Case Study

Navigation Channel Effects on Estuarine Mean Water Level

William H. McAnally, F.ASCE[1]; and Ellie R. Welp, M.ASCE[2]

Abstract: The traditional conceptual model of freshwater-dominated estuarine hydrodynamics states that long-term average within-estuary water level is elevated over long-term average sea level at the sea inlet(s) in order to push freshwater inflows seaward. At low freshwater inflows, other factors, including nonlinear tidal propagation, can cause either setup or setdown in the average estuary water level. The Cumberland Sound estuary straddles the Georgia–Florida state line. Deepening and widening of the Cumberland Sound entrance and interior channels from 1984 through 1988 increased channel dimensions by 25%–66%. A weight of evidence approach considering analytic, physical, and numerical models' results, plus statistical analysis of observed MTL from 1953 through 2019 leads to the conclusion that the channel enlargements reduced a pre-existing Fernandina Beach MTL setdown of up to 0.02–0.05 m. **DOI: 10.1061/(ASCE)WW.1943-5460.0000698**. *© 2021 American Society of Civil Engineers*.

Introduction

The traditional conceptual model of freshwater-dominated estuarine hydrodynamics assumes that long-term average within-estuary water level is elevated over long-term average sea level at the sea inlet(s) in order to push freshwater inflows seaward (e.g., Sassi and Hoitink 2013). The stipulation of longer-term (on the order of years) averages eliminates most wind and wave-induced sets to water level, which vary on the order of days to months. The amount of estuarine setup required to push freshwater flows to the sea varies with the volumetric freshwater flow rate and inversely with size of the inlet(s) connecting an estuary to the sea. For small freshwater inflows, other factors, including nonlinear tidal propagation, can cause either setup or setdown in a bay's mean water level (e.g., Walton 2002).

This paper's purpose is to determine if navigation channel enlargement induced a water-level rise in Cumberland Sound, which straddles the Georgia–Florida state line. The question is significant if induced water-level changes affect sedimentation, marsh and inland flooding, and salinity intrusion. For example, Winterwerp et al. (2013) demonstrated that deepening and narrowing the Ems and Loire estuaries increased hydrodynamic drag and tipped the systems into hyperturbid conditions with substantial environmental consequences.

Previous studies (Granat and Brogdon 1990; McAnally and Granat 1991; Kraus et al. 1997) examined the question of water-level rise in Cumberland Sound because of navigation channel enlargement. Those three separate studies demonstrated the importance of the question but reached differing conclusions. The accumulation of an additional 30 years of observed water-level data now makes possible a resolution of the question.

This article describes the physical setting of the area and summarizes the results of prior analyses using analytical solutions, a physical model, a numerical model, and observed data analyses. It then presents an updated analysis of observed data and draws conclusions based on the weight of evidence approach.

Cumberland Sound and Kings Bay

Cumberland Sound is an estuary near the Georgia–Florida state line with extensive marshes and flats penetrated by numerous channels, as shown in Fig. 1. Kings Bay, a small embayment within Cumberland Sound, is home to a navy submarine base. At the south end of Cumberland Sound, the Amelia River extends toward the Nassau Sound but becomes so narrow that it is effectively closed to tidal exchange (personal observation). At the north end of the Sound, the Cumberland River connects to St. Andrew Sound, with some tidal exchange. A tidal node point is located in northern Cumberland Sound. Granat et al. (1989) provide a detailed description of the system.

Two main rivers, St. Mary's and Crooked Rivers, and the local drainage basin supply the sound with a combined mean freshwater flow of less than 60 $\mathrm{m^3 \cdot s^{-1}}$. Mean tide range at the entrance is 1.8 m. The sound is usually well mixed, with salinity varying during the year from a low of about 26 psu to a high of about 32 psu. St. Mary's inlet was about 1,600-m wide and 3.6-m deep in 1856. Between 1881 and 1887, north and south jetties were built and subsequently extended or raised several times until 1905, at which time the channel was 5.8 m deep (USACE 1986). The present inlet width is about 900 m.

