. 46] (See Chapter IV for details on the form finding process and evaluation methodology). The best performing structures were the curved, triangle, and chevron breakwaters, which induced minimal scour. [Fig 47] All featured curving geometries or bends which pointed into the direction of flow. The variations that performed worst were those which presented a straight or concave surface perpendicular to the direction of flow, such as the square and straight breakwaters. These geometries resulted in deep scour pits at the toe of the breakwater facing the flow.

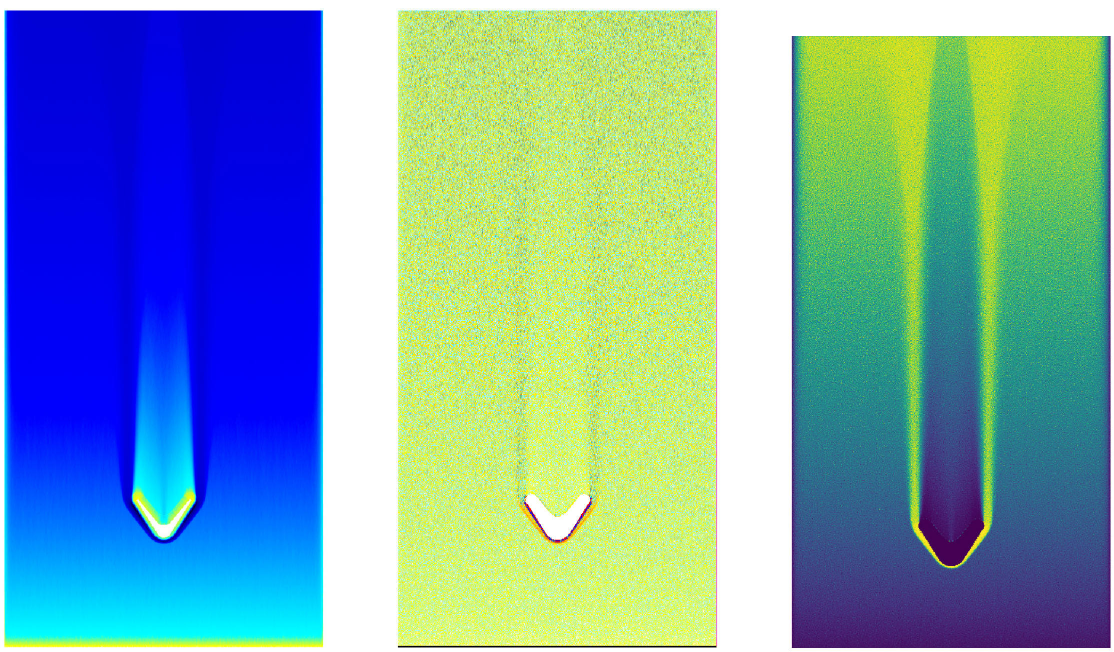


Figure 46. Example of GRASS GIS r.sim.water results.

Breakwater side slope was a key variable across all configurations. Gentle side slopes generated reduced scour and better overall performance across all configurations, and nearly all of the optimal geometries have slopes gentler than typically used for rubble mound breakwaters. Gentler slopes have the added advantage of providing more benthic and intertidal

surface area on the structure for recruitment of marine life and minimizing the height of wave runup. [See Appendix B for complete results]

After initial modeling, a set of optimal geometries was made by combining the highest performing values for each parameter. [Table 4] All five of these optimal geometries outperformed the circular shape used as a control structure [Table 5]

Table 4. Optimal breakwater form parameters.

| | | | | | |
|---|---|---|---|---|---|
| **Crest length** | 500 | N/A | N/A | 500 | 500 |
| **Crest width** | 5 | 5 | 250 | 5 | 5 |
| **Slopes** | 1:3 front<br>1:8 back | 1:8 front<br>1:20 back | 1:8 | 1:8 | 33% front<br>12.5% back |
| **Rotation Angle** | 60º | 60º | 60º | 60º | 60º |
| **Depth of Curve** | N/A | 1000 | 1000 | N/A | N/A |
| **Curve location (x axis)** | N/A | 0 (center) | 0 (center) | N/A | N/A |

Table 5. Optimal form simulation results.

| Geometry | Mean resulting erosion/deposition (Indexed against straight breakwater) |
|---|---|
| Circle (control) | 0.573 |
| Straight | 0.598 |
| Curved | 0.707 |
| Chevron | 0.660 |
| Triangle | 0.713 |
| Square | 0.621 |

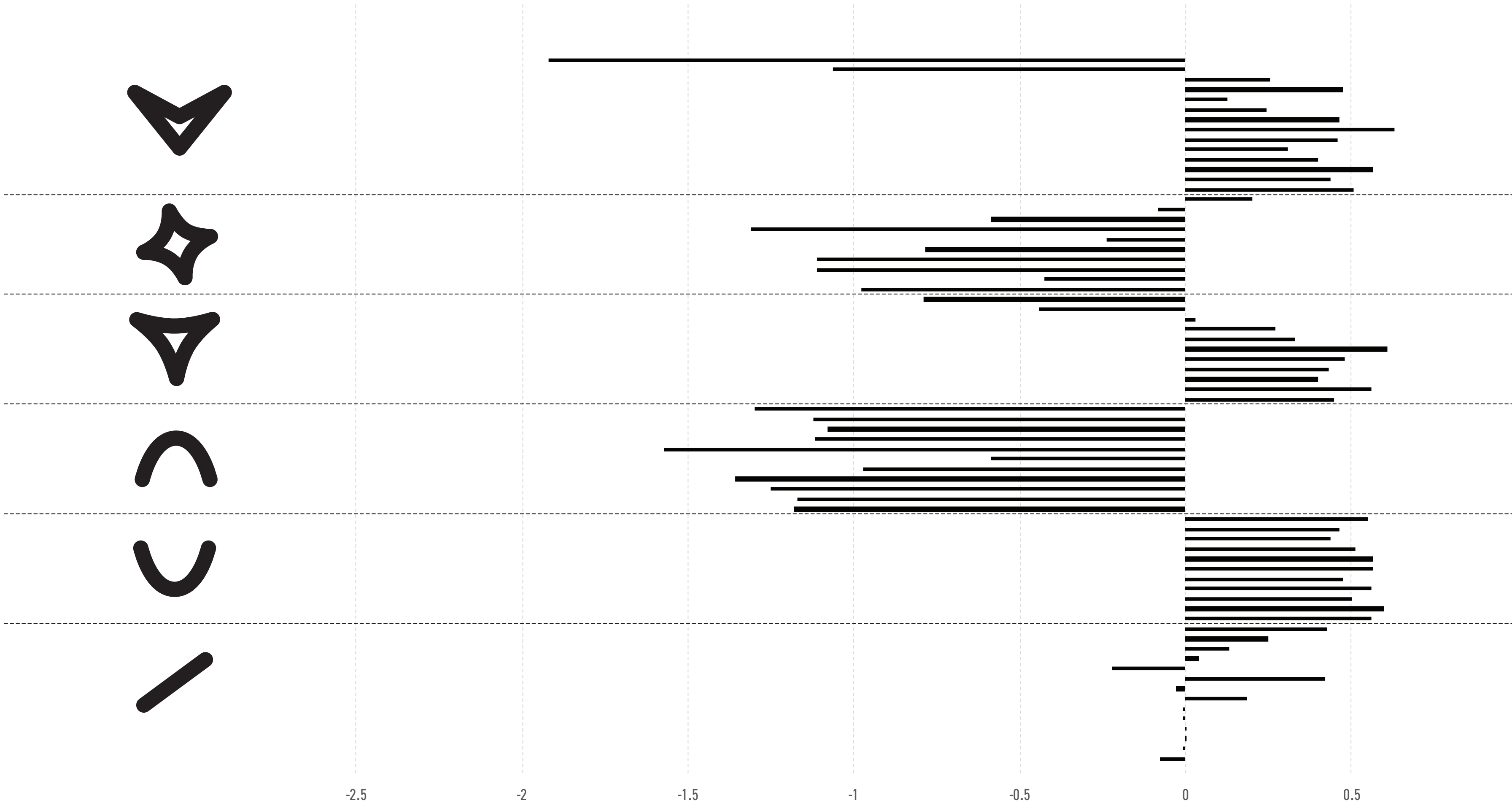



Figure 47. Summary of results from digital modeling tests in GRASS GIS.

From these results, the following general conclusions could be made regarding the tested design parameters:

- Gentle slopes facing the direction of flow reduce scour, whereas steeper slopes induce scour. Slope on the leeward side (facing away from the flow) appears to have no impact on scour.
- Geometries with curves and bends facing the direction of flow result in less scour. Curve placement and depth is somewhat flexible, although deep, centrally aligned bend points performed best.
- Curves and rotation angles resulting in straight or concave geometries perpendicular to the direction of flow will lead to heavy scour at the toe of the structure, whereas those that result in faces tangential or parallel to oncoming flow will result in less scour.
- Smaller geometries performed better than larger ones, and narrower crest widths result in less scour across all tests. However, scour was not normalized for structure area or volume, meaning these results are likely due to the fact that larger structures simply create more area for scour to take place.

In summary, the results of these tests indicate breakwaters which bend or point in the direction of the flow source will result in less overall scour, especially when combined with gentle side slopes. Conversely, structures that present broad faces perpendicular to the direction of flow will produce large amounts of scour and erosion at the toe of the structure. These conclusions served as useful rules-of-thumb which guided and directed future design explorations and decisions.

**DIY Physical Hydrodynamic Modeling**

A total of seventeen initial configurations and three composite configurations were tested on the model table. {Fig. 48} All configurations successfully diverted a portion of flow into the western end of Lake Pontchartrain as compared to the control run, suggesting there is broad room to optimize structure placement depending on desired quantity and location

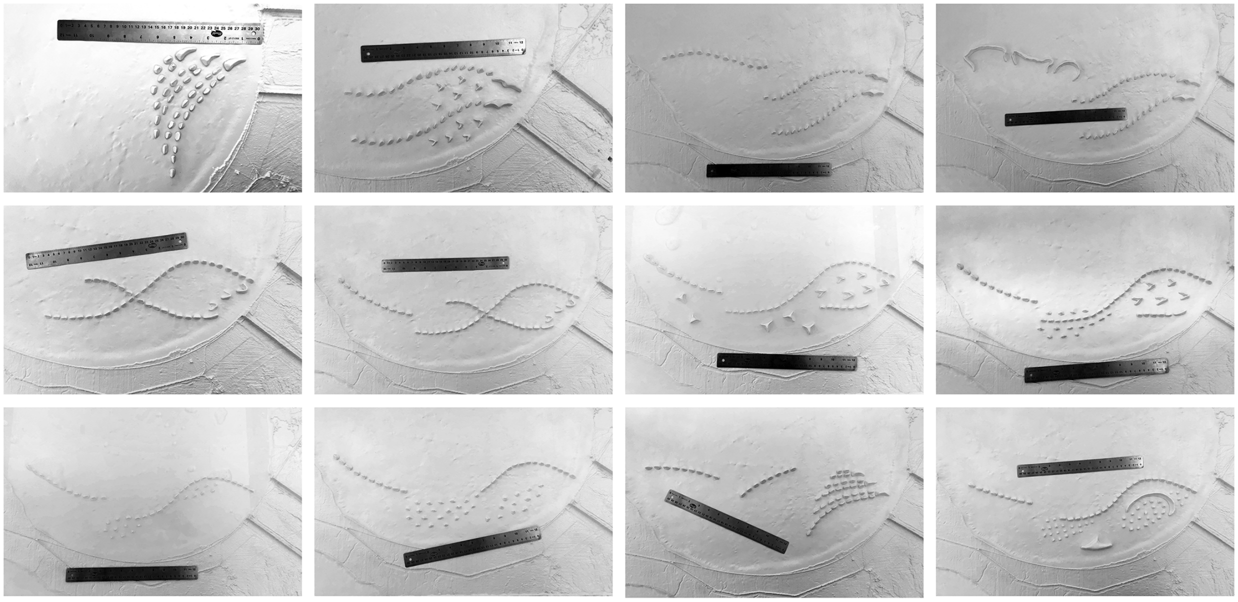


Figure 48. Photos of various configurations texted on the physical model.

of sediment deposition. [Fig. 49] In order to arrive at an optimized configuration, simulation videos and time-series grids of the initial configurations were compared and analyzed for perceived effectiveness at slowing and concentrating flow. With these criteria, three of the seventeen initial configurations were identified as demonstrating highest performance. [Fig. 50] Time-stamped video-stills from these model runs were layered with 20% opacity in Adobe Photoshop, creating composite base images which were used to diagram potential flow and deposition patterns. [Fig. 51]

These diagramming studies provided a clearer understanding of the flow patterns induced by different structure configurations and placements. Subsequent composite design ideas emerged from these studies, [Fig. 52] which were then modeled, tested, recorded, analyzed, and diagrammed in the same manner as the initial configurations. [Fig. 53-56]

(Continued on page 97.)

