Technical Memorandum

Wakulla Spring MFL: Hydrodynamic Model for MFL Evaluation of the Estuarine River

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Acronyms and Abbreviations

cfs - cubic feet per second

COMPS - Coastal Ocean Monitoring and Prediction System (University of South Florida)

EFDC - Environmental Fluid Dynamics Code

FLaSH - Florida Shelf Habitat

GCSM - Gulf Coast Shelf Model

HEC-RAS - Hydrological Engineering Center's River Analysis System (United States Army Corps of Engineers)

IFAS FAWN - Institute of Food and Agricultural Sciences Florida Automated Weather Network

MFLs - Minimum Flows and Levels

NAVD88 - North American Vertical Datum of 1988

NOAA/NOS/CO-OPS - National Oceanic and Atmospheric Administration National Ocean Service Center for Operational Oceanographic Products and Services

NWFWMD - Northwest Florida Water Management District

NWS - National Oceanic and Atmospheric Administration National Weather Service

POR - Period of Record

UF - University of Florida

USF - University of South Florida

USGS - United States Geological Survey

WRV - Water Resource Values

1 Introduction and Objectives

The Northwest Florida Water Management District (NWFWMD or District) is developing minimum flows and levels (MFLs) for Wakulla Spring and Sally Ward Spring in accordance with Section 373.042(1), Florida Statutes. The MFLs will address protection of water resources and ecology that may be affected by reduced spring flows due to future consumptive withdrawals. The MFL technical assessment for Wakulla Spring and Sally Ward Spring will quantify the limit of reductions in spring discharge commensurate with prevention of significant harm to the water resources or the ecology of the area, including those in the downstream freshwater and estuarine reaches of the Wakulla and St. Marks rivers.

Modeling tools have been previously developed to evaluate and predict the effects of spring flow reduction scenarios on selected water resource values (WRVs). These models include a mechanistic model for simulation of the hydrodynamic responses (salinity, temperature, water velocities, water surface elevation) within the combined St. Marks and Wakulla river systems to aid in determination of the St. Marks River and Wakulla River MFLs. This model was developed, calibrated, and used to evaluate flow reductions in the St. Marks River as part of the effort to establish the MFL for the St. Marks River Rise (NWFWMD 2019).

The following sections of this document provide the results of a model review concerning the appropriateness of the existing hydrodynamic model construct for use in this effort, describes the selection of the baseline flow period for flow reduction scenario evaluation including the data used for model input, describes the WRVs of concern for the estuarine Wakulla River, and presents the results of the flow reduction scenarios evaluated with graphical and tabular presentation of comparison of the scenario results to those of the baseline condition.

2 Review of the Existing Hydrodynamic Model

An Environmental Fluid Dynamics Code (EFDC) hydrodynamic model was previously developed (Janicki Environmental 2018a) as part of the effort to establish the MFL for the St. Marks River Rise (NWFWMD 2019). Prior to utilizing the existing model to evaluate effects of potential flow reductions in the estuarine portion of the Wakulla River, a review of the model was completed. This was necessary as the model was developed prior to the impacts on river physiography resulting from Hurricane Michael, which directly impacted the immediate area in October, 2018.

2.1 Model Development and Calibration

The model domain extends from approximately 2 miles (3 km) offshore of the mouth of the St. Marks River upstream to the US 98 bridge crossings on the St. Marks and the Wakulla. The District contracted bathymetric data collection from the mouth of the river upstream past the US 98 crossings (Wantman Group, Inc. 2016), and the bathymetry offshore of the mouth was developed using data obtained from the Florida Shelf Habitat (FLaSH) mapping study (Robbins et al. 2007). These data sources were used to develop the model grid bathymetry as described in Janicki Environmental (2018a) (Figures 1-3).

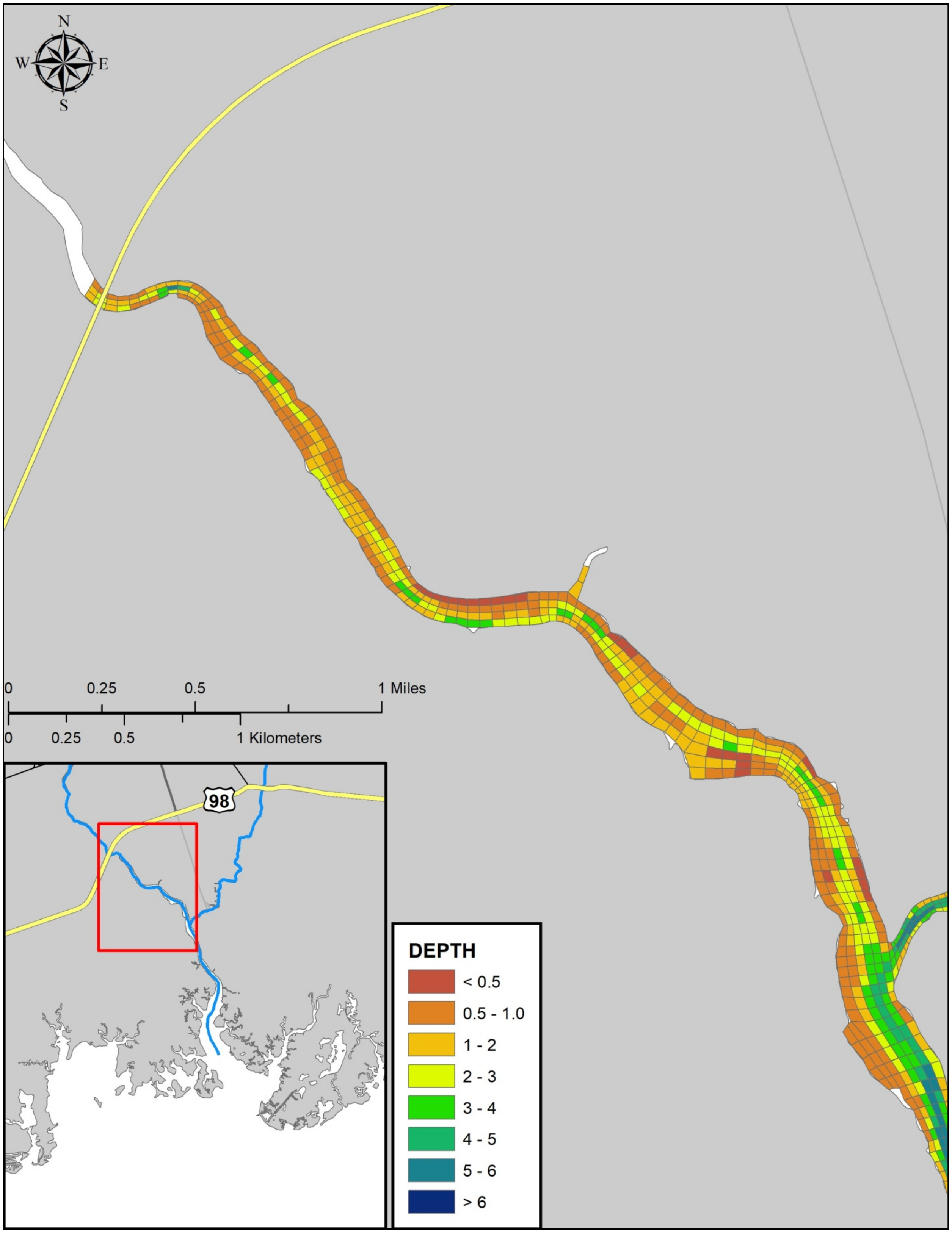

Figure 1. **Model grid and bathymetry for the Wakulla River portion of the model domain. Vertical reference is NAVD88, vertical (depth) units are meters.**