Dredging of navigation channels in Cumberland Sound has occurred in stages over several decades. A 7.9-m-deep (referred to mean low water, mlw) channel was dredged to Fernandina Beach in the 1920s and deepened to 8.5 m in 1940. Dredging of the 3.6 m by 27-m Atlantic Intracoastal Waterway (AIWW) was completed through the sound in 1941. In 1955–1956, the channels through Cumberland Sound and in Kings Bay were enlarged to an average depth of 9.8 m. Maintenance was irregular and dredging records for that channel are sparse, but sedimentation during the period required substantial maintenance in 1967–1970 and 1973–1976. During 1978–1979, major channel realignment and some enlargement were performed to permit Poseidon submarines to use the base. After 1979, facility depths ranged from 10 to 12 m and channel widths ranged from 90 to 120 m over a 11-km reach from the entrance to Kings Bay. Facility enlargement for Trident submarines began in 1982 and channel enlargement dredging was performed

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[1] Engineer, Dynamic Solutions, LLC, Knoxville, TN 37919; Research Professor Emeritus, Geosystems Research Institute, Mississippi State Univ., 2 Research Blvd., Starkville, MS 39759 (corresponding author). Email: whmcanally@dsllc.com

[2] Engineer, McAnally and Associates, 96 Willow Point Rd., Columbus, MS 39705. Email: welp.ellie@gmail.com

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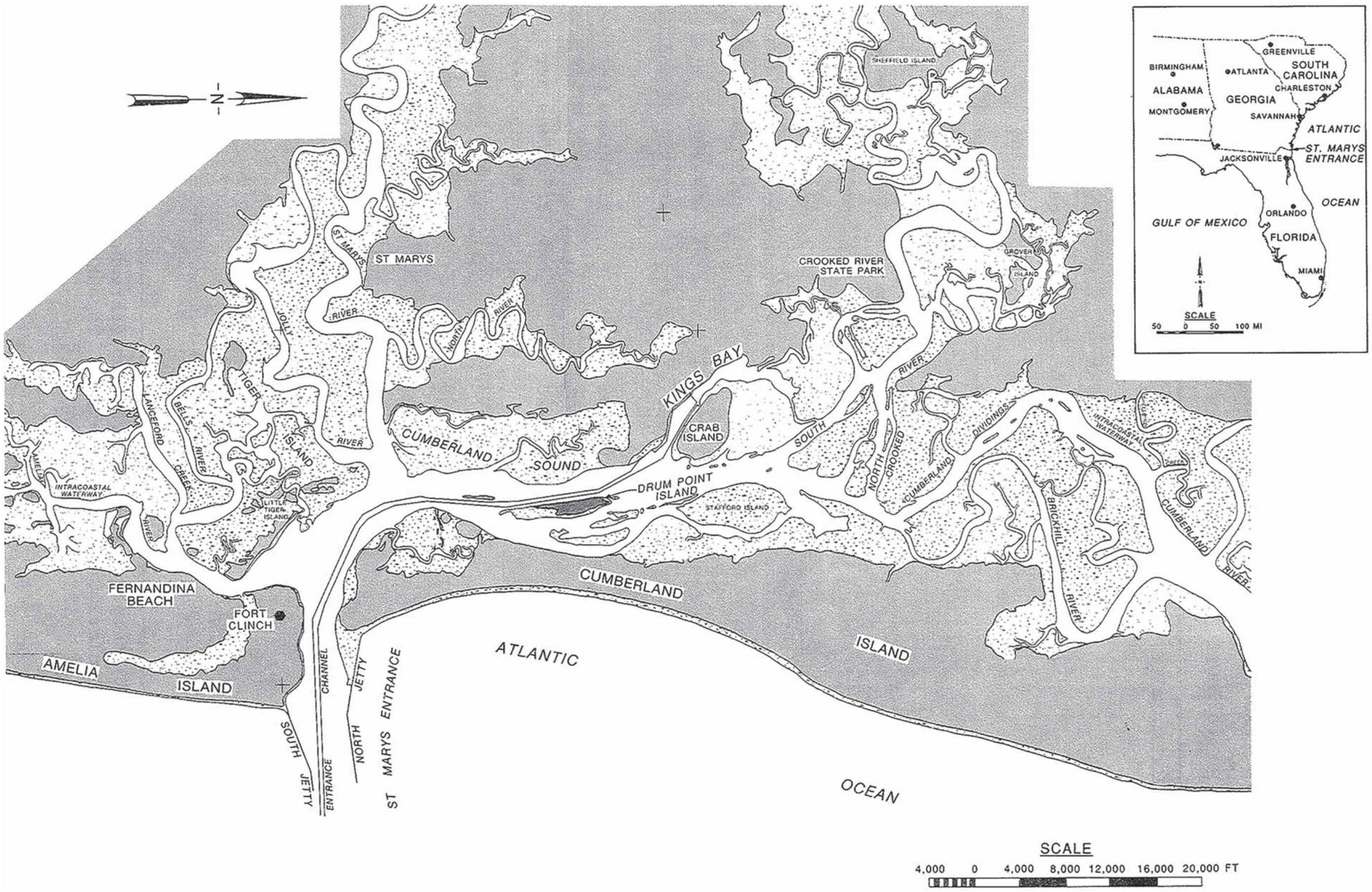