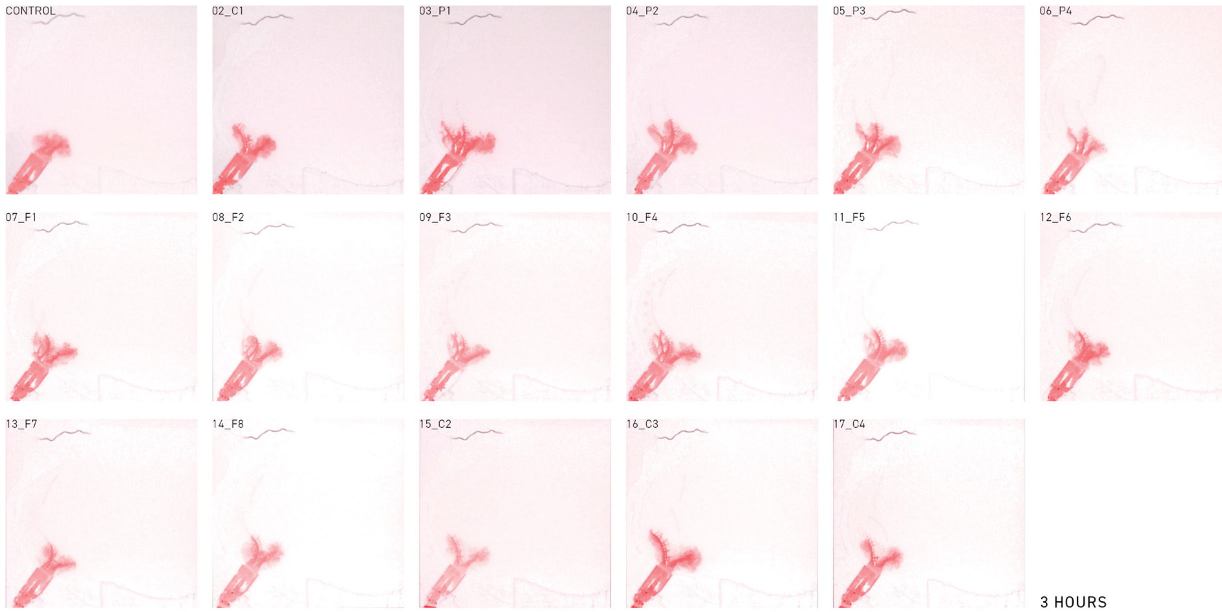



Figure 49a. Initial physical model simulations, 3 hours at model scale.

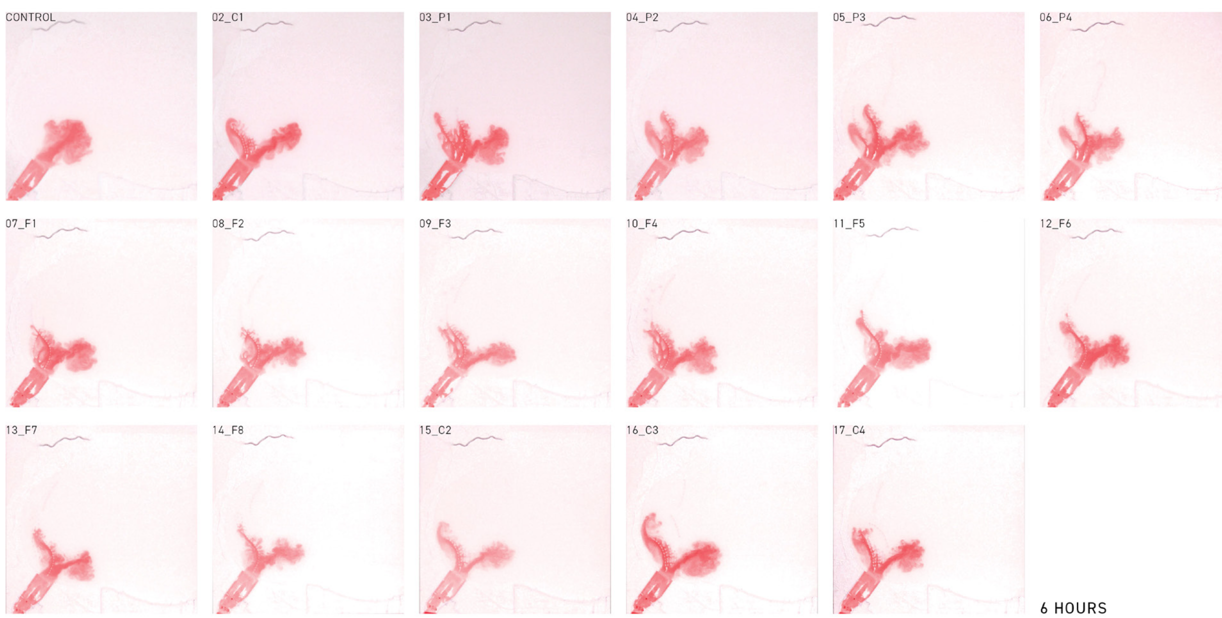



Figure 49b. Initial physical model simulations, 6 hours at model scale.
(fig. cont'd.)

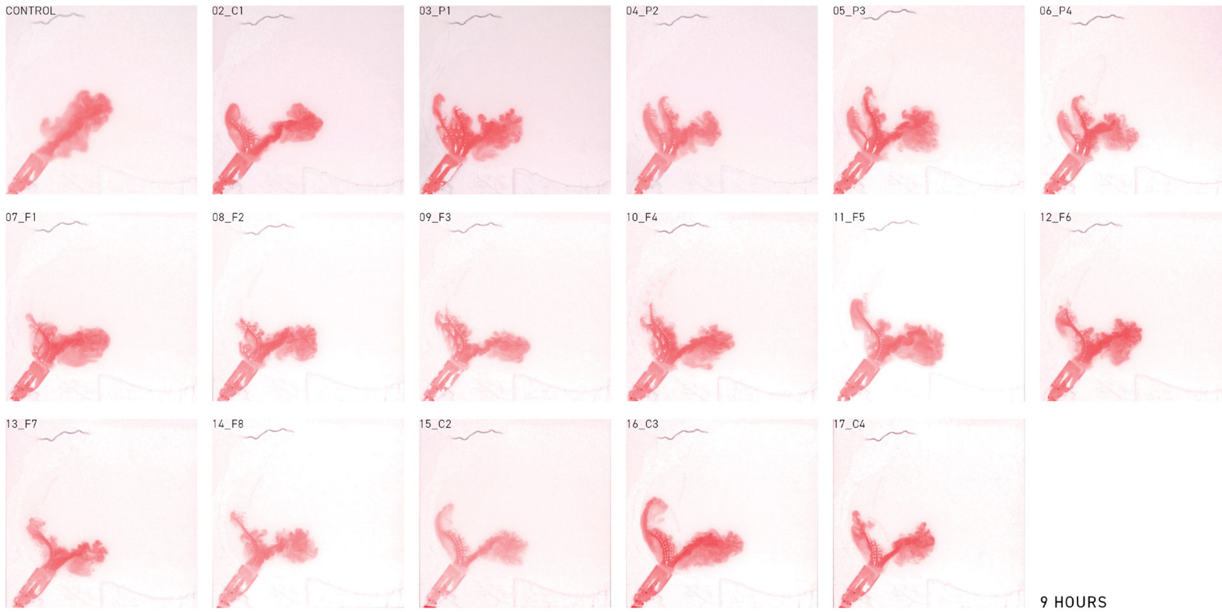



Figure 49c. Initial physical model simulations, 9 hours at model scale.

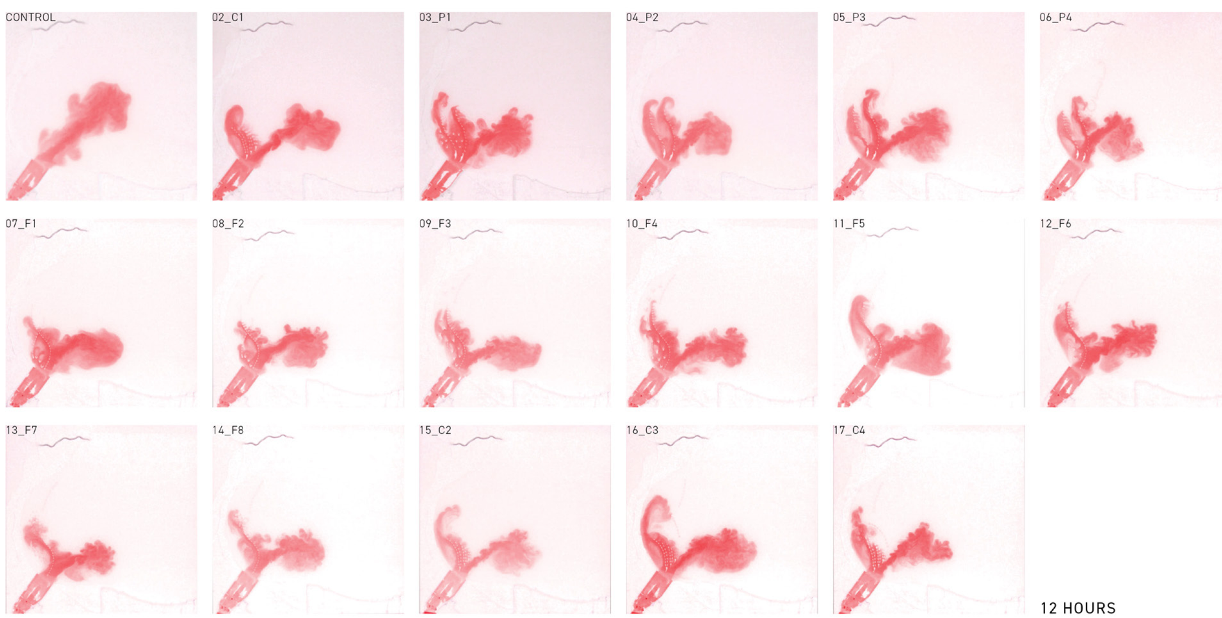



Figure 49d. Initial physical model simulations, 12 hours at model scale.
(fig. cont'd.)