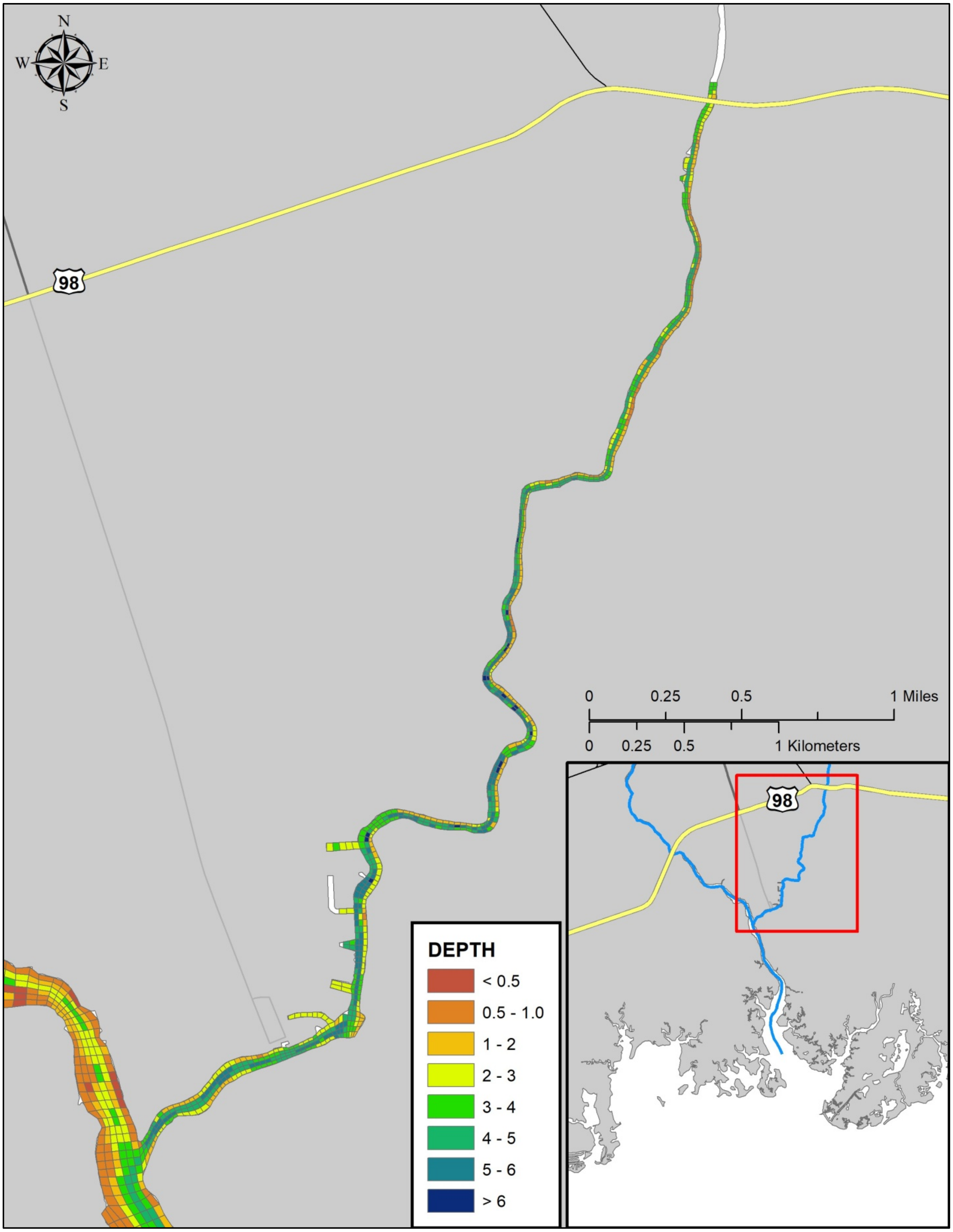

Figure 2. **Model grid and bathymetry for the St. Marks River upstream of the confluence within the model domain. Vertical reference is NAVD88, vertical (depth) units are meters.**

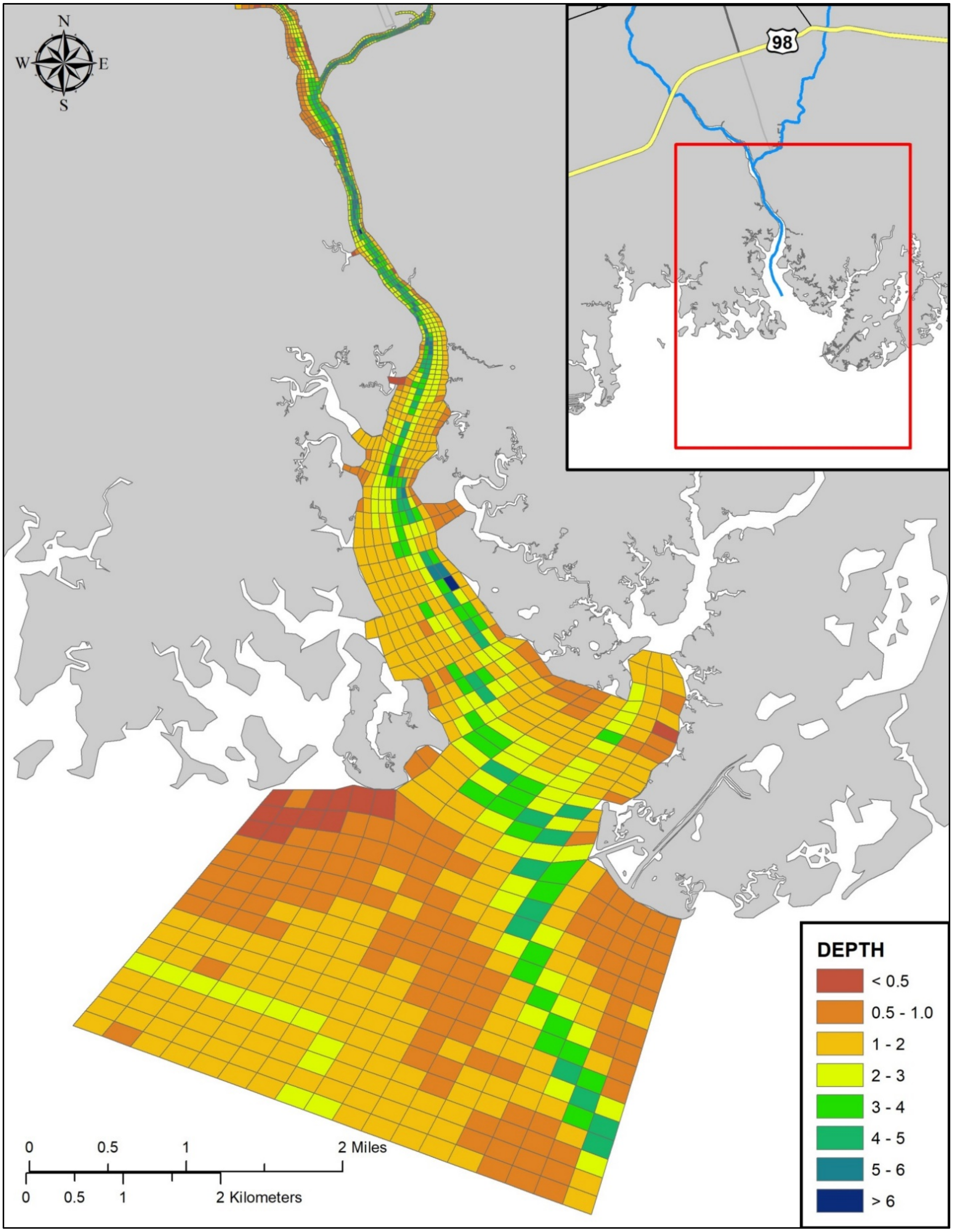

Figure 3. Model grid and bathymetry for the St. Marks River from the confluence downstream to the offshore boundary of the model domain. Vertical reference is NAVD88, vertical (depth) units are meters.

The hydrodynamic model was calibrated for the period May 11 - July 19, 2017. This period was selected based on the availability of reliable datasets for all input data types, including offshore boundary condition data near the mouth of the river and upstream input data collected by the District and USGS in both the St. Marks River and Wakulla River (Janicki Environmental 2018a). This time period also contained additional salinity profile data collected by the District throughout the model domain which were used to aid in model calibration and assess performance. In addition to the District-collected data, other data sources included the National Weather Service (NWS), the University of Florida (UF) Institute of Food and Agricultural Sciences Florida Automated Weather Network (IFAS FAWN), the University of South Florida (USF) Coastal Ocean Monitoring and Prediction System (COMPS), and the United States Geological Survey (USGS). These agencies are acknowledged as following accepted data monitoring protocols with approved quality control procedures. Use of data from these sources ensures the data have been quality controlled, and provides the best available data for the modeling effort. Data obtained from the various sites were assigned to represent boundary condition inputs for the model or calibration data for those sites within the model domain. Model inputs include the following, with the locations of the associated sites provided in Figure 4:

- Meteorological data from the NWS Tallahassee Regional Airport site (air temperature, atmospheric pressure, relative humidity, rainfall, cloud cover), along with daily evapotranspiration and hourly solar radiation data from the IFAS FAWN site at Monticello, FL;
- Wind speed and direction data from the USF COMPS Shell Point site;
- Offshore surface water elevation boundary condition derived using measured data at continuous recorder HD-5 at the mouth of the river (District);
- Offshore boundary conditions for salinity and water temperature derived using measured data at HD-5 (District);
- Upstream boundary conditions for salinity and water temperature as measured at continuous recorders HD-1 and HD-2 (District);
- Initial conditions for salinity and water temperature derived from the five continuous recorders (HD-1 through HD-5) (District); and
- Freshwater inflows from the USGS gages St. Marks near Newport (02326900) and Wakulla near Crawfordville (02327022), with ungaged inflows estimated as part of the HEC-RAS work completed for the St. Marks River Rise MFL development.

Model calibration was accomplished by comparing model output to observed data. This was completed for water surface elevation data collected at all five continuous recorders (HD-1 through HD-5, Figure 4), and for surface and bottom salinity using data collected at HD-5, HD-4, and HD-3. Additionally, longitudinal salinity profile data were collected in both the St. Marks River and Wakulla River (Figure 5), with these data compared to model output. A further test of the model was completed by comparing modeled cross-river water flux to data collected for this purpose.

The appropriateness of the model calibration was evaluated using both qualitative and quantitative approaches. Examination of comparative time series plots via graphical display allowed comparisons of both timing and magnitude, providing for qualitative visual evaluations of water surface elevation and salinity. Additional evaluation of the appropriateness of the calibration was based on quantitative methods using a set of calibration metrics (Janicki Environmental 2018a), including Mean Error (ME), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the Coefficient of Determination (R^2) to compare observed and simulated values of water surface elevation and salinity.

The results of the calibration effort showed that the hydrodynamic model was appropriately calibrated to evaluate the responses in the river to potential flow reductions. Measures of model skill assessment included Mean Error (ME), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the coefficient of determination (R^2) (Janicki Environmental 2018a). Previous work completed for an estuarine modeling effort of Tampa Bay, and subjected to scientific peer review, identified statistics for a good calibration of water surface elevation (Janicki Environmental 2014), and these statistics were used for the St. Marks-Wakulla hydrodynamic modeling calibration effort (Table 1). Other recent hydrodynamic modeling efforts completed as part of MFL evaluations for the estuarine Aucilla River (ATM 2015) and Econfina River (Janicki Environmental 2015) were considered to result in good calibrations, with associated values for the model skill assessment metrics as provided in Table 1. The values of these criteria for the model used here, as provided in Table 1, indicate that the hydrodynamic model of the St. Marks and Wakulla estuarine system is well-calibrated with respect to surface water elevations.

