

The Impacts of the Mississippi River and its Delta on the Oceanography, Ecology and Economy of the Gulf of Mexico Large Marine Ecosystem

ALEX S. KOLKER, SIBEL BARGU, JORGE BRENNER, PHILIP CHU, JOHN CONOVER, KIM DE MUTSERT, CATHERINE FITZPATRICK, DANIELLE R. GREENHOW, DUBRAVKO JUSTIC, STEVE E. LOHRENZ, PAUL A. MONTAGNA, NATALIE SNIDER PEYRONNIN, JEREMY PROVILLE, ALISHA RENFRO, RACHEL RHODE, BRIAN J. ROBERTS, CAZ M. TAYLOR, TERRY L. WADE, NAN D. WALKER, DAVID J. WALLACE

Executive Summary

This manuscript examines what is known about the influence of the Mississippi River and its delta on the oceanography, ecology and economy of the Gulf of Mexico. While it has long been recognized that the Mississippi River plays a dominant role in the Gulf of Mexico, given that it is the largest source of freshwater, nutrients and sediments to this section of the ocean, few previous efforts have actively sought to summarize the multitude of the river's impacts. This document demonstrates the Mississippi River's importance in the Gulf of Mexico, producing a plume of freshwater that extends 10,000 to 35,000 km² in area. The plume's extent is further influenced by dynamical and meteorological factors that govern its distribution. The river's plume has important implications for the ecology of the Gulf of Mexico-it provides large nutrient loads that contribute to highly productive marine ecosystems, and yet it also fuels a seasonal hypoxic zone that is one of the largest such zones on earth. However, recent publications indicate that the stimulatory impacts of the Mississippi River on fish populations outweigh the deleterious impacts of hypoxia- although research on this topic is still ongoing. The Mississippi River plume is also an important source of food and sediment to benthic communities, though this delivery is irregular and this irregularity of river inputs influences the structure of benthic ecosystems.

The delta of the Mississippi River and associated estuaries also provide substantial impacts to the Gulf of Mexico. They are also a source of freshwater to the Gulf, although about 10-50 times smaller, than the river itself. The delta and its estuaries provide important food, habitat, and nursery grounds for numerous species of ecologically and economically important species of vertebrates and invertebrates that live in the Gulf of Mexico. However, the wetlands of the Mississippi River Delta are in a chronic state of land loss. While the implications of this land loss are widespread, for the purposes of this review the most important impact is that Louisiana's degrading wetlands provide an important, but often localized, source of carbon and sediments to the Gulf of Mexico. Small active deltas near the mouth of the Mississippi and Atchafalaya Rivers provide important, but localized, sinks for sediments, carbon and nutrients.

Over the past century humans have had substantial impacts on the Mississippi River, its delta, and the way that these systems impact the Gulf of Mexico. Shifts to the river include major hydrological changes to the channel of the Mississippi River that constrain its flow, the construction of dams in the river's watershed that reduce the river's sediment flux to the coast, and major increases in agriculturally-derived loads that both increase primary production, secondary (e.g., fish) production and hypoxia. Shifts to the delta include a range of geologic, geomorphic and ecosystem impacts that lead to wetland loss, which can increase the flux of carbon and sediments to the Gulf, and which can shift (both positively and negatively) available habitat for estuarine-dependent species.

In the decades ahead, the impacts of the Mississippi River and its delta on the Gulf of Mexico are likely to continue to change, largely (but not entirely) because of human-driven processes. Climate change, global sea level rise, channel aggradation, and continued subsidence

could cause shifts in the lowermost outlet of the Mississippi River, shifting the plume's distribution northward. The State of Louisiana is actively planning to partially divert the flow of the Mississippi River as a means to rebuild its wetlands. These "river diversions" would also shift northward the plume of the Mississippi River, and this could trigger a suite of cascading impacts to the ecosystem. Such changes would have important societal impacts as the Mississippi River is a critical transportation pathway, and Gulf of Mexico fisheries are among the most economically important fisheries in the nation. Overall, it is the intention of this manuscript to provide important supporting material to inform regional decision makers as they prepare for restoration that might occur in continued response to the Deepwater Horizon Oil Spill and future oil spills or large-scale perturbations, prepare to reverse decades of other environmental impacts such as wetland loss, and prepare for a future with a warming climate and rising sea levels.

I. INTRODUCTION

I.A. Background

This paper examines the influence of the Mississippi River and its delta on the Gulf of Mexico. While it is well known that the Mississippi River is the largest source of water, sediments, and nutrients to the Gulf of Mexico (Dunn 1996; McKee et al. 2004), many details regarding the fate, transport, and environmental impacts of these materials remain unresolved. Additionally, many effects of the Mississippi River Delta on the ecology and oceanography of the Gulf of Mexico remain to be fully answered, despite the fact that this delta is one of the largest and most productive components of the Gulf of Mexico Large Marine Ecosystem. Filling these knowledge gaps is particularly important because many people and industries depend on the Mississippi River, its delta and the river-influenced areas of the Gulf of Mexico for their livelihood and culture (LACPRA 2017). Furthermore, the functioning and influence of the river and its delta could change in the years ahead as the climate changes, as the rate of relative sea-level rise accelerates, and as the State of Louisiana initiates a Coastal Master Plan that will partially divert the flow of the Mississippi River.

I.B. Study Region

For the purposes of this paper, the Mississippi River system (Fig.1-1) is considered to be any part of the Mississippi River and its distributaries that discharges into the Gulf of Mexico. This includes the river's mainstem, major

distributaries (such as the Atchafalaya River), flood control structures that discharge into the estuaries (such as the Bonnet Carré Spillway), as well as additional sources of river water to the ocean (such as subterranean flow from the Mississippi River to the coastal zone). This paper considers the entirety of the Gulf of Mexico, including the five U.S. Gulf States, federal waters, as well as those sections of the Gulf of Mexico that are in Mexican, Cuban, and international waters. The Mississippi River system drains an area of $3.2 \times 10^6 \text{ km}^2$, including the entirety or parts of 31 states and 2 Canadian provinces (Day et al. 2007). The outlet of this river system is

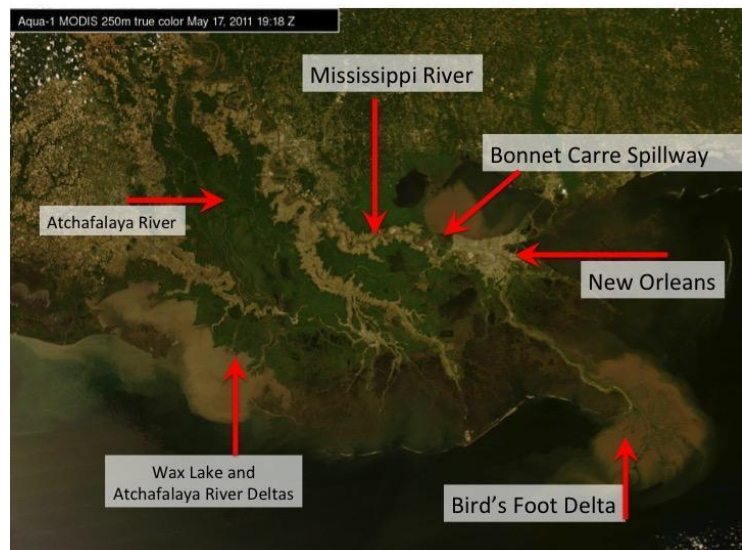


Fig. 1-1. NASA/Modis imagery of the Mississippi River Delta and its coastal zone, with key areas highlighted. Image date: May 17, 2011. Image credit: Louisiana State University Earth Scan Laboratory. www.esl.lsu.edu

the Mississippi River Delta, a 38,600 km² region that contains a vast network of rivers, bayous, wetlands, lakes and open bays (Day et al. 2007).

I.C. Study Scope

A working group was convened to discuss and examine the influences of the Mississippi River and its delta on the ecology, oceanography, and economy of the Gulf of Mexico Large Marine Ecosystem. The study is concerned largely with modern time scales, which as defined here are having occurred during the last 100 years, and changes that are likely to occur over the next 50-100 years. This time scale covers most of the intensive post-industrial human impacts to the river system, and incorporates the reasonably foreseeable changes that could occur with climate change, continued environmental impacts, and planned restoration. Longer time scales will only be examined to the extent that they inform the focus time scale.

This group examined the following five critical questions:

- 1) How does the Mississippi River influence water column processes in the Gulf of Mexico? What material does the river deliver, over what area is this material delivered, and how is it reworked and redistributed over time? What are the impacts of Mississippi River water on living resources in the Gulf of Mexico?
- 2) What is the Mississippi River's influence on the seafloor in the Gulf of Mexico? What are the major benthic communities in the Gulf of Mexico? How do benthic habitats and substrates change from the shallow regions of the Gulf of Mexico to the deep ocean, and what are controls on these changes? How do the processes that control sediment metabolism, sediment reworking, and sedimentary geochemical cycles change from the shallow reaches of the Gulf of Mexico to the deep sea, and how do these processes change as the river's influence becomes increasingly distant?
- 3) What is the impact of the river on the estuarine reaches of the delta, and what is the impact of the delta on the coast?
- 4) What are the human influences on the ways that the Mississippi River and its delta influence the oceanography, ecology, and economy of the Gulf of Mexico?
- 5) What are the potential future impacts on the ways that the Mississippi River and its delta influence the oceanography, ecology, and economy of the Gulf of Mexico?

These questions are addressed through a synthesis-style process that examines existing data, publications and, where appropriate, numerical models. The influence of the Mississippi

River and its delta on the oceanography of the Gulf of Mexico have been addressed by individual researchers and specific teams for decades. Such efforts include, but are not limited to: efforts to study the seasonal hypoxic zone; river/plume physical dynamics; the diversity of abundance of many species; fisheries production; the flux of nutrients, organic matter and contaminants; the impacts of major oil spills; and the ecological restoration of the Mississippi River Delta. Despite this intensity of research, there have been relatively few review efforts that have examined the impact of the river and its delta on the oceanography of the Gulf of Mexico. Many of the best reviews to date have examined the drivers of hypoxia (T. S. Bianchi et al. 2010; N. N. Rabalais, Turner, and Wiseman 2002), the role of large rivers and their deltas in general (Syvitski and Saito 2007; Syvitski et al. 2003; McKee et al. 2004), specific issues related to river management and coastal restoration (Allison et al. 2012; Allison and Meselhe 2010), syntheses in support of the offshore energy industry (Boesch and Rabalais 1987; Shepherd et al. 2016), general introductions to oceanography and ecology the Gulf of Mexico and the Mississippi River Delta (Kumpf, Steidinger, and Sherman 1999; Day et al. 2007), and the impacts of the BP/Deepwater Horizon Oil Spill in 2010 (Shepherd et al. 2016; Colwell 2014). The goal of this paper is to provide a comprehensive, yet easily accessible analysis that can provide managers, decision makers, academics, and the interested public with the information that they need to understand how the largest river in the United States and its delta impact the ocean.

II. WATER COLUMN PROCESSES

II.A. Introduction and Conceptual Model

This section examines how the Mississippi River system influences water column processes in the Gulf of Mexico: the material the Mississippi River delivers, the area over which this material is delivered, and how is it reworked and redistributed over time. A summary of the impacts of the Mississippi River on water column processes in the Gulf of Mexico is in Figure 2-1. This figure traces the flow of water, sediments and nutrients from the time they enter the Gulf of Mexico through their transport and fate in the water column. The figure shows that plume water can be transported through wind-driven processes, such as cold fronts and summer winds, or influenced by offshore processes such as the Loop Current and associated mesoscale eddies. This figure also shows the impact of river water on ecological processes in the Gulf of Mexico, including primary production, secondary production, and nekton production. The figure reaches the benthos, but the total impacts of the Mississippi River on the benthos in the Gulf of Mexico are presented in a separate model (see Fig. 3-1). Finally, the figure demonstrates the time scales over which processes occur, and evaluates the state of the community's knowledge over of these processes.

