

Effects of the Bonnet Carré Spillway Openings on the Mississippi Sound

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Abstract

The Lower Mississippi River basin has recently experienced more frequent and intense flooding. As a result, the Bonnet Carré Spillway, located north of New Orleans, has been opened more regularly to manage. The influx of freshwater has significantly reduced the salinity of the Mississippi Sound, while also introducing high levels of Nitrogen and Phosphorus from agricultural runoff in the upper Mississippi River. This paper investigates the relationship between the Bonnet Carré Spillway openings and changes in the Mississippi Sound's water quality. Specifically, we analyze data on precipitation, salinity, and water depth from 2016 to 2023 to identify patterns and correlations between spillway operations, salinity levels, and sedimentation. The Bonnet Carré Spillway plays a critical role in flood control but can significantly impact on the hydrology and ecology of the Mississippi Sound when activated. Through this analysis, our research seeks to enhance understanding of how human interventions, such as spillway openings, affect the balance of coastal water ecosystems.

Keywords

Bonnet Carré Spillway, Mississippi Sound, Precipitation, Salinity

1. Introduction

The Bonnet Carré Spillway is a massive flood control structure that diverts Mississippi River flood waters into Lake Pontchartrain and the Mississippi Sound, preventing flooding in southern Louisiana and New Orleans [1]. This Spillway was built in response to the 1927 flood and was finished in 1931. The spillway drains floodwater from the Mississippi River into Lake Pontchartrain, a 1630 km² brackish lagoon north of New Orleans [2]. The Mississippi Sound runs across Hancock, Harrison, and Jackson counties, measuring approximately 45 miles (72

km) east-west and 15 - 20 miles (24 - 32 kilometers) north-south. The Mississippi Sound supports diverse marine life, commercial fisheries, and recreational activities, contributing substantially to the regional economy and ecosystem services [3]. The Mississippi Sound comprises various marine environments such as estuaries, bays, and barrier islands [1]. As New Orleans expanded and hydrologic changes were made, it underwent numerous anthropogenic changes, including eutrophication, increased salinities, and wetlands loss [2] [4]. The increased freshwater influx from the Bonnet Carré Spillway freshwater, silt, and nutrients to the surrounding environment [5]. Since 1937, Spillway has opened 15 times, totaling 609 days. The average flow through the Bonnet Carré Spillway during openings from 2011 to 2020 was 3750 m³/s or 0.37 km³ of water per day. As a result, the Spillway fills the whole volume of Lake Pontchartrain every 16 days that it is open [1]. The Bonnet Carré spillway was activated twice in 2019 due to an unprecedented flood in the Mississippi River Basin. The floodgates were opened from February 27th to April 10th and again from May 10th to July 27th, resulting in 123 days of flooding. The water, high in nitrogen and phosphorus from agricultural runoff, led to a toxic algal bloom, causing beach closures for over 90 days. The flood also caused damage to aquatic animals and Mississippi's industries [5]. Introducing fresh water to estuaries has been shown to significantly impact phytoplankton productivity. Freshwater estuaries exhibit high primary productivity due to the influx of nutrients. However, light availability is limited due to high suspended sediment concentrations [2]. However, spillway openings are massive, variable, and frequent; hence, more research is needed to better understand the processes and impacts in estuarine systems and plan for improved management strategies [1]. This study investigates the effects of Bonnet Carré Spillway openings on the Mississippi Sound's water quality and ecosystem. This project aims to combine in-situ water quality data with remotely sensed imagery. This includes evaluating changes in water quality metrics in response to spillway openings, following freshwater plumes and influxes into the Mississippi Sound, and investigating the links between spillway openings, water quality, and ecosystem responses. It is also crucial for comprehending flood operations' effects on estuarine systems and devising effective management strategies to mitigate the spillway opening's impact.

2. Study Area

The Bonnet Carré spillway (**Figure 1**), located about 30 miles outside of New Orleans, was designed to shift floodwater from the Mississippi River into Lake Pontchartrain and the Mississippi Sound to protect New Orleans from flooding. The Bonnet Carré spillway is a U.S. Army Corps of Engineers project that was constructed between 1929 and 1931 after the Great Mississippi Flood of 1927 [6]. The discharge from the spillway into Lake Pontchartrain and eventually into the Mississippi Sound can have profound effects on the water quality and ecological health of the receiving bodies. One of the key parameters reflecting these changes

is salinity, which serves as an indicator of water quality and ecosystem dynamics in estuarine environments. This paper investigates the impact of Bonnet Carré Spillway openings on salinity levels as well as sediment changes of the Mississippi Sound from 2016 to 2023.

