Rethinking the River

The Mississippi River and its delta and plume provide insights into research-informed approaches to managing river-dominated coastal zones.

The Mississippi River (center) with the Fort St. Philip crevasse complex shown to the right. This complex, which is located about 120 kilometers downstream of New Orleans and shunts water eastward, was formed in the early 1970s and now carries roughly 10%–15% of the total flow of the river. Studies into this complex and nearby systems are part of a wave of studies that show that the river functions more like a “leaky pipe” than an efficient conduit of freshwater. Note that the vessel in the center of the river is traveling upstream, toward New Orleans. Credit: Alexander S. Kolker and Southwings

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A complex set of pressing management concerns is driving a shift in the ways that science and management are coupled in the Mississippi River Delta region and how they provide feedback to inform each other. This shift has its origins in a decades-long effort to understand and restore the Mississippi River Delta, but the management concerns that are driving the design of model-intensive scientific research campaigns have brought the issue to the fore.

New and evolving concerns include maintaining shipping and commerce in the Mississippi River, restoring habitats in the river's delta, providing protection from river floods and storm surges, reducing the effects of hypoxia (oxygen depletion) in the waters along the continental shelf, and recovering from the BP Deepwater Horizon oil spill (https://eos.org/research-spotlights/oil-residues-accelerate-coastal-wetland-losses).

Science and management partnerships on the Mississippi provide a model for research and management that can be applied to deltas and coasts worldwide.

Holistically addressing these concerns requires the best science available and, as such, has created new opportunities for research. These opportunities include the coupled development of multiple science programs focused on the Mississippi River and the Gulf of Mexico, research that has led to shifts in our conceptualization of how North America's largest river functions and how it interacts with its delta and the ocean.

This empirically based, multidisciplinary approach also has applications beyond the banks of one river. Globally, deltas and coastal systems are home to billions of people, major centers of biodiversity, and appealing locations for commerce. These systems face a range of environmental threats, and they are naturally dynamic landscapes [e.g., *Giosan et al.*, 2014]. Thus, science and management partnerships on the Mississippi provide a model for research and management that can be applied to deltas and coasts worldwide.

The Mississippi River Delta Region

The Mississippi River has the world's third-largest watershed, sixth-largest freshwater discharge, and fifth-largest delta [*Kolker et al.*, 2013, and references therein]. Here we define the Mississippi River Delta region as the area extending from the Mississippi River's distributary avulsion point (https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=50824) to the continental slope (Figure 1).

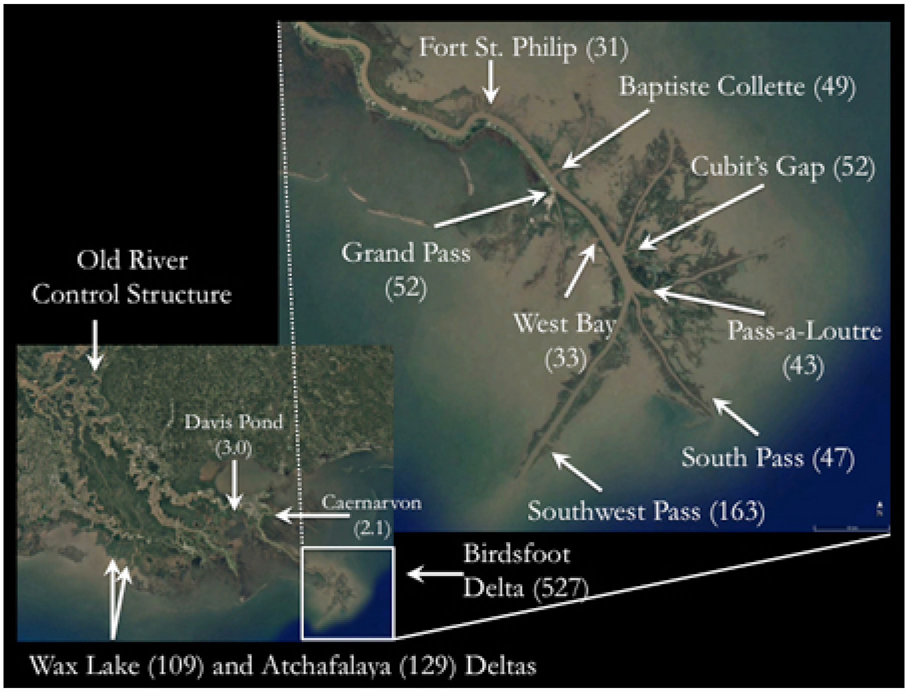


Fig. 1. Map of the lower Mississippi River and its delta, showing major distributaries and their annual discharge volume (cubic kilometers). The image on the right shows a detailed view of the bird's-foot delta region at the river's mouth. Credit: NASA Landsat and Google Earth