Table 1. Calibration metric criteria for St. Marks-Wakulla water surface elevation, with metric values for Aucilla River, Econfina River, and St. Marks-Wakulla hydrodynamic models.

	ME (cm)	MAE (cm)	RMSE (cm)	R^2
St. Marks-Wakulla Criteria	**±3.0**	**5.0**	**5.0**	**0.90**
Aucilla - Mouth	0.3	--	1.8	1.00
Aucilla - Middle	-0.3	--	4.9	0.99
Aucilla - Upstream	-0.3	--	5.8	0.96
Econfina - Mouth	0.3	--	1.5	2.00
Econfina - Middle	2.7	--	4.9	0.99
Econfina - Upstream	-2.1	--	5.5	0.98
St. Marks-Wakulla - HD-3	0.4	1.3	3.4	0.97
St. Marks-Wakulla - HD-4	2.4	4.0	5.1	0.99
St. Marks-Wakulla - HD-5	0.9	2.7	4.1	0.99

Evaluation of the observed and predicted water surface elevations at the three District continuous recorders within the model domain (HD-3, HD-4, and HD-5; Figure 4 and Table 1) found that all the calibration criteria were met at each of the sites, with the exception of the RMSE = 5.1 cm at HD-4. Station HD-4 was located outside of study area analyzed for effects of spring flow reduction on salinity. These statistical results, and the graphical comparison of time series plots of modeled and observed water surface elevations, indicated that the model showed good calibration for water surface elevation.

For skill assessment for salinity, Janicki Environmental (2018a) noted that the error statistics at the continuous recorders (locations shown in Figure 4) provide input concerning the degree of model responsiveness to observed forcing functions (flows, tides, etc.) Both the observed salinity data and the simulated salinity indicate intermittent time frames during which the tidal salinity intrusion reaches HD-3, at the junction of the Wakulla River and the St. Marks River. The nature of a salinity intrusion from the Gulf is such that often a very sharp salinity front moves up into the system, with the greatest level of intrusion occurring during neap tide conditions, when the energy is low and the level or sharpness of density stratification is highest. Due to the sharpness of the salinity front, a small error in the horizontal distance of the intrusion can result in a significant error in the salinity as the front moves up the system. For example, if the level of the salinity front intrusion in the model is 100 m short of the location of the station where salinity measurements are taken, the observed data could show that salinities might reach on the order of 10-15 ppt on the bottom, but the model simulations could show zero salinity, even though the simulated intrusion level was only a short distance downstream of the station location. Models tend to smear sharp gradients based on the level of model vertical or horizontal resolution. For the St. Marks-Wakulla model, the balance between having feasible run times for model scenarios and increased horizontal and vertical resolution (needed to represent the sharp gradients due to stratification in the system) lead to running the model with six vertical layers. While providing relatively good resolution in comparison with the depths, this level of vertical resolution still created some vertical smearing of the salinity profile. This result is very similar to those from the modeling efforts associated with the development of recent MFLs for the nearby Aucilla River and Econfina River (ATM 2015 and Janicki Environmental 2015, respectively).

As a result of these issues, graphical comparisons (Janicki Environmental 2018b) showed that the model reasonably simulated the upstream extent of the salinity intrusion and the overall magnitude response at the surface and bottom. A key aspect of this skill assessment was that during the calibration period, during both low flows and higher flows, the model results showed that the level and timing of salinity intrusions at HD-3 were acceptable given the observed variability in the system. The statistical skill assessment ranges for sites HD-5 (surface and bottom), HD-4 (surface and bottom), and HD-3 (bottom) were as follows:

- ME: range -0.1 to 3.6 ppt;
- MAE: range 0.1 to 4.8 ppt;
- RMSE: range 0.7 to 5.8 ppt; and
- R^2: range 0.12-0.63.

These calibration metric values indicate that although the model does not simulate the exact timing of salinity intrusions at all sites (as indicated by the low R^2 for bottom salinity at HD-3), the combination of the small ranges for the other metrics given the variability in the system, and the comparison of time series plots of observed and simulated salinities, support the model's capability to adequately simulate the variations in salinity intrusion under varying freshwater inflows and tidal forcing conditions (Janicki Environmental 2018b).

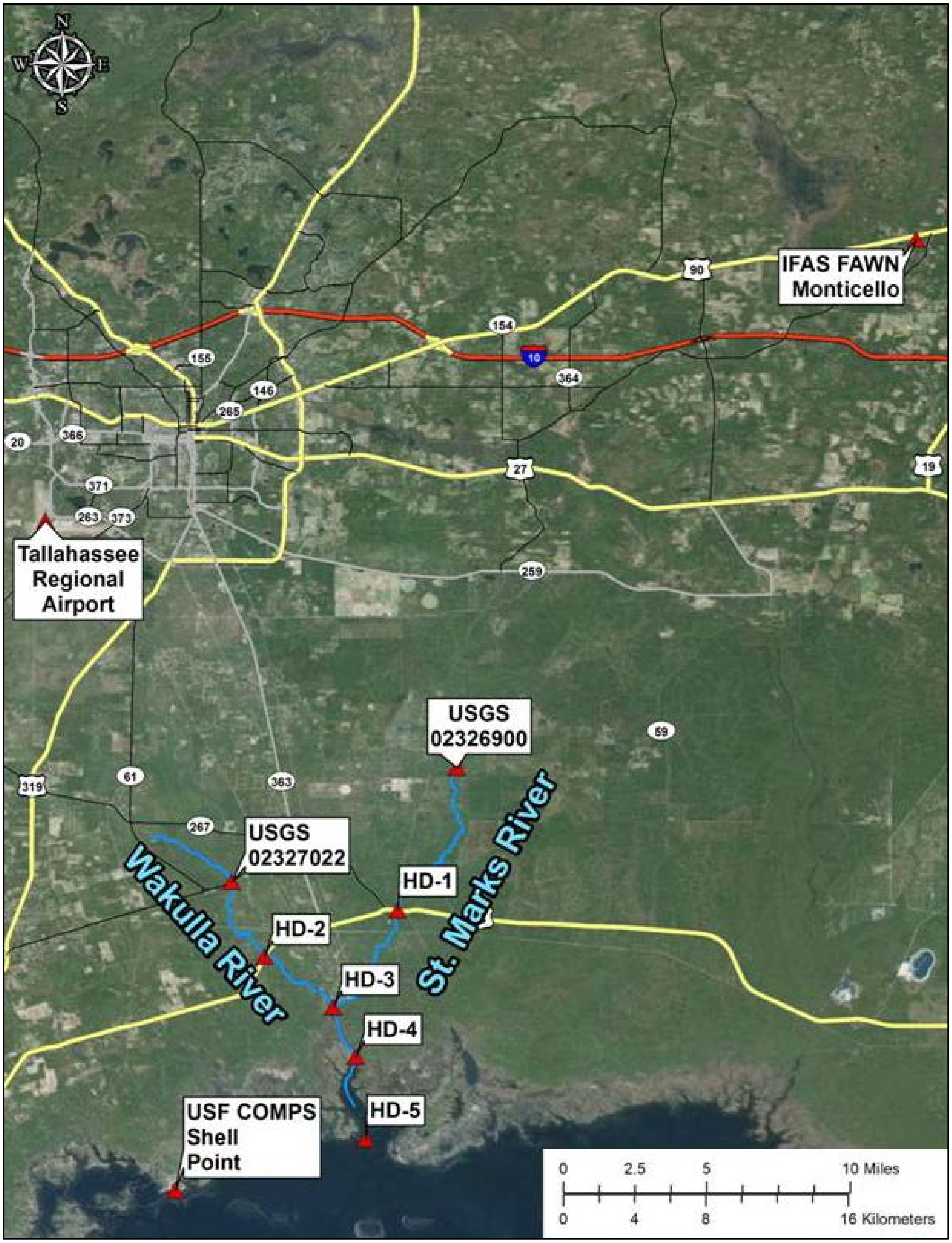

Figure 4. **Locations of data collection sites for continuous recorders (HD-1 through HD-5), USGS flow gages, USF COMPS Shell Point winds, Tallahassee Regional Airport meteorology (including rainfall), and IFAS FAWN Monticello.**

