Bathymetric Alterations Due to Urbanization and Their Effects on Residual Salinity, Flow Field and Transport Time for Tampa Bay, Florida

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Bathymetric Alterations Due to Urbanization and Their Effects on Residual Salinity,
Flow Field and Transport Time for Tampa Bay, Florida

by

Amanda J. Linville

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
College of Marine Science
University of South Florida

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Keywords: model, residence time, estuary, navigational channel, bridges

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Growth and development over the past one hundred years has resulted in the construction of causeways and navigational channels in Tampa Bay. Urbanization has lead to bathymetric alterations of the bay, and thus has effectively changed the residual salinity, flow fields, and transport time in Tampa Bay. In this study a numerical ocean model of Tampa Bay was first used to simulate the circulation for 2001-2003 using present day bathymetry. Then, an identical simulation was performed using the bathymetry generated from 1879 depth soundings. The residual (30-day time average) circulation fields and salinity, along with transport times was intercompared for different freshwater inflow conditions to investigate the impacts of these physical alteration. The salinity for the “present” simulation is about 3 psu higher than the “1879” simulation in the areas of upper Middle Tampa Bay, Lower Hillsborough Bay and Old Tampa Bay, a result of a stronger axial pressure gradient associated with the deeper more extensive channels. Velocities are up to 10 cm/s higher in the “present” run than in the “1879” simulation in the areas where water must converge and diverge through the narrow openings of the bridges/causeways. Transport time is short (~10days) during strong residual circulation, and long (~90 days) during weak residual circulation. Bridges and causeways are associated with longer transport times (~90days), except in the area North of the Courtney Campbell Causeway. The navigational channel is associated with long transport times during dry periods and short transport time during wet periods.
INTRODUCTION

Over the past one hundred years many areas surrounding waterways have experienced rapid human population growth. Coastal counties represent just 17 percent of the total acreage of the contiguous U.S., yet in 2002 they were home to more than half of the nation’s people (Beach, 2002). This high population density has generated a need for all types of infrastructure including roads, causeways, bridges and navigational channels. Many of these are built within semi-enclosed waterways such as bays and estuaries directly altering their bathymetry. Over the coming decades, as population increases, so will the need for additional infrastructure (Beach, 2002). Estuaries, places where rivers meet the sea, are among the most unique and ecologically important ecosystems on our planet (Cloern, 2001). Thousands of species of birds, fish, mammals, and other wildlife depend on estuarine habitat as places to feed, reproduce, and to live. Identifying and assessing the environmental impacts on estuarine systems due to urbanization is essential to managing their ecological health. Bathymetric alterations can significantly impact hydrodynamic circulation within an estuary. The hydrodynamics of the estuary controls the flux of salt and other biological, chemical and geological materials in estuarine environments (Kim, 2005). The second is a non-tidal baroclinic circulation generated by a head to mouth salinity gradient (Galperin et al., 1991; Weisberg and Zheng, 2006; Meyers et al., 2007), with typical speeds on the order of 10 cm/s. The salinity gradient is regulated by the freshwater discharge into the bay and the baroclinic circulation is
modified by the surface wind stress. This study will use a numerical ocean model to examine the hydrodynamic effects of bathymetric alterations due to urbanization and their effects on residual salinity, flow field and transport time in Tampa Bay, Florida.

The bathymetry of Tampa Bay has been significantly altered in the past century due to urbanization. With an average depth of 3.7 meters at Mean Lower Low Water (MLLW), Tampa Bay is a drowned river bed with channels that have been deepened by dredging (Zervas, 1993). A major ship channel has been dredged from the mouth to the upper reaches of Lower Tampa Bay and into Middle Tampa Bay, where it splits into two branches, one entering Old Tampa Bay and the other going into Hillsborough Bay. This dredging has increased the main channel depths from 10 meters to 15 meters (Vincent 2001). In addition to the dredging, four major bridges now span the Bay: the Courtney Campbell Causeway (CCC), the Howard Franklin Bridge (HFB), the Gandy Bridge (Gb), and the Sunshine Skyway Bridge (SSB) (Fig. 1). Physical alterations like these are expected to influence circulation and transport time in estuaries, which in turn can profoundly affect the Bay’s ecosystems. In Kingston Harbour, Jamaica a hydrodynamic modeling study found contrary to what was suspected, stagnant conditions in the bay would occur even without the presence of a major causeway (Andrew et al 1999). A study conducted in Sheepscot River Estuary, Maine found that following the actual removal of a causeway, tidal flows in the main channel increased by almost 50% (McAlice and Jaeger, 1983). These studies suggest that the effect of an infrastructure on an estuary largely depends upon the type of an infrastructure and the local hydrodynamics of the bay.
In this study a numerical ocean model of Tampa Bay will first be used to simulate the circulation for 2001-2003 using present day bathymetry (Fig 2). Then, an identical simulation will be performed using the bathymetry generated from the 1879 depth soundings (Fig 3). The residual (30-day time average) circulation fields and salinity, along with transport times will be intercompared for different freshwater inflow conditions to investigate the impacts of these physical alteration.

**Tampa Bay History And Significance**

The Tampa Bay estuary is located near 82.5 degrees longitude West and 27.60 degrees latitude north on the west-central coast of peninsular Florida, and extends approximately 60 km to the northeast and is about 11 km wide (Vincent 2001). With a surface area of 1032 km² it is one of the largest estuaries in the U.S. (Donahue 2003). Tampa Bay consists of four major water bodies: Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB), Lower Tampa Bay (LTB) (Lewis & Whitman 1985) (Fig. 1).

Tampa Bay is an essential sanctuary for waterfowl, marine life, plants, invertebrates and mammals. The Bay supports the most diverse colonies of shorebirds in North America (TBEP, 2005a) and a resident population of more than 500 dolphins (TBEP, 2005b). More than 200 species of fish can be found in Tampa Bay and it is home to the endangered Manatee.

