

THE MYSTERY OF HISTORICAL CHANNEL SHOALING AT HOUSTON-GALVESTON NAVIGATION CHANNEL, TX

JULIE DEAN ROSATI¹, ALEJANDRO SÁNCHEZ², JENNIFER N. TATE²

1. *U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 109 St. Joseph St., Mobile, AL 36628, USA.*
Julie.D.Rosati@usace.army.mil.
2. *3909 Halls Ferry Rd., Vicksburg, MS 39180, USA.*
Alejandro.Sanchez@usace.army.mil; Jennifer.N.Tate@usace.army.mil.

Abstract: Improvements to coastal-estuarine channels such as deepening and widening increase channel reliability, allow transit of larger vessels at greater speeds, and improve the local and regional economy. However, these benefits are often accompanied by an increase in the rate of channel shoaling, the need to find dredged material placement sites, and environmental concerns. Methods available to estimate the change in magnitude and location of channel shoaling are limited in accuracy because of a lack in understanding of the forcing-response processes. The Houston-Galveston Navigation Channel has a historical dataset with which to evaluate processes causing changes in navigation channel shoaling as a function of channel improvements. We evaluate 7 hypotheses to explain patterns and magnitudes of channel shoaling. Results indicate that it is likely that subsidence in the Houston-Galveston region and a period of decreased storm frequency and intensity affected the observed reduction in channel shoaling from 1948-1995.

Introduction

The first Civil Works mission of the U.S. Army Corps of Engineers (USACE) was established in 1824 to improve navigation on the Mississippi and Ohio Rivers (USACE, 2010). Today, the USACE's navigation mission maintains coastal, intracoastal, estuarine, and inland waterways for transportation, commerce, recreation, and national security. In 2009, the USACE removed 263.6 million cubic yards (Mcy)* of sediment from 12,000 miles of inland and intracoastal waterways. Of this total volume, 66.1% (174.2 Mcy) was removed for Operation & Maintenance (O&M) of the channels and the remaining was primarily New Work (NW) dredging for improving channels through deepening, widening, and lengthening (Navigation Data Center, 2010).

Channel improvements have led to increased, and at many sites, unanticipated maintenance dredging requirements. The Houston-Galveston Navigation Channel (HGNC) has more than 100 years of data on channel shoaling, covering eight different channel improvements. Although O&M dredging quantities in the USACE may be limited by available funding, over long time periods these

*Because the USACE defines navigation channels and dredging activities in U.S. Customary units, data are presented herein with these units.

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14. ABSTRACT Improvements to coastal-estuarine channels such as deepening and widening increase channel reliability, allow transit of larger vessels at greater speeds, and improve the local and regional economy. However, these benefits are often accompanied by an increase in the rate of channel shoaling, the need to find dredged material placement sites, and environmental concerns. Methods available to estimate the change in magnitude and location of channel shoaling are limited in accuracy because of a lack in understanding of the forcing-response processes. The Houston-Galveston Navigation Channel has a historical dataset with which to evaluate processes causing changes in navigation channel shoaling as a function of channel improvements. We evaluate 7 hypotheses to explain patterns and magnitudes of channel shoaling. Results indicate that it is likely that subsidence in the Houston-Galveston region and a period of decreased storm frequency and intensity affected the observed reduction in channel shoaling from 1948-1995.					
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volumes are a reasonable proxy for navigation shoaling to the authorized channel depth and width. Since 1948, data were recorded at 1,000 ft intervals along the estuarine reaches of the HGNC allowing analysis into how processes have altered shoaling patterns and magnitudes.

The most recent HGNC improvements in 1995-2000, channel deepening by 5 ft and widening by 130 ft, have resulted in channel shoaling that is much greater than anticipated given the historical data, primarily evident in the estuarine portion of the channel. The dredging history shows an increase in channel shoaling with improvements since 1904, with decreasing rates that occurred from 1948-1995, followed by unprecedented shoaling rates since improvements were completed in 2000. Herein, we review data for the estuarine reaches of the HGNC and explore the mystery of the shoaling data, both the decrease from 1948-1995 and the dramatic increase since 2000. Seven hypotheses are formulated and tested against available data.