The regions around the lower Mississippi River and its delta are home to nearly 2 million people with a unique cultural heritage. This area also hosts one of Earth's largest port complexes, a massive energy industry, and nearly a third of the United States' seafood production [*Louisiana Coastal Protection and Restoration Authority* (*LACPRA*), 2017].

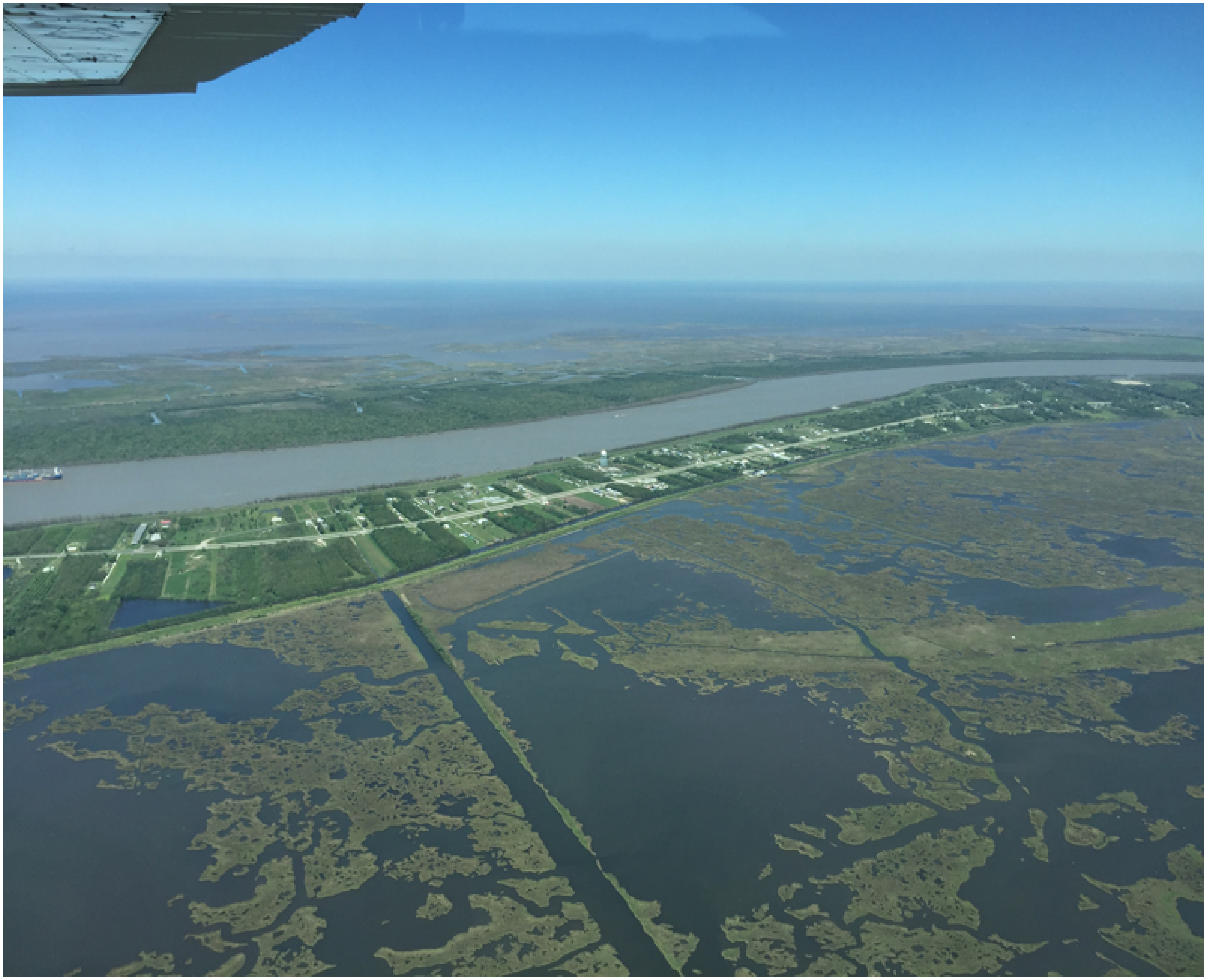
However, these enterprises are at risk because the Mississippi River Delta and associated environments have lost nearly 20% of their coastal wetland area over the past century because of a range of factors that include subsidence, global sea level rise, the construction of canals, reduced freshwater input and sediment deposition, hurricane strikes, and oil spill impacts [*LACPRA*, 2017]. The area is under threat to lose an equivalent amount in the next 50 years [*LACPRA*, 2017].