Tampa Bay encompasses an environment that also provides aesthetic enjoyment, with its miles of blue waterways, white shorelines, and a near-perfect average annual temperature of 72 degrees (The Greater Tampa Chamber of Commerce, 2005). People
flock to Tampa Bay to enjoy activities on the water like swimming, kayaking, boating, and fishing.

Besides having an ecological and recreational value, Tampa Bay has harbors and ports vital for shipping, transportation, and industry. The bay contributes more than 5 billion dollars annually from trade, tourism, development and fishing, and boasts three major seaports (TBEP, 2005b). The three ports that border Tampa Bay support 130,000 jobs and contribute more than $15 billion per year to the local economy (TBEP, 2005b). The Port of Tampa handles nearly half of all sea borne commerce in Florida (Bay Soundings, 2003).

Florida’s population has increased by 600 % in the last 50 years (U.S. Census). Most of the urbanization is taking place alongside the estuary and placing stress on the quality and quantity of this valuable habitat. Today, about 2.5 million people live in the four-county metropolitan statistical area (MSA) that surrounds the bay, making it the second-largest MSA in the Southeast and the 21st-largest MSA in the U.S. It is important to realize the critical role Tampa Bay has in preserving the abundance of wildlife and health of the environment and economy and to minimize adverse effects on it.

Egmont Channel to the north of Egmont Key, at the mouth of the bay, is the major connection between the Gulf of Mexico and Tampa Bay. The Southwest Channel and Passage Key Inlet are channels located on the south side of the bay. The original navigational charts of 1879 reveal a natural central channel running from Egmont Key to the area south of Gadsen point (Kehring, 1985). Natural depths range from 6 to 10 meters and in one area at the Bay’s mouth, the natural depth is 27 meters (NOS, 1990). Dredging of ship channels has increased the main channel depths to 15 meters (NOS, 1990) in
some areas (Fig. 4). As shown in the study by the New South Whales Department of Natural Resources (NWNR, 2005), dredging can have a number of harmful effects on estuarine habitats and ecosystems.

The seagrass beds may be destroyed or degraded by mining the underlying sediment causing increased levels of turbidity and sedimentation. Dredged channels or any deep hole can also cause flow to become stagnant or may adversely affect current patterns also harming seagrass beds.

Bridge and causeway infrastructure as well as dredging can have an adverse effect on an estuary (NWNR, 2005). In particular, causeways across an estuary can severely restrict tidal flows and reduce the tidal prism (NWNR, 2005). The reduced fluctuation in tidal water levels and velocities, together with highly reduced salinity levels, can lead to a progressive, but ultimately marked change to upstream habitat areas, including the loss of mangroves and the smothering of any upstream seagrass beds (NWNR, 2005). These tidal restrictions can also affect transport time scales, or the amount of time a material spends in the bay before exiting. Much work has been done to understand transport time scales because they affect the dilution of nutrient and contaminants inputs. In a transport time study conducted in Tampa Bay by Burwell et al (2001), it was found that in areas restricted by causeways, time scales exceeded 140 days, while areas adjacent to the main channel were 10 to 20 days or less. Predicting the transport and fate of pollutants in the estuaries and the coastal zone appears as one of the most important challenges of the environmental sciences.

Tampa Bay tidal waters are categorized as mixed, semi-diurnal (Goodwin, 1987). Tides of this classification are composed of two high and two low unequal tides during a
one day period. Mean range of tide and great diurnal range are 0.44 meters and 0.74 meters respectively for Tampa Bay (NOS, 1990). Tidal analysis indicates that the tide travels from the mouth of the bay to the head of Old Tampa Bay and Hillsborough Bay in approximately 4.6 hours and 3.2 hours respectively.

The residual water level signal is defined here as the observed water level minus the harmonic water level. The meteorological forcing responsible for this non-tidal contribution ranges from seasonal steric heating to synoptic scale frontal passages and local thunderstorms (Vincent, 2001).

Currents in Tampa Bay are also categorized as mixed predominately semi-diurnal. Maximum current speeds on the order of 1.0-1.5 m/s are observed in the Egmont Channel, the channel near the Skyway Bridge, and in the channel leading to Old Tampa Bay (Vincent, 2001). Like the bay water levels, the currents also contain a large non-tidal component. Zervas (1993) found that the ratio of the standard deviation of the residual currents to the standard deviation of the observed currents ranged from 17.2 % to 88.2%.

The salinity of the bay is governed by that of the Gulf of Mexico, freshwater inflow from rivers, streams, groundwater, non-point sources and rainfall. Evaporation also removes a large volume of water from the bay. Initial bulk aerodynamic calculations suggest that the annual evaporation is approximately the same magnitude as the annual precipitation (Vincent, 2001).

The major rivers include the Alafia, Hillsborough, Manatee and Little Manatee. The Alafia and Hillsborough rivers drain into the bay from the Northeast, near the head of the bay; little Manatee enters on the Eastern side; and the Manatee at the South, near the mouth of the bay. The mean value of the total freshwater inflow is 9.4 million m$^3$ d$^{-1}$.
and ranges from 0.02 to 226 million m$^3$ d$^{-1}$. Forty percent of the average fresh water input is in the form of precipitation (Meyers et al., 2007).

Small freshwater inflow rates combined with shallow depth, and strong tidal mixing lead to a vertical salinity structure that is well mixed (Galperin, 1991). Vertically quasi-homogenous estuaries with strong horizontal salinity gradients have been shown to have developed baroclinic (density driven) subtidal flows (Wong 1994: Pritchard 1956), which that contribute to the residual circulation of the bay.

