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TITLE

"One dimensional hydraulic analysis of the effect of sea level rise on estuarine salinity"

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ABSTRACT

Projections of global climate change over the next century indicate that multiple stresses to coastal ecosystems are expected. Sea level rise is one effect of climate change that may significantly alter current estuarine habitats, resulting in the need to modify current management strategies. A one dimensional (1D) hydraulic analysis was completed for the Caloosahatchee Estuary to determine the potential effects of sea level rise on the salinity distribution in the estuary. Typically, water quality analysis of estuaries is completed with sophisticated three dimensional (3D) models that are proprietary. HEC-RAS version 4.1 is relatively simple, publicly available software that has water quality analysis capabilities applicable to estuaries. We applied the 1D hydraulic and water quality capabilities of HEC-RAS to evaluate salinity distributions in the Caloosahatchee Estuary. The model was successfully calibrated and thus sufficient for scenario analysis of changing sea level boundary conditions. Results showed that under current management strategies, a 0.9 m rise in mean sea level could result in a 4.5 ppt increase at the point of regulatory compliance. Under those conditions, the total managed inflow to the estuary would need to be increased from 14.2 m^3/s to 22.9 m^3/s to maintain current habitats. Additionally, a 0.9 m rise in sea level could reduce the rate of salinity reduction in the estuary under high flow conditions from 0.50 ppt/day to 0.28 ppt/day, with no observable effect on the rate of salinity increase under no flow conditions.

IMPORTANCE OF COASTAL ESTUARIES

Estuaries are semi-enclosed bodies of water subject to both tidal and freshwater inflows. As a result, estuary ecosystems are comprised of organisms that are tolerant to variations in salinity resulting from incoming and outgoing tidal flows. Estuaries inhibit eutrophication of marine water bodies by utilizing the nutrients transported by freshwater inflow. Estuaries protect marine water bodies by removing contaminants from freshwater inflows as well (Kennedy *et al.* 2002).

The high nutrient loading common to estuaries results in highly productive plant communities. The plant communities found in estuaries provide a highly productive habitat for marine organisms. Coastal estuaries in the United States provide habitat for 75 percent of commercially harvested fish and shellfish, as well as provide a significant food source for migratory birds that travel the central flyway (Environmental Health Center, 1998).

ESTUARINE STRESSES FROM CLIMATE CHANGE

Global climate change is projected to alter sea surface temperature, hydrologic processes, marine water quality, and mean sea level. It is estimated that increases in sea surface temperature of up to 3°C can be expected by 2100 (IPCC 2007). Increases in sea surface temperature have the potential to: (1) decrease dissolved oxygen; (2) increase dissolved oxygen demand by increasing the rate of organic matter loading resulting from an increase in biomass production and subsequent decay; (3) reduce habitat for cool water species such as macroinvertabrates.

As outlined by the Intergovernmental Panel on Climate Change (IPCC 2007) it is projected that global climate change will increase storm intensity resulting in higher annual precipitation, but also increase the frequency of drought, with significant variations in climate patterns across the globe. Estuaries could be impacted from increased storm intensity due to increased contaminant loading from urban runoff, increased water column stratification caused by variations in density of freshwater inflows versus brackish/saline water found in the estuary, and flushing of organic matter and organisms out of the estuary during flood conditions. If the frequency of drought were to increase in a region, estuaries could receive reduced flows from viable freshwater tributaries, desiccation of wetland soils, toxic levels of hypersalinity for certain seagrass species, and the reduction in the inflow of nutrients and organic matter (Mulholland *et al*. 1997).

The IPCC estimates that sea level rise over the next century will range between 18 and 81 cm (IPCC 2007). The IPCC estimates that sea level rise will exceed currently observed trends because of the accelerating effect of climate change with increased global temperatures. Increases in temperature are expected to cause expansion of ocean water, melting of glaciers and ice caps, and portions of the ice sheets on Antarctica and Greenland to slide into the ocean (IPCC 2007). The IPCC estimates of sea level rise were completed for two scenarios. The first scenario, called the low scenario, assumes economic growth will occur at a slower than current rate, and the global economy will shift to be more service- based. The second scenario, called the high scenario, assumes global economic growth will occur at the current rate, and the global economy will maintain the current focus with a fossil fuel incentive. The expected range of sea level rise for the low scenario is 18 cm to 38 cm, and 25 cm to 58 cm for the high scenario. Neither scenario of sea level rise incorporates the rise in sea level associated with polar ice sheets sliding into the ocean, which would cause an additional rise of 23 cm. Therefore, the upper limit of the high scenario, coupled with movement of the polar ice sheets, would result in a sea level rise of approximately 81 cm.

The effects of sea level rise will be most devastating to coastal zones. The EPA estimates that nationwide 5,000 square miles (12,950 square kilometers) of land is within 2 feet (0.6 m) of high tide (EPA 2010). Therefore, the projected sea level rise will cause a significant loss of shoreline, including coastal wetlands. In addition to land loss, sea level rise will increase shoreline erosion, increase flooding in areas that are directly hydraulically connected to the ocean, and increase salinity in estuaries, rivers, and coastal aquifers (EPA 2010).

EFFECTS OF SEA LEVEL RISE ON ESTUARIES IN THE SOUTHEAST UNITED STATES

Estimation of the effects of sea level rise on estuaries in the Southeastern U.S. has typically been completed using statistical analysis. There have been few studies that determined the potential effects of alterations in the hydrology due to climate change, or the alteration in salinity resulting from sea level rise (Marshall *et al*. 2008).

A series of studies were completed by the U.S. Geologic Survey (USGS) that incorporated the hydrologic alteration occurring from climate change, and associated changes in salinity due to sea level rise. The studies were completed to determine the potential effects on drinking water sources in the Southeastern U.S. An Artificial Neural Network (ANN) was developed by Conrad et al. (2010a, b) to determine the potential effects of sea level rise on the Grand Strand of the South Carolina coast and the Lower Savannah River. The ANN was developed with between 15 and 20 years of hourly streamflow, water quality data, and water-level data. The projected alterations to current hydrologic processes were incorporated into the ANNs, and the projected increase in mean sea level was evaluated incrementally. The results of the study for the Grand Strand of the South Carolina coast estimated that, near a municipal freshwater intake, a sea level rise of 0.3 m would increase the frequency of specific conductance above 2,000 μS/cm to 4 percent, which is a two fold increase. A 0.6 m increase in mean sea level was estimated to increase the frequency of specific conductance concentrations above 2,000 μS/cm to 9 percent. The results for the study of the Lower

Savannah River provided similar results, indicating the relative magnitude of salination of drinking water sources.

An evaluation of the effects of sea level rise on the salinity distribution of Florida Bay was completed by the Army Corps of Engineers (ACOE). The effect of sea level rise was analyzed by direct and indirect methods. The direct method analysis consisted of the development of a Sea Level Affecting Marshes Model (SLAMM), and altering the mean sea level at Key West to determine the resulting modification in salinity distribution in Florida Bay. An evaluation of the dependence of the effects of sea level rise to water table elevation in the Everglades was completed as well. The indirect method analysis was completed by altering the salinity of an open Gulf monitoring station, and determining the effects on the salinity regime in Florida Bay using univariate models. The study estimated that the effects of sea level rise of 50 cm would result in the increase of 1-2 practical salinity units (psu) of near shore embayments, and that the salinity of Florida Bay was much more sensitive to freshwater stage in the Everglades than mean sea level (Marshall *et al*. 2008).

In my study, my overall goal is to provide a simple evaluation of changing sea levels on an important estuary in southwest Florida, applying a 1D hydraulic simulation model to make relative comparisons of salinity distributions under a range of sea level rise scenarios.

AREA OF STUDY

In order to determine the potential effects of sea level rise on salinity in a Florida estuary, a water body was chosen that is currently under legislative regulation for salinity. The purpose for selecting a legislatively regulated estuary is that in order to establish the legislated rule, intensive study of the estuary was necessary to provide technical justification for the implementation of the regulation. The Caloosahatchee Estuary (Figure 1) is currently regulated under the Florida Minimum Flows and Levels (MFL) Rule, and has been thoroughly analyzed during the development of the MFL Rule; including detailed ecological, hydrologic, and water quality analysis. The results of the various analyses have provided a series of criteria required to maintain the viability of the estuary. The modification of these criteria as a result of sea level rise will help to quantify the potential ecological risk.

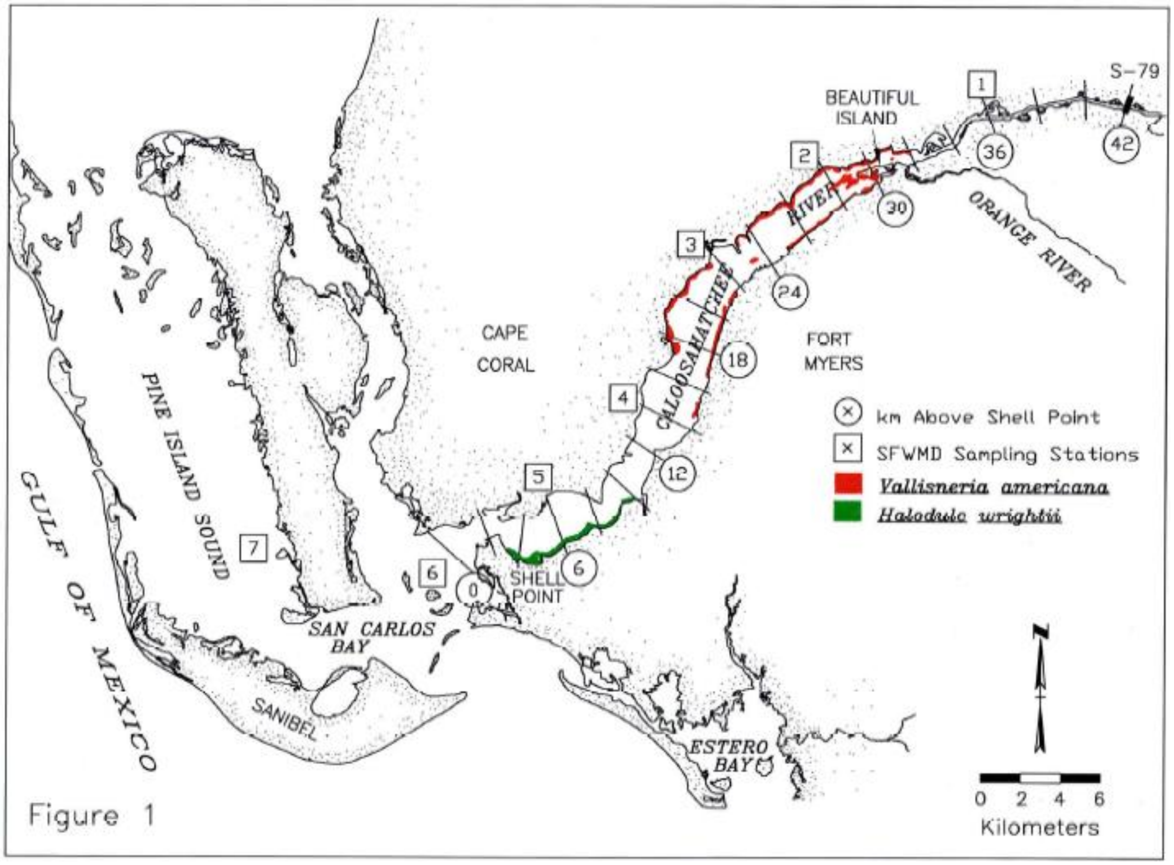

FIGURE 1. Map of Caloosahatchee Estuary (Chamberlain, et al. 2003)

The Caloosahatchee Estuary is located in Southwest Florida near the city of Ft Myers. The estuary originates near the W.P. Franklin Lock & Dam (S-79), and drains to the Gulf of Mexico through San Carlos Bay. S-79 is used to control the stage in the Caloosahatchee River, regulate discharge into the estuary, and prevent upstream migration of salinity. The contributing watershed to the estuary is 3,400 square kilometers, is classified as subtropical, and receives a total annual rainfall of 135 cm. The rainfall in the watershed is seasonal, with 71 percent of the total rainfall typically observed between the months of June and October. The estuary habitat consists of mangrove forests along undeveloped shorelines, shallow bays, an abundance of seagrasses, and sand flats (SFWMD 2000). The estuary ranges in width from 0.2 km at S-79 to 2.4 km at Shell Point, and has a total flow length of 42 km (Scarlatos 1988).