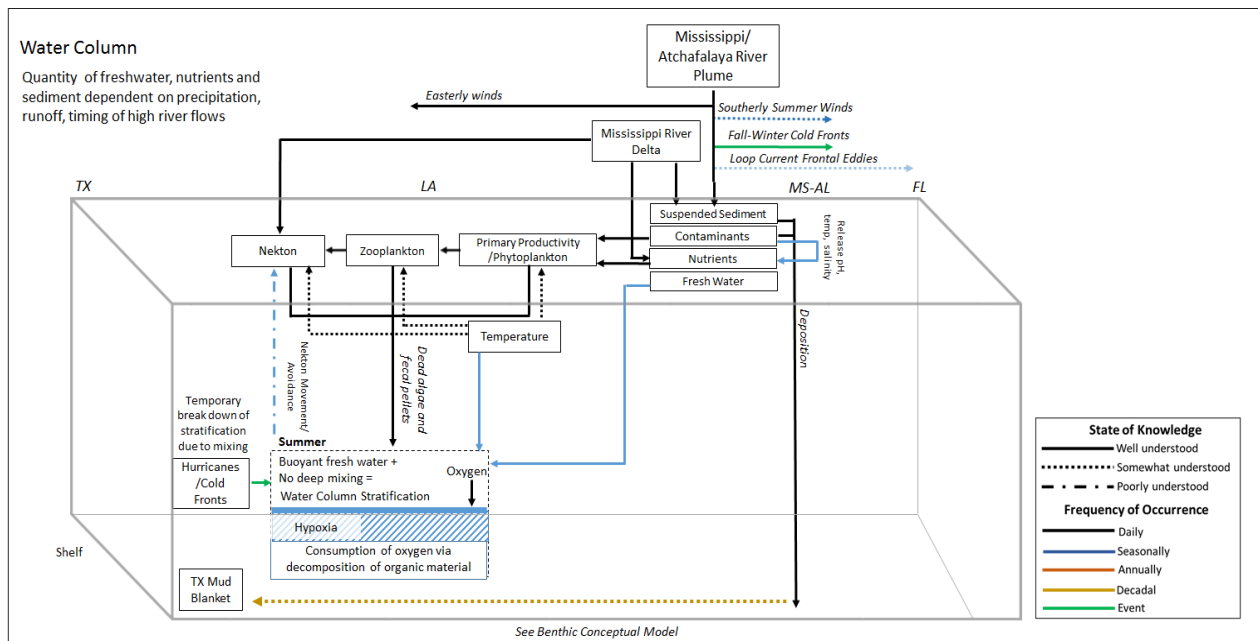


Fig. 2-1. Conceptual model of the impacts of the Mississippi River on the water column of the Gulf of Mexico

II.B. Hydrological Fluxes

The direct inputs of the Mississippi River to the Gulf of Mexico are relatively well known (Figs. 2-2, 2-3). The river system currently delivers approximately 750 km^3 of water to the Gulf, with $\sim 70\%$ of this water flowing through the river's mainstem and $\sim 30\%$ exiting through the Atchafalaya River, to the west (Allison et al. 2012). The system also delivers approximately 108×10^6 metric tons of sediment to the gauging stations near the Gulf of Mexico per year, with $\sim 60 \times 10^6$ metric tons discharging through the mainstem and 48×10^6 discharging through the Atchafalaya River (Allison et al. 2012). The Mississippi River system is also the primary source of biologically important dissolved constituents to the Gulf of Mexico. It delivers $\sim 1.3 \times 10^6$ metric tons of nitrogen per year (Fig. 2-4), 1.4×10^5 metric tons of phosphorus, and 4.2×10^6 metric tons of dissolved silica per year (Turner et al. 2007). However, these numbers fluctuate by a factor of about 2-5 from year to year, primarily with river discharge fluctuations, but also with other environmental factors (Turner et al. 2007).

The inputs of water, sediments, and nutrients are distributed heterogeneously and non-linearly across the Gulf of Mexico. Water from the Mississippi River begins to enter the Gulf about 70 km upstream from Head of Passe, as water begins to flow through degraded levees on the eastern side of the river. Distributaries located between Belle Chasse and Head of Passes distribute about 236 km^3 annually, or about 44% of the total discharge of the Mississippi River (Fig. 2-2). Most of the remaining discharge, about $253 \text{ km}^3 \text{ yr}^{-1}$ exits through the three major distributaries in the Birdsfoot Delta, with Southwest Pass discharging $163 \text{ km}^3 \text{ yr}^{-1}$ of water, and South Pass and Pass a Loutre discharging 47 and $43 \text{ km}^3 \text{ yr}^{-1}$ respectively (Allison et al. 2012).

Thus approximately $305 \text{ km}^3 \text{ yr}^{-1}$ of water are discharged southward or westward towards the Louisiana Bight, and $184 \text{ km}^3 \text{ yr}^{-1}$ of water are discharged eastward or northward toward Breton Sound or the Mississippi coast (Allison et al. 2012). Additionally, about 31 km^3 of water flow from the Mississippi River to the estuaries of the delta through subterranean pathways, though this discharge likely varies with river stage (A. S. Kolker et al. 2013).

Approximately 29.4×10^6 metric tons (MT) of sediment are discharged to the coastal zone between Belle Chasse and Head of Passes (~33% of the Belle Chasse load or $\sim 88 \times 10^6 \text{ MT yr}^{-1}$), with $30.3 \times 10^6 \text{ MT}$ of sediment discharged south of Head of Passes. Across the entire lower Mississippi River, approximately $34.7 \times 10^6 \text{ MT}$ of sediment are discharged westward and southward, and $25 \times 10^6 \text{ MT}$ of sediment are discharged eastward and northward. About $26 \times 10^6 \text{ MT}$ of sediment, or about 29% of the annual discharge at Belle Chasse, are discharged into the deepwater reaches of the Gulf of Mexico at South Pass and Southwest Pass (Allison et al. 2012).

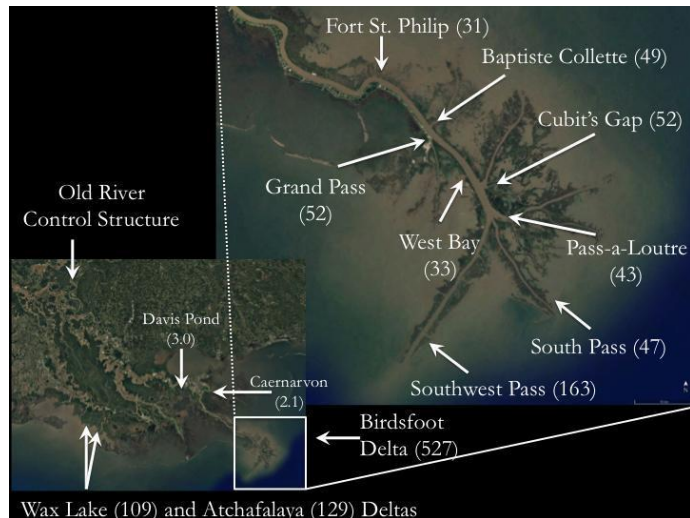


Fig. 2-2. Annual inputs of freshwater (in km^3) from the Mississippi and Atchafalaya River to the Gulf of Mexico. Source: Allison et al., (2012), Kolker et al., (In Press)

Water and dissolved constituents are transported over a wide area across the northern Gulf of Mexico. An analysis of the U.S. Navy's Global Hybrid Coordinate Ocean Model (HYCOM), and its associated reanalysis data indicates that the plume of the Mississippi and Atchafalaya Rivers, operationally defined as surface areas that are $< 33 \text{ PSU}$, range from 10,000 - 35,000 km^2 (Fitzpatrick, Kolker, and Chu 2017).

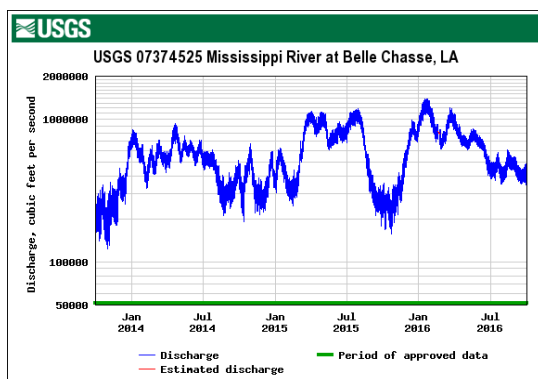


Fig. 2-3. Daily discharge in the lower Mississippi River at Belle Chasse. Source: USGS

These data (Fig. 2-5), coupled with earlier work, indicate that some sections of the open ocean regions of the Gulf of Mexico are always influenced by freshwater from the Mississippi River (Fitzpatrick, Kolker, and Chu 2017; Schiller et al. 2011; Walker et al. 1996), a finding that stands in contrast to many other Atlantic and other Gulf Coast rivers and their associated estuaries--such as the Hudson and the Chesapeake, where much less freshwater reaches the open ocean. On average, the plume extent is at its greatest in May and June, when the 33 PSU contour regularly extends to Mobile Bay to the east, and to

Matagorda Bay to the south and west. The size of the plume (Fig 2-6) is only partially correlated with the discharge of the Mississippi and Atchafalaya Rivers (Fitzpatrick, Kolker, and Chu 2017), confirming previous study results that winds, tides and the Loop Current and associated eddies play an important role in governing its distribution (Walker et al. 2005; Schiller et al. 2011; A. S. Kolker et al. 2014; Walker et al. 1996; Walker 1996). Indeed, Walker (1996) and Walker et al. (1996) demonstrated that wind is a critical controlling factor for the distribution of the river plume around the Mississippi River Delta. Easterly (westward) winds increase the freshwater flow towards the west and westerly (eastward) winds force the river water to the southeast and east side of the delta. Eddies are closer to the delta to the east due to the deeper depths and thus they play a more frequent role in offshore transport there (Walker et al. 2005).

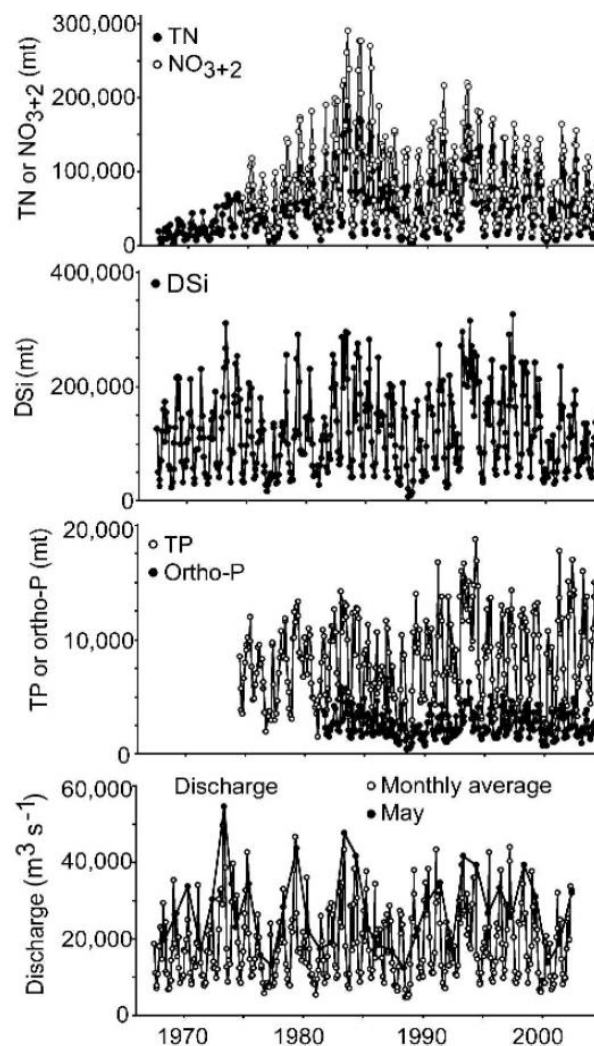


Fig. 2-4. Concentrations of dissolved nitrate, silica, and phosphorus and the discharge of the lower Mississippi River. Source: Turner et al. (2007) and refs therein.

