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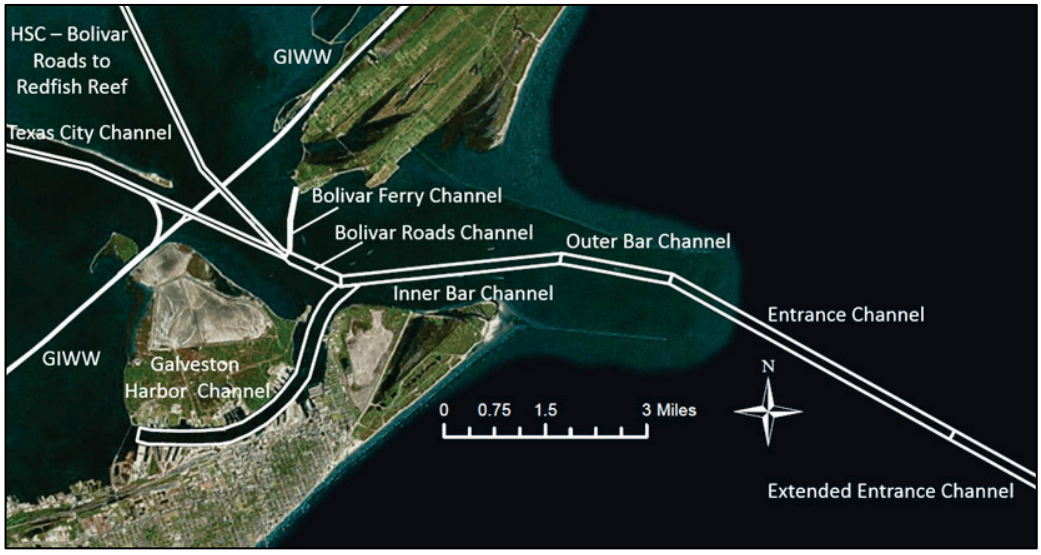
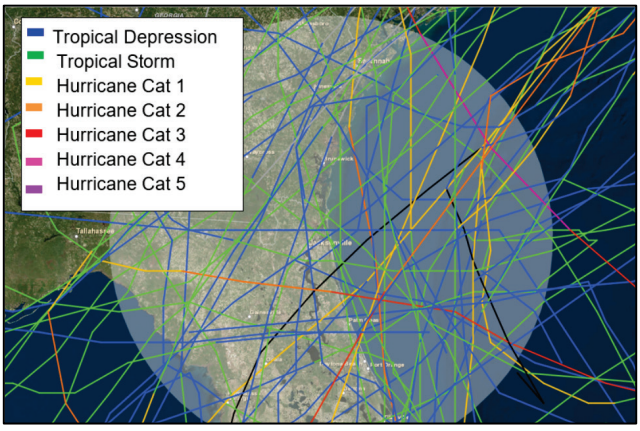
Effect of Tropical Storms and Precipitation on Dredging Volumes: Houston-Galveston, TX, and Mayport, FL

Ashley E. Frey and Lauren A. Coe

June 2020





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Effect of Tropical Storms and Precipitation on Dredging Volumes: Houston-Galveston, TX, and Mayport, FL

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Abstract

This study characterizes infilling responses within dredged navigation channels to rainfall from tropical storms and hurricanes. This project created a web tool based on the methods described in this report. This report discusses the different analysis methods considered to relate storm and rainfall to dredging volumes at two pilot sites, Galveston, TX, and Mayport, FL. A comprehensive storm Impact Factor for hurricanes was developed to quantify the impact at a site based on proximity, duration, and wind speed. The methods vary based on the length and timing of periods of storms and rainfall prior to a dredge event. At Galveston, TX, when 2-year dredging volume totals were compared to hurricane activity occurring in the previous 2 years, the maximum dredging volume removed was higher after higher hurricane activity when compared to low activity periods. The average amount dredged was higher following periods of high hurricane activity. At Mayport, FL, dredging volumes were compared to hurricane activity occurring since the last dredging action took place. Similarly to Galveston, TX, the maximum dredging volume removed was higher after higher hurricane activity periods when compared to low activity periods. The average amount dredged was higher following periods of high hurricane activity.

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Preface

This study was conducted for Headquarters, US Army Corps of Engineers (HQUSACE) as part of the Dredging Operations and Environmental Research (DOER) Program, Project Number 14-03, "Channel Infilling Analysis." The DOER Program Manager was Dr. Todd Bridges. Mr. Jeffrey A. McKee was the HQUSACE Navigation Business Line Manager overseeing the DOER Program.

The work was performed by the Coastal Engineering Branch, Navigation Division, and the Coastal Processes Branch, Flood and Storm Protection Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Lauren M. Dunkin was Chief, Coastal Engineering Branch; Mr. Charles E. Wiggins was the Technical Director, Navigation; Dr. Jacqueline S. Pettway was Chief, Navigation Division; Ms. Ashley Frey was Chief, Coastal Processes Branch; Dr. Cary Talbot was Chief, Flood and Storm Protection Division; and Mr. Mike Ott was the HQUSACE Navigation Business Line Manager overseeing the DOER Program. The Deputy Director of ERDC-CHL was Mr. Jeffrey R. Eckstein, and Dr. Ty V. Wamsley was the Director.

The Commander of ERDC was COL Teresa A. Schlosser, and the Director of ERDC was Dr. David W. Pittman.

1 Introduction

As part of the "Evaluation of Dredging Requirements as a Function of Channel Infilling Processes" Research Task in the US Army Corps of Engineers (USACE) Dredging Operations and Environmental Research Program, dredging records were analyzed to determine the impact of meteorological conditions on future dredging requirements. Research began in mid-Fiscal Year (FY)14 and concluded in FY17. This technical report describes the process and analysis for two sites: (1) Galveston Harbor, TX, and (2) Mayport Basin, FL (US Navy aircraft carrier basin at Naval Station (NS) Mayport, FL).

1.1 Background

The need for this research came from discussions with USACE dredging managers who are responsible for making decisions regarding nationwide channel maintenance. Generally, maintenance dredging of a channel occurs on a regular dredging cycle where the channel is dredged to a target-maintained depth suitable for navigation and then allowed to incur natural sediment deposition until the next dredging event. As the tidal hydraulics and long-shore sediment transport forcings acting in coastal entrance channels are very complex, dynamic, and highly localized, there is often a significant amount of uncertainty associated with the volumes of sediment that accrue between dredging events. This fact coupled with the USACE 2-year budget formulation cycle can make it difficult for dredging managers to accurately predict channel maintenance budgetary needs.

The experience knowledge of long-time USACE dredging managers, coupled with uncertainty-driven conservatism in the submitted budgetary formulations, helps to minimize the instances where vessel draft restrictions are required due to severe shoaling and thus minimizes disruptions to waterborne commerce. However, due to limited outlays from the Harbor Maintenance Trust Fund, the USACE maintenance dredging program is budget constrained and therefore cannot afford to maintain full authorized channel dimensions at all deep-draft navigation projects. Additionally, many of the most experienced USACE district dredging managers have been retiring in recent years, mirroring trends across the federal government. This loss of institutional knowledge has exacerbated the need for improved predictive tools that provide USACE practitioners with a better understanding of channel infilling processes.

Additional site-specific information can be collected to better inform managers about how channel infilling processes respond to hurricane activity and precipitation totals between dredging events. A more comprehensive approach would include the evaluation of dredging records and meteorological forcing data so that locations and volumes within the channel can be predicted to achieve more efficient management of dredging.

1.2 Objective

The main objectives of this study are to (1) determine the effects of tropical storm activity and precipitation on future maintenance dredging requirements and (2) develop a generalized method that can be applied to different sites with the use of readily available data. An average dredging amount is typically used as a guideline for the request of funds because those requests may be made a significant time prior to when actual dredging takes place. This analysis should provide additional information about how a site has reacted to storms or rainfall in the past and inform managers on how similar conditions may impact dredging volumes in the future. This study analyzed channel infilling based on forcing data and historical dredging events.

1.3 Approach

Two pilot sites were chosen to develop the analysis: (1) Galveston Harbor, TX, and (2) Mayport Basin, FL. Galveston and Mayport were selected since they both experience tropical events and precipitation and have a river input or bay system. After completing the analysis at these sites and applying the methodology at additional test sites, a more uniform method for predicting channel dredge volumes was developed that can be expanded to any other channel system in the country.

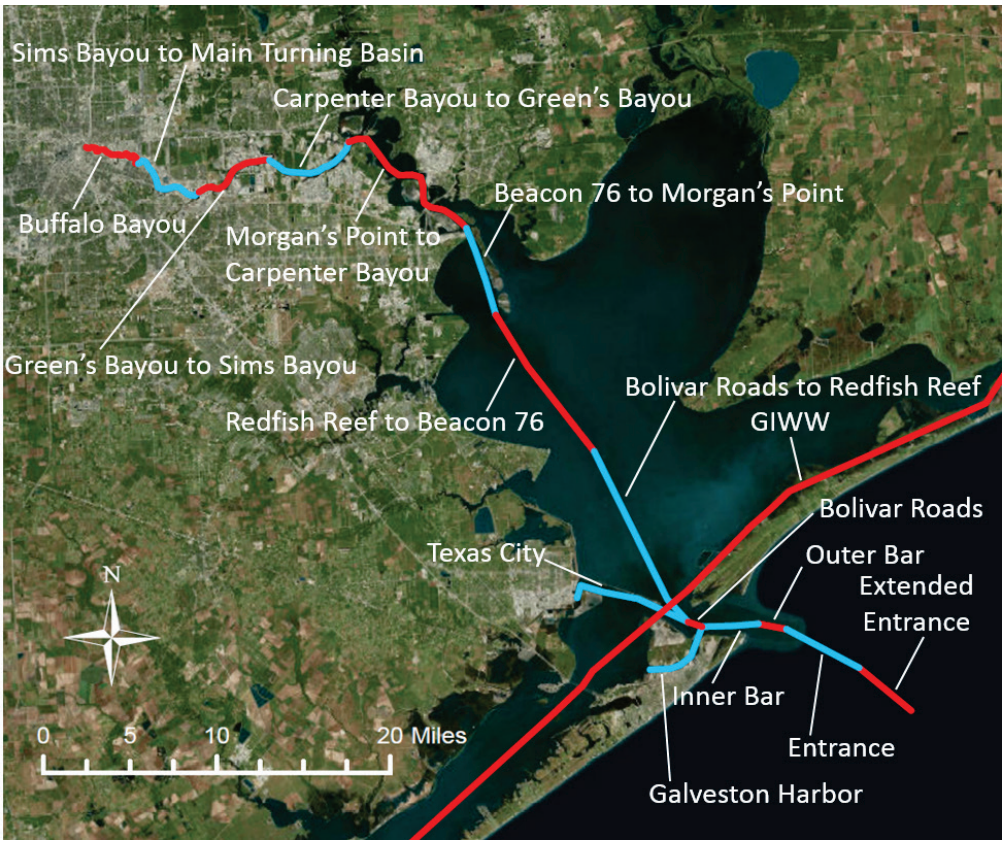
Previous studies focusing on Galveston Island and the Houston Ship Channel, TX, and Mayport, FL, made analysis data readily available. Dredging data that had been processed and analyzed in support of those studies were applied to the infilling processes questions being investigated in this effort, which greatly reduced the amount of time needed to conduct this analysis. Additionally, the Houston-Galveston channel system consists of many interconnected channels within Galveston Bay and the Gulf Intracoastal Waterway (GIWW) and thus provides a very complex case to test.

1.4 Galveston, TX

Houston-Galveston refers to two connected channels, the Galveston Entrance Channel and the Houston Ship Channel, which combine to make up one of the busiest waterways in the world. The Houston-Galveston navigation channels are labeled in Figure 1. More than 60 ships and 340 barge movements transit the Houston Ship Channel each day (Houston-Galveston Navigation Safety Advisory Committee 2011). The authorized project channel depth is 45 ft.[1] (All depths in this document are referenced to mean lower low water.) The total distance from the Galveston Entrance Channel to the end of the Houston Ship Channel at Buffalo Bayou/Light-Draft Channel is approximately 65 miles. From the GIWW to the end of the Galveston Extended Entrance Channel in the open waters of the Gulf of Mexico, the distance is 16 miles. The distance between the Houston Main Turning Basin and the intersection with the GIWW is 49 miles.

[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Figure 1. Houston-Galveston navigation channels and Galveston Harbor, TX.



Although the entire system is very complex and extends into the City of Houston, not all of the navigation channels are included in this dredging analysis. The focus of this analysis is to determine dredging based on storms and precipitation. Although some of the more inland channels may experience shoaling due to storm events, the effects of storms are more apparent nearer to the Gulf where the storms are more impactful. For that reason, this analysis only considered the Galveston Harbor; however, dredging for all Gulfward channels (the last mile of Bolivar Roads to Redfish Reef, Bolivar Roads, Inner Bar, Outer Bar, Entrance Channel, and Extended Entrance Channel) is presented in Appendix A.

1.5 Mayport, FL

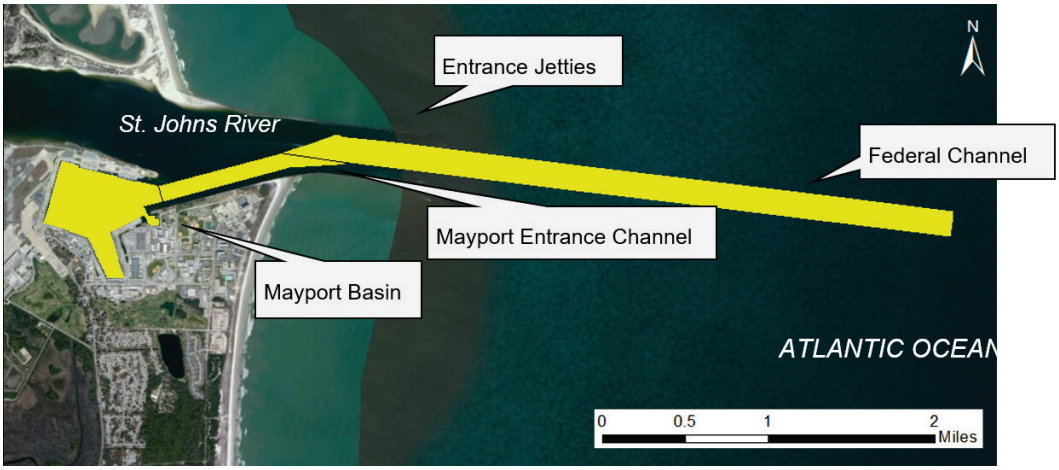
The Mayport, FL, Entrance Channel and NS Mayport Basin are located on the eastern coast of Florida just north of Jacksonville. The NS facilities are situated at the mouth of the St. Johns River as it meets the Atlantic Ocean. The entrance channel to the Basin extends approximately 4 miles offshore into the Atlantic Ocean. Figure 2 shows a map of the greater Jacksonville area, and Figure 3 shows the region of focus at Mayport.

Mayport functioned well as a pilot site because much of the data record was long, the site undergoes frequent dredging, and the site experiences sedimentation from both river and coastal sources influenced by rainfall and tropical storms, respectively. Furthermore, the Mayport, FL, site was also the focus of a comprehensive shoaling study completed by the US Army Engineer Research and Development Center for the US Navy[1], and therefore, the data were readily available.

Figure 2. US NS Mayport, FL, location near Jacksonville, FL.

[1] Thomas, R. T., and L. M. Dunkin. Unpublished manuscript. *US Navy FCA Shoaling Study: Demonstration Project, Mayport, FL.* Vicksburg, MS: US Army Engineer Research and Development Center.

Figure 3. Mayport Basin and Entrance Channel, FL.



1.6 Report organization

This report is organized into five chapters. Chapter 1 discusses the purpose of the research and the site locations. Chapter 2 describes the site conditions: tropical events, precipitation, and dredging history. Chapter 3 discusses methodologies for the analysis of storms and precipitation, and the appropriateness of each method. Chapter 4 gives an estimate of dredging needs for future years. Summary and conclusions are presented in Chapter 5.

2 Site Conditions

To make the methodology discussed in this report as widely applicable as possible, readily available and easily accessible datasets of historical rainfall and hurricanes were chosen to discern trends between dredging and varying site conditions.

2.1 Hurricanes and tropical storms

Hurricanes and tropical storms up to 150 miles from a chosen site are considered in this analysis. The distance of 150 miles was chosen to capture strong distant storm that have a wide radius of influence. For larger storms, hurricane force winds (>74 mph) can extend up to 150 miles from the storm center (NOAA 1999). Hurricane activity is reported to have influence on 1% probability extreme precipitation at a distance of up to 230 miles (Barlow 2011). The storms range from minor tropical depressions to major hurricanes. The Saffir-Simpson Scale ranks hurricanes from 1 to 5 according to sustained wind speed and is commonly used as a tool to alert the public of potential damage for each category (NHC CPHC 2020). Wind speeds in this analysis can be considered a proxy for wave conditions and surge-induced currents that drive the movement of sediment in open waters. The maximum storm surge typically occurs near the radius of maximum winds (NOAA NHC 2020).

2.1.1 Galveston, TX

All hurricanes and tropical storms that occurred between 1945 and 2013 within 150 miles of the Galveston Entrance Channel were considered in this analysis. During that period, 50 storms impacted the Houston-Galveston area. Figure 4 shows all tropical events since 1945 with maximum wind speed within 150 miles of the Galveston Entrance Channel. While some of these storms may have been Category 5 hurricanes at some point, only the wind speed within the 150 mile radius circle is important for this analysis. During the time period considered in this analysis, there were 12 storms that had maximum winds of tropical depression strength within 150 miles of Galveston, twenty tropical storms, eleven Category 1 hurricanes, two Category 2 hurricanes, three Category 3 Hurricanes, two Category 4 hurricanes, and no hurricanes that reached Category 5 strength within 150 miles of Galveston. The strongest storm was Hurricane Audrey, which reached a wind speed of 144 mph and is in

the middle of the range for Category 4 wind speeds. The other Category 4 hurricane was an unnamed storm known as the 1949 Texas Hurricane. The other major hurricanes (classified as Category 3 or higher) were an unnamed storm known as the 1945 Texas Hurricane, Hurricane Alicia, and Hurricane Rita. Hurricane Ike made landfall on Galveston Island and produced a devastating storm surge; however, when considering only wind speed, it was classified as a Category 2 hurricane. Figure 4 shows the maximum wind speed of all hurricanes that were tracked within 150 miles of Galveston Harbor, TX, with those strongest storms labeled.

Figure 4. Maximum wind speed of tropical storms and hurricanes between 1945 and 2013 within 150 miles of Galveston, TX.

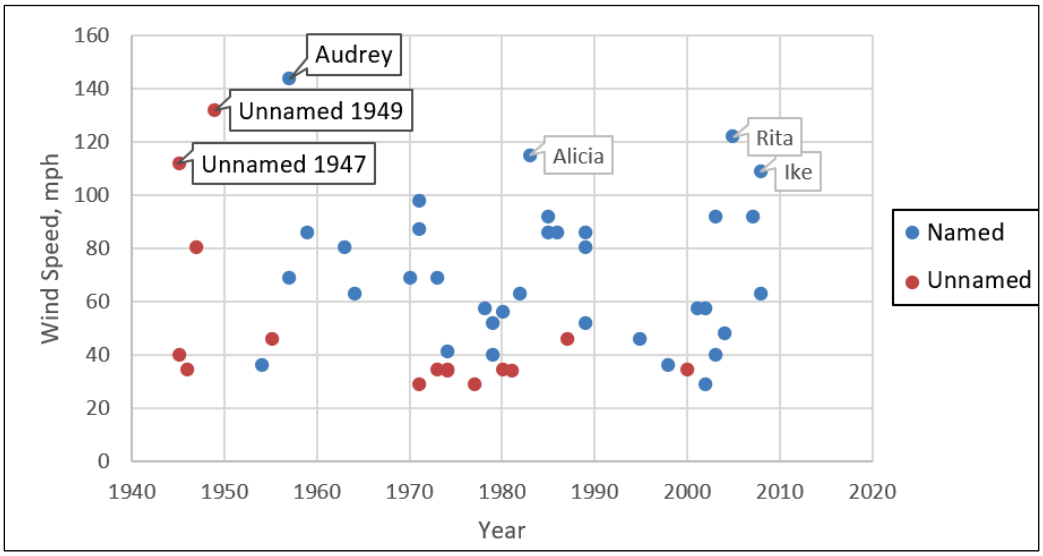


Figure 5 shows the tracks of all hurricanes and tropical events within 150 miles of the Galveston Entrance Channel. Figure 6 shows only Category 3, 4, and 5 hurricanes, and Hurricane Ike, which was only a Category 2 hurricane but was a direct hit on Galveston, TX, and resulted in large-scale damage. The analysis of tropical events considered wind speed, duration, and distance from the Galveston Entrance Channel and will be described in more detail in Chapter 3.

Figure 5. Tracks of all hurricanes and tropical events within 150 miles of Galveston, TX, 1945–2013 (NOAA [2015a]).