**Recent studies in estuary circulation**

In 1987 Carl Goodwin of the U.S. Geological Survey conducted a study similar to this one only he used a two-dimensional, finite difference, hydrodynamic model to simulate flood, ebb, and residual transport of both water and dissolved constituent for the physical conditions that existed in Tampa Bay during 1880 and 1972 and for the conditions that were likely to exist in 1985 (Goodwin, 1987). The model employed by Goodwin assumes that the density driven mode of circulation is not important due to the vertical mixing and the shallowness of the bay. The goal of the project was to try to assess the impact of dredge and fill projects on water circulation. The model predicted the tidal stages at different locations in the bay reasonably well; however, it could not model the density-driven (baroclinic) residual circulation in Tampa Bay (Li, 1993) and therefore is not useful for examining issues related to long-term transport within the bay.

Weisberg and Williams (1991) concluded that although Tampa Bay is vertically well-mixed in salinity, it does have a dynamically significant horizontal salinity gradient due to the distribution of inflowing freshwater. These horizontal gradients and surface
wind forcing maintain a fully three-dimensional circulation in the Bay. Galperin et al (1991) used a three-dimensional, time-dependent model of circulation in Tampa Bay, they have found that the circulation in the bay, is complex and three-dimensional, it is influenced by the horizontal density gradients throughout the estuary. The force generated by the horizontal salinity gradient in Tampa Bay drives a non-tidal, baroclinic circulation (Galperin et al 1992a, Li 1993, Weisberg et al 2006). This baroclinic circulation, also known as estuarine circulation, is characterized as a two layer flow, with more saline water flowing landward beneath a top layer of fresher water flowing seaward (Pritchard, 1956). The strength of the baroclinic currents varies with the magnitude of the salinity gradient (Meyers et al., 2007).

The numerical model used here is based on the three dimensional Estuarine and Coastal Ocean Model (ECOM-3D), a variation of the Princeton Ocean Model (Blumberg and Mellor, 1987). The Tampa Bay model is a three-dimensional, time-dependent model of the hydrodynamics of circulation in Tampa Bay (Galperin et al., 1992a, b; Vincent et al., 1997)

The need to calculate transport time scales (ex. flushing, residence time) arises in many studies of estuaries. Transport time scales affect the dilution of nutrient and contaminants inputs as well as a variety of ecological processes, and can be used to assess the ecological implications of changes in the circulation of an estuary. Better descriptors of estuarine and coastal dynamics will enable coastal managers to more effectively make decisions.

There is a historical lack of consistency in the definition of transport time scales. Many terms are used in the literature and are often inconsistent and sometimes imprecise.
Care must be exercised to determine the meaning of terms being used, to avoid misinterpretation or incorrect comparisons of data. Recent works identify three different concepts of transport time; flushing time/retention time, age and residence time (Monsen et al., 2001). Flushing time/retention time is defined as time to replace the volume of the estuary by the total freshwater input influx (Officer and Kester, 1991). Age is defined as the time elapsed since the material entered the system (Zimmerman, 1988). Residence time has been defined as the time it takes a water parcel to leave the system (Dronkers and Zimmerman, 1982). Flushing time is an integral system measure (baywide calculation) of transport time, whereas both residence time and age are local measures (spatial calculations) (Monsen, 2001).

There is no single transport time scale for a system that is applicable to all time periods, locations, and constituents, and no one time scale describes all transport processes (Monsen et al., 2001). Therefore, identifying the underlying assumptions associated with the application of that concept and its validity will determine which concept to adopt. Here, the calculation of both “system”, specifically flushing time, and “local” parameters, specifically residence time, are performed to help give a more complete characterization of transport time scales for Tampa Bay.

Calculating flushing time and/or residence time itself can be estimated using many different methods (Pilson, 1985, Geyer, 1997, Solis and Powell, 1999, Callaway, 1981, Dettmann et al., 1989, Dettmann et al., 1992, Hagy et al., 2000, and Miller and McPherson, 1991). In this study a numerical computer model will be used calculate a global flushing time similar to the method used by Monsen (2001), and Oliveira and Baptista (1997), where the number of particles is fit to an exponential decay. The same
model will also be used to calculate a local residence time. The method for calculating
residence time will be the same Lagrangian method used by Burwell in 2001 on Tampa
Bay, it is a method similar to the ones used by Brooks et al. (1999), Signell (1992),

Burwell (2001) conducted a numerical study in Tampa Bay that compared two
distinct numerical model methodologies (Eulerian and Lagrangian) for determining
spatiotemporal variation in estuarine residence times. The Eulerian approach was based
on the concentration equation, using advection and diffusion of a passive tracer in the
model domain, while the Lagrangian method is based on a particle tracking approach,
where neutrally buoyant dimensionless particles are advected by the model velocity and a
small random Markovian displacement (Burwell 2001). Burwell concluded that the
Eulerian method is sensitive to the value of the horizontal diffusivity whereas the
Lagrangian approach provides a more realistic sub-grid scale motion (Burwell 2001). He
also concluded that the Lagrangian spatial distributions show more detail in each sub-
region of the bay, and thus indicates how the relative residence time varies spatially
within these regions. The Lagrangian approach is therefore the method used in this study
for calculating the residence time.

The Tampa Bay Numerical Circulation Model

The Tampa Bay model solves equations for the conservation of mass, momentum,
salt, heat and turbulence quantities in an incompressible hydrostatic fluid (Blumberg-
model uses a grid with 70 by 100 cells in the horizontal and 11 sigma levels in the vertical. The dimensions of active cells range from 2240 meters to 307.67 meters, with a mean of 668.34 meters. The mean cell area is 0.425 square kilometers. The maximum, mean and minimum depths of the grid cells are 13.93, 3.62 and 1.3 meters mean lower low water (MLLW) respectively. Turbulence closure is provided by an embedded Mellor Yamada 2.5 level closure submodel (Mellor and Yamada, 1982) as modified by Galperin et al (1988). A mode splitting technique is used that separates the fast external gravity waves and the slow moving internal gravity waves (Blumberg and Mellor, 1987). In Tampa Bay, the model is forced with hourly water levels, and daily winds, freshwater inflows, precipitation, evaporation, and monthly salinity at the mouth. Along the lateral boundaries, rivers are prescribed by temperature (set to 25 C), salinity (set to zero), and flow rates as set by Meyers et al. (2007). Among the important parameters computed from the model are free surface height, magnitude and direction of currents, and the fields of temperature and salinity.