How Leaky Is the Pipe?

Our understanding of water transport in the lower Mississippi River (the region downstream of the Atchafalaya distributary) is changing rapidly. Figuring out how things are changing is a critical research need, given the importance of maintaining water flows to support navigation in the Mississippi River channel, the need to protect against river floods (https://eos.org/research-spotlights/reimagining-a-fatal-flood), the relevance of this information for basic deltaic hydrogeology and restoration, and the goals of large-scale river management worldwide.

> Recent studies indicate that almost half of the river’s water leaves the channel north of the lower Mississippi River’s mouth at Head of Passes.

Until recently, the prevailing view was that extensive flood control levees caused the lower Mississippi River to function like a pipe: It was assumed that water flowed through it efficiently and there was little exchange of water, sediment, and dissolved constituents between the river and the delta plain. Although levees do prevent freshwater and sediment from reaching large areas of the delta plain, recent studies indicate that almost half of the river’s water leaves the channel north of the lower Mississippi River’s mouth at Head of Passes, where the main stem of the river branches off into three distinct directions and creates a bird’s-foot delta at the river’s mouth (Figure 1) [*Allison et al.*, 2012]. Most of this outflow occurs in the lowermost 75 kilometers of the river through natural and man-made exits having capacities that range from about 100 to 4,000 cubic meters per second (Figure 1) [*Allison et al.*, 2012]. In some cases, the flow magnitude is increasing at individual exits upstream of the bird’s-foot delta [*Suir et al.*, 2014].



The Mississippi River is flanked by levees that severely restrict the exchange of freshwater, sediments, and nutrients between the river and its delta. Seen here is the river, surrounded by wetlands that are restricted from interacting with it. Credit: Alexander S. Kolker and Southwings

Some scientists see this as indicative of an early phase of channel realignment in which some of the major river distributaries shift northward [*Kemp et al.*, 2014]. The abovementioned studies, coupled with recent work indicating groundwater discharge from the Mississippi River to the coastal zone [*Kolker et al.*, 2013], suggest that the system functions more like a leaky pipe than an unbroken conduit connecting the land and the sea.

Sediment Transport, Then and Now

Research has also transformed how researchers and stakeholders understand sediment dynamics in the Mississippi River Delta system. Previously, the dominant view was that most sediments from the lower Mississippi River were shunted into the deep waters of the Gulf of Mexico, a view that appeared to be consistent with remotely sensed imagery showing large surface sediment plumes seaward of the river's mouth (Figure 2) [*Allison et al.*, 2012, and references therein]. However, a detailed sediment budget [*Allison et al.*, 2012] indicates that less than 50% of the sediment load in the lower Mississippi River is transported through the Southwest and South passes—the major deepwater discharging outlets—in part because these sediments are settling out of the river's water column and are aggrading on the channel floor [*Little and Biedenharn*, 2014].