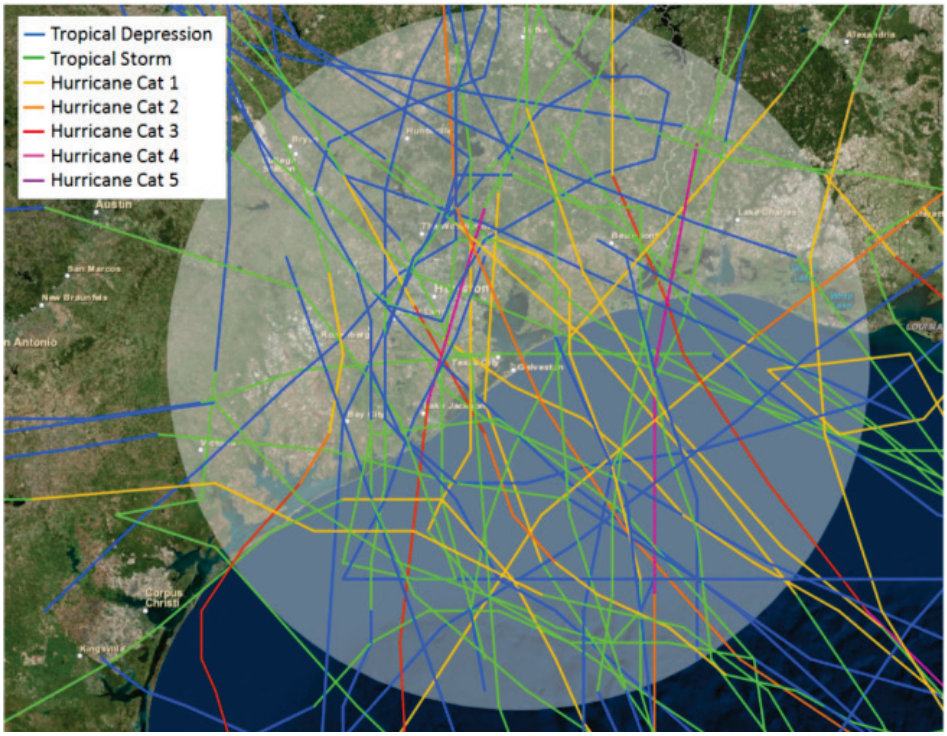
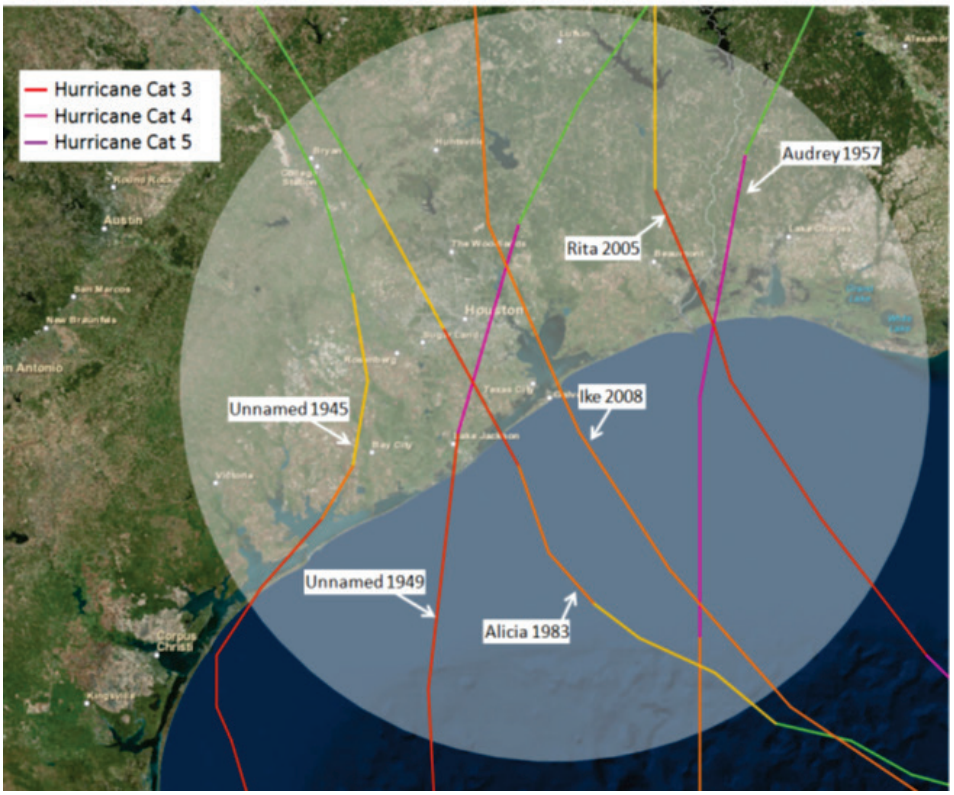


Figure 6. Category 3, 4, and 5 hurricanes, and Hurricane Ike, affecting Galveston, TX, 1945–2013 (NOAA [2015a]).



2.1.2 Mayport, FL

All hurricanes and tropical storms that occurred between 1954 and 2013 within 150 miles of the Mayport Entrance Channel were considered in this analysis. During that time period, 70 storms impacted the Mayport, FL, area. These storms ranged from minor tropical depressions to major hurricanes. Figure 7 shows the maximum wind speed of all tropical storms and hurricanes that were tracked within 150 miles of Mayport, FL, since 1953, with those strongest storms labeled. While some of these storms may have been Category 5 hurricanes at some point, only the wind speed within the 150 mile (radius) circle is important for this analysis. Figure 8 shows the tracks of all hurricanes and tropical events within the radius of interest. During the time period considered in this analysis, there were just three storms that were Category 3 or higher (Figure 9). The strongest storm was Hurricane Gracie, which reached a wind speed of 138 mph. The other two Category 3 storms were Donna (1960) and Dora (1964).

Figure 7. Maximum wind speed of tropical storms and hurricanes between 1954 and 2013 within 150 miles of Mayport, FL.

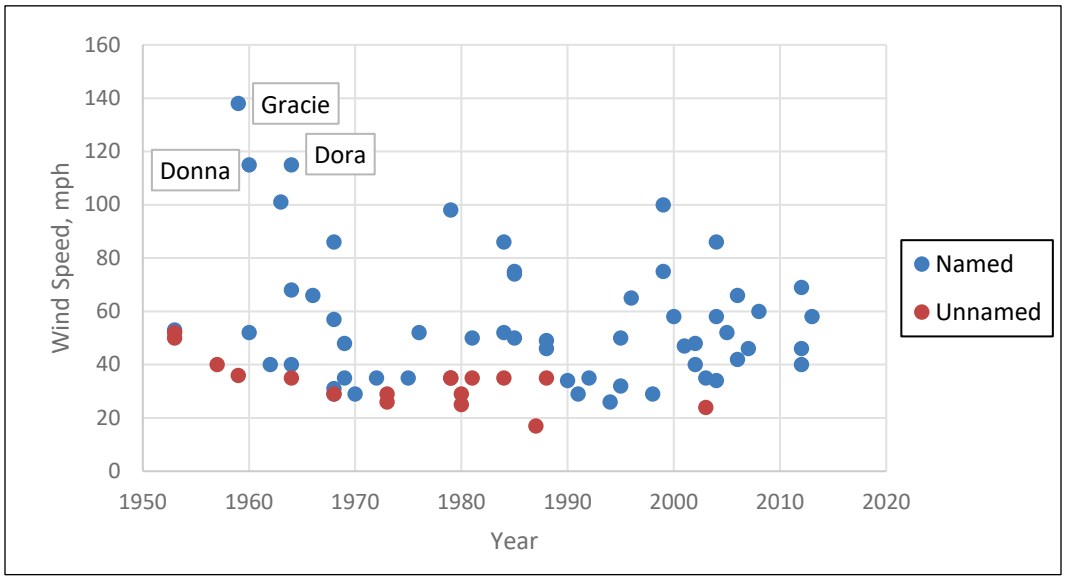


Figure 8. All hurricanes and tropical events within 150 miles of Mayport, FL, 1954–013 (NOAA [2015a]).

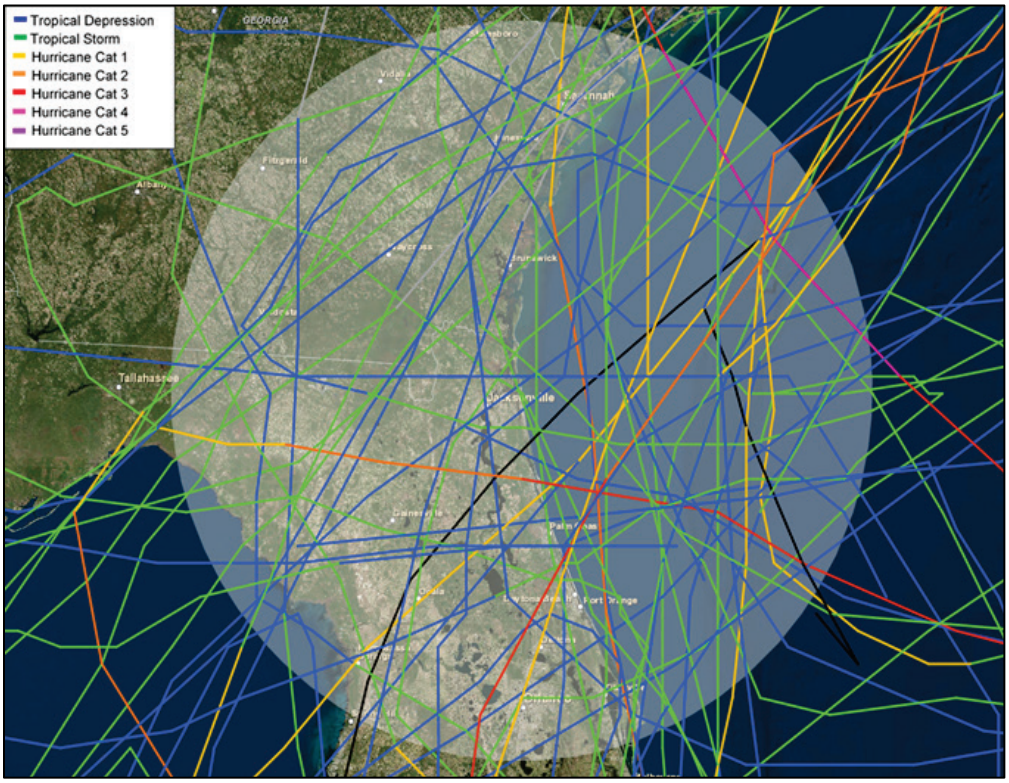
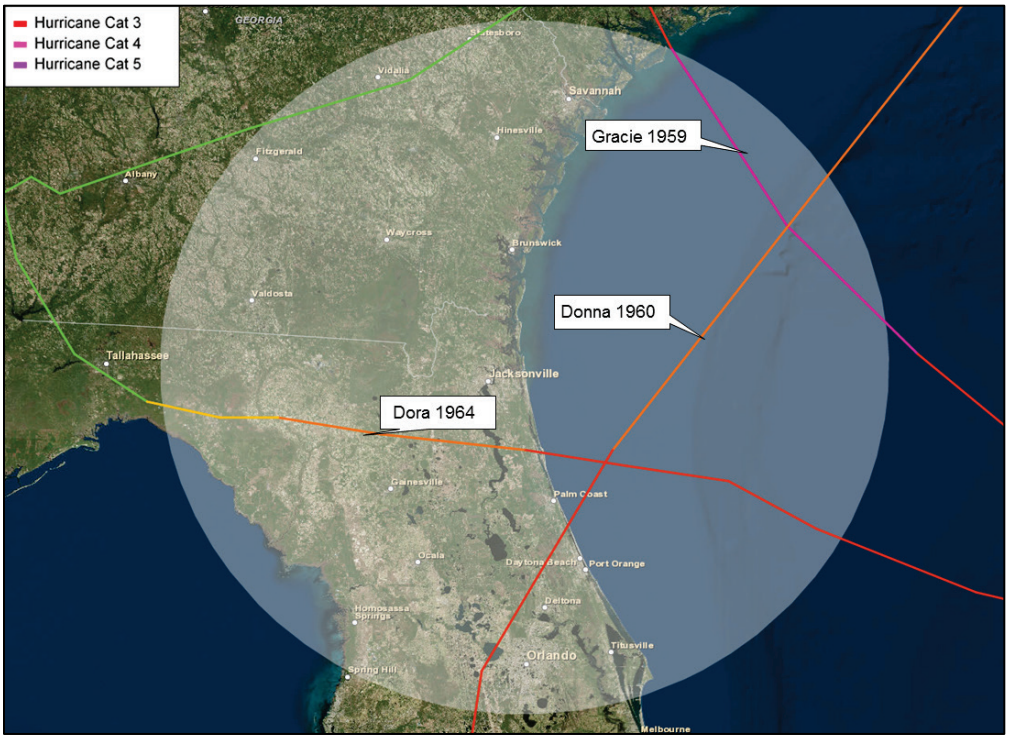


Figure 9. Category 3, 4, and 5 hurricanes affecting Mayport, FL, 1954-2013 (NOAA [2015a]).



2.2 Precipitation

Precipitation data from the Galveston, TX, and Mayport, FL, regions were obtained from the NOAA National Climatic Data Center.

2.2.1 Galveston, TX

There were two stations used in the vicinity of the Galveston Bay system: (1) Galveston and (2) Galveston Scholes Field. Two other stations (Deer Park and Alvin) had insufficient data coverage. These locations are shown in Figure 10. (Note: *Rainfall* will be used synonymously with *precipitation* for the remainder of this report.)

Figure 10. Locations of NOAA National Climatic Data Center stations from which precipitation data near Galveston Harbor, TX, were obtained.

The Galveston station recorded rainfall from 1947 to 2008, but data from 1999 to 2008 were so incomplete they were removed from the analysis. Galveston Scholes Field provided rainfall data from 1946 to 1962 and from 1999 to 2014. Rainfall data were collected at Deer Park from 1946 until 2010 while data were recorded at Alvin from 1946 to 2010. There were gaps within each dataset. These gaps lasted from 1 month to multiple years. The average monthly rainfall was calculated at each location based

on the data available. This monthly average was used when the data were unavailable and is noted by the red diamonds in Figure 11 and Figure 13.

Figure 11 and Figure 12 show the annual precipitation from 1947 to 2008 and the average monthly rainfall at the Galveston station, respectively. The only year that included a monthly average to replace an incomplete month of data was 1994. The three driest years were 1948, 1954, and 1956, which experienced 22 in. or less rainfall. The wettest year was 1998 when nearly 67 in. of rain fell. More than 60 in. of rain also occurred in 1961, 1973, and 1997. Monthly rainfall in Galveston during this time period ranged from 2 to 6 in. The driest months were February, March, and April where less than 3 in. of rain fell, and the wettest months were June, August, and September where more than 4 in. occurred. The average rainfall in September was more than 5.5 in.

Figure 13 and Figure 14 show annual precipitation and average monthly rainfall at the Galveston Scholes Field station, respectively. Average rainfall for specific months replaced incomplete data in 1948 and 1999. Rainfall was not available from 1964 to 1998. The driest years were 1954, 2008, and 2011. Less than 15 in. of rain fell in 2008; however, approximately 6 weeks of rainfall data are missing following Hurricane Ike. Similar to the Galveston station data, the driest months occurred in the winter and early spring while September is the wettest month with an average of more than 5.5 in. of rain.

Figure 11. Annual precipitation at Galveston station from 1947 to 1998.

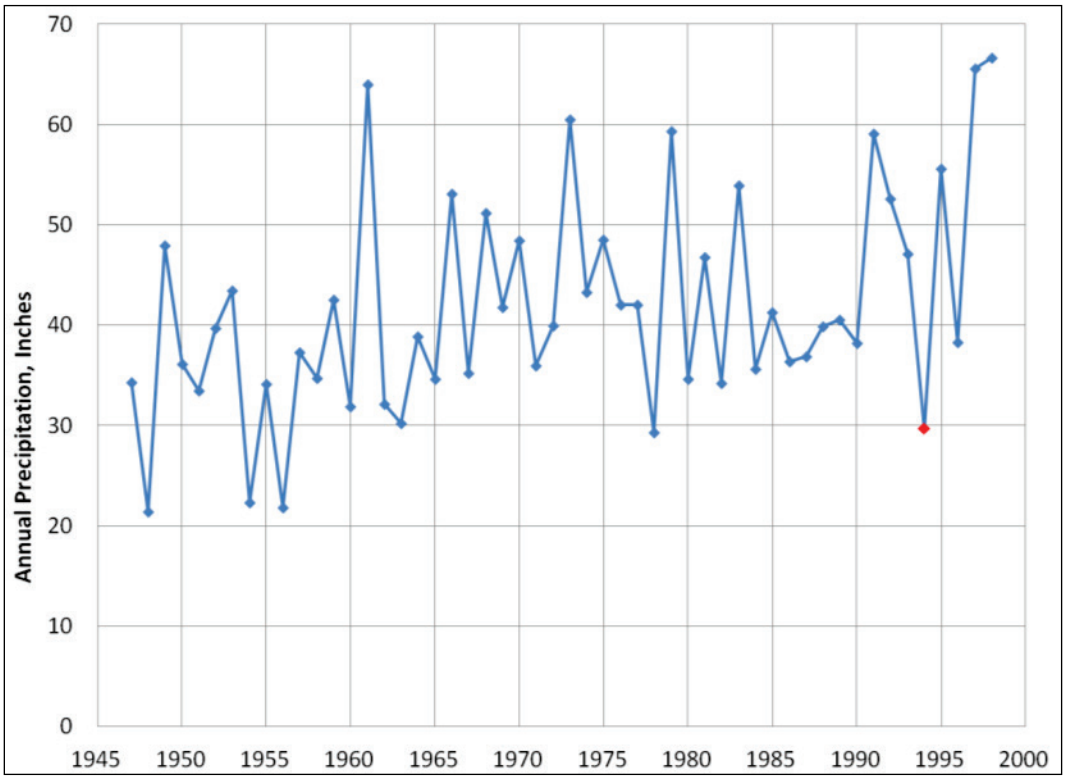


Figure 12. Average monthly rainfall at Galveston station.

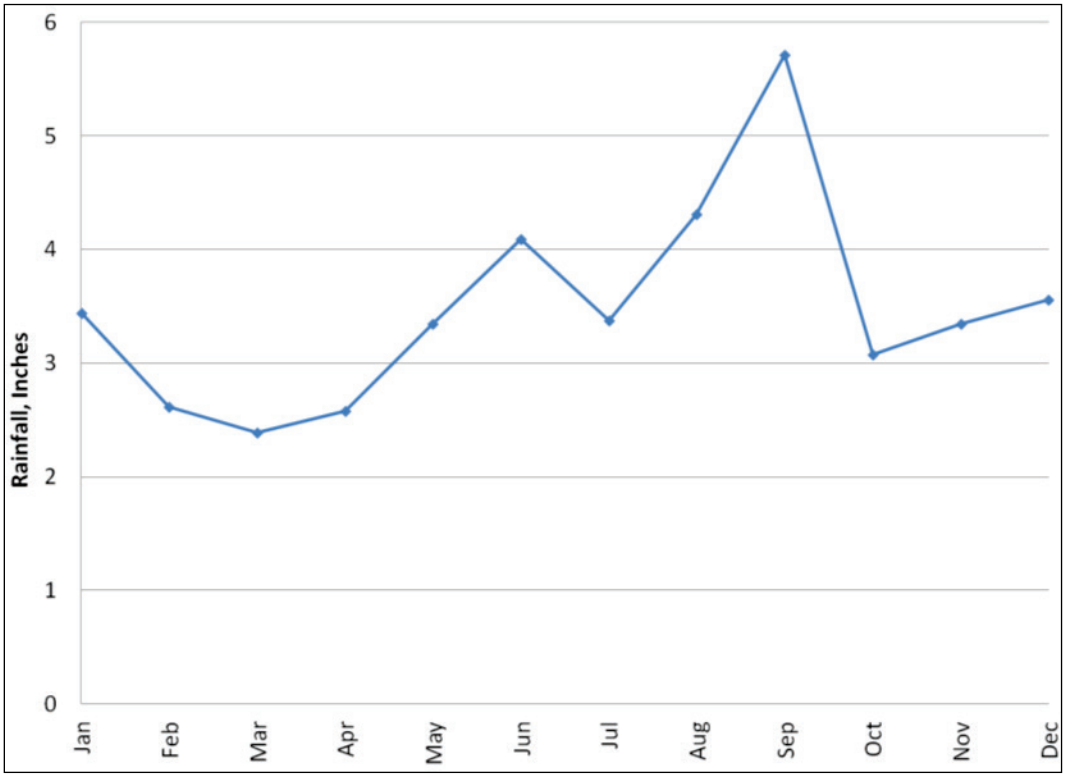


Figure 13. Annual precipitation at Galveston Scholes Field station from 1946 to 2014.

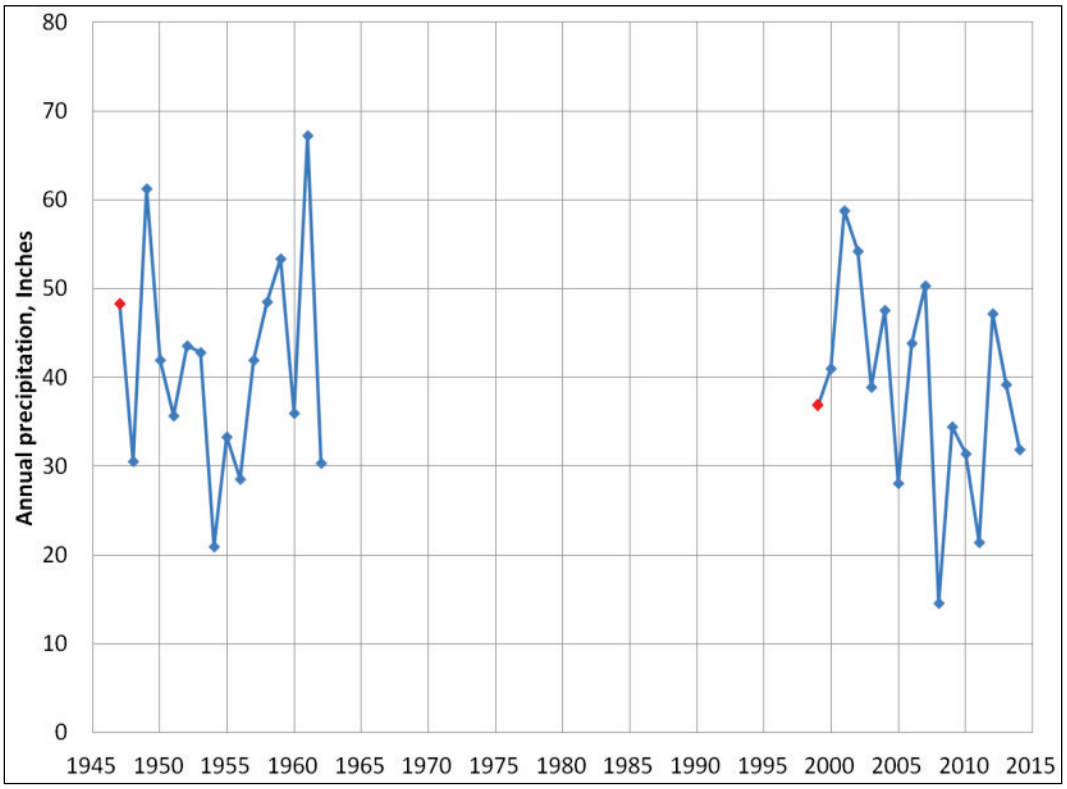
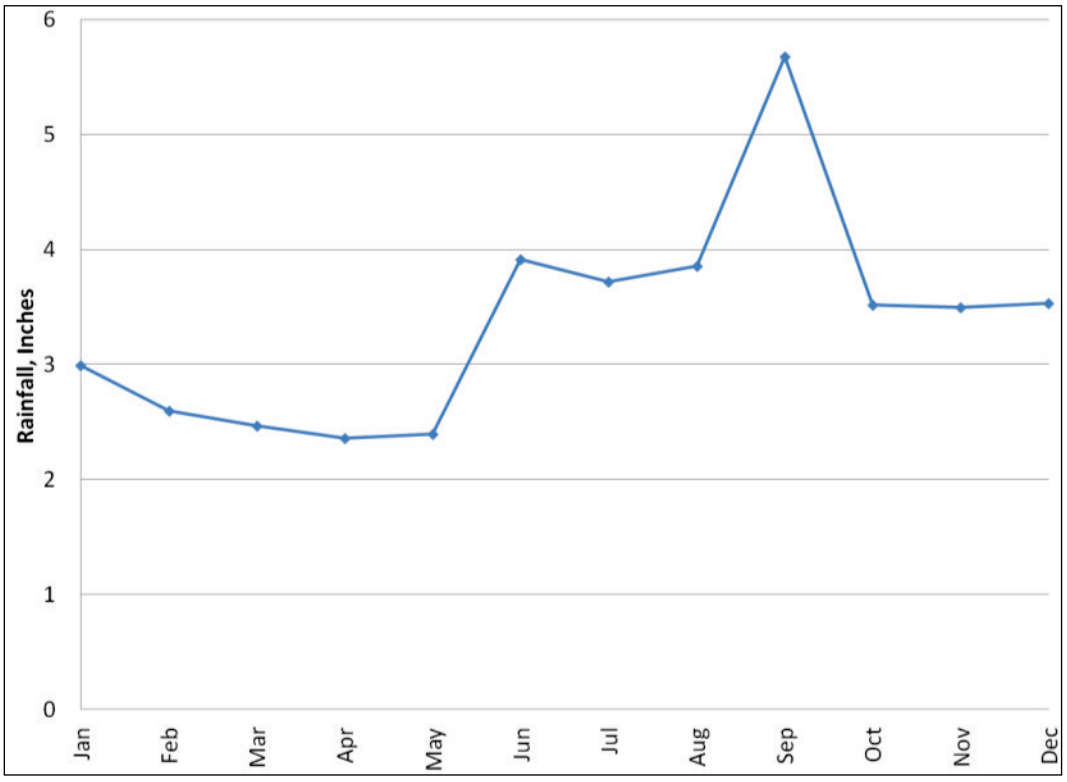


Figure 14. Average monthly precipitation at Galveston Scholes Field station.