Several of the model boundary conditions are obtained from PORTS (Physical Oceanographic Real-Time System) and COMPS (Costal Ocean Monitoring and Prediction System) data. Tampa Bay PORTS includes the measurement of real-time currents, water levels, winds, wave height, visibility, air and water temperatures, and barometric pressure at multiple locations with a data dissemination system. COMPS is a network of instruments both along the coast of Tampa Bay and offshore of Florida that measure current, temperature, salinity, and meteorological parameters, which satellite telemetry of the data to the shore. These data streams are automatically updated every 6
minutes and can be viewed from the OMPL Web site (http://ompl.marine.usf.edu) and accessed via a DODS (Distributed Ocean Data System) server.

River flow data used to run the model is either from the United States Geological Survey or interpolated using an algorithm based on drainage areas. River flow includes estimates of underground seepage into rivers of about 8% of the mean flow (Vincent, 2001). Direct precipitation into the bay is estimated from regional rain gauges. Observational evaporation was provided by the Southwest Florida Water Management District (SWFWMD). Details of the boundary conditions are available in Meyers et al. (2007).

The modeled channel is shallower and wider than the actual channels. However the model has been extensively evaluated against observations and has been shown to capture the hydrodynamics of Tampa Bay realistically. For more information about the evaluations see Vincent et al (1991) and Meyers et al. (2007).

Near Egmont Key, at the mouth of the Tampa bay, a naturally scoured hole exists with a depth of about 27 meters. The depth of the area surrounding this hole is around 10 meters in the 1879 bathymetric grid, and about 15 meters in the present bathymetric grid. This area of steep topography may have potential to create a vorticity error in the model. Studies have indicated that the use of sigma coordinates may cause numerical errors when dealing with steep topography (Haney 1991, Mellor et al 1993, Mellor et al 1997). More specifically the study by Mellor et al (1997) found that three-dimensional sigma models contain a vorticity error the authors call “a sigma coordinate error”, that unlike in two-dimensional models, the error does not decay advectively. The error however is described by the authors of that study as being tolerably small. The potential
numerical error produced by steep topography in Tampa Bay was therefore not taken into account for this study.
MATERIALS AND METHODS

Two model runs are performed for this study. The first utilizes the model output variables from Meyers et al. (2007). In particular, model salinity and velocity are recorded every model hour for the years 2001-03 using realistic boundary conditions and modern bathymetry (“present day”) (Fig 2). The second model run is identical to the first except the bathymetry was based on depth soundings from 1879 (“1879”) (Fig 3), whose development is described below. By only changing the bathymetric grid, differences in model output between each simulation will solely derive from changes due to construction and dredging. This study is not an attempt to recreate the circulation in Tampa Bay in 1879.

Bathymetry

Bay bathymetry used for the present day grid scheme was obtained from the National Geophysical Data Center GEODAS version 3.3 and 4.0 data set. For the present grid scheme, the bathymetry at the center of each cell (i,j) was computed from the mean of all data points within a radius of (m1(i,j) + m2(i,j))/4, which was converted to units of degrees. M1 (i,j) and m2 (i,j) are the model grid cell matrices. A plot of the present day grid bathymetry is provided in Figure 2. For the 1879 grid scheme, depth soundings were obtained from the United States Geological Survey of St. Petersburg Florida. To construct the 1879 bathymetric grid, the 1879 depth sounding locations were compared to the present day bathymetric grid. The depth soundings that fell within each grid cell were
averaged and used as the depth for that particular cell. Since the model requires that the grid cells surrounding freshwater inflow to be land, it was necessary to add a few cells of land to the 1879 bathymetry. The cells of land were added to Hillsborough Bay where the Hillsborough power plant is now located. Figure 3 is a plot of the reconstructed 1879 bathymetric grid. Some of the major differences in bathymetry can be seen in HB. The ship channel has been extended to reach upper Hillsborough bay, increasing the depth by 3-4 meters, and depths around the port of Tampa have also been deepened by up to 9 meters. Eight meters of dredged soil has been added to areas in HB. In OTB bridges/causeways now span the bay resulting in a 9 meter bathymetric gain in some areas. The natural channel in OTB has been dredged, increasing depth by 4 meters. MTB and LTB have also been dredged, resulting in a depth increase of about 2-3 meters. A four meter gain, in areas of LTB, is the result of the Sunshine Skyway Bridge.

**Model Simulations**

Thirty day averages of model output variables were computed in order to filter out the tidal signal and reveal the non-tidal, or residual, circulation. Three time periods were selected to represent minimal, moderate, and maximal differences between the present and 1879 runs. The difference between the averaged model velocities from each simulation (Present-1879) was calculated for each grid point at every time. Then root-mean square (RMS) of the difference was calculated over the 3D grid at each time, yielding a time series of rms velocity difference. A thirty-day running mean was applied to each time series. The first time period selected for analysis, T1, corresponds to model days 150-180, the second, T2, corresponds to days 370-400, and third, T3, to model days
The mean freshwater inflow for T1, T2, and T3 is 5.4 million m$^3$ d$^{-1}$, 1.6 million m$^3$ d$^{-1}$, and 31.2 million m$^3$ d$^{-1}$, respectively (Table 1). However, a very high freshwater impulse occurred about 100 days before the start of T2 (Fig. 6). During T1 mean wind speed is 1.1 m s$^{-1}$ and the mean direction is -197.4 (degr) (Table 1) (Figs 7 & 8, resp.) For T2, the mean wind speed is 0.6 m s$^{-1}$ and the mean direction is 60.5 (degr) (Table 1) (Figs 7 & 8, resp). For T3, the mean wind is 2.68101 m s$^{-1}$ and the mean wind direction is 77.2 (degr) (Table 1, Figs 7 & 8).