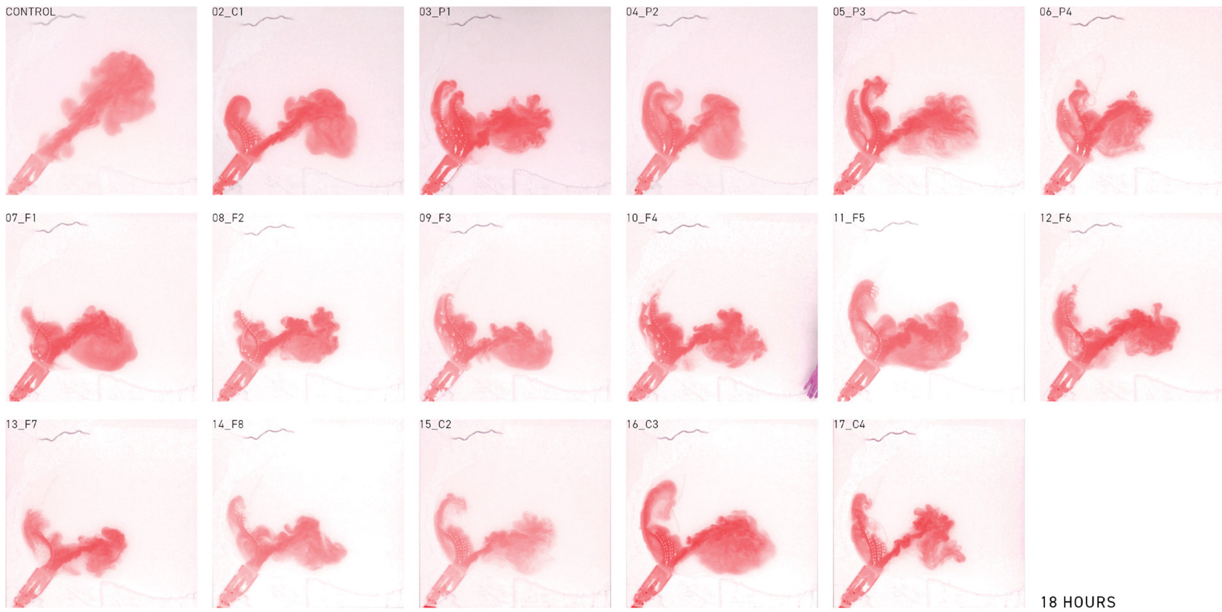



Figure 49e. Initial physical model simulations, 18 hours at model scale.

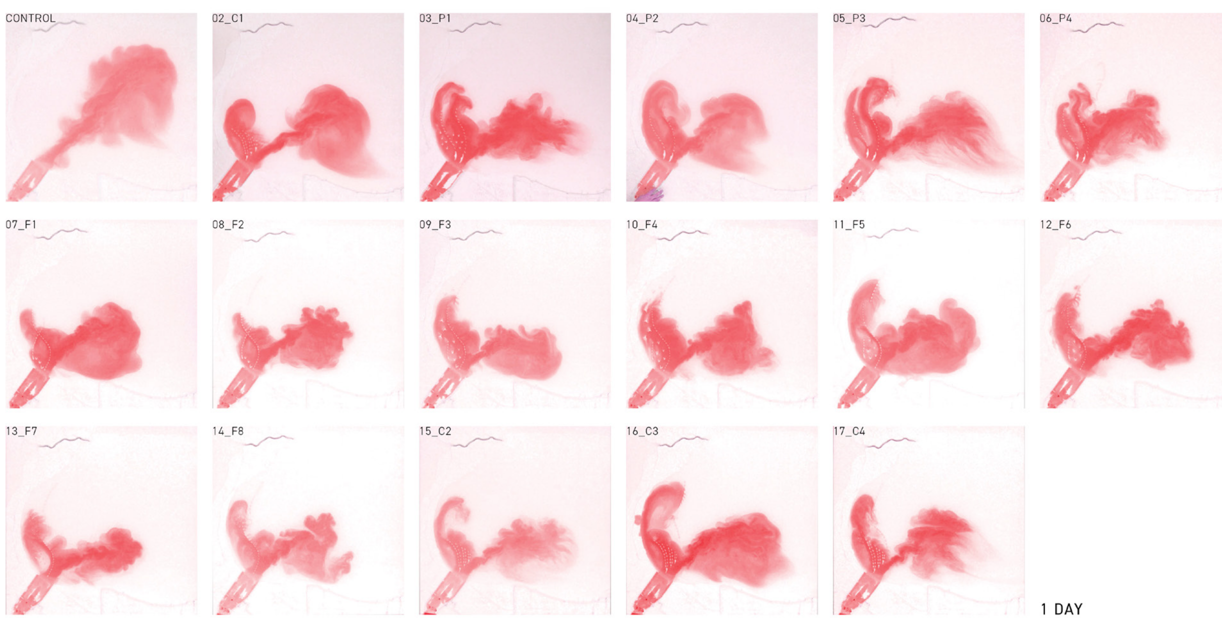



Figure 49f. Initial physical model simulations, 1 day at model scale.
(fig. cont'd.)

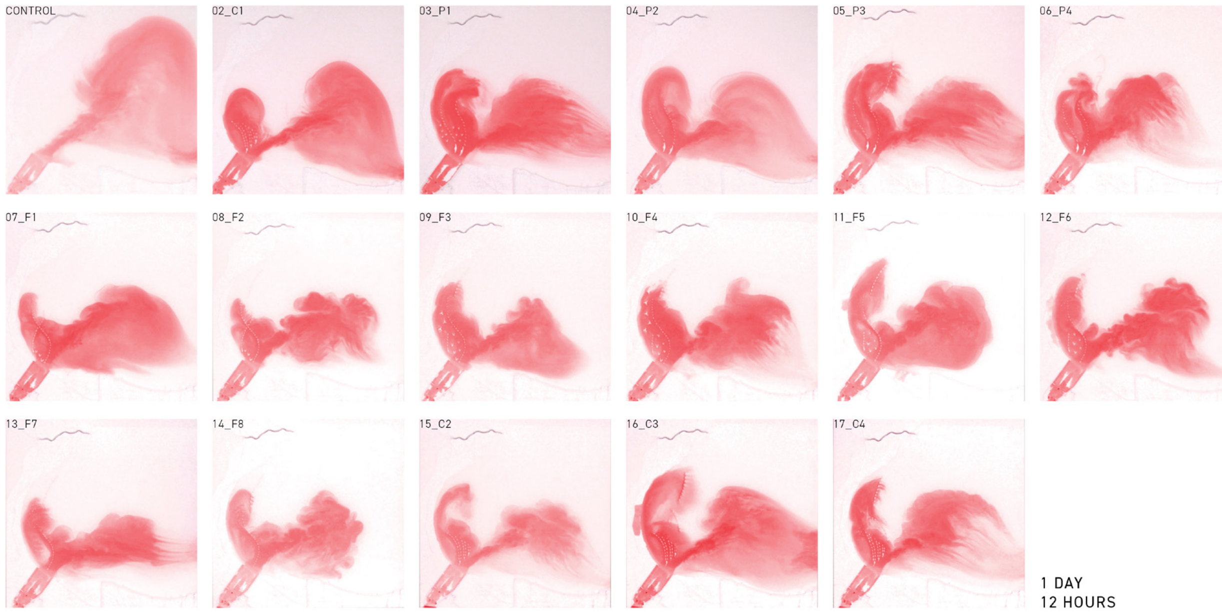



Figure 49g Initial physical model simulations, 1 day and 12 hours at model scale.

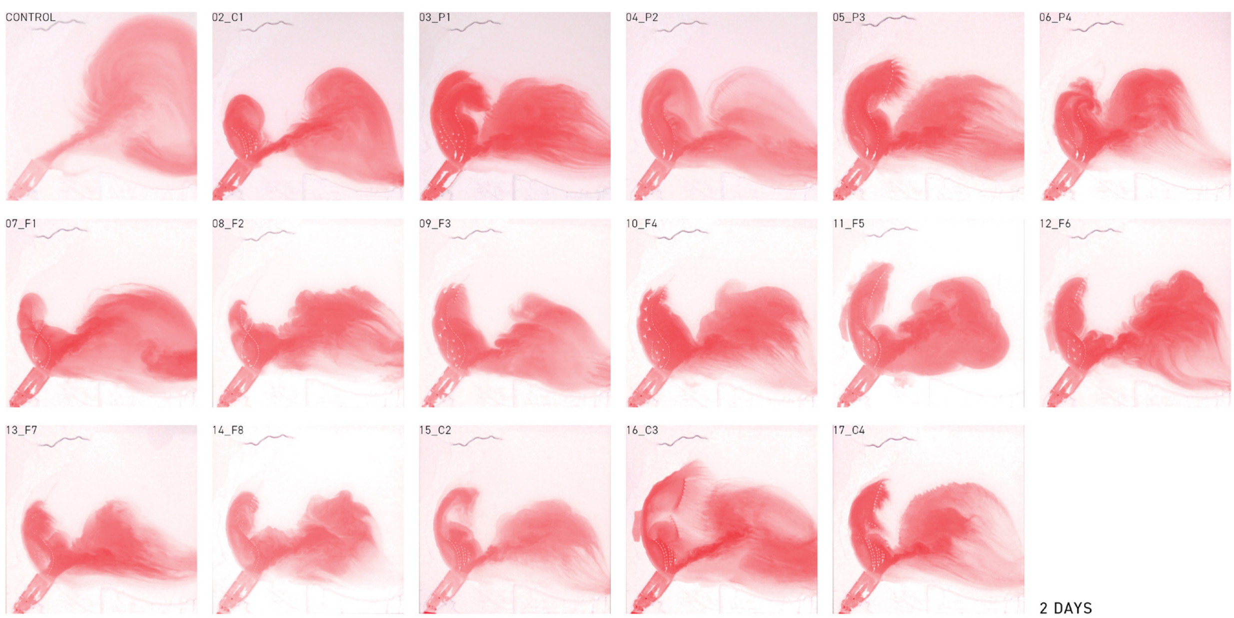
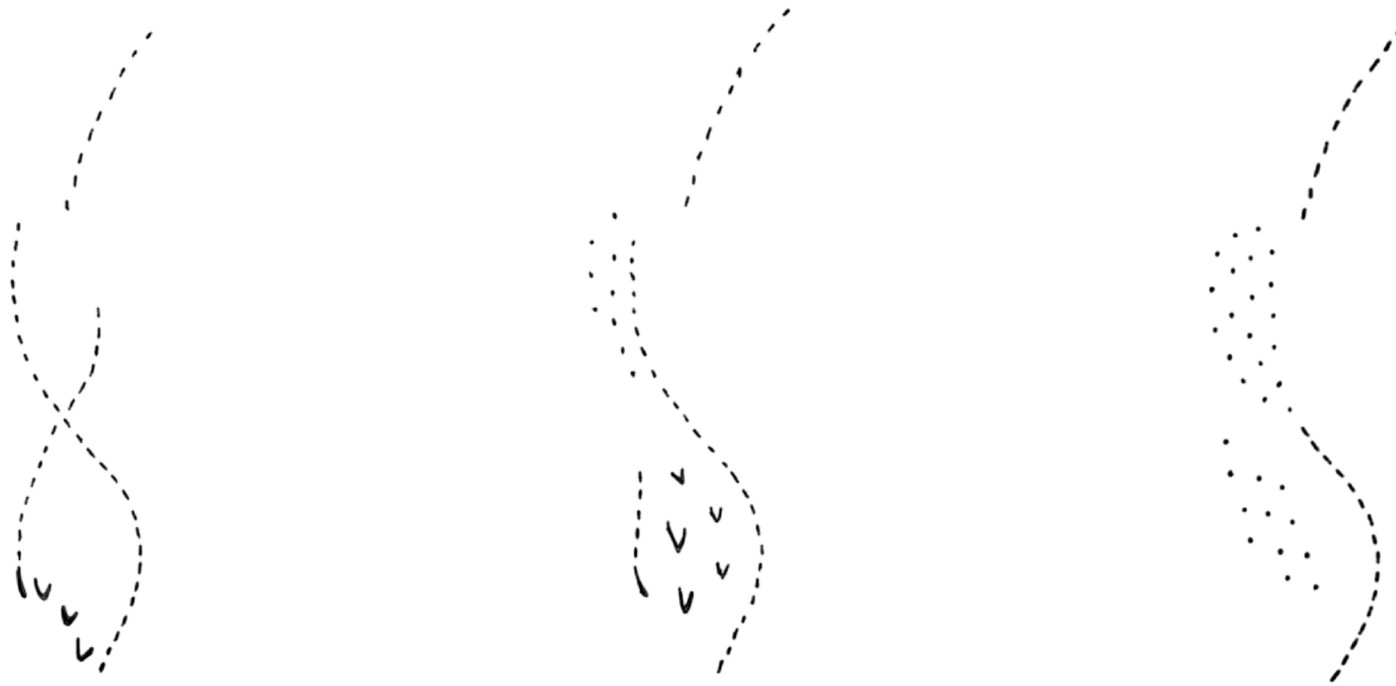
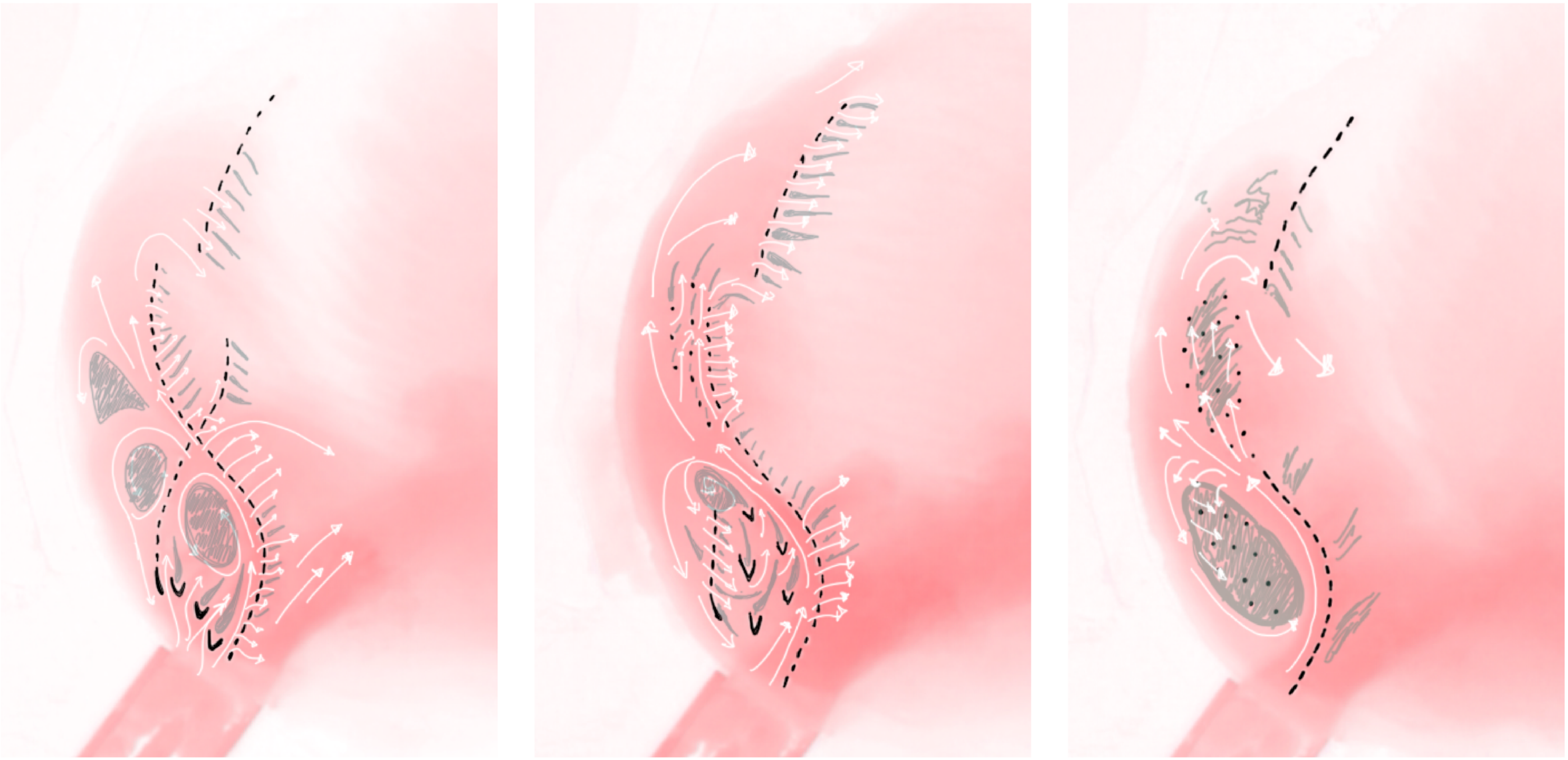