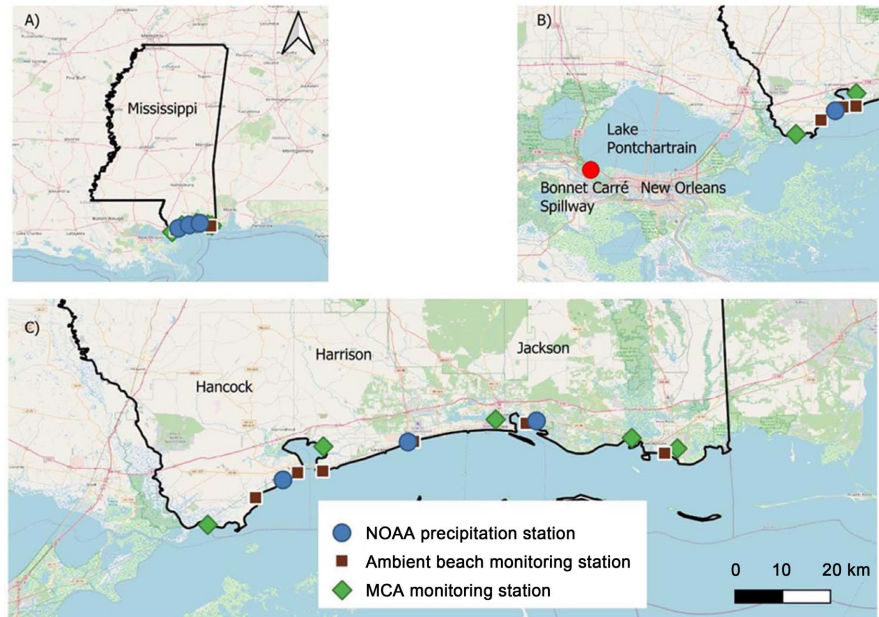


Figure 1. (A) Map of Mississippi, (B) Location of Bonnet Carré Spillway and the surrounding of New Orleans and Lake Pontchartrain, (C) Location of selected three NOAA precipitation stations (Waveland, Gulfport, and Ocean Springs), six MDEQ Ambient beach monitoring stations (1, 4, 5, 9, 14, and 19), and five MCA monitoring stations (113A23, CS208, 646BBB12, 113A24, and T14).

3. Data and Methodology

We compile salinity data from 2016 to 2023, from monitoring stations in the Mississippi Sound region. These datasets are first checked for data quality control and then are analyzed to identify temporal trends and anomalies. We then associate Bonnet Carré Spillway openings timing. Statistical techniques, including time series analysis and correlation analysis are employed to quantify the relationship between spillway operations and salinity fluctuations.

3.1. Bonnet Carré Spillway Opening Data

We acquire data regarding the opening of the Bonnet Carré spillway from the US Army Corps of Engineers. Datasets include the date of opening, number of days open, bays open at peak, percentage of max flow, peak flow rate, and daily discharge during opening as shown in **Table 1** [6]. Spillway data from the years 2016, 2018, 2019, and 2020 are also collected.

The total discharge (cubic feet per second) is converted into the volume (in gallons) of freshwater that was discharged and would eventually enter the Mississippi Sound. For instance, 5.37 trillion gallons discharged in 2016, 4.48 trillion

gallons discharged in 2018, 87.1 trillion gallons discharged during the two openings in 2019, and 3.51 trillion gallons discharged in 2020.

Table 1. Bonnet carré spillway historical opening [6].

Year	Date Opened	Days Open	Bays Opened at Peak	Percentage Of Max Flow (%)	Peak Flow Rate (cfs)
1945	March 23	57	350	100	250,000
1950	February 10	38	350	100	250,000
1973	January 28	48	285	81.4	203,571
1973	April 8	75	350	100	250,000
1975	April 14	13	225	64.3	160,714
1979	April 17	45	350	100	250,000
1983	May 20	35	350	100	250,000
1997	March 17	31	298	85.1	212,857
2008	April 11	31	160	45.7	114,286
2011	May 9	42	330	94.3	235,714
2016	January 10	22	210	81.2	203,000
2018	March 8	22	183	78.4	196,000
2019	February 27	43	206	85.2	213,000
2019	May 10	79	168	64.4	161,000
2020	April 3	29	90	36.0	90,000

3.2. Mississippi Coastal Assessment Program Data

The Mississippi Department of Environmental Quality's (MDEQ) Mississippi Coastal Assessment Program (MCA) conducts annual monitoring of the coastal waters of Mississippi, utilizing a sampling protocol that encompasses approximately 30 randomly selected sites each year. Key ecological indicators such as water quality, sediment quality, biota, and habitat are systematically evaluated as part of MCA's monitoring efforts (MDEQ, 2023). For the specific scope of this study, five fixed monitoring sites were selected: 113A23, CS208, 646BBB12, 113A24, and T14. To analyze trends in water conditions, data from 2016 to 2023 are utilized, focusing particularly on salinity and depth measurements recorded at each site annually. Through the analysis of water profile data across these years and locations, salinity and depth profiles are generated for each site, allowing for the identification of temporal and spatial variations in these key parameters within the Mississippi coastal region.