In order to capture the baroclinic structure of the residual circulation the averaged model fields of salinity and velocity are examined across the model surface (level 1 of the model) and near-bottom (level 9 of the model). Differences in the variables (salinity and velocity) between the two simulations (present and 1879) are examined for T1, T2, and T3.

For estimating transport time each model grid cell was seeded with 100 particles and then run for three, 90 day time periods, T1r, T2r, and T3r. The 90 day time periods begin at the same start time as T1, T2, and T3. The mean freshwater inflow for T1r, T2r, and T3r is 5.5 million m$^3$ d$^{-1}$, 2.7 million m$^3$ d$^{-1}$ and, 22.9621 million m$^3$ d$^{-1}$, respectively (Table 1) (Fig. 9). During T1r mean wind speed is 0.462738 m s$^{-1}$ and the mean direction is -194.4 (degr) (Table 1) (Figs 10 & 11, resp). For T2r, the mean wind speed is 1.1 m s$^{-1}$ and the mean direction is 47.0 (degr) (Table 1) (Figs. 10 & 11, resp.). For T3r, the mean wind is 3.2 m s$^{-1}$ and the mean wind direction is 68.0961 (degr) (Table 1, Figs 10 & 11).

In this study, transport time is defined as the amount of time for the number of particles N, to drop below the e-folding threshold N0/e, where N0 is the initial number of particles and e=2.71828. Two calculations are performed. The first is the flushing time.
In this case $N$ is only a function of time, and $N = N(t)$, is the total number of particles in the bay. The particle count $N(t)$, is fit with an exponential function $A \exp(t/F)$, where $A = 1$. The value of $FT$ is the flushing time. The second calculation is residence time where $N$ is a function of both space and time, and $N = N(x,y,t)$ is the total number of particles in the water column of each grid cell. For this calculation $N$ does not fit an exponential curve. Residence time (RT) is defined as the last time, within the period of the calculation, where $N$ drops below $N_0/e$. Also, twenty five hour averages of $N$ are used in order to filter out the tidal signal.
RESULTS

Salinity

Surface

Overall surface salinity in both (present & 1879) simulations is higher at the mouth of the bay and lower at the head of the bay. This gradient varies over time, with T1 having the weakest gradient (34 to 33psu) and T3 having the strongest (27 to 17psu). The biggest salinity differences between the present and the 1879 run occurs during T3, up to 5 psu near the head of the bay.

The present surface salinity during T1 is around 34 psu at the mouth of the bay, and about 33 psu at the head of the bay (Fig 12). The surface salinity for 1879 run is almost the same as the present (Fig 13). For the present run, bay salinity is < 0.5 psu lower throughout most of the bay than in the 1879 run (Fig 14). In Lower Tampa Bay (LTB) around the Northern section of the Sunshine Skyway Bridge (SSB), the salinity is <0.5 psu higher than in the 1879 run (Fig 14).

During T2, for the present salinity run, a salinity tongue stretches from the mouth of the bay into Middle Tampa Bay (MTB), the mouth of the bay is around 33psu and about 27psu at the head of the bay (Fig 15). In the 1879 run the salinity tongue is much wider, and there is a weaker salinity gradient in Old Tampa Bay (OTB) than in the present run (Fig 16). The present run is <1 psu higher in upper Tampa Bay, and <1 psu lower in LTB than in the 1879 run (Fig 17) The present salinity run is also higher by
about 2 psu near river inputs in Hillsborough Bay (HB), the Howard Franklin Bridge (HFB) and the Gandy Bridge (GB) (Fig 17). The present salinity run is around 2 psu lower near the Northwestern part of the SSB, and about 3 psu lower around the Northeastern part of the Courtney Campbell Causeway (CCC) (Fig 17).

For T3, the present run is about 27 psu at the mouth of the bay where a salinity tongue stretches past the SSB, decreasing in salinity to about 17 psu in OTB (Fig. 18). Nearly half of these gradients occur within OTB (Fig 19). The salinity structure in the 1879 run is similar to the present, except in 1879, the salinity tongue is much wider at the mouth of the bay and in HB the salinity gradient is weaker (Fig 20). For the present run, salinity is about 3-5 psu higher in the Eastern part of HB and <1.5 higher in OTB as compared to the 1879 run (Fig 21). The present run is lower by about 2.5psu near the Northeastern side of the CCC, and <1-3 psu lower around the Northwestern part of the SSB (Fig 21).

**Bottom**

Baywide bottom salinity in both (present & 1879) simulations is higher at the mouth of the bay and lower at the head of the bay. These salinity gradients vary over time with the strongest gradient (28-17psu) in T3 and the weakest (34-33psu) in T1. In both runs, a salinity tongue stretches from the mouth of the Bay into MTB. This tongue is narrower in width and stretches further into MTB in the present run. The tongue stretches furthest in the present run during T3.

Present bottom salinity for T1 is about 34psu at the mouth of the bay and around 33psu at the head of the bay (Fig 22). The horizontal salinity structure for the 1879 run is
almost the same as the present run (Fig 23). The salinity over the entire bay is <0.5 psu lower in the present run than in the 1879 run, except the area around the North portion of the SSB, where it is <0.5 psu higher in the present (Fig 24).