Fig. 1. Cumberland sound location map and model limits. (Reprinted from Granat et al. 1989.)

from 1984 through 1988, with depths increased to 14–15 m (25%–40% increase) and channel widths increased to 150 m (25%–66%). Kings Bay itself was enlarged considerably, with shallows at the north end widened and deepened to 15 m over a length of about 1,600 m. The entrance channel was dredged during the period June 1987–June 1988. Interior channels were dredged from 1984 to July 1988, with a turning basin completed in October 1988. These latter channel enlargements had a relatively small effect on cross-sectional area of the inlet (McAnally and Granat 1991).

These successive channel enlargements are displayed along with dredged volumes by year in Fig. 2. Shading denotes channel enlargement dredging periods. Letters and vertical lines in the figure represent channel conditions by period:

A. 8.5-m-deep channel ocean to Fernandina Beach.
B. 9.8-m-deep channel ocean to Kings Bay.
C. 10–12-m-deep × 90–120-m-wide channel ocean to Kings Bay.
D. Active dredging of entrance and sound channels.
E. 14–15-m-deep × 150-m-wide channel ocean to Kings Bay.
F. Analytic models of setup/setdown.

Keulegan (1967) developed an analytical solution for tides in a bay connected to the sea. It assumed vertical walls, no freshwater inflow, a sinusoidal sea tide, and a rectangular inlet connecting the embayment to the sea. It produced a solution in which mean water level inside the embayment was equal to that in the sea. Several others (e.g., Escoffier and Walton 1979) extended Keulegan's model to more complex situations, but still did not allow for tidal setup/setdown in the bay.

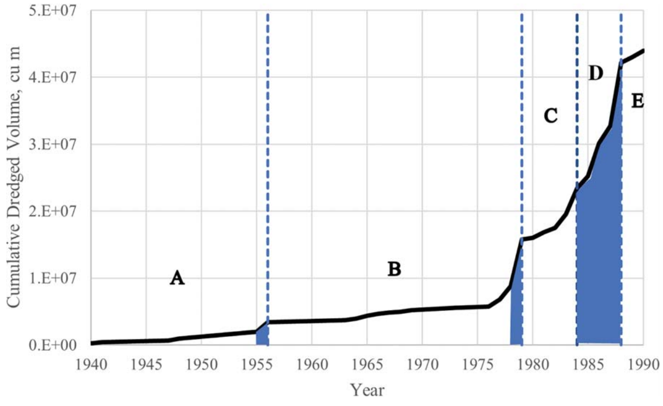

Fig. 2. Cumulative dredged volume for St. Mary's Entrance and Cumberland Sound with channel enlargement status and periods. Section labels indicate: (A) 8.5-m-deep channel ocean to Fernandina Beach; (B) 9.8-m-deep channel ocean to Kings Bay; (C) 10–12-m-deep × 90–120-m-wide channel ocean to Kings Bay; (D) active dredging of entrance and sound channels; and (E) 14–15-m-deep × 150-m-wide channel ocean to Kings Bay.