2.2.2 Mayport, FL

Rainfall data from Jacksonville International Airport station (station ID 084358) was used at Mayport, FL. The location of this station is shown in Figure 15. The data were comprised of annual and monthly rainfall summaries from 1948 to 2013. Based on this station's records, the average annual rainfall for Jacksonville, FL, is approximately 50 in. per year. Rainfall precipitation in this study must be considered carefully so that the effects of storm-related rainfall and monthly rainfall are not double counted as a factor in dredging events in the following time period. Rainfall peaks in the month of September at the height of hurricane season. Figure 16 shows the annual precipitation rate at the site from 1948 to 2012. Figure 17 shows the average monthly rainfall for Jacksonville, FL.

Figure 15. Location of rainfall station near Jacksonville, FL, used for Mayport, FL.

Figure 16. Annual precipitation for Jacksonville, FL, station from 1948 to 2012, used for Mayport, FL.

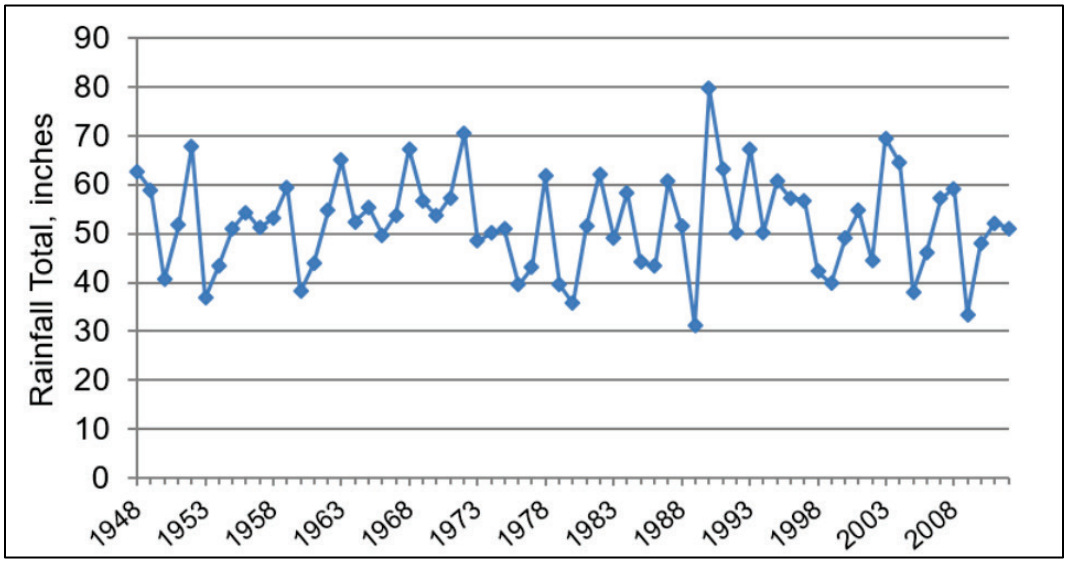
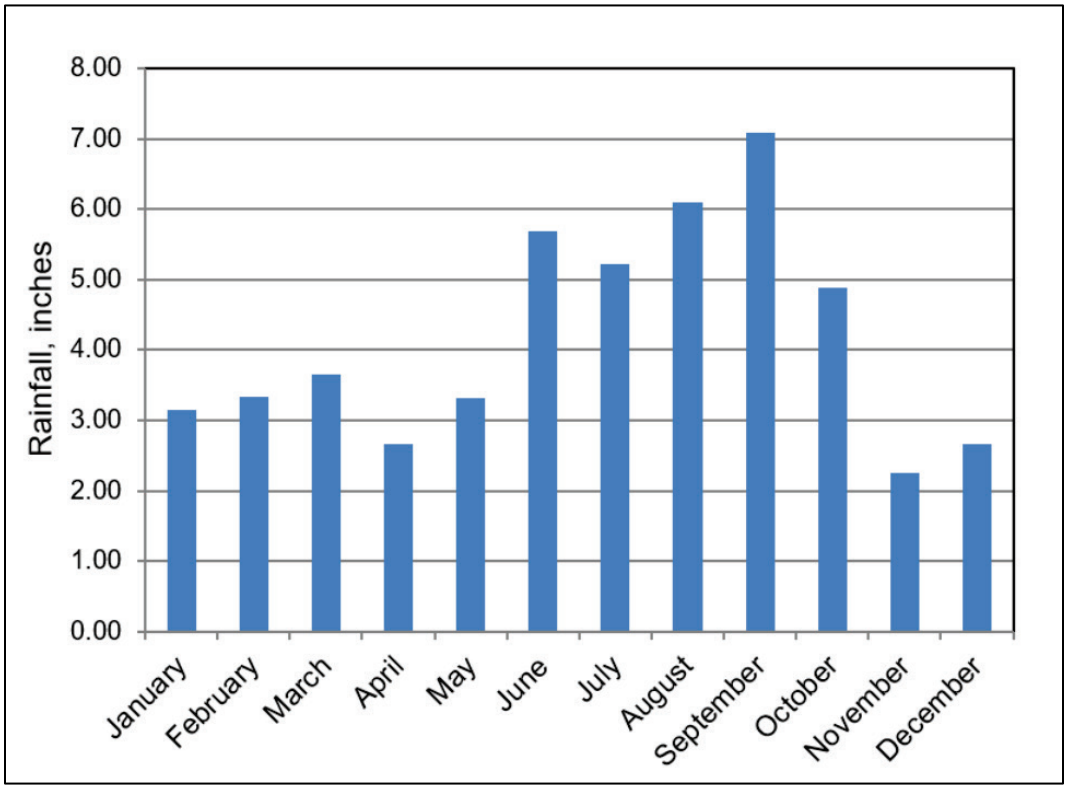


Figure 17. Average monthly precipitation for Jacksonville, FL, station.

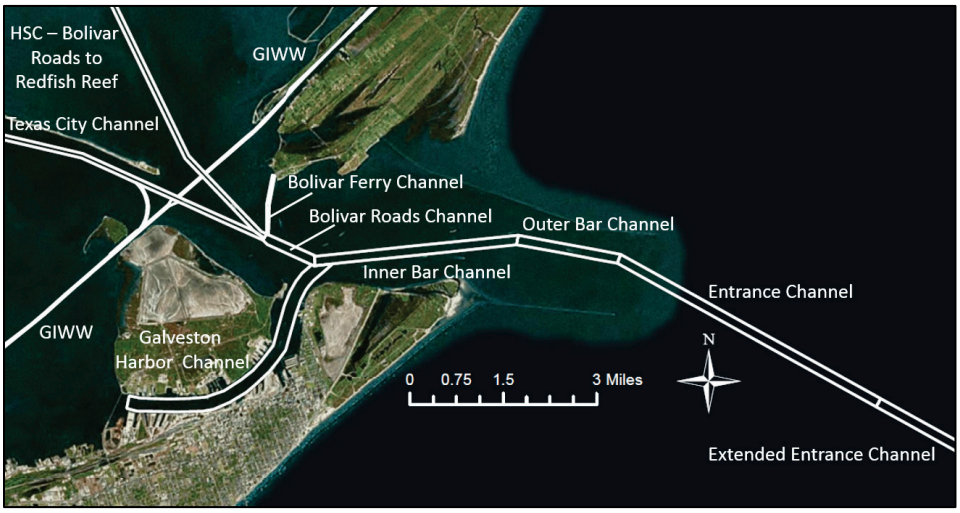


2.3 Dredging history

2.3.1 Galveston Harbor, TX

To support this study, the USACE Galveston District (SWG) provided a record of all historical dredging events within the District up until early 2014. Each entry includes dredging start and completion dates, the project name, a project key, project ID, channel ID, reach ID, stationing information, and estimated and actual dredged volumes. However, the channels of interest are not subdivided further than Houston Ship Channel or Houston-Galveston Navigation Channels. Therefore, it became necessary to subdivide each channel based on stationing information. The authorized depth of the Extended Entrance Channel, Entrance Channel, Outer Bar Channel, Inner Bar Channel, Galveston Harbor Channel, Bolivar Roads Channel, Texas City Channel, Bolivar Roads to Redfish Reef, Redfish Reef to Beacon 76, and Beacon 76 to Morgan's Point is 46 ft. SWG reports Morgan's Point to Carpenter Bayou has a maintenance depth of 46.5 ft. Between Carpenter Bayou and Green's Bayou, the authorized depth decreases from 46.5 to 41.5 ft. Green's Bayou to Sims Bayou is 41.5 ft. Sims Bayou to the Main Turning Basin and Buffalo Bayou depths are 37.5 ft. The GIWW is maintained at 13 ft. Figure 18 shows the channel locations.

Figure 18. Channel locations in the Galveston Harbor, TX, area.



A thorough analysis would include all of the Houston-Galveston channels considered together. However, in many cases, dredging begins in one channel and moves to the next immediately following completion. The first 12 events took place in Galveston Harbor while many of the later events encompass multiple channels (Table A-1, Appendix A). Due to the

complexity of including all channels, Galveston Harbor was selected to test the method. Galveston Harbor has a long dredging history and has a fairly small footprint so that the approximate area where dredging occurred is well known. The complete dredging history for Galveston Harbor is presented in Table 1, and the dredging history for the remaining Galveston area channels can be found in the Appendix A.

Table 1. Galveston Harbor, TX, dredging volumes.

Dredging Contract End Date	Volume Dredged, yd^3
6/25/1947	6,082,994
1/9/1950	5,004,824
10/23/1951	3,212,051
4/24/1953	2,894,868
8/21/1955	3,902,472
6/15/1958	2,149,535
12/11/1960	4,032,000
7/23/1962	5,376,500
5/29/1964	1,777,693
7/20/1965	3,640,080
11/21/1966	4,842,983
6/2/1969	4,312,942
10/28/1972	4,055,450
6/1/1974	3,482,921
3/20/1976	4,993,000
4/12/1982	6,022,633
8/31/1982	2,262,062
10/7/1985	4,301,050
10/17/1986	1,266,653
9/30/1989	4,038,896
6/18/1994	5,162,753
4/6/1998	5,400,565
7/9/2000	3,818,488
8/3/2003	819,428
10/15/2005	998,152
8/31/2006	2,822,400

Dredging Contract End Date	Volume Dredged, yd^3
12/31/2007	2,956,986
7/31/2009	2,448,267
12/31/2009	969,085
3/31/2010	899,667
4/30/2012	2,084,922

The Galveston Harbor Channel connects to the Bolivar Roads Channel. It extends almost to the GIWW and is 4.4 miles long. Dredging records for Galveston Harbor are the most comprehensive of any channel in the Houston-Galveston Navigation System; more than 100M yd^3 have been dredged since 1947, as shown in Table 1. Usually between 1 and 6M yd^3 are dredged per event. On average, 3.3M yd^3 are dredged every 2.2 years. The average shoaling rate of Galveston Harbor is 1.5M yd^3/year, which is the highest shoaling rate of any channel in the lower portion of the Houston-Galveston Navigation Channels.

2.3.2 Mayport Basin, FL

Dredging records for NS Mayport Turning Basin and Entrance Channel date back to 1954, 12 years after the NS was commissioned in 1942. At the time of commissioning in 1942, the entrance channel was deepened to 42 ft to provide maintenance and refueling of submarines. In 1953, the arrival of the Midway carrier class of ships led to a deepening of the basin from the original 29 ft depth to 40 ft. In 1959, the basin was deepened an additional 2 ft to 42 ft. Table 2 lists both the maintenance and new work dredging history at NS Mayport Turning Basin and Entrance Channel.

Table 2. Mayport Turning Basin and Entrance Channel, FL, dredging volumes.

Dredging Contract End Date	Volume Dredged, yd^3 (*indicates new work dredging)
1/6/1954	346,312
8/1/1956	897,777
10/19/1959	1,411,640
9/1/1961	1,373,350*
10/20/1962	559,092
1/1/1964	289,050
3/1/1965	1,962,067
12/1/1966	868,479
3/10/1969	716,858
9/1/1969	441,323
8/4/1972	570,972
3/25/1974	547,565
2/1/1975	736,084
3/1/1978	1,789,701
10/24/1978	173,558
7/5/1979	47,148
3/1/1982	1,793,031
8/19/1983	81,363
11/19/1983	48,000
8/24/1984	223,000
6/1/1985	1,280,151
1/1/1990	1,600,135
5/29/1993	27,680
5/21/1994	1,230,507
1/29/1997	1,099,371
3/27/2000	1,097,800
10/22/2001	174,832
4/24/2003	1,289,138
1/1/2005	1,069,754
5/19/2008	629,034
1/30/2010	174,941
4/16/2012	4,552,000*

3 Storm and Precipitation Analysis

3.1 Tropical storm and hurricane analysis

3.1.1 Hurricanes and infilling

Tropical storms and hurricanes have the potential to bring increased sediment deposition into coastal inlets, harbors, and channels. Wind-driven storm surge can bring about coastal and inland flooding and sediment deposition. If this occurs in a maintained navigation channel, dredging will be needed to bring the channel back to pre-storm conditions. The category of the storm, which is based solely on wind speed, cannot alone be used to predict how the storm will impact a site in terms of flooding or sediment deposition. A study comparing the impacts of Hurricane Wilma and Hurricane Andrew by Smith et al. (2007) demonstrated that a Category 3 storm like Hurricane Wilma could be more damaging than a Category 5 storm like Hurricane Andrew. While Hurricane Wilma was only a Category 3, the vastness of its wind field led to storm surges of 15 ft, three times that of Hurricane Andrew and a total area of deposition of 110 square miles, 2.5 times the area affected by Hurricane Andrew depositions (Smith et al. 2007). It is important that, when attempting to quantify a storm's impact on a site, other storm characteristics are considered in addition to category.

3.1.2 Determination of Impact Factor

Before determining an Impact Factor for each tropical event, it was necessary to develop a list of all tropical events within a 150 mile radius of the location of interest and download the track for each event. The Historical Hurricane Tracks (NOAA 2015a) is an ideal resource allowing users to select a point on the map and specify a distance from the point to refine their search. These NOAA data provide a time stamp, exact location, and wind speed for several points along the storm's track.

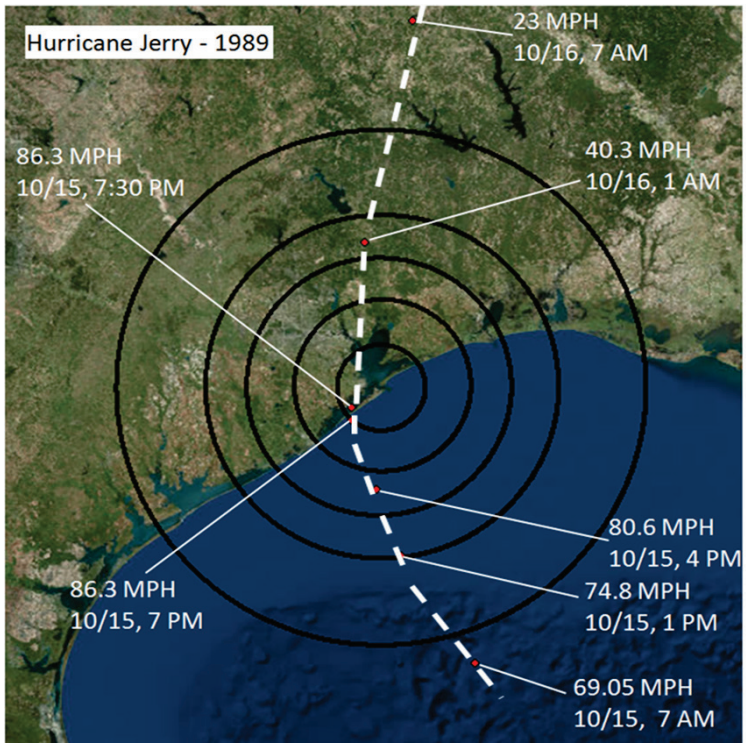
For Galveston Harbor, the point selected to develop the 150 mile radius was centrally located within the Inner Bar Channel. There were 103 storms that passed within 150 miles of the Inner Bar Channel between 1851 and 2013. The first recorded dredging event occurred in December 1943, so the time period from 1942 to 2013 was used for the Galveston Harbor analysis. Storms occurring 1 year prior to the initiation of dredging and later have a potential impact on volumes. Fifty storm tracks occurred within 150 miles

of the Inner Bar Channel during that time period. This list of storms was cross-checked with the list of all hurricane positions in the Atlantic and Gulf. The storm track information was used to determine the maximum wind speed and time spent within each radius within different radii from the chosen location.

There were 70 storms that passed within 150 miles of the Mayport Entrance Channel between 1953 and 2013. This time period was chosen because the dredging record begins in 1954. This list of storms was cross-checked with the list of all hurricane positions in the Atlantic and Gulf. The storm track information was used to determine the maximum wind speed and time spent within each radius within different radii from the chosen location.

To further describe the calculations, an example is provided. Hurricane Jerry made landfall on 15 October 1989 on Galveston Island. The hurricane track information is shown in Figure 19. The location of the center of circulation was recorded five times within the 150 mile radius. Based on the date and time, it is possible to calculate the amount of time the center of circulation was located within each concentric circle (Figure 19), representing a different radial distance from the site.

Figure 19. Hurricane Jerry storm track, 15–16 October 1989.



According to NOAA location data, Hurricane Jerry spent a total of 19.96 hr within 150 miles of the Galveston Entrance Channel. This total can be broken down further by time. For example, the eye was located within 100 miles of the Galveston Entrance Channel for 13.27 hr of those 19.96 hr. Hurricane Jerry's center of circulation was located within 75 miles for 10.09 hr, 50 miles for 6.51 hr, and within 25 miles for 2.58 hr.

Because each recorded location also gives the wind speed, a similar calculation was completed to determine the maximum and minimum wind speed reported within each circle. When the storm eye was located between 100 and 150 miles (the biggest ring around the Galveston Entrance Channel), the maximum wind speed was 74.8 mph. This wind speed was recorded on 15 October 1989 at 1:00 pm. The minimum wind speed within the ring was calculated based on the wind speeds recorded on 16 October 1989 at 1:00 am and 7:00 am, the time-stamped data points on either side of this ring.

A linear decrease in wind speed was assumed, so the wind speed north of Houston at 150 miles from the Galveston Entrance Channel was calculated as 31.43 mph. The maximum wind speed within the 75- to 100-mile distance ring occurred between 1:00 and 4:00 pm on 15 October 1989. The location of the maximum wind reported in that ring is at 75 miles to the south of the Galveston Entrance Channel, and the maximum wind was 78.32 mph. The minimum wind speed of 38.01 mph occurred between 1:00 and 7:00 am on 16 October 1989 at a distance of 100 miles from the Galveston Entrance Channel.

The same process was used to determine the maximum and minimum wind speeds within each ring, and the results are shown in Table 3. Note that duration is the time within each circle (for example, duration within 150 miles means total time within 150 miles of the Galveston Entrance Channel and will therefore be the highest duration entry) while 150 miles for maximum and minimum wind speed refers to the ring (for example, 150 miles means the maximum and minimum wind speed between 100 and 150 miles away from the Galveston Entrance Channel). The maximum wind was 86.3 mph, which occurred less than 25 miles away from the Galveston Entrance Channel. The minimum wind speed was 31.43 mph, which occurred 150 miles away.

Table 3. Time and maximum wind speed classified by distance from Galveston Entrance Channel for Hurricane Jerry.

Distance from Entrance Channel, miles	Duration, hr*	Maximum Wind, mph	Minimum Wind, mph
25	2.58	86.3	70.3
50	6.51	86.3	56.5
75	10.09	82.2	44.4
100	13.27	78.3	38.0
150	19.96	74.8	31.4

* Duration is time inside each circle.

The wind speed in each circle and the duration of the storm's center within each circle were used to calculate the Impact Factor for storms. These factors are somewhat arbitrary in that they have no meaning other than to classify storms as weak, average, or strong. When the amount of time a storm's eye was located within a ring increased to the next time bin, the factor increased by 0.1. When a storm had wind speeds under 74 mph, the factor increased by 0.15 each time the wind speed increased to the next speed bin. Once the storm reached hurricane winds speeds, the Impact Factor increased by 0.25 each time the wind speed increased to the next speed bin. When the storm was nearer to the site, the distance factor was lower.

Winds speeds lower than 39 mph (the threshold for a tropical storm) have been removed from consideration. Additionally, tropical storms with winds speeds of 39–50 mph were only included in calculation of the Impact Factor when the wind speed was within 50 miles of the site. Wind speeds between 50 and 60 mph were included in the calculation within 75 miles while wind speeds between 60 and 73 mph were included within 100 miles of the location of interest. Modifying the wind speed factors only decreased the Impact Factor of weaker storms that stall near the site. Lower wind speeds were removed based on distance away from the site because maximum winds of tropical storm force speed did not have much impact beyond a certain distance. These bins and their assigned values for distance, wind speed, and duration are shown in Table 4.

Table 4. Factors to determine storm impact. Left, distance (miles); middle, wind speed (mph); right, time (hr).