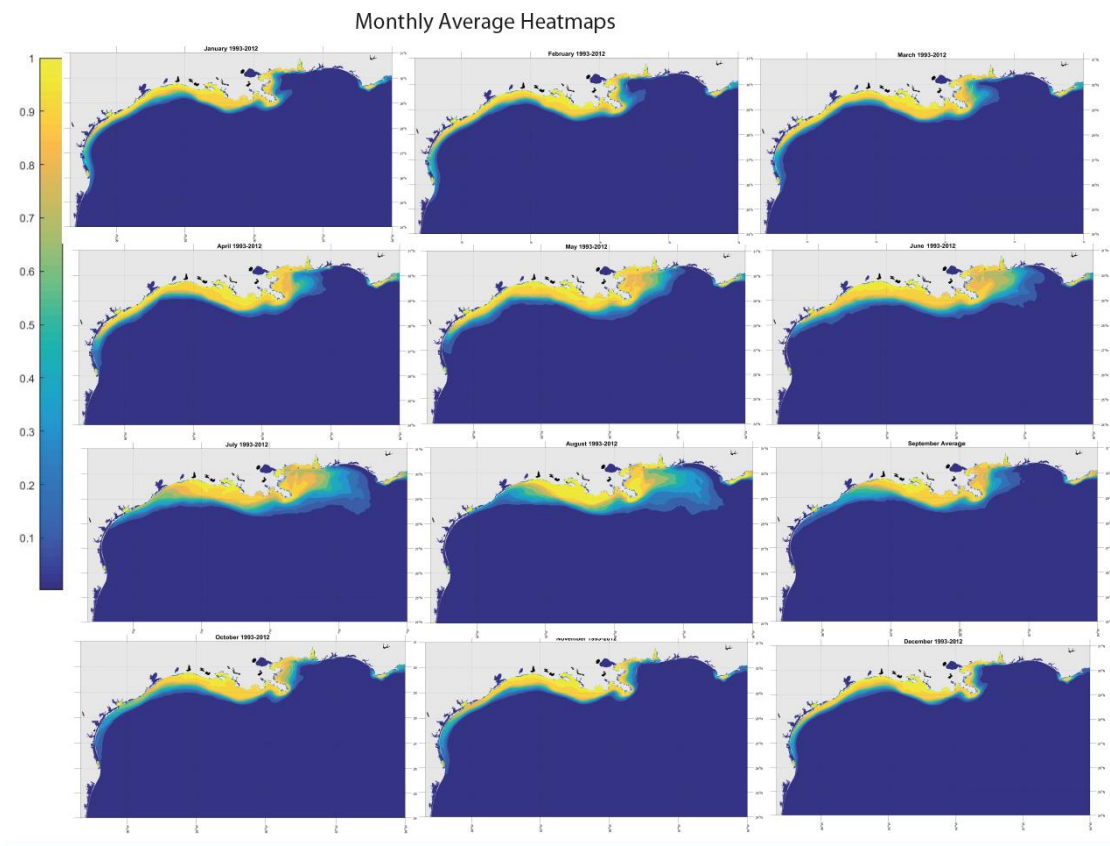


Fig. 2-5. Average monthly distribution of the Mississippi River plume, as defined by the 33 PSU, and determined from the HYCOM Model. Source: Fitzpatrick et al. (2017, and Fitzpatrick In Prep.).

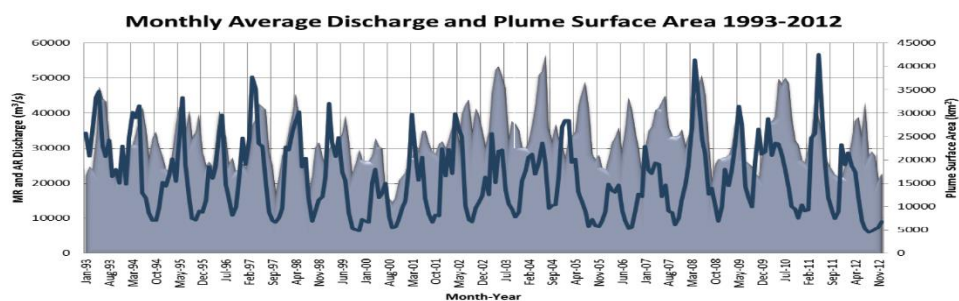


Fig. 2-6. Relationship between the monthly area of the Mississippi River plume (set at 90% the 33PSU contour in Fig 2-5) and the monthly discharge of the Mississippi River. Source: Fitzpatrick et al., (2017) and Fitzpatrick et al., (In Prep.).

The impacts of the Mississippi River plume on the Gulf of Mexico are governed, to an important degree, by stratification. River-dominated stratified waters are dominantly moved by wind transport, with about 60% of the time the wind directing the plume westward (Walker and Hammack 2000). In some cases, stratification can increase as the plume moves westward, as freshwater from the Atchafalaya River is added to the plume. This is also known to happen east of the delta, though to a lesser degree, as freshwater from rivers (such as the Pearl River) enter the Gulf of Mexico (Dzwonkowski et al. 2014). Despite this, there are time periods when the thickness of the freshwater plume on the continental shelf prevents mixing with deeper layers, effectively shutting down additional transport and mixing (Androulidakis, Kourafalou, and Schiller 2015).

The Atchafalaya and the Mississippi River have different discharge patterns that govern how they interact with the Gulf of Mexico. First, whereas the Mississippi River discharges its water over ~225 km of shoreline (along a curvilinear pathway from near Venice to Mardi Gras Pass; Fig. 2-2), the Atchafalaya River discharges through a 47 km passage at the mouth of Atchafalaya Bay. This means that while the total discharge of the Atchafalaya River is less than the Mississippi River, nearshore salinities on the Atchafalaya Shelf can be lower than nearshore salinities in many parts of the immediate region of the Birdsfoot Delta (A. S. Kolker et al. 2014). Second, the Atchafalaya River discharges into a shallow continental shelf where seafloor depths are often < 10m, which means that the plume can interact directly with the seafloor (Wright 1997; Walker and Hammack 2000). In contrast, the Mississippi River discharges onto both the shelf and into deepwater, and flow from the deepwater discharging distributaries do not interact with the seafloor, meaning that dynamics are driven largely by buoyancy, rather than friction (Wright and Coleman 1971; Wright 1997; Walker et al. 2005; Walker and Hammack 2000; Walker et al. 1996).

These differences have important implications for how the plumes behave and how they influence the Gulf of Mexico. Since the plumes of the Atchafalaya River, and the shallow water discharge sections of the Mississippi River (e.g., Baptiste Collette) interact with the bottom, they tend to have a wide, fan-shaped plume (Wright 1997; A. S. Kolker et al. 2014). Sediments near these plumes are readily resuspended by winds, though intense flood-driven stratification can limit such resuspension (Jaramillo et al. 2009). In contrast, the deepwater discharging distributaries of the Mississippi River (i.e., South and Southwest Pass) tend to have highly focused, jet shaped plumes that rarely interact with the bottom (Wright 1997; Falcini and Jerolmack 2010). Recently transported sediments here are rarely resuspended, and, instead, can be transported to the deep sea (Roberts 1997).

II.C. Contaminant Fluxes

The Mississippi River is also an important source of trace metal and rare earth elements to the Gulf of Mexico (Joung and Shiller 2014; Shiller 1997). Interestingly, studies have indicated strong seasonal cycles in the transport of elements in the Mississippi River such as Fe,

Mn, Zn, Pb, V, Mo, U, Cu, Ni, Cd, Rb, and Ba, but relatively little year-to-year variability (Shiller 1997). Furthermore, even a high energy event with the strong potential to resuspend sediments, such as Hurricane Katrina, showed relatively little impact on the distribution of metals in areas in the Gulf of Mexico near the outfalls of the mainstem of the Mississippi River (Shim, Swarzenski, and Shiller 2012). Both the transport and fate of this material is highly phase sensitive, with some elements being transported primarily in the dissolved phase (U, Ba), others in the particulate phase (e.g., Fe, Pb), and others in both (Mn, Zn) (Shiller 1997). Plume shelf processes, including hypoxia, can change the solubility of elements--for example, V has been shown to be released from shelf sediments under hypoxic conditions (Shiller and Mao 1999).

The Mississippi River also carries numerous contaminants associated with agriculture in the central part of the United States. Among the most abundant and problematic contaminant is nitrate (which comes from fertilizer), and its impact on the Gulf of Mexico ecosystem is discussed in sections II.E, and V.E. Other agricultural contaminants include numerous pesticides and herbicides, though they generally appear at levels below that considered unsafe by drinking water standards (Goolsby and Pereira 1995; Pereira and Hostettler 1993). More recent research has indicated an increase in salinity in the Mississippi River (Kaushal et al. 2018); however, given the relatively recent nature of this finding it is too early to ascertain the full impacts of increased river salinity on the Gulf. While there are concerns about contaminants along industrial corridors of the Mississippi River and their potential relationship to cancer nearby residents, relatively less is known about the impacts of these contaminants on the chemistry or ecology of the Gulf of Mexico (Watanabe et al. 2003).

II.D. Example of the Influence of the Plume on Distal Regions: The Texas Mud Blanket

The influence of the Mississippi River on the Gulf of Mexico's seafloor can extend 100s of kilometers laterally, and 1000s of meters vertically from the river mouth. One example of distal influence is the "Texas Mud Blanket." This collection of sedimentary deposits is located offshore of central Texas in up to 150 m of water and ~500 km from the delta. The Texas Mud Blanket evolved during the late Pleistocene and early Holocene into a system that is up to 20 m thick, and which has a total sedimentary volume of about 300 km³ (Weight, Anderson, and Fernandez 2011). Overall, ~33% of the sedimentary volume of the Texas Mud Blanket can be attributed to the Mississippi River.

II.E. Influence of the Mississippi River Plume on Coastal Hypoxia

The Mississippi River plays an important role in the development of hypoxia along the continental shelf in the northern Gulf of Mexico (N. N. Rabalais, Turner, and Wiseman 2002). The formation of hypoxia is complex (Figs. 2-7, 2-8) and involves multiple interacting factors (T. S. Bianchi et al. 2010; N. N. Rabalais, Turner, and Wiseman 2002). A brief overview of the process is as follows. Nutrients from the Mississippi River trigger primary production along the

continental shelf, which produces vast amounts of organic matter (N. N. Rabalais, Turner, and Wiseman 2002). Microbes then degrade this organic matter, and this microbial activity requires oxygen. While this decomposition can take place throughout the water column, it is greatest in the lower depths of the water column and in sediments. Additionally, the large freshwater plume from the Mississippi River creates a highly stratified water column, particularly during summer, and this intense stratification prevents the resupply of dissolved oxygen to the bottom waters (T. S. Bianchi et al. 2010; Y. Feng, DiMarco, and Jackson 2012). The microbial respiration, coupled with the physical stratification, produces large areas of hypoxia (defined as having dissolved oxygen < 2.0 mg/L), which is particularly pronounced during summer along the Louisiana and Texas continental shelves (N. N. Rabalais, Turner, and Wiseman 2002; T. S. Bianchi et al. 2010).

While the Mississippi River plays a dominant role in providing the nutrients and stratification that drive hypoxia along the northern Gulf of Mexico, other physical and biogeochemical oceanographic factors also contribute to this process (T. S. Bianchi et al. 2010). Winds play a critical role in mixing the water column, and in the dispersal of the Mississippi River plume (Y. Feng, DiMarco, and Jackson 2012). A tropical cyclone, or other period of intense winds can mix the summer water column, injecting oxygen to deeper waters of the Gulf of Mexico. Additionally, westward blowing winds, currents, and the

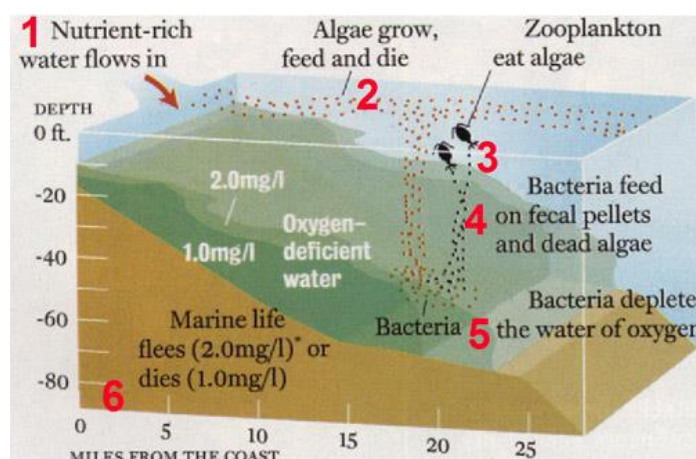


Fig. 2-7. Schematic depicting the evolution of hypoxia in coastal waters. Source: Gulfhypoxia.net

Coriolis Effect tend to expand the area of the hypoxic zone on the Texas shelf, by forcing Mississippi River waters westward; while eastward blowing winds have the opposite effect, at least as regards the Texas shelf (Y. Feng, DiMarco, and Jackson 2012). Less is known about the impacts of hypoxia on the eastern shelf (Engle, Summers, and Macauley 1999; Smith, Engle, and Summers 2006). Freshwater inputs from other discharging rivers along the Gulf Coast may play a role. For example, the Brazos River appears to contribute to stratification, and thus hypoxia locally on the Texas shelf (DiMarco et al. 2012). Finally, other sources of carbon exist in the region that can fuel hypoxia. One potential source is the input of degrading organic matter from eroding marshes in the bays of the Mississippi River Delta (C. A. Wilson and Allison 2008; T. S. Bianchi et al. 2011), which have been in an erosional mode for almost a century, and are expected to remain so for the foreseeable future (Day et al. 2007; LACPRA 2017).