Inflows to the estuary are comprised of runoff and baseflows from the east and west Caloosahatchee basins, regulatory releases from Lake Okeechobee via S-79, and runoff and baseflows from the tidal Caloosahatchee basin; which represent 58 percent, 19 percent, and 22 percent of the total basin inflow, respectively. Annual total basin inflow is estimated to be 1,887 Mm^3 per year (Konhya 2003). Regulated releases are typically completed for two purposes, with releases during the dry season occurring for ecological benefit of the estuary, and releases during the wet season occurring for flood control purposes. The variation in salinity in the estuary resulting from variation in the regulatory releases can cause irregular fluctuations that exceed the tolerance of both the oligohaline and the marine species that inhabit the estuary (Edwards et al. 2000).

The Caloosahatchee Estuary has been impacted by anthropogenic stresses of increased storm water runoff rates, reduction in natural storage, and the increase in fresh water consumption. These stresses have led to concerns about the future health of the estuary, resulting in an extensive effort to restore the natural hydrology to the estuary. Projected sea level rise will increase salinities in portions of the estuary and thus impact seagrass beds, compounding the difficulty of protecting and restoring this resource. Additionally, the estuary is unable to adjust to the effects of sea level rise due to the salinity partition imposed by S-79, where oligohaline species would otherwise be able to migrate upstream in the occurrence of increased salinities in currently occupied habitats. Importantly, the effects of sea level rise have yet to be quantified for the estuary, and could have a significant impact on the management plan for the estuary, especially the legally required MFL.

FLOW REGULATION RULES AND SALINITY

Florida water management agencies are required to develop rules which describe the minimum allowable quantity of managed freshwater flows that are necessary to maintain the ecology of targeted water bodies in the state. The determination of such Minimum Flows and Levels (MFL) needed for the ecology of the Caloosahatchee Estuary is a highly contested issue between various stakeholders.

Water Management Districts are the primary agencies responsible for the development of the MFL Rules for all priority water bodies in Florida. The establishment of MFL Rules is required under subsection 373.042(2) of the Florida Statutes (F.S.). MFL Rules are designed to prevent any significant harm to Florida water bodies by determining the minimum flow necessary to allow for habitat preservation, beneficial use, and allocated consumptive use. Minimum levels are developed for lakes, wetlands, and aquifers, and minimum flows are developed for rivers, streams, and estuaries. Once MFL Rules have been implemented they are commonly used to evaluate whether any further consumptive use from a water body is permissible, and to help develop operation protocols for water control structures (SFWMD 2011).

In accordance with Florida law, Districts must use the best available information and methods to develop MFL Rules. Therefore, extensive evaluations are necessary to determine the extent and frequency that flows and levels can be reduced without causing significant harm, where significant harm is defined as the loss of water resource function that will take more than two years to recover. Due to the complex interactions that occur within natural water bodies, it is commonplace for models to be implemented when developing technical justifications for MFLs. Depending on the complexity of the hydrologic interactions occurring within a water body, statistical and simulation models for hydrology, hydraulics, water quality, and ecology may be required (SFWMD 2003).

In September 2000 the South Florida Management District first proposed the MFL Rule for the Caloosahatchee. The September 2000 report identified the 640 acre bed of seagrass species *Vallisneria americana*, commonly known as wild celery, as the primary resource within the Caloosahatchee that would be affected from reduced freshwater flows. The wild celery habitat in the Caloosahatchee estuary is located in the low salinity zone between Ft Myers and S-79. Wild celery is a seagrass that is adapted to low salinity zones of an estuary, and therefore increases in salinity in the upper portion of the Caloosahatchee Estuary would result in losses of that habitat (Edwards et al. 2000).

Using the best information known on the salinity requirements of wild celery, SFWMD (2003) used a simple regression model of flow at S-79 vs. salinity within the wild celery habitat to estimate the freshwater inflow required at S-79 to maintain appropriate salinities for that habitat.

The MFL Rule for the Caloosahatchee was adopted in September 2001, after an independent panel of reviewers (Edwards et al. 2000) concluded that the scientific basis for the Rule was the best information available at the time.

The 2001 MFL rule states that:

> "A minimum mean monthly flow of 300 cfs (8.5 m^3/s) is necessary to maintain sufficient salinities at S-79 in order to prevent a MFL exceedance. A MFL exceedance occurs during a 365 day period, when:
> (a) A 30-day average salinity concentration exceeds 10 parts per thousand at the Ft. Myers salinity station (measured at 20% of the total river depth from the water surface […]; or
> (b) A single, daily average salinity exceeds a concentration of 20 parts per thousand

at the Ft. Myers salinity station.
Exceedance of either paragraph (a) or (b), for two consecutive years is a violation of the MFL."

The initial study that was completed to determine the MFL for the estuary predicted that the MFL criteria would be frequently exceeded (i.e., significant harm to the wild celery community would occur) under 2000 operation protocols for controlled releases to the estuary from Lake Okeechobee. Therefore, the MFL study and the MFL Rule included a science-based strategy for prevention and recovery for the MFL exceedances. The prevention and recovery strategy included additional storage in the freshwater portion of the basin to be used during low flow conditions, revised operational protocols, revised consumptive use permitting procedures, and required continual refinement of the MFL if and when needed (Edwards et al 2000).

A peer review of the MFL study completed in 2000 by the USGS and various academic institutions identified four major areas of concern (SFWMD 2003); they are, lack of a hydrodynamic/salinity model, lack of a numerical population model for *Vallisneria americana*, no quantification of the habitat value of *Vallisneria* beds, and lack of documentation of the effects of MFL flows on downstream estuarine biota (SFWMD 2003).

This led to research efforts to further support the MFL criteria and refine the "prevention and recovery" strategy for the Caloosahatchee Estuary (SFWMD 2003). A variety of research efforts were utilized. Monitoring data were used to evaluate the effects of the salinity variations on fish larvae, plankton, and oysters; field monitoring and mesocosm experiments were performed to determine the maximum allowable salinity concentrations within the estuary that is protective of the current ecosystem (Doering 2003); a hydrodynamic model was applied to determine the salinity distribution in the estuary for various flow conditions (Qiu 2003); and a basin model was developed to determine the expected freshwater flow contribution to the estuary from the tidal portion of the basin (Konyha 2003).

Field monitoring and mesocosm experiments were performed to evaluate the sensitivity of wild celery to increased concentrations of salinity, as part of the MFL Rule technical justification (Doering 2003). Doering (2003) determined that wild celery growth decreased as salinity increased, and that mortality rates increased when salinity concentrations exceeded 15 ppt. It was determined that salinities greater than 18 ppt would cause a 50 percent mortality within 38 days, and a salinity of 20 ppt would cause a 50 percent mortality within 16 days. The field monitoring and experiments demonstrated that wild celery can withstand salinities less than 10 ppt for greater than a month and salinities less than 20 ppt for 3 days. Therefore, salinities of 10 ppt and 20 ppt were chosen to regulate long term and acute exposures, respectively (SFWMD 2003).

As part of this overall research effort (SFWMD 2003), a hydrodynamic model (Sheng 2001) was applied to the estuary to determine the salinity distribution under various freshwater flow conditions within the estuary (Qiu 2003). CH3D is a 3-dimensional finite difference hydrodynamic model that employs a curvilinear grid developed to evaluate surface elevation, 3-D velocity, salinity, and density (Sheng 1987, 1989, 2001). The CH3D model for the Caloosahatchee estuary is comprised of 145 by 225 horizontal grid cells with 8 vertical layers. Inputs to the model included freshwater inflow, tides, wind, rainfall, and evapotranspiration. The model was calibrated with 77 days of observations (October 15, 2000 to December 31, 2000). The calibrated model was then applied in six scenarios of varying S-79 inflows, assuming no other inputs (such as rainfall or groundwater contribution) and conducting model simulations of 40 days to achieve equilibrium conditions. The salinity concentrations at four locations along the river/estuary were averaged over the last 10 days of simulation, providing the flow-salinity response curves shown in Figure 2 (Qiu 2003). Qiu (2003) determined that a total flow of 14.2 m^3/s of total freshwater inflow to the system was required to maintain the appropriate salinity distribution in the upper estuary that is protective of wild celery communities in the Ft. Meyers location.

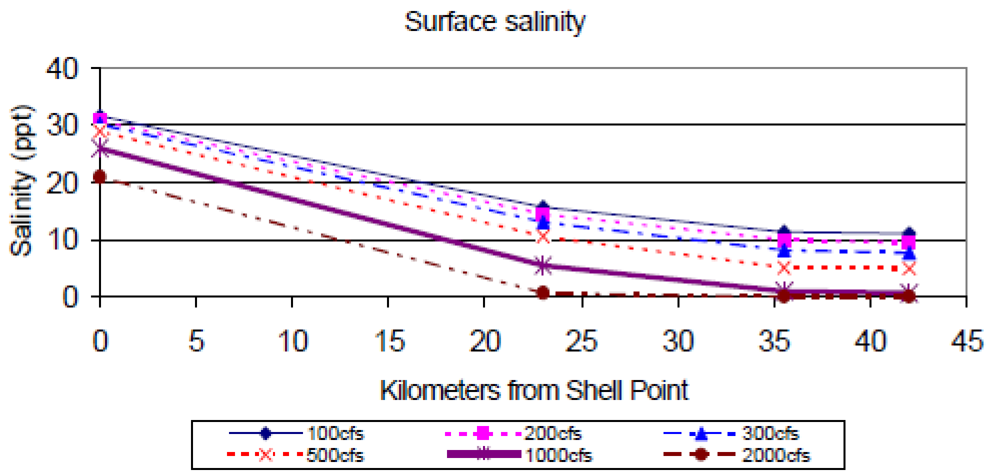

FIGURE 2. Caloosahatchee estuary salinities in response to scenarios of varying freshwater inflow rate (Qiu 2003). The six response curves quantify mean salinities along an upstream gradient from Shell Point for various inflows at S-79. The locations along the x-axis from left to right are Shell Point (tailwater of the estuary), Ft Myers, Bridge 31, and S-79. The inflows of 100 cfs, 200 cfs, 300 cfs, 500 cfs, 1000 cfs, and 2000 cfs correspond to 2.8 m^3/s, 5.7 m^3/s, 8.5 m^3/s, 14.2 m^3/s, 28.3 m^3/s, and 56.6 m^3/s, respectively.

Because the hydrodynamic model did not incorporate freshwater inflows to the Caloosahatchee system other than those managed flows via S-79, it was important to determine the magnitude of freshwater inflows from the watershed surrounding the lower Caloosahatchee. A third modeling effort undertaken to support the MFL was a model of the "Tidal Basin Watershed", developed to estimate the expected freshwater inflows from the surrounding watershed between S-79 and Shell Point (Konyha 2003). The basin model was used to determine the average watershed inflows that would supplement S-79 inflows. Information from this basin model was then used in combination with information from the hydrodynamic river model to estimate the freshwater inflows at S-79 needed to maintain appropriately low salinities that would support the wild celery habitat. It was concluded that under current conditions, an additional 5.7 m^3/s may be available from watershed sources greater than 54 percent of the time. Therefore, a total system inflow of 14.2 m^3/s that Qiu (2003) indicated was desirable would occur 54 percent of the time under the MFL-derived S-79 flow of 8.5 m^3/s. However, a flow of 8.5 m^3/s at S-79 would be insufficient to maintain salinity levels in accordance with the MFL Rule during the dry season when inflows from the tidal portion of the basin are diminished.

Evaluation on the effects of sea level rise was not considered during the development of the MFL (SFWMD 2003). Similarly, sea level rise has not yet been considered in the Caloosahatchee Watershed Protection Plan, a plan partly developed to mitigate exceedances of the MFL Rule (SFWMD 2009). This paper presents the first attempt to evaluate the relative effects of sea level rise on regulating freshwater flows to maintain the ecology of the Caloosahatchee Estuary.