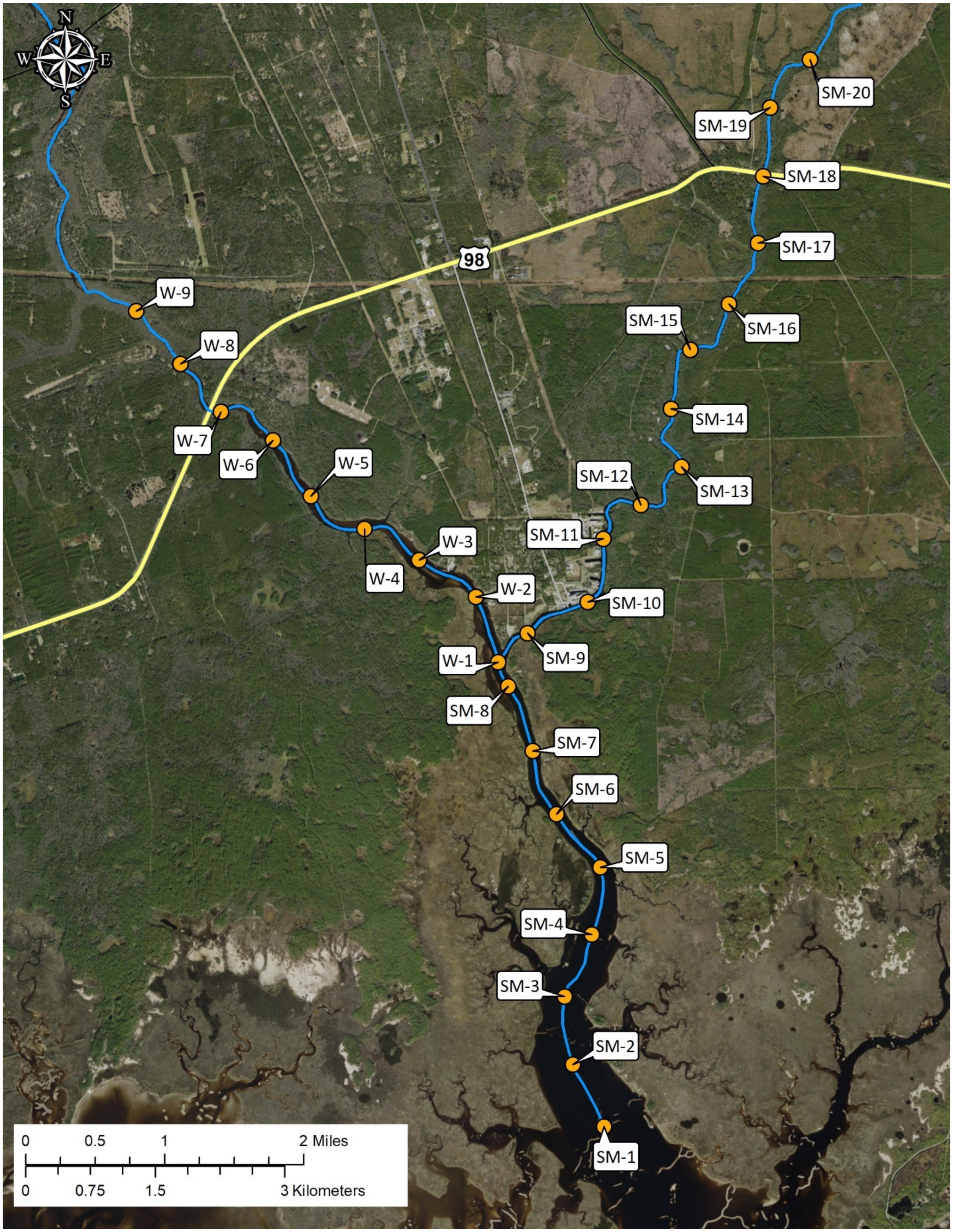

Figure 5. Locations of vertical profile sampling sites in St. Marks River and Wakulla River.

2.2 Review for Appropriateness Post-Hurricane Michael

Hurricane Michael impacted the St. Marks/Wakulla region in October 2018, after the initial bathymetry data collection that was used for developing the model grid bathymetry. Post-Michael, the District obtained updated bathymetric data for the Wakulla River after observing some scouring of the river bed downstream of the spring. These effects were limited to the region upstream of the US 98 bridge, which is the upstream-most extent of the model domain in the Wakulla River. The updated bathymetry data collected downstream of the US 98 bridge (Figure 6) indicated that there was no need to revise the model bathymetry in the Wakulla River portion of the model domain, as the new bathymetry data in this portion of the river were all very near the shore and showed no changes sufficient to warrant modification of the existing grid bathymetry. The new bathymetry data matched very well with existing model bathymetry, and with the original bathymetry data used to derive the grid bathymetry. The bottom elevation of each model grid cell is estimated as the mean elevation over a relatively large area, so that very small changes in bottom elevations at a few locations (the squares in Figure 6) do not result in changes in grid cell mean bottom elevations.

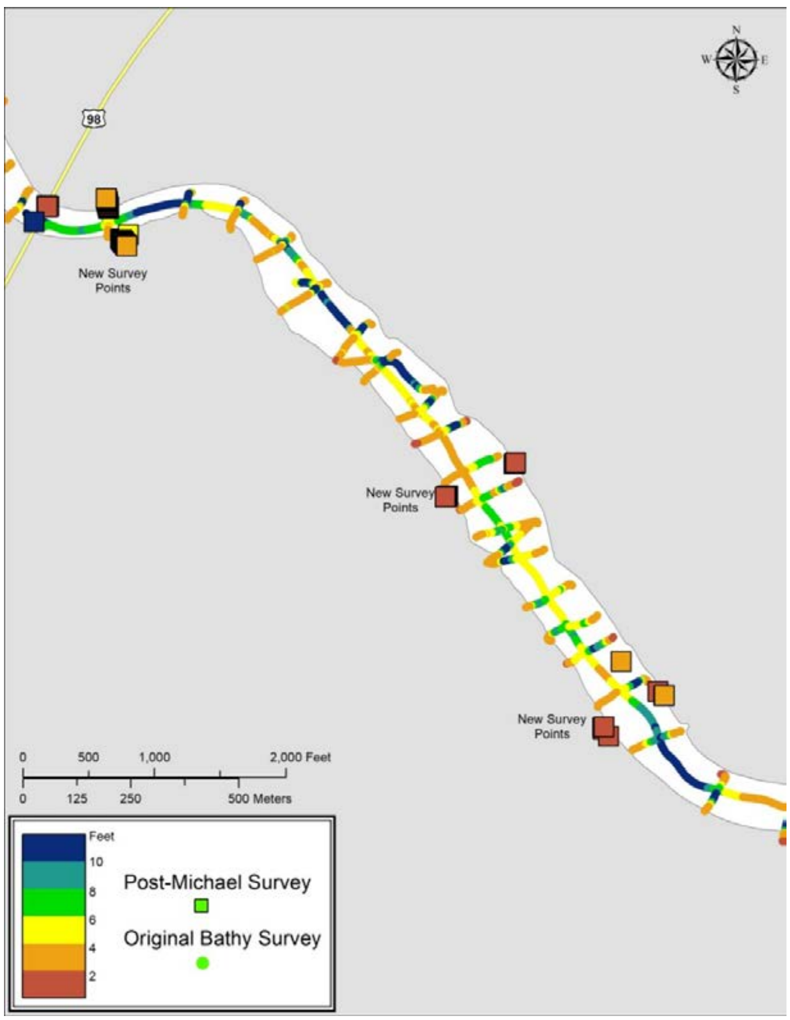

Figure 6. **Locations of new transect data collection sites for elevation (squares marked as "New Survey Points") with original bathymetric data in the Wakulla River below the US 98 crossing.**

3 Determination of Baseline Period

The long-term record for Wakulla river flows at the USGS gage 02327022, Wakulla River near Crawfordville (at Shadeville Rd), begins in 2004. Using this record for the entire period of 2004-2019 provides a flow distribution to guide the selection of a shorter time period, one amenable to modeling evaluation. Examination of consecutive 2- and 3-yr periods resulted in selection of the flow record for January 1, 2008 - October 4, 2010, as most representative of the long-term flow distribution (Figure 7). The flow distribution statistics for the period of record and the selected baseline period are provided in Table 2.

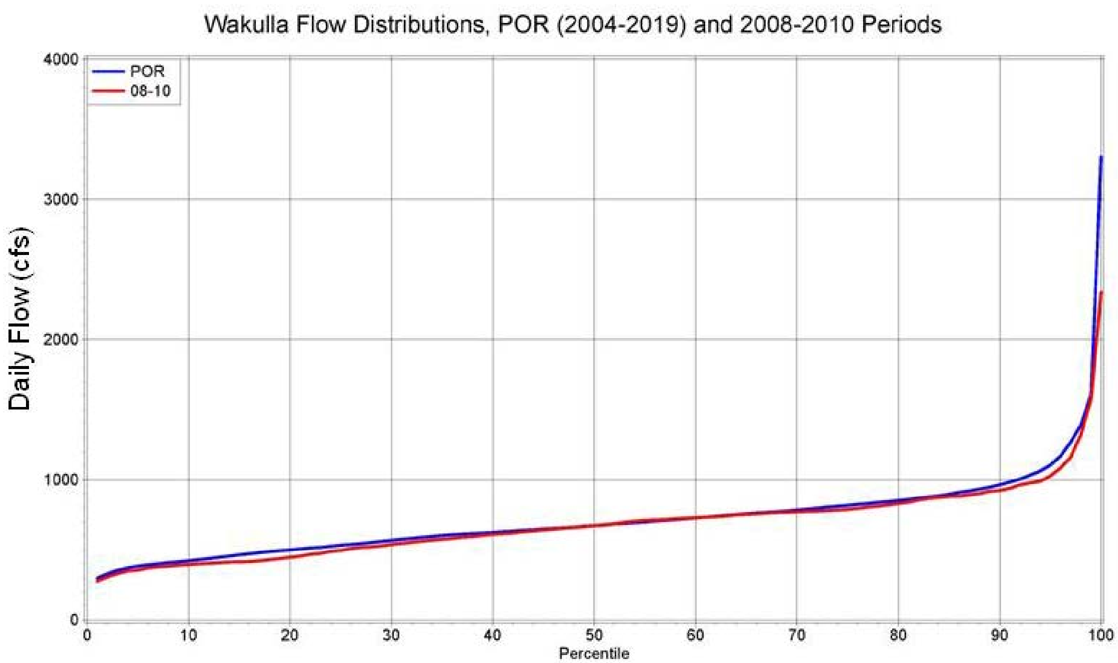

Figure 7. **Comparison of flow distributions at USGS gage 02327022, for period of record (2004-2019) and 2008-2010.**