II.F. Impacts of the River and Hypoxia on Fish and Fisheries in the Gulf of Mexico

The impacts of Mississippi River-driven hypoxia on fisheries production in the Gulf of Mexico are complex, and driven by environmental factors that have impacts that are different in both sign and magnitude (Smith et al. 2014; Nancy N. Rabalais 2015). On one hand, the Mississippi River provides nutrients to the Gulf that stimulate the “Fertile Fisheries Crescent,” a band of the Gulf of Mexico that is about 200 km wide and extends roughly from the Alabama/Florida border to the Texas/Mexico border, where fisheries production and landings are among the highest in the nation (Gunter 1963). On the other hand, nutrients from the Mississippi River also fuel bottom hypoxia, which can be detrimental to marine fisheries (Nancy N. Rabalais 2015). Indeed, ample ecological and physiological evidence exists that dissolved oxygen concentrations of about 2.0 mg/L or less can cause detrimental physiological impacts and/or mortality to many marine fish, and fish kills associated with hypoxia have been noted in the Gulf of Mexico (Nancy N. Rabalais 2015; Chesney and Baltz 2000). However, studies also indicate that many species, including demersal fish, and brown shrimp have the ability to migrate away from the hypoxic zone, reducing its impact (Switzer, Chesney, and Baltz 2009; Smith et al. 2014; Purcell et al. 2017). Results from modeling studies indicate that stimulatory effects of high nutrient loads on productivity substantially outweigh the deleterious impacts of hypoxia development on fisheries production (De Mutsert et al. 2016). Overall, the impacts of river-derived nutrients on fisheries production must be regarded as complex, and full of non-linearities (Chesney and Baltz 2000).

The impacts of Mississippi River water on production is dependent both on the ratio of key nutrients in that water, and the spatial position location of the plume. For example, the rise in nitrate concentrations that have occurred in Mississippi River water have fueled a shift from communities dominated by hard shelled diatoms to communities dominated by diatoms with less hard shells, and, in some cases, communities with fewer diatoms (N. N. Rabalais et al. 1996). This is because the nitrate loadings, which are largely anthropogenic, have not been matched by an increase in silicate loadings, which has more of a natural source (N. N. Rabalais et al. 1996). Furthermore, the increases in nitrate have likely fueled an increase in harmful algal blooms in the Gulf of Mexico, which can have cascading impacts for humans and ecosystems (Anderson, Glibert, and Burkholder 2002).

Primary production is also influenced by location within waters of the Mississippi River plume. Waters closest to the mouth of the Mississippi River are largely light limited by suspended sediments and dissolved organic matter, waters a moderate distance from the

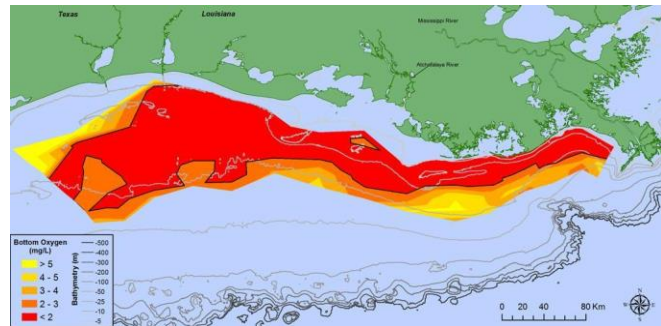


Fig. 2-8. Concentration of dissolved oxygen in bottom waters of the Gulf of Mexico during summer 2017. Source: Gulfhypoxia.net

Mississippi River (approximately the areas offshore of Barataria and eastern Terrebonne Bays) are most productive given the high nutrient loads and clear waters, and areas on the western side of Terrebonne Bay are typically less productive as nutrients have largely been removed (M. J. Dagg and Breed 2003; Michael J. Dagg et al. 2007). These patterns also impact the distribution of copepods, with greatest copepod abundances typically noted in the middle region (M. J. Dagg and Breed 2003). This is particularly significant given that copepods are a primary food source for numerous species of fish--including economically important ones - e.g. Gulf menhaden (M. J. Dagg and Breed 2003).

III. BENTHIC COMMUNITIES

III.A. Introduction and Conceptual Model

The primary impacts of the Mississippi River on the benthos of the Gulf of Mexico are governed through the deposition of mineral sediments and the accumulation of organic detritus of biological material produced in the river-influenced waters of the Gulf of Mexico. Inorganic sediments contribute to the physical structure, both providing habitat and potentially burying organisms in high sedimentation areas. Organic material provides an important, but often irregular food source to the benthos. The benthos off the Mississippi River are dependent upon the constant rain of organic materials to the bottom, as in all depositional areas of the world where light and thus primary production is limited. Suspension feeders dominate the muddy bottoms at the water-mud interface. Deposit feeders then process organic matter further as materials are reworked into the sediment by bioturbation and new materials covers older material. These communities are dominated by three taxa Crustacea, Polychaeta, and Mollusca, which can be highly diverse. Bottom feeding fish and mobile epifauna exploit the infauna. These processes are summarized in Figure 3-1, are their time scale of occurrence and the current state of knowledge.

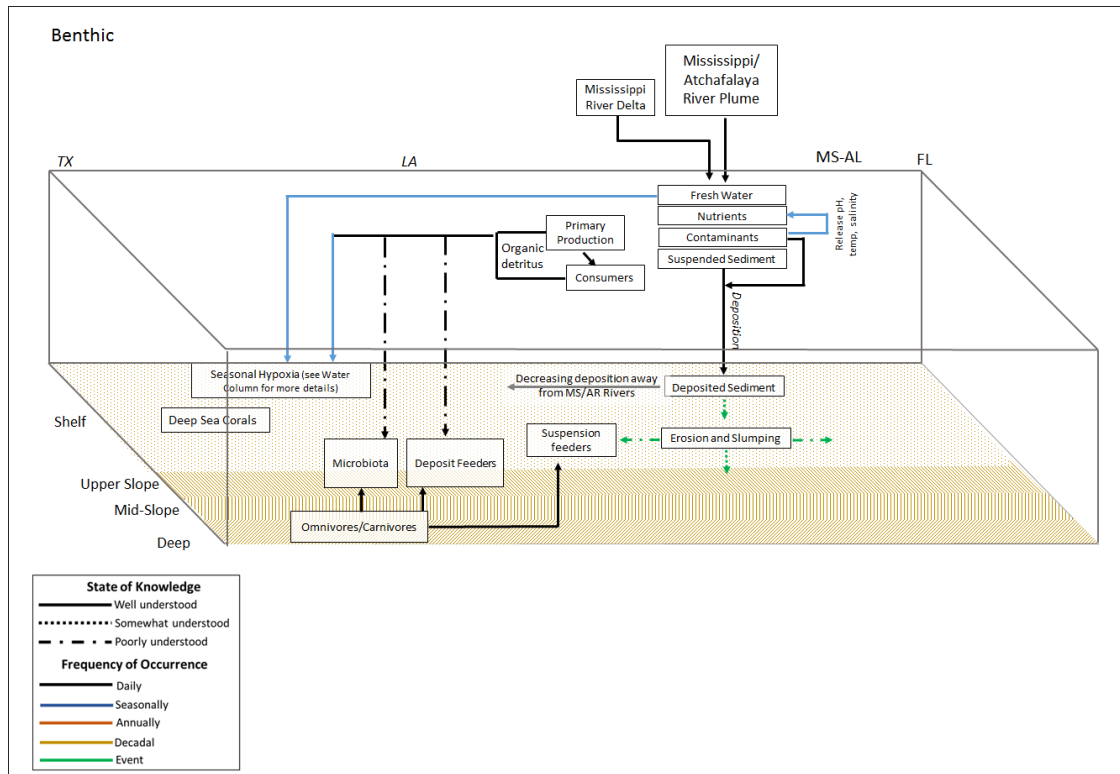


Fig. 3-1. Conceptual model of the influence of the Mississippi River on benthic processes in the Gulf of Mexico.

II.B. Geographic Distribution of Benthic Communities

Benthic communities in the Gulf of Mexico extend from shallow regions near land to depths of over 3,500 m in the Sigsbee Deep (Fig. 3-2). Soft bottom communities, both meiobenthic (Baguley et al. 2006) and macrobenthic (Haedrich, Devine, and Kendal 2008) can be divided into 9 regions, based on geographic location (western, central, eastern) and depth (shallow, meso, and deep; where 800 to 1200 m is the meso depth). Abundance of all benthic groups declines exponentially with depth, including bacteria (Deming and Carpenter 2008), protozoan foraminiferans (Bernhard, Sen Gupta, and Baguley 2008), meiofauna (Baguley et al. 2006), and macrofauna (Escobar-Briones, Estrada-Santillan, and Legendre 2008; G. D. F. Wilson 2008); and this relates to a decline in sediment organic matter (Morse and Beazley 2008). Diversity has a bell-shaped pattern, with maximum on the mid to upper continental slope at depths of about 1.5 km (Haedrich, Devine, and Kendal 2008; Powell, Haedrich, and McEachran 2003; G. D. F. Wilson 2008). Soft bottom muds dominate the Gulf of Mexico, and regions that are influenced by the Mississippi River, such as those in the central Gulf and within the Mississippi fan and trench, are strongly influenced by depositional processes related to sediments exported onto the shelf and slope. The western and eastern sides of the Mississippi River have different benthic communities from each other, which is in part a function of the often fine-grained siliciclastic sediments in the western Gulf of Mexico and the coarse-grained carbonate sediments found in the eastern Gulf of Mexico.

Benthic communities in the Gulf, the river and its delta can be divided into hard and soft bottoms (C. R. Fisher, Montagna, and Sutton 2016). The river is a major source of mud to the Gulf seafloor, and this mud primarily forms the soft bottoms (Fig. 4-3). Additionally, the Gulf contains many salt domes that protrude to the surface, which is where hard bottom communities can establish. Hard bottom communities, which can contain corals, are also found to the east of the Mississippi River off the Mississippi and Alabama coasts, particularly in the DeSoto Canyon. The Flower Gardens, which is the deepest coral reef in the world, is much further west of the influence of Mississippi River. However, some corals are also found within 60 km of the Birdsfoot Delta. Ecological communities around seeps of oil and other hydrocarbons are important in the benthos of the Gulf of Mexico, however, since these systems are rarely influenced by the Mississippi River on modern decadal time scales they are not included in this review (Cordes, Bergquist, and Fisher 2009). The salt domes are reservoirs of hydrocarbons and can also seep brines and methane (C. Fisher et al. 2007), which produce unique benthic



Fig. 3-2. Map of the major features of the seafloor of the Gulf of Mexico. Source: marinecadastre.gov, <http://www.arcgis.com/> and refs therein.

communities, in addition to being major stores of extractable energy.

In many deep communities around the world, energy transfer is relatively small; in the Gulf of Mexico, this is not the case. The presence of the Mississippi River system, and its large load of nutrients and organic carbon, as well as the productive pelagic regions this area supports, are responsible for a more much greater levels of energy transfer (Rowe et al. 2008). Sedimentation rates in the Gulf of Mexico are typically greatest in closest proximity to the mouth of the

Mississippi River, and then decrease with distance from the river's mouth. This pattern often makes episodic events increasingly important with distance from the Mississippi River plume. However, sedimentation rates and patterns are not uniformly consistent. The flux of mineral sediments to the seafloor is strongly influenced by associated fluctuations in the delivery of sediment and water from the Mississippi River, and near surface currents that direct the Mississippi River plume (Fig. 3-1). The flux of organic matter to benthic communities is governed by oceanographic processes that govern primary and secondary production in euphotic

and mesophotic zones, as well as the physical process (river, storm driven resuspension) that transport sediment-bound organic material.