MODEL SELECTION

Prior to development of the hydraulic model, a review of publicly available software was completed. Information provided on the Surface water and water quality Modeling Information Clearinghouse (SMIC) developed by the USGS indicates that the only publicly available software with a graphic user interface that is capable of analyzing conservative constituent transport through an estuary is version 4.1 of the hydraulic analysis software Hydraulic Engineering Center – River Analysis System (HEC-RAS) developed by the U.S. Army Corps of Engineers (USACE) in January 2010.

HEC-RAS is designed to perform one-dimensional hydraulic calculations of natural and constructed channels for steady and unsteady state flow conditions. Unsteady flow analyses deals with flow conditions that vary temporally and spatially. The hydraulic software is capable of analyzing the addition of culverts, bridges, levees, tributaries, storage areas and traversing dams in the flow network. In addition to the flow routing capability, HEC-RAS incorporates numerous auxiliary components such as dam breach analysis, sediment transport, river encroachment analysis, and water quality modeling. The hydraulic calculations performed in HEC-RAS are completed using one dimensional energy equations, and the unsteady flow equation solver was adapted from Dr. Robert L. Barkau's UNET model. Version 4.1 of HEC-RAS allows for water quality analysis of negative flows that are observed within an estuary during an incoming tide, a feature that was not included in version 4.0 (USACE 2010).

The USACE has also developed an extension of ArcGIS that is capable of performing spatial analysis of Digital Elevation Models (DEMs), and extracting geometric information from the DEM for direct import into HEC-RAS. HEC-GeoRAS is also capabable of importing HEC-RAS results into ArcGIS, and automatically generating inundation boundaries for a river system (USACE 2010).

In contrast to the complex CH3D model developed for the MFL Rule justification, HEC-RAS is a one-dimensional hydraulic model that does not account for multi-directional flow paths or variations in fluid density. However, given the long, slender geometry of the estuary, a one-dimensional hydraulic model was expected to reasonably represent the estuarine dynamics since there are few bays and large tributaries within the area of study (SFWMD 2000).

MODEL IMPLEMENTATION - HYDRAULICS

The model domain was selected to extend from S-79 through San Carlos Bay (Figure 1) and 17 km into the Gulf of Mexico. The decision to the extend the model into the Gulf of Mexico was made to reduce the effects of boundary conditions, and the reliance on observed data to describe the conditions at the model boundary. This is based on the observation that the salinity distribution plots developed by the CH3D model (see Figure 2) demonstrate that the salinity at Shell Point is dependent on the total inflow to the Caloosahatchee estuary, and cannot be assumed to be a constant value of 35 ppt; which is an average value for the Gulf of Mexico.

In order to capture the bathymetry of the Caloosahatchee estuary for the HEC-RAS model, HEC-GeoRAS was utilized. The 2005 bathymetry dataset for Southwest Florida (that was obtained by the USGS working in conjunction with the SFWMD) was utilized to capture the 1D channel geometry from the Gulf of Mexico to 33 km above Shell Point (SFWMD 2005a). The channel geometry for the portion of the estuary 33 km above Shell Point to S-79 was digitized from the cross sections presented in SFWMD Technical Report 88 (TR-88) [(Scarlatos 1988)]. The overbank portions of all cross sections were described to an elevation of 1.5 m NAVD 88 using the Southwest Florida topographic dataset (SFWMD 2005b). The spatial resolution of the bathymetric dataset is 90 m, and the spatial resolution of the topographic dataset is 30 m. The two GIS datasets were clipped for the area of interest and merged into a continuous Triangular Irregular Network (TIN). The alignment of the channel centerline of the estuary between S-79 and Shell Point was obtained from the National Hydrography Dataset (NHD) for subbasin 03090205 published by the USGS. The layout of the cross sections was chosen to describe non-linear changes in channel width or depth, and the location of the cross sections 33 Km above Shell Point were digitized according to TR-88. The cross section data that was obtained from TR-88 was converted into geo-referenced points, and used to modify the TIN to describe upper estuary channel geometry. Additionally, an assumed crest elevation of 1.5 m NAVD 88 was incorporated into the TIN to represent S-79, and captured in HEC-GeoRAS as an inline structure layer. The channel geometry and stream alignment were generated into an import file for HEC-RAS directly through HEC-GeoRAS. The layout of the channel cross sections and stream centerline is depicted in Figure 3.

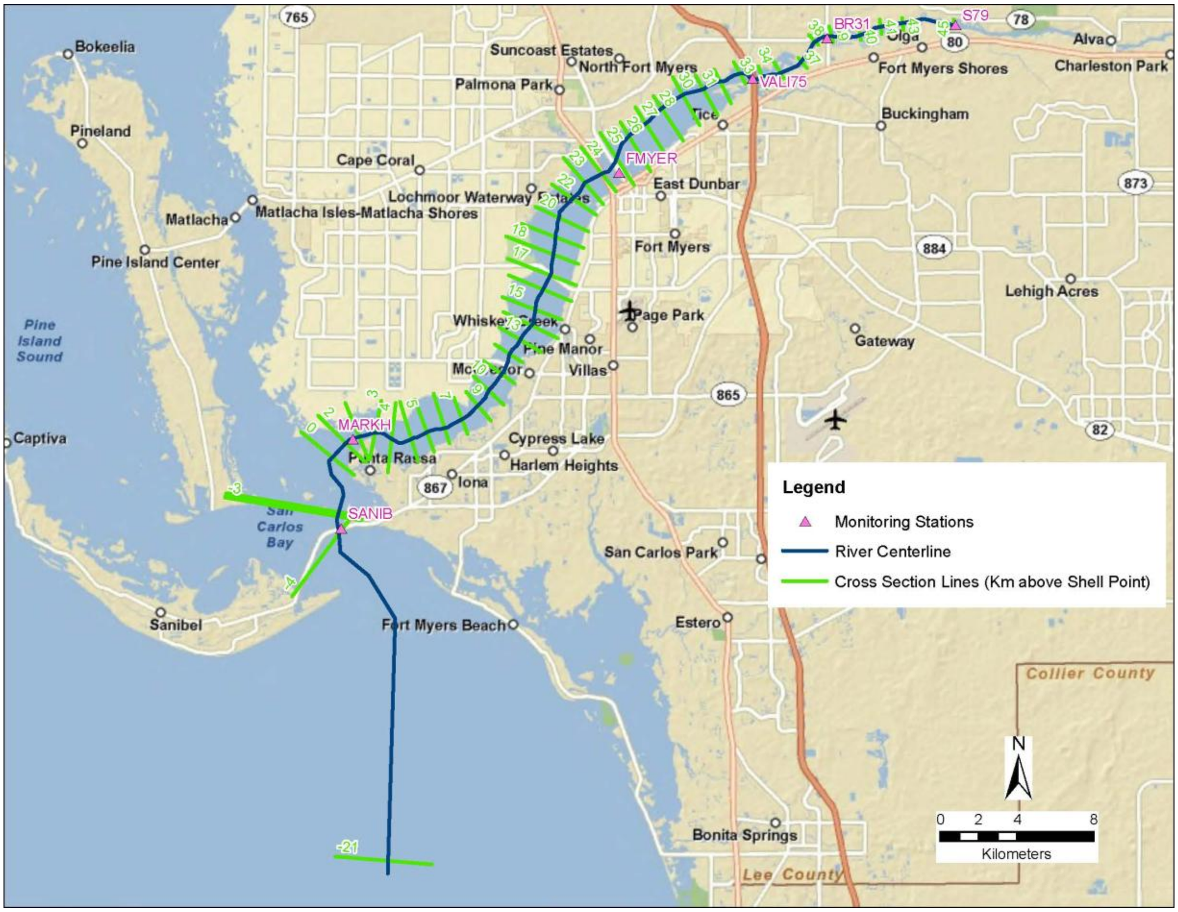

FIGURE 3. Layout of HEC-GeoRAS layers. *Sources: Base Map (ESRI Library – US street map layer), Centerline (NHD dataset for subbasin 03090205 with modifications), Cross Sections (Scarlatos 1988 with modification), Monitoring Stations (SFWMD – Salinity Monitoring Stations).*

Following the import of the geometry file, a calibration of the Manning's n values for the hydraulic model was completed to replicate observed tidal data. In order to facilitate the calibration of Manning's n values, observed tidal data at SFWMD monitoring station MARKH located near Shell Point was incorporated as the tailwater boundary condition, rather than trying to extrapolate the tidal stages in the Gulf of Mexico; since a monitoring station further downstream of Shell Point is not available. The headwater boundary condition was the observed discharge at SFWMD monitoring station S-79 T (located at the tailwater of S-79) with additional inflow that was assumed to be representative of the groundwater inflow between S-79 and SFWMD salinity monitoring station FTMYERS. In subsequent salinity simulations it was determined that the representation of groundwater inflow as lateral inflow into the estuary with 0 ppt salinity caused instability in the water quality simulation module. Therefore all freshwater inflow into the estuary had to be input in the headwater at S-79. The total inflow at S-79 was chosen to be representative of the total inflow at Ft Myers since salinity monitoring station FTMYERS is the regulatory point of compliance for the MFL Rule. The total groundwater inflow into the estuary was approximated as 22 percent of the 30 day average discharge at S-79 in accordance with the estimate by Konyha (2003) that the groundwater inflow to the estuary comprised 22 percent of the total inflow with the remainder entering the estuary at S-79. The groundwater inflow between S-79 and Ft Myers was estimated to be a fraction of the total groundwater inflow to the estuary based on the fractions provided by Konhya (2003) who estimated that 64.4 percent of the groundwater inflow to the estuary occurred between S-79 and Ft Myers.

The observed stage at NOAA monitoring station 8725520 located near Ft Myers and SFWMD monitoring station VAL-I75 located near the I75 overpass were input into HEC-RAS to facilitate comparison to the observed stages in the estuary. The model was simulated from November 1, 2007 to November 27, 2007. Following the initial simulation and adjustment of the Manning's n value in the estuary, it was observed that the mean sea level calculated during the simulation for both Ft Myers and VAL-I75 were greater than the observed mean sea level for the simulation period by approximately 15 cm, but that the calculated ranges at both locations closely replicated the observed ranges. Additionally, it was noted that the observed mean sea level at Shell Point was 3 cm NAVD 88, and -10 cm NAVD 88 at Ft Myers and VAL-I75. Therefore, the tidal data at the tailwater boundary condition was reduced by 14.9 cm, and the simulation was rerun. The comparison of observed and calculated values for Ft Myers and VAL-I75 are presented below.

TABLE 1. Comparison of calculated to observed tidal stages at Ft Myers and VAL-I75. Note the maximum residual at any location being 1.5 cm.

Monitoring Location	Mean Sea Level Observed (cm above NAVD 88)	Mean Sea Level Calculated (cm above NAVD 88)	Observed Tidal Range (cm)	Calculated Tidal Range (cm)
Ft Myers	-9.8	-8.6	42.2	42.1
VAL-I75	-9.9	-8.4	44.2	42.9

The Manning's n values in the estuary ranged from 0.036 to 0.0225, with three transitions occurring at 33 km, 28 km, and 15 km above Shell Point. Once the Manning's n values had been determined, the extrapolation of the tidal stage in the Gulf of Mexico 17 km from San Carlos Pass was completed. It was observed by comparison to observed tidal data that the mean sea level in the Gulf of Mexico was similar to the modified (reduced by 15 cm) mean sea level at Shell Point. However, it was determined that the tidal range would need to be increased by 21 percent in order to replicate the tidal range in the estuary. The Nash-Sutcliff Efficiency (NSE) for the hydraulic simulation was calculated to be 0.87 for Ft Myers and 0.85 for VAL-I75. The results of the tidal simulations are presented in Attachment A.