Figure 49h. Initial physical model simulations, 2 days at model scale.



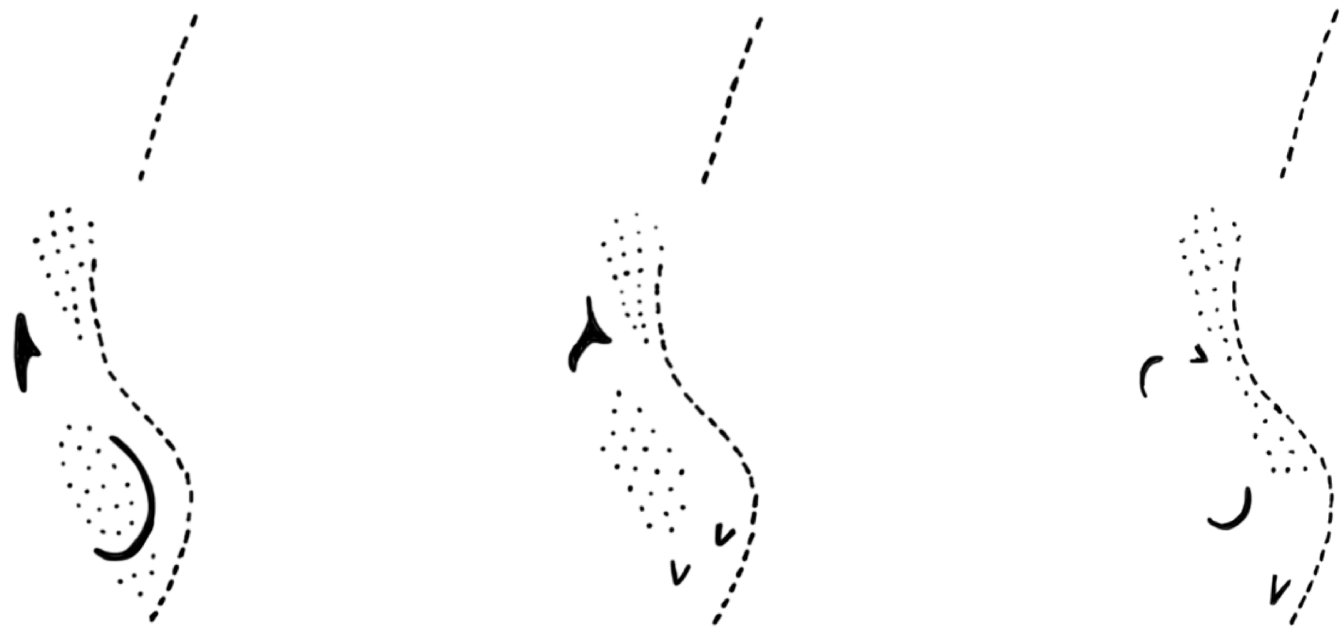
08_F2 12_F6 13_F7

Figure 50. Configurations selected for further study and development.



08_F2 | 12_F6 | 13_F7

Figure 51. Initial flow and accumulation pattern diagrams.



20_COMP1 21_COMP2 22_COMP3

Figure 52. Composite configurations developed from analysis of flow and deposition patterns.

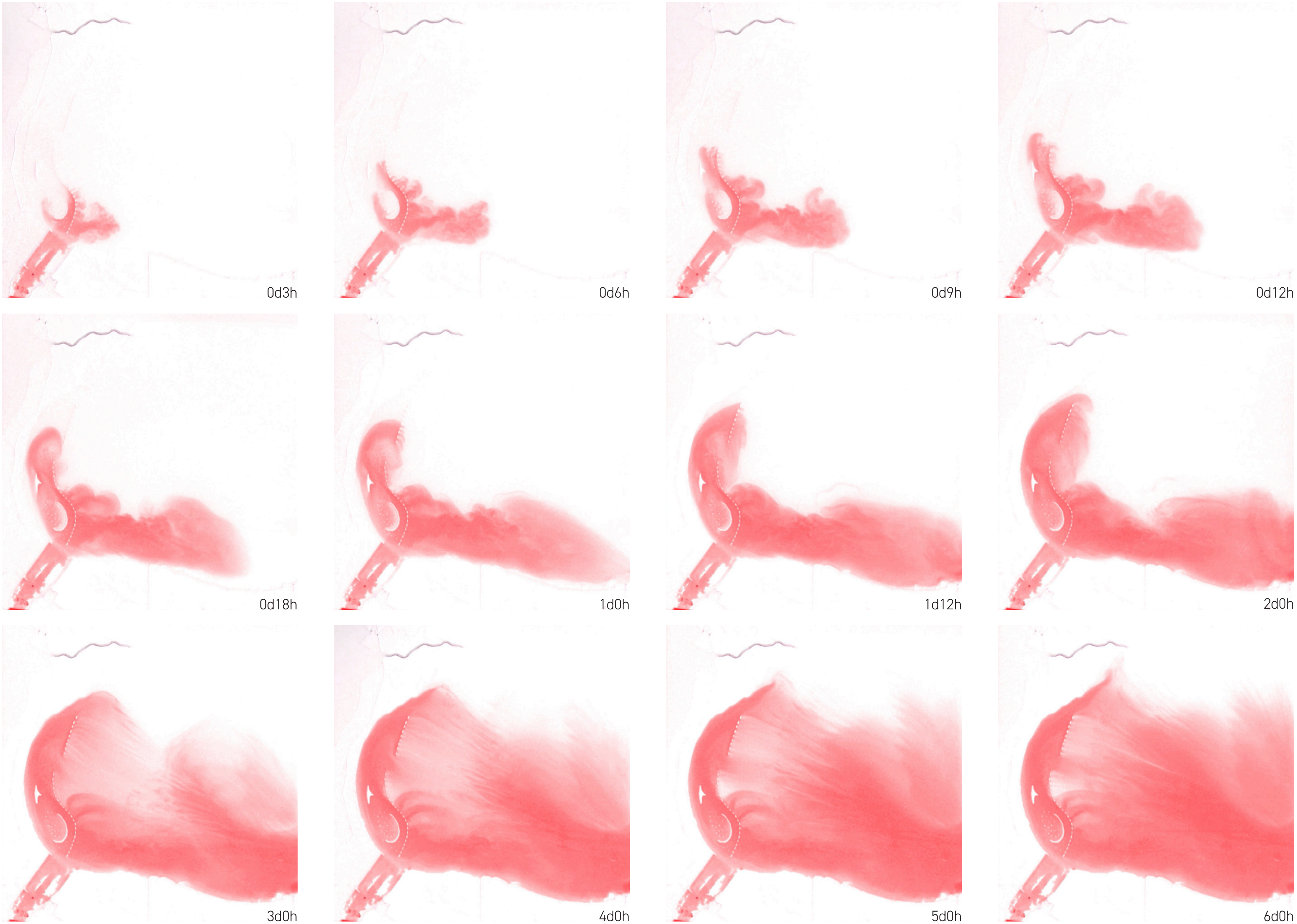



Figure 53. Time series of first composite configuration (20_COMP1)