Background and Orientation to HGNC

Since the early 1800s, vessels have transited Galveston Bay both to and from Galveston and Houston (Galveston Bay Estuary Program, 2002). Galveston Bay is a micro-tidal, diurnal, wind-dominated, lagoon-type estuary with a 1.4 ft tide range (NOAA, 2005). The earliest improvements to the navigation channel were in the early 1870s to widen and deepen the channel (Alperin, 1977). Today the HGNC extends a total of 26 miles from the 45-ft depth contour in the Gulf of Mexico to Houston. The channel traverses through Galveston Inlet, also called Bolivar Roads, which is bordered by Bolivar Island to the north and Galveston Island to the south. Two jetties approximately 6,900 ft apart were constructed in 1880-1890s to stabilize the entrance channel. The north and south jetties are 4.9 and 6.8 miles in length, respectively. The HGNC continues through the bay to Houston (Fig. 1). Since 1903, O&M dredging has been conducted to maintain authorized channel dimensions. Sediment dredged in the bay, primarily silt and clay, has been used beneficially to create and restore islands in the bay. Sand dredged offshore is placed in a Beneficial Use Berm located southwest of the channel in depths ranging from 26-47 ft relative to Mean Lower Low Water (MLLW).

History of Channel Improvements

The HGNC has been deepened and widened from the natural bay depth of 4 ft in the 1800s to the present-day 45-ft depth (relative to Mean Low Tide, MLT, a local navigation datum) and 530-ft width, as shown in Table 1. Figure 2 shows the cumulative volume of O&M dredging through time as a function of channel dimensions. The slope of a line through the cumulative volume data indicates the shoaling rate for that time period.