MODEL IMPLEMENTATION - WATER QUALITY

Upon the completion of the hydraulic simulation, a water quality simulation was completed to determine the ability of the model to replicate observed salinity data. The boundary conditions for the simulation were a constant salinity of 0 ppt at the inflow at S-79, and a constant salinity of 35 ppt at the tailwater cross section located 17 km into the Gulf of Mexico from San Carlos Pass. The simulation period was chosen to encompass calendar year 2000, with the hydraulic analysis for the simulation period completed pursuant to the previously described methodology. Prior to initiating the water quality analysis, an inspection of calculated tidal stages was completed to confirm that the observed tidal stages were being replicated. It was observed that the values at Shell Point were being closely replicated, but that the predicted values at Ft Myers were below the observed values by approximately 13.8 cm. Tidal monitoring station VAL-I75 was not utilized since the period of record for this station begins in October 2006. Based on the fact that the mean sea level at Ft Myers was approximately equal to the mean sea level at VAL-I75 during the 2007 simulation, it was assumed that the mean sea level at Shell Point was again incorrectly referenced to NAVD 88, and that an adjustment of the observed tidal data at Shell Point was required. The fact that the 2007 tidal simulation required a datum decrease of 15 cm at Shell Point, and the 2000 tidal simulation required a datum increase of 14 cm at Shell Point is attributed to the fact that the two simulation periods were recorded by two different tidal gauges; with tidal gauge MARKERH being replaced tidal gauge MARKH due to damage occurring in 2003.

The year 2000 was chosen because there were numerous droughts, periods of high flow, and periods of maintained moderate flow (as reflected in salinities, see Figure 4). Therefore, it was determined that a simulation of the salinity regime changes throughout 2000 would analyze the ability of the model to replicate the salinity response to a wide variation in flow regimes. Observed salinity data at SFWMD monitoring stations SANIBEL, SHELL POINT, FT MYERS, BRIDGE 31, and S-79 was collected and incorporated into to the model to facilitate comparison and calibration. The data provided by the SFWMD is comprised of specific conductance and temperature for both the surface and bottom interval at each location. Since the MFL Rule is dependent on surface salinity, daily surface readings were utilized. The specific conductance and temperature readings were converted into salinity values referenced to the Practical Salinity Scale of 1978 (PSS 78) using the methodology and constants provided in the 19th edition of standard methods (Clesceri *et al.* 1996). The initial salinity distribution in the estuary was set to equal the observed values for January 1, 2000. The dispersion coefficients in the estuary were computed in HEC-RAS for each water quality cell in accordance with Fischer's equation (USACE 2010).

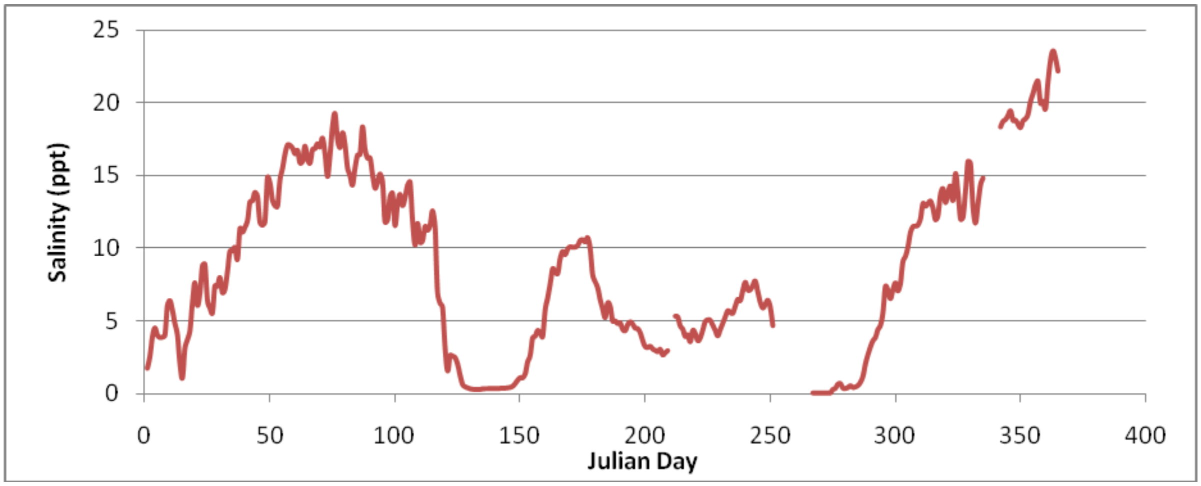

FIGURE 4. Surface salinity at Ft Myers for the year 2000. The figure depicts a rise and fall of salinity from 2 ppt to 19 ppt and return between Julian day 0 and 130, a moderate period of salinity between Julian day 160 and 250 of approximately 6 ppt, and a rapid rise in salinity from 0 ppt to 24 ppt between Julian day 275 and 365.

Following the initial simulation it was observed that rapid oscillation in salinity in the lower estuary was occurring. Following inspection of the average dispersion coefficients in each water quality cells, it was determined that an overestimation of the dispersion coefficient between San Carlos Bay and the estuary was occurring as a result of rapid changes in geometry. Therefore, the HEC-RAS computations of dispersion coefficients were truncated at 2 km above Shell Point. Additionally, it was determined that a reduction in cross section spacing was required to increase model accuracy. Therefore, the cross section interpolation function available through HEC-RAS was utilized to interpolate cross sections with a maximum offset of 90 meters. Figures 5a & 5b depict the average dispersion coefficients throughout the model domain and 2 km above Shell Point, respectively.

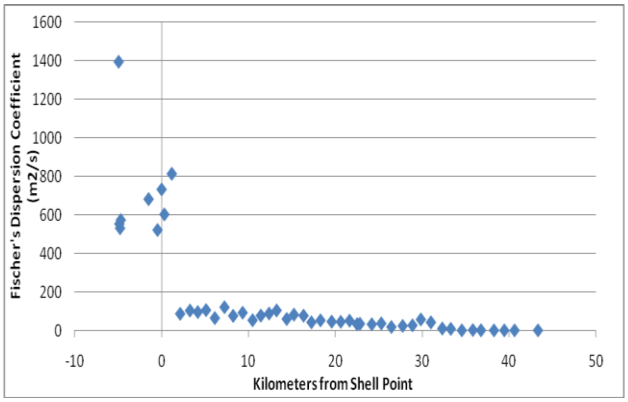

FIGURE 5a. Average dispersion coefficients throughout the model domain. The figure depicts a six fold increase below Shell Point.

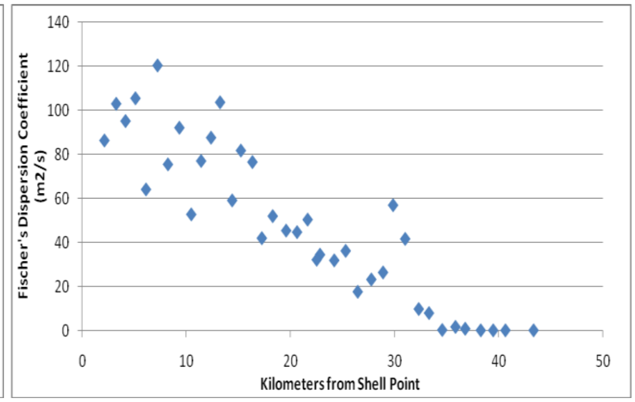

FIGURE 5b. Average dispersion coefficients 2 km above Shell Point. The figure depicts a uniform decrease in values.

The NSE for the calculated salinity values for year 2000 were determined to be 0.23, 0.42, 0.67, 0.64, and 0.61 for salinity monitoring stations SANIBEL, SHELL POINT, FT MYERS, BRIDGE 31, and S-79, respectively. The low NSE for Sanibel and Shell Point are attributed to the constant salinity of 35 psu at the tailwater boundary conditions. This is especially true when the conditions in San Carlos Bay are hypersaline. An evaluation of the NSE when the observed salinity values at Sanibel are below 35 psu, estimates values of 0.32 and 0.46 at Sanibel and Shell Point, respectively. However the effect of this boundary condition does not cause an undesirable NSE at Ft Myers. The greatest disparity between observed and calculated values at Ft Myers was observed to occur during the wet season. Therefore, it is assumed that of the 22 percent of the total estuary inflow from groundwater, that a recognizably more substantial fraction is incurred to the estuary during the wet season. The results of the salinity simulation are presented in Attachment B.

MODEL APPLICATION - ASSUMPTIONS

The potential effects of sea level rise on the salinity distribution in the estuary was evaluated for three separate scenario combinations of sea level rise and managed inflows. Incremental increases in mean sea level of 0.3 m were analyzed for all scenarios up to a total increase of 0.9 m. The first scenario was developed to evaluate the effects of incremental increases in mean sea level under a constant inflow of 14.2 m^3/s at S-79, which represents the recommended total inflow to the estuary to maintain the current habitat viability. The second scenario was to evaluate the change in the rate of salinity increase under no flow conditions. The evaluation was completed with initial salinity values set to represent moderate conditions, and subsequent inflow conditions at S-79 equal to 0. The third scenario was developed to evaluate the change in the rate of salinity decrease under high flow conditions. The initial salinity values were set to represent acute conditions where the salinity at Ft Myers was 20 ppt, and the inflow conditions at S-79 were a constant value of 36.8 m^3/s. For all scenarios the values presented by the CH3D modeling effort were utilized for comparative purposes (Qiu 2003). The tidal boundary condition for all scenarios is a synthetic stage hydrograph developed from the stage datums for Shell Point. The synthetic stage hydrograph was developed by calculating the Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Low Water (MLW), Mean Lower Low Water (MLLW), and Mean Sea Level (MSL) datums for Shell Point for all available stage recordings from monitoring station MARKERH (January 22, 1992 00:15 to July 19, 2001 0:00); then increasing each datum by 13.8 cm and multiplying by 1.21 (as described in the implementation of the hydraulics simulation above). The sinusoidal hydrograph centered around the extrapolated MSL datum was generated by assuming that each datum was equally distributed across the diurnal period, and the incremental increases in mean sea level were assumed to not affect the tidal ranges. The synthetic stage hydrograph developed from current tidal datums is illustrated in Figure 6. The results of the three scenarios are presented in Attachment C.

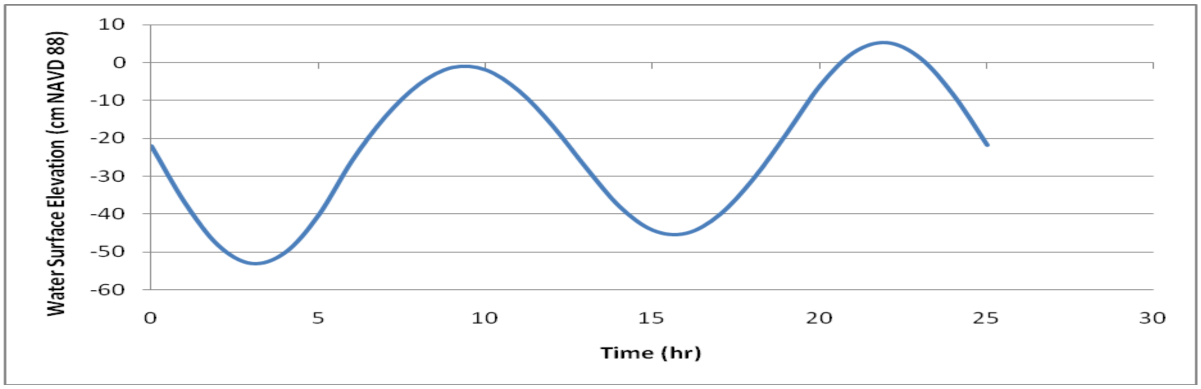

FIGURE 6. Synthetic tidal hydrograph developed from current tidal datums. Values of MHHW, MHW, MLW, MLLW, and MSL extrapolated to 21 km below Shell Point were determined to be 5.4 cm NAVD 88, -5.7 cm NAVD 88, -45.1 cm NAVD 88, -53.8 cm NAVD 88, and -21.9 cm NAVD 88, respectively.

MODEL APPLICATION - RESULTS

The evaluations of the three scenario combinations demonstrated that salinity changes within the estuary could be observed under significant increases in sea level, if alterations in current management strategies do not occur. Scenario 1 indicated that a 0.9 m rise in mean sea level will increase the average salinity at Ft Myers (ca. 23 km from Shell Point) from 15.6 ppt to 20.1 ppt if the total basin inflow is 14.2 m^3s (Figure C1). The highest sea level rise led to salinity at Ft Myers that was 29 percent higher than without sea level rise (Figure 7). With linear increases (0.3 - 0.9 m) in mean sea level rise for scenario one, there was an approximately linear increase in salinity. The percent increase was less at Shell Point (9 percent) and greater at Bridge 31 and S-79 (150 percent and 340 percent, respectively.