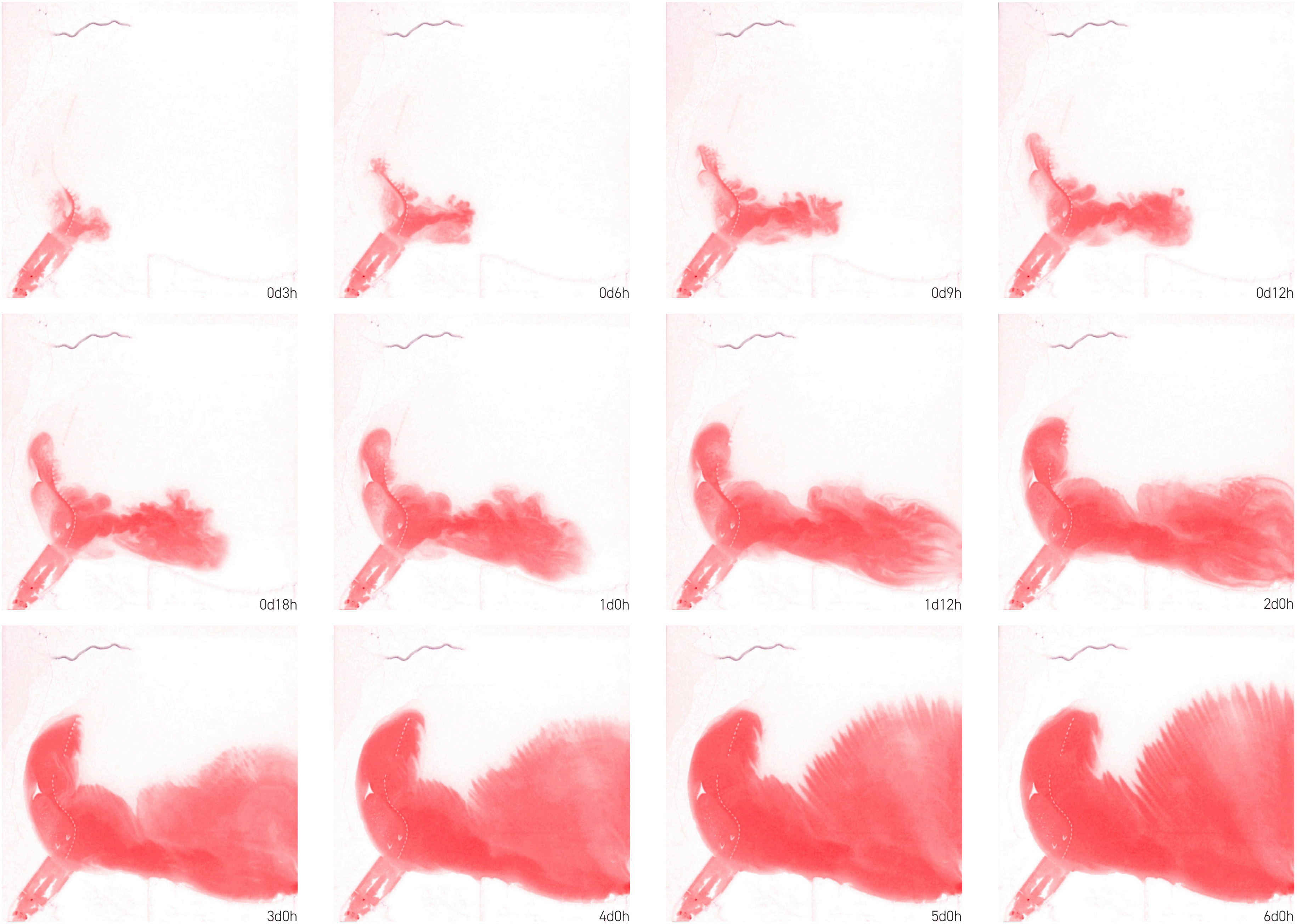


Figure 54. Time series of second composite configuration (21_COMP2)

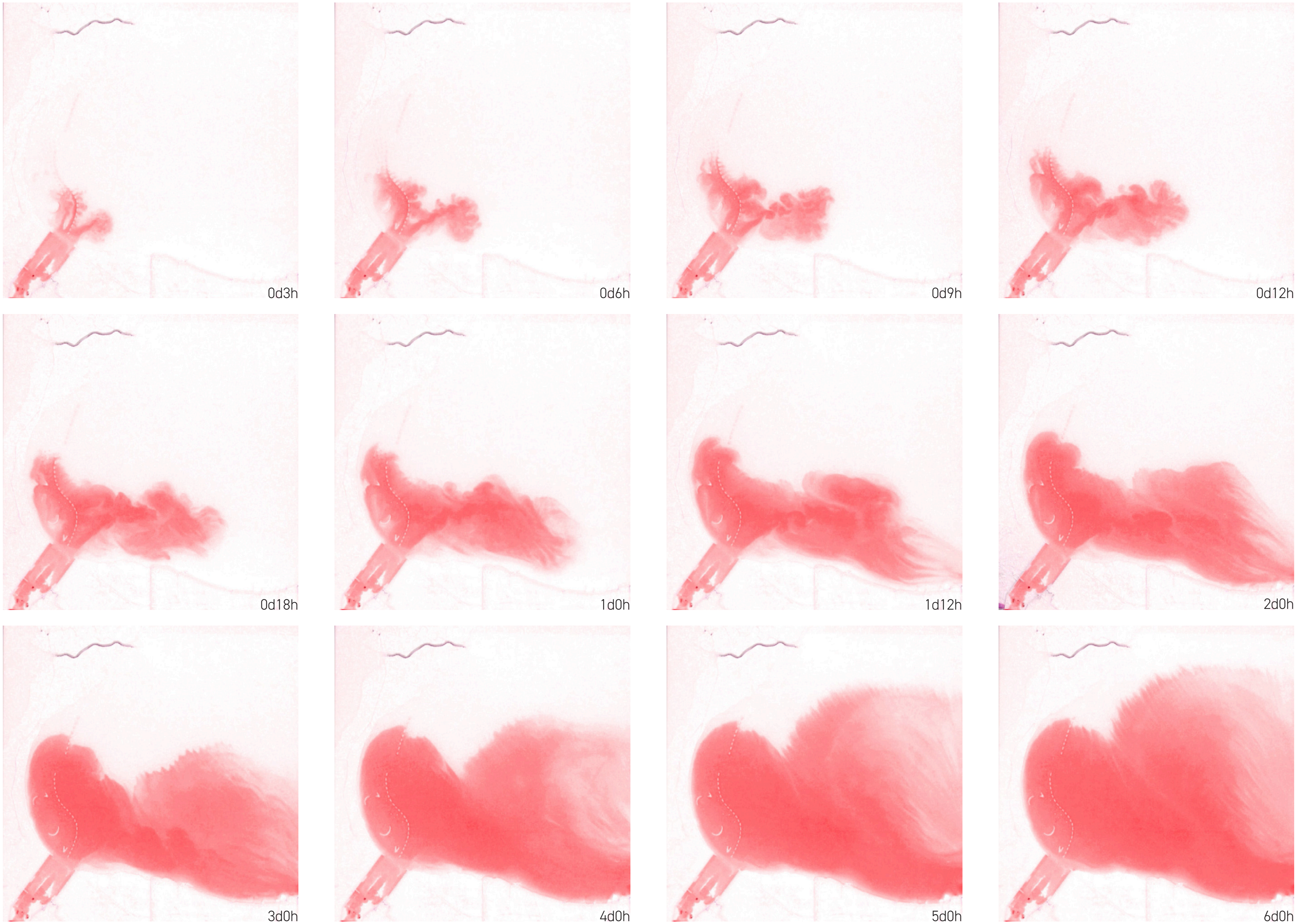
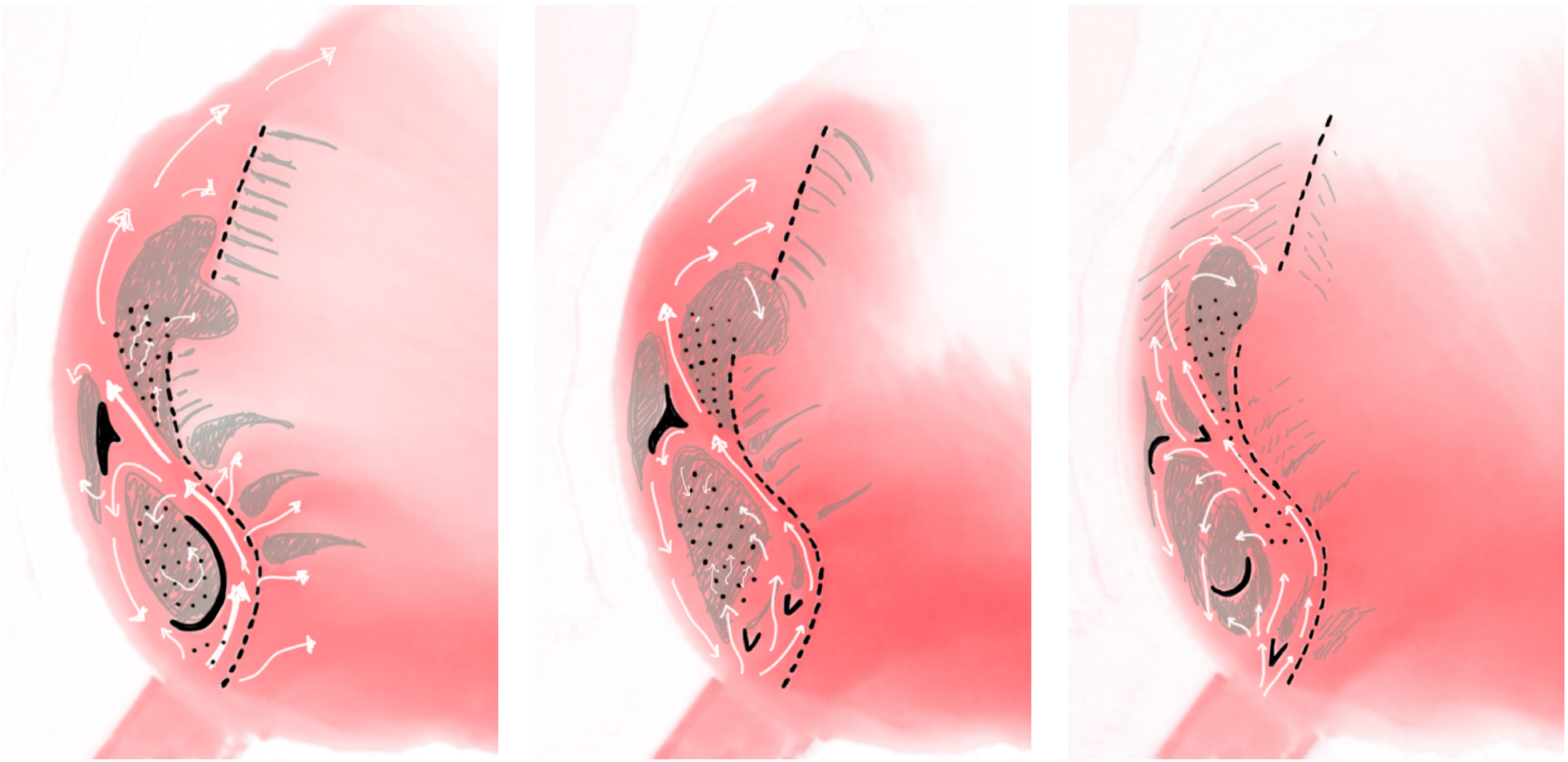


Figure 55. Time series of third composite configuration (22_COMP3)



20_COMP1 21_COMP2 22_COMP3

Figure 56. Composite configuration flow and accomulation diagrams

These composite configurations reflect observations and lessons learned from the physical modeling process, which can be summarized as follows:

- Large structures can be used to redirect, bend, and concentrate flows. However, this concentration can cause flow to accelerate in a way that may not be desirable. Therefore, redirection and concentration of flow must be paired with complementary measures and design tactics to slow flow.
- Flow is most effectively slowed through large baffle fields of relatively small structures and features, which introduce friction to the system and induce diffusion.
- The challenge of designing the proposed system therefore rests in crafting a balance between redirection and flow concentration and diffusion and flow deceleration. Decisions about where and how these elements are deployed can have a large impact on resulting on where and how apparent sediment deposition zones occur.
- The redirection and manipulation of flows can create apparent deposition zones in the form of large eddies, which result from flow velocity gradients.
- Multiple layers of structures are required to redirect and baffle flows, as well as protect nascent deposition zones from wind-driven currents and resultant sediment resuspension.

All of the composite designs performed similarly, creating a large eddy (and apparent sediment deposition zone) just north of the Bonnet Carré Spillway and smaller apparent deposition areas resulting from interactions from structures. These composite designs demonstrated an apparent improvement at slowing flow and creating zones for sediment deposition as compared to the initial configurations. Further analysis indicates that the third composite configuration, 22_COMP3, presents the most promise for further modeling a design development, as both created apparent deposition zones and most effectively slowed down water exiting the spillway.