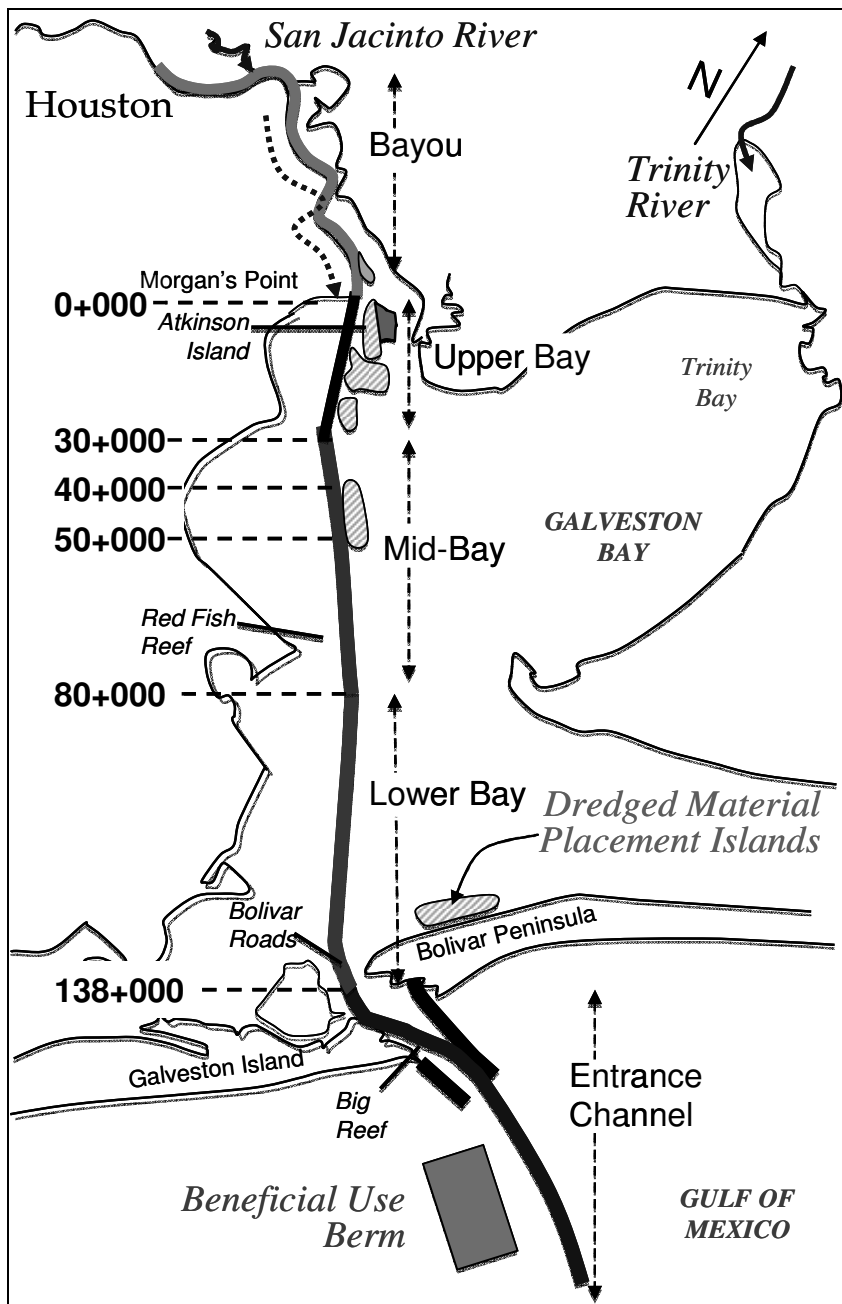


Fig. 1. HGNC location map and definition of channel reaches

Shoaling rates have increased from near zero in the early 1900s to more than 4.4 Mcy/yr from 2004-2010. For most of these data, trends are as anticipated: increasing channel dimensions resulted in greater shoaling rates. As a general rule, wider, deeper channels are more efficient at trapping sediment (e.g., Trawle, 1981; Galvin, 1982; Rosati and Kraus, 2009). However, a long-term deviation from this trend occurred at HGNC from 1948 until 1995. During this period of time, channel shoaling rates decreased from 3-3.5 Mcy/yr (1926-1948) to 1.2-1.5 Mcy/yr (1948-1995), even though the channel was deepened from 34 to 40 ft, and widened from 250 to 400 ft in the latter period. This decrease was attributed to an adjustment of the channel with the surrounding bay processes (USACE Galveston District, 1995).

Table 1. HGNC Dimensions, Average Annual Shoaling Rates, and Cumulative New Work

Date	Depth, ft MLT	Width, ft	O&M Shoaling Rate, Mcy/yr	Cumulative New Work Dredging, Mcy
1851	4	--	0	0
1870	4	70	0	0
1874	9	120	0	0.06
1889	12	100	0	3.84
1893	14	100	0	3.86
1903	18.5	150	0.51	8.17
1914	25	150	1.83	28.9
1926	30	250	3.17	46.0
1932	32	250	0.74	46.1
1935	34	250	3.51	48.2
1948	36	250	1.57	63.5
1964	40	400	1.15	81.0
2004	45	530	4.38	107.0

*Combined from data in Alperin (1977), Trawle (1981), and analysis of data provided by the U.S. Army Corps of Engineers, Galveston District.

When designing the most recent channel improvement, the USACE Galveston District calculated future shoaling and the placement area capacity required based on the historical record. Trawle's (1981) method was applied to estimate shoaling with the 1995-2000 deepening, in which a quadratic relationship was formulated based on the cumulative NW volumes and associated historical shoaling rates. Each shoaling data point was weighted according to the number of O&M dredging events for that channel dimension. The District anticipated that the trends from 1948-1995 would continue and the only increase in O&M dredging would be caused by the lengthening of the channel offshore. However, for the estuarine portion of the channel, shoaling rates were projected to *decrease* 20% because of confined dredged material practices that would reduce loss of sediment during the dredging process. The final design estimated 1.42 Mcy/yr maintenance dredging for the 45 ft by 530 ft channel (Fig. 3).

