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Mitigating Anthropogenic Influences on Tidal Circulation: A Case Study of McKay Bay, Florida, USA

Elizabeth L Royer[†*] and Ping Wang[†]

[†]School of Geosciences
University of South Florida
Tampa, Florida, USA

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ABSTRACT

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McKay Bay is a heavily altered 3.5 km^2 shallow sub-estuary at the northeastern end of Tampa Bay. The circulation within McKay Bay is mainly driven by tides from the Gulf of Mexico. Typical of many estuaries, a bridge and causeway were built crossing the mouth of the bay in addition to numerous dredge and fill projects within the bay substantially altering the bathymetry and circulation pattern. This heavily engineered system provides an opportunity to understand how historical management decisions and practices can influence the current and future health of the bay and to explore nature-based solutions to mitigate negative effects. A numerical flow model was built using the US Army Corps of Engineer's Coastal Modeling Systems (CMS). The model was calibrated and verified using measured current velocities throughout the bay. Under present conditions, tidal flow is concentrated in the dredged channel through the middle of the bay while low flow zones occur along the shoreline, negatively impacting nearshore habitat. These nearshore "dead zones" were not computed over the natural conditions before anthropogenic modifications. Flow patterns under different bathymetry alterations were simulated with the goal of improving nearshore circulation. The modeling results were used to evaluate various nature-based solutions to mitigate negative impacts from past engineering activities. The best results were achieved by filling the channel in the middle of the bay along with an elongated shoal and spur, mimicking the removed bay-head delta. This approach is applicable to other shallow estuaries.

ADDITIONAL INDEX WORDS: *nature-based solution, numerical modeling, coastal resilience, estuary*.

INTRODUCTION

Throughout human history estuaries have been essential for navigation and are often locations for towns and cities (McLusky and McLusky, 1989). In the US, 17 of the 20 fastest growing cities are along the coast (Tibbetts, 2002). This ever-increasing coastal population has required the construction of coastal infrastructure like housing, bridges and causeways, and port- and shipping-infrastructure (Bishop et al., 2017). Tampa Bay, along Florida's Gulf of Mexico (GOM) coast, has undergone drastic anthropogenic changes over the past century attending a coastal population boom (Foley, 2007). Large-scale infrastructure was built within the estuary including dredged shipping channels, spoil islands, dredge-material spoil sites, and four major bridge-and-causeway systems (Goodwin, 1991). Linville et al., (2007) and Zervas (1993) determined that these alterations significantly impacted the hydrodynamics within the estuary, ultimately increasing the stress on the estuarine environment, especially at the terminus of the estuary where hydrologic connectivity to the tidal inlets is quite delicate. Burger and Petrus (2004) determined both a dissolved oxygen (DO) and nutrients impairments were present within McKay Bay concluding overall poor water quality.

McKay Bay is a heavily altered 3.5 km^2 shallow sub-estuary at the northeastern terminus of Tampa Bay, adjacent to the Port of Tampa (Figure 1). McKay Bay has been heavily engineered, with a bridge and causeway built crossing the mouth in the late 1920s (Cox, 2008). From the 1950s numerous dredge-and-fill projects through the middle of the bay and near the mouth of the Six-Mile River, later converted to the dammed Tampa Bypass Canal (TBC) (SWFWMD, 2005). The circulation of McKay Bay is driven by tides from the GOM, and discharge from the TBC.

Figure 1. Time-series aerial photos of McKay Bay. A: 1938 photo, visible bayhead delta at the mouth of the historic Six-Mile River. B: 1957 photo, with the bayhead delta removed and Six-Mile River converted to the TBC. C: 1968 photo, with landfill completed along northern and southern shorelines and a channel dredged through the middle of the bay. D: 2023 photo. E: Location of McKay Bay within Tampa Bay.

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*Corresponding author: elroyer@usf.edu

A numerical model was built, calibrated, and validated to quantify how historical engineering decisions have influenced the circulation pattern within McKay Bay and how natural or nature-based features can be utilized to improve the circulation pattern. This study aims to provide valuable information on modeling estuary circulation, quantifying impacts of engineering alterations, and application of nature-based solutions (NBS) to improve circulation. The majority of NBS projects are focused on small-scale wave attenuation, erosion control, or storm surge reduction (Bridges et al., 2015). However, this study provides a new perspective by focusing on bay-wide circulation improvement.

