A Hydrodynamic Model of the Mississippi Sound, USA

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Abstract. In this paper, an initial hydrodynamic model for the Mississippi Sound is presented. The paper presents the conceptualization of the problem, the computational mesh and boundary conditions, results of on-going model calibration, and a computational experiment for estimating Lake Pontchartrain flushing time. In addition, existing observed data on nutrients, salinity, suspended solids, and chlorophyll-a are presented to support the framework on which a future water quality model will be developed.

Keywords: Mississippi Sound · Groundwater · Salinity · Southeast Florida · Karst · Aquifer · MODFLOW

1 Introduction

The largest anthropogenically induced hypoxic area in North American coastal waters forms every summer in the northern Gulf of Mexico requiring load reductions of up to 63% in total nitrogen, and 48% in total phosphorus to reach a hypoxic area of 5000 km^2 [1]. In the Mississippi Sound (Fig. 1), Sankar et al. [2] identified seasonal changes in phosphate and ammonia concentrations. Observed concentrations were higher by 800% during both summers of 2018 and 2019 than in winter of 2018.

Nutrient loadings are clearly linked to anthropogenic nutrient inputs [1] and have strong implications for the health of oyster reefs' habitats in the Mississippi Sound (MS Sound) that support the economy of the State of Mississippi coastal area [2]. A better understanding of nitrogen and phosphorus loading to MS coastal waters, and their circulation through hydrodynamic processes is necessary to support sound management strategies that take into account the hydrological, hydraulic, and biochemical connectivity between estuaries and their watersheds [3].

Moreover, bacterial pollution risks in the Northern Gulf of Mexico are evident. Powers et al. [4] found that one third out of 66 beaches in the area were 'hotspots' of bacterial pollution. Enterococci were correlated with time, urban population size, and sea level, although additional factors influencing enterococci levels stressed the need for targeted studies to pinpoint drivers of fecal pollution. Zhang et al. [5] identified six independent environmental variables, including rainfall, tide, wind, salinity, temperature,

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and weather type, as important to characterize fecal coliform levels at Louisiana beaches. Brewton et al. [6] found that septic system- groundwater- surface water couplings are a crucial factor for coastal waters bacterial contamination along Florida's Gulf Coast.

In addition to the anthropogenic sources of pollution, the Mississippi Sound also receives pollutant loads from the Bonnet Carré Spillway (Louisiana). The Bonnet Carré Spillway (BCS) is a flood control structure operated by the United States Army Corp of Engineers in the Lower Mississippi Valley that allows floodwaters from the Mississippi River to flow into Lake Pontchartrain (Louisiana). The Lake is an estuary connected to the Gulf of Mexico through the Rigolets strait. Over the past few decades, the impacts of BCS openings to adjacent estuaries have been scientifically investigated [7]. Biological response and habitat alteration from spillway outflows have the potential to degrade essential fish habitat as defined by federal law [8].

The Magnuson-Stevens Fishery Conservation and Management Act is the principal law governing marine fisheries in the United States. The Act defines Essential Fish Habitat (EFH) and identifies modeling studies as potential research to support fishery conservation and management [9].

Identifying the sources of pollution and characterizing the circulation of pollutants throughout the Mississippi Sound requires a thorough understanding of hydrodynamic processes throughout the study area (Fig. 1). This research present initial steps in this direction.

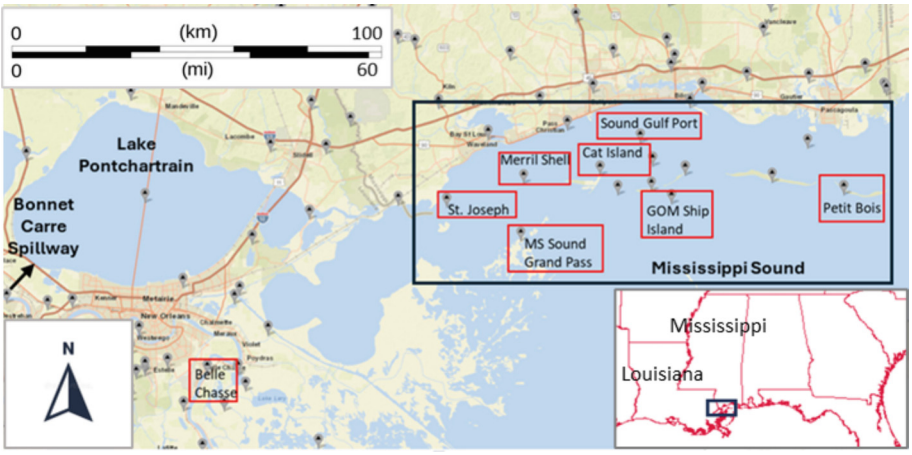

Fig. 1. Study area. The Mississippi Sound, Lake Pontchartrain and the Bonnet Carré Spillway are shown. United States Geological Survey (USGS) water quality stations in the area are shown as red rectangles.

In this paper, a partially calibrated hydrodynamic model for the MS Sound is presented. A comprehensive analysis of observed data including salinity, nutrients, coliform, suspended solids, and chlorophyll-a is performed to determine the spatial reach and boundary conditions of the model. A computational grid is presented, including preliminary hydrodynamic calibration results. The model is used for estimating Lake Pontchartrain flushing times under hypothetical BCS openings.