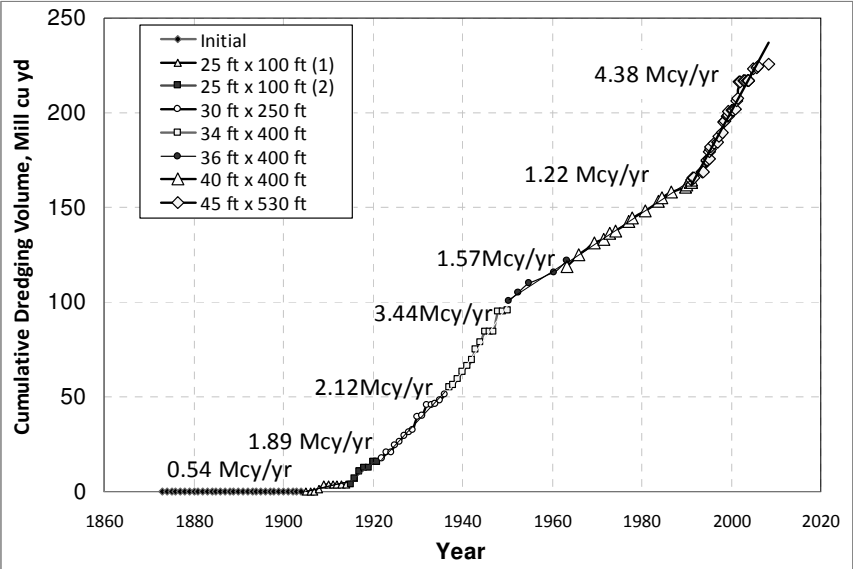


Fig. 2. Cumulative O&M dredging in HGNC through time and as a function of channel dimensions

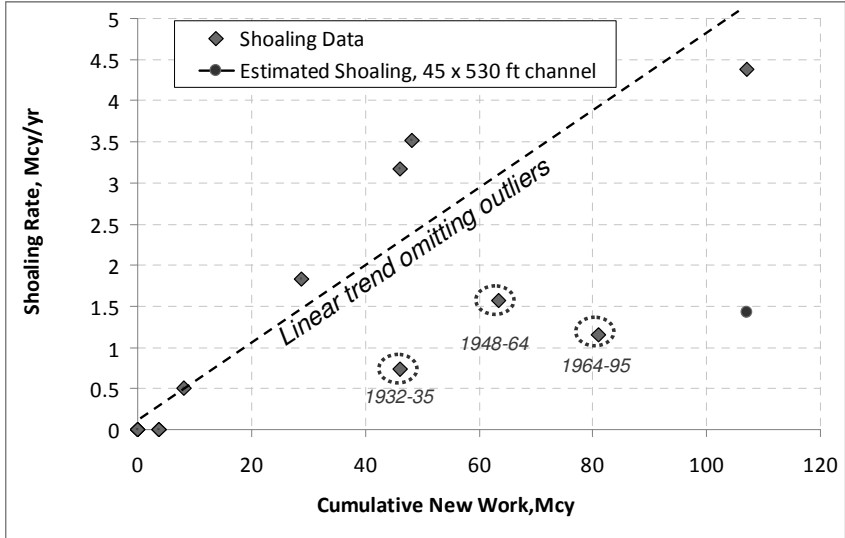


Fig. 3. Comparison of NW dredging volumes and shoaling rates for HGNC, with a linear relationship for selected data

Observed channel shoaling since completion of new work has been more than 3 times greater than estimated. If we omit data from 1948-1995, as well as the shoaling from 1932-1935 (outlier based on 3 years' data), shoaling for the most recent improvement is within a linear trend based on the earlier data. Herein, we seek to understand why the decreases occurred from 1948-1995, and what is causing the increase in shoaling since 2000.