King (1974) extended Keulegan's approach with a solution of the equations for mass and momentum conservation, relaxing Keulegan's assumptions to allow for a linear slope of the basin and inlet sides between high and low water levels. Solving the resulting equations numerically, he showed that for large plan area differences in the bay between high and low water (i.e., mild side-slopes), a setdown in mean water level occurred in the bay relative to the sea. McAnally and Granat (1991) found that King's model predicted a setdown of 0.03 m in Cumberland Sound; however, the change in areas (due to expanding Kings Bay in dredging event E above) between pre-enlargement and post enlargement amounted to only a 5% decrease in that setdown.

Dilorenzo (1986) employed a harmonic solution to the bay-inlet-sea problem and found that either setup or setdown could be produced, depending on phasing of the fundamental harmonic tide component (e.g., lunar semidiurnal, M2) and its first overtide component (e.g., shallow water lunar quarter-diurnal, M4) between the sea and the bay. McAnally and Granat (1991) reported that NOAA's calculated tidal constituents for Fernandina Beach showed the M_2 constituent's phase remained at nearly constant between 1937 and 1987, varying between 229° and 233°. The M_4 constituent's phase declined over that period from 245°. in 1937 to 230° in 1987, putting it in phase with the M_2 constituent. The two constituents' phases have since separated to 16° (NOAA 2020a), approximately the same as the 1937 phasing. McAnally and Granat (1991) applied DiLorenzo's (1986) solutions to the Kings Bay preconstruction conditions and predicted a Cumberland Sound setdown of 0.03 m, the same as King's model.

Walton (2002) followed DiLorenzo's approach with a detailed assessment of setup/setdown under varying bay-inlet areas, energy losses, and sea tide range. He found that, depending on interactions among those characteristics, the maximum probable setdown or setup due to harmonics was about 8% of the principle tidal constituent in the sea. For Cumberland Sound, that translates to 0.07 m [M_2 component of 0.89 m at Fernandina (NOAA 2020a)], confirming the reasonableness of the 0.03 m value described previously.

Prior Work

A physical (scale) model of the Cumberland Sound system, including Kings Bay, was reported by Granat et al. (1989) to be a distorted-scale fixed-bed model reproducing approximately 206 mi^2 (534 km^2) of southeast Georgia and northeast Florida, and about 220 mi^2 (570 km^2) of the adjacent Atlantic Ocean (Fig. 1). Constructed to linear scale ratios, model to prototype, of 1:100 vertically and 1:1,000 horizontally, the vertical scale in the physical model was stretched 10 times relative to the horizontal scale, a typical distortion for estuarine physical models. Salinity was maintained at a 1:1 ratio. The vertical and horizontal scales dictated the other scaling factors (time, velocity, and discharge) based on Froudian relations.

Granat et al. (1989) reported validation of the model to two field observation data sets by concluding, "Agreement between model and prototype phenomena, as evidenced by the comparison of model and prototype tide, current velocity, and salinity data, has been demonstrated. The model is considered to be sufficiently similar to its prototype to be used confidently in assessing three-dimensional (lateral, longitudinal, and vertical) effects of proposed plans on hydrodynamic processes." Model uncertainty bounds were not reported. Fig. 3 shows an example plot of tidal elevation validation at Fernandina Beach. It suggests that the model high and low waters at that location reproduced field observations within 0.03 m, with a somewhat steeper rise to, and fall from, high water.

Granat et al. (1989) described the numerical hydrodynamic model RMA-2 and its application to Cumberland Sound. The depth-integrated model mesh contained 2,382 nodes with resolution varying from about 30 to 1,800 m and included wetting and drying of marshes. Upstream boundary conditions were specified as average freshwater flows. Downstream boundary conditions consisted of water levels as measured in the physical model. They reported that the numerical model demonstrated agreement with the previously described physical model main channel tidal elevations plus ebb and flood velocity phase and magnitude. Numerical model high- and low water elevations at Fernandina Beach were essentially identical to those of the physical model.

Granat and Brogdon (1990) employed the previously described physical and numerical models to test changes between the pre-enlargement (1983) and post-enlargement (1989) channel conditions in Cumberland Sound-St. Mary's Inlet. Through base-to-plan model comparisons, they concluded that the channel enlargements of 1984–1988 might cause Fernandina Beach mean tide level (elevation halfway between high and low tide, denoted by MTL and also called mid-tide level) to increase by 0.03–0.06 m through almost equal increases in high and low water elevations. Fig. 4 shows an example plot of the tide elevation changes at Fernandina Beach. Both high and low water elevations are seen to increase and high water arrives about 30 min in advance in the plan (post-channel enlargement).