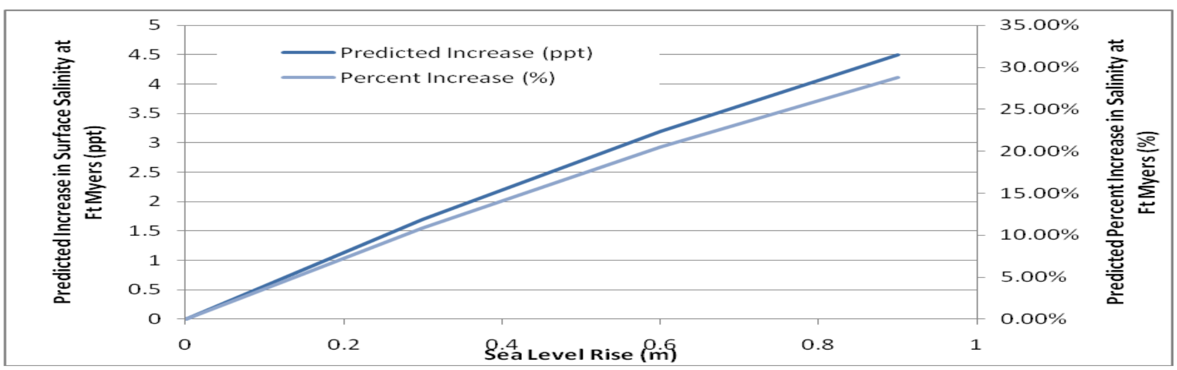

FIGURE 7. Response of surface salinity at Ft Myers to increases in mean sea level, with total inflows of 14.2 m^3/s at S-79..

An iteration of flows at S-79 for scenario 1 demonstrated that an increase in total S-79 inflow to 22.9 m^3/s would be required to maintain the salinity distribution initially calculated for the current mean sea level. The subsequent additional volume of flow to maintain an average flow of 22.9 m^3/s versus an average flow of 14.2 m^3/s is estimated to be 275 Mm^3/year. The second scenario demonstrated that no observable change in the relative rates of salinity increase under no flow conditions will occur as a result of sea level rise (all increase at similar rates, Figure C2). However, the third scenario demonstrated that a reduction (in the rate of salinity decrease) from 0.50 ppt/day to 0.28 ppt/day may occur under high flow conditions (36.8 m^3/s total inflow) under a 0.9 m increase in mean sea level (rates of salinity decreases vary among scenarios, Figure C3). As observed in previous scenarios, the incremental increases in mean sea level resulted in a linear change in salinity regime in the estuary.

MODEL UNCERTAINTIES AND LIMITATIONS

The HEC-RAS simulation resulting in a salinity of 15.6 ppt at Ft Myers with an inflow of 14.2 m^3/s and no sea level rise is greater than the CH3D predicted value of 10.6 ppt (Figure 8). The disparity is possibly due to an apparent under prediction by the CH3D model when compared to observed values (SFWMD 2003), and an apparent over prediction by HEC-RAS when compared to observed values, with the expected value being located between the two estimations (Qiu 2003).

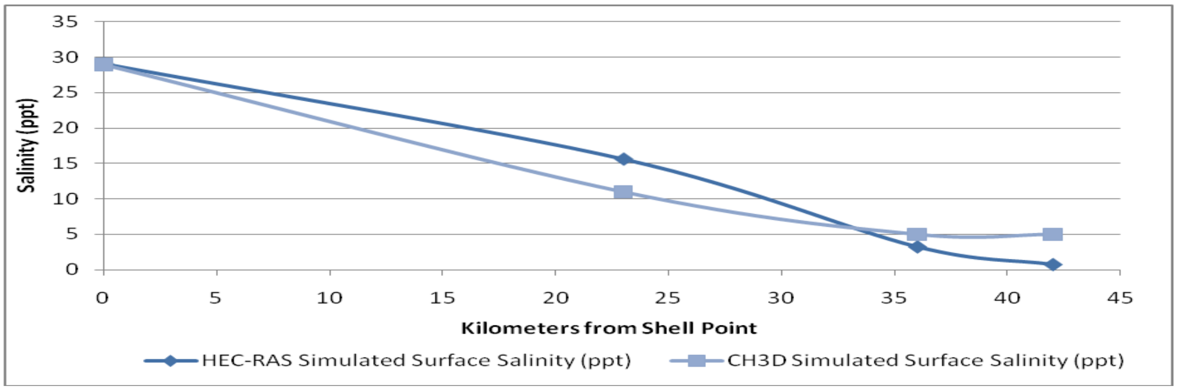

FIGURE 8. Comparison of predicted salinity distribution in the estuary between HEC-RAS and CH3D for total inflow of 14.2 m^3/s at S-79.

The HEC-RAS model tended to overestimate salinities (compared to observations) during the wet season at Ft Myers, likely due to the omission of runoff contributions from the watershed. Similar to previous modeling efforts (SFWMD 2003), a number of assumptions were made to accommodate such uncertainties, and improved modeling and data may improved our understanding of those contributions to total Caloosahatchee flows. Further study to possibly develop a hydrologic model that could interface with the HEC-RAS model, such as through HEC-HMS, would likely be fruitless; since this study demonstrates that inflows of 0 ppt salinity into the estuary other than at the headwater causes HEC-RAS instability. However, further troubleshooting could be completed to determine if the water quality module could allow freshwater inflow into the estuary if the inflow points were represented as tributaries, and water control structures were implemented as necessary. Contrary to this effort is the observed instability resulting from the representation of San Carlos Bay and Pine Island Sound as tributaries that merged with the model near Sanibel.

The model simulations at SFWMD salinity monitoring stations BRIDGE 31 and S79 under predicted surface salinity compared to observed data. It is proposed that these results are inaccurate due to the rapid channel geometry change that occurs 33 Km above Shell Point, but that the inaccuracy at these locations do not significantly affect the accuracy further downstream at Ft Myers.

The estimates of salinity increase of 4.5 ppt at Ft Myers resulting from a 0.9 m rise in mean sea level may appear to be insignificant given the limited model sensitivity, and the relatively minimal predicted increase; especially since the HEC-RAS estimate is greater than the CH3D estimate for surface salinity at Ft Myers under a constant flow of 14.2 m^3/s by 5 ppt. However, it is proposed that the expected increase of 4.5 ppt, and the subsequently required flow increase of 8.7 m^3/s to restore the initial salinity distribution is a reliable estimate based on the ability of the model to represent the modification of the salinity regime in the estuary as a result of changes in the flow conditions. The implications of the potential flow increase that would be required become especially significant when put into the context of the reservoir storage required to deliver such additional flow.

The analysis of estuarine water quality utilizing HEC-RAS can also be limited by various geometric aspects. The necessity to include multiple tributaries into the estuary may cause instabilities in the water quality module. Also rapid variations in the Fischer dispersion coefficient can cause inconsistent estimates, and the inclusion of multiple water quality structures such as levees and storage areas may possibly cause computational instabilities. As previously mentioned, if lateral inflow boundary conditions are incorporated in the simulation, then a significant disparity in inflow concentrations and in-situ concentrations cannot be present; otherwise computational instabilities may occur.

CONCLUSIONS

This study demonstrates that a one-dimensional hydraulic analysis of estuaries can provide informative estimates of the water quality responses to scenarios of sea level rises and counter-acting freshwater inputs. The agreement between simulated and observed data was sufficient to indicate that the general response of the salinity distribution in the estuary to flow conditions is reasonably represented. Applications of this model provided the first estimates of the sensitivity of salinity distributions to changes in long-term sea level, and associated assumptions of the upstream freshwater flows that may be necessary to maintain healthy seagrass beds in the Caloosahatchee Estuary

We recognize the limitations of this model and it simplifying assumptions (in the above section). Nevertheless, this model excercise provided a broad understanding to the relative magnitudes of managed flows that may be necessary to maintain existing salinity distributions in the Caloosahatchee Estuary under different scenarios of sea level rise. While the magnitudes of the salinity changes may be relatively small (ca. 5 ppt) among scenarios, other studies may use these results to estimate whether the potential changes are ecologically significant over long time scales. One of the most significant aspects of this study is its relative ease (i.e., low cost) of implementation, providing bounding information that can spur further consideration of sea level rise on MFL refinement for the Caloosahatchee Estuary.

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Attachment A

Tidal Simulation Results

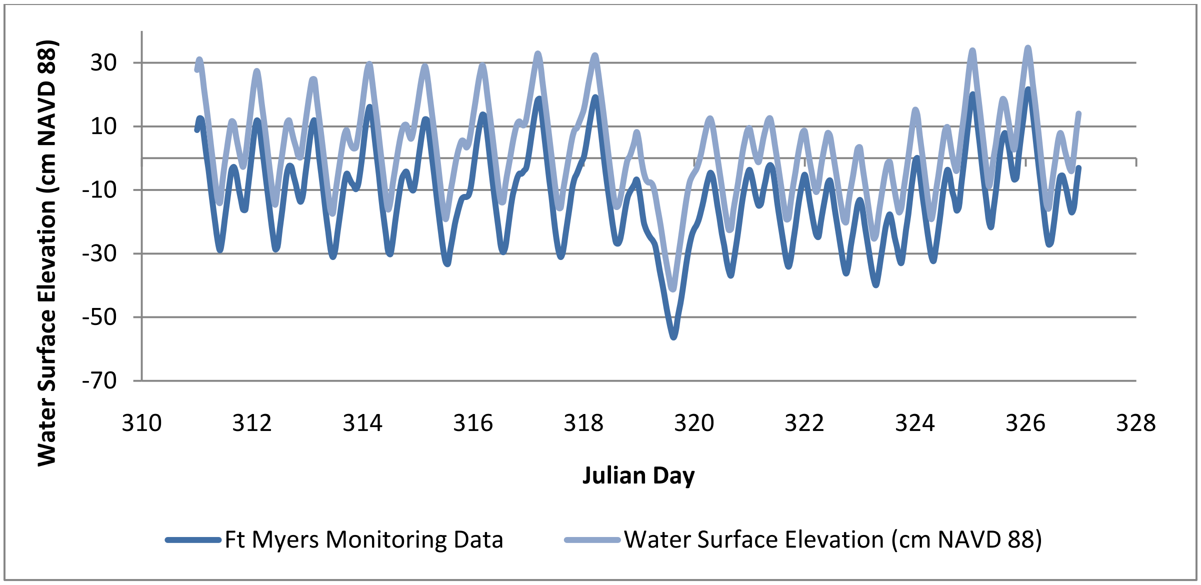

FIGURE A1. Initial tidal simulation at Ft Myers prior to modification of the Shell Point boundary condition.

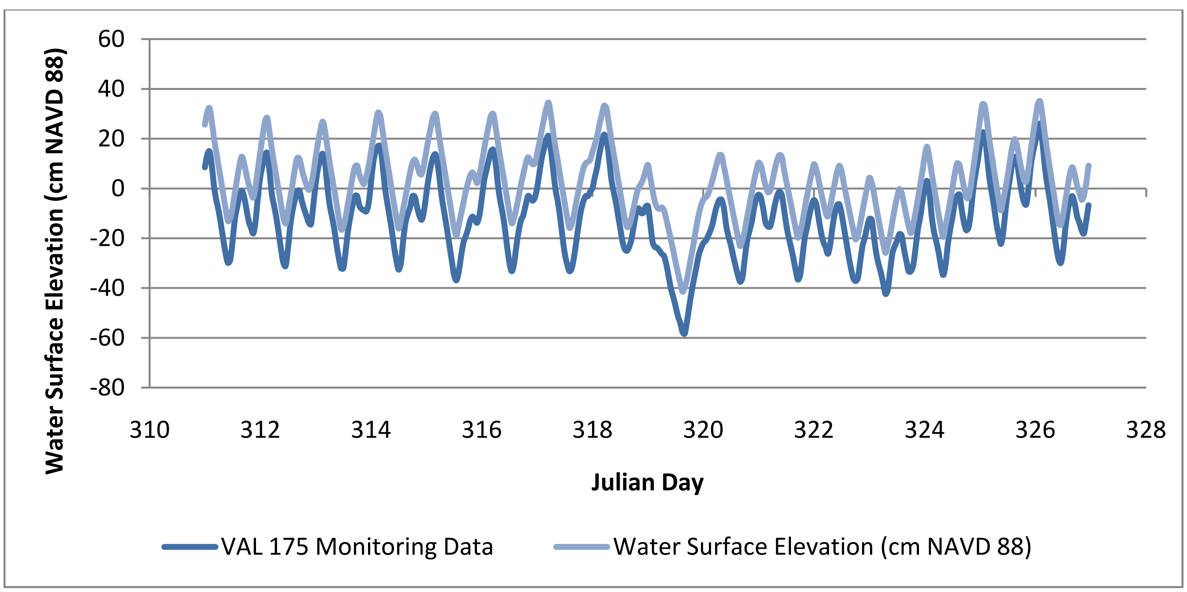

FIGURE A2. Initial tidal simulation at VAL-I75 prior to modification of the Shell Point boundary condition.