Sediment Sources

Because of the complexity of natural processes and the number of anthropogenic activities occurring in the region, there are many possible sources of shoaling for the navigation channel that most likely have varied with time. Natural sediment sources to the bay include sand transport through Bolivar Roads; sediment from the Trinity and San Jacinto Rivers in the northeast and northwest corners of the bay, respectively; erosion of the bay shoreline and islands; and suspension of sediment in the shallow bay. Processes that suspend sediment in the bay include wind-generated waves during winter cold fronts (October through April) and tropical storms that strike the Texas coast every 1.5 years on average (Byrne, 1975). Dellapenna et al. (2003) deployed bottom-mounted tripods in Galveston Bay and measured currents and sediment concentrations during winter cold fronts. They estimated that a wind speed of 6 m/s out of the north is sufficient to generate resuspension of sediments in the bay. Based on the time wind from the north exceeded 6 m/s (13.4 miles per hour) in 2000, Dellapenna et al. estimated that 17.9 billion kg of sediment had the potential to be resuspended in Galveston Bay during this year. However, in December 2005, Tate et al. (2008) measured suspended sediment at 3-ft depth in the bay as generated by winds ranging from 11-22 miles per hour and did not find significant sediment suspension. Numerical modeling of bed shear stresses with winds from 1995-1996 confirmed the field measurements. Many variables affect wind-generated sediment suspension in shallow bays, including location of measurements, depth within the water column, wind speed, circulation, and sediment properties.

Phillips (2005) analyzed the sediment sources from rivers and shoreline change for Galveston Bay and found that these sources are not enough to account for the sedimentation rates in the bay or to provide enough sediment to keep up with relative sea level rise. Phillips concluded that a major source of sediments to the bay may be transport through Bolivar Roads (see Fig. 1), which would require a net source larger than all other sources combined. However, there are no published estimates of sediment transport rates through Bolivar Roads, and numerical modeling by Tate et al. (2006) indicated that transport potential did not supply a significant net sediment source into the bay.

Human activities have influenced processes in Galveston Bay as well as rates and patterns of channel shoaling during the past 100 years. Actions within the Galveston Bay area that may have influenced navigation channel shoaling include construction of islands using dredged sediments. After the Hurricane of 1900 that devastated Galveston and surrounding towns, the decision was made to dredge a deep-water channel to Houston. Dredged sediment was placed east of the channel, eventually forming a long island parallel to the channel, named Atkinson Island (Galveston Bay Estuary Program, 2002). In October 2002, Atkinson Island was enlarged to increase the available placement sites.

Other activities in the bay that may have altered channel shoaling include oyster dredging and shrimp trawling, which artificially suspend sediment in the bay (Dellapenna et al., 2003, 2006); construction of the Lake Livingston dam in 1968 on the Trinity River (Phillips et al., 2004); subsidence and faulting induced by subsurface groundwater and oil removal (Coplin and Galloway, 1999); and ship passage through the deep-draft channel. In addition to ship wakes which can erode shorelines and dredged material islands, vessels can resuspend sediment in the channel (Hart, 1969; Tate et al., 2006, 2008), and create bores with potential to transport sediment (Ravens and Thomas, 2008; Tate et al., 2006, 2008). Tate et al. (2006, 2008) modeled vessel movement and found that ship passage generates circulation patterns that can suspend sediment in the channel behind the vessel, and increased shear stresses in the shallow depths adjacent to the channel.

Shoaling Hypotheses

Hypotheses were developed to explain the reasons for the decrease in channel shoaling during 1948-1995 and the unprecedented present-day shoaling rate. Through understanding what has happened in the past, we can improve present-day simple methods and more complex numerical models to calculate channel shoaling. Hypotheses that could be tested with the historical shoaling data are separated into natural phenomenon and anthropogenic activities.

Hypotheses for Natural Processes:

1. Flows on Trinity and/or San Jacinto Rivers have varied through time and have modified shoaling magnitudes and patterns.
2. The magnitude and frequency of storms has varied through time, affecting the amount of shoreline erosion in the bay and sources available to shoal in the channel.