3.3. Ambient Beach Monitoring Program Data

The Mississippi Department of Environmental Quality's (MDEQ) Ambient Beach Monitoring Program collaborates with various agencies to comprise the Beach Monitoring Task Force. As part of MDEQ's program, weekly sampling is con-

ducted at 21 beach monitoring stations, providing insights into seasonal water quality conditions along publicly accessible and recreational beaches (MDEQ, 2023). In this study, six specific beach monitoring stations are chosen (**Figure 2**). Stations 1 (Lakeshore Beach) and 4 (Bay St. Louis Beach) in Hancock County, stations 5 (Pass Christian West Beach) and 9 (Gulfport Harbor Beach) in Harrison County, and stations 14 (Front Beach) and 19 (Pascagoula West Beach) in Jackson County. We compile salinity data from 2016 to 2023 for each of these stations. Monthly averages of salinity are then computed for each site and plotted across years to visualize trends in salinity levels over time.

3.4. Precipitation Data

We gather daily precipitation data from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information for Hancock County, MS (Waveland), Harrison County, MS (Gulfport), and Jackson County, MS (Ocean Springs) which are located (**Figure 3**) near the selected beach station sites of this study. The daily precipitation data is aggregated into monthly totals. The precipitation for each month from the 8-year period is also averaged to determine normal precipitation for the selected timeframe. The temporal examination includes a comprehensive evaluation of the yearly and monthly precipitation trends from January to December over the eight-year period. While salinity levels can vary for many reasons, this data is analyzed to investigate the relationship between salinity fluctuations and precipitation patterns, as well as to examine the impact of openings of the Bonnet Carré Spillway on salinity levels.

4. Results

4.1. Precipitation Trends Analysis

Our analysis reveals a significant similarity in the average total precipitation across the three stations, indicating a low disparity in precipitation readings. **Figure 2** shows year-to-year variation of monthly precipitation totals (shown for the month of July), compared with normal precipitation values (solid line). Notably, in January 2016, 2017, and 2019, precipitation levels seem to be consistently higher than the average at all three stations. Similarly, precipitation levels in February 2018, and 2021 consistently exceed the normal averages at all three stations. In March 2016, 2018, 2021, and 2022, precipitation levels also exceed long-term averages. Notably, the month of April reveals an increased precipitation, with 2016 and 2021 emerging as consistently above average across all stations.

Similarly, May precipitation trends reveal notable above-average elevations, particularly in 2017, 2021, and 2022. Similarly, June shows higher precipitation levels in 2017, 2020, and 2021. Precipitation levels in August are significantly higher than average in 2017, 2021, and 2022, while precipitation levels in September are consistently higher in 2018 and 2022 across all stations. October shows increased precipitation levels in 2017 and 2019, while November demonstrates similar trends in 2018, 2020, 2022, and 2023. Finally, December seems to have

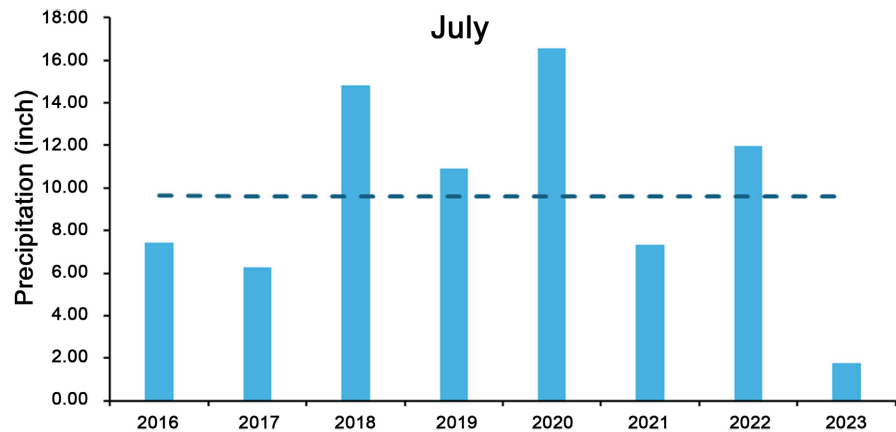


Figure 2. Year-to-year variation of July precipitation total and normal precipitation (solid line).