## VII. Discussion and Conclusion

The study successfully demonstrates the feasibility of incorporating small-scale hydrodynamic modeling into an iterative design process. The digital and physical tools utilized in the design process provided valuable insights and guided design decisions in a way that would not have been possible through more conventional tools of landscape architecture such as drawing and 3D modeling. Furthermore, the design process employed in this study demonstrates that these models can be designed and developed on a relatively modest budget, using tools, techniques, and processes already commonly used by landscape architects.

The physical hydrodynamic modeling employed in this study also provide preliminary support for the feasibility of the Siltcatcher concept. All designs tested on the physical model were successful at diverting a portion of the flow exiting the Bonnet Carré Spillway, and many also successfully slowed down the flow as well. Furthermore, the results demonstrate the feasibility of optimizing structure placement for specific desired results and suggest the potential for further refinement with the use of more sophisticated and precise modeling methods.

These results come with important limitations and qualifications, however. Hydrodynamic modeling is a powerful tool, but its ability to model complex natural phenomena does not constitute a perfect substitute for the system being modeled. Designers should be wary of the temptation to view the system through the lens of the model, as opposed to understanding the model through the lens of the system. Kristie Cheramie described this danger in her 2011 essay on the now-defunct Mississippi River Basin Model in Jackson, Mississippi:

> "...I am struck by the disconnect that can occur when a model becomes the substitute for the "real thing," when the copy, which can never replicate the complexity of its source, becomes the fulcrum around which decisions are made. Beyond the achievement of constructing such a model, what effect has this fake river had on our relationship with the real river it seeks to mimic?[196]

196. This large-scale model of the Mississippi River basin was built to inform the U.S. Army Corps of Engineers' flood protection strategies in the aftermath of the flood of 1927. The river and its tributaries were modeled in concrete at a 1:100 scale across a 200 acre site. Construction was initiated by German and Italian prisoners of war during the height of World War II, but the model was not completed and fully operational until 1966, more than 20 years later. In 1971, use of the model slowed abruptly and was gradually superseded by numerical models such as the HEC-RAS system. The Army Corps ceased use and maintenance of the model in the early 1990s. For more,

In her critique of the large-scale Mississippi River Basin model, Cheramie identifies how abstractions of scale, scope, and materials used to construct models both frame the question being asked of the model and influence interpretation of the model's results. These abstractions are also factors in the model constructed for this study.

**Scale**

As discussed in Chapter V, the small scale of the model and distortions of scale required to facilitate water flow are a key limitation. This limitation became apparent in testing the model, especially with regards to the effects of viscosity and surface tension of the water itself. In initial calibration runs of the model, the lake level was held in place by surface tension, and water backed up into Lake Maurepas and the Manchac Landbridge instead of overflowing across the outfall weirs as intended. It was determined that the outflow weirs, which had been cut to match mean tide at model scale, did not account for surface tension and therefore were too high. A second set of outflow weirs was fabricated at a new lower height (1.5 inches total height) and with a sharp-crested profile to induce outflow from the lake. Additionally, small volumes of Tide laundry detergent were added to water in future test runs to break the water's surface tension and mitigate any effects it may cause.[197]

Even with this modifications, surface tension influenced flow exiting the model, which tended to concentrate in the area due east of the Bonnet Carré Spillway, along the southern shore of the lake. This in turn influenced flow patterns, with viscous effects in essence pulling water out of the system and introducing unrealistic current and flow patterns. This effect could clearly be seen in test run for configuration 02_C1, in which a single point of outflow along the northern boundary of the model produced a clear circulation pattern that did not appear in any subsequent test runs. [Fig 57]

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see Kristi Dykema Cheramie, "The Scale of Nature: Modeling the Mississippi River," *Places Journal*, March 21, 2011, https://doi.org/10.22269/110321.

197. Tide, like most detergents, is a surfactant, which increases the distance between water molecules and reduces the water's surface tension. Tide is also used for the same purpose at the ESPM at the LSU Center for River Studies.

At the scale of the model used in this study, these effects are to a certain extent unavoidable. The elimination of this limitation would have required the construction of a much larger and more costly model. As discussed in Chapter V, constructing a model at such a scale was not possible due to budget, fabrication, and facility limitations.[198] These same limitations would likely apply for most landscape architecture practices or researchers looking to conduct a similar study. However, as this study demonstrates, limitations and distortions due to scale effects and surface tension are not fatal. Small-scale hydrodynamic models can still provide useful insights, especially in the early stages of a design process, provided that the designer is cognizant of the model's limitations.


02_C1

Figure 57. Example of the impact of model outflow and viscosity on apparent flow patterns.

198. To avoid scale effects due to surface tension, the American Society of Civil Engineers recommends horizontal scale ratios of 1:100 to 1:1,000, and vertical scale ratios of 1:20 to 1:100, with a minimum flow depth of 75 mm over spillway crests. A model covering the same area studied in this project, at a scale of 1:1,000, would measure 120 feet square. See American Society of Civil Engineers, "Design, Construction, and Operation of Hydraulic Models," in *Hydraulic Modeling: Concepts and Practice*, ed. R. Ettema, 2000, doi:10.1061/9780784404157.

## Scope

The questions of surface tension and edge effects are also related to the model's scope, or what is and is not included in a model. In the case of this study, the scope of the physical model is limited both geographically and systemically. In order to produce a model at a workable scale given the limitations on fabrication, the eastern and northern shores of Lake Pontchartrain were omitted from the model. Their absence obscures the lake's hydrodynamic relationship with Lake Borgne, the Rigolets, and Chef Menteur Pass. Perhaps most significantly, the model eliminates wind from the system, and therefore does not include wind-driven currents or flows. Under normal conditions, Lake Pontchartrain's currents are primarily driven by wind, making this a significant, if unavoidable, omission.

Omissions such as these are common in model development, however, and are largely influenced by the primary research question being asked. For example, wetland hydrologists will sometimes disregard the influence of precipitation on a system when investigating discharge entering and exiting a wetland system through surface runoff. In this case, the research was focused on the interaction between in-lake structures and flow from the Bonnet Carré Spillway, not on the interaction between the structures and wind. While modeling the effects of wind-driven currents on the system may have created more "realistic" flow patterns, such a result would not have clarified, and may have even interfered with, the pursuit of the primary research question.

## Materials

The model constructed for this study is made of rigid, high-density urethane foam coated with water-resistant epoxy. These materials are ideal for hydrodynamic modeling, but create a distinct water/land interface that is not reflective of the system's real-life materiality. Fluvial, wetland, and estuarine landscapes occupy a transitional space between land and water and consist of unstable muds, silts, and sands that flow, shift, and sink with the effects of water, wind, and time. "In the real world, river systems cannot be reduced to the dialectic of water-or-land; they are materially ambiguous," Cheramie writes. "To remove slurry from an

alluvial landscape…is to negate wetlands, to deny the exigencies of an entire ecosystem that thrives on particulate matter caught in-between states."[199]

In the physical model used in this study, this "matter caught in-between states" is represented with tracer dye. This is in keeping with engineering precedent – tracer dye was used to visualize potential fine-grain sediment transfer on the Small Scale Physical Model operated by LSU prior to the construction of the large Expanded Scale Physical Model, for example. Tracer dye is appropriate for the present research given the scale of the model, the difficulties and impracticalities of modeling with actual sediment at such a scale, and the fact that the vast majority of sediment that enters Lake Pontchartrain from the spillway consists of fine-grained silts and clays. However, tracer dye cannot be understood as one-to-one substitute for sediment, as it does not flocculate, settle, or accumulate. Rather, it visualizes flow and provides hints and suggestions about where such settlement might take place. Therefore, analyzing and interpreting results from the model simulations requires a qualitative understanding of the dynamics of fluid mechanics and sediment transport, introducing subjectivity and uncertainty into the design and evaluation process. For a preliminary feasibility study such as this one, such uncertainty is acceptable. Further development and research of this concept, however, will require a better and more quantitative method of simulating sediment transfer and deposition, likely with numerical models or moveable-bed physical models.

**Avenues for further research**

The limitations enumerated above also suggest multiple avenues for future research. Most evident is the need for quantitative numerical modeling to better understand the potential flow and deposition patterns the proposed Siltcatcher system might impart. There are a number of numerical models suited to such a task, some of which are open-source and freely available online.[200] Feedback from such models would provide more detailed information on

199. Cheramie, "The Scale of Nature: Modeling the Mississippi River."

200. Free models include Delft3D, i-RIC, and HEC-RAS. These tools remain outside the scope of landscape architectural practice and present a steep learning curve for those unfamiliar with hydrology and hydrodynamics. The theory, use, and implementation of such models represents a rich area for future research from the perspective

flow velocities and deposition volumes, which in turn would allow for further refinement of the proposed structure locations and configurations. These quantitative data would also allow for forecasting of land-building scenarios under different sediment input regimes (i.e., with spillway openings annually, every 5 years, every 10 years, etc.). These data could also be used to model and quantify storm surge protection, wave action reduction, and pollutant and nutrient uptake under different storm and land-building scenarios.

In addition to quantifying benefits through advanced numerical modeling, further research is needed to understand the system's potential costs. These include monetary costs of construction as well as any potential broader economic, social, or environmental costs. Quantifying these costs will allow for the calculation of cost-benefit analyses to aid in determining the ultimate feasibility and effectiveness of the Siltcatcher approach as compared to other, more conventional strategies such as levees and floodwalls.

Beyond these technical concerns, further research is needed to ensure that the system becomes not just a piece of ecological infrastructure but a sociocultural asset that provides true educational, recreational, and cultural opportunities for those that live and work in the West Lake Pontchartrain Region. Captivating design ideas have the power not just to change the built environment, but also to organize and direct communities toward a shared vision and common purpose.[201] While the educational and recreational opportunities are a key component of the Siltcatcher concept, more work is needed to articulate exactly how nearby communities might relate to and engage with the project on both immediate and long term bases.

Finally, while the Siltcatcher concept was conceived in response to a very specific location and set of factors, the concepts and tools developed in this study demonstrate potential for application to other locations, contexts, and scales along the Louisiana coastline. For

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of landscape architecture. For an example of the possibilities suggested by such research, see Karen M'Closkey and Keith VanDerSys, *Dynamic Patterns: Visualizing Landscapes in a Digital Age* (Abingdon: Routledge, 2017).

201. A clear example of this can seen in the planned 11th Street Bridge Park in Washington, DC. The park was developed through hundreds of community meetings, and is paired with a substantial equitable development plan. See Andrew Wright, "Can the 11th Street Bridge Park Slow Gentrification in DC?," The Dirt, June 18, 2018, https://dirt.asla.org/2018/06/18/can-the-11th-street-bridge-park-slow-gentrification/.

example, lessons learned from this research could be applied to marsh terracing, a restoration technique which has been widely adopted in coastal Louisiana due to its relative affordability and ease of construction, but whose efficacy has been called into question.[202] The Siltcatcher concept may also have application in conjunction with the planned Mid-Breton and Mid-Barataria sediment diversions downriver of New Orleans, which will deposit large volumes of sand in the vicinity of the diversion outfalls as well as introduce large volumes of silts and clays that will travel much further from the immediate outfall zone. If some of this fine-grained sediment could be captured and detained with Siltcatcher-like structures, it would potentially increase the efficacy of the diversion system at large, providing a forward line of defense from the wind driven waves that contribute to coastal land loss.

**Conclusion**

The state of Louisiana's now decades-long efforts to salvage, protect, and restore its coastline are approaching a critical juncture. On one hand, Louisiana is a nationwide leader in coastal planning, management, and restoration efforts. The Coastal Protection and Restoration Authority's $50 billion master plan is a model for ambitious regional coastal management that prioritizes functioning ecosystems and natural processes. The long-planned Mid-Breton and Mid-Barataria sediment diversions will be the first of their kind, annually depositing millions of cubic yards of sand into degraded and sediment starved coastal wetlands.[203]

There is a risk that these efforts may not be enough, however. As Bob Marshall reported in a recent column for the *New Orleans Advocate*, "even the best-case scenarios in the 2017 master plan show the state could lose another 1,200 square miles by 2067 even with all the projects built" due to accelerating sea level rise. Compounding the issue, other states have begun to follow Louisiana's lead in developing comprehensive coastal resilience plans, increasing competition for federal funding. "If a congressional committee is deciding between

202. See Brasher, "Review of the Benefits of Marsh Terraces in the Northern Gulf of Mexico."

203. "Mid-Barataria and Mid-Breton Sediment Diversions: Overview & Frequently Asked Questions" (Louisiana Coastal Protection and Restoration Authority, 2017), http://coastal.la.gov/wp-content/uploads/2017/09/FAQs_MidBarataria-and-MidBreton-Sediment-Diversions-FINAL-web.pdf.

a floodwall that can protect a city for 80 years and a wetland that might only live 30 years, Louisiana will lose," Marshall warns.[204] And so, even as coastal restoration efforts reach one milestone, designers, engineers, and planners must begin to look ahead and identify new strategies for living with and on Louisiana's rapidly changing coast.