The Mississippi River is also a source of contaminants to the deep waters of the Gulf of Mexico. Because many contaminants are bound to fine-grained particles, the broad distribution of contaminants across the Gulf of Mexico is governed by the distribution of the Mississippi River plume. Sediment from the Mississippi River plume also has the potential to cap and bury contaminants that entered the Gulf of Mexico from the BP/Deepwater Horizon oil spill and other oil spills. However, given current sedimentation rates in this region, such a burial might take a century to occur.

III.C. Spatial Controls on Sediment Metabolism, Sediment Reworking, and Geochemical Cycles.

The physical processes that influence sedimentary metabolism, sediment reworking and geochemical cycles are strongly influenced by the Mississippi River. A study of metabolism along the continental shelf indicates that rates of carbon respiration range from 16.2 to 46.6 g C m³ yr⁻¹, with the greatest rates found in the nearshore, shallow reaches of the Gulf (< 10m) and the lowest rates found in the deepest (20 - 200 m) reach sections of the continent shelf (Benway and Coble 2014). Because sedimentation rates generally decrease with distance from the Mississippi River (Corbett, McKee, and Allison 2006), episodic events tend to increase in the offshore direction. Likewise, particle size tends to decrease with distance from the Mississippi River. Temperature decreases with depth and salinity tends to increase with distance from the river. The relationships between temperature, salinity, and turbidity are also influenced by the position of the Atchafalaya River plume, which enters the Mississippi River plume ~ 200 km downdrift of Southwest Pass. These relationships also have implications for the structure of benthic communities, as biodiversity tends to peak at 1,000 to 1,500 m water depth. Furthermore, in the deep ocean, chemosynthesis becomes an important energy source, around seeps of methane and petroleum.

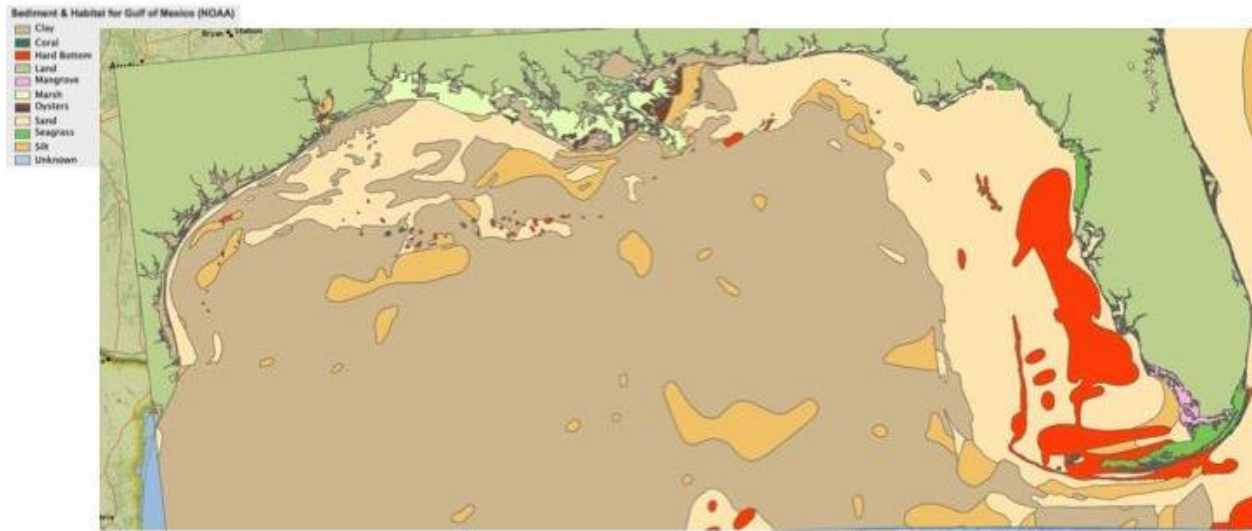


Fig. 3-3. Map of benthic habitats in the Gulf of Mexico. Source:
https://erma.noaa.gov/layerfiles/33001/files/gom_efhhapc_poster.pdf

IV. DELTAIC PROCESSES

IV.A. Introduction and Conceptual Model

This section examines the impact of the Mississippi River Delta and its estuaries on the Gulf of Mexico. This section covers the formation of the delta and its estuaries, and how they exchange sediments, nutrients, carbon and living organisms with the Gulf of Mexico. These processes can be well understood through a conceptual model that is presented in Figure 4-1. (Note that this figure does not explain all processes in the Mississippi River Delta, only those processes that influence the ways that the delta impacts the Gulf of Mexico, as in keeping with the theme of this document.) The conceptual models shows the inputs of fluids, sediments and dissolved material to the delta, how nutrients fuel primary and secondary production, and pathways by which contaminants can be taken up by nekton. The model as traces how land loss in the Mississippi River Delta impacts the Gulf of Mexico, which occurs primarily through the export of carbon and nutrients to the Gulf. Finally, the model explains the physical processes and ecological processes that drive exchange material and fluids between the delta, its estuaries, and the open Gulf of Mexico. As the other conceptual models presented this paper, the time scales over which processes occur, and an estimate of the state of our knowledge are presented.

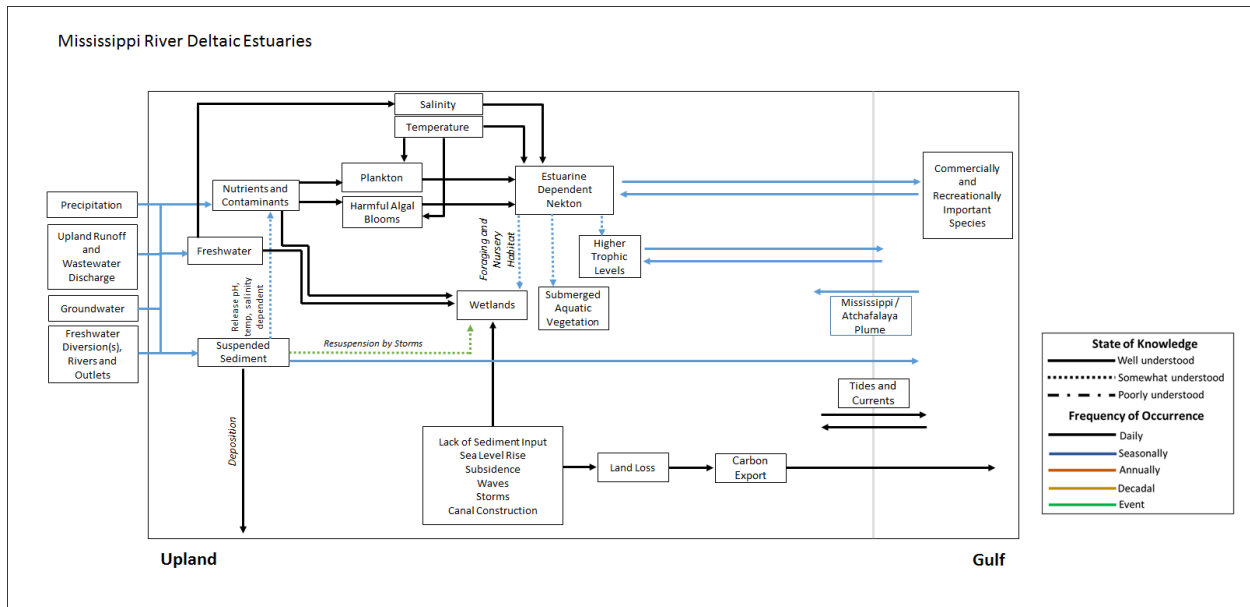


Fig. 4-1 Conceptual model of the influence of the Mississippi River Delta and its estuaries on the Gulf of Mexico.

IV.B. Formation of the Mississippi River Delta

The Mississippi River Delta, by nature of the continual processes that built and shaped it is characterized by constant change. As a result, the processes and interactions between the northern Gulf of Mexico, and the spatial and temporal scales over which they operate, also change. The Mississippi River Delta was built over the last ~7,000-8000 years by sediments drained from the Mississippi River's 3.4×10^6 km² drainage basin (Coleman et al. 1998; Syvitski and Milliman 2007). The sediment was carried to the Gulf of Mexico and deposited by the river and its distributaries, constructing a series of deltaic headlands that pushed into the Gulf (Fig. 4-1). Every 1,000 to 1,500 years the locus of active delta building would change, as the main flow of the river would shift course. Following abandonment by the river, each delta lobe underwent the delta cycle, a succession of events over time that include subsidence, landward translation of marsh shoreline, and marine reworking of

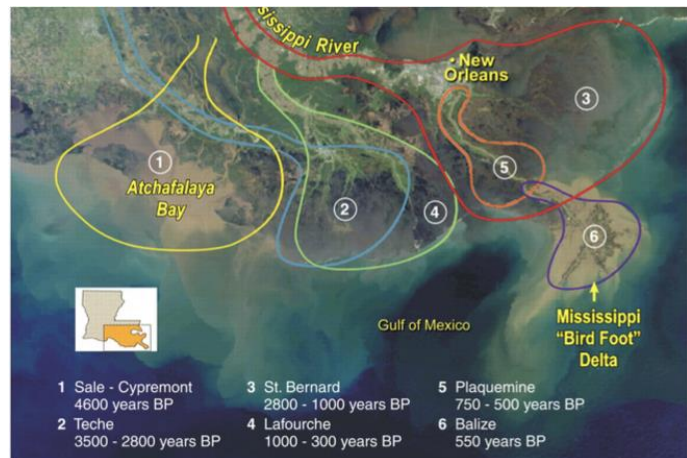


Fig. 4-2. Historical evolution of lobes in the Mississippi River Delta complex. Source: Day et al., (2007) and refs therein.

delta-front sands into transgressive barrier island arcs and, finally, submerged and shoal features (Coleman 1988; Penland et al. 1988). The formation of the Mississippi River Delta occurred at the same time as most Holocene delta plains, a time of decelerated sea-level rise (Blum and Roberts 2012).

More recently, the development of the Mississippi River Delta has been characterized by an overall trend of wetland loss. Between 1932 and 2016, the Mississippi River Delta (Fig. 4-3), which includes the Pontchartrain, Breton Sound, Barataria, Terrebonne, Atchafalaya and Teche-Vermillion Basins, lost 3,800 km² of land; a reduction of 25% of the land area that existed in 1932 (Couvillion et al. 2017). The loss of the Mississippi River Delta can be attributed to a combination of natural and anthropogenic drivers, such as subsidence, sea level rise, hurricanes, construction of canals, reduced sediment loads due to upstream dams, and the construction of levees along the Mississippi River which has almost entirely halted the active phase of the delta cycle (Day et al. 2007).

IV.C. Mississippi River Delta Estuaries

Estuaries form at the mouths of rivers, between the boundary of the sea and the land. Typically geologically ephemeral, estuaries undergo near constant alteration by erosion, sediment deposition and changes in sea level. While estuaries can take a variety of forms worldwide, the largest (by area) estuaries in the Mississippi River Delta are shallow, well mixed systems such as Barataria and Terrebonne Bays and Breton Sound, which have areas that are ~ 5,000 km² in area, and which have average depths of ~ 2m (Reed et al. 1995). During low flow periods, the mouth of the mainstem of the Mississippi River functions as a salt-wedge (unmixed) estuary (Galler and Allison 2008). The estuaries of the Mississippi River Delta highly productive ecosystems; in the Gulf 97% (by weight) and 93% (by value) of the Gulf's commercial and recreational fish species depend on estuaries for at least part of their life-cycle (Lellis-Dibble et al. 2008).

IV.D. Magnitude and Spatial Extent of the Mississippi River Delta's Influence in the Gulf of Mexico

While the mainstem of the Mississippi and Atchafalaya Rivers are the primary pathway by which river-derived freshwater is delivered to the Gulf of Mexico, the estuaries of the Mississippi River Delta are important sources of freshwater to the Gulf of Mexico. Total discharge in individual estuaries is on the order of 1000 m³ s⁻¹ (Das, Justić, and Swenson 2011; Z. Feng and Li 2010), though these values can fluctuate substantially with tides, seasons, and local rainfall. Patterns of freshwater discharge are influenced by density-dependent circulation (i.e. classic estuarine circulation), and by meteorological processes, and particularly cold front-driven flushing. Strong cold fronts can cause up to 50% of the volume of estuaries (Atchafalaya Bay) to be discharged to the shelf (Walker and Hammack 2000), resulting in a discharge of ~ 10⁷

to 10^9 m^3 from each bay over a period of approximately 1 day (Z. Feng and Li 2010), though some of this water is returned during the next cold front.