Hypotheses for Anthropogenic Activities:

3. Subsidence in the bay during 1943-1973 caused a change in channel shoaling.
4. Construction of the Lake Livingston Dam in 1968 on the Trinity River, 65 miles upstream from Galveston Bay, reduced a source of sediment to the channel.
5. Extension of Atkinson Island to the east in October 2002 (HVJ Associates, 2003) changed flow from the San Jacinto River, altering shoaling patterns and magnitudes.
6. Trawling has increased suspended sediment in bay since 1995 which shoals in the channel.
7. Vessel speed and the number of vessels have increased since deepening/widening in 1995-2000. The increased speed and number of vessels result in more ship wakes capable of eroding shorelines and entraining sediment in relatively shallow depths adjacent to the channel.

Variation in Flow on San Jacinto and Trinity Rivers (Hypotheses 1 and 4)

Mean and maximum annual river discharge data for the San Jacinto and Trinity Rivers from 1940-1988 and 1925-2010, respectively, were compared with the timing and magnitude of dredging on the HGNC. The data show that the annual mean for both rivers is dominated by individual precipitation events. Comparison with dredging magnitudes and timing indicated very poor or zero correlation with average and maximum river flow.

These data show a decrease in flow rates on the Trinity River since 1968 when the Lake Livingston Dam was constructed. Phillips et al. (2004) developed a sediment budget for the river and found that sediment trapped by the dam is offset by increased erosion downstream and other sources to the Trinity River. They conclude that the dam has not affected the supply of sediment provided to Galveston Bay. Thus, Hypotheses 1 and 4 do not hold true given the resolution of the historical data available.

Magnitude and Frequency of Storms has Varied through Time (Hypothesis 2)

Storm intensity and frequency vary on multi-year to decadal time scales (e.g., Hebert et al., 1995; Lin and Dean, 1998; Goldenberg et al., 2001). Here, we investigated the number and intensity of tropical storms and hurricanes that made a direct hit or influenced the Galveston Bay area. The purpose of the analysis was to see if storm frequency and intensity decreased during the 1948-

1995 time period, when shoaling magnitudes declined; and, similarly, if there has been an increase in the number and intensity of storms since 2000.

The cumulative number of tropical storms and hurricanes from 1871 thru 2008 (Hurricane City, 2010; Roth, 2010) was compared to the cumulative O&M shoaling rates (Fig. 4). Although these data do not include storm intensity, they do indicate a multi-decadal cycle related to the number of tropical storms and hurricanes affecting Galveston Bay. Three stormy periods were identified: from 1871 -1902 (31 years), 1932-1948 (16 years), and 1979-2008 (29 years). The periods 1903-1931 (28 years) and 1949-1978 (29 years) were relatively calm. A similar analysis with the intensity of hurricanes indicated that the 1942-1947 period was intense (two Category 1 Hurricanes; one Hurricane at Category 2) as well as 2005-2008 (2 Category 2 Hurricanes). Thus, although this analysis was qualitative, it indicates that the number of storms and the intensity of these storms decreased during the observed decrease in channel shoaling during 1948-1995, and the intensity was increased during the most recent period from 2005-2008. It is likely that storms do influence navigation channel shoaling in HGNC, although the magnitude of correlation must be quantified.

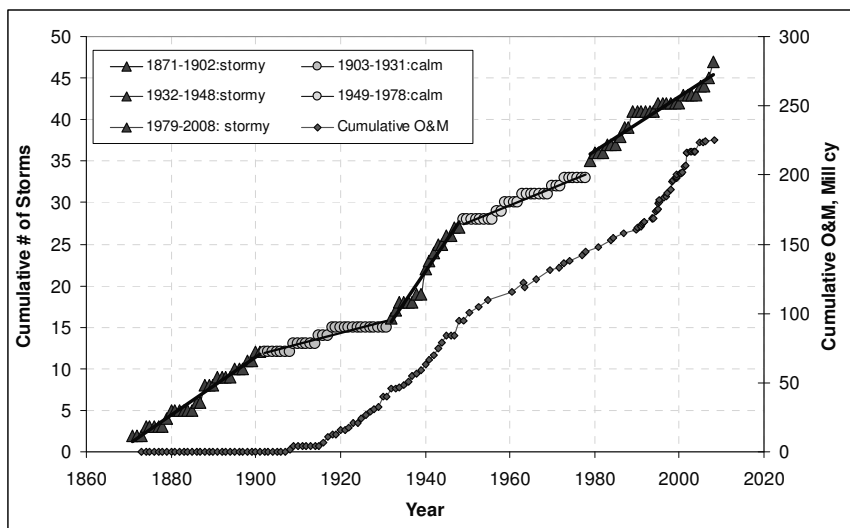


Fig. 4. Cumulative number of tropical storms and hurricanes near or making landfall in Galveston.