Table 2. Distribution of flows during period of record (2004-2019) and selected baseline period.		
Flow Percentiles	**Period of Record Flow (cfs)**	**1/1/08-10/4/10 Flow (cfs)**
5th	383.9	354.5
10th	421.5	395.7
25th	531.0	495.7
50th	672.6	673.0
75th	817.7	788.5
90th	963.7	922.8
95th	1103.5	1026.5
Mean	700.5	676.2

The input data for the Baseline Scenario were compiled and prepared for input to the EFDC hydrodynamic model, for the period December 1, 2007 - October 4, 2010, with the December

2007 data providing for a 1-month spinup of the model prior to the baseline period. The downstream boundary condition for water surface elevation was estimated using predicted values at the St. Marks Lighthouse from the NOAA/NOS/CO-OPS tide prediction website, as no measured data were available for use during this period. Similarly, the downstream boundary condition for salinity and temperature was developed using output from the Gulf Coast Shelf Model (GCSM), as described below. Other data sources included the NWS, UF IFAS FAWN, USF COMPS, and the USGS, as noted in the listing below. Use of data from these sources ensures the data have been appropriately collected and quality controlled, and provides the best available data for the modeling effort. These data included the following:

- Meteorological and Wind Data:
  - Air Temperature: Tallahassee Airport, NWS (hourly)
  - Atmospheric Pressure: Tallahassee Airport, NWS (hourly)
  - Relative Humidity: Tallahassee Airport, NWS (hourly)
  - Rainfall: Tallahassee Airport, NWS (hourly)
  - Cloud Cover: Tallahassee Airport, NWS (hourly)
  - Evapotranspiration: Monticello, UF IFAS FAWN (daily)
  - Solar Radiation: Monticello, UF IFAS FAWN (hourly)
  - Wind Speed and Direction: Shell Point, USF COMPS (6-minute), with missing data filled from USF COMPS Keaton Beach site
- Water Surface Elevation Offshore Boundary Condition:
  - Water Surface Elevation: Predicted at the St. Marks Lighthouse on Apalachee Bay, NOAA/NOS/CO-OPS daily tide prediction website (6-minute)
- Salinity and Temperature Offshore Boundary Conditions:
  - Gulf Coast Shelf Model (GCSM) output at the offshore river model limit, as used in the St. Marks MFL flow reduction scenarios evaluation (Janicki Environmental, 2018b). The GCSM output used was for June 1997 - May 1999, with mean values taken by day and month to develop the offshore records for salinity and temperatures.
- Freshwater Inflows:
  - Wakulla River: gaged flows at USGS 02327022 (daily)
  - St. Marks River: gaged flows at USGS 02326900 (daily) adjusted to account for the St. Marks River Rise MFL, and adjusted for downstream ungaged flows between the gage and the upstream model extent as estimated as part of the HEC-RAS work completed for the St. Marks River Rise MFL development.

Time series plots of the hourly meteorological data used for this period are provided in Figures 8-14, with the NWS site at Tallahassee Regional Airport providing relative humidity, atmospheric pressure, air temperature, cloud cover, and rainfall. Hourly solar radiation data were obtained for the IFAS FAWN Monticello site, along with daily evapotranspiration data.

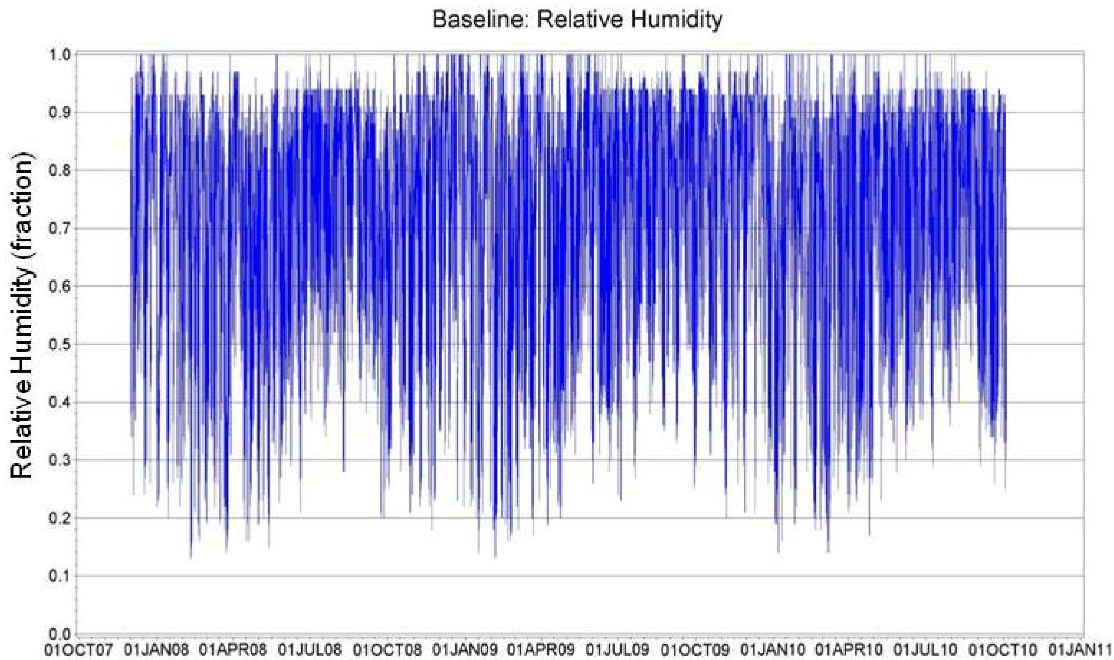

Figure 8. Hourly relative humidity from Tallahassee NWS site, December 1, 2007 to October 4, 2010.

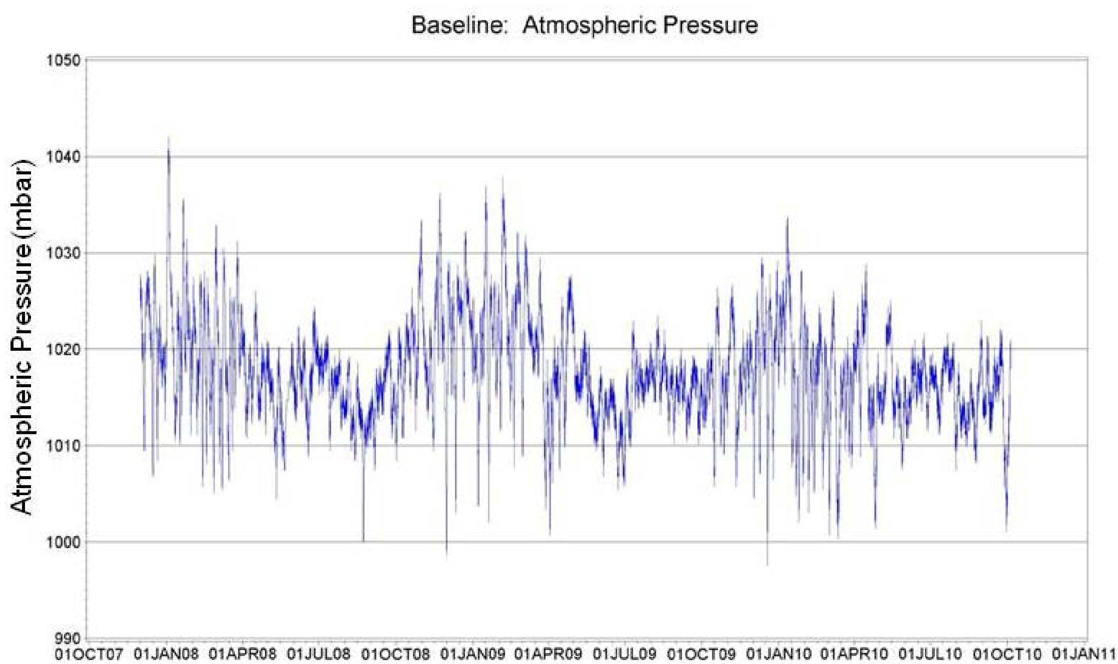

Figure 9. Hourly atmospheric pressure from Tallahassee NWS site, December 1, 2007 to October 4, 2010.