higher precipitation levels in 2016, 2018, and 2023. The graphical representations clarify the distinction between wet and dry seasons, with April, May, June, July, and August having the highest average of the average total precipitation values across the three stations, at 7.13, 6.51, 9.94, 8.88, and 9.89 inches, respectively. Conversely, the dry months, which primarily last from September to November, have comparatively lower average total precipitation values of 3.81, 3.96, and 3.26 inches, respectively, with a subsequent increase in December, registering at 5.64 inches. Notably, precipitation levels in January, February, and March are lower than in December, at 4.95, 4.05, and 4.28 inches, respectively. These results are summarized in **Table 2**.

Table 2. Average total precipitation for three stations from January to December over 8 years.

Month	Waveland	Gulfport	Ocean Springs	Average Total Precipitation	Seasonal
January	5.62	3.89	5.34	4.95	
February	4.56	3.96	3.62	4.05	Dry Months
March	4.60	3.65	4.60	4.28	
April	7.59	6.76	7.05	7.13	
May	7.55	5.49	6.49	6.51	
June	9.81	9.55	10.46	9.94	Wet Months
July	9.63	7.68	9.32	8.88	
August	11.18	9.30	9.19	9.89	
September	3.91	3.33	4.18	3.81	
October	3.21	4.00	4.68	3.96	Dry Months
November	3.36	3.28	3.15	3.26	
December	6.56	5.11	5.26	5.64	

4.2. Salinity and Precipitation during Spillway Closure

In general, salinity in the Mississippi Sound is shown to increase in dry, winter months for many reasons including less rainfall and less input freshwater input. Therefore, salinity and precipitation are inversely proportional, which is shown in the data of this study. However, there are several occurrences where precipitation increased, and salinity increased as well, some of which are noted as follows:

Hancock County

In December 2023 (Figure 3) there was significant precipitation, but salinity continued to climb. December salinity is typically stable. December 2023 received more precipitation than the previous 7 years, and salinity was the highest than the previous 7 years as well. Similarly, there is a noticeable increase in precipitation and salinity in June 2022.

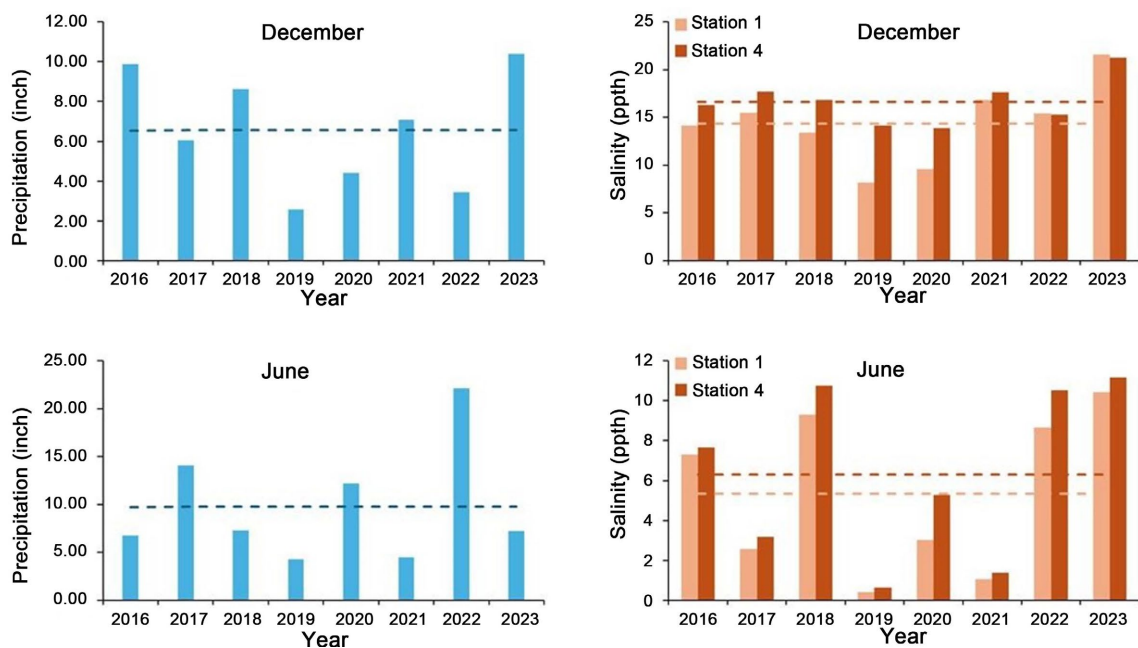


Figure 3. Year-to-year variation of December (Top panel) and June (Bottom panel) for Precipitation (Blue), and Salinity (Brown) for Hancock County. Waveland is a NOAA precipitation station, and Stations 1 and 4 are MDEQ Ambient Beach Monitoring stations.