METHODS

Field Data Collection

A detailed hydrographic survey, using a synchronized precision echo sounder and a Real-Time Kinematic (RTK) GPS, was conducted to accurately capture the bathymetry for the numerical model construction. The land elevation was obtained from the 2019 NOAA NGS Topobathy LIDAR data (https://www.fisheries.noaa.gov/inport/item/64532). The above two datasets were used to construct the numerical model (Figure 2).

To gather both temporal and spatial flow velocity data within the bay, an Acoustic Doppler Velocimeter (ADV) and an Acoustic Doppler Current Profiler (ADCP) were used. The ADV was deployed for 20 days to provide current velocity and water-level data over a spring-neap tidal cycle. The ADV data was used to calibrate the numerical model. The vessel-mounted ADCP was used to gather velocity data at various locations in the bay. This spatial data was used to verify the model.

Model Setup

The Coastal Modeling System (CMS), developed by the US Army Corps of Engineers Research and Development Center (USACE ERDC), was used in this study. The CMS consists of CMS-Flow and CMS-Wave, with the capability of coupling wave and flow computation (Buttolph et al., 2006; Larson et al., 2011; Lin et al., 2011; Reed et al., 2011; Sánchez & Wu, 2011; Sánchez et al., 2014; Wu et al., 2011). Since waves in McKay Bay are typically low, only CMS-Flow was utilized to compute flow field.

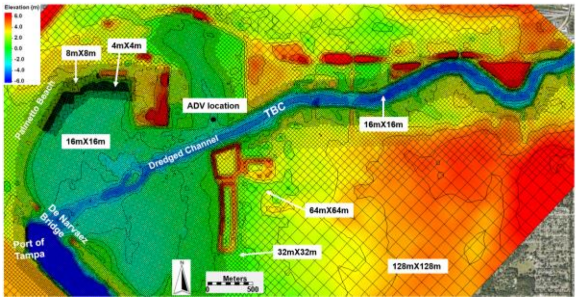

Figure 2. The telescoping model grid with accurate capture of bathymetry.

The modeling grid spanned from the seaward-most dam at the TBC to the entrance of the Port of Tampa to encompass the entire McKay Bay (Figure 2). The grid was orientated roughly parallel to the mouth of McKay Bay. The telescoping grid contained cells ranging from 4-x-4-m adjacent to the north shoreline (a focus area), to 128-x-128-m in the terrestrial areas along the model-domain margins (Figure 2). The flow model was driven by 22 days of measured tidal data extracted from NOAA tide station 8726674 located in East Bay on the southwest side of the bridge.

The model was calibrated using the measured velocity and water-level data at the ADV location (Figure 2). The spatially uniform friction coefficient, Manning's n in this case, was the only parameter used in the calibration. The Willmott (1981) skill (Eq. 1) was used for the model calibration.

$$S_W = 1 - \frac{\sum(V_{model} - V_{measure})^2}{\sum(|V_{model} - \overline{V_{measure}}| + |V_{model} - \overline{V_{model}}|)} \quad (1)$$

Skill values closer to one signify a closer match between the modeled and measured values and therefore, a better model skill (Willmott, 1981).

RESULTS

This section presents the results of this study including several key model-production runs. The results from the model calibration and verification are described first, followed by the results of select modeling scenarios.

Model Calibration and Verification

The calibration run was conducted using the bathymetry representative of the existing conditions. The computed water level and velocity matched well with the measured values and produced a Willmot Skill (S_W) of 0.989, signifying the ability of the model to accurately predict current velocity (Figure 3). The calibrated model was verified using 14 ADCP velocity measurements from various locations within the bay.

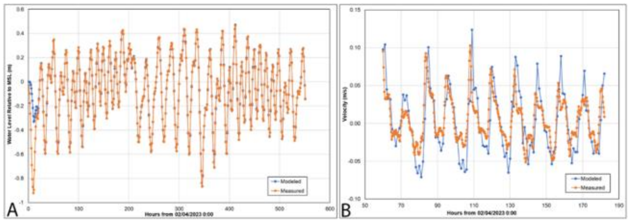

Figure 3: Model calibration using measured data from the ADV. A: modeled vs. measured water level. B: modeled vs. measured velocity.

Modeled Flow Field under Different Scenarios

The selected scenarios discussed in this paper include the existing conditions, pre-engineering natural conditions (1885), and the most successful NBS scenario to assess and mitigate the impact of the anthropogenic influences. All flow velocity values discussed below were depth-averaged velocities computed by the numerical model.