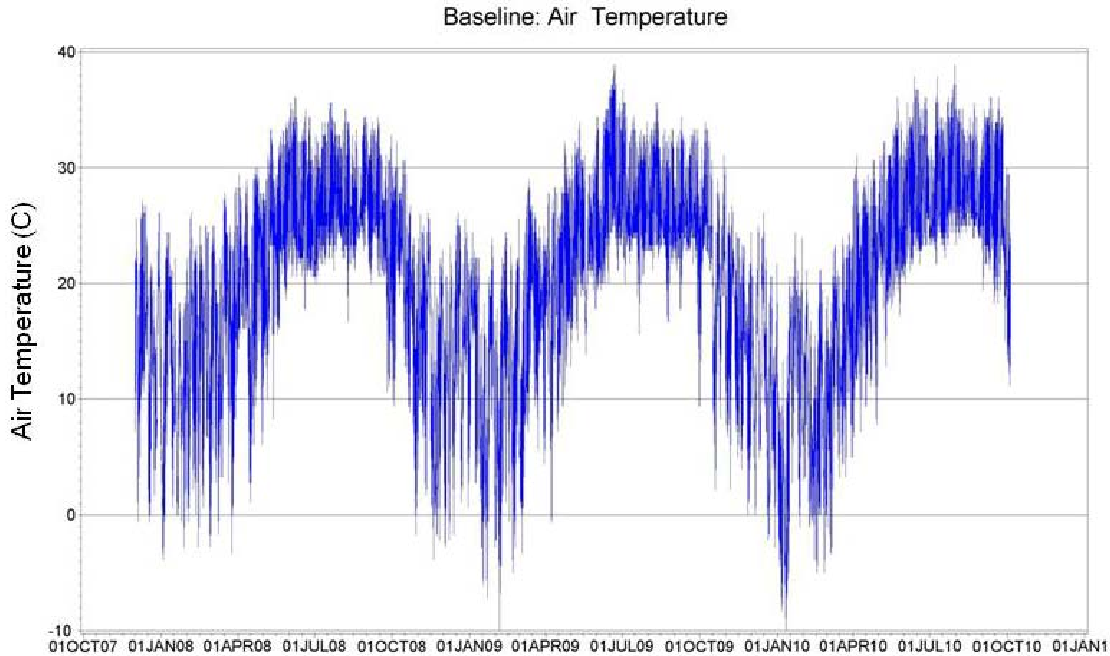

Figure 10. **Hourly air temperature from Tallahassee NWS site, December 1, 2007 to October 4, 2010.**

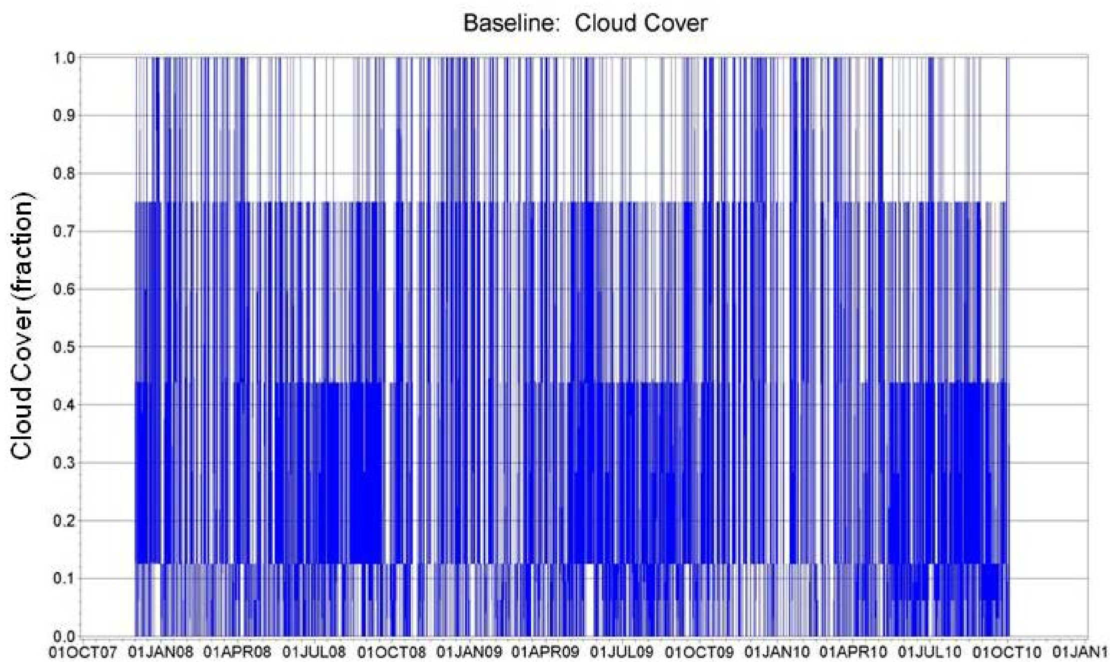

Figure 11. **Hourly cloud cover from Tallahassee NWS site, December 1, 2007 to October 4, 2010.**

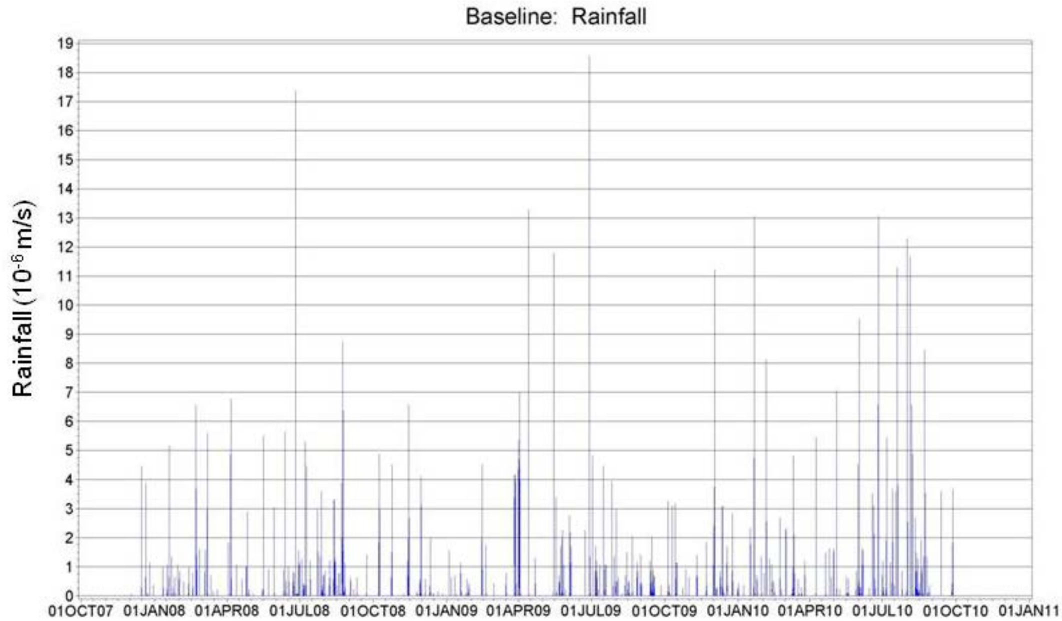

Figure 12. **Hourly rainfall from Tallahassee NWS site, December 1, 2007 to October 4, 2010.**

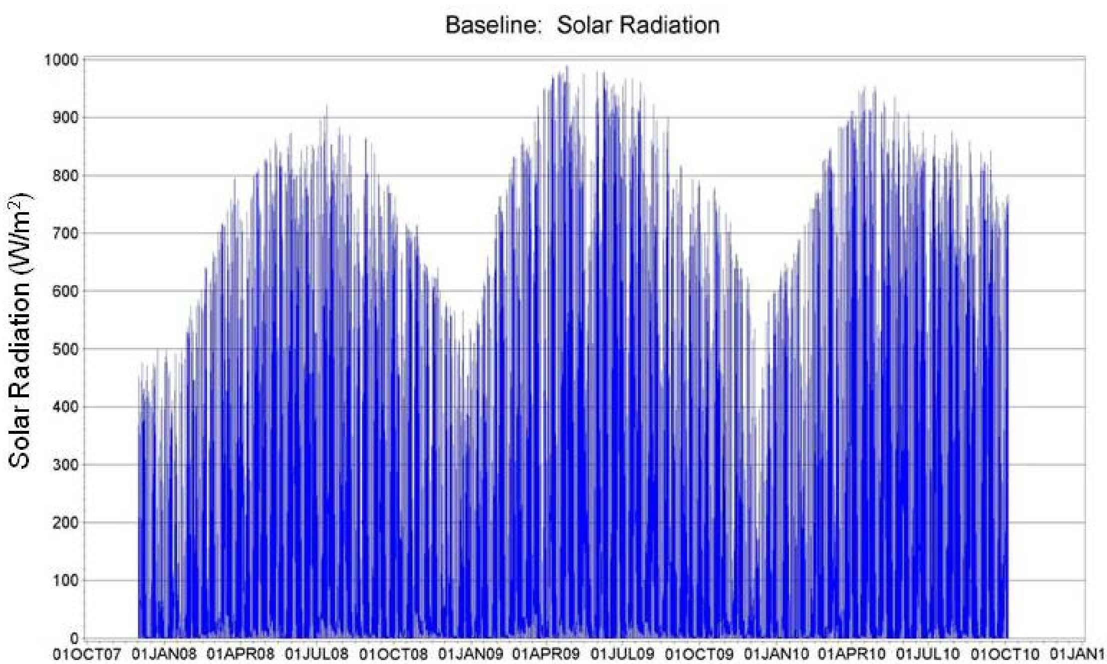

Figure 13. **Hourly solar radiation from Monticello IFAS FAWN site, December 1, 2007 to October 4, 2010.**