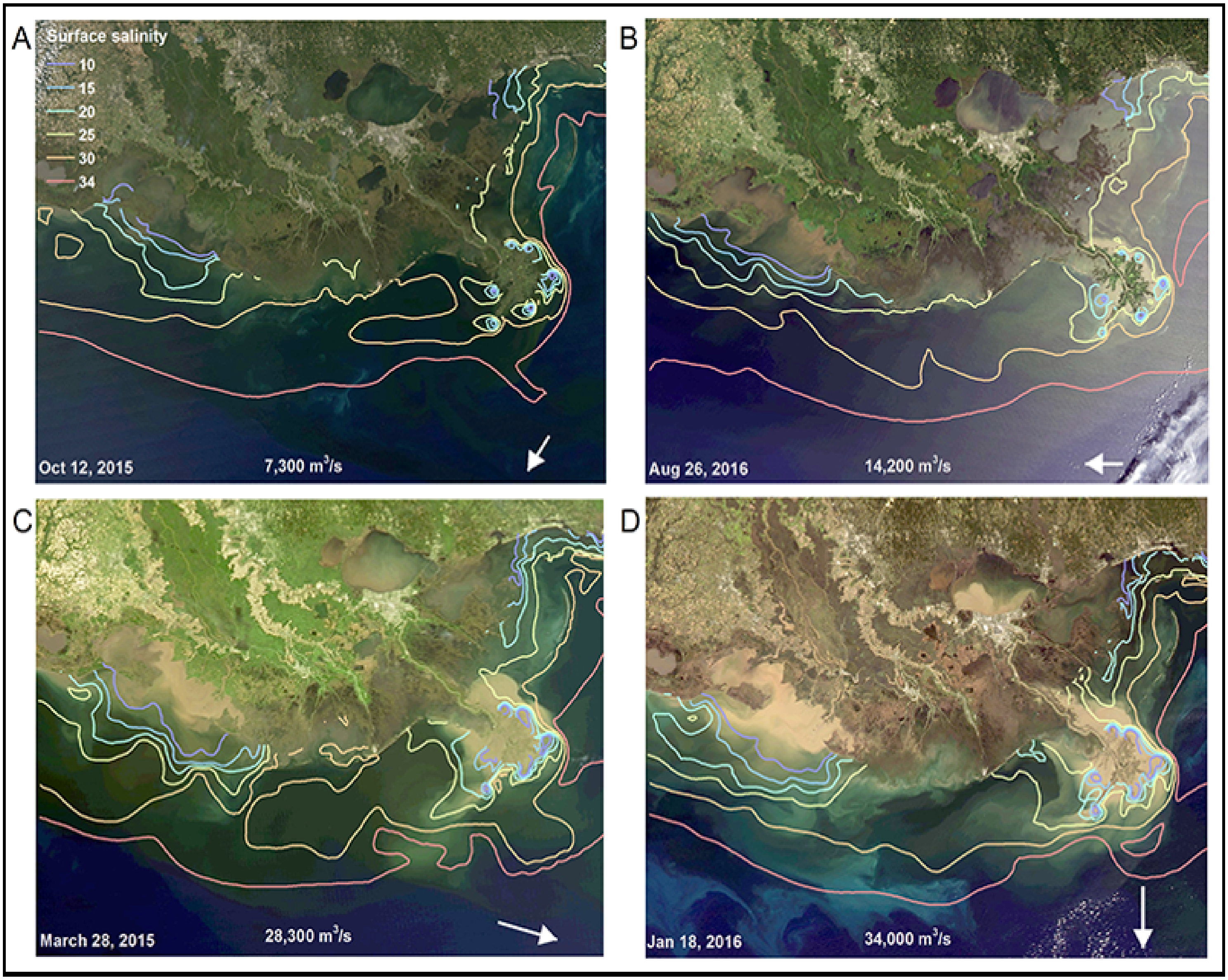


Fig. 2. These true-color images from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Aqua satellite show the Mississippi River plume and the Louisiana continental shelf during periods of (a) low, (b) medium, and (c) and (d) high discharge as measured by the U.S. Geological Survey at Belle Chasse, La. (located in the center of each image). Note that Figure 2(d) captures a time when the Bonnet Carre Spillway, a flood control structure that shunts Mississippi River water eastward to Lake Pontchartrain and beyond, was active. White arrows in the lower right corners indicate wind direction. Salinity (conductivity, measured as practical salinity units) and wind data are based on output from the National Oceanic and Atmospheric Administration's Northern Gulf of Mexico Operational Forecast System Finite Volume Coastal Ocean Model (NGOFS FVCOM).

Today's conditions reflect system-scale shifts that may be coupled to changes in channel dynamics. The channel shifted from a transport-limited system (the amount of sediment transported is limited by the stream power's ability to transport the plentiful sediment supply) during the 19th century to a supply-limited system in the 20th century (stream power is sufficient to transport the limited sediment supply).

This shift happened as the result of a series of engineering efforts between the late 19th and mid-20th centuries, which converted almost the entire Mississippi River channel south of the confluence with the Ohio River into a naturally dredged self-scouring system [*Alexander et al.*, 2012]. This series of engineering efforts included shortening the river and adding levees that limited overbanking and increased velocities, thereby enhancing sediment export.