2 Methods

2.1 Study Area

Figure 1 shows the study area for this research. Lake Pontchartrain (located in Louisiana) at the western border of the figure, and Petit Boise USGS station (located at eastern Mississippi Sound) constitute the geographical limits for the study. Figure 2 shows the predominant land use and land cover in the inland watersheds that drain to the Mississippi Sound. The location of economically important oyster reefs is also shown. As depicted, urban areas along the Mississippi coast are significantly close to the oyster reefs. While densely populated areas are clearly potential sources of pollution, the dense network of rivers and minor streams in the land area may also collect non-point source pollutants from agricultural areas (cultivated crops, pasture/hay) located outside of the urban sprawl.

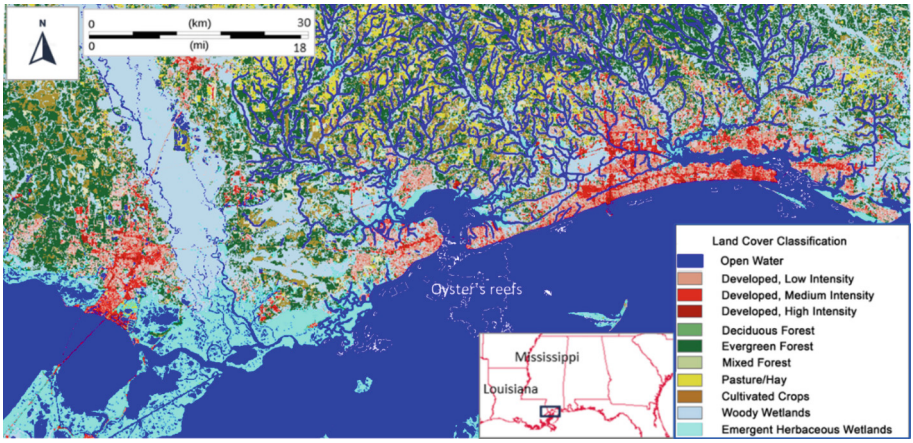

Fig. 2. Land use and land cover in the Mississippi Sound. Land use/land cover in urban areas draining to the MS Sound are shown.

2.2 Observed Water Quality Data

The Mississippi Department of Environmental Quality (MDEQ) and the United States Geological Survey (USGS) perform routine water quality analyses in the Mississippi Sound and Pontchartrain Lake. Nutrients and bacteria are considered indicators of potential water contamination from human and animal waste. Under the MDEQ Mississippi Beach Monitoring Program, water is monthly tested for the presence of fecal bacteria and nutrients. USGS stations collect monthly data although some stations are not operational and provide incomplete records with data gaps of several years or even a decade. The datasets obtained from these organizations are described in the following sections.

MDEQ Data
Monthly observed Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP), Total Suspended Solids (TSS), and salinity are used in the analysis. Basic statistical indicators were calculated for each of the water quality variables. In particular, we were interested on detecting the effects of the Bonnet Carré Spillway openings on the water quality of the MS Sound. Those openings occurred in years 2016, 2018 and 2019.

USGS Data
Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP), Total Suspended Solids (TSS), chlorophyll-a (chl-a), salinity (SAL), are analyzed. In this research, due to the very low NO_3 and NO_2 concentrations observed at all water quality stations, TKN observations are treated as surrogates of Total Nitrogen since it includes ammonia as well as organic N. Since the USGS stations collect water quality data sparingly (some stations collect data only a couple of months in the year), descriptive statistics (median, quartiles, minimum and maximum) were calculated using all observed data collected at selected stations. Nevertheless, salinity data for selected USGS stations were used at higher temporal resolution to detect effects of BCS opening on salinity. A comparison was performed for years 2014 (no BCS opening) and 2016 (BCS was opened for 23 days). Salinity data for years 2017 through 2019 were incomplete and a comparison was not possible.

2.3 Hydrodynamic Modeling

A hydrodynamic model that simulates the hydrodynamic and salinity regime for the area encompassed between Bonnet Carré Spillway (BCS) at Lake Pontchartrain and the Petit Bois USGS station (see Fig. 1) has been developed. In this model, freshwater inputs from the BCS, Pass Manchac, Tchefuncte, Pearl, Jourdan, and Wolf Rivers, will be set up as freshwater boundary conditions. Three open ocean boundaries are setup between the Grand Pass USGS St. and Petit Bois USGS Station are implemented to capture salinity and tidal effects throughout the MS Sound and Lake Pontchartrain.

3 Results

3.1 Water Quality at USGS Stations

Figure 3 shows a map that provide a geographical reference to the results shown in this section. Figure 4 shows boxplots for water quality data collected at the USGS stations. Salinity is shown to increase eastwards, while stations that are located close to Lake Pontchartrain (St. Joseph, Merrill Shell, Grand Pas and Cat Island) report salinity values below 25 parts per thousand (PPT), with episodical lows close to 0.0 PPT. These may be related to freshwater being hydrodynamically transported from the lake to those locations during rain events or BCS openings. The decrease in salinity is relevant because concentrations below 5 PPT may have strong implications for the health of key habitats that require higher salinity levels.