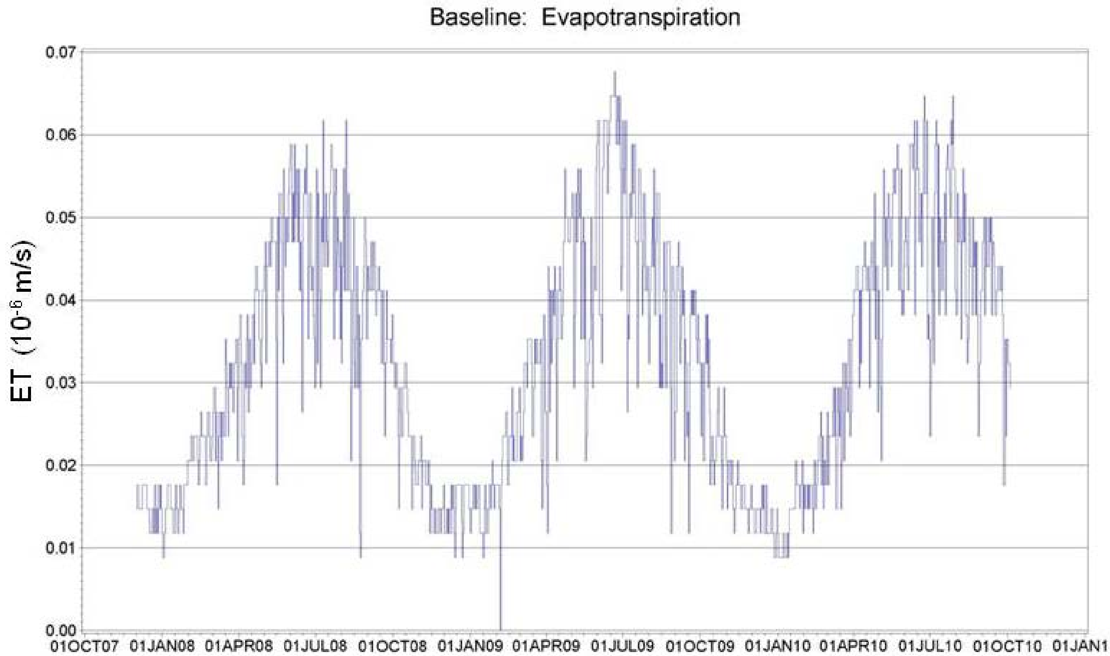

Figure 14. **Daily evapotranspiration from Monticello IFAS FAWN site, December 1, 2007 to October 4, 2010.**

Wind speed and wind direction data for the baseline period were obtained at 6-minute frequency from the USF COMPS Shell Point site on the Gulf Coast (Figure 4), with time series plots of wind speed and direction provided in Figures 15 and 16, respectively.

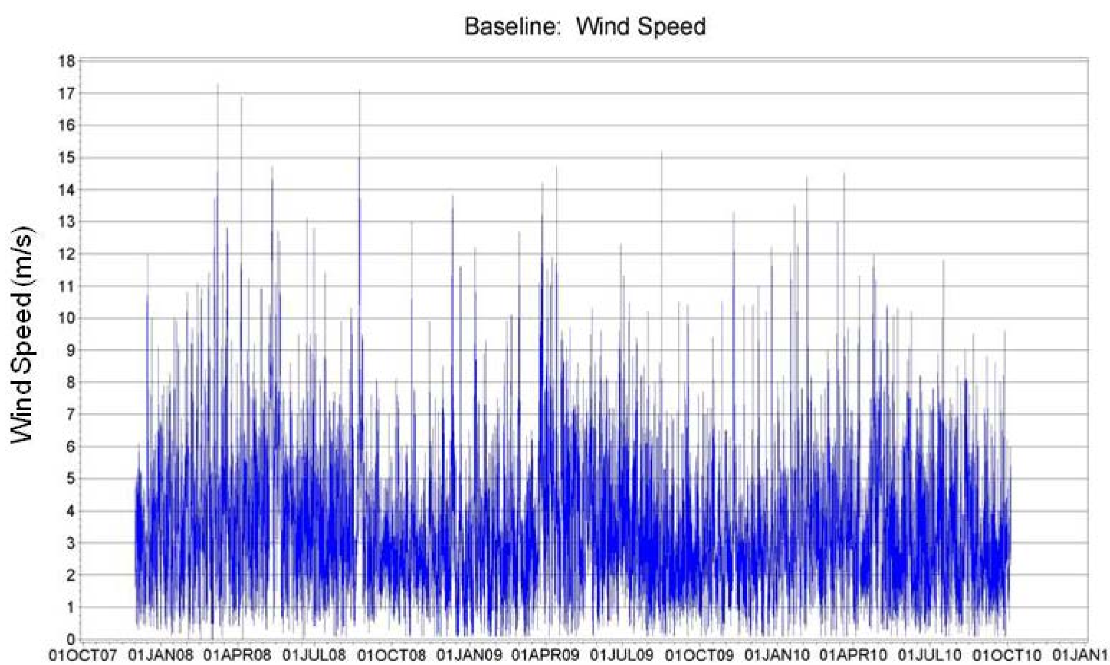

Figure 15. **6-minute frequency wind speed from Shell Point USF COMPS site, December 1, 2007 to October 4, 2010.**

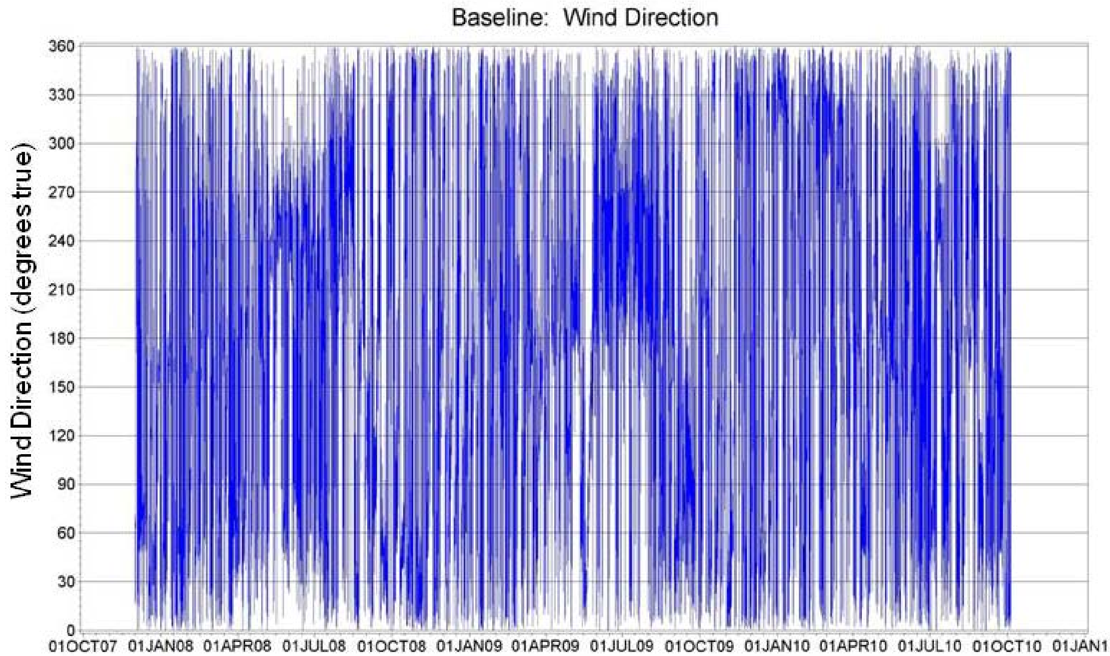

Figure 16. 6-minute frequency wind direction from Shell Point USF COMPS site, December 1, 2007 to October 4, 2010.

Predicted water surface elevations at the St. Marks Lighthouse on Apalachee Bay were obtained from NOAA/NOS/CO-OPS daily tide prediction website at 6-minute intervals, and used to set the offshore water surface elevation boundary condition, as no observed data existed for this period. The time series for December 1, 2007 - October 4, 2010 is provided in Figure 17.

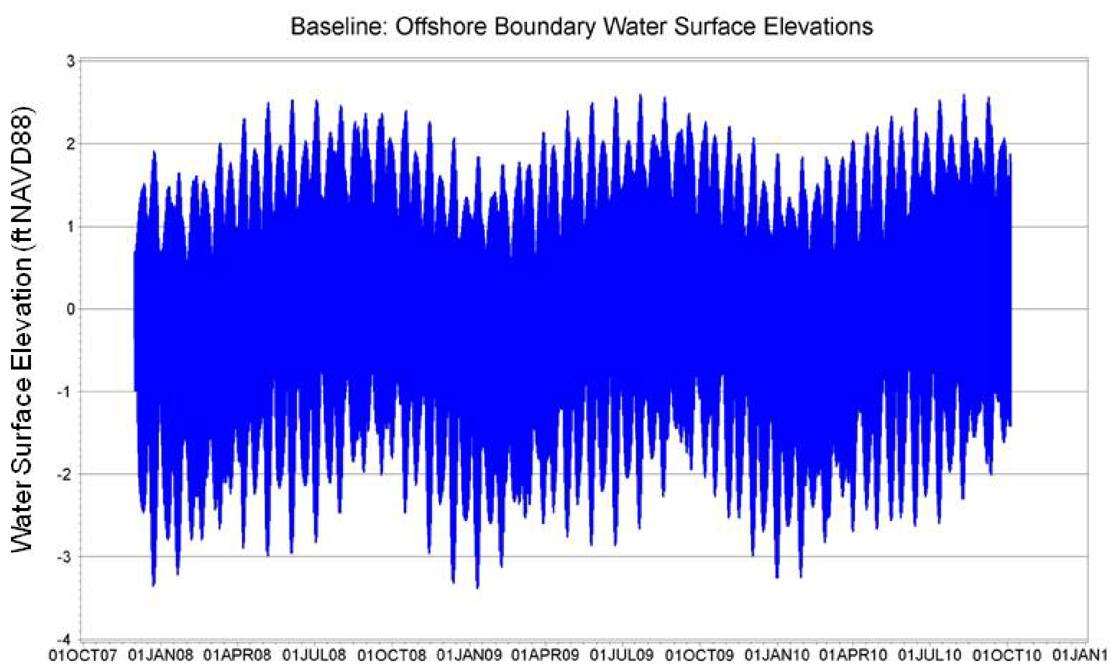

Figure 17. Water surface elevations at St. Marks Lighthouse on Apalachee Bay, from NOAA/NOS/CO-OPS, for December 1, 2007 to October 4, 2010, used for downstream boundary condition.