Harrison County

In 2022 July, there was significant precipitation as well as a significant increase in salinity (Figure 4). In 2018 July, there was significant precipitation as well as a significant increase in salinity. Although there was a spillway opening in 2018, the discharge only occurred in the month of March.

Jackson County

Years 2017-2018 May precipitation (Figure 5) increased as well as salinity. The Spillway opening in 2018 only occurred in the month of March. Noticeably, 2017 October precipitation increased as well as salinity.

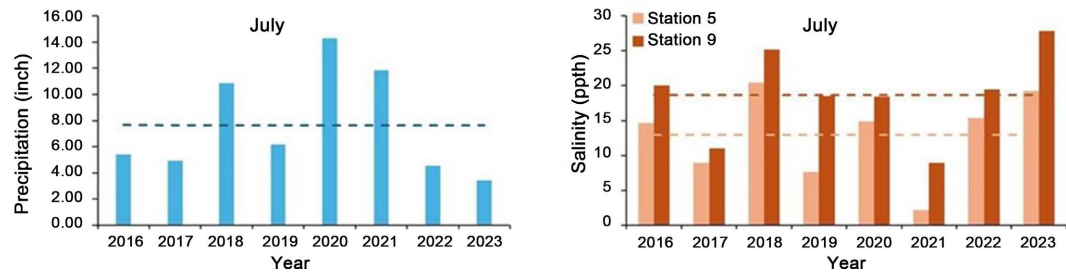


Figure 4. Year-to-year variation of July for Precipitation (Blue), and Salinity (Brown) for Harrison County. Gulfport is a NOAA precipitation station, and Stations 5 and 9 are MDEQ Ambient Beach Monitoring stations.

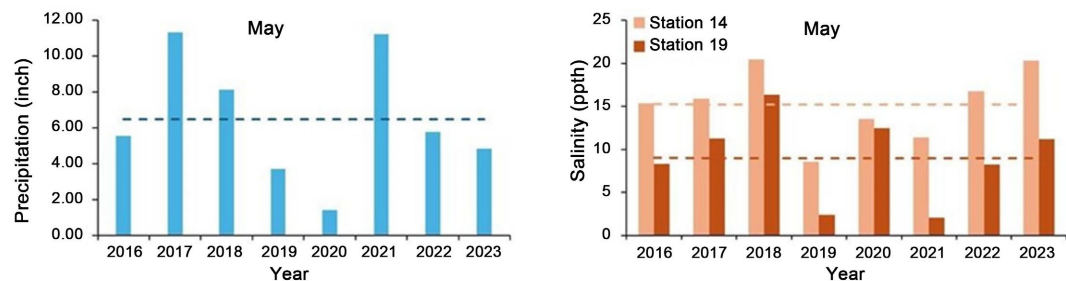


Figure 5. Year-to-year variation of May for Precipitation (Blue), and Salinity (Brown) for Harrison County. Ocean Spring is a NOAA precipitation station, and Stations 14 and 19 are MDEQ Ambient Beach Monitoring stations.

4.3. Salinity and Precipitation during Spillway Openings

In addition, decreased salinity levels which were unrelated to precipitation can be attributed to the Bonnet Carré Spillway discharge events for 2016, 2018, 2019, and 2020. The changes in salinity were highly evident in 2019, while smaller discharge events had a moderate or no effect on salinity depending on location. The effects of the spillway openings were observed as follows.

Hancock County

2016 January precipitation was below average to average precipitation (Figure 6), and salinity was also lower than average, which could potentially contribute to the Bonnet Carré opening. Similar findings can be noticed in 2018 March (figures not shown). Importantly, 2019 March to July, the salinity is almost non-existent, due to spillway openings. The precipitation starts to increase in July, and the salinity starts to increase. This increases as well in salinity, even with the precipitation increase, is an indicator of recovery for the Mississippi Sound, which coincides with spillway closure. There was no noticeable effect from the spillway opening in the year 2020.

Harrison County

2016 January precipitation was an average precipitation, but salinity was lower than average which can be contributed to the Bonnet Carré opening. In contrast, the pattern is opposite.

Jackson County

2019 salinity remained unaffected until May, and the severity was compara-

tively milder than the stations in Hancock and Harrison County. There was no noticeable effect from the spillway opening in 2020.