The channel was largely in an erosive state during the middle part of the 20th century; many reaches are now either in a dynamic equilibrium or aggrading (adding sediment) today.
Now, the channel could be shifting back to a transport-limited system [*Alexander et al.*, 2012]. An analysis (http://www.mvd.usace.army.mil/Missions/Mississippi-River-Science-Technology/MS-River-Geomorphology-Potamology) of lower Mississippi River channel bathymetries from the 1960s through the 2000s indicates that whereas the channel was largely in an erosive state during the middle part of the 20th century, many reaches are now either in a dynamic equilibrium or aggrading (adding sediment) today [*Little and Biedenharn*, 2014].

Questions of channel dynamics are of critical concern in the years ahead because of a phenomenon known as shoaling, in which the river channel becomes more shallow. Shoaling could accelerate if relative sea level rise reduces the slope of the Mississippi River or if changes to the volume of water carried by the river's distributaries occur. Either of these scenarios could affect navigation and commerce in this critically important pathway.

River and Delta Dynamics

Across the region, efforts are under way to study the coupling between the Mississippi River and its delta. One such program is Louisiana's Comprehensive Master Plan for a Sustainable Coast (http://coastal.la.gov/wp-content/uploads/2017/01/DRAFT-2017-Coastal-Master-Plan.pdf)—a 50-year, $50 billion effort that, if fully implemented, is predicted to build or maintain more than 2,070 square kilometers of land and reduce storm damages by nearly $150 billion [*LACPRA*, 2017]. Such coastal restoration plans rely heavily on partially diverting the flow of the river to bring new sediments and freshwater into the subsiding basin [*LACPRA*, 2017; *Fisk et al.*, 1954; *Twilley et al.*, 2016]. Recent research has revealed multiple new insights.

The flow through a gated, controlled diversion can potentially be optimized to maximize land building and reduce adverse impacts, such as shoaling in the Mississippi River or eutrophication in the receiving basin.
First, systems that function like the river diversions proposed in Louisiana's coastal master plan can deposit enough sediment to match (~1–3 centimeters thick per seasonal flood), or in some cases exceed, the high rates of relative sea level (https://eos.org/editors-vox/water-world-sea-level-rise-coastal-floods-and-storm-

surges) that exist across the region (~1–3 centimeters per year [*Esposito et al.*, 2013; *LACPRA*, 2017]). Although sediment budgets indicate that there is insufficient sediment to rebuild the entire delta over the plan's 50-year period [*Allison et al.*, 2012], extensive modeling conducted as part of Louisiana's coastal restoration efforts indicates that sediment delivery through diversions can provide enough material to rebuild and maintain some critical areas [*LACPRA*, 2017, and references therein].

Second, the flow through a gated, controlled diversion can potentially be optimized to maximize land building and reduce adverse impacts, such as shoaling in the Mississippi River or eutrophication in the receiving basin [*Peyronnin et al.*, 2017]. If the operations strategy is not well managed, inundation associated with diverting freshwater into existing marshes has the potential to affect their productivity [*Snedden et al.*, 2015]. However, despite these strong river inputs, hydrodynamics in many diversion-receiving basins are heavily influenced by winds and offshore forcings [*Roberts et al.*, 2015], environmental complexities that require robust models to support management decisions.

Port Fourchon in the lower Mississippi River Delta, the largest offshore-servicing oil and gas port in the Gulf of Mexico. This port, surrounded by wetlands and open water, exemplifies the complex network of competing demands of ecosystems, infrastructure, and offshore activities in the Mississippi River Delta region. Credit: Alexander S. Kolker and Southwings

Research is also changing the community's view of the Mississippi River plume, particularly the development of the seasonal (summer) hypoxic zone (https://eos.org/articles/gulf-of-mexico-dead-zone-largest-since-2002). Although hypoxia has long been considered detrimental to fisheries, recent modeling studies indicate that the stimulative effect of nutrient enrichment on fisheries biomass is often greater than the negative effects of hypoxia caused by this enrichment [*de Mutsert et al.*, 2016].

Furthermore, the size and shape of the plume are governed by factors other than Mississippi River discharge, the primary contributor to the hypoxia forecast (https://gulfhypoxia.net/); these factors include winds, storms, and fronts [*Justic and Wang*, 2014]. The complexity associated with all of these factors indicates the need for, and benefit of, complex, multidimensional models to inform complex management decisions in large-scale systems [e.g., *Meselhe et al.*, 2016; *LACPRA*, 2017].