McAnally and Granat (1991) employed King's (1974) model to calculate a resulting MTL setdown of 0.03 m for the Cumberland Sound system based on the existing planform area. They also reexamined Granat and Brogdon's (1990) model data and refined the original conclusions. They noted that the as-built channel enlargements were somewhat different from the plans tested and estimated model errors in high and low water elevations at ±0.03 m. They reported that the models showed a pre-enlargement setdown of up to 0.06 m in Cumberland Sound MTL which might have been *relaxed*, or removed, by enlargement of the model channels.

McAnally and Granat (1991) also analyzed the relationship among mean water levels in Cumberland Sound, Mayport Naval Station to the south, and Savannah River to the north. A strong correlation was identified, and the relative rise in Cumberland Sound was slightly larger than the other two locations. They concluded that "Mean water level in Cumberland Sound may increase by a

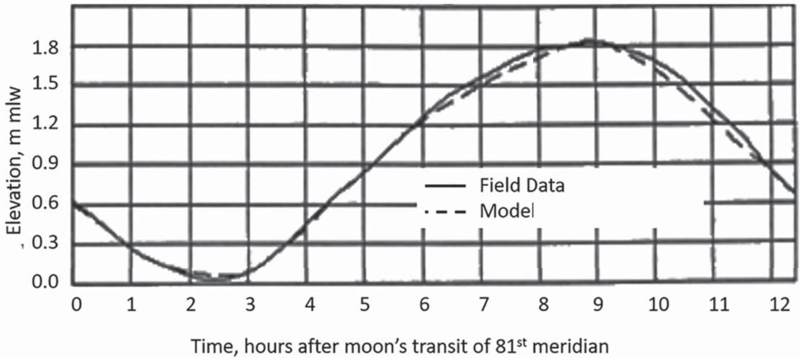

Fig. 3. Physical model tidal validation at Fernandina Beach. (Modified from Granat et al. 1989.)

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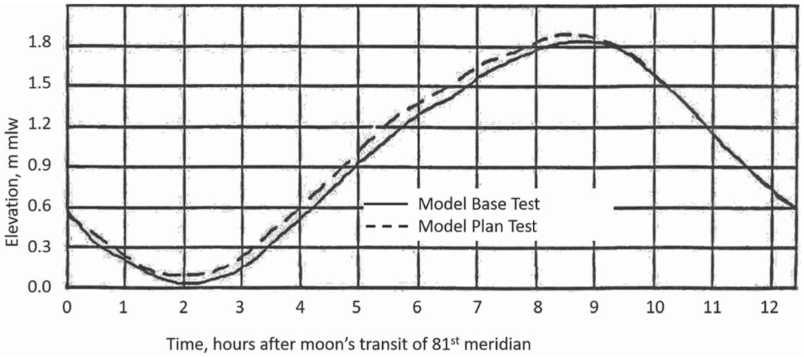

Fig. 4. Fernandina Beach tidal elevation physical model results for base and plan. (Modified from Granat and Brogdon 1990.)

small amount," and that a period of observed tide data longer than 1989–1991 was required to corroborate or refute the setdown and subsequent relaxation predicted by the models.

Despite McAnally and Granat's (1991) conclusion that the post-construction time period was too short, Kraus et al. (1997) analyzed observed tide data for two periods—1935 through 1985 and 1986 through 1992, splitting the construction period. After detrending the data, they compared MTL before and after 1986 with a correlated Student's *t*-test and reported that the 1935–1985 MTL was not statistically significantly different from the 1986–1992 MTL to a 99% degree of confidence. Although they cited the model studies of Granat et al. (1989), Kraus et al. did not mention the physical and numerical model results in their report, nor did they explain why they used time periods during which channel enlargement dredging was occurring instead of before and after enlargement.