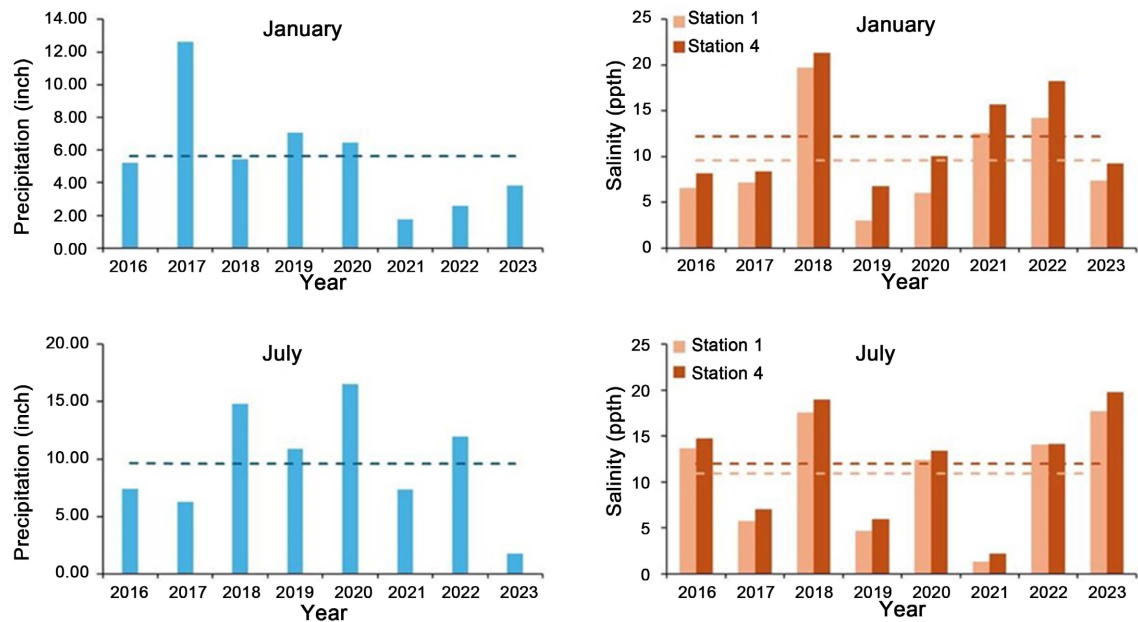


Figure 6. Year-to-year variation of January (Top panel) and July (Bottom panel) for Precipitation (Blue), and Salinity (Brown) for Hancock County. Waveland is NOAA precipitation station, and Stations 1 and 4 are MDEQ Ambient Beach Monitoring stations.

4.4. Correlation Analysis: Salinity and Precipitation

In instances of heightened precipitation, there is typically a decrease in salinity, suggesting a negative correlation. However, it's worth noting that the wetter months coincide with the warmer seasons in our study area, during which salinity tends to rise. Upon scrutinizing the data for each month from 2016 to 2023, no significant correlations between salinity and precipitation are observed. The distribution in **Table 3** revealed a minority of instances with high correlation (11.11%), along with a comparable proportion of medium and low correlations (20.83% each), while the majority exhibited no discernible correlation (47.22%). Although the prevailing trend leaned towards negative correlation, there were instances of positive correlation, notably during drier months. For stations with a positive correlation in February, March, May, November, and December, the precipitation and salinity were noted to both be above average for most years. For stations with positive correlation in June, July, and September, the precipitation and salinity were noted to both be below average for several years. In October, stations 14 and 19 were shown to have a positive correlation, some years the precipitation and salinity were above average, and some years were below average.

4.5. Water Depth and Sediment

Utilizing the MCA dataset, fluctuations in water depths alongside corresponding

Table 3. Correlation coefficients precipitation/salinity (2016-2023).

Month	Salinity 1	Salinity 4	Salinity 5	Salinity 9	Salinity 14	Salinity 19
January	-0.4	-0.49	0.07	-0.39	-0.65	-0.69
February	0.69	0.73	0.32	0.19	0.12	0.11
March	0.52	0.6	0.62	0.66	-0.12	-0.67
April	-0.09	-0.25	-0.14	-0.14	-0.82	-0.11
May	-0.22	0.36	-0.51	-0.53	-0.09	-0.09
June	0.26	0.07	-0.16	-0.25	-0.63	-0.44
July	0.11	0.01	-0.5	-0.71	-0.63	-0.82
August	-0.7	0.07	-0.23	0.04	0.32	0.6
September	0.25	0.08	-0.33	-0.3	0.32	0.63
October	-0.06	0.07	0.21	0.2	0.2	0.02
November	-0.06	0	0.08	0.09	0.32	0.56
December	0.67	0.76	0	0.02	0.28	0.16