Subsidence in the Bay modified Channel Shoaling (Hypothesis 3)

During 1943-1973, up to 10 feet of subsidence in the Houston-Galveston region occurred because of groundwater removal and oil and gas extraction (Coplin and Galloway, 1999; Holzer, 1989; Houston-Galveston Subsidence District, 2010).

Within the HGNC, subsidence was a maximum near Morgan's Point and decreased towards Bolivar Roads (Fig. 5). Subsidence of the navigation channel would have increased the navigable depth, reducing the dredging requirement. However, calculation of the increased volume within the channel over this 30-year period resulted in only 120,700 cu yd/yr additional capacity, and the decrease from pre-1948 to post-1948 rates was of the order 1.5-2 Mcy/year (see Fig. 3). It is concluded that Hypothesis 3 is a potential contributor to the decrease in channel shoaling that was observed from 1948-1995, but is not sufficient to explain the magnitude.

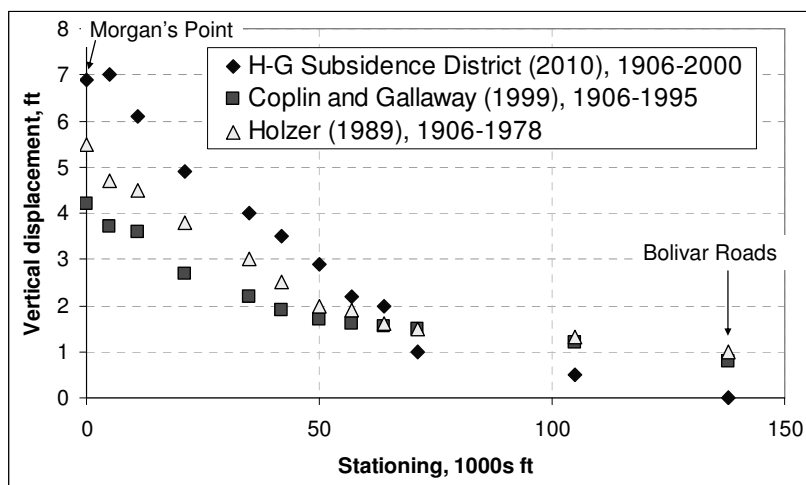


Fig. 5. Subsidence in HGNC by channel stationing from Morgan's Point to Bolivar Roads.

Extension of Atkinson Island modified shoaling (Hypothesis 5)

Historical shoaling data are not available to evaluate this hypothesis, because the extension of Atkinson Island (October 2002) and channel improvements (1995-2005) occurred during the same period. We are evaluating this hypothesis with numerical modeling and field data collection in 2011.

Trawling has increased in the bay since 1995 (Hypothesis 6)

Data from the Houston Advanced Research Center (2010) for brown, white, and pink shrimp caught per hour for Trinity, Galveston, and East Bays from 1982 through 2009 were evaluated as a proxy for the magnitude of trawling in the bay through this period. The assumption in this analysis was that an increase in the number of shrimp caught per hour related directly to the amount of trawling in

the bay. Shrimp trawls are dragged along the bay bottom behind a vessel at 3 miles per hour for a ten minute period, catching species that inhabit the bay seabed and stirring bay sediment. Results from the analysis indicated only a slight increase in the number of shrimp caught during this 27-year period (increase of 2 shrimp/hour/year) with weak correlation coefficient ($R^2=0.022$). This hypothesis is dismissed as a reason for the increased channel shoaling.