This spatial trend is also shown by TSS and turbidity observations. While turbidity at two locations on the Mississippi River (Baton Rouge and Belle Chase) ranges between 20 and 100 NTU, most turbidity values at the MS Sound stations are reported to be below 20 NTU. This seems to suggest that during BCS openings (BCSO), turbid waters from the Mississippi River may be diluted through mixture with less turbid waters from Lake Pontchartrain and/or the ocean, thereby decreasing turbidity at the MS Sound. The dilution effect is also observed in TSS concentrations, which slightly decrease eastwards.

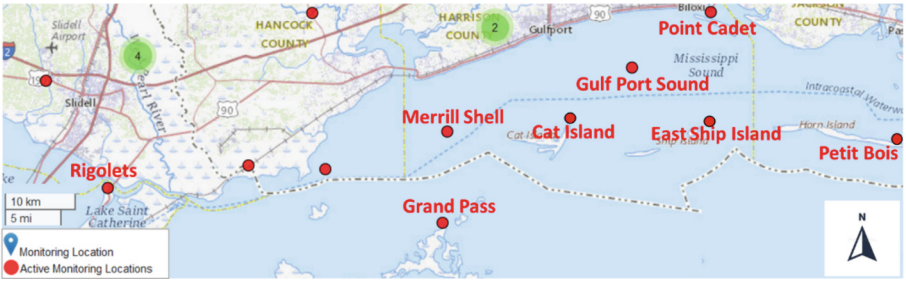

Fig. 3. Reference map for USGS stations results.

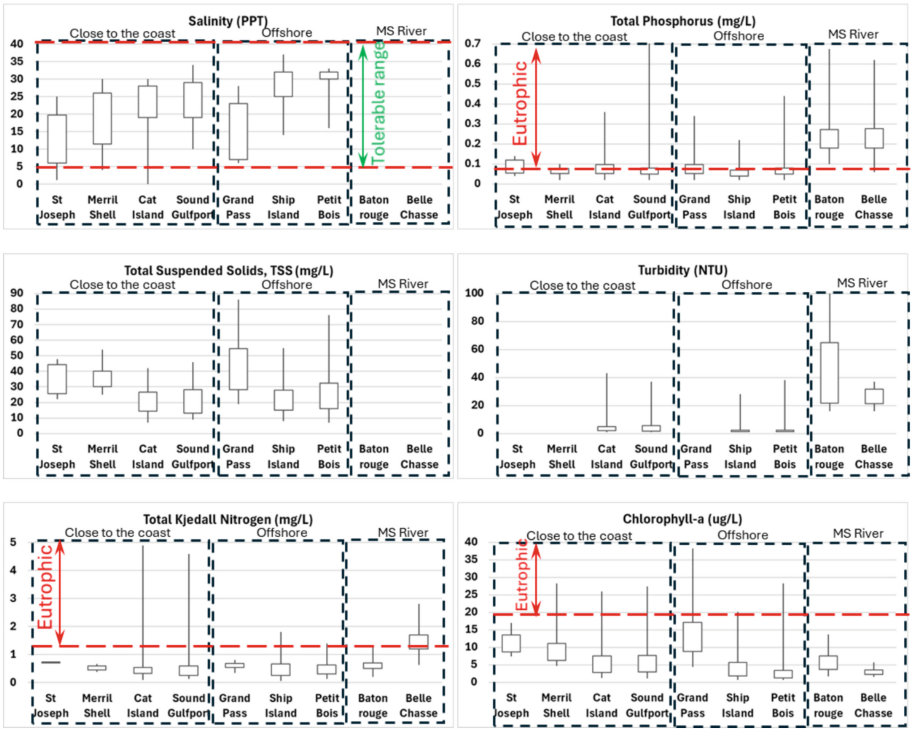

Fig. 4. Salinity and water quality at USG stations.

TKN and TP show a slight eastward decrease in concentrations. Most TKN concentrations are smaller than 2 mg/L which indicates mild eutrophication. The majority of TP concentrations are above 0.04 mg/L in the MS Sound ND above 0.15 mg/L in the Mississippi River, which indicates that eutrophication is a potential risk.

Chlorophyll-a concentrations are also shown to decrease eastwards. The majority of the concentration values are below 20 ug/L indicating that algal biomass is not substantial. Nevertheless, there are chlorophyll-a episodical peaks that are above 20 mg/L indicating that eutrophic conditions were observed in the past.

In general, there seems to be an eastward dilution effect for most of the water quality parameters observed at USGS stations.

Hourly Observations of Salinity at Selected USGS Stations

In order to ascertain if waters from the MS Sound are directly affected during rain events or BCS openings, hourly salinity concentrations observed at selected USGS stations during years 2014 and 2016 were explored. During year 2014, the Bonnet Carré Spillway was not opened but precipitation in the area was more intense from February 2014 to June 2014 than in the rest of the year, therefore 2014 was ideal to observe rainfall effects on salinity in the MS Sound. During 2016, there was a short opening of BCS (22 days during January 2016).