Existing Conditions

The existing conditions represented a highly altered environment with the bridge and causeway system, landfill along the northern and southern shorelines, and a roughly 4-m deep and 200-m wide dredged channel through the middle of the bay (Figure 2). The existing conditions are discussed first because the model scenario depicts the current hydrodynamics of McKay Bay and served as the basis for potential future restoration planning.

Under existing conditions for both ebb and flood flows, most of the bay had a depth-averaged current velocity of less than 0.05 m/s, particularly along the northern and southern shorelines (Figure 4). Within the deep dredged channel through the middle bay, current velocities were greater, between 0.05-0.10 m/s.

The dominant flood flow direction was southwest to northeast along the dredged channel from the bridge to the TBC (Figure 4A and 4B). Under peak flood conditions and -0.28 m water level relative to MSL, the current velocity was highest at the bridge, at about 0.20 m/s (Figure 4A). The flood current at the mouth of McKay Bay was slightly greater along the south side of the bridge (Figure 4A and 4B). Within the dredged channel east of the bridge the flood tide current velocity was the greatest under the lower water level, peaking around 0.10 m/s (Figure 4A).

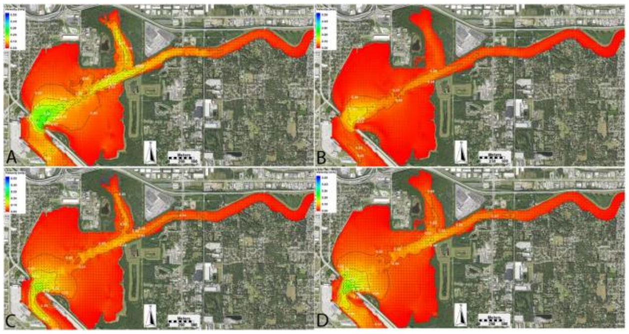

Figure 4. Computed current velocity under the existing conditions. Warmer colors indicate lower velocities and cooler colors represent higher velocities. A: Peak flood flow under a -0.28 m water level relative to MSL B: Peak flood flow under a -0.16 m MSL. C: Peak ebb conditions under a -0.42 m MSL D: Peak ebb conditions under a 0.05 m MSL. All selected and outputted scenarios follow this same four panel format.

The ebb current within the channel was fairly uniform at 0.05 m/s at both high and low water levels (Figure 4C and 4D). Two areas of conspicuously low flow (dead-zones) with current velocities approaching zero were computed under the existing conditions for both flood and ebb currents. These areas are located along the northern and southern shoreline (Figure 4). Overall, under the existing conditions the flow pattern is greatly controlled by the dredged channel, with low velocities outside the channel—leading to chronic poor circulation that has contributed to modern ecological degradation in the nearshore region.

Historical/Natural Conditions (A3_1885)

The historic scenario represented natural or baseline conditions in McKay Bay before the onset of 20th century engineering alterations (Figure 5). This was used as a theoretical restoration goal for this study. The 1885 bathymetric chart showed the bay with a fairly uniform and shallow depth, the deepest portion being about -2.0 m MSL, along the southern shoreline, but the majority of the bay was -1 to -1.5 m MSL (Figure 5B). This scenario indicates that tidal circulation was widespread throughout the entire shallow bay, with the velocity between 0.05-0.20 m/s (Figure 5C-F).

There was a substantial bay head delta at the mouth of the Six-Mile River that became emerged at low tide (Figure 5). This delta drove both flood and ebb flow north of the shoal, along the northern shoreline. The effect of the bay head delta was greater at a lower water level, with the flood flow peaking at about 0.20 m/s, and ebb flow peaking at about 0.10 m/s (Figure 5C and 5E).

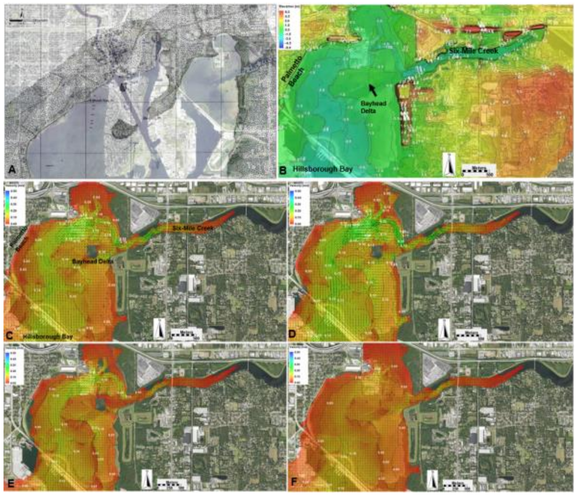

Figure 5: A: 1885 map overlayed with present day imagery. B: 1885 bathymetry with significant features labeled. C-F current velocity outputs, warmer colors indicate lower flow velocities and cooler colors represent higher velocities. C: Peak flood conditions under a lower water-level. D: Peak flood conditions under a higher water. E: Peak ebb conditions under a lower water level. F: Peak ebb conditions under a higher water level.