During T2, for the present bottom salinity, a saline tongue stretches from the mouth of the bay and narrows into MTB (Fig 25). Salinity at the mouth of the bay, for the present run, is about 33psu and around 27 psu at the head, with more than half of the salinity gradient occurring in OTB (Fig 26). In the 1879 run, the salinity tongue is wider and does not stretch as far into MTB as in the present run (Fig 27). For the 1879 run, the salinity gradient in OTB is weaker than in the present run (Fig 28) Compared to the 1879 run, the present run is 2-3 psu higher in HB near the river inputs and 1.5-2.5 psu higher around the HFB and the GB (Fig 29). For the present run, salinity is 1-3 psu lower around the Northeastern section of the CCC and 1.5-2 psu lower around the Northwestern part of the SSB (Fig 29).

Bottom salinity during T3 for the present run, has a salinity tongue that stretches from the mouth of the bay, and narrows into strips in MTB (Fig 30). The salinity at the mouth of the bay for the present run is about 28 psu and 17 psu at the head (Fig 30). The bottom salinity structure for the 1879 run is similar to the present, except the tongue is wider and does not narrow into pronounced strips (Fig 31). Compared to the 1879 run, the present run is 2-3 psu higher in upper HB, and 2.5-3 psu higher in the areas just west of the land spoils and around river inflows (Fig 32). In MTB the present salinity run is higher by about 2-3 psu (Fig 32). In OTB the present run is 1-2 psu higher, except around the Northeastern portion of the CCC where salinity is lower by 1.5-2 psu. (Fig 33) The area around the Northwestern section of the SSB is 1.5-2.5 psu lower in the present run.
than in the 1879 run (Fig 32).
Velocity

Surface

In both simulations, residual surface velocity is seaward and is strongest in HB around the dredge spoils, in OTB and through the gaps in the CCC, the HFB, the GB, and in LTB around the SSB. The highest velocities seen are during T3 for both runs.

During T1, surface residual flow in Tampa Bay is seaward at about 2-4 cm/s, except the southern part of OTB where velocity is about 4-8 cm/s, and near the mouth of the bay where velocities range up to 20 cm/s (Fig 34). The difference in residual velocity between present and 1879 for T1 is 1cm/s or less except near the mouth of the bay where the difference is about 3-5cm/s (Figs. 35 & 36).

During T2, surface velocity is <4cm/s, except near the bridges/causeways, the channels and the mouth of the bay, where velocities are around 4-8 cm/s (Fig. 37). Surface velocity for the 1879 run has a similar pattern (Fig. 38). Surface velocity in Hillsborough bay is 4-6cm/s stronger in the present run than in the 1879 run (Fig. 39). Also during T2, areas around the openings of the CCC, the HFB, and the GB, have a surface velocity that is around 4-10 cm/s stronger in the present run than in the 1879 run (Fig. 39). As compared to the 1879 run, the surface velocity in the present run is about 4-6 cm/s stronger in a strip from middle Tampa Bay down to mouth of the Bay and around the SSB (Fig. 39).

During T3, residual surface velocity is seaward from about 4-8 cm/s, with velocities ranging from to 10-20 cm/s near the openings of the causeways/bridges, and
over the channels (Fig. 40). Compared to the 1879 run, the present run, during T3 has a surface velocity up to 10 cm/s stronger around the spoils in and near river inputs in HB (Figs. 41 & 42). The present run is also around 3-6cm/s stronger throughout the rest of HB (Fig 42). In OTB, the surface velocity in the present run is about 10cm/s stronger around the openings of the CCC, the Howard HFB, the GB, and the SSB (Fig. 42). In MTB the surface velocity is 4-6 cm/s stronger in the present run, and 8-10 cm/s stronger in LTB (Fig. 42).

**Bottom**

In the present run, bottom velocity in the bay is generally a landward flow of about 2cm/s. During T1, there is little change in velocity between the two runs, only a 1cm/s or less difference, near the mouth of the bay, and near the opening of the SSB (Figs. 43, 44, & 45). During T2, flow is generally landward by about 2cm/s or less, 4cm/s or less in the channel. The difference in velocity is about 1-4cm/s stronger for the present run in the channels, the dredge spoils in HB, and through the openings of causeways/bridges, except the CCC where the difference ranges up to about 8cm/s (Figs. 46, 47, & 48). Flow during T3 is almost the same as T2 with the increased flow associated with the channels being more extensive (Figs. 49, 50, 51).
Transport Time

Flushing Time

Flushing time for the present run, as compared to the 1879 run, is longer in both T1r and T2r, with the longest residence time occurring during T1r (Figs. 52 & 53). During T1r, for the present run, residence time is 187 days and is 144 days for 1879 run (Figs. 52 & 53). Residence time during T2r, for the present run is 97 days and 85 days for 1879. T3r residence time for the present is 27 days and is 32 days for the 1879 run (Figs 52 & 53).

Residence Time

Residence time across the bay varies locally from a few days to 90 days (the limit of this study’s computation). In HB residence times are relatively short compared to the rest of the bay. In OTB, the area north of the CCC, and the lower area in the western region of OTB both have short residence times as well. MTB near/in the channels, residence time is locally long during T1 and T2, but locally short during T3. On the Eastern side of OTB between the bridges, residence time is locally long, in the present run but short in the 1879. LTB has locally long residence times at the mouth of the bay and locally short residence times to the North of the SSB, in the present run, which is the opposite of the 1879 run.