Distance, miles	Factor
25	1
50	1.5
75	1.75
100	2
150	4

Wind, mph	Factor
39-50	0.5
50-60	0.65
60-73	0.8
73-80	1
80-90	1.25
90-100	1.5
100-110	1.75
110-120	2
120-130	2.25
130-140	2.5
140-150	2.75
150+	3

Time, hr	Factor
57 to 60	2
54 to 57	1.9
51 to 54	1.8
48 to 51	1.7
45 to 48	1.6
42 to 45	1.5
39 to 42	1.4
36 to 39	1.3
33 to 36	1.2
30 to 33	1.1
27 to 30	1
24 to 27	0.9
21 to 24	0.8
18 to 21	0.7
15 to 18	0.6
12 to 15	0.5
9 to 12	0.4
6 to 9	0.3
3 to 6	0.2
0 to 3	0.1

The initial equation used to determine the Impact Factor of each storm is

$$\frac{W_1 \times T_1}{D_1} + \frac{W_2 \times T_2}{D_2} + \frac{W_3 \times T_3}{D_3} + \frac{W_4 \times T_4}{D_4} + \frac{W_5 \times T_5}{D_5} = \text{IF}$$

where W is the factor for wind, T is the factor for time, D is the factor for distance, and IF is the Impact Factor. The subscripts refer to the distance from the site. Subscript 1 is 100 to 150 miles away, subscript 2 represents the factors for a distance of 75 to 100 miles away, subscript 3 is a distance of 50 to 75 miles away, subscript 4 is a distance of 25 to 50 miles away, and subscript 5 represents the factors inside a distance of 25 miles. D_1 is 4, D_2 is 2, D_3 is 1.75, D_4 is 1.5, and the factor representing D_5 is 1. It is also important to note that the method to determine the Impact Factor was completed through ArcGIS, spreadsheets, and calculations. Future development efforts will automate the procedures employed here for any user-specified location.

The Impact Factors for all storms within the Galveston, TX, area and the Mayport, FL, area are shown in Table 5 and Table 6, respectively. The overall maximum and minimum wind speeds observed and total duration within the 150 mile radius are illustrated.

Table 5. Impact Factors, duration, and maximum and minimum wind speed for each tropical event, Galveston Harbor, TX.

Name	Year	Impact Factor	Total Time, hr	Maximum Wind, mph	Minimum Wind, mph
Unnamed	Jul-45	0	19	40	40
Unnamed	Aug-45	0.34	30	112	45
Unnamed	Jun-46	0	16	35	23
Unnamed	Aug-47	0.6	46	81	35
Unnamed	Oct-49	0.73	20	132	61
Barbara	Jul-54	0	20	36	29
Unnamed	Aug-55	0	12	46	40
Audrey	Jun-57	0.5	14	144	67
Bertha	Aug-57	0	23	69	29
Debra	Jul-59	0.97	58	86	37
Cindy	Sep-63	0.77	62	81	29
Abby	Aug-64	0.11	23	63	33
Felice	Sep-70	0.2	16	69	35
Unnamed	Jul-71	0	20	29	26
Fern	Sep-71	0.35	25	87	68
Edith	Sep-71	0.4	13	98	83
Delia	Sep-73	0.26	47	69	39
Unnamed	Sep-73	0	41	35	35
Unnamed	Jul-74	0	13	35	29
Unnamed	Aug-74	0	11	34	29
Carmen	Aug-74	0	20	40	29
Unnamed	Jun-77	0	15	29	29
Debra	Aug-78	0.07	20	58	33
Claudette	Jul-79	0.11	60	52	33
Elena	Sep-79	0	27	40	29
Unnamed	Jul-80	0	40	35	29
Danielle	Sep-80	0.12	22	56	44
Unnamed	Jun-81	0	11	34	29
Chris	Sep-82	0.18	28	63	45
Alicia	Aug-83	1.18	44	115	44
Danny	Aug-85	0.13	9	92	83
Juan	Oct-85	0.09	7	86	86

Name	Year	Impact Factor	Total Time, hr	Maximum Wind, mph	Minimum Wind, mph
Bonnie	Jun-86	0.5	26	86	38
Unnamed	Aug-87	0.12	22	46	37
Allison	Jun-89	0	116	52	23
Chantal	Aug-89	0.37	22	81	40
Jerry	Aug-89	0.32	20	86	31
Dean	Jul-95	0.1	29	46	23
Frances	Sep-98	0	5	36	35
Unnamed	Sep-00	0	16	35	29
Allison	Jun-01	0.1	105	58	17
Bertha	Aug-02	0	26	29	23
Fay	Sep-02	0	42	58	35
Claudette	Jul-03	0.22	17	92	69
Grace	Aug-03	0.12	17	40	30
Ivan	Sep-04	0	13	48	29
Rita	Sep-05	0.34	17	122	62
Humberto	Sep-07	0.55	31	92	32
Eduard	Aug-08	0.2	21	63	33
Ike	Sep-08	0.9	19	109	73

Table 6. Impact Factors, duration, and maximum and minimum wind speed for each tropical event, Mayport, FL.

Name	Date	Impact Factor	Total time, hr	Maximum Wind, mph	Minimum Wind, mph
UNNAMED 1953 1	Aug. 1953	0.00	13	52	31
UNNAMED 1953 2	Sep. 1953	0.00	8	50	29
FLORENCE	Sep. 1953	0.00	8	53	42
UNNAMED 1957	Jun. 1957	0.00	7	40	40
UNNAMED 1959	Jun. 1959	0.00	2	36	35
GRACIE	Sep. 1959	0.13	3	138	131
BRENDA 1960	Jul. 1960	0.00	13	52	35
DONNA	Sep. 1960	0.38	12	115	104
ALMA 1962	Aug. 1962	0.00	4	40	29
GINNY 1963	Oct. 1963	0.25	21	101	75
UNNAMED 1964	Jun. 1964	0.00	39	35	35
CLEO	Aug. 1964	0.29	33	68	37
DORA	Sep. 1964	1.14	35	115	79
HILDA	Oct. 1964	0.00	3	40	40

Name	Date	Impact Factor	Total time, hr	Maximum Wind, mph	Minimum Wind, mph
ALMA 1966	Jun. 1966	0.00	15	66	46
ABBY	Jun. 1968	0.29	31	57	47
BRENDA 1968	Jun. 1968	0.00	21	29	29
DOLLY	Aug. 1968	0.00	10	31	29
UNNAMED	Aug. 1968	0.00	33	29	29
GLADYS	Oct. 1968	0.41	18	86	81
GERDA	Sep. 1969	0.00	11	48	34
JENNY	Oct. 1969	0.00	29	35	29
ALMA 1970	May. 1970	0.00	17	29	29
DAWN	Sept. 1972	0.00	28	35	35
UNNAMED 1973 1	Jun. 1973	0.00	6	26	26
UNNAMED 1973 2	Sept. 1973	0.00	20	29	29
HALLIE	Oct. 1975	0.00	27	35	35
DOTTIE	Aug. 1976	0.00	14	52	41
UNNAMED 1979 1	Jun. 1979	0.00	13	35	35
UNNAMED 1979 2	Jul. 1979	0.00	8	35	35
DAVID	Aug. 1979	0.62	19	98	80
UNNAMED 1980 1	Jul. 1980	0.00	26	29	23
UNNAMED 1980 2	Nov. 1980	0.00	8	25	23
UNNAMED 1981	Jul. 1981	0.00	13	35	30
DENNIS	Aug. 1981	0.07	17	50	40
UNNAMED 1984	Jun. 1984	0.00	21	35	30
DIANA	Sept. 1984	0.38	33	86	63
ISIDORE	Sept. 1984	0.29	26	52	52
BOB	Jul. 1985	0.18	18	74	62
ISABEL	Oct. 1985	0.00	55	50	29
KATE	Nov.1985	0.08	6	75	75
UNNAMED 1987	Aug. 1987	0.00	18	17	17
CHRIS	Aug. 1988	0.08	9	49	44
UNNAMED 1988	Aug. 1988	0.00	15	35	35
KEITH	Nov. 1988	0.00	4	46	46
MARCO	Oct. 1990	0.00	10	34	23
ANA	Jul. 1991	0.00	31	29	23
EARL	Sept. 1992	0.00	9	35	23

Name	Date	Impact Factor	Total time, hr	Maximum Wind, mph	Minimum Wind, mph
GORDON 1994	Nov. 1994	0.00	9	26	23
ALLISON	Jun. 1995	0.00	3	50	44
JERRY	Aug. 1995	0.00	17	32	27
JOSEPHINE	Oct. 1996	0.00	5	65	52
GEORGES	Oct. 1998	0.00	9	29	28
FLOYD	Sept. 1999	0.05	3	115	109
IRENE	Oct. 1999	0.15	15	75	75
GORDON 2000	Sept. 2000	0.00	15	58	29
GABRIELLE	Sept. 2001	0.00	20	47	46
EDOUARD	Sept. 2002	0.00	48	48	23
KYLE	Oct. 2002	0.03	17	40	35
UNNAMED 2003	Jul. 2003	0.00	23	24	24
HENRI	Sept. 2003	0.00	6	35	29
BONNIE	Aug. 2004	0.00	6	34	29
CHARLEY	Aug. 2004	0.28	9	86	78
JEANNE	Sept. 2004	0.00	12	58	43
TAMMY	Oct. 2005	0.13	17	52	38
ALBERTO 2006	Jun. 2006	0.00	10	42	37
ERNESTO	Aug. 2006	0.07	13	66	45
BARRY	Jun. 2007	0.00	18	46	35
FAY	Aug. 2008	0.26	53	60	46
ALBERTO 2012	May. 2012	0.00	21	46	46
BERYL	May. 2012	0.28	60	69	29
DEBBY	Jun. 2012	0.00	15	40	35
ANDREA	Jun. 2013	0.00	8	58	46

At Galveston, TX, Alicia had the highest Impact Factor. Alicia's area of maximum winds traveled directly through Galveston metropolitan area, and water levels at Galveston Island were as high as 12 ft (National Research Council 1984). At Mayport, FL, the storm with the highest associated Impact Factor was Hurricane Dora, which is often cited as the most powerful and damaging hurricane to hit the Jacksonville area in recorded history (Doehring et al. 1994). Dora made landfall 10 September 1964 and brought 125 mph winds and a 12 ft storm surge. Tide levels in St. John's River were pushed up to 5 ft above normal conditions, and high tides at the beaches were up to 7 ft above normal (Kerr 2010).

One drawback of using 150 miles as the maximum radius is that some strong storms potentially are not included in the analysis. For example, Hurricane Carla made landfall on the northeast part of Matagorda Island, TX. The nearest Hurricane Carla's center of circulation came to the Galveston Entrance Channel was 155 miles; therefore, it was not included in the analysis. However, Hurricane Carla was the most intense hurricane to make landfall on the Texas coast in the twentieth century (NOAA 2015b) and had a diameter of hurricane-force winds of 300 miles. The average hurricane-force winds are felt in a 100 mile diameter. Due to the size and intensity of Hurricane Carla, a 10 ft storm surge was recorded in Galveston. Even though Hurricane Carla's eye was very far from Galveston, it still had a significant impact on the Houston-Galveston area. While this method generates no Impact Factor associated with Hurricane Carla, it was important to consider it in the analysis. In cases such as these, the Impact Factor can be estimated based on known storm surges, and additional information about the storm and its relative strength compared to other storms for which an Impact Factor was calculated.

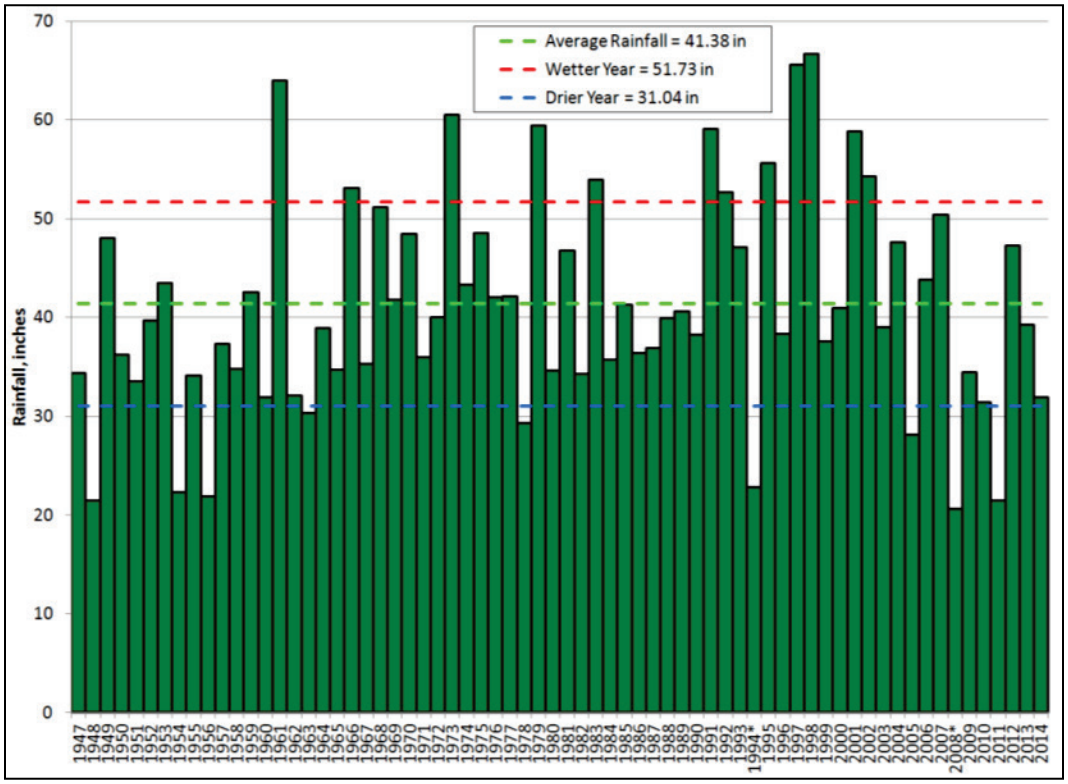
3.2 Precipitation analysis

3.2.1 Galveston, TX

Since no station provided a full record from 1947 to present, both the Galveston station and the Galveston Scholes Field station (Figure 10) were used for the analysis. Except for 2 months in 1994, the Galveston station had a complete record of rainfall from 1947 to 1999. Beginning in 1999, rainfall records at the Galveston station became intermittent. Rainfall at the Galveston Scholes Field station was collected from June 1999 to present. Several months of data were not available after Hurricane Ike, so these months were excluded from the analysis.

Rainfall totals for years 1947–2014 for Galveston, TX, are shown in Figure 20. Based on historical data between 1947 and 2014, the average annual rainfall was calculated as 41.38 in. A year with 25% greater precipitation, 51.73 in. or more, was considered a wetter year. A drier year in which 25% less precipitation fell was classified as less than 31.04 in. of rainfall per year. Note that several months of rainfall data were missing in 1994 and 2008; therefore, the totals are much less than average. When calculating the average, it was assumed that the months with missing rainfall totals had average amounts of precipitation.

Figure 20. Yearly precipitation totals, Galveston, TX, 1947–2014.



Twelve years had annual precipitation greater than 51.73 in. Those years were 1961, 1966, 1973, 1979, 1983, 1991, 1992, 1995, 1997, 1998, 2001, and 2002. The year with the highest precipitation was 1998 when 66.66 in. of rain fell. For the rainy years, it was important to determine whether most of the precipitation occurred during a handful of events or if the year was consistently wet. The first rainy year was 1961 when the precipitation total was 63.97 in. Nearly 65% of the rain during that year occurred during June, September, and November. A significant rain event occurred in each of those months. On 18 June 1961, 10.44 in. of rain fell. The total precipitation between 10 and 12 September 1961 was 15.26 in., while 7.58 in. of rain fell on 13 November 1961. The rain in September 1961 coincides with Hurricane Carla, but the other two events were purely rain and thunderstorms and not a named storm.

There were no storm events in 1966, but heavy amounts of precipitation fell in May and September 1966. Rain was distributed throughout each month, but no significant rainfall event was noted. In 1973, more than 10 in. of rain fell in April and August. The highest single-day rainfall total was 8 in. on 24 March 1973. Other than a rainfall total of 6.9 in. on 16–17 April 1973, there were no significant rain events during the year. In 1979,

more than 17 in. of rain was recorded in July. More than 14 in. of this rain can be attributed to Tropical Storm Claudette. In 1983, the only significant amount of rainfall (6.28 in.) occurred on 18 August during Hurricane Alicia. While 1991 and 1992 were wetter than average years, there were no single or multi-day storms that produced more than 5 in. of rain. Most of the months were wetter than average due to El Niño.

Although rain was distributed fairly evenly throughout 1995, two events (one in early October and one in the middle of December) produced more than 6 in. of rain. Neither was associated with a named storm. The two wettest years on record were 1997 and 1998. Rainfall totals in March 1997, June 1998, and September 1998 were in excess of 10 in. In 1997, 6.7 in. of rain fell from 1 to 3 October, and 7.82 in. fell on 17–18 December. Nearly 12 in. of rain fell on 28–29 June 1998. Almost 10 in. of rain was recorded on 10–11 September 1998 while 5.09 in. fell on 4–6 October 1998. The 10–11 September 1998 event was the only rain associated with a named storm (Frances). In 2001, 5.59 in. of rain was recorded on 9 June, and 12.1 in. of rain fell between 28 August and 1 September. The rain event in June 2001 was associated with Tropical Storm Allison. Finally, more than 11 in. of rain fell in September and October 2002, but no extreme single or multi-day rainfall events occurred.

Nine years (1948, 1954, 1956, 1963, 1978, 1994, 2005, 2008, and 2011) experienced rainfall of less than 31.04 in. However, several months of rainfall amounts are missing from 1994 and 2008. If the average monthly rainfall for each month were used for the missing months, the total rainfall in 1994 would be 29.67 in. If the same calculations were made for 1998, the rainfall total would be 32.79 in., which is classified as an average year.

The driest year on record was 1948 with 21.41 in. of rain. In that year, less than an inch of rain was recorded in April, June, July, October, and December. The only month that had a rainfall total exceed the monthly average was January. The total rainfall from January to July 1948 was less than half of the average rainfall during that time period. In 1954, only October and November rainfall totals were greater than the average for each month. Less than 2 in. of rainfall was recorded in eight separate months during 1954. The third driest year on record was 1956; however, 6.15 in. of rain fell in December of that year. 1956 was the driest year from January through November. Less than an inch of rain fell between 24

February and 16 June 1956 while less than 2 in. of rain fell between 1 May and 31 July 1956.

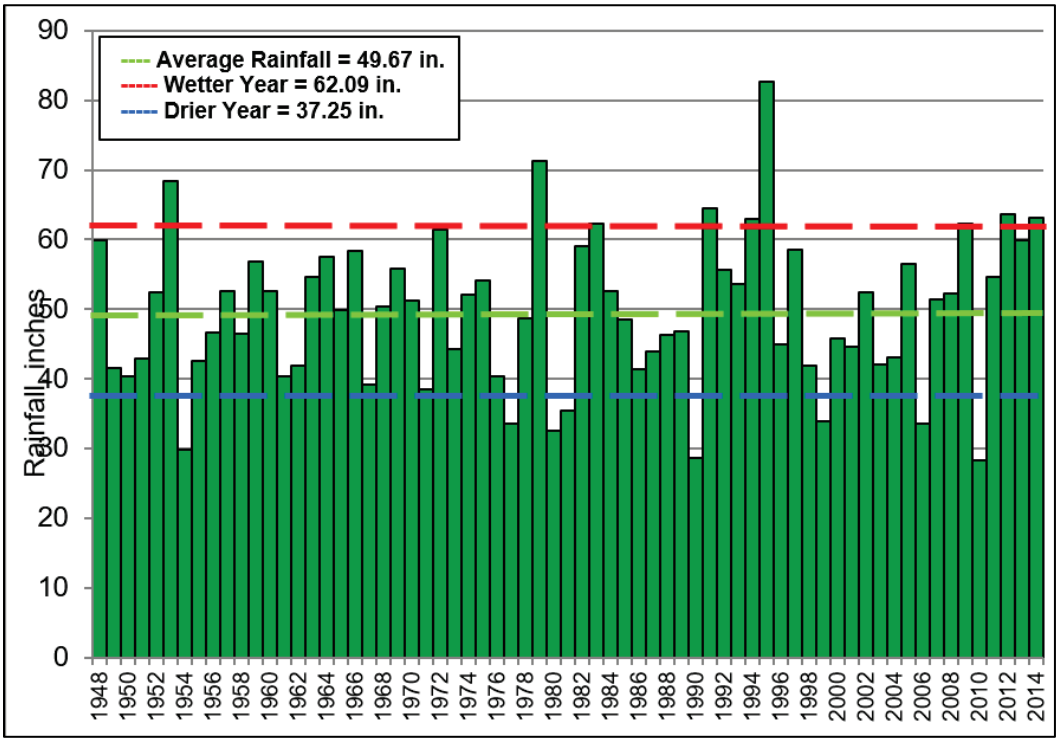
Although 9.3 in. of rain fell in September 1963 (Hurricane Cindy), the rest of the year was very dry. More than 30% of the rain that fell in 1978 occurred in January; the rest of the year was extremely dry. In total, 2005 was a drier than average year. The driest month compared to the average was August. The second driest year on record was 2011. December 2011 was the only month where more than 2.75 in. of rain was recorded. Four separate months recorded less than an inch of rain. During the 4-month period between early March and early July 2011, only 1.64 in. of rain fell.

3.2.2 Mayport, FL

Several stations in the immediate area were available; however, the Jacksonville International Airport Station site was the nearest to Mayport, FL, and had the most complete monthly rain totals from 1948 to 2014.

Rainfall totals for each year are shown in Figure 21. Based on historical data between 1948 and 2014, the average rainfall for the site was calculated as 49.67 in. A year with 25% greater precipitation, 62.1 in. or more, was considered a wetter year. A drier year in which 25% less precipitation fell was classified as less than 37.25 in. of rainfall per year. Nine years had annual precipitation greater than 62.1 in. Those years were 1953, 1979, 1983, 1991, 1994, 1995, 2009, 2012, and 2014. The year with the highest precipitation was 1995. Eight years had an annual precipitation less than 37.35 in. Those years were 1954, 1977, 1980, 1981, 1990, 1999, 2006, and 2010.

Figure 21. Yearly precipitation totals, Mayport, FL, 1948–2014.



3.3 Dredged volume comparison methods

The assumption was made that a higher rainfall or storm activity in the months or years prior to dredging will lead to increased infilling and therefore a larger volume of sediment to be removed. Two principal methods were used to classify years based on rainfall totals and tropical storm activity and predict dredged volume. These methods included the analysis of the influence of storms and rainfall at a variety of intervals prior to dredging at both Galveston, TX, and Mayport, FL.

The first method (Method 1 – Time between Dredging Events, discussed in Section 3.3.1) analyzed the time between historical dredging events. Annual rainfall and storm Impact Factors following one dredge event were compared to the dredging volume of the succeeding dredge event. Since operational decisions are made well in advance of a dredging event, two alternatives to this Method 1 (Method 1a and Method 1b) were also performed: (1) an approximate period between 6 months before the first event and 6 months before the second event and (2) the period between 1 year prior to the first event and 1 year before the second event was analyzed. This timing may be more representative because a decision to dredge and the volume required to justify the dredging is made several

months before a dredge makes its way to the site. These two alternates to Method 1 (6 months before, and 1 year before) are presented in Appendix B Method 1a, and Appendix B Method 1b, respectively

For the second method (Method 2 – Set Blocks of Time, discussed in Section 3.3.2), every 2- and 3-year interval between 1948 and the present was analyzed. The dredged volumes, rainfall totals, and storm Impact Factors were totaled over each interval time period. This procedure provides additional information related to rainfall and storm trends. This method allowed for a certain amount of smoothing of spikes or dips in dredging from year to year. Grouping the dredge events gives more of an average volume that should typically be seen over a given interval and shows how the rainfall or storms will cause a divergence from this expected volume. One benefit of this method is that it may more closely mirror how decisions are made over a multi-year budget or multi-year dredging cycle for planning purposes. Alternatives to this Method 2 of examining 2- and 3-year intervals (Method 2a and Method 2b, respectively), examined 5- and 6-year intervals and are presented in Appendix B.