This project presents one such strategy, one that utilizes deltaic processes and, more significantly, accepts their inherent indeterminacy. Designers and planners have grown increasingly comfortable with the former in recent decades, but the latter continues to be seen as a risk in need of mitigation. The Maurepas River Reintroduction project, for example, will be closely monitored, with computer actuated sluice-gates and manually operated release valves to regulate flows of fresh water ultimately diverted into the swamp. In some respect, this approach repeats the mistakes of 20th century approaches to coastal infrastructure by adhering to the stubborn illusion that the fluxes of water, mud, and energy which define the Mississippi River delta can ultimately be controlled.[205] In the face of climate change and sea level rise–indeterminacies of a global scale–this adherence to certainty must ultimately relent. As ecologist Nina-Marie Lister observes, "resilient systems are defined by diversity and by inherent but irreducible uncertainty...Successful strategies for resilient design should use a diversity of tactics through in situ experimental and ecologically responsive approaches which are safe-to-fail, while avoiding those erroneously assumed to be fail-safe."[206]

As demonstrated by this project, such an approach offers ecological, economic, sociocultural, and even aesthetic value, as dynamic and temporal coastal processes are transformed from risks to be managed to sources of design inspiration. The designer, rather than a sculptor of a static object, becomes conductor of an unruly orchestra, organizing and directing the flows, fluxes, and processes responsible for creating the "complex and lyrical" deltaic land-

204. Bob Marshall, "Will Rising Seas Overwhelm Louisiana's Coastal Restoration Plans?," The *New Orleans Advocate*, February 23, 2020, https://www.nola.com/our_drowning_louisiana_coast/article_48978236-5431-11ea-89ab-eb7620be8a2d.html.

205. John McPhee outlined the tenuousness of this proposition in his touchstone essay on the Old River Control Structure. See John McPhee, "Atchafalaya," in *The Control of Nature* (New York: Farrar, Straus, and Giroux, 1989).

206. Nina-Marie Lister, "(Re)Think (Re)Design for Resilience," in *Sustainable Coastal Design and Planning*, ed. Elizabeth Mossop (Boca Raton: CRC Press, 2019), 46.

scape described by Paul Keddy while acknowledging their autonomy and agency.[207] In a time and place where the prevailing narratives are centered on erosion and loss, the Siltcatcher would become a space where the life-giving poetry of deltaic land creation could be witnessed, enjoyed, and celebrated.

207. Keddy, *Water, Earth, Fire: Louisiana's Natural Heritage*, 22.

## Appendix A. Hydrodynamic Model Scaling Using Froude Similitude

For physical surface flow models in which gravity is the predominant force governing water movement, scaling is determined by Froude similitude.[208] The Froude number (*Fr*) of a given flow is defined as the relationship of the fluid's internal forces to the force of gravity and is expressed as:

$$Fr = \frac{V}{\sqrt{gH}}$$

- Where:
- *V* = velocity,
- *g* = gravitational constant, and
- *H* = the depth of water.[209]

For a small-scale model to satisfy Froude similitude with the real-world system it is attempting to emulate (the prototype), the Froude numbers for both model $(Fr_m)$ and prototype $(Fr_p)$ must be equivalent:

$$\frac{Fr_m}{Fr_p} = 1$$

More simply put: for a physical surface flow model to accurately simulate real-world conditions, the relationship between flow velocity, gravity, and depth must be the same at both model and prototype scales.

(Continued on next page.)

208. Waldron, "Physical Modeling of Flow and Sediment Transport Using Distorted Scale Modeling," 5. I am deeply indebted to Ryan for his clear and understandable dissection of various scaling factors and their calculations. His thesis is the primary source referenced for this section.

209. Physical models constructed by the CPRA, including the Expanded Scale Physical Model housed at the LSU Center for River Studies, use Froude similitude for scaling. For an in-depth review of the design process for these models, see Brown Cunningham Gannuch, Coastal Restoration Consultants, and Louisiana State University, "Report on Feasibility Of Small Scale Physical Model of the Lower Mississippi River Delta for Testing Water and Sediment Diversion Projects," and BCG Engineering & Consulting, Inc., "Expanded Scale Physical Model Design Memorandum."

## Siltcatcher Physical Model Scaling

### Horizontal scaling

A 4' x 4' model extent was selected for fabrication, taking into account ease and feasibility of fabrication and transport of the finished model. A study area encompassing the Bonnet Carré Spillway and a large portion of Lake Pontchartrain was delineated as a study area for inclusion in the model. The study area measures approximately 23.25 miles (123,000 feet) in each direction. Therefore, a horizontal scale of 1:30,000 (123,000 x 0.25 = 30,750) was required to construct a 4' x 4' model of the selected study area.

### Vertical scaling

The guide levees on the sides of the Bonnet Carré floodway are approximately 15 feet tall, and Lake Pontchartrain is approximately 15 feet deep at its deepest point within the study area, making for a total elevation gradient within the study area of approximately 30 feet. If modeled on a 1:1 basis with the horizontal scale (1:30,000), the Bonnet Carré guide levees would measure less than 1 one-hundredth of an inch in height:

$$\frac{1}{30{,}000} = \frac{h}{15}$$

$$15 = 30{,}000h$$

$$h = \frac{15}{30{,}000}$$

$$h = 0.0005 \text{ ft}$$

$$\frac{0.0005}{0.08333} = 0.006 \text{ in}$$

Because of the effects of surface tension and fluid viscosity, vertical exaggeration is required in order to produce a model capable of simulating surface water flow. The CPRA Expanded Scale Physical Model (ESPM) housed at the LSU Center for River Studies uses a vertical scale

of 1:400, while its predecessor (the so-called Small Scale Physical Model, or SSPM) used a vertical scale of 1:500.[210] At 1:500, a 15 foot tall levee becomes approximately 3/8" high, and total elevation change on the model (from levee to the deepest point on the lake) measures approximately 3/4". Due to limitations of scale and the need to simulate turbulent water flow, a vertical scale of 1:500 was selected for the physical model.[211]

### Vertical Distortion

A horizontal scale of 1:30,000 and a vertical scale of 1:500 represents a distortion factor of 60 . While vertical distortion is common in physical modeling, a distortion factor of 60 is extreme. For comparison, The CPRA ESPM features a horizontal scale of 1:6,000 and vertical scale of 1:400, for a distortion factor of 15.[212] However, the Siltcatcher model was primarily conceived as a qualitative tool for rapid, iterative design exploration, whereas physical models constructed for engineering purposes are typically intended to semi-quantitatively simulate a specific phenomenon under a given set of conditions. Furthermore, due to the limitations of fabrication and storage, it was not feasible to construct a larger physical model with less vertical exaggeration. For these reasons, the extreme vertical exaggeration was deemed acceptable.

### Dynamic Scaling

The model length (horizontal scale) and depth (vertical scale) represent geometric scale factors, but do not ensure similitude on their own. Dynamic scaling, i.e. the scaling of the movement of water across the model surface over time, must also be accounted for. These dynamic scale factors can be calculated using the geometric scale factors and Froude similitude.[213]

210. BCG Engineering & Consulting, Inc., "Expanded Scale Physical Model Design Memorandum."

211. Coincidentally, engineer William Reynolds used a model with the same combination of horizontal and vertical scales (1:30,000 and 1:500) for the development of the number and formula which today bear his name. For more, see American Society of Civil Engineers, *Hydraulic Modeling: Concepts and Practice*, 15.

212. BCG Engineering & Consulting, Inc., "Expanded Scale Physical Model Design Memorandum," 7-1.

213. Waldron, "Physical Modeling of Flow and Sediment Transport Using Distorted Scale Modeling," 12. For moveable bed models, sedimentation scaling, distinct from dynamic scaling, is also required. However, because this

As discussed above, for accurate scaling of any given variable $S$ in a model,

$$E(S) = \frac{S_M}{S_P} = 1$$

Therefore, the model velocity scale factor E(V) can be determined as follows:[214]

$$E(Fr) = \frac{Fr_m}{Fr_p} = 1$$

$$E(Fr) = \frac{\frac{V_m}{\sqrt{gH_m}}}{\frac{V_p}{\sqrt{gH_p}}} = 1$$

$$\frac{V_p}{\sqrt{gH_p}} = \frac{V_m}{\sqrt{gH_m}} = 1$$

$$V_p\sqrt{H_m} = V_m\sqrt{H_p} = 1$$

$$\frac{V_m}{V_p} = \frac{\sqrt{H_p}}{\sqrt{H_m}} = 1$$

$$E(V) = \sqrt{E(H)}$$

From the model scale velocity, flow rate (***Q***) is determined by multiplying velocity by area:

$$Q = VA$$

Where area (***A***) is defined as:

$$A = HL$$

Therefore, the flow rate scale E(Q) can be defined as:

$$E(Q) = E(V) \cdot E(H) \cdot E(L)$$

Because $E(V) = E(H)^{1/2}$ ,

model does not include physical sediment particles, no sedimentation scaling calculations are required.
214. Ibid, 13.

$$E(Q) = \sqrt{E(H)} \cdot E(H) \cdot E(L)$$

$$E(Q) = E(H)^{\frac{3}{2}} \cdot E(L)$$

Finally, time scale is determined by dividing velocity into length:

$$E(T) = \frac{E(L)}{E(V)}$$

$$E(T) = \frac{E(L)}{\sqrt{E(H)}}$$

Therefore, scaling factors to achieve dynamic similitude can be calculated using the previously determined geometric scale factors.

- E(L) = 1:30,000 = 0.00003...
- E(H) = 1:500 = 0.002
- $E(V) = E(H)^{½} = (0.002)^{½} \approx 0.04472$
- $E(Q) = E(H)^{3/2} \cdot E(L) = (0.002)^{3/2} \cdot 0.00003 \approx 2.981424 \cdot 10^{-9}$
- $E(T) = E(L) \cdot 1/E(H)^{½} \approx 0.0007454$

Model conditions can then be determined by multiplying the calculated scale factors by the real-world condition they are modeling:

Prototype condition • Model scale factor = Model condition

Therefore, for this model, 250,000 cubic feet per second (the maximum discharge of the Bonnet Carré Spillway) equates to 0.000745356 cubic feet per second, or 0.3345 gallons per minute.

Bonnet Carré maximum discharge • Discharge scale factor = Maximum model discharge

$250,000 \text{ cfs} \cdot (2.981424 \cdot 10^{-9}) = 0.000745356 \text{ cfs}$

$0.000745356 \text{ cfs} \cdot 7.4085 \text{ gal/cf} \cdot 60 \text{ s/min} \approx 0.33 \text{ gal/min}$

One day of real-world time equates to approximately one minute of model time.

Prototype day in minutes • Time scale factor = Model day in minutes

1,400 minutes per day • 0.0007454 = 1.073

Therefore, a model run simulating a one-month long opening with maximum flow would last for 30 minutes and require roughly 10 gallons of water (0.33 gal/min * 30 min ≈ 10 gal).

**Reynolds Number**

The Reynolds Number (Re) is a dimensionless number used to characterize whether a flow is laminar or turbulent. It is calculated by dividing a flow's inertial forces by its viscous forces. Reynolds number values less than 2,000 are considered laminar, while Reynolds number values over 4,000 are considered turbulent. Values in between are considered transitional.[215] Exact scaling of both Reynolds and Froude numbers in a model is not possible except at full scale, but similitude is considered sufficient if the model's flow broadly matches the prototype (that is, laminar or turbulent). Therefore, because the Bonnet Carré Spillway represents a turbulent system, the flow in the model should be turbulent as well.