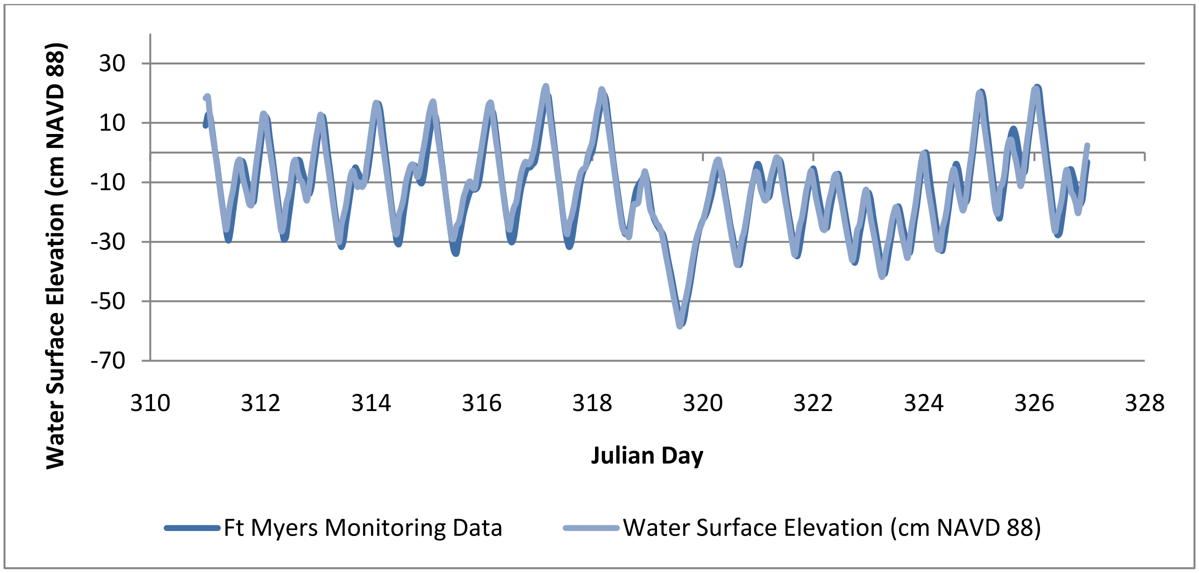

FIGURE A3. Tidal simulation at Ft Myers with extrapolated boundary condition 21 Km below Shell Point.

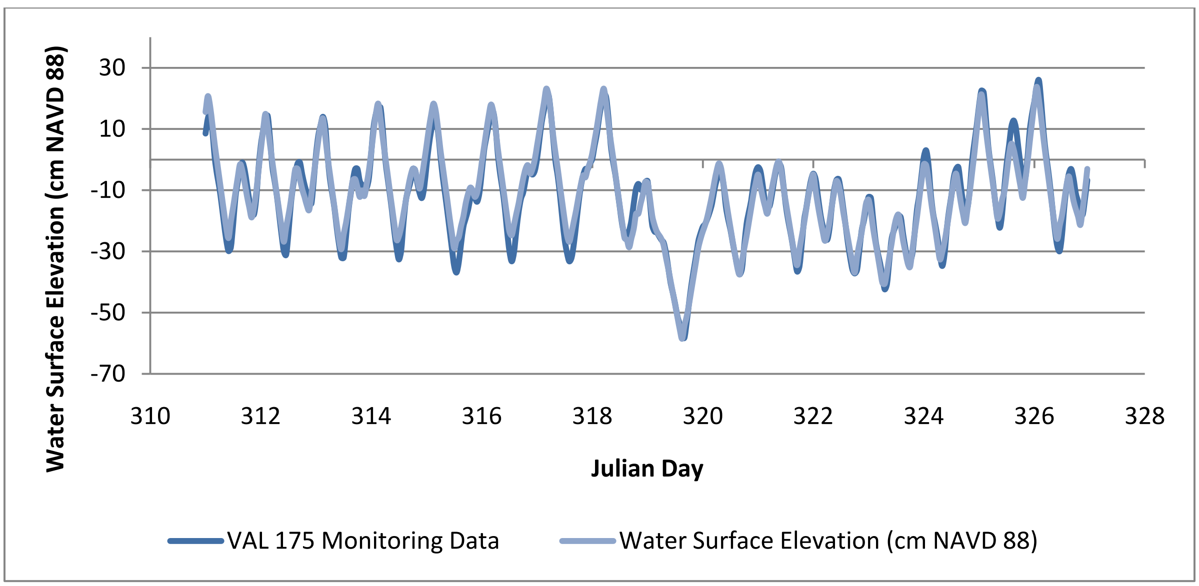

FIGURE A4. Tidal simulation at VAL-I75 with extrapolated boundary condition 21 Km below Shell Point

Attachment B

Salinity Simulation Results

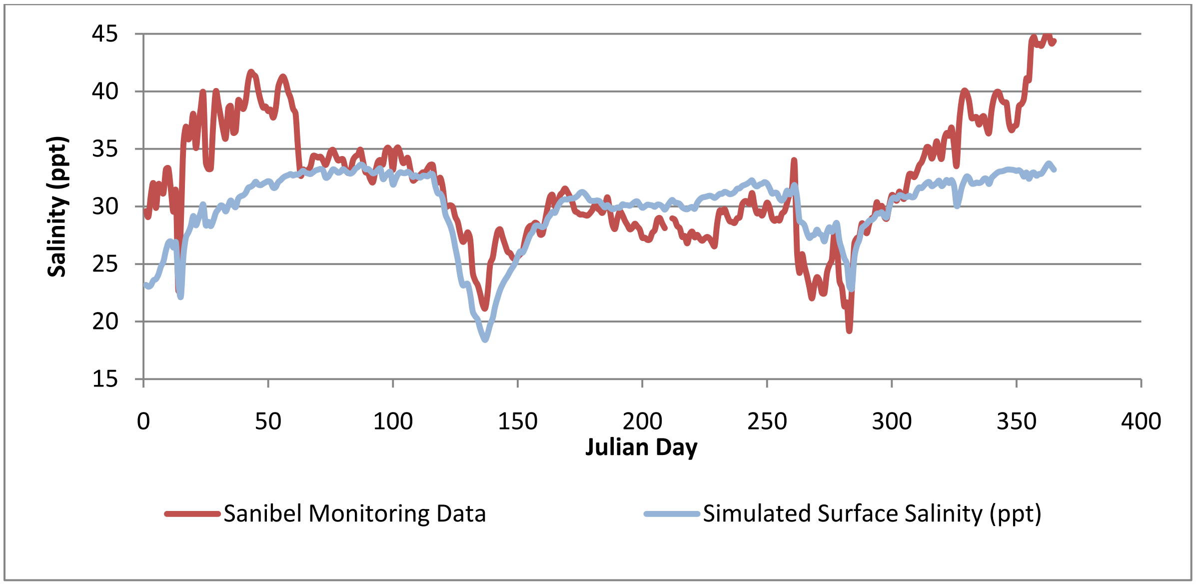

FIGURE B1. Simulated surface salinity at Sanibel for calendar year 2000.

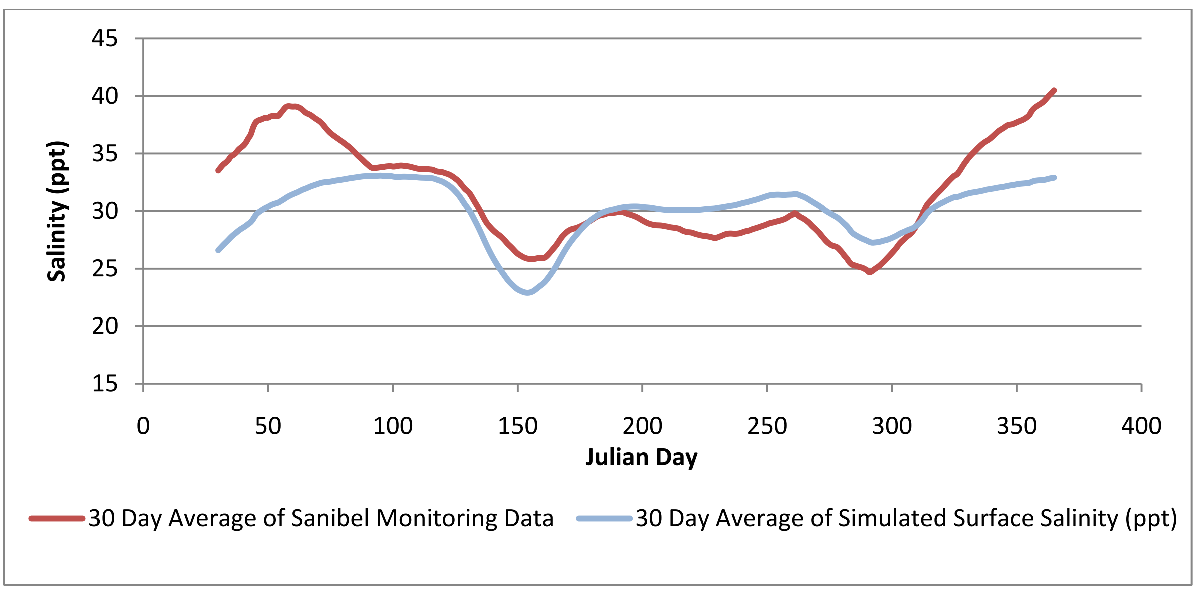

FIGURE B2. Simulated 30 day average surface salinity at Sanibel for calendar year 2000.

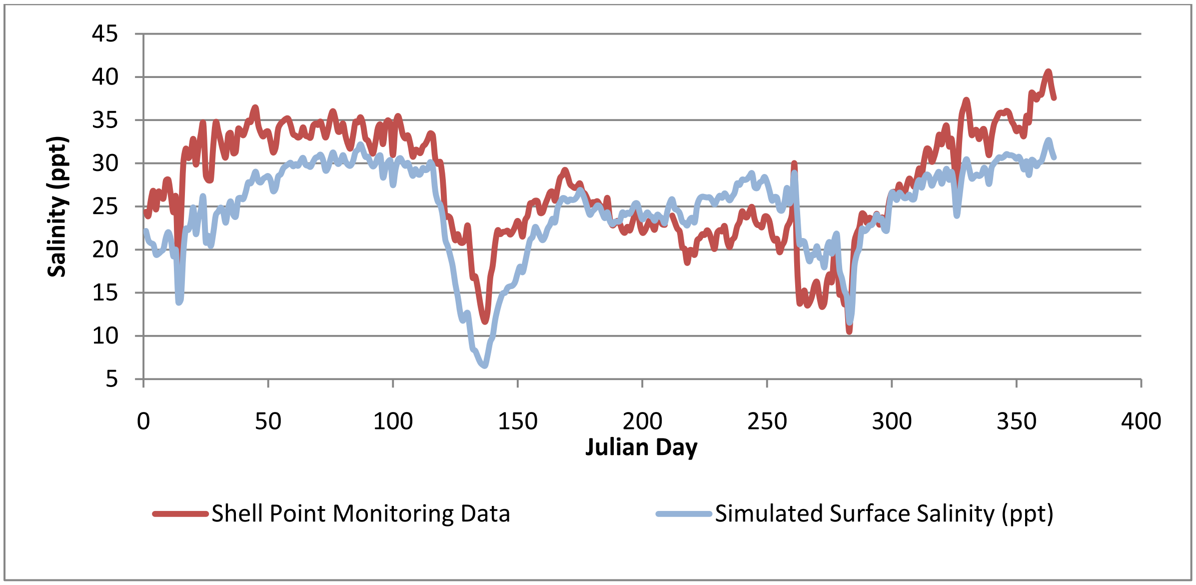

FIGURE B3. Simulated surface salinity at Shell Point for calendar year 2000.