These analysis methods were performed for both Galveston, TX, and Mayport, FL; however, the Galveston, TX, site will be used to demonstrate each of the two methods.

3.3.1 Method 1 – Time between dredging events

The first method tested was the analysis of the time between dredging events. There was a total of 31 dredging events in Galveston Harbor, TX, between 1947 and 2012. For each time period between dredging events, the actual rainfall and storm Impact Factor were calculated. The average rainfall for the given months between events was calculated based on monthly and yearly rainfall between 1946 and 2013. The actual rainfall was compared to the average rainfall over the time period between events to obtain a percentage of average rainfall. This percentage can provide information about drought periods or times of heavy rainfall.

The storm Impact Factor for each period was calculated by totaling the Impact Factors of storms occurring since the last dredging event. An annualized Impact Factor was calculated as the total Impact Factor divided by the dredging interval. If no storm occurred during a time

period, or if the time period included only storms that had Impact Factors of zero, then there was no Impact Factor for that period.

Table 7 lists the dates of the first dredging event and the second dredging event, the actual and average rainfall, the percentage of average rainfall, the rainfall category, and the total and annualized storm Impact Factors. The 10 lowest rainfall percentages were classified as low, the next 10 were medium, while the highest 10 rainfall totals compared to the average were considered high. The highest rainfall total compared to the average over that period of time is 138% between 27 October 1972 and 1 June 1974. The lowest rainfall compared to the average is 81% between 25 June 1947 and 9 January 1950. The highest rainfall total is nearly 260 in. between 20 March 1976 and 12 April 1982. The greatest annualized storm Impact Factor occurred between 31 December 2007 and 31 July 2009. The highest storm Impact Factor was 1.486, which occurred between 31 August 1982 and 7 October 1985. There were 10 periods between dredging events that did not experience any storms. There were also three periods in which a weak storm with an Impact Factor of zero occurred.

Table 7. Rainfall and storm Impact Factors between dredging events, Galveston Harbor, TX, 1947–2010.

Prior Event	Event	Actual Rainfall, in.	Average Rainfall, in.	Percent Rainfall	Category Based on Rainfall	Actual Impact Factor	Annual Impact Factor
6/25/1947	1/9/1950	87.32	107.99	81	Low	1.326	0.521
1/9/1950	10/23/1951	65.17	74.02	88	Medium	-	-
10/23/1951	4/24/1953	48.64	59.42	82	Low	-	-
4/24/1953	8/21/1955	85.66	93.27	92	Medium	0	0
8/21/1955	6/15/1958	76.41	115.86	66	Low	0.499	0.177
6/15/1958	12/11/1960	98.5	106.12	93	Medium	0.972	0.390
12/11/1960	7/23/1962	82.71	64.03	129	High	-	-
7/23/1962	5/29/1964	58.4	75.99	77	Low	0.771	0.416
5/29/1964	7/20/1965	37.04	47.83	77	Low	0.111	0.097
7/20/1965	11/21/1966	76.16	58.20	131	High	-	-
11/21/1966	6/2/1969	108.87	101.33	107	Medium	-	-
6/2/1969	10/28/1972	135.85	117.46	116	High	0.95	0.279
10/28/1972	6/1/1974	86.1	62.56	138	High	0.255	0.160
6/1/1974	3/20/1976	78.05	76.29	102	Medium	0	0
3/20/1976	4/12/1982	259.64	250.15	104	Medium	0.302	0.050
4/12/1982	8/31/1982	11.51	16.13	71	Low	-	-

Prior Event	Event	Actual Rainfall, in.	Average Rainfall, in.	Percent Rainfall	Category Based on Rainfall	Actual Impact Factor	Annual Impact Factor
8/31/1982	10/7/1985	138.11	130.59	106	Medium	1.486	0.479
10/7/1985	10/17/1986	34.85	42.47	82	Low	0.595	0.579
10/17/1986	9/30/1989	121.95	122.23	100	Medium	0.488	0.165
9/30/1989	6/18/1994	212.28	192.09	111	High	0.325	0.069
6/18/1994	4/6/1998	192.77	158.16	122	High	0.1	0.026
4/6/1998	7/9/2000	103.79	92.78	112	High	0	0
7/9/2000	8/3/2003	156.17	127.01	123	High	0.319	0.104
8/3/2003	10/15/2005	91.88	93.81	98	Medium	0.455	0.207
10/15/2005	8/31/2006	32.37	34.21	95	Medium	-	-
8/31/2006	12/31/2007	68.83	57.31	120	High	0.555	0.416
12/31/2007	7/31/2009	39.16	62.71	62	Low	1.1	0.695
7/31/2009	12/31/2009	22.8	20.06	114	High	-	-
12/31/2009	3/31/2010	6.87	8.32	83	Low	-	-
3/31/2010	4/30/2012	63.26	85.15	74	Low	-	-

Figure 22 shows in chart form the actual rainfall as a percentage of the average rainfall. Each period between dredging events from 20 July 1965 to 12 April 1982 experienced more rainfall than the average. No period between dredging events before 11 December 1960 experienced more rainfall than the average.

Figure 22. Actual versus average rainfall between dredging events, Galveston Harbor, TX, 1947–2012.

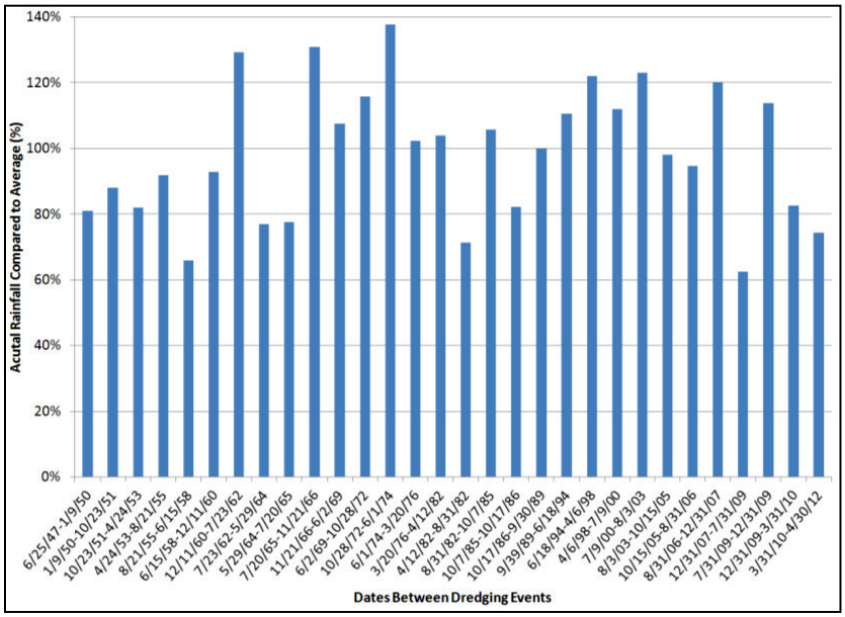
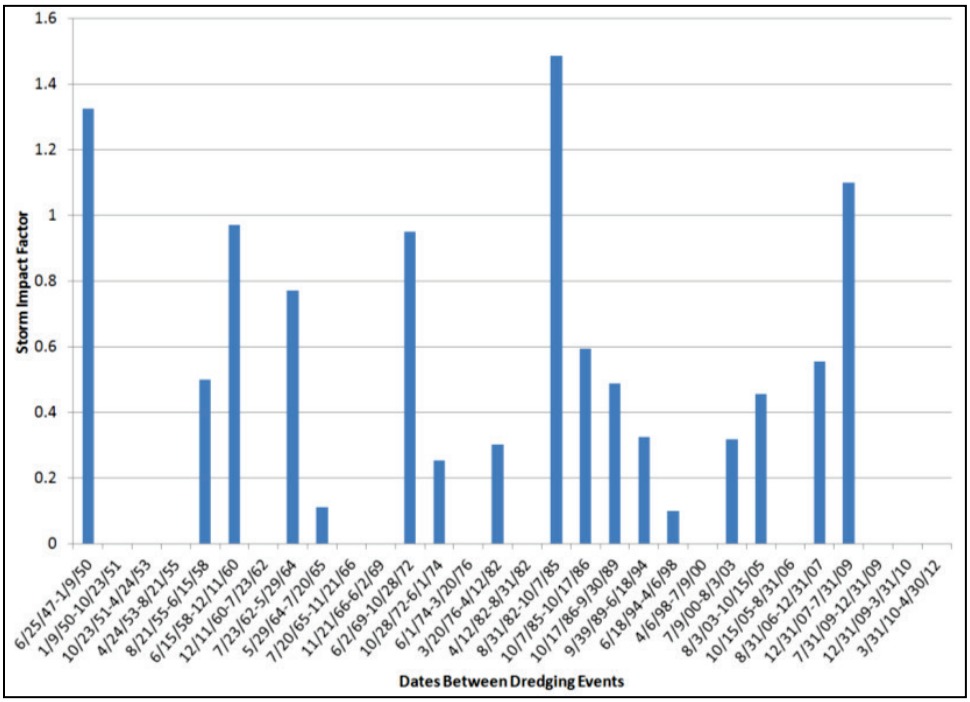


Figure 23 shows the cumulative storm Impact Factor between each dredging event. Each dredging period between 1982 and 1998 included at least one storm event. The period from 9 January 1950 to 21 August 1955 was characterized by weak storms (Impact Factor of zero) or no storms. The longest period of weak or no storms is the present ongoing period. No storm impacted the Houston-Galveston area between the 31 July 2009 dredging event and Hurricane Harvey on 25 August 2017. Harvey was an intense hurricane when it made landfall near Rockport, TX, but was a tropical storm by the time it impacted the Houston-Galveston area (Blake and Zelinsky 2018). Although Harvey caused severe flooding in the Houston-Galveston area due to unprecedented rainfall (Blake and Zelinsky 2018), the storm Impact Factor does not take rainfall into account. Based on the wind speed, duration, and distance from Houston-Galveston, Harvey was considered a weak storm in terms of storm Impact Factor. However, because dredging records were not available beyond 2012, Harvey was not considered in the storm or precipitation analysis.

Figure 23. Storm Impact Factors between dredging events, Galveston Harbor, TX, 1947–2012.



3.3.2 Method 2 – Set blocks of time

To gain a better understanding of the short-term and long-term trends for rainfall and hurricanes, an analysis was conducted that calculated the total rainfall quantities, cumulative storm Impact Factor, and total dredging volumes over a 2-, 3-, 5-, and 6-year period, for Galveston Harbor, TX. For each analysis, the final year considered was 2013. Therefore, the starting date for the 5-year blocks was 1949 compared to 1948 for the 2-, 3-, and 6-year blocks of time.

The first analysis considered thirty-three 2-year time periods from 1948 to 2013. For each 2-year period, rainfall totals in inches, storm Impact Factor, and total dredged volume were calculated. Figure 24 compares rainfall (blue bars) for 2-year time periods to the volume dredged (red circles) over those 2 years. The red horizontal dashed line represents the threshold between an average rainfall and a wetter time period. All rainfall totals below the blue horizontal dashed line represent dry periods while rainfalls between the blue and the red lines represent average rainfall totals. The driest 2-year period was 2010–2011. The wettest period was 1998–1999. Dredging did not occur in the 1948–1949, 1956–1957, 1970–1971, 1978–1979, 1980–1981, 1990–1991, 1992–1993, and 1996–1997 time periods. The greatest volumes of dredging over a 2-year period occurred in 1950–1951 and 1982–1983 when more than 8M yd^3 were dredged.

Figure 24. Rainfall and volume dredged over 2-year intervals, Galveston Harbor, TX, 1948–2013.

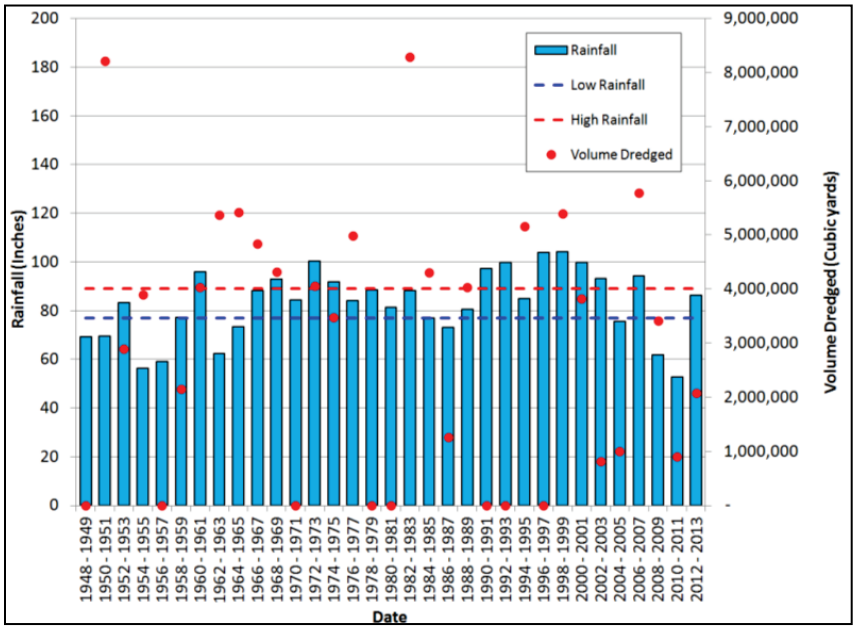
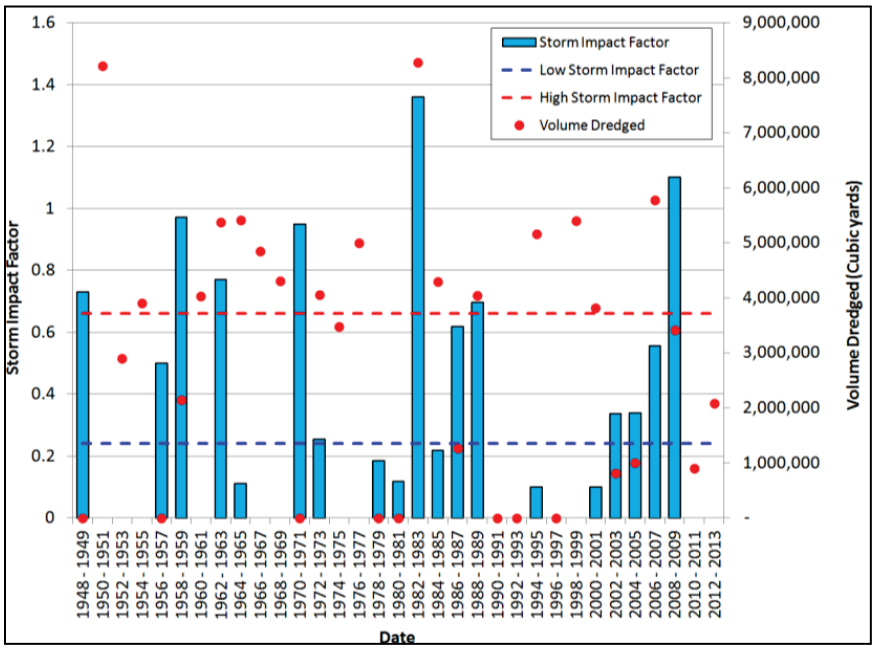


Figure 25 compares storm Impact Factors to volume dredged over the same 2-year intervals. Fourteen time periods did not experience any storms with Impact Factors greater than zero. The thresholds for weak and strong storms were based only on time periods where storms with Impact Factors occurred. For example, storms with Impact Factors greater than zero occurred during 19 of the time periods. Seven of the time periods were classified as strong storms, six as average, and six as weak. The highest Impact Factor occurred for 1982–1983, which is to be expected due to Hurricane Alicia. The longest period of no storm impacts was between 1950 and 1955. However, the decade of the 1990s only experienced one weak storm during the 1994–1995 time period.

Figure 25. Storm Impact Factors and volume dredged over 2-year intervals, Galveston Harbor, TX, 1948–2013.



There are twenty-two 3-year time periods considered for the second analysis. Figure 26 shows the rainfall in inches for each 3-year period, and the volume dredged during the same time period. The greatest volume dredged occurred during the 1960–1962 time period. The 1978–1980 and 1990–1992 time periods did not experience any dredging. The threshold between dry and average was 115 in. while any rainfall greater than 134 in. was classified as wet for a 3-year period. The driest 3-year time period was 1954–1956 while the wettest time period was 1996–1998. The 1996–1998 time period experienced more than twice as much rain as the 1954–1956 time period.

Figure 26. Rainfall and volume dredged over 3-year intervals, Galveston Harbor, TX, 1948–2013.

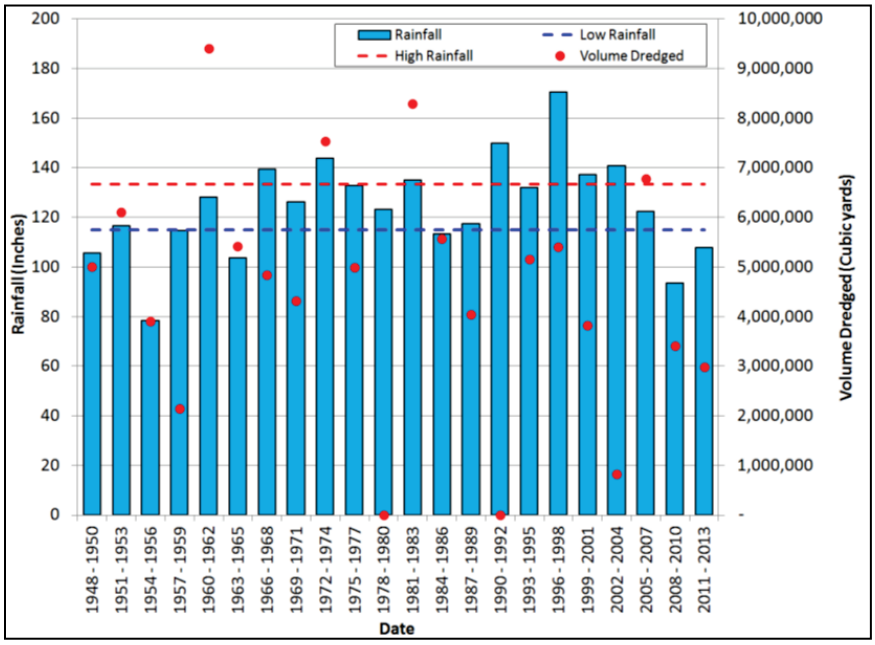
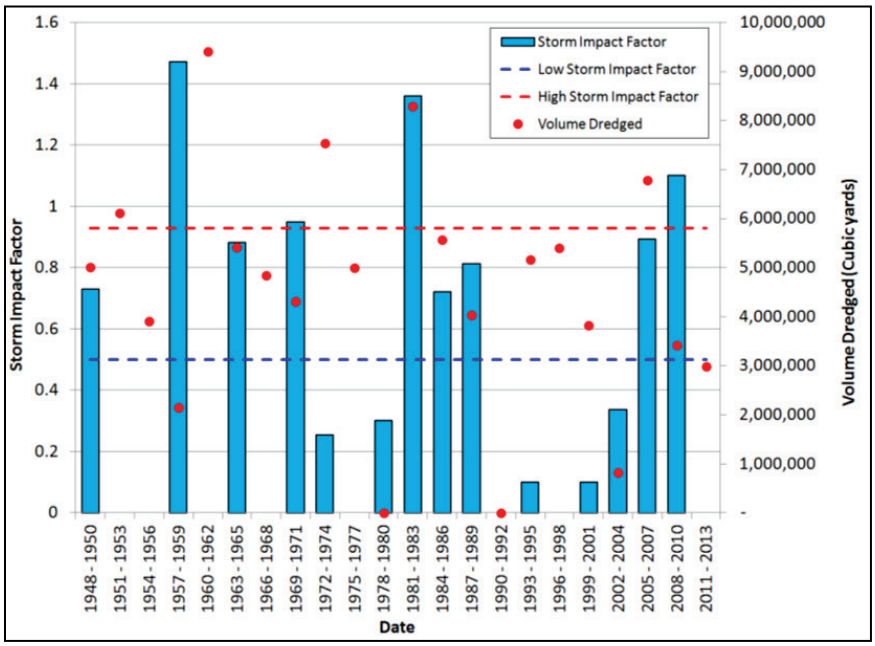


Figure 27 shows the storm Impact Factor for each 3-year period and the volume dredged during the same period. Eight of the time periods did not have any storms with an Impact Factor greater than zero. The highest Impact Factor was from 1957 to 1959. The lowest Impact Factor (other than zero) occurred during the 1993–1995 and 1999–2001 time periods. A storm Impact Factor of less than 0.5 over a 3-year period was considered a weak storm period.

The calculation of a storm Impact Factor is described in Part 3: "Storm and Precipitation Analysis," sub-section 3.1.2 "Determination of Impact Factor," of this document. If a single storm happened during the 3-year period, for it to be classified as having a weak storm Impact Factor, the storm must have been more than 100 miles from the point of interest and more than 150 mph, with a duration of 15 to 18 hr. However, it is unlikely that such a strong storm would maintain that wind speed for a long period of time after making landfall, so a single storm with a wind speed of 60 to 73 mph and a duration of 3 to 6 hr in each circle (less than 25 miles, 25–50 miles, 50–75 miles, 75–100 miles, and 100–150 mile radius) would also be classified as having a weak storm Impact Factor. If a smaller storm occurred in each one of the years, a storm of 39 to 45 mph winds with a duration of 3 to 6 hr inside of a 25 mile radius and between the 25 to 50 mile radius would have a storm Impact Factor around 0.167 per year. A

storm or storms over the 3-year period with a storm Impact Factor of greater than 0.93 was considered a time period of strong storms. A single storm with winds of 85 to 90 mph, a track that made landfall within 25 miles of the site of interest, and a total duration of 21 hr or longer would have an Impact Factor of greater than 0.93. If a smaller storm made landfall each year, each storm would have a wind speed between 50 and 52 mph and a duration of 3 to 6 hr within each circle up to 75 miles away from the location of interest.

Figure 27. Storm Impact Factors and volume dredged over 3-year intervals, Galveston Harbor, TX, 1948–2013.



While this analysis does not give specific information relating volume dredged to rainfall and storms over each period, it does provide information about the trends. It is much easier to see which periods of time had greater amounts of rain or larger storms, which helps develop the final analysis to provide a range of volumes for dry, average, or wet conditions or weak, average, or strong storms. By having identical lengths of time for each period (1 January to 31 December), each time period can be compared to each other. During a 5-year time period, a large dredging event might occur in the first year, but the rainfall over that period of time might be low and there might not be any storm events. Generally, larger dredging events correspond with storms or wet periods of time. If the storm happened early in the time period, the prior 5-year period would provide better information for rainfall totals and storms prior to the

dredging event. Also, choosing an appropriate time interval that approximately matches the dredging interval is likely the best way to apply this method at a site. At Galveston, a slight variation of Method 2 was used where the 2-year dredging totals were paired with the previous 2-year storm activity and rainfall totals. Table 8 presents the rainfall totals and storm Impact Factors based on this method.