The impact of the Mississippi River Delta on the flux of sediments, nutrients and organic matter to the Gulf of Mexico has been a matter of substantial research, with recent studies indicating that fluxes change with space and time. For some constituents, different research teams have different perspectives.

In the case of sediments, it appears that major embayments like Barataria Bay have become net exporters of mineral sediments to the Gulf of Mexico. Research by Fitzgerald and colleagues (2004) indicates that land loss in Barataria Bay contributes to a positive feedback loop in which land loss increases the tidal prism, which increases sediment export to the Gulf, which in turn increases the tidal prism. As a result, some parts of the ebb tidal delta offshore of Barataria Bay have accreted by $> 10 \text{ m}$ since the 1930s (Fitzgerald et al. 2004). However, in other areas--most notably the Atchafalaya, Wax Lake, and parts of the Birdsfoot Delta--the Mississippi River Delta acts as sink for sediments, preventing river sediments from reaching the Gulf (Roberts 1997; Wellner et al. 2006). While no sediment budget exists for the entire coast, given the state of land loss across Louisiana (Couvillion et al. 2017), it appears more likely that the Mississippi River Delta is more likely a source than a sink for mineral sediments.

The Mississippi River Delta is likely a source of organic carbon to the continental shelf. Primary production in both the estuaries and the wetlands of the delta provide a source of carbon to the continental shelf, as do the degradation and erosion of coastal wetlands in the delta. One estimate indicates that each meter of shoreline in Barataria Bay exports 0.09MT per year of organic carbon, and that each meter of shoreline in Breton Sound exports 0.07 MT per year of organic carbon, and that these systems exported 3.7×10^4 and 4.6×10^4 MT respectively between 1932 and 1990 (C. A. Wilson and Allison 2008). A study of biomarkers and other organic compounds on the Louisiana continental shelf indicates that wetlands can contribute between 3.4 and 31.6% of the organic carbon on the continental shelf, with greater values found during the

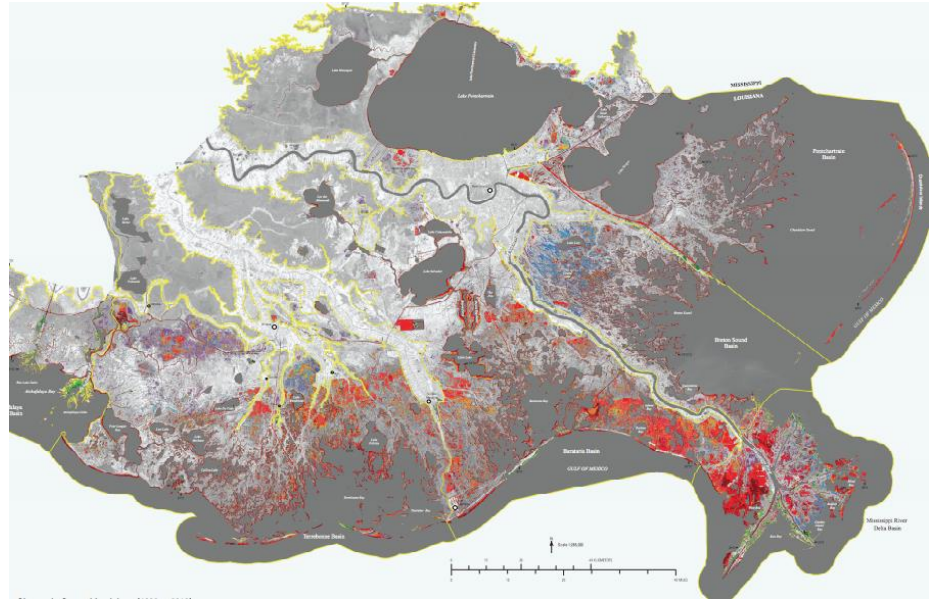


Fig 4-3. Land area change in the Mississippi River Delta 1932-2016, with red, yellow and orange colors indicating land loss and green colors indicating land gain. Source: Couvillion et al., (2017)

spring (high river flow season) than during the autumn (T. S. Bianchi et al. 2011). However, other authors suggest that a substantial fraction of this organic matter could be derived from terrestrial sources in the Mississippi River watershed--namely grasslands in the central United States (Goñi, Ruttenberg, and Eglinton 1998; Goni, Ruttenberg, and Eglinton 1997). Actively developing deltas also serve as a sink for riverine organic carbon, as noted by a recent study from the Wax Lake Delta (Shields et al. 2017).

Many organisms that live in the deltaic estuaries have an ecological distribution that substantially exceeds the estuaries themselves, as they use broad reaches of the Gulf, and even the open Atlantic Ocean. The Mississippi River Delta provides food and habitat for a large number of estuarine-dependent species of fish, including bay anchovy, Atlantic croaker, spot, white, brown and pink shrimp, as well as Gulf menhaden, spotted seatrout, red drum, blue crabs and flounder (Brown et al. 2013; Lang, Grimes, and Shaw 1994; Chesney and Baltz 2000). That Louisiana has the highest commercial fisheries landings in the Gulf of Mexico for most estuarine-dependent species speaks to the importance of the estuaries in the Mississippi River Delta for the Gulf of Mexico (<https://www.st.nmfs.noaa.gov/>). The overall impact of estuaries is potentially larger--species such as Yellowfin Tuna feed off estuarine-dependent species (and those influenced by the Mississippi River), and individuals of this species can be tracked across the Gulf of Mexico and the Atlantic Ocean (Lang, Grimes, and Shaw 1994). The Mississippi River and its delta can potentially act as a barrier to dispersal for Blue Crabs, potentially leading to different genetic populations across the northern Gulf. However, this barrier is governed by a number of physical/ecological interactions, including the salinity of the water, circulation patterns and the local geomorphology (Yednock and Neigel 2014; Jones et al. 2015; Grey et al. 2015).

Physical exchange between the deltaic estuaries and the Gulf of Mexico is governed by a number of fluvial/deltaic processes. The flow of river water through wetlands and estuaries, while substantially restricted over the past ~ 150 years, still occurs to a large extent through deltas of the Atchafalaya and Mississippi Rivers; and to a lesser extent through exchange between other channels, such as the Gulf Intracoastal Waterway (Day et al. 2007; Swarzenski 2003). Exchange is also strongly influenced by wind-driven events, and particularly the cold front cycle, which forces water on and offshore (Roberts et al. 2015; Z. Feng and Li 2010). Wind-driven forcings can substantially increase exchange of particulate matter, either through contributing to wave erosion of coastal wetlands, or by resuspending sediments from the seafloor (Roberts et al. 2015). Additional physical forcings occur through tidal exchange, though this is limited relative to many other coastal systems, given the relatively small tidal range in the Mississippi River Delta (~ 30 cm) and the diurnal nature of the tide (tidesandcurrents.noaa.gov).

Exchange between the delta and the Gulf also occurs through biota as nekton and plankton move between the estuaries and the Gulf of Mexico. The Gulf, the deltaic estuaries, and the marshes of the Mississippi River Delta are all used by various organisms for spawning, habitat, growth, and feeding. While the nursery function of the deltaic estuaries seems evident, marsh loss has not been associated with declines in fisheries production (Browder, Bartley, and

Davis 1985; Lewis et al. 2016). While it was often thought that marsh edge rather than area was a primary factor governing nekton/marsh interaction--and that therefore a positive correlation between marsh area and fisheries productivity, including a decline in fisheries productivity with marsh loss, has not been found (Browder, Bartley, and Davis 1985), recent geospatial research has indicated that a correlation between marsh edge length and fisheries productivity is equally elusive (Lewis et al. 2016). A more likely explanation for the resilience in fisheries production in the face of marsh loss (area and edge), is the estuarine-like conditions on the continental shelf during high Mississippi River flow (Cowan, Grimes, and Shaw 2008).

V. HUMAN INFLUENCE

V.A. Introduction and Conceptual Model

This section examines how humans have influenced the ways that the Mississippi River and its delta impact the Gulf of Mexico. Human impacts to both have been widespread, and taken together, these are two of the most human-impacted aquatic systems in the nation. In keeping with the theme of this paper, this section only concerned with human impacts that influence the way that the river and its delta influence the Gulf, which can be well understood through the conceptual model that is presented in Figure 5-1. This figure lays out the drivers of human impacts, the ecological pressures that these drivers exert, and their overall impact. Many drivers are associated with hydrological changes (levees, canals, dams), and chemical changes (agriculture runoff); pressures are associated with hydrological responses (changes in river outlets), geochemical responses (changes in nutrient loadings, salt water intrusion), geological responses (subsidence, sea level rise, climate change) and extraction (oil and gas, sediment, fishing and hunting). Many of the impacts are results of ecosystem change (wetland loss, flood control, hypoxia, and changes in fisheries production). As above, the frequency of occurrence and the state of the knowledge are summarized as well.

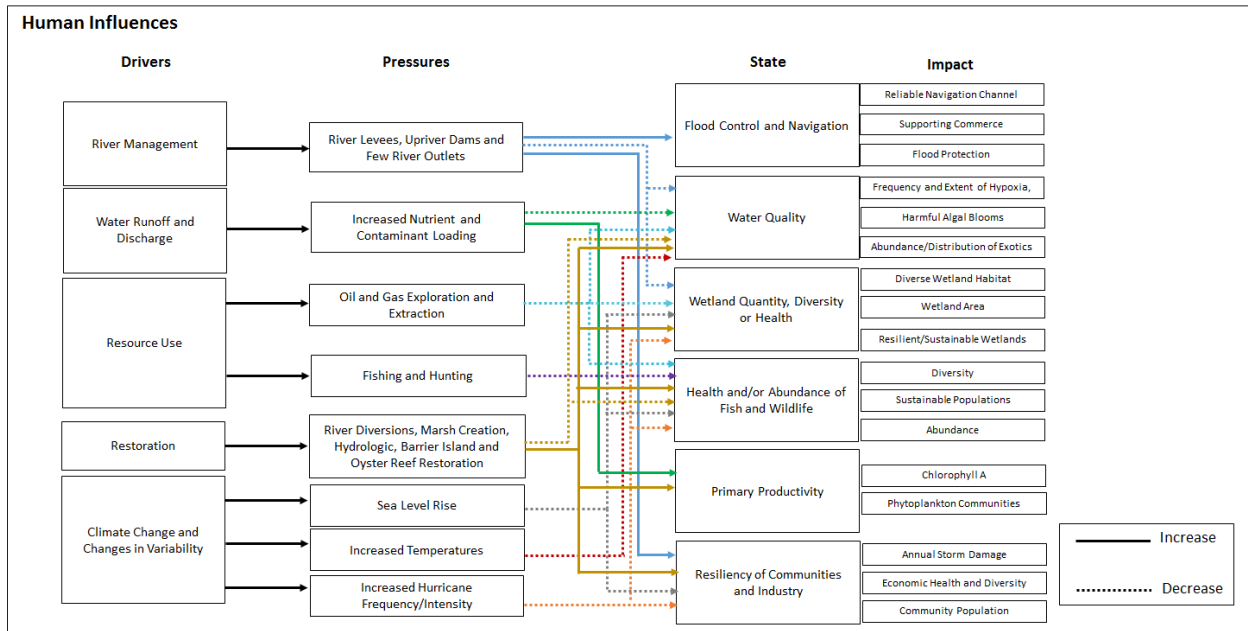


Fig. 5-1. Conceptual model of the impacts of humans in river and delta processes that impact the Gulf of Mexico.

V.B. Human Impacts on the Mississippi River

Human impacts to the Mississippi River system range from the watershed impacts to the ocean, through river channel, and into the delta. Watershed impacts includes the construction of dams and locks, along with agricultural practices that reduce the flow of sediment, all of which have reduced sediment loads in the river by about 50% since the 1800s (Meade and Moody 2010). However, sediment loads during the 19th century may have been abnormally high, a result of land clearing by European-Americans that led to enhanced erosion (Tweel and Turner 2012). The decline in sediment loads reduces the material available for marsh sustenance and growth, thereby contributing to the multi-stressor problem of land loss (Day et al. 2007), and reduces the amount of sediment that could be delivered to the ocean.