During T1r, the Present day residence time is around 45 days near the dredging spoils in Hillsborough Bay, which is about 25 days longer than the 1879 simulation (Figs. 54 & 55). The local residence time, north of the CCC, is around 20 days for the present run and around 70 days for the 1879 run (Figs. 54 & 55). Between the HFB and the GB on
the Eastern side, local residence time for present run is about 75 days and about 20 days in the 1879 run (Figs. 54 & 55). MTB around where the channels run, residence time is about 60-75 days in the present and 50-70 days in the 1879 run. On the Eastern flanks of MTB, local residence time for the present run is approximately 45 days and is approximately 20 days for the 1879 run (Figs. 54 & 55). Local residence time near the Eastern portions of the SSB for the present run is 35-70 days and 5-20 days for the 1879 run (Figs. 54 & 55). The Western portion of the SSB is 5-35 days for the present run and 5-10 days for the 1879 run (Figs. 54 & 55).

Residence time during T2r in HB around the dredge spoils, is about 60 days for the present run and is about 20 days for the 1879 run (Figs. 56 & 57). In OTB, North of the CCC, residence time is about 5 days for the present run and about 10 days for the 1879 run (Figs. 56 & 57). On the Eastern side of Old Tampa Bay (OTB), between the HFB and the GB, the local residence time for the present run is approximately 45 days and is approximately 20 days for the 1879 run (Figs. 56 & 57). During T2r there is not a visible area of residence time that is associated with the channels. In MTB on the Eastern side, the present run is about 80 days and is about 40 days for the 1879 run (Figs. 56 & 57). The Western flank of MTB is around 40 days in the present and around 20 days in 1879 run (Figs 56 & 57). The local residence time near the Eastern portions of the SSB for the present run is 45-75 days and 20-35 days for the 1879 (Figs. 56 & 57). The Western portion of the SSB for the present is 5-40 days and 30-35 days for the 1879 run (Figs. 56 & 57).

During T3r, local residence time in Hillsborough Bay is about 10 days for the present run, and about 5 days for the 1879 run (Figs. 58 & 59). In OTB North of the
CCC, local residence time is approximately 5 days for the present run and approximately 7 days for the 1879 (Figs. 58 & 59). The channels in MTB have a residence time of about 15-25 days for both runs, except the part of the channel near the SSB where during the present run it is about 35-65 days and about 10-35 days in the 1879 run (Figs. 58 & 59).
DISCUSSION

Salinity and Velocity

The flow pattern observed in Tampa Bay is a typical two-layered estuarine flow, a process first described by Pritchard (1956). Salinity contrast from the head to the mouth of the bay, sets up an axial pressure gradient that drives a non-tidal gravitational circulation in the bay (Galperin et al 1992a,b, Weisberg 2005). Internal pressure gradient force drives flow into the bay in the deeper channels (Galperin et al 1992a,b, Weisberg 2005). External pressure gradient force drives flow out of the bay at shallower depths (Galperin 1992a,b, Weisberg 2005).

Residual circulation is greatly modulated by freshwater influx. T1 and T2 both have low freshwater inflow (5.5 million m$^3$d$^{-1}$or less). A large freshwater inflow pulse occurred about 100 days before the start day of T2. This impulse caused the density gradient to be stronger in T2 than in T1, despite the fact that T2 had the lowest mean freshwater inflow. This higher density gradient resulted in T2 having a stronger residual circulation, compared to T1. T3 features the greatest amount of freshwater inflow and corresponds to the time period with the greatest salinity gradient and the strongest residual circulation in both the present and the 1879 simulations.

During T3, the salinities in upper MTB, lower HB and OTB are higher in the present run than in the 1879. This is a result of more extensive channels and a greater pressure gradient associated with the added depth of the channels. Salty Gulf of Mexico
(GOM) water is funneled at depth up Tampa Bay through the channels, which is a baroclinic consequence of increasing depth. The baroclinic contribution to the pressure gradient force is due to the vertical integral of the horizontal salinity gradient, and this integral is largest in the channel, see e.g., Galperin 1992a,b, and Weisberg 2005).

The relatively high surface velocities seen in lower Western HB, in both runs, are the result of water convergence due to bay geometry. Higher surface velocities in HB during the present run are the result of water converging and diverging around dredge spoils (which are not in the 1879 run). Higher bottom velocities in eastern HB are also the result of a stronger internal pressure gradient that exists in the present run due to a more extensive, deeper channel.

Three bridges/causeways exist in OTB for the present run. In OTB, the cells adjacent to the Northeastern portion of the CCC has a lower salinity in the present run during T3 because the CCC impedes circulation by trapping freshwater input from upper OTB. The strong velocities seen in OTB during T2 & T3 for the present run result from water converging and diverging around the bridges/causeways, through their narrow openings. These infrastructures do not exist in the 1879 run and these strong velocities are not seen in that run. Of the bridges/causeways, the CCC has the strongest velocities through its opening and it also has the narrowest opening.

In the present, the salinity tongue at the mouth of the bay must converge and squeeze through the SSB, resulting in a narrower tongue in the present run than the 1879 run, as the SSB does not exist in the 1879 run. This constriction associated with the SSB also causes velocities to be higher, as water converges and diverges in order to moves through the narrow opening. In MTB, the internal pressure gradient force is larger in the
present run due to a deeper channel. This causes more saline Gulf of Mexico (GOM) water to be funneled into MTB, thus contributing to the higher salinities and stronger velocities seen in the present run. This feature is most prominent during T3, when salinity gradients are the largest, and thus the pressure gradient is the strongest.

**Transport Time**

T1r has the longest flushing time, and is the period with the weakest salinity gradient and residual circulation. T3r has the shortest flushing time and is the period with the strongest density gradient and residual circulation. Flushing time is longer in the present run than the 1879 run, except during T3r, where the 1879 run is 5 days longer. The biggest difference between the runs is during the time when the residual circulation is the weakest, suggesting that this is time period when the bathymetric alterations have the greatest effect on circulation.

Regions of distinct geometry/flow regime tend to behave as “units” with regard to residence. Here, channels are associated with long residence times (60-90 days) during T1r and T2r (relatively dry periods) and short residence times (5-30 days) during T3 (relatively wet period).