Vessel speed and number have increased since 1995(Hypothesis 7)

Vessel transit and tonnage data from the USACE's Annual Reports (USACE, 1944 through 2002) were evaluated with respect to channel improvements (Fig. 6). Some of the vessel transit data do not support the tonnage values (e.g., 1993-1998) and will be investigated further; here we will focus on the tonnage data as a proxy for vessel size and number. The tonnage data indicate a steady increase in tonnage of 1.5 Mill tons/year from 1948-1963, which increased to 2.6 Mill tons/year in 1964-1994. Channel improvements in 1964 facilitated larger shipments, and slightly increased the number of vessel transits from 60,000-70,000 per year to up to 90,000 transits/year. Since channel improvements began in 1995, tonnage has increased by 6.4 Mill tons/year. If we assume that tonnage data are a proxy for vessel speed and number, then Hypothesis 7 is supported by data from 1995 to 2002. However, we note that tonnage increased annually from 1948-1995 but shoaling decreased in this period. Historical vessel speed data are not readily available. We conclude that Hypothesis 7 cannot be supported on vessel tonnage data alone and needs further investigation.

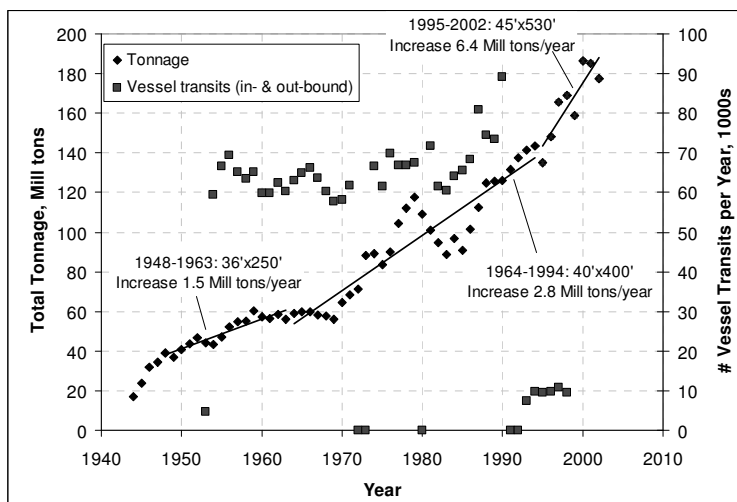


Fig. 6. Tonnage and number of vessel transits by year for HGNC

Conclusions

Historical shoaling data for the Houston-Galveston Navigation Channel were analyzed as part of a comprehensive study to understand reasons for changes in shoaling through time, make recommendations for reducing present-day quantities and cost, and develop guidance for USACE shoaling studies. Seven hypotheses were evaluated as reasons for a decrease in channel shoaling from 1948-1995, and the increase in shoaling that has occurred since deepening and widening in 1995. Preliminary conclusions based on the historical analysis are:

- A period of lower storm intensity and frequency as well as subsidence in the Houston-Galveston area likely contributed to a reduction in HGNC channel shoaling from 1948-1995, although analysis herein is not sufficient to explain the entire magnitude of the observed decrease.
- River flow, construction of a dam on the Trinity River, and shrimp trawling in the bay do not appear to influence channel shoaling magnitudes.
- Historical data were not sufficient to evaluate two hypotheses. The influence of the extension of Atkinson Island to the east in 2002, and vessel number, draft, and speed. Vessel tonnage has increased through time, resulting in conflicting trends with historical shoaling. Numerical modeling and field data collection are underway to evaluate these hypotheses.
- Channel shoaling from 2002-2010 agrees with a linear trend based on data from the 1900s, if anomalies in 1932-35, 1948-64, and 1964-95 are dismissed.

The characterization that channel shoaling with the present channel dimensions is greater than the historical trend may not be accurate; it is more likely that shoaling during the period of subsidence and low storm activity is the anomaly in the historical record. Field data and numerical modeling are planned to further test hypotheses and continue to unravel the mystery of channel shoaling at HGNC.

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