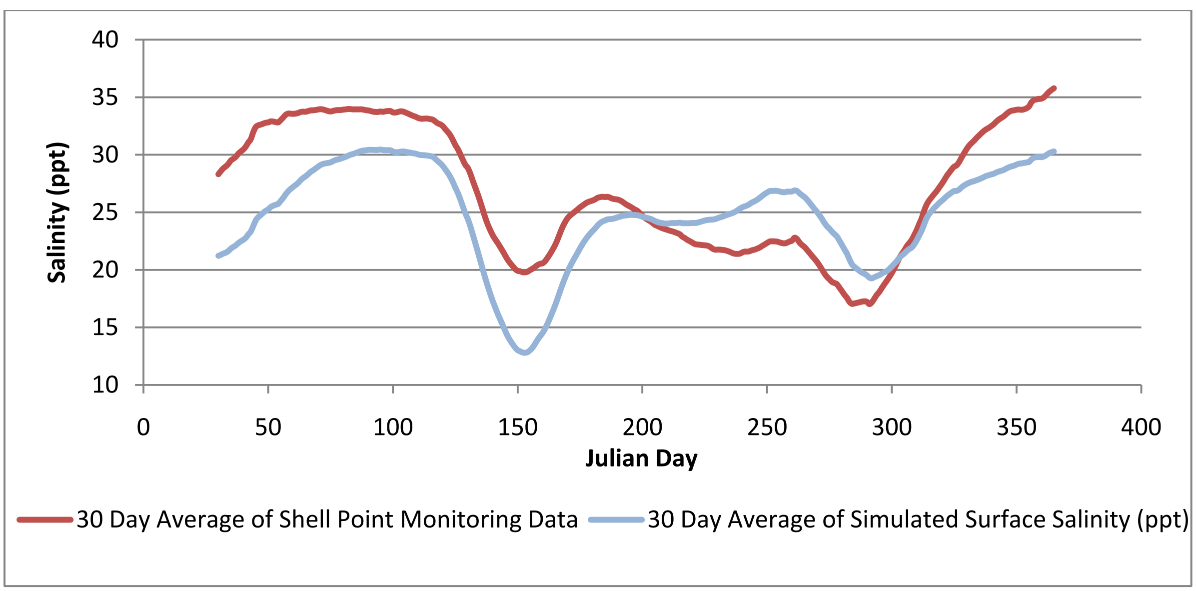

FIGURE B4. Simulated30 day average surface salinity at Shell Point for calendar year 2000.

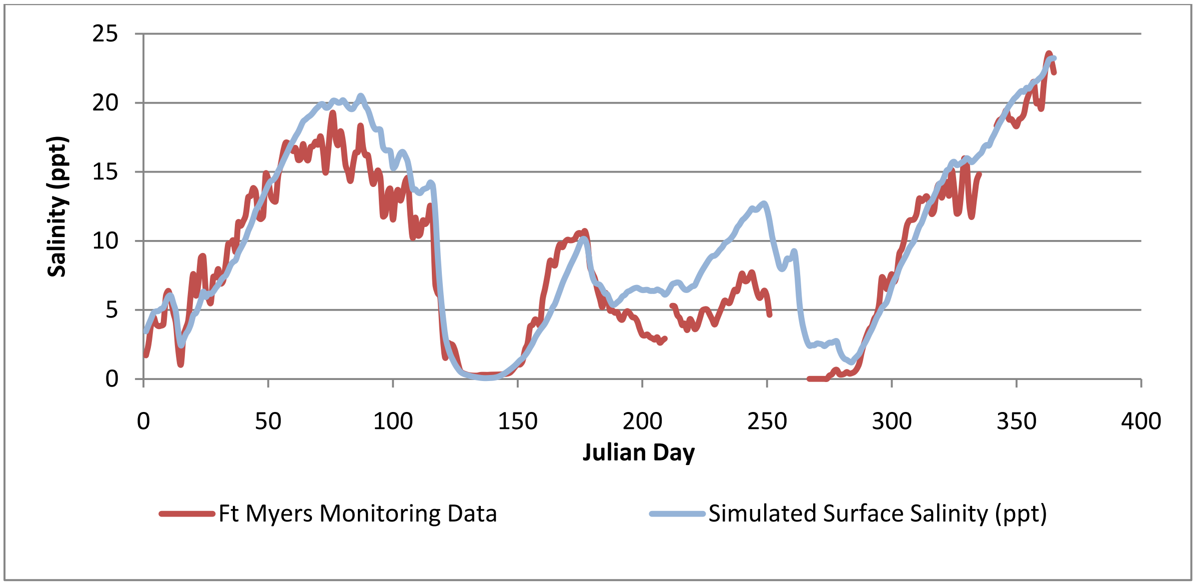

FIGURE B5. Simulated surface salinity at Ft Myers for calendar year 2000.

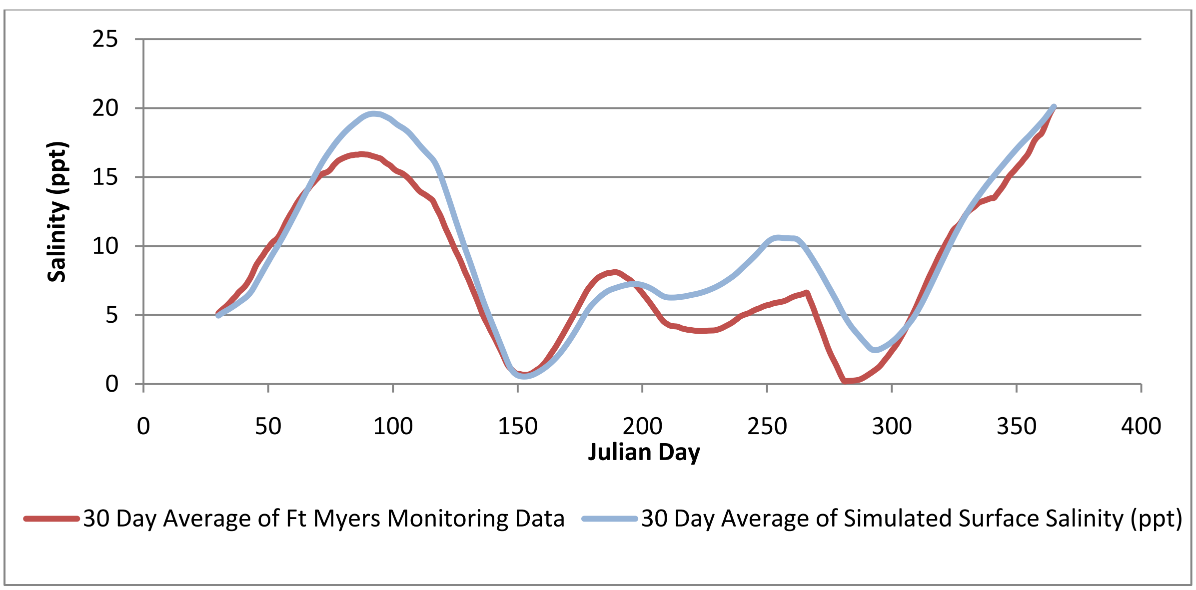

FIGURE B6. Simulated 30 day average surface salinity at Ft Myers for calendar year 2000.

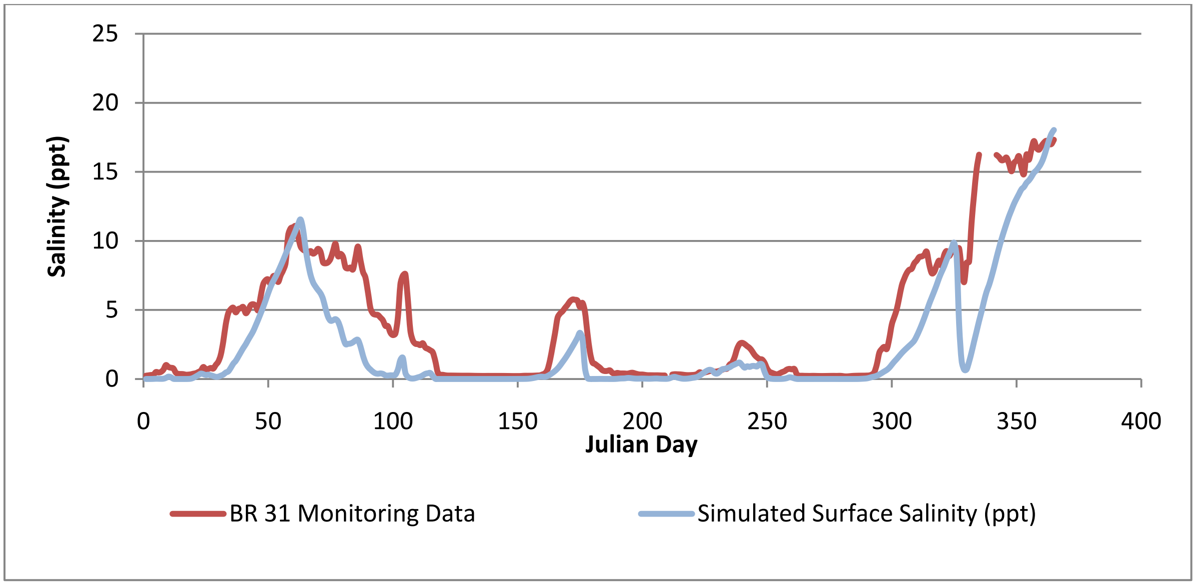

FIGURE B7. Simulated surface salinity at Bridge 31 for calendar year 2000.

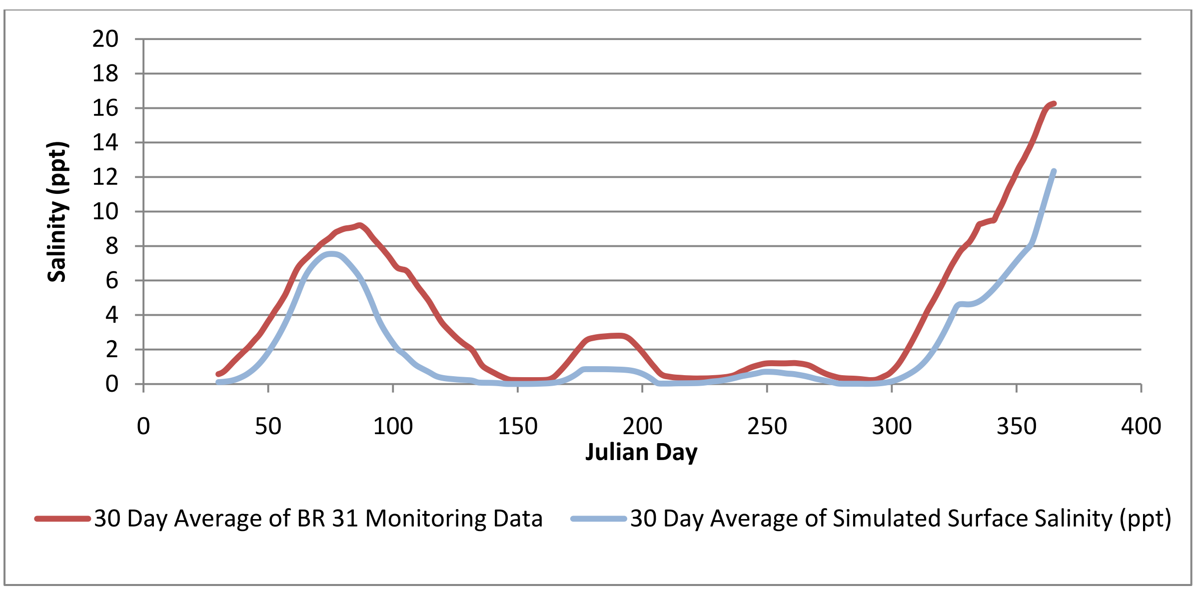

FIGURE B8. Simulated 30 day average surface salinity at Bridge 31 for calendar year 2000.