Table 8. Total rainfall and storm Impact Factors for 2-year intervals, Galveston Harbor, TX, 1947–2012.

2-year Interval	2-year volume, yd^3	Previous 2-year Interval	Total Impact Factor	Total Rainfall, in.
1947-1948	6,082,994	1945-1946	0.34	80.1
1949-1950	5,004,824	1947-1948	0.6	66.1
1951-1952	3,212,051	1949-1950	0.73	85.6
1953-1954	2,894,868	1951-1952		68.7
1955-1956	3,902,472	1953-1954	0	63.5
1957-1958	2,149,535	1955-1956	0	56.7
1959-1960	4,032,000	1957-1958	0.5	75.4
1961-1962	5,376,500	1959-1960	0.97	63.8
1963-1964	1,777,693	1961-1962		98.9
1965-1966	8,483,063	1963-1964	0.88	72.5
1967-1968	0	1965-1966		90.4
1969-1970	4,312,942	1967-1968		83.2
1971-1972	4,055,450	1969-1970	0.2	92.9
1973-1974	3,482,921	1971-1972	0.75	70.6
1975-1976	4,993,000	1973-1974	0.26	104.7
1977-1978	0	1975-1976		87.0
1979-1980	0	1977-1978	0	82.3
1981-1982	8,284,695	1979-1980	0.23	95.4
1983-1984	0	1981-1982	0.18	70.1
1985-1986	5,567,703	1983-1984	1.18	89.7
1987-1988	0	1985-1986	0.72	74.7
1989-1990	4,038,896	1987-1988	0.12	89.5
1991-1992	0	1989-1990	0.69	76.9
1993-1994	5,162,753	1991-1992		105.9
1995-1996	0	1993-1994		80.2
1997-1998	5,400,565	1995-1996	0.1	91.8
1999-2000	3,818,488	1997-1998	0	132.3
2001-2002	0	1999-2000	0	58.3
2003-2004	819,428	2001-2002	0.1	88.6

2-year Interval	2-year volume, yd³	Previous 2-year Interval	Total Impact Factor	Total Rainfall, in.
2005-2006	3,820,552	2003-2004	0.34	91.9
2007-2008	2,956,986	2005-2006	0.34	77.6
2009-2010	4,317,019	2007-2008	1.65	61.7
2011-2012	2,084,922	2009-2010		66.4

3.4 Classification of years

Periods between events and in 2-year intervals were categorized based on both their rain totals and storm activity. For the 2-year interval method, the prior 2 years of storm activity were used to rank the following 2-year total dredging volume. The categories of low, medium, or high were assigned based on a relative relationship with the other events occurring within the dredging record period. Both percentage of average rainfall and storm Impact Factor were categorized into low, medium, and high for each time period and 2-year interval.

The storms were ranked according to percentile thresholds for both the total Impact Factor and the annualized Impact Factor. Those Impact Factors below the thirty-third percentile were categorized as low, those between the thirty-third and sixty-seventh percentile were categorized as medium, and those above the sixty-seventh percentile were ranked as high. Similarly, the percentage of average rainfall was used to categorize the rainfall totals along these thresholds. The calculation of the modified storm Impact Factor (Table 8) is fairly conservative so that any storms that have a calculated Impact Factor greater than zero are fairly significant. The moderate-to-high categories are assigned to any period above the thirty-third percentile because the majority of periods categorized as low have either a relatively low ranking Impact Factor, a total Impact Factor of zero, or no storm activity at all.

Table 9 shows the categorization of storm activity based on the total Impact Factor from the previous 2-year interval at Galveston. To demonstrate the usefulness of using the period between dredging events, Method 1 was used at Mayport, FL, to compare storm and rainfall activity from the previous dredge event to the succeeding dredge event. Table 10 shows the categorization of storm activity based on the time period between dredging events at Mayport, FL. Because the time between dredging is variable, the Impact Factor total and dredging volume are presented in an annualized fashion as well.

Table 9. Two-year interval categorization based on storm Impact Factor, Galveston, TX, 1947–2012.

2-year Interval	2-year Volume, yd^3	Previous 2-year Interval	Total Impact Factor	Impact Factor Category
1947-1948	6,082,994	1945-1946	0.34	Moderate
1949-1950	5,004,824	1947-1948	0.6	Moderate
1951-1952	3,212,051	1949-1950	0.73	High
1953-1954	2,894,868	1951-1952		Low
1955-1956	3,902,472	1953-1954	0	Low
1957-1958	2,149,535	1955-1956	0	Low
1959-1960	4,032,000	1957-1958	0.5	Moderate
1961-1962	5,376,500	1959-1960	0.97	High
1963-1964	1,777,693	1961-1962		Low
1965-1966	8,483,063	1963-1964	0.88	High
1967-1968	0	1965-1966		Low
1969-1970	4,312,942	1967-1968		Low
1971-1972	4,055,450	1969-1970	0.2	Moderate
1973-1974	3,482,921	1971-1972	0.75	High
1975-1976	4,993,000	1973-1974	0.26	Moderate
1977-1978	0	1975-1976		Low
1979-1980	0	1977-1978	0	Low
1981-1982	8,284,695	1979-1980	0.23	Moderate
1983-1984	0	1981-1982	0.18	Moderate
1985-1986	5,567,703	1983-1984	1.18	High
1987-1988	0	1985-1986	0.72	High
1989-1990	4,038,896	1987-1988	0.12	Low
1991-1992	0	1989-1990	0.69	High
1993-1994	5,162,753	1991-1992		Low
1995-1996	0	1993-1994		Low
1997-1998	5,400,565	1995-1996	0.1	Low
1999-2000	3,818,488	1997-1998	0	Low
2001-2002	0	1999-2000	0	Low
2003-2004	819,428	2001-2002	0.1	Low
2005-2006	3,820,552	2003-2004	0.34	Moderate
2007-2008	2,956,986	2005-2006	0.34	Moderate
2009-2010	4,317,019	2007-2008	1.65	High
2011-2012	2,084,922	2009-2010		Low

Table 10. Classification of rainfall and storm Impact Factors, Mayport, FL, 1954–2008.

Prior Event	Event	Volume, yd^3	Actual Impact Factor	Category	Annualized Impact Factor	Category
1/1/1954	8/1/1956	346,312	0	Low	0	Low
8/1/1956	10/1/1959	897,777	0.13	Moderate	0.04	Moderate
10/1/1959	10/1/1962	1,411,640	0.38	High	0.13	High
10/1/1962	1/1/1964	559,092	0.25	High	0.20	High
1/1/1964	3/1/1965	289,050	1.43	High	1.23	High
3/1/1965	12/1/1966	1,962,067	0	Low	0	Low
12/1/1966	9/1/1969	868,479	0.7	High	0.25	High
9/1/1969	8/1/1972	1,158,181	0	Low	0	Low
8/1/1972	3/1/1974	570,972	0	Low	0	Low
3/1/1974	2/1/1975	547,565	0	Low	0	Low
2/1/1975	3/1/1978	736,084	0	Low	0	Low
3/1/1978	10/1/1978	1,789,701	0	Low	0	Low
10/1/1978	7/1/1979	173,558	0	Low	0	Low
7/1/1979	3/1/1982	47,148	0.69	High	0.26	High
3/1/1982	11/1/1983	1,793,031	0	Low	0	Low
11/1/1983	8/1/1984	129,363	0	Low	0	Low
8/1/1984	6/1/1985	223,000	0.67	High	0.80	High
6/1/1985	1/1/1990	1,280,151	0.34	High	0.07	Moderate
1/1/1990	5/1/1994	1,600,135	0	Low	0	Low
5/1/1994	1/1/1997	1,230,507	0	Low	0	Low
1/1/1997	3/1/2000	1,099,371	0.2	Moderate	0.06	Moderate
3/1/2000	10/1/2001	1,097,800	0	Low	0	Low
10/1/2001	4/1/2003	174,832	0.03	Moderate	0.02	Moderate
4/1/2003	1/1/2005	1,289,138	0.28	High	0.16	High
1/1/2005	5/1/2008	1,069,754	0.2	Moderate	0.06	Moderate
5/1/2008	1/1/2010	629,034	0.26	High	0.16	High

3.5 Methods discussion

The two methods reviewed have both advantages and disadvantages for predicting dredging volumes at a site. The main distinction between the methods is the time period prior to a dredging event that is used to analyze the storms and rainfall. Deciding when a dredging decision should be made to capture the correct period of conditions that influence the channel makes choosing the appropriate period difficult. For the purpose of this

study, two methods are used to find the relationship between dredging volumes and varying site conditions: (1) Method 1 – Time between dredging events (the storms occurring during the 2 years prior to the succeeding 2-year total of dredging volumes) and (2) Method 2 – Set blocks of time (the storms occurring between dredging events).

The biggest lesson learned when working through each of the methods listed in Section 3.3.1 (Method 1) and Section 3.3.2 (Method 2) is that using the rainfall or storm activity as the sole predictor to determine a single value of dredging is difficult and likely unrealistic. This type of deterministic approach to accurately predict the volume that will be seen in the next year or over the next interval of dredging years would require more data points than are presently available at most sites. The results of the analysis conducted at a site have not shown that storm or rain activity can accurately and consistently provide a single deterministic value for expected dredging. Alternatively, integrating a probabilistic approach could provide valuable information about how dredging volumes change under varying levels of storms or rainfall. The results of the analysis will include the range of volumes dredged following each rainfall or storm activity level, an average volume seen at each level, and the probability of exceeding the annual average dredging rate based on the level of rainfall or storms. For Galveston Harbor, TX, the analysis method chosen was Method 1, the 2-year interval blocks for totaling storm Impact Factor and dredge volumes, and for Mayport, FL, Method 2, the method using the time between dredging events, was chosen.

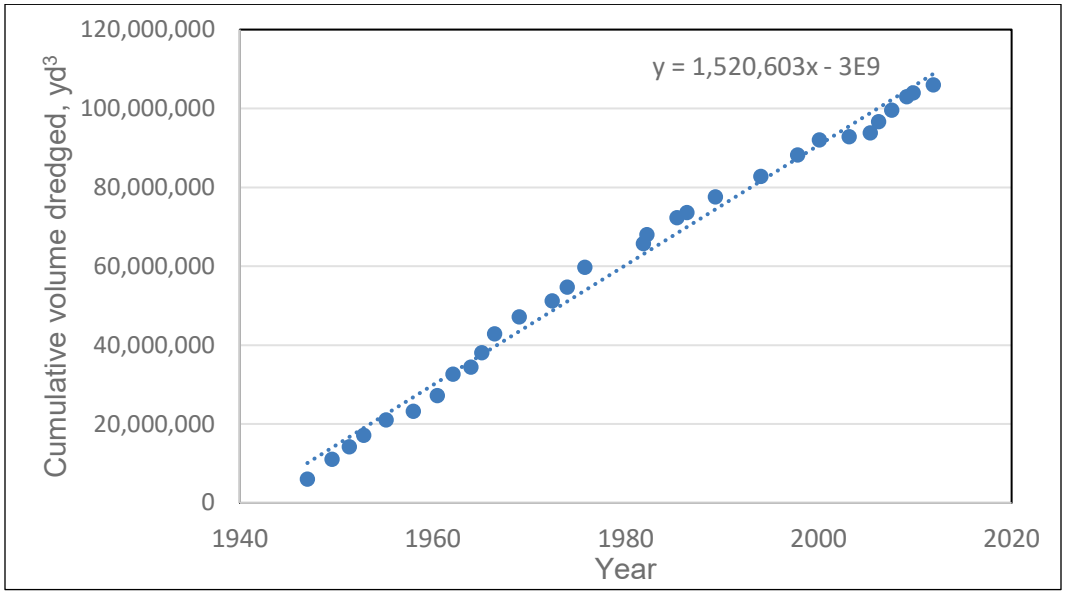
4 Results and Discussion

4.1 Galveston Harbor, TX

Analysis at Galveston Harbor, TX, consisted of both categorizing years based on their storm and rainfall activity to extract trends in dredging. For Galveston Harbor, the analysis was completed based exclusively on total storm Impact Factor over 2-year intervals as presented in section 3.4.

Establishing an average annual dredging rate is a common first step in predicting future dredging at a site. It is typically a linear regression of the cumulative dredging volume in which the slope of that line represents an estimate for the average annual dredging rate. Figure 28 is the cumulative dredging plotted against time for a period of 65 years from 1947 to 2012. The line of best fit is shown along with the equation of linear regression.

Figure 28. Linear regression of cumulative dredging at Galveston, TX.



This regression gives an average annual rate of 1,520,600 yd^3, and the equation represents a linear model of cumulative dredging at Galveston, TX. The residual differences between the actual cumulative dredging volumes and the modeled results can bring insight into how storms can cause variation from the expected average annual dredging rate. Table 11 lists the cumulative, modeled, and residual volume values. Negative residuals indicate a lesser-than-average dredging rate, and positive residuals indicate a greater than average rate.

Table 11. Cumulative volume and residuals from modeled dredging volume, Galveston Harbor, TX, 1947–2012.

2-Year Interval	Actual Cumulative Dredging Volume, yd^3	Modeled Cumulative Dredging Volume, yd^3	Residual Dredging Volume, yd^3
1947-1948	6,082,994	11,632,487	-5,549,493
1949-1950	11,087,818	14,673,693	-3,585,875
1951-1952	14,299,869	17,714,899	-3,415,030
1953-1954	17,194,737	20,756,105	-3,561,368
1955-1956	21,097,209	23,797,311	-2,700,102
1957-1958	23,246,744	26,838,517	-3,591,773
1959-1960	27,278,744	29,879,723	-2,600,979
1961-1962	32,655,244	32,920,929	-265,685
1963-1964	34,432,937	35,962,135	-1,529,198
1965-1966	42,916,000	39,003,341	3,912,659
1967-1968	42,916,000	42,044,547	871,453
1969-1970	47,228,942	45,085,753	2,143,189
1971-1972	51,284,392	48,126,959	3,157,433
1973-1974	54,767,313	51,168,165	3,599,148
1975-1976	59,760,313	54,209,371	5,550,942
1977-1978	59,760,313	57,250,577	2,509,736
1979-1980	59,760,313	60,291,783	-531,470
1981-1982	68,045,008	63,332,989	4,712,019
1983-1984	68,045,008	66,374,195	1,670,813
1985-1986	73,612,711	69,415,401	4,197,310
1987-1988	73,612,711	72,456,607	1,156,104
1989-1990	77,651,607	75,497,813	2,153,794
1991-1992	77,651,607	78,539,019	-887,412
1993-1994	82,814,360	81,580,225	1,234,135
1995-1996	82,814,360	84,621,431	-1,807,071
1997-1998	88,214,925	87,662,637	552,288
1999-2000	92,033,413	90,703,843	1,329,570
2001-2002	92,033,413	93,745,049	-1,711,636
2003-2004	92,852,841	96,786,255	-3,933,414
2005-2006	96,673,393	99,827,461	-3,154,068
2007-2008	99,630,379	102,868,667	-3,238,288
2009-2010	103,947,398	105,909,873	-1,962,475
2011-2012	106,032,320	108,951,079	-2,918,759

Based on the categorization of periods preceding a dredge event, ranges of annual dredged volumes were established from the historical trends for a given period type. The 2-year dredging volumes were halved to give an annualized dredging volume. Table 12 presents the ranges based on type of storm period prior to dredging along with the average dredging rate by period type and difference from the average dredging rate.

Table 12. Range of annual dredged volumes and average annual dredged volumes based on previous 2-year interval storm period level, Galveston Harbor, TX.

Period Type	Minimum, yd^3	Maximum, yd^3	Average, yd^3	Difference from Mean, yd^3
Low/ No Storm	409,714	2,700,283	1,136,330	-494,936
High Storm	1,478,493	4,241,532	2,049,111	417,844

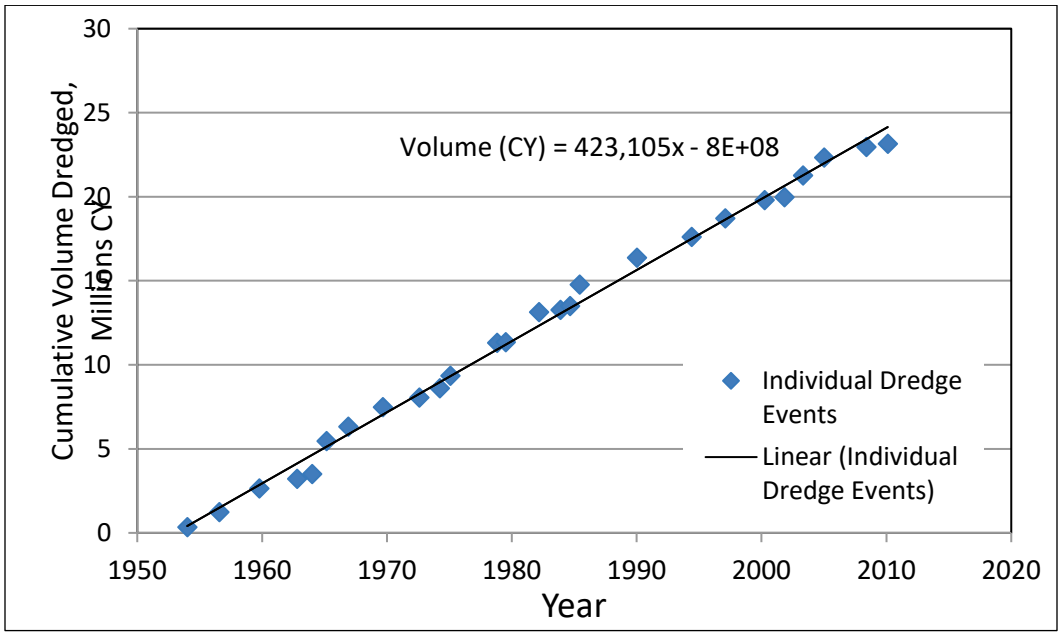
A t-test can be used to determine if the difference in average between two groups is indicative of a significance difference. A t-test was used to determine if the difference in mean dredge volume under each storm intensity classification is statistically significant. As described previously, mean dredge volumes following low or no storm periods and high storm intensity conditions were compared. The difference between the average volumes dredged following a low storm period versus a high storm period is statistically significant at the 95% confidence interval with a p-value of 0.013.

4.2 Mayport Basin, FL

Analysis at Mayport, FL, consisted of categorizing years based on their storm and rainfall activity. As discussed previously, there seems to be a clearer relationship between storms and dredging at this site, so the results will focus on storm activity as it relates to dredging volume.

Establishing an average annual dredging rate is a common first step in predicting future dredging at a site. It is typically done with a linear regression of the cumulative dredging volume in which the slope of that line represents an estimate for the average annual dredging rate. Figure 29 is the cumulative dredging plotted against time for a period of 56 years from 1954 to 2010. The line of best fit is shown along with the equation of linear regression.

Figure 29. Linear regression of cumulative dredging at Mayport, FL.



This regression gives an average annual rate of 423,105 yd^3, and the equation represents a linear model of cumulative dredging at Mayport, FL. The residual differences between the actual cumulative dredging volumes and the modeled results can bring insight into how storms can cause variation from the expected average annual dredging rate. Table 13 lists the cumulative, modeled, and residual volume values. Negative residuals indicate a lesser-than-average dredging rate, and positive residuals indicate a greater than average rate.

Table 13. Cumulative volume and residuals from modeled dredging volume, Mayport, FL, 1954–2010.

Dredge Event	Actual Cumulative Dredging Volume, yd^3	Modeled Cumulative Dredging Volume, yd^3	Residual Dredging Volume, yd^3
1/6/1954	346,312	406,816	-60,504
8/1/1956	1,244,089	1,494,138	-250,049
10/19/1959	2,655,729	2,855,029	-199,300
10/20/1962	3,214,821	4,126,662	-911,841
1/1/1964	3,503,871	4,634,388	-1,130,517
3/1/1965	5,465,938	5,127,045	338,893
12/1/1966	6,334,417	5,868,928	465,489
9/1/1969	7,492,598	7,033,915	458,683
8/4/1972	8,063,570	8,271,932	-208,362

Dredge Event	Actual Cumulative Dredging Volume, yd³	Modeled Cumulative Dredging Volume, yd³	Residual Dredging Volume, yd³
3/25/1974	8,611,135	8,965,129	-353,994
2/1/1975	9,347,219	9,327,956	19,263
10/24/1978	11,310,478	10,905,616	404,862
7/5/1979	11,357,626	11,200,051	157,575
3/1/1982	13,150,657	12,324,467	826,190
11/19/1983	13,280,020	13,052,439	227,581
8/24/1984	13,503,020	13,375,854	127,166
6/1/1985	14,783,171	13,701,587	1,081,584
1/1/1990	16,383,306	15,643,233	740,073
5/21/1994	17,613,813	17,499,099	114,714
1/29/1997	18,713,184	18,639,744	73,440
3/27/2000	19,810,984	19,976,292	-165,308
10/22/2001	19,985,816	20,641,668	-655,852
4/24/2003	21,274,954	21,278,064	-3,110
1/1/2005	22,344,708	21,994,445	350,263
5/19/2008	22,973,742	23,424,887	-451,145
1/30/2010	23,148,683	24,144,745	-996,062

Based on the categorization of periods preceding a dredge event, ranges were established based on the minimum and maximum dredging volumes recorded under each storm categorization. Dredging volumes were considered on an annual basis and on an event basis. Hence, if 800,000 yd³ were dredged 2 years after the previous event, the annual volume would be 400,000 yd³, and the event volume would be 800,000 yd³. Table 14 presents the ranges based on type of storm period prior to dredging.

Table 14. Range of dredging volumes on annual and per-event basis for low and high storm periods, Mayport, FL.

Annual Dredge Volume			Volume by Dredge Event		
Period Type	Minimum, yd³	Maximum, yd³	Period Type	Minimum, yd³	Maximum, yd³
Low/ No Storm	67,752	858,373	Low/ No Storm	47,148	1,789,701
Stormy Period	186,059	1,685,069	Stormy Period	174,941	1,962,067

Table 14 shows the full range of possibilities seen at Mayport, FL, and it is highly varied. The average annual dredging rate is 423,100 yd^3/year as determined by the linear regression of cumulative dredging (Figure 29) and the average volume dredged on an event basis is 857,360 yd^3.

Table 15 presents statistics for the mean dredging volumes for annualized and event totals. Statistics provided in Table 14 and Table 15 provide a starting point on understanding how dredging at Mayport, or another site of interest, is impacted by varying levels of hurricane and tropical storm activity.

Table 15. Deviation from average dredging volume on annual and per-event basis for low and high storm periods, Mayport, FL.