Applying the Science to Decision-Making

Restoring the Mississippi River Delta and associated environments is a major policy objective. This delta, as with other large rivers worldwide, is a major center for human population, transportation, industry, and critical ecosystem services (https://eos.org/opinions/understanding-ecosystem-services-from-a-geosciences-perspective) [*LACPRA*, 2017]. The Mississippi River Delta and many of these systems are similarly threatened by relative sea level rise [*Giosan et al.*, 2014]. As such, findings from the Mississippi River Delta and its coastal zone have the potential to influence science and inform decision-making on a global scale.

One particularly critical area is the planned diversions of the Mississippi River, which are designed to restart natural deltaic land-building processes.

Issues facing the Mississippi River Delta involve multiple interacting natural and anthropogenic components. Management actions are required to maintain or expand functionality in such critical areas as navigation, energy production, and fisheries while also restoring damaged habitats and providing flood protection for coastal communities. Restoration, protection, and river management decisions require the use of a multitude of models linked through a series of computational inputs and outputs. These models are exemplified by their use in Louisiana's coastal master plan.

One particularly critical area is the planned diversions of the Mississippi River, which are designed to restart natural deltaic land-building processes. Models are being developed to predict locations in the river and in the receiving waters where diversions will be most beneficial to land building [*Meselhe et al.*, 2016]. These modeling efforts (http://www.mvd.usace.army.mil/Missions/Mississippi-River-Science-Technology/MS-River-Geomorphology-Potamology/) examine how diverting the Mississippi River could induce river shoaling, which would be hazardous to navigation. Modeling efforts also examine how to optimize the amount of water and sediment diverted from the river [*Peyronnin et al.*, 2017]. Models of diversions also provide insights into the salinity and hydrodynamics of coastal bays, water quality, and fisheries [*LACPRA*, 2017, and references therein].

The Mississippi River cuts through the center of this image as it flows from downstream, from left to right. Examples of the multiple uses of the river and surrounding environments can be seen, including petrochemical facilities (circular tanks on the left side of photograph and left side of the river), navigation and shipping (note barges along the river and the railroad on the river side of the river), and residential housing (small buildings on both sides of the river). Also present along the right bank of the river and on the right of the image is the outfall channel of the Davis Pond Freshwater Diversion, a small

(30–300 cubic meter per second) diversion that is part of environmental restoration and management activities. Balancing the needs of navigation and ecosystem restoration in an era of high subsidence and accelerating global sea level rise requires science-informed management solutions. Credit: Alexander S. Kolker and Southwings

Entirely different sets of models are used to evaluate how restoration and protection features affect storm surge dynamics changes to land area, marsh type, flood risk, inundation depths, carbon sequestration, and economic impacts [*LACPRA*, 2017, and references therein]. These models are informed by data from local platforms (https://www.lacoast.gov/crms2/home.aspx) monitoring salinity, water levels, and shallow subsidence rates, as well as by global climate models and global sea level projections, all of which affect model projections of storm surge and land building [*LACPRA*, 2017, and references therein].

All of these models are integrated into a comprehensive modeling framework that is used to inform science-based decision-making processes.

Applying the Concepts Around the World

Complex environmental management in large river systems requires broad-based and complex science, engineering, and monitoring.
The Mississippi River Delta region is similar to many other large river deltaic systems that also experience high rates of subsidence and have accelerating rates of global sea level rise, are subject to altered water and sediment fluxes, and are home to large human populations. Such regions include the delta systems of the Ganges-Brahmaputra (https://eos.org/opinions/monitoring-coastal-zone-changes-from-space), Yellow, Danube, Nile, Tigris-Euphrates, Fly, and Po rivers [*Giosan et al.*, 2014].

The approach being implemented in the Mississippi River Delta demonstrates how complex environmental management in large river systems requires broad-based and complex science, engineering, and monitoring. With regard to delta management worldwide [e.g., *Giosan et al.*, 2014], robust research can lead to paradigm shifts in understanding how large river systems function and interact with the ocean.

Coastal and deltaic research programs must continue to evolve, especially by incorporating ongoing changes in global sea level rise rates, to ensure that information and outcomes reflect emerging changes in landscape sustainability and human safety. Ultimately, the feedback between management and research that is ongoing in the northern Gulf of Mexico is a framework that can be applied worldwide.

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