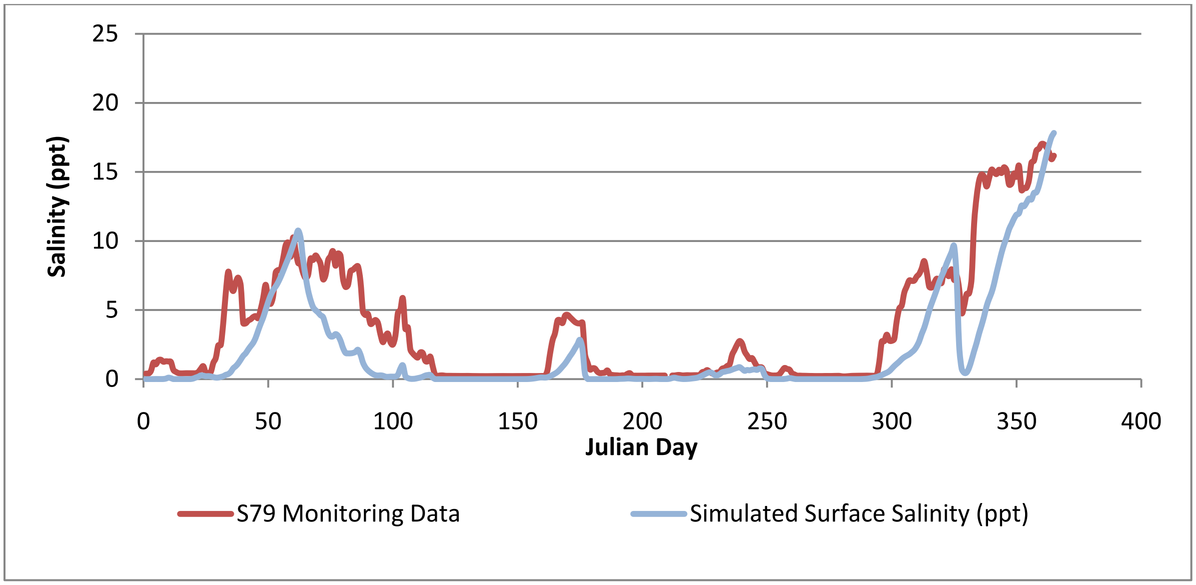

FIGURE B9. Simulated surface salinity at S-79 for calendar year 2000.

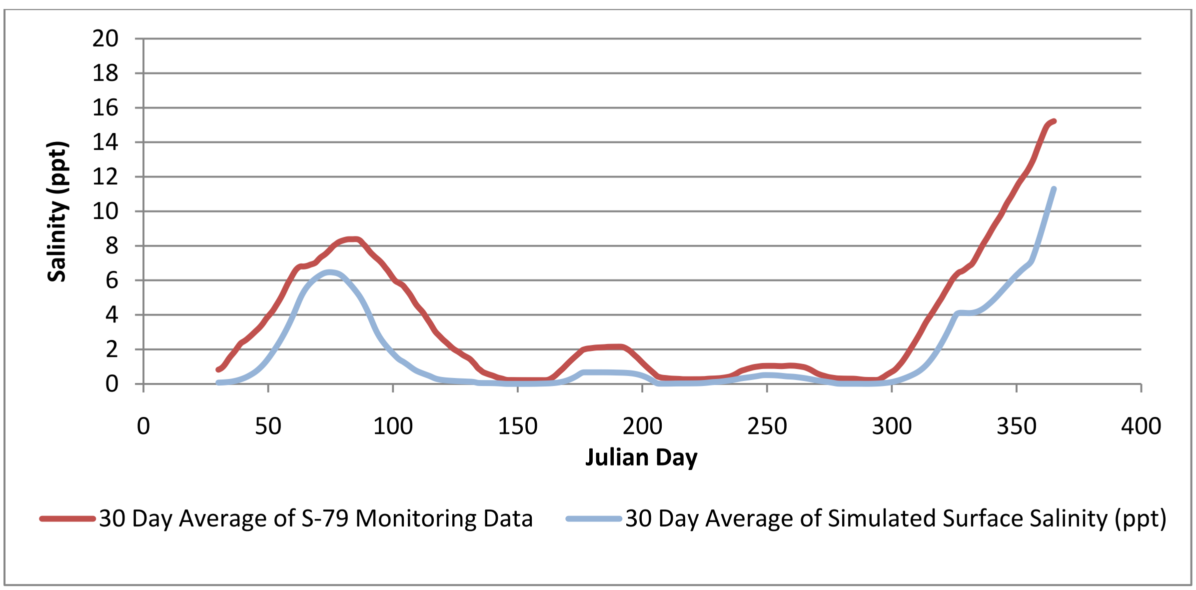

FIGURE B10. Simulated 30 day average surface salinity at S-79 for calendar year 2000.

Attachment C

Sea Level Rise Simulation Results

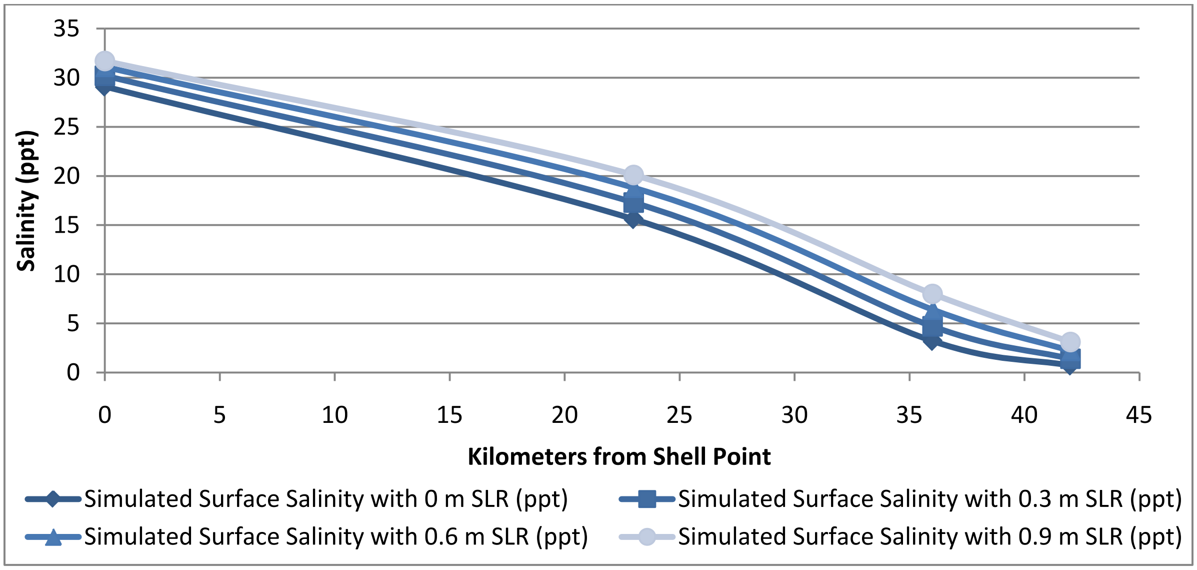

FIGURE C1. Estimation of the effects of sea level rise on the salinity distribution in the estuary with a total inflow of 14.2 m^3/s at S-79.

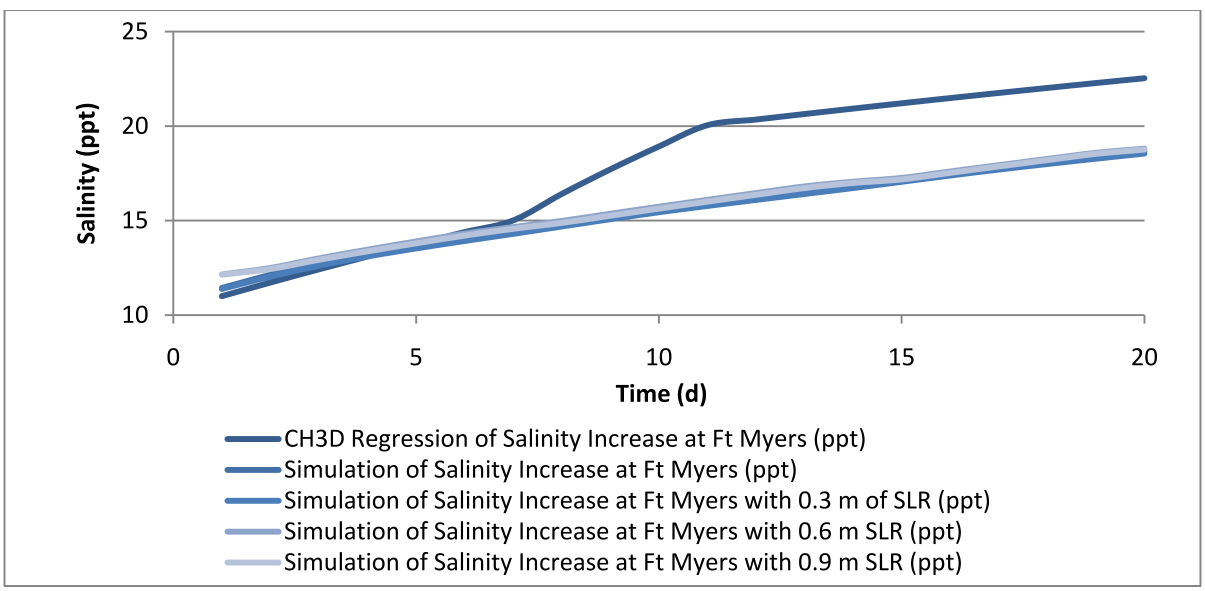

FIGURE C2. Estimates of the effects of sea level rise on the rate of salinity increase at Ft Myers under no flow conditions.

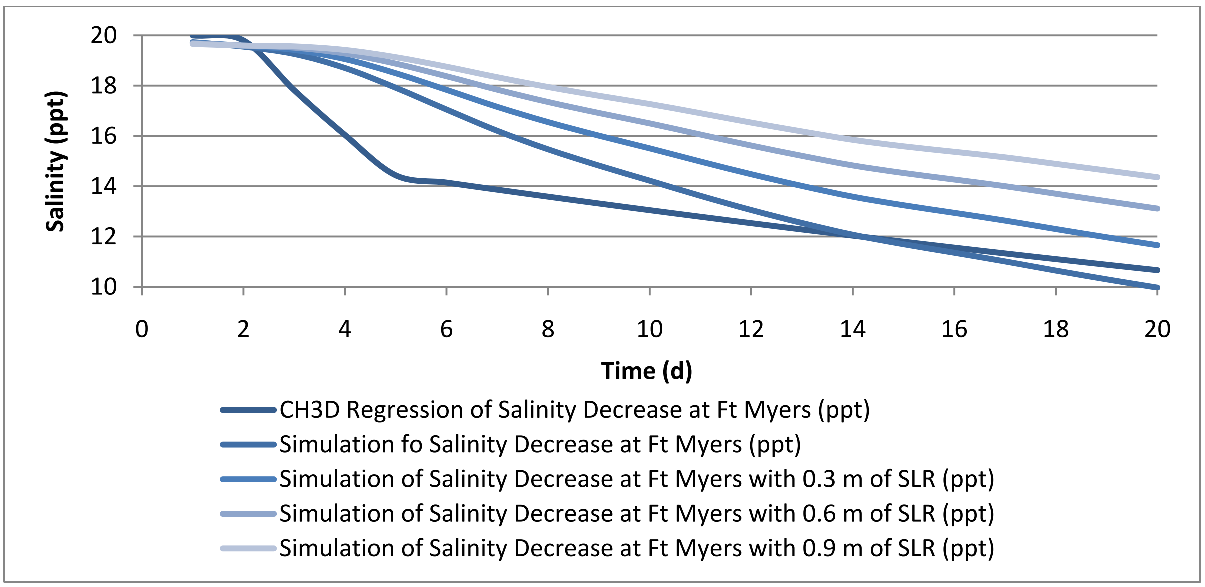

FIGURE C3. Estimates of the effects of sea level rise on the rate of salinity decrease at Ft Myers under high flow conditions of 36.8 m^3/s at S-79.