Annual Dredge Volume Average: 423,105 yd^3			Volume by Dredge Event Average: 857,359 yd^3		
Period Type	Average, yd^3	Difference From Mean, yd^3	Period Type	Average, yd^3	Difference From Mean, yd^3
Low/ No Storm	340,737	-85,794	Low/ No Storm	652,951	-204,408
Stormy Period	568,121	+145,016	Stormy Period	1,102,696	+245,337

A t-test was used to determine if the difference in mean dredge volume under each storm intensity classification is statistically significant. As described previously, mean dredge volumes following low- or no-storm periods and high storm intensity conditions were compared. The difference between the average annual volumes dredged following a low-storm period versus a high storm period is statistically significant at the 90% confidence interval with a p-value of 0.05. The difference between the average volumes dredged on an event basis following a low storm period versus a high storm period is statistically significant at the 95% confidence interval with a p-value of 0.013.

5 Conclusions

Several factors play a role in the volume removed and frequency with which a channel or harbor is dredged. Because the aim of this effort was to develop a simple generalized methodology applicable to a wide range of sites using only readily available storm and rainfall data, predicting a single future volume of dredging that occurs during a given period is difficult. Dredging does not correlate to either one factor or another factor solely, and attempting to correlate to one factor would likely yield inaccurate results. If a similar methodology were developed on a site-specific basis, a more deterministic result could be accurately developed. Still, in this generalized approach, using storm and/or rainfall data as a means of gaining better understanding about how little or how much a given channel or harbor responds to different levels of hurricane activity or rainfall is a valuable application of available data.

If the analysis methods provided in this report are applied for different channels elsewhere in the country, they would also provide insight into how different conditions cause variations in infilling patterns for different areas at coastal inlets, harbors, or inland waterways. Furthermore, if sediment information is known, it could provide guidance on a range of volumes for a given type of sediment, an important aspect of beneficial use planning.

The statistical significance for results determined with the methods in this report may be limited by the sample size available at a site. A site with 30 dredging events dating back 60 years is considered a fairly long record, and many sites have fewer available records or less frequent dredging. As additional historical dredging records are gathered, and future dredging volumes are collected and retained, this approach will become more robust, and more confidence can be placed on the results.

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Appendix A: Additional Houston-Galveston, TX, Channels Dredging History

Channel locations are shown in Figure 1.

Table A-1. Comprehensive dredging data for the Houston-Galveston navigation channels.

Date	Volume, yd^3	Location(s)
6/25/1947	6,082,994	Galveston Harbor
1/9/1950	5,004,824	Galveston Harbor
10/23/1951	3,212,051	Galveston Harbor
4/24/1953	2,894,868	Galveston Harbor
8/21/1955	3,902,472	Galveston Harbor
6/15/1958	2,149,535	Galveston Harbor
12/11/1960	4,032,000	Galveston Harbor
7/23/1962	5,376,500	Galveston Harbor
5/29/1964	1,777,693	Galveston Harbor
7/20/1965	3,640,080	Galveston Harbor
11/21/1966	4,842,983	Galveston Harbor
6/2/1969	4,312,942	Galveston Harbor
3/19/1972	3,150,027	Entrance Channel
10/28/1972	4,055,450	Galveston Harbor
3/4/1973	1,892,841	Entrance Channel
4/24-6/1/1974	4,669,594	Galveston Harbor, Inner Bar, Entrance Channel
5/13/1975	1,702,292	Entrance Channel
3/20/1976	4,993,000	Galveston Harbor
7/8/1976	1,293,203	Entrance Channel
3/25/1977	1,686,819	Entrance Channel
9/7/1979	3,667,687	Inner Bar, Entrance Channel
8/5/1980	1,170,578	Inner Bar, Outer Bar, Entrance Channel
4/12/1982	6,022,633	Galveston Harbor
8/31/1982	2,262,062	Galveston Harbor
7/25/1984	4,487,405	Inner Bar, Outer Bar, Entrance Channel
10/7/1985	4,301,050	Galveston Harbor
7/31/1986	2,212,568	Inner Bar, Outer Bar, Entrance Channel
10/17/1986	1,266,653	Galveston Harbor
10/4/1988	949,621	Inner Bar, Outer Bar, Entrance Channel
9/30/1989	4,097,834	Galveston Harbor, Inner Bar, Outer Bar, Entrance Channel
12/5/1990	2,171,188	Inner Bar, Outer Bar, Entrance Channel
8/25/1993	2,596,462	Inner Bar, Outer Bar, Entrance Channel
6/18/1994	5,162,753	Galveston Harbor
9/21/1995	691,683	Inner Bar
5/6/1996	8,653	Inner Bar
3/31/1997	1,921,837	Inner Bar, Outer Bar, Entrance Channel
4/6/1998	5,400,565	Galveston Harbor
7/9/2000	3,818,488	Galveston Harbor
3/31/01	9,005,085	Bolivar Roads, Inner Bar, Outer Bar

Date	Volume, yd³	Location(s)
6/28-8/3/2003	3,504,669	Galveston Harbor, Entrance Channel
9/17/2004	6,412,367	Bolivar Roads, Inner Bar, Outer Bar, Entrance Channel, Extended Entrance Channel
10/15/2005	998,152	Galveston Harbor
8/22/2006	5,347,564	Bolivar Roads, Galveston Harbor, Inner Bar, Entrance Channel, Extended Entrance Channel
12/31/2007	2,956,986	Galveston Harbor
1/31/2009	2,042,695	Inner Bar, Outer Bar
7/31/2009	2,448,267	Galveston Harbor
12/31/2009-1/31/2010	3,778,737	Galveston Harbor, Entrance Channel, Extended Entrance Channel
3/31/2010	899,667	Galveston Harbor
12/31/2011	1,952,526	Inner Bar, Outer Bar, Entrance Channel, Extended Entrance Channel
4/30/2012	2,084,922	Galveston Harbor
11/30/2012	775,000	Inner Bar, Outer Bar, Entrance Channel, Extended Entrance Channel
12/31/2013	2,151,298	Inner Bar, Outer Bar, Entrance Channel, Extended Entrance Channel

Table A-2. Bolivar Roads Channel dredging quantities or history.

Date	Volume, yd³
12/5/1990	22,535
3/31/2001	1,631,075
9/17/2004	255,453
8/22/2006	67,172
Total	1,976,235

Table A-3. Inner Bar Channel dredging.

Date	Volume, yd³
11/24/1965	4,147,166*
5/20/1974	247,746
9/7/1979	1,136,736
8/5/1980	130,552
7/25/1984	1,382,393
7/31/1986	469,624
10/4/1988	319,240
9/30/1989	21,951
12/5/1990	769,126
8/25/1993	708,020
9/21/1995	691,683
5/6/1996	8,653

Date	Volume, yd³
3/31/1997	377,611
3/31/2001	4,936,613
9/17/2004	1,741,064
8/22/2006	77,291
1/31/2009	1,634,156
12/31/2011	155,500
11/30/2012	480,000
12/31/2013	882,300
Total	20,317,425
	* Deepening

Table A-4. Outer Bar Channel dredging.

Date	Volume, yd³
9/7/1979	144,503
8/5/1980	67,730
7/25/1984	195,505
7/31/1986	86,475
10/4/1988	162,052
9/30/1989	11,143
12/5/1990	30,373
8/25/1993	136,992
3/31/1997	87,215
3/31/2001	2,437,397
9/17/2004	252,533
1/31/2009	408,539
12/31/2011	38,875
11/30/2012	120,000
12/31/2013	220,575
Total	4,399,907

Table A-5. Entrance Channel dredging.

Date	Volume, yd³
3/14/1971	1,910,021
3/19/1972	3,150,027
3/4/1973	1,892,841
4/24/1974	938,927
5/13/1975	1,702,292
7/8/1976	1,293,203
3/25/1977	1,686,819
9/7/1979	2,530,951
8/5/1980	972,296
7/25/1984	2,909,507
7/31/1986	1,656,469
10/4/1988	468,329
9/30/1989	25,844
12/5/1990	1,371,689
8/25/1993	1,751,450
3/31/1997	1,457,011
6/28/2003	2,685,241
9/17/2004	1,930,702
8/22/2006	1,009,951
1/31/2010	1,404,826
12/31/2011	879,076
11/30/2012	87,500
12/31/2013	524,212
Total	34,239,184

Table A-6. Extended Entrance Channel dredging.

Date	Volume, yd³
7/16/1999	3,271,463
9/17/2004	2,232,615
8/22/2006	1,370,750
1/31/2010	1,404,826
12/31/2011	879,075
11/30/2012	87,500
12/31/2013	524,211
Total	9,770,440

Table A-7. Anchorage Area dredging.

Date	Volume, yd^3
5/25/1968	3,554,498
7/9/1978	1,130,462
8/5/1980	408,300
10/4/1988	89,325
12/5/1990	1,235,500
8/25/1993	296,160
3/31/1997	603,695
Total	7,317,940

Table A-8. GIWW – East dredging.

Date	Volume, yd^3
12/13/1943	1,350,023
12/20/1947	400,943
1/15/1950	330,161
4/11/1952	1,563,402
12/9/1954	760,151
2/25/1956	79,464
3/23/1957	438,074
1/18/1959	698,219
2/29/1960	240,615
3/3/1962	2,352,746
2/4/1963	123,635
6/29/1964	705,485
8/9/1966	665,283
2/12/1967	731,948
3/26/1969	812,722
3/20/1971	422,302
3/16/1972	764,667
10/12/1974	804,143
10/13/1978	572,765
9/9/1980	301,633
7/21/1983	1,668,601
11/22/1985	755,164
12/31/1987	227,793

Date	Volume, yd³
10/4/1989	522,137
4/24/1991	709,799
5/13/1993	667,975
7/23/1995	467,293
10/31/1996	474,603
7/6/1997	24,052
2/7/2000	695,622
5/26/2001	423,489
3/1/2004	358,653
8/21/2004	604,113
5/16/2005	369,706
10/17/2006	412,800
4/16/2008	118,243
6/23/2009	463,487
5/4/2011	478,829
Total	23,560,740

Table A-9. GIWW – West dredging.

Date	Volume, yd³
5/22/1954	2,692,498
3/23/1957	585,924
8/16/1960	718,256
3/3/1962	181,126
5/24/1963	737,464
1/28/1966	859,340
7/8/1968	754,837
9/11/1970	368,304
6/6/1973	658,908
12/5/1978	788,695
5/8/1982	753,923
12/25/1986	622,368
10/31/1996	570,919
5/26/2001	550,033
3/1/2004	365,515
10/17/2006	345,532
6/23/2009	473,723
Total	11,862,037

Table A-10. Bolivar Roads to Redfish Reef dredging.

Date	Volume, yd^3
12/15/1950	4,162,149
10/23/1963	6,204,956
12/22/1971	1,949,878
4/24/1978	1,892,890
9/5/1984	1,790,978
3/6/1991	1,143,815
7/19/2000	10,298,831
4/24/2012	360,952
Total	27,804,449

Appendix B: Alternate Dredge Volume Comparison Methods, Galveston, TX

Generally, decisions about dredging are made several months prior to the initiation of dredging. Therefore, it is important to conduct an analysis of the time period prior to each dredging event. For the first additional analysis, the time period 6 months prior to the first event until 6 months prior to the second dredging event is considered. For example, the first two dredging events occurred on 25 June 1947 and 9 January 1950. The first time period considered in this analysis is 25 December 1946 to 9 July 1949. The purpose of this secondary analysis is to determine if any large storm or rainfall event occurred in the 6 months prior to each dredging event. If such an event occurred during that time, it is possible that dredging volumes were based on previous estimates, and the channel might not have been dredged to the specified depth. Table B-1 lists the rainfall and storm impacts between 6 months prior to dredging events. In most cases, “high” rainfall or storm categories remain “high,” and “low” rainfall or storm categories remain “low.” The rainfall category only changed seven times. The changes were generally from low to medium, high to medium, or medium to high. In one case, the category changed from high to low. In this case, the period between dredging events was only 5 months; therefore, shifting the time period of interest by 6 months resulted in no overlap of time. The previous 6 months had much heavier rainfall than the 5 months between dredging events. The rainiest period compared to the average for that period of time was between 6 October 1997 and 9 January 2000. The driest period compared to the average rainfall values was between 15 April 2005 and 28 February 2006. The stormiest period was between 30 June 2007 and 31 January 2009.

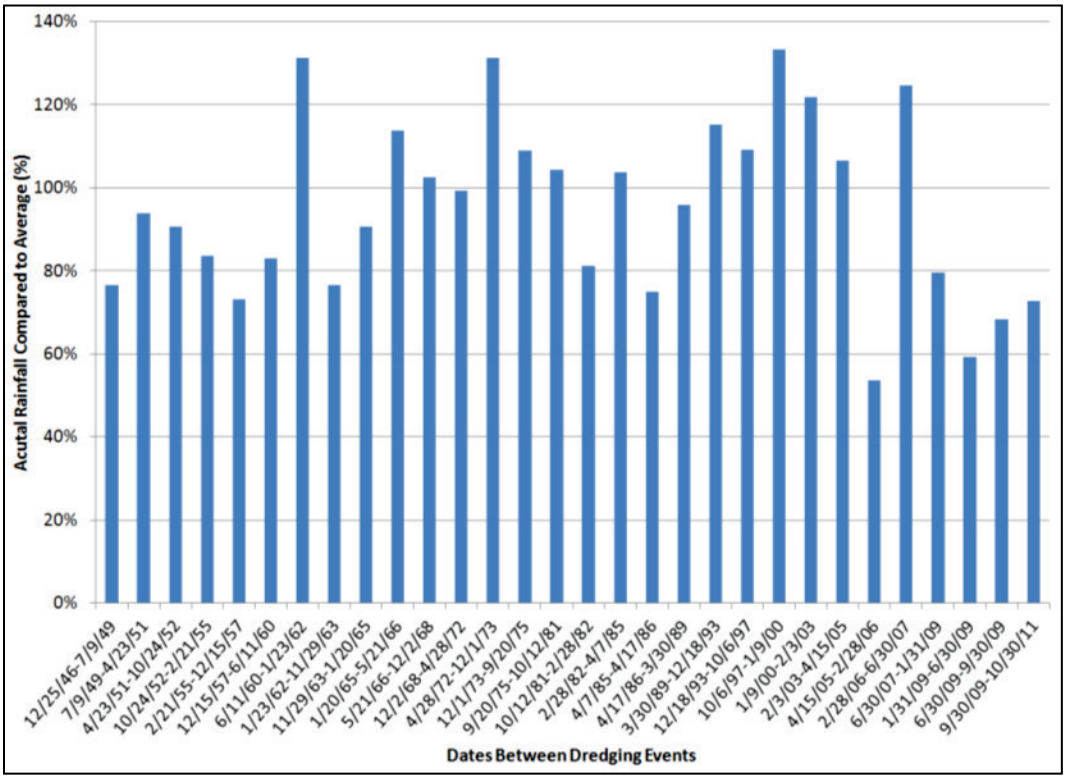
Method 1a: Between dredging events (6 months prior)

Table B-1. Rainfall and storm Impact Factors between dredging events (6 months prior), Galveston, TX.

Start Date	End Date	Dredge Date	Actual Rainfall, in.	Average Rainfall, in.	Percent Rainfall	Category	Actual Impact Factor	Annual Impact Factor
12/25/1946	7/9/1949	1/9/1950	78.34	102.28	77	Low	0.597	0.235
7/9/1949	4/23/1951	10/23/1951	69.39	73.99	94	Medium	0.729	0.407
4/23/1951	10/24/1952	4/24/1953	58.85	64.92	91	Medium	-	-
10/24/1952	2/21/1955	8/21/1955	79.89	95.66	84	Medium	0	0
2/21/1955	12/15/1957	6/15/1958	85.54	117.16	73	Low	0.499	0.177
12/15/1957	6/11/1960	12/11/1960	82.79	99.82	83	Medium	0.972	0.390
6/11/1960	1/23/1962	7/23/1962	91.8	69.98	131	High	-	-
1/23/1962	11/29/1963	5/29/1964	58.67	76.72	76	Low	0.771	0.417
11/29/1963	1/20/1965	7/20/1965	42.72	47.11	91	Medium	0.111	0.097
1/20/1965	5/21/1966	11/21/1966	59.23	52.05	114	High	-	-
5/21/1966	12/2/1968	6/2/1969	110.68	108.10	102	Medium	-	-
12/2/1968	4/28/1972	10/28/1972	136.92	137.95	99	Medium	0.95	0.279
4/28/1972	12/1/1973	6/1/1974	90.39	68.86	131	High	0.255	0.160
12/1/1973	9/20/1975	3/20/1976	80.41	73.87	109	High	0	0
9/20/1975	10/12/1981	4/12/1982	262.11	251.38	104	Medium	0.302	0.050
10/12/1981	2/28/1982	8/31/1982	12	14.80	81	Low	-	-
2/28/1982	4/7/1985	10/7/1985	131.98	127.23	104	Medium	1.361	0.438
4/7/1985	4/17/1986	10/17/1986	31.63	42.18	75	Low	0.219	0.213
4/17/1986	3/30/1989	9/30/1989	117.61	122.72	96	Medium	0.618	0.209
3/30/1989	12/18/1993	6/18/1994	226.92	197.21	115	High	0.696	0.147
12/18/1993	10/6/1997	4/6/1998	171.57	157.36	109	High	0.1	0.026
10/6/1997	1/9/2000	7/9/2000	124.35	93.36	133	High	0	0
1/9/2000	2/3/2003	8/3/2003	154.27	126.71	122	High	0.1	0.033
2/3/2003	4/15/2005	10/15/2005	94.37	88.68	106	High	0.336	0.153
4/15/2005	2/28/2006	8/31/2006	20.24	37.72	54	Low	0.338	0.387
2/28/2006	6/30/2007	12/31/2007	66.53	53.40	125	High	-	-
6/30/2007	1/31/2009	7/31/2009	54.29	68.29	80	Low	1.655	1.040
1/31/2009	6/30/2009	12/31/2009	8.58	14.48	59	Low	-	-
6/30/2009	9/30/2009	3/31/2010	9.06	13.28	68	Low	-	-
9/30/2009	10/30/2011	4/30/2012	62.54	86.02	73	Low	-	-

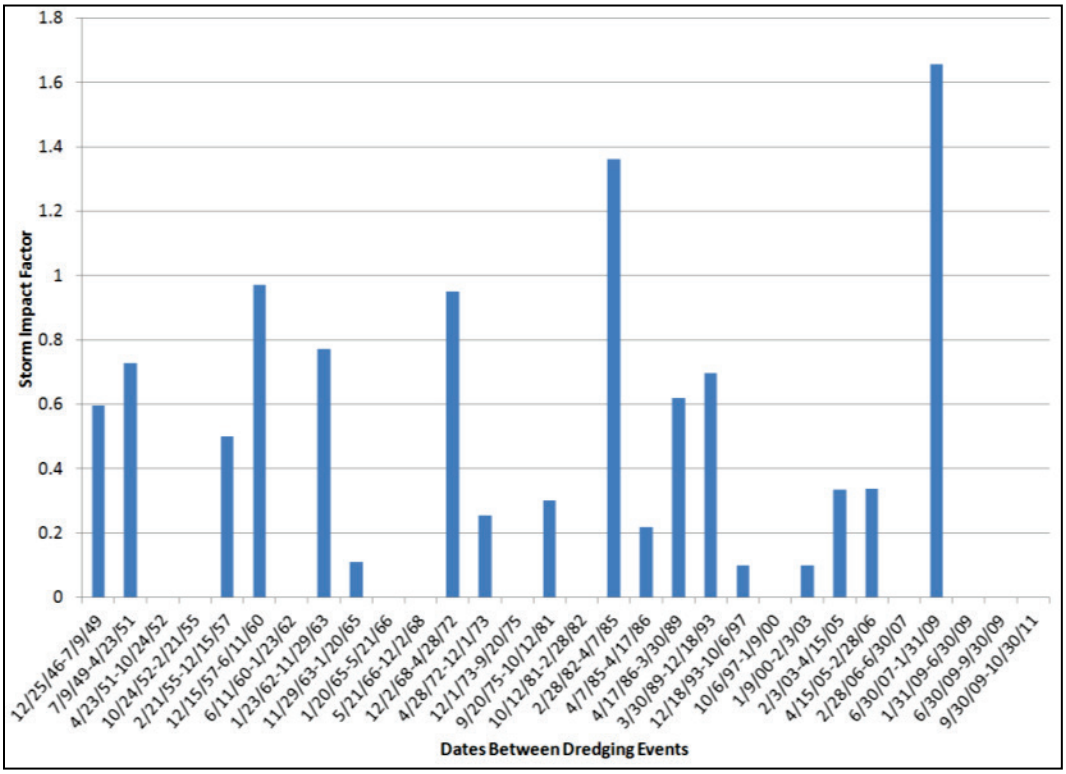
The actual rainfall compared to the average rainfall as a percentage for each period of time is shown in Figure B-1. The rainfall total between 25 December 1946 and 11 June 1960 is significantly below the average. The longest period of above average rainfall occurred between 30 March 1989 and 15 April 2005.

Figure B-1. Actual versus average rainfall between dredging events (6 months prior), Galveston, TX.



The cumulative storm Impact Factors for each time period are shown in Figure B-2. The period between 30 June 2007 and 31 January 2009 had the highest storm Impact Factor, 1.65. Both the time periods of 18 December 1993 to 6 October 1997 and 9 January 2000 to 3 February 2001 had a total storm Impact Factor of 0.1, which was the lowest Impact Factor excluding time periods that did not have storms.

Figure B-2. Storm Impact Factors between dredging events (6 months prior), Galveston, TX.