During year 2014 (when no BCSO occur), the sustained rain events that took place from February to June decreased salinity below 5 PPT at the exit of Lake Pontchartrain (Rigolets) during the same period (Fig. 5). At the most eastward station (Point Cadet), salinity also decreases below 5 PPT but from mid-March to mid-June. These stations are located at the MS Sound coast and are primarily affected by runoff from inland watersheds; therefore, it was expected to observe the decrease in salinity due to rainfall alone.

During 2016, the BCS was opened from January 10 to February 1 (22 days). The effect of BCSO on salinity is evident in Rigolets station even though lower than mean precipitation was observed concurrently. A gradual decrease to less than 5 PPT salinity values was observed (Fig. 5). A slight decrease is also observed at Point Cadet station (the most eastward monitoring location) although the salinity variation may also be attributed to the January precipitation events.

Since water quality constituents such as Nitrogen or Phosphorus in the water column react, transform, or are up taken by other biological organisms, it is unlikely that the effects of the short 2014 BCSO on nutrients will reach the Point Cadet station. Nitrogen and Phosphorus related concentrations at coastal locations will most likely depend on contaminants carried by inland runoff or leaked from urban areas.

Stations that are located in mid MS Sound (Merrill Shell and Gulf Port) show a similar trend as the coastal stations (Rigolets and Point Cadet) in year 2014 (Fig. 6). Nevertheless, salinity at Gulf Port station is greater than 7 PPT during the rainy months (February-June) and the rest of the year. Salinity at Merrill Shell station decreases episodically to less than 5 PPT during April and May, probably because this station is located close to Bay Saint Louis (an estuary that receives freshwater from two rivers).

During 2016 (year in which BCSO occur), salinity decreases gradually (at Merrill Shell station) to less than 5PPT during the BCSO (Fig. 6), evidencing the effect of the Bonnet Carré spillway openings. For Gulf Port station, however, salinity is greater than

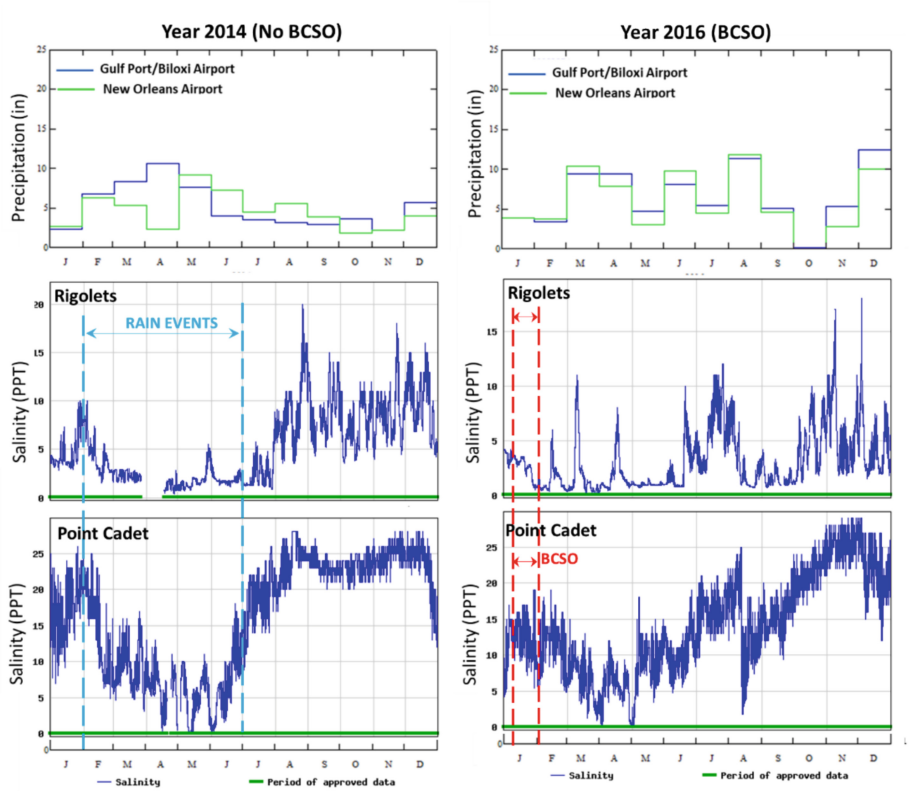

Fig. 5. Hourly salinity at coastal stations: Rigolets and Point Cadet.

10 PPT during all the BCS opening event, showing that the BCSO effects at this location are mild to none. Therefore, from a water quality modeling perspective, at Gulf Port station nitrogenous and phosphorus compounds concentrations in the water column will not likely be affected by short BCSO events such as the 2014's.

At offshore stations (Fig. 7), the effects of either rain events or BCSO are milder than in mid MS Sound or the coast. During 2014, salinity at Grand Pass station is mostly greater than 5 PPT during the rainy months and greater than 18 PPT during the rest of the year. At East Ship Island station, salinity seems to be not affected by rain events since it is shown to be greater than 10 PPT year-round. In January 2016 (month in which BCSO occurred) salinity at Grand Pass station decreases gradually to less than 5 PPT but also increases episodically to 10 PPT after January 20 (mid BCSO). This indicates a moderate effect of the BCSO at this location. At East Ship Island station (Fig. 7), salinities increase during the 2016 BCSO evidencing that the spillway opening does not affect salinities at this location. Therefore, water quality constituents will most likely be not affected by BCSO at locations as far as East Ship Island.