Water Levels in Cumberland Sound

Monthly average MTL data for years 1953–2019 were downloaded from the National Oceanic and Atmospheric Administration's website (NOAA 2020a). MTL was chosen because the prior studies used that measure. The time period was selected to capture equal 31-year-long intervals before and after channel enlargement. NOAA published the data with precision to the nearest 0.001 m and NOAA (2020b) reports with an accuracy of ±0.005 m for those data. Fig. 5 displays the downloaded data, referenced to the local mean sea level (MSL) datum plane. The data had 16 monthly data gaps, primarily in 1995 and 1996. Over the period shown, MTL shows a distinct upward trend of 0.0028 m/year, which can be mainly attributed to relative sea-level rise (RSLR). For 1897 through 2019, NOAA estimated RSLR at 0.0021 m/year^{-1} with 95% confidence limits of $\pm 0.00018\ \text{m/year}^{-1}$ (NOAA 2020c).

Variability in the monthly MTL caused by rainfall runoff, storms, and seasonal variation makes visual inspection of Fig. 5 difficult, so a 5-year-block average is shown in Fig. 6 to better illustrate the trends. The 5-year-long channels enlargement period is depicted by gray shading. Visual inspection of Fig. 6 suggests a step increase in MTL occurred in the late 1960s, corresponding to substantial maintenance dredging of existing channels, and again in 1984–1988, corresponding to the channel enlargement examined in prior model studies previously described ; however, confirming or refuting prior studies' findings requires the following more rigorous examination of observed MTL.

Because the purpose of analyzing observed MTL data is to determine if water levels at Fernandina did or did not rise in the years after channel enlargement, a standard whole-record trend removal

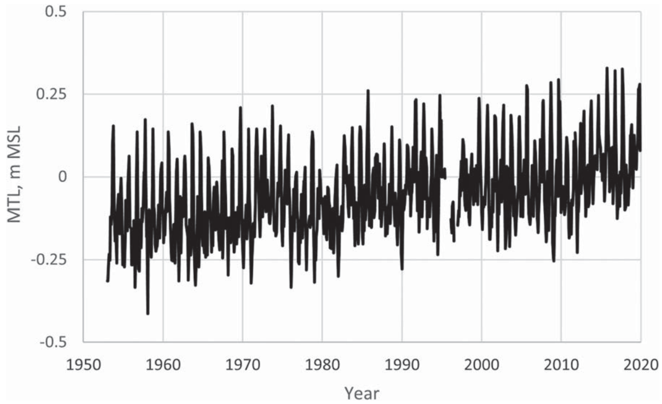

Fig. 5. Fernandina Beach monthly mean tide levels.

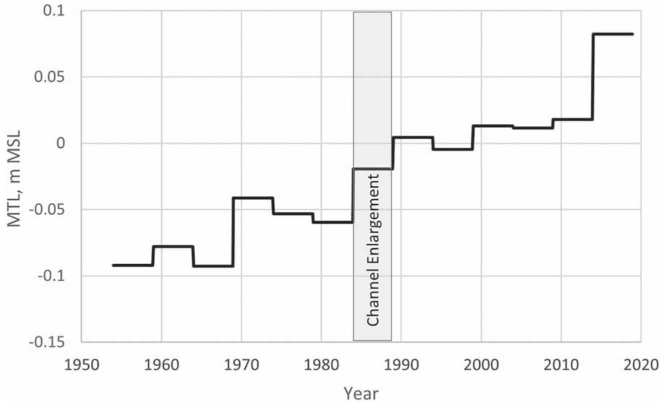

Fig. 6. Fernandina Beach monthly mean tide levels averaged over 5-year periods.

can be expected to be counterproductive, because enlargement-induced rise in MTL will contribute to the trend. Removing the overall trend from the data record may also remove any induced change. For that reason, a variety of data analyses described subsequently were performed to identify any change that is not part of the relative sea level rise experienced at the site.