The Reynolds number for a given system is calculated as

$$Re = \frac{\rho U L}{\mu}$$

Where $\rho$ is the density of the fluid, $U$ is the velocity of the fluid flow, $L$ is some characteristic length dimension, and $\mu$ is the fluid's viscosity.[216] Because the system's Reynolds number is influenced by a characteristic length parameter, it is also location dependent. The Reynolds number of flow at the base of a weir will like be much higher than some distance downstream of the weir, for example.

215. George M. Hornberger et al., *Elements of Physical Hydrology*, 2nd ed. (Baltimore: Johns Hopkins University Press, 2014), 80-82.

216. Ibid.

For the model constructed for this study, the area of most importance was section of the lake at the outfall of the Bonnet Carré Spillway. Assuming an average real-world depth for this area of 3 feet and a width of 10,500 feet,[217]

$$\text{prototype dimension(scale factor)} = \text{model dimension}$$

$$d_m = 3 \text{ feet } (0.002) = 0.006 \text{ feet}$$

$$w_m = 10{,}500 \text{ feet}(0.0000\overline{3}) = 0.35 \text{ feet}$$

$$A_m = h_m l_m = 0.006 \text{ ft} \cdot 0.35 \text{ ft} = 0.0021 \text{ ft}^2$$

Because the model discharge is approximately 0.000745 cfs,

$$Q_m = A_m U_m$$

$$U_m = \frac{Q_m}{A_m} = \frac{0.000745 \text{ cfs}}{0.0021 \text{ ft}^2} = 0.3548 \text{ ft s}^{-1} = 0.1081 \text{ m s}^{-1}$$

At 20° C (room temperature), the density of water is approximately 998 kg $m^{-3}$ and its viscosity is 1.002 x $10^{-3}$ Pa·s (or kg $m^{-1}$ $s^{-1}$). Because model was constructed primarily to investigate two-dimensional flow, the characteristic length *L* is the width of the flow, 0.35 ft or 0.1067 m. Therefore, the Reynolds number at this point on the model can be calculated as follows:

$$Re = \frac{\rho U L}{\mu} = \frac{(998 \text{ kg m}^{-3})(.1081 \text{ m s}^{-1})(0.1067 \text{ m})}{1.002 \cdot 10^{-3} \text{kg m}^{-1} \text{ s}^{-1}} = 1.149 \cdot 10^4$$

Because this number is greater than 4,000, two-dimensional flow across the model at the outfall of the Bonnet Carré spillway into Lake Pontchartrain is turbulent and therefore the model is valid.

217. These values reflect measurements taken from the 2014 NOAA topobathymetry DEM used to fabricate the physical model. Measurements were taken using QGIS 3.10.

## Appendix B. Complete Numerical Modeling Variations and Results

Table B1. Straight

| Model Name | Crest Length | Crest Width | Front Slope | Back Slope | Side Slope | Rotation | Indexed Mean Value |
|---|---|---|---|---|---|---|---|
| straight_fs_12.5 | 1250 | 20 | 12.50% | 33% | 33% | 0º | 0.025 |
| straight_fs_45 | 1250 | 20 | 45% | 33% | 33% | 0º | 0.087 |
| straight_bs_12.5 | 1250 | 20 | 33% | 12.50% | 33% | 0º | 0.101 |
| straight_bs_45 | 1250 | 20 | 33% | 45% | 33% | 0º | 0.096 |
| straight_ss_12.5 | 1250 | 20 | 33% | 33% | 12.50% | 0º | 0.096 |
| straight_ss_45 | 1250 | 20 | 33% | 33% | 45% | 0º | 0.095 |
| straight_l_500 | 500 | 20 | 33% | 33% | 33% | 0º | 0.263 |
| straight_l_2000 | 2000 | 20 | 33% | 33% | 33% | 0º | 0.072 |
| straight_w_5 | 1250 | 5 | 33% | 33% | 33% | 0º | 0.478 |
| straight_w_40 | 1250 | 40 | 33% | 33% | 33% | 0º | -0.106 |
| straight_r_15 | 1250 | 20 | 33% | 33% | 33% | 15º | 0.132 |
| straight_r_30 | 1250 | 20 | 33% | 33% | 33% | 30º | 0.214 |
| straight_r_45 | 1250 | 20 | 33% | 33% | 33% | 45º | 0.322 |
| straight_r_60 | 1250 | 20 | 33% | 33% | 33% | 60º | 0.481 |
| straight_control | 1250 | 20 | 33% | 33% | 33% | 0º | 0.096 |
| **straight_optimal** | **500** | **5** | **33%** | **12.50%** | **33%** | **60º** | **0.637** |
| circle_control | | | | | | | 0.573 |

(Continued on next page.)

Table B2. Curved

| Model Name | Front Slope | Back Slope | Depth of Curve | Location of Curve Point (x axis) | Crest Width | Angle of Rotation | Length (Control) | Indexed Mean Value |
|---|---|---|---|---|---|---|---|---|
| curved_control | 33% | 8% | 750 | 0 | 20 | 0º | 1,000 | 0.601 |
| curved180_control | 33% | 8% | 750 | 0 | 20 | 180º | 1,000 | -0.971 |
| curved_fs_12.5 | 12.5% | 8% | 750 | 0 | 20 | 0º | 1,000 | 0.638 |
| curved_fs_45 | 45% | 8% | 750 | 0 | 20 | 0º | 1,000 | 0.547 |
| curved_bs_4 | 33% | 4% | 750 | 0 | 20 | 0º | 1,000 | 0.605 |
| curved_bs_12 | 33% | 12% | 750 | 0 | 20 | 0º | 1,000 | 0.605 |
| curved_doc_1000 | 33% | 8% | 1,000 | 0 | 20 | 0º | 1,000 | 0.601 |
| curved_doc_500 | 33% | 8% | 500 | 0 | 20 | 0º | 1,000 | 0.524 |
| curved_cvx_150 | 33% | 8% | 750 | 150 | 20 | 0º | 1,000 | 0.557 |
| curved_cvx_300 | 33% | 8% | 750 | 300 | 20 | 0º | 1,000 | 0.493 |
| curved_cw_5 | 33% | 8% | 750 | 0 | 5 | 0º | 1,000 | 0.591 |
| curved_cw_40 | 33% | 8% | 750 | 0 | 40 | 0º | 1,000 | 0.516 |
| curved180_fs_12.5 | 12.5% | 8% | 750 | 0 | 20 | 180º | 1,000 | -0.961 |
| curved180_fs_45 | 45% | 8% | 750 | 0 | 20 | 180º | 1,000 | -1.035 |
| curved180_bs_4 | 33% | 4% | 750 | 0 | 20 | 180º | 1,000 | -0.436 |
| curved180_bs_12 | 33% | 12% | 750 | 0 | 20 | 180º | 1,000 | -1.325 |
| curved180_doc_1000 | 33% | 8% | 1,000 | 0 | 20 | 180º | 1,000 | -1.131 |
| curved180_doc_500 | 33% | 8% | 500 | 0 | 20 | 180º | 1,000 | -0.781 |
| curved180_cvx_150 | 33% | 8% | 750 | 150 | 20 | 180º | 1,000 | -0.915 |
| curved180_cvx_300 | 33% | 8% | 750 | 300 | 20 | 180º | 1,000 | -0.877 |
| curved180_cw_5 | 33% | 8% | 750 | 0 | 5 | 180º | 1,000 | -0.917 |
| curved180_cw_40 | 33% | 8% | 750 | 0 | 40 | 180º | 1,000 | -1.076 |
| **curved_optimal** | **33%** | **12.50%** | **33%** | **60** | **5** | **0º** | 1,000 | **0.707** |
| circle_control | | | | | | | | 0.573 |

(Continued on next page.)

Table B3. Chevron.

| Model Name | Side Slope | Y-axis bend point | X-axis bend point | Width at Center | Rotation | Length (Control) | Indexed Mean Value |
|---|---|---|---|---|---|---|---|
| chevron_control | 33% | 750 | 0 | 250 | 0 | 1250 | 0.554 |
| chevron_ss_12.5 | 12.5% | 750 | 0 | 250 | 0 | 1250 | 0.665 |
| chevron_ss_45 | 45% | 750 | 0 | 250 | 0 | 1250 | 0.514 |
| chevron_by_500 | 33% | 500 | 0 | 250 | 0 | 1250 | 0.490 |
| chevron_by_1000 | 33% | 1,000 | 0 | 250 | 0 | 1250 | 0.609 |
| chevron_bx_200 | 33% | 750 | 200 | 250 | 0 | 1250 | 0.459 |
| chevron_bx_400 | 33% | 750 | 400 | 250 | 0 | 1250 | 0.376 |
| chevron_cw_500 | 33% | 750 | 0 | 500 | 0 | 1250 | 0.512 |
| chevron_r_30 | 33% | 750 | 0 | 250 | 30° | 1250 | 0.318 |
| chevron_r_60 | 33% | 750 | 0 | 250 | 60° | 1250 | 0.210 |
| chevron_r_90 | 33% | 750 | 0 | 250 | 90° | 1250 | 0.525 |
| chevron_r_120 | 33% | 750 | 0 | 250 | 120° | 1250 | 0.328 |
| chevron_r_150 | 33% | 750 | 0 | 250 | 150° | 1250 | -0.863 |
| chevron_r_180 | 33% | 750 | 0 | 250 | 180° | 1250 | -1.640 |
| **chevron_optimal** | **250** | **1000** | **0** | **250** | **0°** | **1250** | **0.693** |
| circle_control | | | | | | | 0.573 |

Table B4. Triangle.

| Model Name | Slope | Curve Depth | Segment Length | Rotation Angle | Indexed Mean Value |
|---|---|---|---|---|---|
| triangle_control | 33% | 0 | 1000 | 0 | 0.502 |
| triangle_ss_12.5 | 12.5% | 0 | 1000 | 0 | 0.602 |
| triangle_ss_45 | 45% | 0 | 1000 | 0 | 0.459 |
| triangle_cd_40 | 33% | 40 | 1000 | 0 | 0.487 |
| triangle_cd_-40 | 33% | -40 | 1000 | 0 | 0.529 |
| triangle_l_500 | 33% | 0 | 500 | 0 | 0.644 |
| triangle_l_1500 | 33% | 0 | 1500 | 0 | 0.395 |
| triangle_r_15 | 33% | 0 | 1000 | 15° | 0.340 |
| triangle_r_30 | 33% | 0 | 1000 | 30° | 0.121 |
| triangle_r_60 | 33% | 0 | 1000 | 60° | -0.302 |
| **triangle_optimal** | **12.5%** | **-40** | **500** | **0°** | **0.740** |
| circle_control | | | | | 0.573 |

(Continued on next page.)

Table B5. Square.

| Model Name | Slope | Curve Depth | Segment Length | Rotation Angle | Indexed Mean Value |
|---|---|---|---|---|---|
| square_control | 33% | 0 | 1000 | 0 | 0.502 |
| square_ss_12.5 | 12.5% | 0 | 1000 | 0 | 0.602 |
| square_ss_45 | 45% | 0 | 1000 | 0 | 0.459 |
| square_cd_40 | 33% | 40 | 1000 | 0 | 0.487 |
| square_cd_-40 | 33% | -40 | 1000 | 0 | 0.529 |
| square_l_500 | 33% | 0 | 500 | 0 | 0.644 |
| square_l_1500 | 33% | 0 | 1500 | 0 | 0.395 |
| square_r_15 | 33% | 0 | 1000 | 15º | 0.340 |
| square_r_30 | 33% | 0 | 1000 | 30º | 0.121 |
| square_r_40 | 33% | 0 | 1000 | 60º | -0.302 |
| **square_optimal** | **12.5%** | **-40** | **500** | **45º** | **0.6580** |
| circle_control | | | | | 0.573 |

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