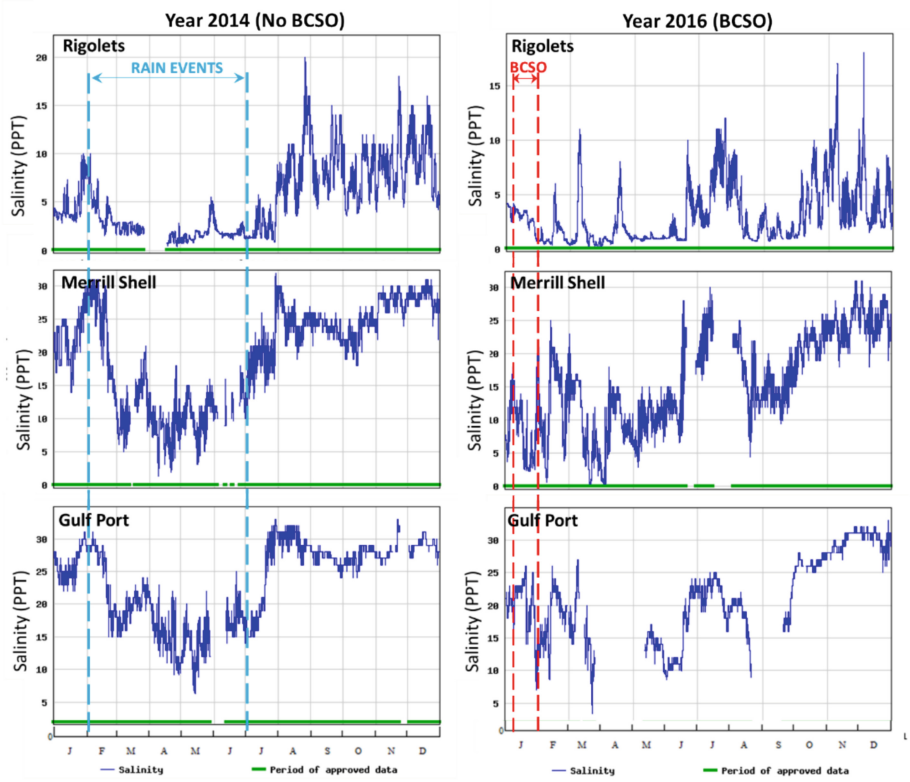

Fig. 6. Hourly salinity at stations close to the coast: Merrill Shell, Gulf Port Sound.

3.2 Water Quality at MDEQ Stations

As explained in previous sections, the MDEQ stations collect salinity and water quality data at a monthly frequency. Those stations are located at the MS Sound coast and are probably strongly affected by coastal surface runoff. Nevertheless, since it was detected that at the Point Cadet USGS coastal (the easternmost USGS station) salinity is decreased during rain events and/or BCSO, analyzing salinity data at MDEQ stations may help to providing bounds to BCSO effects at coastal waters of the MS Sound. Figure 8 shows the locations of selected MDEQ water quality stations which data was analyzed in this research.

Stations 1, 4, 7 and 8 are denominated "eastern stations" in this paper, while stations 11A, 12A, 14 and 20 are denominated "western stations". Western stations are geographically located close to Pontchartrain Lake, the Bonnet Carré Spillway, and the Saint Louis Bay estuary. Eastern stations are located close to Biloxi and Pascagoula rivers.

Figure 9 shows monthly salinity data at eastern and western MDEQ stations. As shown, salinity decreases during BCSO and/or sustained precipitation. The most extended BCSO (that took place in 2019) decreased salinity at western MDEQ stations