changes in salinity levels can be observed. However, for this study, the focus was on water depth levels as an indication of sedimentation. An increase in water depth suggests a decrease in sedimentation, while a decrease in water depth indicates an increase in sedimentation. Data which corresponded to time periods of spillway openings was closely analyzed. The depths fluctuated 2 - 3 feet at all sites for the years 2016-2023, but no discernible pattern was observed. Regarding the site closest to the Bonnet Carré Spillway, 113A23 (**Figure 7**), water depths were greater than the other locations. There were fluctuations in depth (2 feet lower in 2019 than 2018 and 2020), but no pattern was identified. Sites CS208 (**Figure 7**) and T14 (**Figure 7**) were noted to have the greatest changes between 2018 and 2020. Site 646BBB12 (**Figure 7**) appeared to have the most stable water depth (except for 2020) and was also noted to be the shallowest site.

5. Discussion

5.1. Water Depth and Sediment

Spillway discharge typically occurs in the spring due to higher rainfall and snowmelt. In 2019, the discharge of the Bonnet Carré lasted through the month of July. The data from MCA in **Figure 7** is collected in summer months (typically July or August), which could explain why 2019 discharge event. Resulted in more prominent variations in the water depth. Because the water depths fluctuated for all sites between the years and there were no patterns detected, this could be explained by the many hydrologic factors that influence sedimentation in the Mississippi Sound. In addition to discharge from the Bonnet Carré and the Mississippi River, tidal/wave action, storm events, coastal erosion, and human activities can also alter sedimentation dynamics.

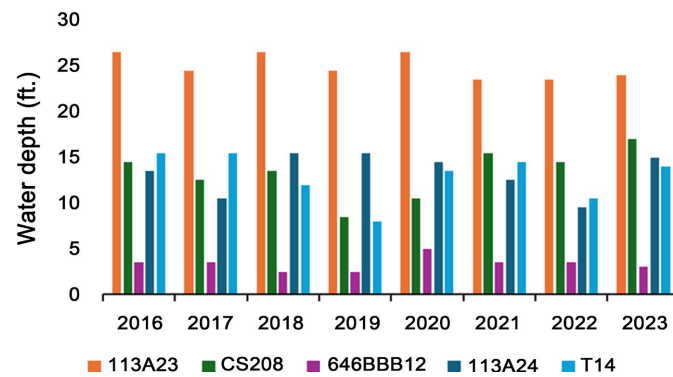


Figure 7. Water depths at five MCA monitoring stations.

5.2. Salinity and Precipitation

While precipitation can greatly affect the salinity levels of the Mississippi Sound, there are many factors that contribute to salinity changes. As seen from the data analyzed in this study, freshwater inflow from the Bonnet Carré Spillway can greatly reduce salinity. In some cases, salinity levels were extremely low and there was no correlation to precipitation or discharge events. This could be explained by some of the many other factors which contribute to salinity in the Mississippi Sound. Tidal and wave action can affect the mixing of saltwater and freshwater which can contribute to fluctuations. Mixing can also be hindered by geography and topography such as shape and depth of the sound, as well as the presence of barrier islands. Additionally, human activities such as dredging or pollution can have impacts on salinity. The correlation between salinity and precipitations in the Mississippi Sound can vary depending on the season and other environmental factors. Generally, salinity and precipitation are negatively correlated in coastal environments like the Mississippi Sound, meaning that increased precipitation tends to lower salinity levels and vice versa. However, the strength and direction of this correlation can fluctuate throughout the year due to seasonal variations in weather patterns, river discharge, and other factors. During periods of heavy rainfall, such as in the spring and early summer, freshwater inputs from precipitation and river runoff can significantly reduce salinity levels in the Mississippi Sound. This influx of freshwater dilutes the seawater, leading to lower salinity levels near river mouths and estuarine areas. Conversely, during drier periods or in the absence of significant rainfall, salinity levels in the Mississippi Sound may increase due to reduced freshwater input and higher rates of evaporation. This is particularly evident in the summer months when evaporation rates are typically higher, leading to the concentration of salts in the water and elevated salinity levels. A summary of average salinity and precipitation for each month from 2016-2023 is shown in [Table 4](#).

6. Results and Discussion

6.1. Precipitation and Salinity Trends

In the Mississippi Sound, salinity levels typically showed an inverse relationship

Table 4. Average salinity/precipitation for 3 stations stretching through January to December over 8 year's period.