The low-flow zones along the northern and southern shorelines under the existing conditions did not occur under natural conditions (Figure 5). Overall, the bay-wide circulation before the engineering alternations is very different from the heavily engineered existing conditions.

Enhancing Nearshore Flow

A series of model runs was designed to enhance the nearshore flow. Figure 6A shows restoration alternative A5_D with a constructed shoal and spur to an elevation of -0.5 m MSL; additionally, a ~40-m wide and 3.0-m-deep channel was designed across the middle of the shoal for boat traffic. The shoal measures 860 m from north to south and 350 m from east to west. The designed spur was 400-m long, at maximum 190 m wide and with an azimuth of 337 degrees. An estimated volume of 1,032,000 m^3 of material will be needed to construct the shoal which mimics the removed bayhead delta but at a different location. Under peak flooding conditions this shoal induced flow of 0.10 to 0.20 m/s along the northern shoreline and 0.05 to 0.20 m/s along the southern shoreline, representing a major increase from existing conditions (Figure 6C and 6D). Under peak ebbing conditions flow velocities were lower than under peak flood; however, the A5_D shoal and spur remained effective in forcing flow to the north, and—to a lesser degree—to the south (Figure 6E and 6F).

DISCUSSION

The circulation pattern within McKay Bay has been heavily altered by various 20th Century engineering projects, including bridge and causeway construction, intensive dredging, and land reclamation (Cox, 2007). These dramatic anthropogenic changes are not unique to McKay Bay nor Tampa Bay. They are quite common in many shallow developed estuaries around the world (Cattrijsse et al., 2002; Freeman et al., 2019). The influence of past engineering decisions and possible restoration alternatives to mitigate the anthropogenic degradation caused by urbanization of the estuary are discussed here.

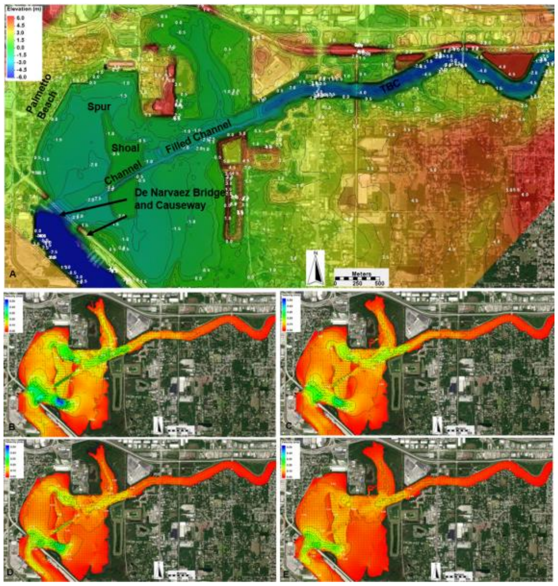

Figure 6: A: restoration alternative A5_D with important features labeled; warmer colors indicate lower velocities and cooler colors represent higher velocities. B: Peak flood conditions under a lower water-level. C: Peak flood conditions under higher water. D: Peak ebb conditions under a lower water level. E: Peak ebb conditions under a higher water level.

The focus of this analysis was on determining historical tidal current velocities along the northern and southern shorelines and comparing them to the existing conditions and restoration alternatives, to better quantify how the anthropogenic changes influenced tidal circulation. This was done by extracting time-series velocities at 8 locations from the three selected scenarios (Figure 7). Locations P1 and P2 along the northern shoreline, and P8 along the southern shoreline are the focus of this discussion.

Anthropogenic Influences on Bay-Wide Circulation

At location P1 when comparing the existing conditions to the natural conditions, the velocities were low in both the natural and existing conditions with only about a 0.01 m/s difference in both the flood and ebb directions (Figure 7B). However, this still represents a 22.4% reduction in velocity under flooding conditions, and a 28.7% reduction in the ebbing direction (Figure 7B). At location P2 the velocity decreased more drastically between the natural and existing conditions, the peak flood flow under the natural conditions was about 0.15 m/s, however after the anthropogenic influences the velocity decreased to 0.04 m/s (Figure 7C). Under a peak ebb flow scenario, the natural conditions once again had a higher velocity at 0.09 m/s and 0.03 m/s under the existing conditions. This is a decrease of 72.0% at the peak flood and 72.1% in the ebb (Figure 7C). The pattern at P2 suggests that the existing sluggish circulation along the northern shoreline can be attributed to the dredge and fill projects, as well as the bridge construction (Figure 7C).