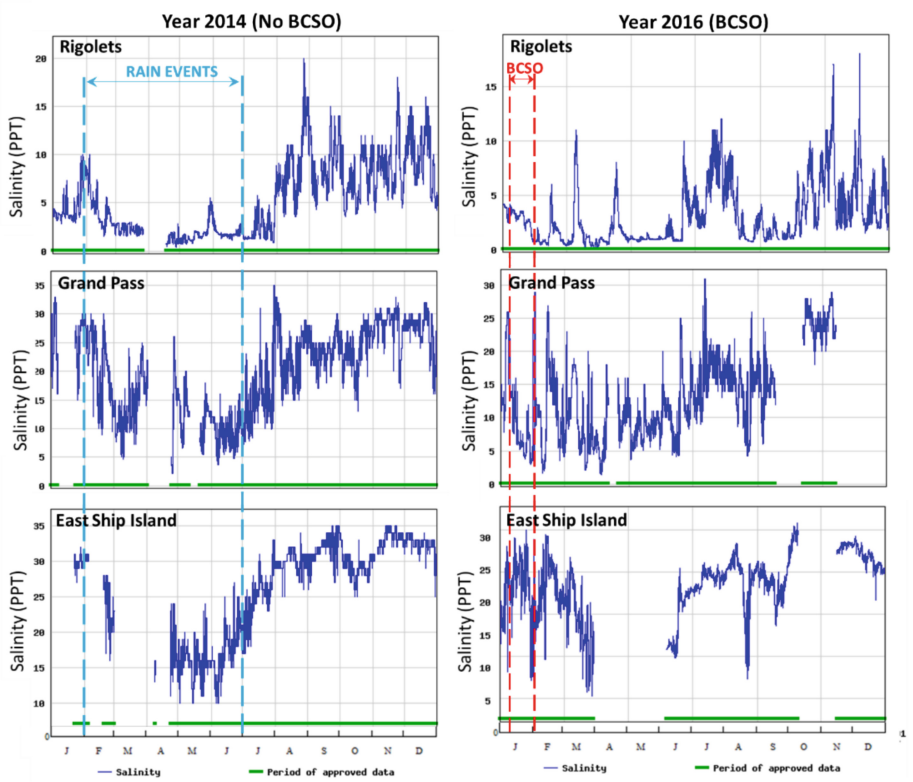

Fig. 7. Hourly salinity at offshore stations: Grand Pass, East Ship Island.

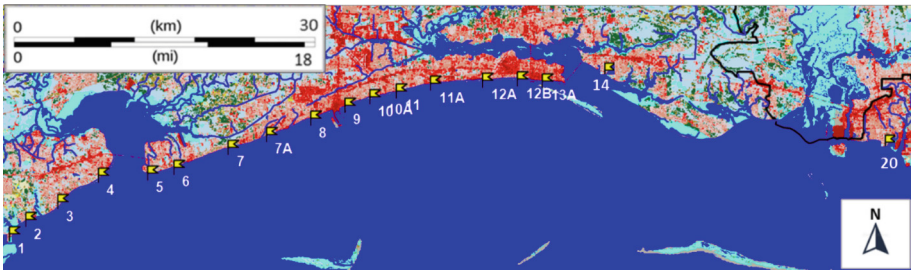

Fig. 8. Reference map for MDEQ stations results.

(MSDB01to MSDB 08) to less than 5 PPT. The 2016 and 2018 also decreased salinity below the 5 PPT threshold but only at western MDEQ stations MSDB01 and MSDB04. These results indicate that the spatial impact of short BCSO in salinity reaches MSDB04, while extended BCSO effects reach MSDB08. Salinity at all western stations is not less than 4.8 PPT.

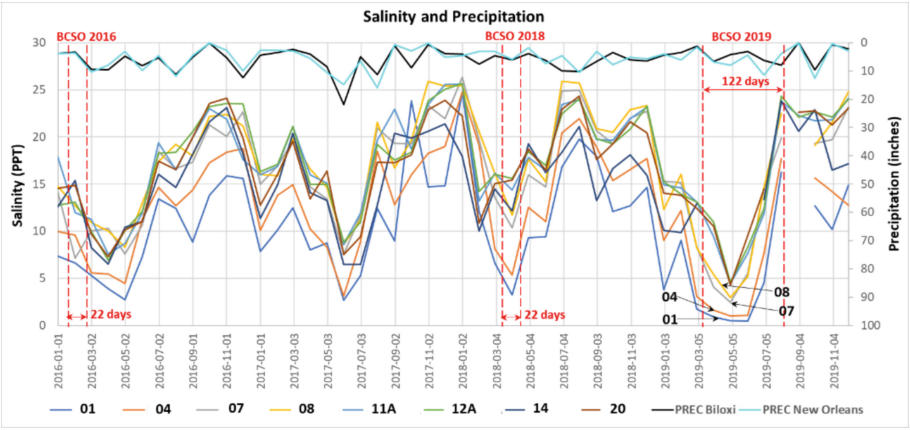

Fig. 9. Salinity and precipitation at selected MDEQ stations.

Since all BCSO occurred concurrently with precipitation events (see Fig. 9), assessing the actual effect of the spillway opening on salinity and its spatial reach is not straightforward. However, the precipitation events that took place during June and July 2017 (a year in which no BCSO occurred) show that salinity may decrease below 5 PPT because of coastal freshwater inputs, at stations MSDB01 and MSDB04. Salinity at western MDEQ stations that are not close to a river is above 7.5 PPT. Since during the longest BCSO salinity at those stations reached 4.8 PPT, therefore maximum the effect of precipitation alone is approximately 2.7 PPT during an extended opening of the Bonnet Carré spillway.

3.3 Computational Grid

Based on the previous discussion the proposed computational grid to simulate hydrodynamics and water quality in the study area is shown in Fig. 10.

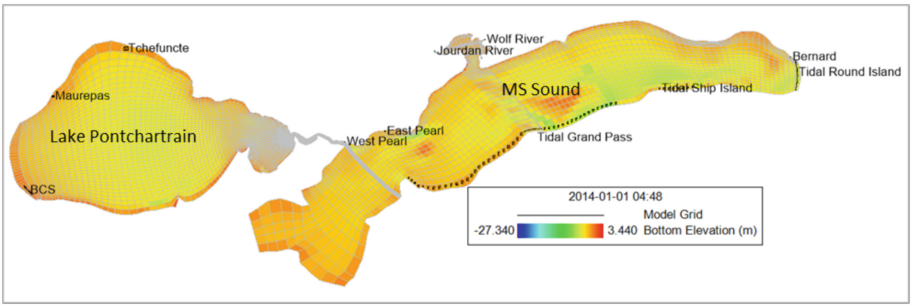

Fig. 10. Computational grid, bathymetry, and boundary conditions.