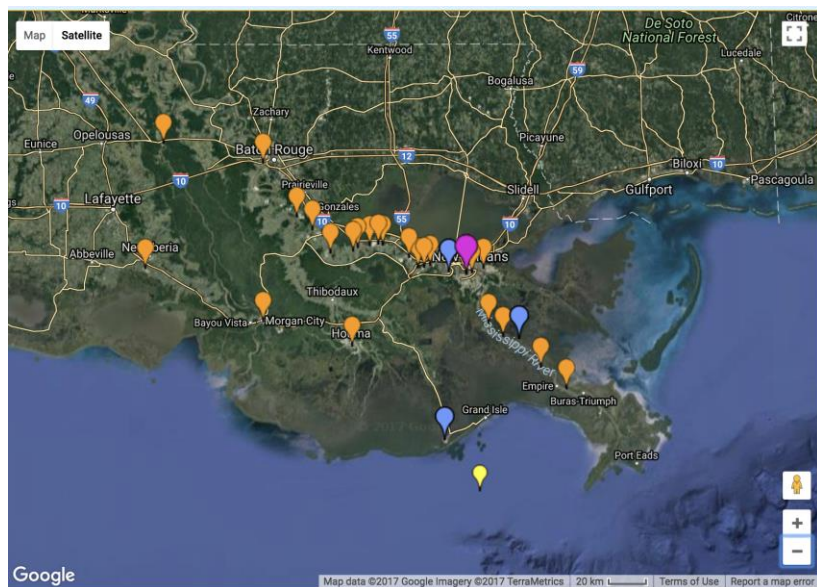


Fig. 5-2. Distribution of port facilities in southern Louisiana.
Image Source: http://www.worldportsource.com/ports/USA_LA.php

The flow of water from the drainage basin to the Mississippi River itself is regulated by dams, which can be used to moderate flood pulses. Indeed, the timing of the spring flood is governed partially by decisions by various water management agencies to store and release water in dams. Of particular importance are decisions made by the Tennessee Valley Authority, which manages the Tennessee River, the largest tributary of the Ohio River, which, in turn, is the largest tributary of the Mississippi River (<https://www.tva.gov/Environment/Flood-Management>). Flood pulses in the Tennessee River can be controlled so that they come after flood pulses in the mainstem--which is done to reduce flooding concerns in the lower Mississippi River.

Another major control on the impacts of the Mississippi River system on the Gulf of Mexico stems from agriculture in the watershed. Levels of nitrogen-based fertilizer increased exponentially during the mid-20th century, and have remained elevated since then (N. N. Rabalais, Turner, and Wiseman 2002; Turner et al. 2007), though the total discharge in individual years varies, often as a function of river discharge (Turner et al. 2007). As described in Section II.E. and Figures 2-1 and 2-7, these nutrients fuel large plankton blooms on the continental shelf; when the blooms die, the subsequent consumption of organic matter fuels hypoxia (N. N. Rabalais, Turner, and Wiseman 2002; T. S. Bianchi et al. 2010).

The primary source of nitrate to the Gulf of Mexico is agriculture in the upper Mississippi River, which account for about 51% of total nitrate loading, despite the fact that this system only accounts for about 22% of the total water discharge (Fig. 5-4). The Ohio River, the largest (41%) source of water to the lower Mississippi River, only accounts for 21% of total nitrate loadings (Alexander, Wilson, and Green 2012). In addition to nitrate loadings, carbon loads from the Mississippi River to the Atchafalaya River have also been increasing over time. There are long-term trends in both the amount of carbon being transported by the Mississippi River and the dissolved inorganic carbon (DIC) loads of the Mississippi River (Raymond et al. 2008; Sampere, Bianchi, and Allison 2011). There are strong signals in contaminant fluxes to the Gulf from the Mississippi River, including historical pesticides used agriculturally, (DDT, Chlordane, Lindane ect.), as well as industrial byproducts such PCBs, dioxins/furans, petroleum, PBDE, anthropogenically used metals (e.g. Fe, Mn, Cu- Shiller 1997), and trace elements.

The fluxes of water, sediment, nutrients and carbon, and other dissolved constituents are dependent on human activities on a range of scales and processes. For example, nitrogen loads in the river are partially a function of decisions made by farmers in this watershed--which are governed by a suite of economic and environmental considerations (Alexander, Wilson, and Green 2012; Mitsch et al. 2001). The flux of nitrogen to the coastal zone (particularly during the spring flood, which is a major control on hypoxia) is also governed by climatic and meteorological processes, which are under a degree of human control. Modeling studies have also highlighted the effects of both human activity and climate-related processes on the export of various forms of carbon through the river system (Tian et al., 2015; Ren et al., 2015, 2016).

Many of the impacts to the lowermost Mississippi River were either to provide flood protection, or to support navigation and the maintenance of one of the largest port complexes on

earth (Figs. 5-2, 5-3). The channelization of the Mississippi River both greatly reduced exchange with the delta and increased the concentration of river water discharging to the Gulf (Alexander, Wilson, and Green 2012). Under the current configuration of the Mississippi River and Tributaries system, under non-flood conditions, > 95% of the water leaves the delta in the lower ~ 75 km of the river, and ~ 33% of the flow of the Mississippi River downstream of Tarbert Landing is discharged to the open ocean via Southwest Pass and South Pass (Allison et al. 2012). This creates a concentrated plume of freshwater in the open reaches of the Gulf of Mexico, and the Barataria Bight. While more research on historical conditions is necessary, this physical structure likely impacts the severity of the hypoxic zone along the Louisiana/Texas shelf (Zhao et al. 2012). The reduction of Mississippi River through its wetlands reduces the “filtering” of sediments, nutrients and contaminants from river water (Sampere, Bianchi, and Allison 2011; Thomas S. Bianchi and Allison 2009). Humans have also constrained the flow distribution between the Mississippi and Atchafalaya Rivers by building the Old River Control Structure. This system shunts a discharge equivalent to 70% of the combined flow of the Mississippi and Red Rivers down the mainstem of the Mississippi River and 30% of that flow down the Atchafalaya River. This constrains the amount of water that enters into the deepwater (i.e. the Mississippi side) and the amount of water that enters a shallow shelf (e.g. the Atchafalaya side), thus influencing the river’s impact on the water column and the benthos (e.g. Figs. 2-1, 3-1).

V.C. Direct Human Impacts to the Delta

Humans have also had a large number of impacts on the Mississippi River Delta and the way that it interacts with the Gulf of Mexico. These impacts include the construction of canals, intensive extraction of hydrocarbon, salt and other compounds from the subsurface, and the inducement of subsidence which results from fluid

withdrawal and induced degradation of peat (Day et al. 2007; Turner 1997; Alexander S. Kolker, Allison, and Hameed 2011). These impacts, along with a suite of other factors, (reductions in sediment supply, naturally high rates of subsidence, hurricanes, oil spills and climate change) have resulted in massive land loss across the region (Couvillion et al. 2017; Day et al. 2007). While this land loss has numerous implications, this study considers those changes that affect the

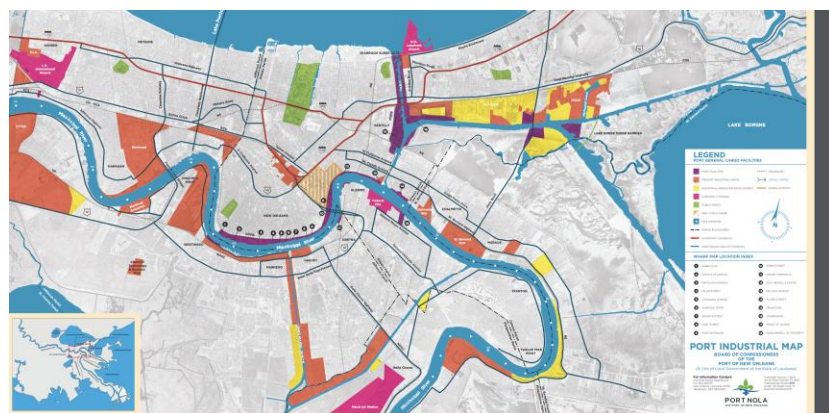


Fig. 5-3. Location of key port complexes around the City of New Orleans, and along the lower Mississippi River.

influence of the delta on the Gulf of Mexico, which include loss of habitat for estuarine-dependent species, and increased carbon export to the Gulf.

V.D. Impacts Climate Change has had on the River System

Climate change stands out as another major human impact to coastal Louisiana. Known impacts of climate change that have occurred to date include an acceleration in the rate of global sea level rise from about 1.8 mm yr⁻¹ during the 19th and much of the 20th century to about 3.1 mm yr⁻¹ starting in the 1990s, with current rates possibly as high as 3.3 mm yr⁻¹ or more (Merrifield, Merrifield, and Mitchum 2009; Church and White 2006; Wuebbles et al. 2017). This rise in global sea levels contributes to wetland loss (Day et al. 2007), which results in a loss of ecological function as described in sections IV.D. and Figures 4-1 and 5-1. The rise in global sea levels may also be contributing to the changed distribution of flow at the outlets of the Mississippi River (G. P. Kemp, Day, and Freeman 2014). Other climate change impacts relevant to this analysis include an increased intensity of major hurricanes (Trenberth and Fasullo 2008, 2007), which could also accelerate wetland loss. Global warming may be increasing ocean temperatures which could increase the intensity of bottom water hypoxia (Turner, Rabalais, and Justić 2017). Additionally, warmer temperatures may be shifting ocean circulation patterns that adversely impact Gulf of Mexico fisheries (Karnauskas et al. 2015).



Fig.5-4. Sources of nitrate and water, by percent, to the lower MR from its' tributaries. Source: Alexander et al., (2012).

V.E. Human Impacts to the River and Delta That Have Impacted Economically Important Fish and Fish Landings

Human impacts to the Mississippi River and its delta have had important impacts on the distribution and abundance of numerous economically and ecologically important species. The most prominent impacts are the prevalence of the seasonal hypoxic zone along the northern Gulf Coast, the widespread land loss that has occurred in Louisiana, and overfishing (N. N. Rabalais, Turner, and Wiseman 2002; Chesney and Baltz 2000). Oil spills are another human-induced impact on the Gulf of Mexico. While oil spills are relatively frequent events in the Gulf of Mexico, the Deepwater Horizon Oil Spill in April 2010 was among the most significant because it was the single largest marine oil spill on record releasing over 4 million barrels of oil into the Gulf for a period of over 85 days (Colwell 2014). While it is not the intention of this review to examine all of the impacts of this spill on either the Mississippi River Delta or the Gulf of Mexico, as those have been discussed at length elsewhere (Colwell 2014; Nixon et al. 2016; C.

R. Fisher, Montagna, and Sutton 2016; Rangoonwala, Jones, and Ramsey 2016), basic issues need to be addressed as they pertain to the way that the delta impacts the Gulf. The primary relevant impacts occurred through the oiling of nearly 1055 km of wetlands and 293 km of beaches in Louisiana--most in the Mississippi River Delta (Nixon et al. 2016). This oiling led to reductions in plant function, and in many cases to wetland loss (Hester et al. 2016). This wetland loss resulted in similar loss of ecological function as other forms of wetland loss, such as the loss of important habitat for estuarine-dependent species. The direct toxicity of oil was problematic as well for indicator species such as Gulf killifish - aka *Fundulus grandis* (Whitehead et al. 2011), though some species, like white and brown shrimp appeared to be largely unimpacted (van der Ham and de Mutsert 2014). A more comprehensive understanding of the impacts of this spill on the ecology of the Gulf can be found in other references (e.g Colwell 2014; Fisher et al. 2016; Nixon et al. 2016; Rangoonwala et al. 2016).

V.F. Impacts of the Mississippi River and its Delta on the People Who Live Here, and the Impacts of These People on the Landscape

The Mississippi River and its delta also has a major impact on the people who live in the region, and the ways that they impact the Gulf of Mexico. Indeed, much of the economy of South Louisiana depends on the water. The Mississippi River provides a transportation means by which goods are delivered from the other continents to North America via the world's oceans. Ports along the Mississippi River, including the Port of New Orleans, the Port of South Louisiana, as well as other facilities along the river's mouth, constitute the one of the world's largest port complexes.