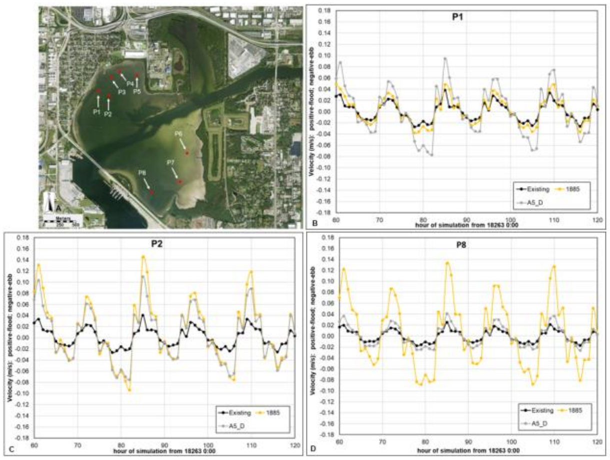

Figure 7: A: Eight locations where time-series velocities were extracted from the numerical model. B-D: extracted velocities comparing existing conditions, natural conditions, and the restoration scenario.

At location P8, tidal flow velocities appeared to be drastically reduced by the bridge/causeway construction and subsequent dredge-and-fill operations. The peak flood velocity at this point was about 0.03 m/s under existing conditions, but about 0.13 m/s under the natural conditions. Under a peak ebbing scenario the velocity was about 0.02 m/s under the existing conditions and 0.09 m/s under the natural conditions (Figure 7D). This represents an 81.2% reduction in velocity under flooding conditions and 80.1% reduction under ebbing conditions (Figure 7D).

The bay-wide impacts of the bridge/causeway construction, the dredging of the channel in the middle, and land reclamation on the flow field were evident under the existing conditions, when compared to the natural pre-engineered scenario (Figure 4). Overall, the engineering alternations resulted in channelized flow through the center of the bay and suppressed flows outside of the channel (Figure 5), while simultaneously restricting flow into the greater Tampa Bay because of the bridge and causeway system.

NBS Design to Improve Bay-Wide Circulation

Due to the development along the shorelines and the nearby Port of Tampa, restoring the bay to its natural bathymetry and configuration is not practical. However, key morphological features from the natural conditions could be mimicked to improve the circulation and meet the restoration goals. Scenario A5_D was designed using an NBS concept to mimic the positive influence of the historical bayhead delta by diverting tidal flow toward the northern and southern shorelines, reducing the negative impacts of past engineering interventions in the bay.

This scenario was successful at increasing tidal current velocity along the northern shoreline. At location P1, closest to the northern shoreline, peak flood and ebb velocities exceeded that of the natural conditions. The peak flood velocity increased by 91.3% and the peak ebb velocity by 107.7% (Figure 7B). The peak flood velocity increased by 146.5% and peak ebb velocity increased by 185.8% against existing conditions (Figure 7B). At location P2, the restoration scenario produced peak flood and ebb velocities that were about 20% slower than the natural conditions. However, when compared to existing conditions the peak flood and ebb velocities increased by about 180% (Figure 7C). At location P8 along the southern shoreline, the shoal restoration was slightly less effective. The peak flood velocity was reduced by about ~70% under both flood and ebb conditions compared to the natural conditions (Figure 7D). However, compared to the existing conditions the velocities increased by 64.1% under peak flood and by 48.8% under peak ebb. Overall, this restoration design would lead to a significant improvement in circulation in nearshore areas.

CONCLUSIONS

The calibrated and verified numerical model developed by this study accurately quantified the impacts of engineering alterations on tidal circulation within McKay Bay. Under present day conditions both ebb and flood flows are channelized by the deep and wide dredged channel through the middle of the bay, creating stagnant zones in the nearshore areas. The computed flow along both the north and south shorelines under natural conditions was much stronger than that under existing conditions. By restoring the bayhead delta, although at a different location, the natural circulation can be roughly restored, with about three times stronger flow along the northern shoreline as compared to existing conditions. As the nearshore areas within numerous estuaries continue to be squeezed through urbanization, our findings should have broad applications.

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