The model will simulate hydrodynamics covering the area encompassed between Bonnet Carré Spillway (BCS) at Lake Pontchartrain (Fig. 10 left) and the Round Island

USGS station (Fig. 10 right). In this model, freshwater inputs from the BCS, Lake Maurepas' Pass Manchac River, and Tchefuncte River will be set up as freshwater boundary conditions for the grid area representing Lake Pontchartrain.

West Pearl River freshwater boundary drains to the Rigolets (a strait that connects Lake Maurepas to the MS Sound. Fresh water boundaries for the MS Sound, are East Pearl, Jourdan and Wolf rivers. Those freshwater boundaries are setup using observed flow at USGS stations located on the rivers or area-averaged estimates in ungauged watersheds.

Three open ocean boundaries are setup between the Grand Pass USGS St. and Round Island USGS Station. Through these boundaries, salinity and tidal effects throughout the MS Sound and Lake Pontchartrain will be estimated. This modeling approach has been used for similar purposes in the MS Sound area [10–12], and other coastal water bodies in the Southeastern USA [13, 14].

The computational grid and corresponding hydrodynamic model were developed using the EEMS Modeling System (https://eemodelingsystem.com/). The curvilinear grid shown in Fig. 10 consists of 7255 grid cells and covers an area 3943.39 km^2.

3.4 Hydrodynamic Calibration

Hydrodynamic calibration is on-going. Nevertheless, Fig. 11 shows the current status of the calibration process showing simulated versus observed tidal elevations charts. Representative results for three USGS stations are shown: Rigolets (western station), Gulfport Light (central station), and Biloxi Point (eastern station).

The model successfully captures the tidal trend and magnitudes at central locations (Gulfport), captures trends and average magnitudes at western locations, and noticeably overestimates tidal elevations at eastern locations (Biloxi Point).

3.5 Lake Pontchartrain Flushing Time

A computational experiment for estimating Lake Pontchartrain flushing time was performed using the partially calibrated hydrodynamic model. Initial salinity in all the computational domain was setup to 2 PPT. Four Bonnet Carré Spillway openings (BCSO) inflow simulations were implemented in the model. Each simulation mimicked a real 43-day long BCS opening that occurred in year 2019. This spillway was the first of two openings during that year. During the first 2019 opening, gradually increasing flows from the Mississippi River were diverted towards Lake Pontchartrain. The maximum flow was 6031.5 m^3/s. After reaching the maximum, flows were decreased gradually until reaching 0.0 m^3/s. In this research, the historical flow timeseries was multiplied by 1.0, 0.75, 0.5, and 0.25, to explore the effect of flow magnitude in Lake Pontchartrain flushing time and salinity in the MS Sound. Figure 12 shows the scenario simulations.

Figure 13 shows that Lake Pontchartrain flushing time ranges between 24 days (for 100% of maximum flow, 6031.5 m^3/s) and 33 days for 75% of maximum flow. Figure 13 shows that after 43 days of BCSO, the Lake Pontchartrain would not be completely flushed for 50% and 25% of maximum inflow. Salinity at the Bay Saint Louis entrance (MDEQ stations 4 and 5 in Fig. 8) and coastal locations to the east of Bay Saint Louis

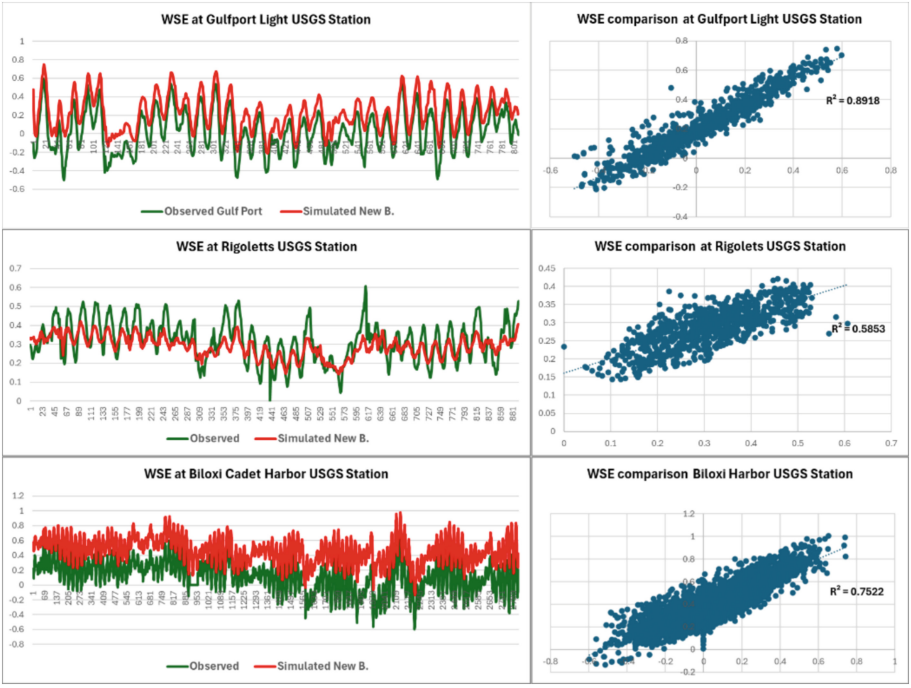

Fig. 11. Hydrodynamic calibration.