Month	Waveland-Salinity	Gulfport-Salinity	Ocean Springs-Salinity	Avg Salinity (2016-2023)	Waveland-Precip	Gulfport-Precip	Ocean Springs-Precip
January	10.9	17.07	17.4	15.12	5.62	3.89	5.34
February	9.18	9.79	14.83	11.27	4.56	3.65	3.62
March	7.43	12.16	13.08	10.89	6.72	6.76	4.6
April	4.75	9.52	12.16	9.99	7.59	5.76	7.05
May	4.95	9.06	11.4	8.72	8.91	5.49	6.49
June	5.83	9.7	11.4	8.47	9.63	5.95	9.46
July	11.46	15.8	14.41	13.89	11.18	7.6	8.39
August	15.42	19.73	18.14	17.76	9.31	6.33	9.12
September	12.54	17.42	19.38	16.44	3.91	3.33	4.18
October	14.84	19.45	24.1	19.46	3.21	4.06	4.68
November	15.56	21.91	23.49	20.32	3.26	2.38	3.15
December	15.48	21.52	21.6	19.63	2.6	5.11	5.26

with precipitation, rising during drier months (like winter) and falling during times of substantial precipitation (like spring). However, anomalies like the consecutive rises in salinity and precipitation in June 2022 and December 2023 demonstrate the impact of restricted freshwater mixing and localized hydrodynamic variables. The estuarine balance was upset by spillway events, especially the extended openings of 2019, which caused salinity levels in Hancock and Harrison counties to fall to almost nil. These occurrences highlight the Mississippi Sound's susceptibility to freshwater inflows, highlighting the necessity of adaptive management to lessen long-term effects even in the event of salinity recovery after closure.

6.2. Water Depth, Sedimentation and Correlation Analysis

Variations in water depths of two to three feet were noted at several monitoring locations, with the biggest shifts occurring close to the spillway. This suggests that the sediment redistribution is influenced by tidal pressures, spillway operations, and human activity. While deposition patterns affected benthic habitats, increased water depths after spillway openings suggested sediment scouring. Precipitation and salinity were found to have modest to moderate negative associations, with seasonal and regional variability, according to correlation analysis. Positive correlations in some months indicated intricate relationships between evaporation, spillway operations, and tidal mixing, underscoring the variety of factors affecting the salinity and sedimentation dynamics of the Mississippi Sound.

6.3. Discussion

The ecological and hydrological balance of the Mississippi Sound is significantly impacted by the Bonnet Carré Spillway operations. Extended spillway openings, like the one that occurred in 2019, led to notable salinity declines, seriously upset-

ting estuarine ecosystems and creating toxic conditions like algal blooms. Even if salt levels increased after the closure, the system's resilience is limited, and recurrent interventions run the danger of causing long-term deteriorations. Sedimentation patterns showed limited effects, with water clarity and benthic ecosystems being impacted by sediment redistribution. Multifactorial interactions, such as tidal action, coastal erosion, and human activity, further impact these processes. The necessity for adaptive spillway management solutions that strike a compromise between flood control and ecological preservation is highlighted by the rising frequency of extreme weather occurrences. Future initiatives should concentrate on long-term monitoring, sophisticated hydrodynamic modeling, and cooperative stakeholder involvement to ensure sustainable management of this crucial estuarine ecosystem to reduce cumulative consequences.

7. Conclusion and Recommendation

This investigation explores the complex relationship between the operations of the Bonnet Carré Spillway and variations in the water quality of the Mississippi Sound. We find that there is a general negative correlation between salinity and precipitation in the Mississippi Sound. Also, the strength and direction of this correlation can vary seasonally and are influenced by a combination of factors including weather patterns, river discharge, tidal fluctuations, and human activities. While precipitation significantly influences salinity levels, many other factors modulate as well. These include tidal and wave action, storm events, coastal erosion, human activities, such as dredging and pollution, the area's geography and topography, and the presence of barrier islands.

The interplay of these factors creates a dynamic, multifaceted ecosystem where changes are often unpredictable. To deepen our understanding of these complex dynamics, future research could adopt a more comprehensive approach, by incorporating additional data sources and analytical techniques to account for the various influences on water quality. Establishing long-term monitoring programs would allow for tracking of seasonal and interannual variations over extended periods. Additionally, advanced modeling techniques could simulate various likely scenarios, helping to assess the potential ecological impacts of human interventions, including spillway operations. Collaborative efforts among researchers, policymakers, and stakeholders are essential to develop sustainable management strategies that mitigate the adverse effects of human activities while preserving the integrity of this vital coastal ecosystem.

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Declarations

All authors have read, understood, and have complied as applicable with the state-

ment on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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