Relative sea level rise (RSLR) at Fernandina Beach was estimated by means of a Corps of Engineers calculator (USACE 2020). The calculator is site-specific, using NOAA data for water level and ground motion. The calculator provides estimates for high, low, and intermediate rates of RSLR with a base year of 1992. Fig. 7 shows the high estimate RSLR against the observed

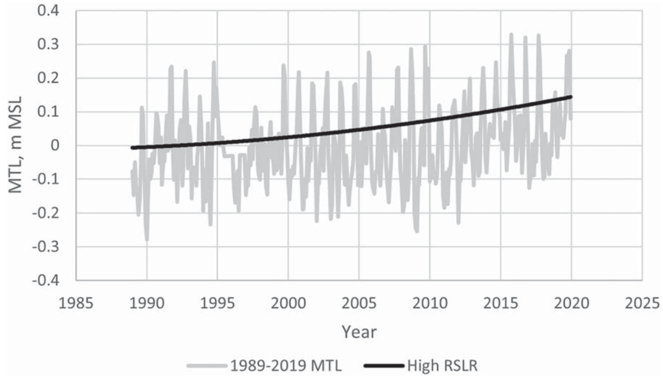

Fig. 7. Fernandina Beach monthly MTL and USACE high RSLR estimate.

MTL, with the RSLR matched to the observed 1992 MTL value such that the curves are comparable.

The MTL data were split into two 31-year long sets—1953 through 1983 and 1989 through 2019, with the five active channel enlargement years of 1984–1988 separating them. Table 1 lists properties of the raw, trend-removed, gap-filled, and RSLR-corrected data sets.

The Kolmogorov–Smirnov normality test statistics for Data sets A and B were 0.06 and 0.07, respectively, indicating that their data distributions approximated a normal distribution. A Pearson's correlation coefficient of 0.62 indicated a degree of correlation between the two data sets, which is to be expected, because they match month for month and share seasonal variations. The data sets' normal distributions and essentially equal variances allow application of Student's *t*-test for correlated data sets.

Student's *t*-test for correlated data sets produced results shown in Table 2. [The large number of data points (356 or 372 in each set) resulted in very similar outcomes under the assumption of noncorrelated data sets.] The critical *T*-statistic (with at least 358 degrees of freedom) for a positive MTL changes with 99.9% confidence was 3.1; thus, *T*-statistic values greater than 3.1 indicate a high probability that MTL at Fernandina Beach rose in the post enlargement period.

Test A versus B, with a *T*-statistic of 19 confirms that the post-enlargement period MTL increased over the pre-enlargement value, as would be expected from known RSLR and inspection of Figs. 5 and 6. Test C versus D, with a *T*-statistic of 4.7, shows that removing the 1953–1983 linear trend from both data sets produces data sets with a high probability of an increase of about 0.02 m. Test C versus E demonstrates that filling data gaps makes little difference in the probability results, but raises the estimated increase to 0.03 m. Test F versus G, in which the trend for the entire analysis period is removed from both data sets, does not support an MTL increase, with a *T*-statistic of 0.3 and a probability of only 61% for an estimated 0.002-m rise, less than the estimated error in the original data. Test A versus H, on the contrary, suggests that estimated RSLR does not explain an MTL increase. With an estimated post-enlargement MTL increase of 0.05 m and a *T*-statistic of 9.1, a high estimate of RSLR explains only about half the observed increase in MTL. Lower estimates suggested by the Corps' calculator will explain even less of the observed MTL rise.

Freshwater Inflows

Freshwater inflows to Cumberland Sound, while small, might influence water levels there, so those were examined also.

Table 1. Fernandina MTL data sets

Set label	Years	Adjustments	Number of points	Mean[a] (m)	Variance (m^2)
A	1953–1983	None	372	−0.1058	0.013
B	1989–2019	None	356	−0.0029	0.014
C	1953–1983	1953–1983 trend removed	372	−0.0002	0.012
D	1989–2019	1953–1983 trend removed	356	0.0260	0.013
E	1989–2019	Gaps filled, 1953–1983 trend removed	372	0.0265	0.013
F	1953–1983	1953–2019 trend removed	372	−0.0004	0.012
G	1989–2019	Gaps filled, 1953–2019 trend removed	372	0.0012	0.013
H	1989–2019	Gaps filled, high SLR removed	372	−0.0551	0.013

[a] Additional significant digits shown to illustrate small differences. Mean elevation referred to local MSL.