In T2r, residence times associated with the channels is not distinguishable as in the other time periods. During T2r, residence times in the main segment of the bay are short on the west side and long on the east side. This could be because there was a strong eastward wind in T2r that occurred during the last 10 days of the simulation period. The eastward wind possibly moved particles to the eastern section of the channels and to the
shallow eastern flanks of MTB. Then the simulation period ended, possibly before mixing could take place, and the particles could be moved.

The SSB, which only exists in the present run, is also associated with longer residence times as it impedes bay inflow and outflow and traps particles in areas immediately surrounding the infrastructure. South of the CCC in OTB, particles become trapped and restricted by the bridges/causeways, causing a longer residence time in the present run, with the longest residence time occurring in T1r, the period with the weakest residual circulation. This effect is also most prominent on the eastern side of OTB, south of the CCC, because the flow is weaker here than in the western side. The western side has stronger velocities that are associated with natural bay geometry. These longer residence times associated with flow constrictions do not occur in the 1879 run as these infrastructures do not exist.

Upper OTB, North of the CCC, has a locally short residence time due to tidal rectification, which is most pronounced during T3r, when residual circulation is the strongest. This effect is exaggerated further in the present run by the magnified velocity through the opening of the CCC, a result of the water constriction by the infrastructure.

The calculation of flushing time is an exponential curve, so the introduced mass never completely leaves the system and flushing is never complete. It only reflects the average amount of time the mass spends in a system.

Flushing time in the present run during T1r, and T2r is probably longer than in the 1879 because of the impediment of circulation caused by the bridges/causeways, and from particle entrapment associated with the channels during weak residual circulation. For T3r, flushing is probably shorter in the 1879 run as compared to the present run.
because it has a strong residual circulation. It is possible that the channels do not entrap particles when residual circulation is strong. Strong residual circulation enhances flow in the channels, and because the present run has deeper more extensive channels, flow is stronger and thus flushing time is shorter than in the 1879 run. Also, the causeways/bridges do not appear to impede circulation as much during a strong residual circulation. These effects may be why the biggest difference in flushing time between the present and 1879 runs is during T1r, a time with the weakest residual circulation. T3r has the strongest residual circulation and the difference in flushing time between runs is the smallest, demonstrating that these infrastructures are not greatly effecting flushing during this time.
CAVEATS

1) The model output is not data, the results are numerical approximations.

2) This study did not take into account potential numerical vorticity errors that could have resulted due to the steep topography at the mouth of the bay.

3) This study did not attempt to reconstruct the circulation of the bay in 1879, as it did not use/recreate boundary conditions that would have existed.

3) When calculating transport time, the open boundary condition at the mouth of the bay did not allow for particle re-entry or for non-zero concentration input to the domain, which could possibly effect transport time.

   It is important to emphasize that any modeling effort that attempts to stimulate realistic flow field dynamics is greatly influenced by the quality of boundary condition data used to force the model and by the data used to validate the flow fields’ characteristics. This thesis attempted to simulate the dynamics of the bay in a realistic manner by using high resolution environmental data inputs to the model, when available. Even when great care is taken, there are limitations of all modeling exercises that must be borne in mind when interpreting the results, especially when applying them to environmental effects.
FUTURE WORK

Possible future research includes:

1) A finer bathymetric grid should be added in order to better resolve the channels.

2) Since the model open boundary concentration is set at zero at the mouth of the bay, it does not allow for particles or concentration to exit the bay and then re-enter. A larger model domain is needed to test the influence of re-entry on residence time.

3) Bay geometry should be altered in the model to better determine which features play the most significant role in altering transport time (e.g. remove just the bridges and/or causeways).

4) Various bridge/causeway configurations should be modeled to assess their impact on bay circulation and transport time (e.g. double the size of bridge/causeway openings, and/or add more openings).

5) Specific wind fields should be modeled with specific bathymetric alterations to determine specifically how each combination affects bay circulation and transport time.
Figure 1. Bridge and causeways spanning Tampa Bay.
Figure 2. Present bathymetric grid for Tampa Bay, FL.
Figure 3. 1879 Bathymetric grid for Tampa Bay, FL.
Figure 4. Bathymetric grid difference, Present - 1879.
Figure 5. Differenced residual RMS speed, grey strips indicate the three 30day periods selected for analysis.
### Conditions for Model Experiments

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<th>RMS Wind Speed (m s$^{-1}$)</th>
<th>Mean Wind Speed (m s$^{-1}$)</th>
<th>Mean Wind Direction (deg True)</th>
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Table 1. The conditions during the model time periods examined. Given are the start date and duration of the time period, the mean total freshwater, rms wind speed, and mean wind during the duration of the time period indicated.
Figure 6. Tampa Bay Freshwater Inflow graph, boxes indicate the three 30day periods selected for analysis, T1, T2, and T3 respectively.
Figure 7. Tampa Bay Model wind speed, boxes indicate the three 30day periods selected for the analysis, T1, T2, and T3 respectively.
Figure 8. Tampa Bay Model direction speed, boxes indicate the three 30day periods selected for the analysis, T1, T2, and T3 respectively.
Figure 9. Tampa Bay Freshwater Inflow graph, boxes indicate the three 90day periods selected for the residence time analysis, T1r, T2r, and T3r respectively.
Figure 10. Tampa Bay Model wind speed, boxes indicate the three 90-day periods selected for the residence time analysis, T1r, T2r, and T3r, respectively.
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Figure 47. Residual bottom velocity during T2 for the 1879 run.
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Figure 52. Flushing time in days during T1 (bold solid line) 187 days, T2 (solid line) 97 days, and T3 (dotted line) 36 days for the Present run.
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Figure 58. Residence time during T3r for Present run.
Figure 59 Residence time during T3r for the 1879 run.
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