Method 1b: Between dredging events (1 year prior)

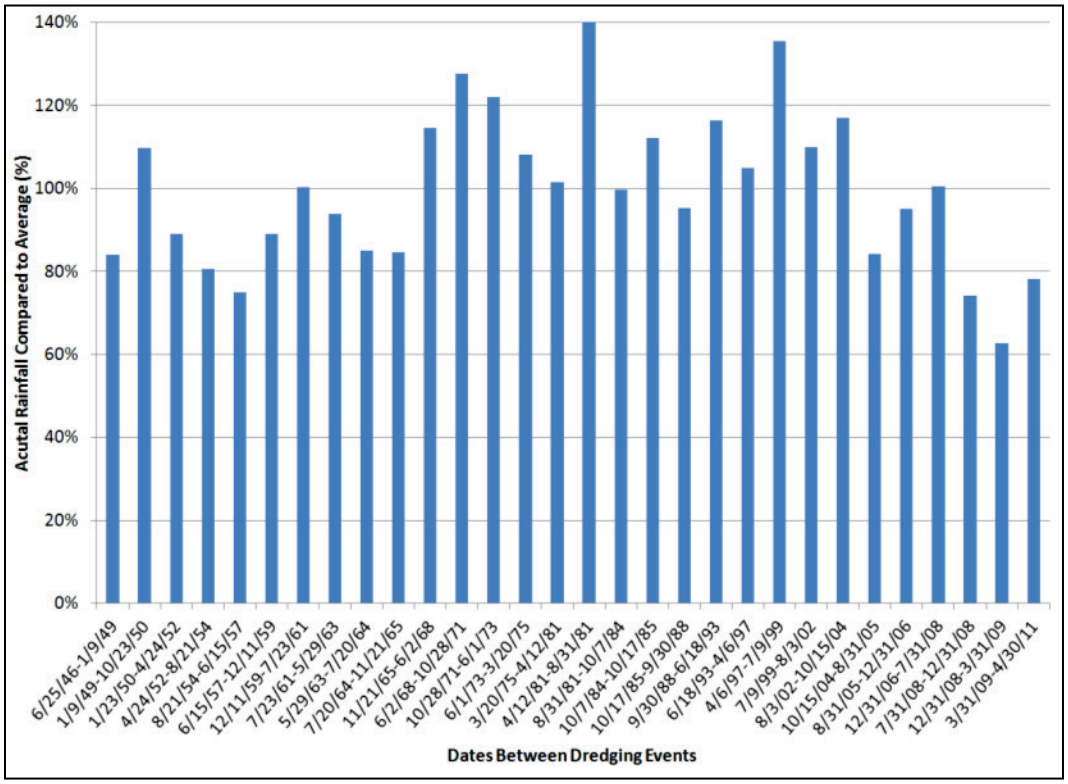
To further understand when specific events impact the dredging needs, the time period between 1 year prior to the first dredging event and 1 year before the second dredging event was analyzed. For example, the first dredging event occurred on 25 June 1947 and the second was on 9 January 1950. Therefore, the first time period used in this analysis was from 25 June 1946 to 9 January 1949. Table B-2 lists the start date and end date, actual and average rainfall, actual and annualized storm Impact Factor, the percent rainfall, and the rainfall categories. The wettest time period compared to the average was 12 April 1981 to 31 August 1981. The driest period compared to the average was 31 December 2008 to 31 March 2009. Eighteen of the time periods resulted in an Impact Factor, two had an Impact Factor of zero, and 10 time periods were not impacted by any storms.

Table B-2. Rainfall and storm Impact Factors between dredging events (1 year prior), Galveston, TX.

Start Date	End Date	Dredge Date	Actual Rainfall, in.	Average Rainfall, in.	Percent Rainfall	Category	Actual Impact Factor	Annual Impact Factor
6/25/1946	1/9/1949	1/9/1950	90.63	107.99	84	Low	0.597	0.235
1/9/1949	10/23/1950	10/23/1951	81.17	74.02	110	High	0.729	0.408
10/23/1950	4/24/1952	4/24/1953	52.85	59.42	89	Medium	-	-
4/24/1952	8/21/1954	8/21/1955	75.18	93.27	81	Low	-	-
8/21/1954	6/15/1957	6/15/1958	86.79	115.86	75	Low	0	0
6/15/1957	12/11/1959	12/11/1960	94.35	106.12	89	Medium	1.471	0.591
12/11/1959	7/23/1961	7/23/1962	64.22	64.03	100	Medium	-	-
7/23/1961	5/29/1963	5/29/1964	71.35	75.99	94	Medium	-	-
5/29/1963	7/20/1964	7/20/1965	40.6	47.83	85	Low	0.771	0.673
7/20/1964	11/21/1965	11/21/1966	49.23	58.20	85	Low	0.111	0.083
11/21/1965	6/2/1968	6/2/1969	116.01	101.33	114	High	-	-
6/2/1968	10/28/1971	10/28/1972	149.87	117.46	128	High	0.95	0.279
10/28/1971	6/1/1973	6/1/1974	76.26	62.56	122	High	-	-
6/1/1973	3/20/1975	3/20/1976	82.46	76.29	108	High	0.255	0.142
3/20/1975	4/12/1981	4/12/1982	253.74	250.15	101	Medium	0.302	0.050
4/12/1981	8/31/1981	8/31/1982	22.63	16.13	140	High	-	-
8/31/1981	10/7/1984	10/7/1985	130.13	130.59	100	Medium	1.361	0.438
10/7/1984	10/17/1985	10/17/1986	47.64	42.47	112	High	0.125	0.122
10/17/1985	9/30/1988	9/30/1989	116.27	122.23	95	Medium	0.712	0.241
9/30/1988	6/18/1993	6/18/1994	223.5	192.09	116	High	0.696	0.148
6/18/1993	4/6/1997	4/6/1998	166.02	158.16	105	Medium	0.1	0.026
4/6/1997	7/9/1999	7/9/2000	125.71	92.78	135	High	0	0
7/9/1999	8/3/2002	8/3/2003	139.57	127.01	110	High	0.1	0.033
8/3/2002	10/15/2004	10/15/2005	109.66	93.81	117	High	0.336	0.153
10/15/2004	8/31/2005	8/31/2006	28.79	34.21	84	Low	-	-
8/31/2005	12/31/2006	12/31/2007	54.48	57.31	95	Medium	0.338	0.253
12/31/2006	7/31/2008	7/31/2009	62.98	62.71	100	Medium	0.555	0.350
7/31/2008	12/31/2008	12/31/2009	14.86	20.06	74	Low	1.1	2.624
12/31/2008	3/31/2009	3/31/2010	5.22	8.32	63	Low	-	-
3/31/2009	4/30/2011	4/30/2012	66.5	85.15	78	Low	-	-

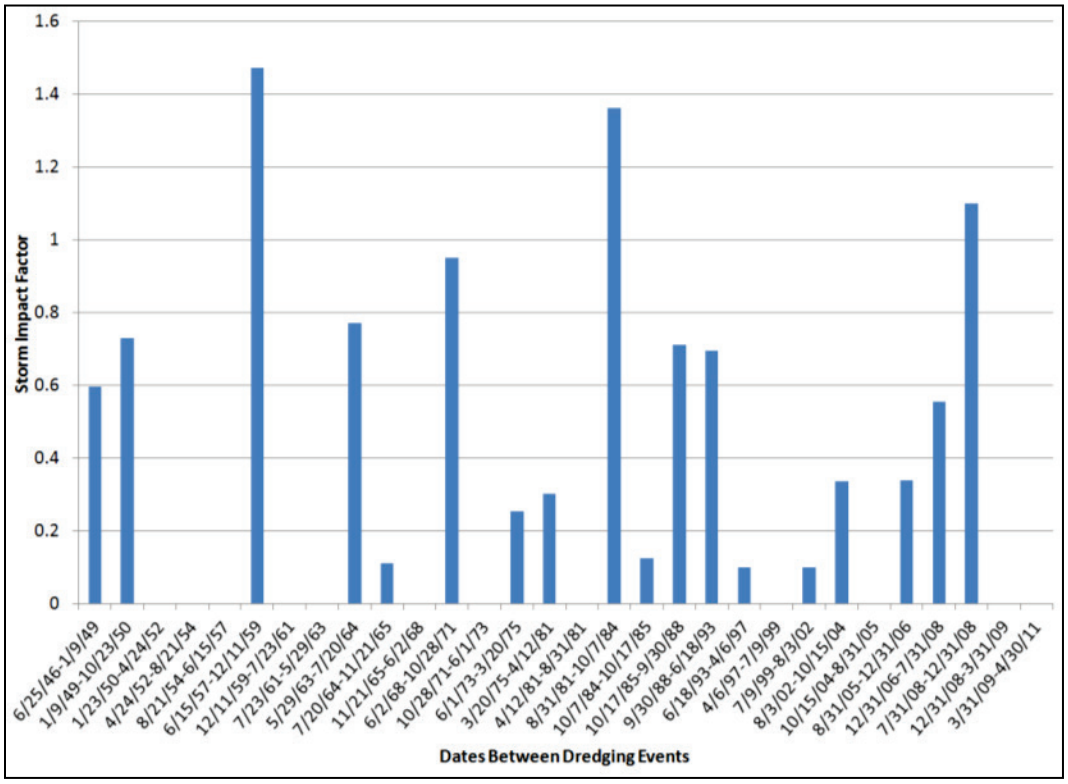
The actual rainfall compared to the average rainfall as a percentage for each period of time is shown in Figure B-3. The longest period of time in which the actual rainfall was greater than the average was between 21 November 1965 and 17 October 1985. The longest period of less than average rainfall occurred between 23 January 1950 and 21 November 1965.

Figure B-3. Actual versus average rainfall between dredging events (1 year prior), Galveston, TX.



The storm Impact Factors for the specified time periods are shown in Figure B-4. The period between 15 June 1957 and 11 December 1959 had the highest storm Impact Factor, 1.47. The weakest storm Impact Factor, 0.1, was calculated for the time periods of 18 June 1993 to 6 April 1997 and 9 July 1999 to 3 August 2002.

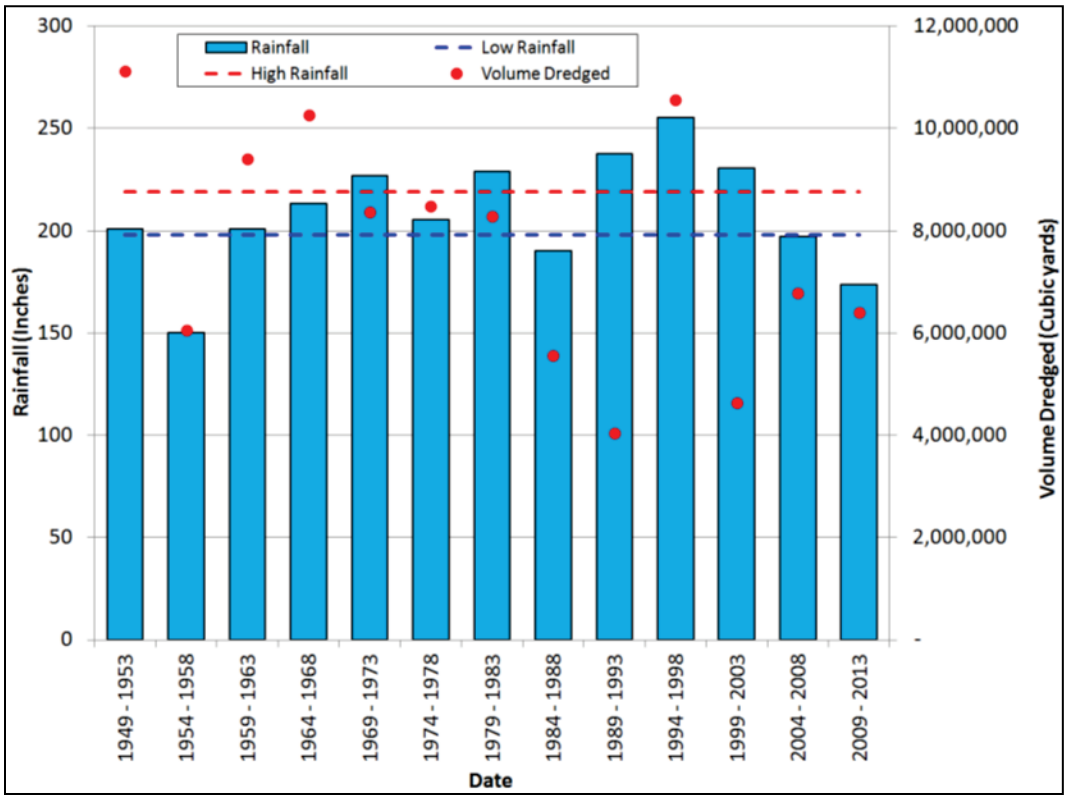
Figure B-4. Storm Impact Factors between dredging events (1 year prior), Galveston, TX.



Method 2a: Set blocks of time (5 years)

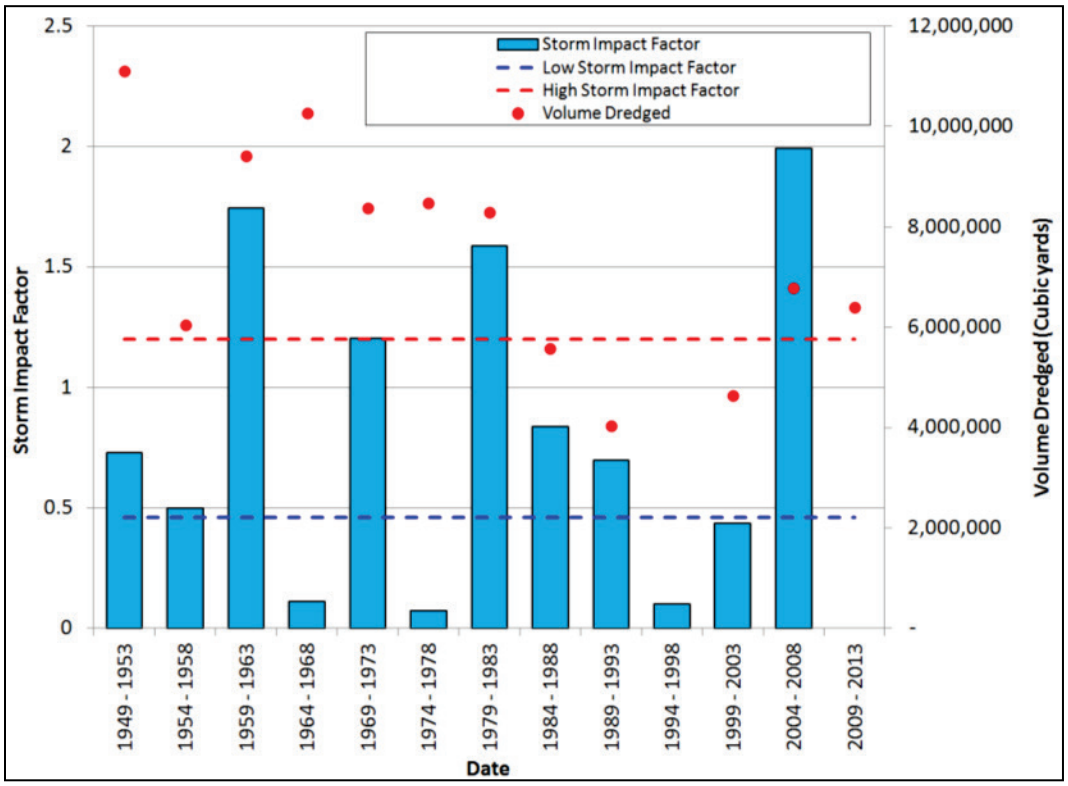
Rainfall and volume dredged are divided into thirteen 5-year time periods shown in Figure B-5. The greatest dredging took place during the 5-year time period of 1949–1953. The least amount of dredging occurred between 1989 and 1993. The wettest period of time was 1994–1998 when more than 250 in. of rain fell. The driest period of time was 1954–1958. Average precipitation for a 5-year period ranged from 198 to 219 in.

Figure B-5. Rainfall and volume dredged over 5-year intervals, Galveston, TX.



Storm Impact Factors and dredged volumes are shown for 5-year intervals in Figure B-6. All time periods except 2009–2013 experienced at least one storm event which had a storm Impact Factor greater than zero. The weakest storm Impact Factor was 0.074 for 1974–1978. The strongest storm period was 2004–2008 which had a storm Impact Factor of 1.993. There were four storms with Impact Factors during that period of time.

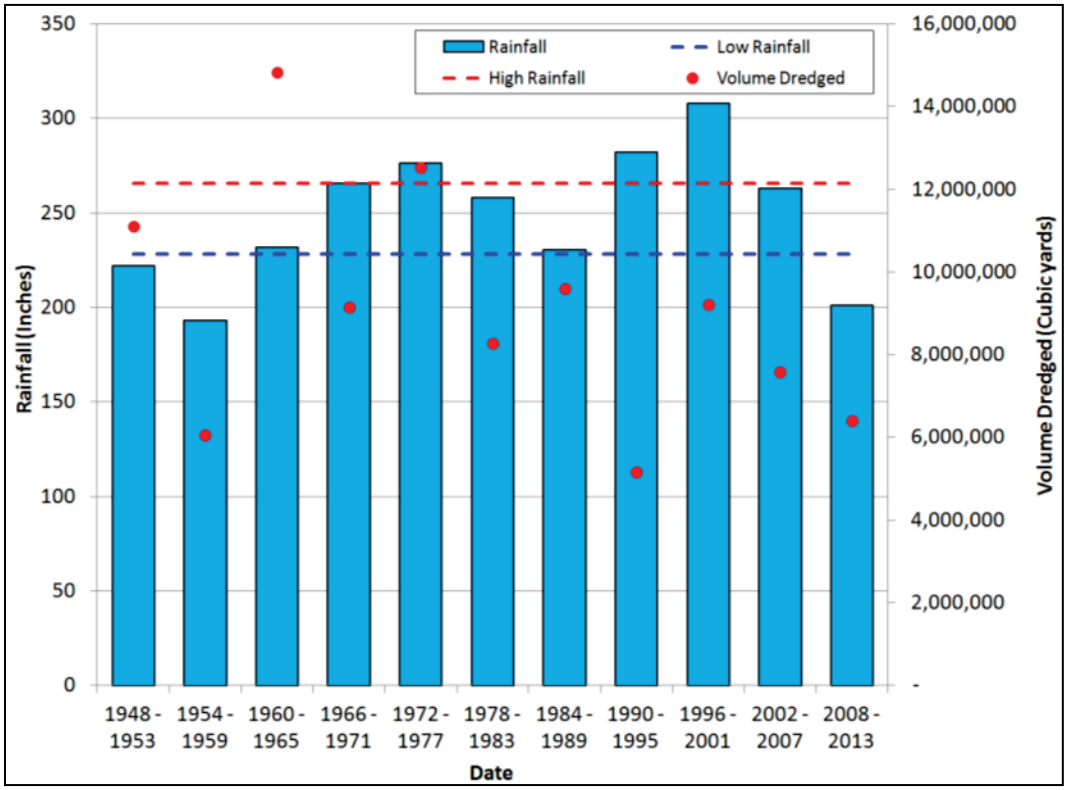
Figure B-6. Storm Impact Factor and volume dredged over 5-year intervals, Galveston, TX.



Method 2b: Set blocks of time (6 years)

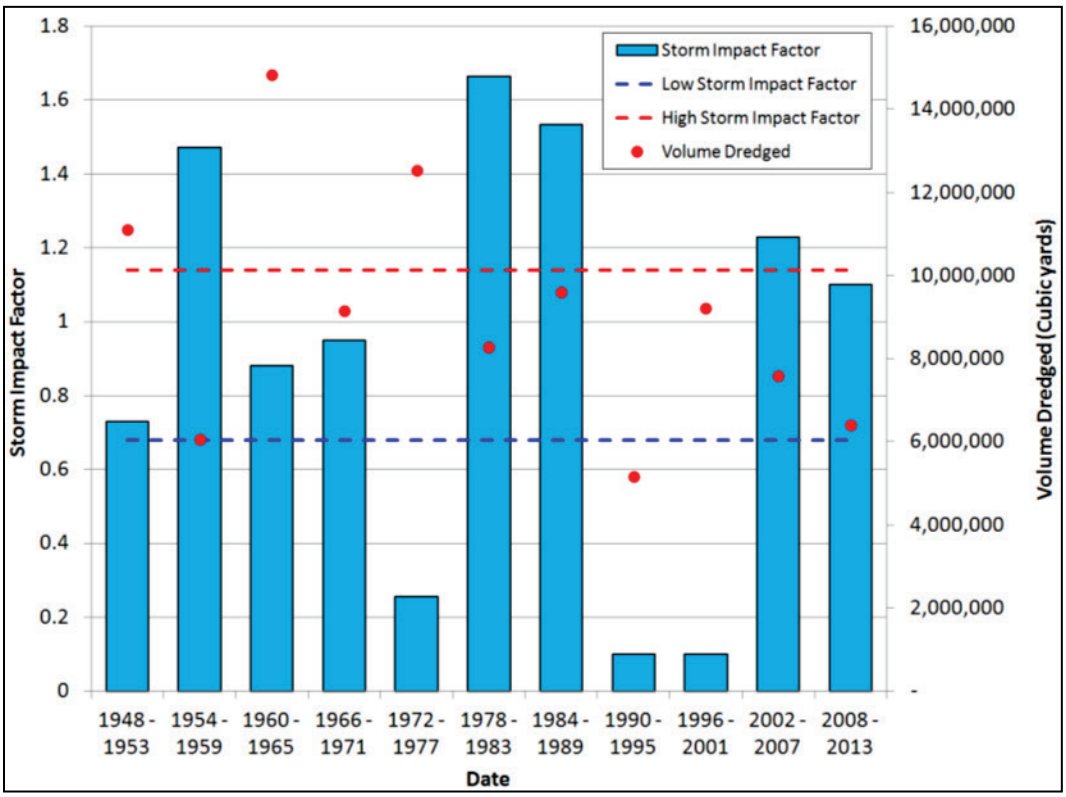
Figure B-7 shows rainfall and dredging volume over 6-year intervals. The driest 6-year time period was 1954–1959 while the wettest was 1996–2001. The time period with the greatest volume of dredging was 1960–1965. The least amount of dredging occurred between 1954 and 1959.

Figure B-7. Rainfall and volume dredged over 6-year intervals, Galveston, TX.



The storm Impact Factor and volume dredged over each 6-year interval are shown in Figure B-8. All 6-year time periods experienced at least one storm event with a measurable storm Impact Factor. The 1978–1983 time period experiences storms with the strongest Impact Factors, 1.65. Both 1990–1995 and 1996–2001 had a single storm with an Impact Factor of 0.1. The 12-year period from 1978 to 1989 was the period of the strongest storms since 1948.

Figure B-8. Storm Impact Factor and volume dredged over 6-year intervals, Galveston, TX.



Unit Conversion Factors

In this document, most units are reported as US customary units, in keeping with common usage. Some of the analyses were performed in metric units, but the results are reported in US standard units.

Multiply	By	To Obtain
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
miles (US statute)	1,609.347	meters
miles per hour	0.44704	meters per second
square feet	0.09290304	square meters
square mi	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

Acronyms and Abbreviations

FY	Fiscal Year
GIWW	Gulf Intracoastal Waterway
NOAA	National Oceanic and Atmospheric Administration
NS	Naval Station
SWG	Galveston District
USACE	US Army Corps of Engineers

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14. ABSTRACT
This study characterizes infilling responses within dredged navigation channels to rainfall from tropical storms and hurricanes. This project created a web tool based on the methods described in this report. This report discusses the different analysis methods considered to relate storm and rainfall to dredging volumes at two pilot sites, Galveston, TX, and Mayport, FL. A comprehensive storm Impact Factor for hurricanes was developed to quantify the impact at a site based on proximity, duration, and wind speed. The methods vary based on the length and timing of periods of storms and rainfall prior to a dredge event. At Galveston, TX, when 2-year dredging volume totals were compared to hurricane activity occurring in the previous 2 years, the maximum dredging volume removed was higher after higher hurricane activity when compared to low activity periods. The average amount dredged was higher following periods of high hurricane activity. At Mayport, FL, dredging volumes were compared to hurricane activity occurring since the last dredging action took place. Similarly to Galveston, TX, the maximum dredging volume removed was higher after higher hurricane activity periods when compared to low activity periods. The average amount dredged was higher following periods of high hurricane activity.

15. SUBJECT TERMS
Channels (Hydraulic engineering), Dredging, Dredging spoil, Galveston, (Tex.), Hurricanes, Mayport (Jacksonville, Fla.), Precipitation (Meteorology)

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