Table 2. Statistical test comparisons of data sets

Combination	Difference in mean (m)	*T*-statistic	Probability of increase (%)
A versus B	0.10 ± 0.01	19	>99.9
C versus D	0.02 ± 0.01	4.7	99.9
C versus E	0.03 ± 0.01	5.0	99.9
F versus G	0.002 ± 0.01	0.3	61
A versus H	0.05 ± 0.01	9.1	>99.9

The numerical and physical model experiments of Granat et al. (1989) and Granat and Brogdon (1990) used a constant freshwater flow and provided results essentially similar to the above water-level analyses. St. Marys and Crooked River discharge data for the period of water-level analyses were too limited for analysis, so Fernandina Beach precipitation data (Florida Climate Center 2020) for the two 31-year periods were examined instead. A two-sample *z*-test showed that the pre-deepening period and post-deepening periods had the same mean precipitation of 132 cm/year to a 99% level of significance. In the absence of a substantial change in land use/land cover in the basin, it can be safely assumed that long-term mean freshwater flows into Cumberland Sound have been constant and water-level changes are due to channel enlargements.

The question of land use/land cover was explored but the data were, again, sparse. Blair et al. (2009) reported that the St. Mary's basin land use has remained predominately rural and unchanged, which is surprising considering the population growth of the towns of St. Marys and Kingsland, Georgia, produced by the Kings Bay submarine base. In the absence of contradictory evidence, the authors believe the water-level evidence is sufficient.

Summary and Discussion

Dredging of the Cumberland Sound entrance and interior channels from 1984 through 1985 increased navigation channel depths by up to 40% and widths by up to 66%. The question of whether those channel enlargements caused Cumberland Sound MTL to increase has been examined by three methods:

- Analytic solutions of simplified equations of motion by King (1974), DiLorenzo (1986), and Walton (2002) demonstrated that bay setdown can be caused by the interaction of inlet and bay geometries and phasing of tidal constituents. Their results demonstrated that the setdown phenomenon is physically plausible and potentially of the magnitude reported by Granat and Brogdon (1990).

- Physical and numerical models reported by Granat and Brogdon (1990) determined that MTL in Cumberland Sound would increase by 0.03–0.06 m as a result of the 1984–1988 channel enlargements.
- Statistical analyses of NOAA tide data for Cumberland Sound produced two interpretations:
  - Kraus et al. (1997) examined observed tide data for 1935 through 1992 and concluded that the pre-1985 MTL was not significantly different from the 1986–1992 MTL.
  - Analyses presented here of 1953–2019 tide and precipitation data indicated that MTL increased by about 0.1 m between the pre-enlargement and post-enlargement periods. Of that amount, between 0.02 and 0.05 m can be attributed to the 1984–1988 channel enlargements and the remainder to RSLR with a high degree (99.9%) of confidence.

The weight of evidence cited previously suggests that Cumberland sound MTL increased as a result of 1984–1988 channel enlargement dredging. The sole contradicting result by Kraus et al. (1997) may have been limited by the short (4-year) period of post-enlargement data available at the time, producing an unreliable result.

The amount of post-enlargement estimated MTL rise is relatively small—about 5 cm (2 in.)—compared with the tide range and monthly fluctuations. That may or may not cause secondary impacts in Cumberland Sound. Addressing that question is beyond the scope of this paper.

Conclusions

Deepening and widening of the Cumberland Sound entrance and interior channels from 1984 through 1988 increased channel dimensions by 25%–66%.

A weight of evidence approach considering analytic, physical, and numerical models' results, plus statistical analysis of observed MTL from 1953 through 2019 leads to the conclusion that the described channel enlargements reduced a pre-existing Fernandina Beach MTL setdown of up to 0.02–0.05 m. The net rise in MTL was relatively small, less than 3% of the system tide range of 1.8 m.

Hydrodynamic interaction of inlet and bay geometries plus phasing of tidal constituents caused a pre-existing Cumberland Sound setdown. A rise in MTL occurred through the relaxation of that setdown by channel dredging.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article. The data and models that support the findings of this study are available from the cited references.

Acknowledgments

Data used here were obtained from US Army Corps of Engineers and National Oceanic and Atmospheric Administration publications as cited in the text and listed in the references.

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