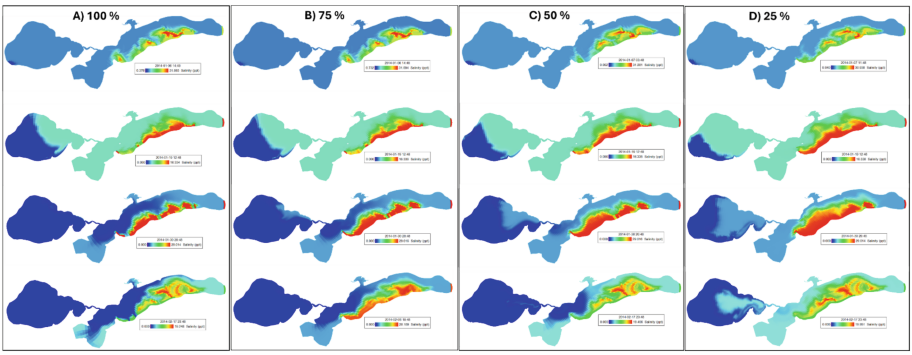

Fig. 12. Lake Pontchartrain flushing time and salinity in the MS Sound. A 2019 Bonnet Carré opening in which gradually increasing flows from the Mississippi River were diverted towards Lake Pontchartrain (maximum flow 6031.5 m^3/s). The historical flow timeseries was multiplied by A) 1.0, B) 0.75, C) 0.5, and D) 0.25, to simulate the effect of flow magnitude in Lake Pontchartrain flushing time and Mississippi Sound salinity.

(MDEQ stations 6 to 14 in Fig. 8) are above 6 PPT for scenarios where Lake Pontchartrain is not completely flushed. On the other hand, for scenarios where the Lake is flushed, salinities are between 1 PPT and 4 PPT. In particular, when BCS flows are not decreased

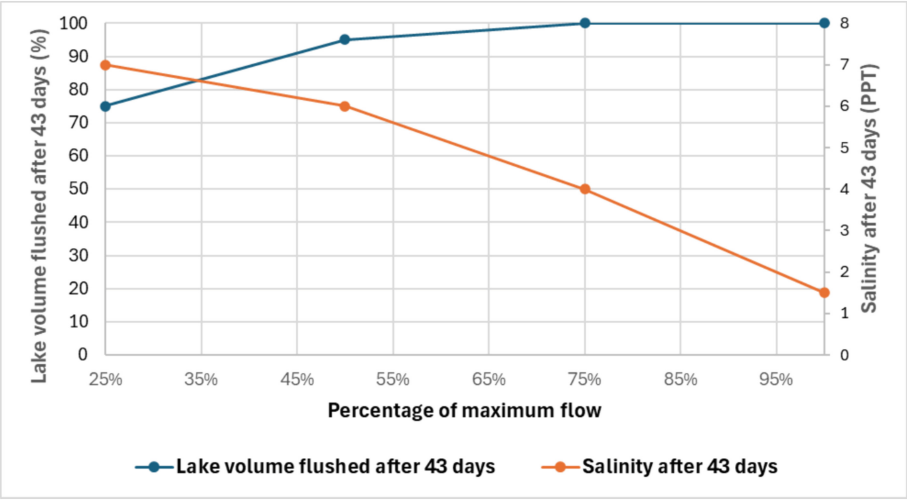

Fig. 13. Flushing time and salinity at MDEQ stations 4 and 5 (Saint Louis Bay entrance).

(Fig. 12 A), simulated salinities at MDEQ station locations 1 to 20 are similar to those observed in 2019 (Fig. 9).

The results shown in Figs. 12 and 13 are significant because they show that MS Sound's extreme decreases in salinity (< 5 PPT) occur after full flush of Lake Pontchartrain. Several biological species depend on salinity ranges above 5 PPT and their survival would be impaired.

4 Conclusions

Observed precipitation, salinity, TKN, TP, suspended solids, chlorophyll-a, and turbidity data collected at USGS and MDEQ monitoring stations in the Mississippi Sound indicate that Bonnet Carré Spillway openings may affect water quality as eastward as Gulf Port (Mississippi), and with lower intensity up to Biloxi. The effects seem to reach as southward as Grand Pass USGS stations and Cat Island (Mississippi). The hydrodynamic model presented in this paper simulates the effects of Bonnet Carré Spillway openings successfully. Also, a preliminary estimation of Lake Pontchartrain flushing times shows that it ranges between 24 days (for maximum flow = 6031.5 m^3/s) to 45 days (for maximum flow = 1507.9 m^3/s), and consequently, decreases in salinity in the MS Sound after BCSO will occur more slowly for BCSOs that divert smaller flows into Lake Pontchartrain.

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