Both the river and the delta provide food and habitat to support one of the largest commercial fisheries in the United States. While not without some stock management problems, these fisheries are among the most stable fisheries in the continental United States. The estuaries of the Mississippi River Delta are also used by recreational fishers, and by recreational birders. One study found that in Louisiana that wildlife-related activities had an economic impact of \$6.75 billion, within \$1.71 billion attributed to recreational fishing, \$2.4 billion attributed to commercial fishing, \$1.3 billion attributed to recreational boating, \$975 attributed to hunting \$517 million attributed to wildlife viewing, photographing and feedings, with additional contributions from smaller activities such as reptile and amphibian harvesting (LADWF 2008). While these numbers are statewide, a large (if not the largest) fraction of each category take place in the Mississippi River Delta or its associated environments (LADWF 2008).

The Mississippi River Delta serves as a major hub of oil and gas activity. There are extensive oil and gas mining facilities in the northern Gulf of Mexico (Fig. 5-5). Large volumes of imported oil are delivered to the United States from abroad through complexes in this region. The largest of these complexes is the Louisiana Offshore Oil Port (LOOP), which imports ~ 10% of the nation's oil. Finally, the region is home to many oil refineries, which process oil that is mined locally, imported from ships abroad, as well as transported from other regions of the

United States and North America.

While the Gulf of Mexico is a source of revenue and economic activity for some, it also holds the potential to be a source of economic and personal destruction. Hurricane-initiated flooding is one of the most powerful drivers of economic problems in the Gulf Coast. The destruction of large areas of metropolitan New Orleans and the Mississippi Gulf Coast during Hurricane Katrina killed nearly 1,800 people and caused \$80-\$150 billion in economic damages (in 2005 dollars). The impacts of hurricanes have likely become more destructive as land loss has reduced the size of the coastal buffer.

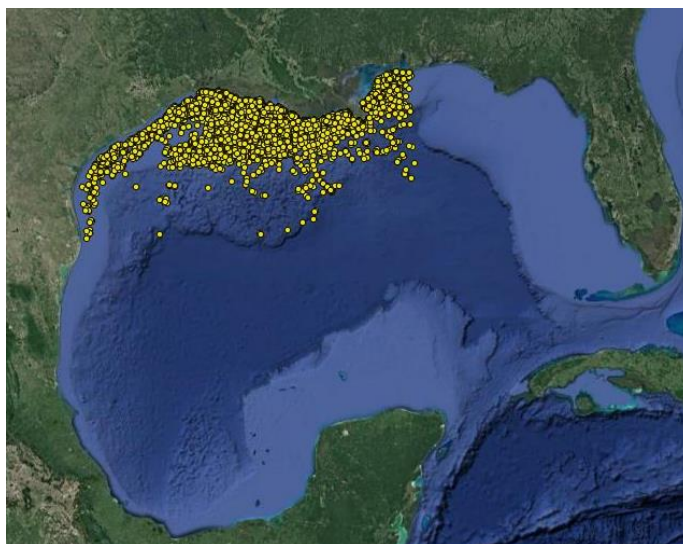


Fig. 5-5. Location of oil platforms in the US Gulf of Mexico waters.
Data Source: boem.gov.

VI. FUTURE CHANGES

VI.A. Introduction

This section examines what is known about future impacts to the ways that the Mississippi River and its delta influence the oceanography, ecology and economy of the Gulf of Mexico. While future projects inherently involve a level of uncertainty, this section largely focuses on future changes that are considered likely to occur. As such, this section focuses on predicted changes that have been published in the technical and peer-reviewed literature, and future changes that are likely to occur given management plans that have been endorsed by state, local and federal governments.

VI.B. Climate Change and Relative Sea-Level Rise

It is known that climate change could have a major impact on several of the ways that the Mississippi River and its delta influence the oceanography, ecology and economy of the Gulf of Mexico. An acceleration in the rate of global sea level rise is among the most prominent climate change attributes that could impact the Mississippi River and its delta (Wuebbles et al. 2017; Sweet et al. 2016). Current projections indicate that there will likely be 1 m of global sea level rise by 2100, with the possibility of up to 2 m or more in extreme cases (Sweet et al. 2016). The State of Louisiana's Coastal Master Plan projects that, with both global sea level rise, and subsidence that about 0.8 to 2.8 meters of total relative sea level rise could occur by 2067

(LACPRA 2017). These high rates of relative sea-level rise could contribute to at least 4,500 km² of land loss by 2065 if no action is taken (LACPRA 2017). Even if large-scale restoration takes place in the manner envisioned by the state's coastal Master Plan, over 2,400 km² of net land loss would occur by 2065. This land loss has several implications for the topic at hand: it could reduce the availability of habitat for some estuarine-dependent species; it could increase the habitat for species that prefer more marine-like conditions; it could result in the re-emission export of carbon and material as marshes degrade and sediment eroded; it could allow storm surges to propagate further inland; finally, it can impact the outfall locations of Mississippi River system distributaries, impacting critical infrastructure and communities. Other likely known major climate change impacts include an increase in either the frequency and/or intensity of tropical cyclones (Trenberth and Fasullo 2008; Wuebbles et al. 2017), an increase in precipitation, and an increase in regional temperatures.

Global sea level rise, when coupled with subsidence, may also lead to a shift in the location of the Mississippi River depocenter, and the outfall channels of the Mississippi River- resulting in an upstream shift of this discharge point of the Mississippi River (G. P. Kemp, Day, and Freeman 2014; G. Kemp et al. 2016). This could alter the dynamics of the river plume and the ecological communities it influences. Such disruptions could lead to change in the location of infrastructure, but the human response to broad scale changes in the location of lower Mississippi River distributions is at present difficult to predict.

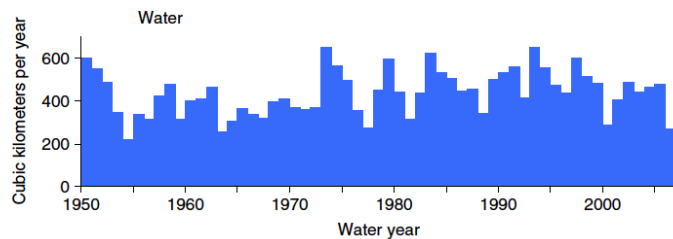


Fig. 6-1: Annual average discharge of the Mississippi River.
Source: Meade and Moody, 2010.

The impacts of climate change on river discharge remains less well known, as current data indicate no major impacts to the annual average discharge of the Mississippi River (Meade and Moody 2010), despite climate changes that have occurred here in the past several decades (Fig. 6-1). This assertion does not mean that there are no climate related impacts that have occurred in the Mississippi River watershed; indeed, there have been pronounced floods and droughts that have been linked to climate change. Instead, the finding of no major impacts to the annual average discharge of the Mississippi River suggests that, over annual time scales and greater, floods and droughts in the drainage basin have been roughly in balance, resulting in little overall change in the annual discharge of the river. Projections of climate change using a suite of global climate models indicate a roughly 6% decrease in mean river flow by the end of the 21st century (van Vliet et al. 2013).

This does lead to the potential for a shift in the way that the Mississippi River impacts the Gulf of Mexico- for example, that there may be more extreme droughts or floods--and the occurrence of a historic flood in 2011 which was followed by a historic drought in 2012 is potentially evidence of this occurring. Changes in hurricane climatology could impact mixing

dynamics in the Gulf of Mexico, though the resolution of many global climate models is not yet fine enough to resolve this (Wuebbles et al. 2017).

VI.C. Coastal Restoration as a Driver of Change

The implementation of Louisiana's Coastal Master plan stands out as another major change that is likely to occur in the Mississippi River Delta region (LACPRA 2017). This plan aims to both rebuild wetlands, barrier islands and other natural features while also building large structural protections such as levees and flood walls, while also strengthening resiliency through non-structural adaptations such as home elevations, flood proofing, and targeted buy-outs. The plan involves numerous restoration and protection tactics.

The controlled diversion of large amounts (up to $1,500 \text{ m}^3 \text{ s}^{-1}$) of river water into subsiding and eroding embayments to rebuild land is a particularly important change (LACPRA 2017; Paola et al. 2011; A. S. Kolker, Miner, and Weathers 2012). The diversion of river water could lead to a more dispersed and diffuse plume, as river water will enter the Gulf in additional exits (Das et al. 2012; Das, Justić, and Swenson 2011). As river water flows through coastal wetlands, there is the potential for the removal of sediments, nitrogen, and other suspended and dissolved constituents (Henry and Twilley 2013). The removal of nitrogen in particular could reduce the impacts of the size of the hypoxic zone on the continental shelf. However, the increased diversion of nutrient-laden freshwater in coastal embayments could cause inshore hypoxia (Das, Justić, and Swenson 2011). Modeling studies indicate that these diversions are likely to cause some reductions in fish biomass relative to a future without action, but that these reductions are largely localized, and that relatively little overall change is realized delta wide (de Mutsert et al. 2017). Additional impacts from Louisiana's Master Plan can include direct marsh creation, which could lead to habitat creation for many estuarine-dependent fish, and the construction of storm-surge levees which could focus flood waters (LACPRA 2017).

VI.D. Societal Impacts

Over the long-term, there could be numerous societal changes to the way that the Mississippi River and its delta interact with the Gulf of Mexico. While such changes are largely speculative at this point, given the pronounced changes that could occur, they are worth mentioning. Long-term changes to the stability of the Mississippi River channel could impact navigation and shipping. Given that the Mississippi River is the largest (by tonnage) pathway for waterborne commerce in the nation, as are ports along the lower river, changes to shipping would substantially shift the impacts of the river and the delta on global oceanic shipping. Furthermore, changes to the physical stability of the delta could have a long-term impact on the infrastructure that governs the offshore oil and gas industry. Widespread land loss and flooding could lead to the relocation of over 500,000 people in Louisiana's coastal zone (Hauer 2017). Given that many of these people impact the Gulf of Mexico through their work in fishing,

navigation and the offshore energy industry, such relocations could have a widespread impact on the Gulf of Mexico region.

VII. CONCLUSION

This manuscript has examined the multitude of ways that the Mississippi River and its delta impact the oceanography, ecology and economy of the Gulf of Mexico. Results from the published literature indicate that the Mississippi River system is the largest source of freshwater, nutrients and sediments to the Gulf of Mexico, and as such, is one of the most important features to understand in this large marine ecosystem. The freshwater plume from the Mississippi River extends over an area of 10,000 - 35,000 km², and often covers much of the Northern Gulf of Mexico, from Matagorda Bay to Mobile Bay. Dynamical processes, however, are critically important for transporting and mixing this plume across the Gulf of Mexico. The Mississippi River plume is responsible for delivering large quantities of nutrients to the Northern Gulf of Mexico, which, when taken together and in contribution with dynamical processes in the Gulf of Mexico, contribute to the development of a large seasonal hypoxic layer. The Mississippi River plume also contributes to the structure of the seafloor in the Gulf of Mexico, by adding sediment, contaminants, and organic detritus to benthic ecological communities.

The delta of the Mississippi River and its estuaries substantially contribute to the Gulf of Mexico. They provide an important source of freshwater though over an order of magnitude less than the river itself. The wetland and shallow reaches of the Mississippi River Delta provide important habitat and food for numerous economically and ecologically important species. However, many wetlands of the Mississippi River Delta are in a state of erosion and loss. This loss provides a locally important source of sediments and carbon to the Gulf of Mexico.

Human actions over the past century have played an important role in structuring the ways that the Mississippi River and its delta impact the Gulf of Mexico. These actions have occurred from the far reaches of the watershed to the global ocean. In the watershed, numerous dams have been constructed that regulate the flow of water and reduce the flow of sediment to the ocean, as the expansion of agriculture has increased the flow of nutrients to the ocean. Levees constructed along the Mississippi River constrain and focus the flow of water, while also contributing the development of navigation. Numerous actions in the delta have contributed to land loss, which as mentioned above, provides locally significant amounts of sediments and carbon to the Gulf of Mexico.

In the decades ahead, the impacts of the Mississippi River and its delta on the Gulf of Mexico are likely to continue to change. Climate change, in combination with high rates of subsidence, will likely contribute to high rates of relative sea-level rise in the region which could further accelerate wetland loss and potentially shift the outlets of the Mississippi River northward. Furthermore, the State of Louisiana Coastal Master Plan proposes to partially divert the flow of the Mississippi River northward, potentially altering the river-influenced regions of the Gulf of Mexico accordingly. These changes, when coupled with the large amount of other

restoration projects that are proposed or being implemented, point to the need for a comprehensive research and monitoring program across the region that builds on existing research platforms and which recognizes the substantial advances that have been made in the region over the past 5-7 decades.

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