For the offshore boundary conditions for salinity and temperature, no data for the model period were available. Since the comparison of flow reduction scenarios to baseline conditions requires that the offshore boundaries be the same for each model implementation, it was only necessary that the offshore boundaries for salinity and temperature be reasonable and unmodified between scenarios. To this end, the offshore boundary conditions as utilized for the St. Marks MFL scenario evaluation (Janicki Environmental, 2018b) were used to develop salinity and temperature time series records for the baseline Wakulla evaluation. The GCSM was developed under contract with the Southwest Florida Water Management District and with the Suwannee River Water Management District contributing funding, and used to provide offshore boundary conditions for MFL evaluations (Janicki Environmental 2007). Hourly records as output from the GCSM for the offshore boundary during June 1997 - May 1999 were selected as being reasonable, as these were also used for the St. Marks evaluation. Mean values by calendar day and hour were developed, so that the boundary conditions were the same for a given calendar day and hour of each year of the baseline model period. These time series of salinity and temperature are provided in Figures 18 and 19, respectively. The GCSM output data are the only known available data to establish reliable temperature and salinity downstream boundary conditions.

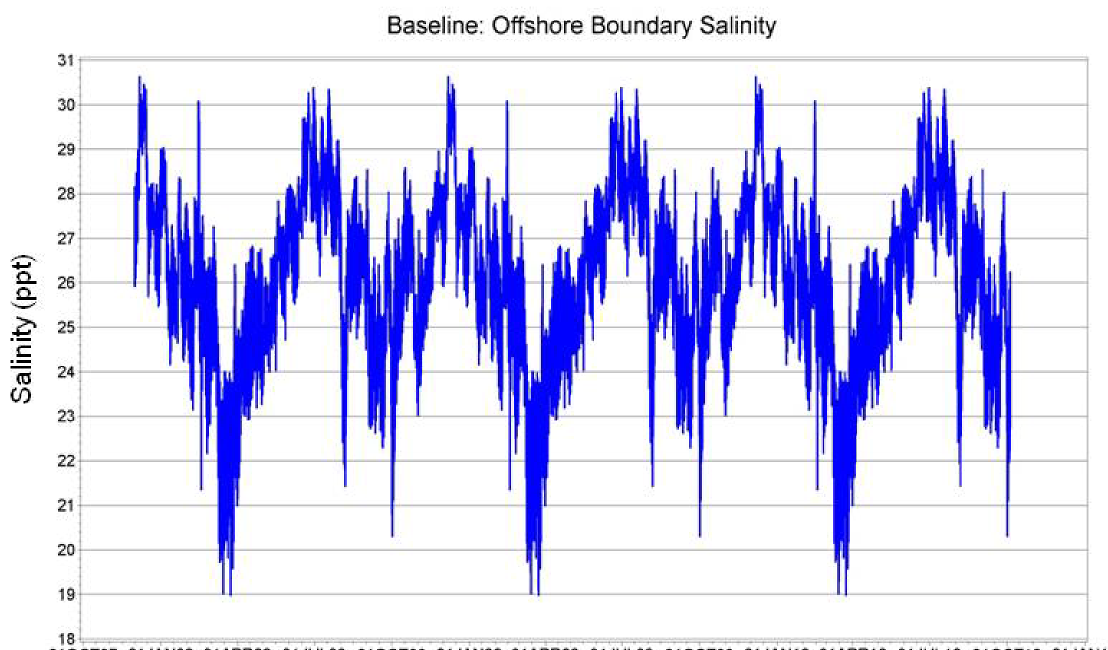

Figure 18. Salinity used for downstream boundary condition derived from offshore GCSM output.

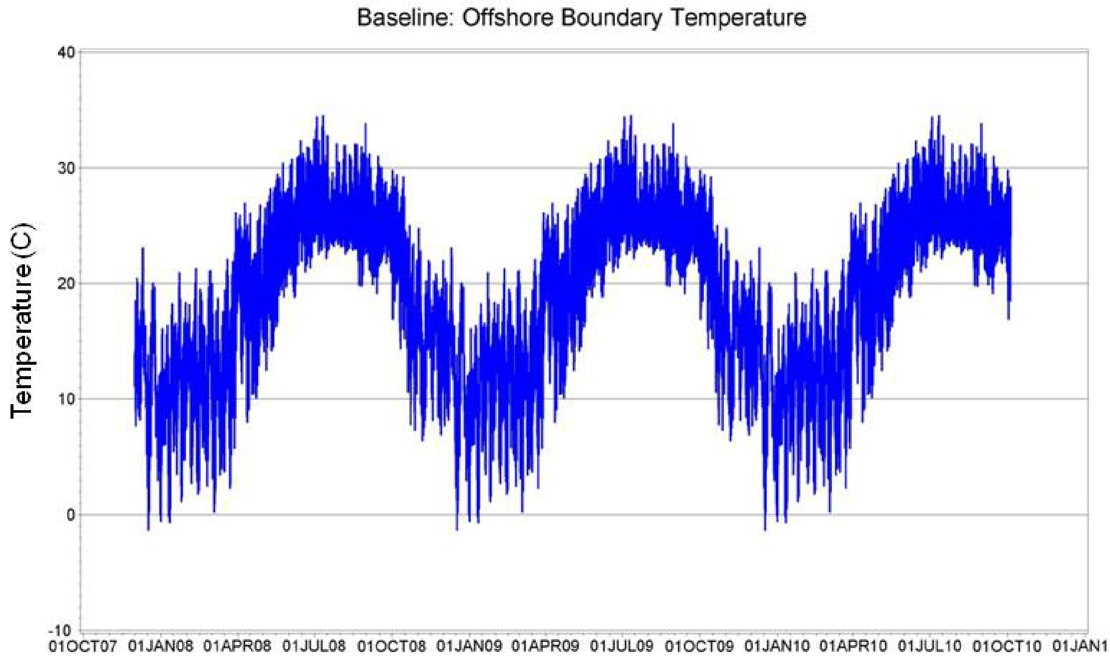

Figure 19. **Water temperature used for downstream boundary condition derived from offshore GCSM output.**

Freshwater inflows are from the USGS gages St. Marks near Newport (02326900) and Wakulla near Crawfordville (02327022), with ungaged inflows to the St. Marks River between the gage and the upstream extent of the model domain estimated as part of the HEC-RAS work completed for the St. Marks River Rise MFL development. In addition, the adopted St. Marks River Rise minimum flow is accounted for by a 7.3% reduction in the spring flow contribution to the gaged flow at 02326900. The freshwater inflows to the model are provided in Figures 20 and 21, for the Wakulla River and St. Marks River, respectively.

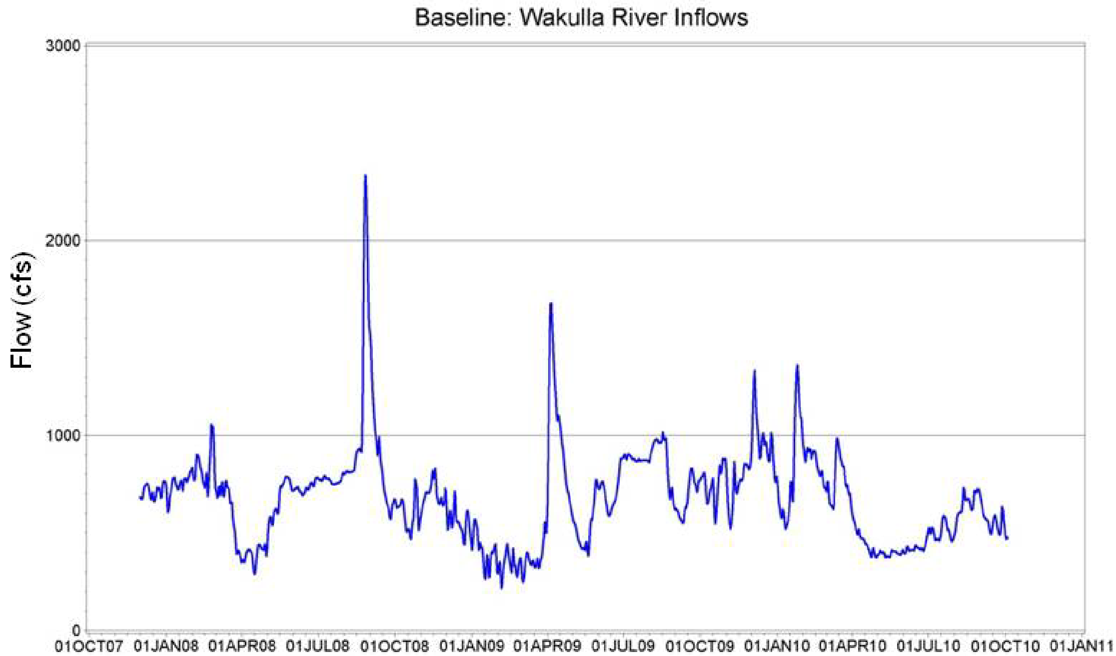

Figure 20. **Freshwater flows to upstream baseline model in Wakulla River.**

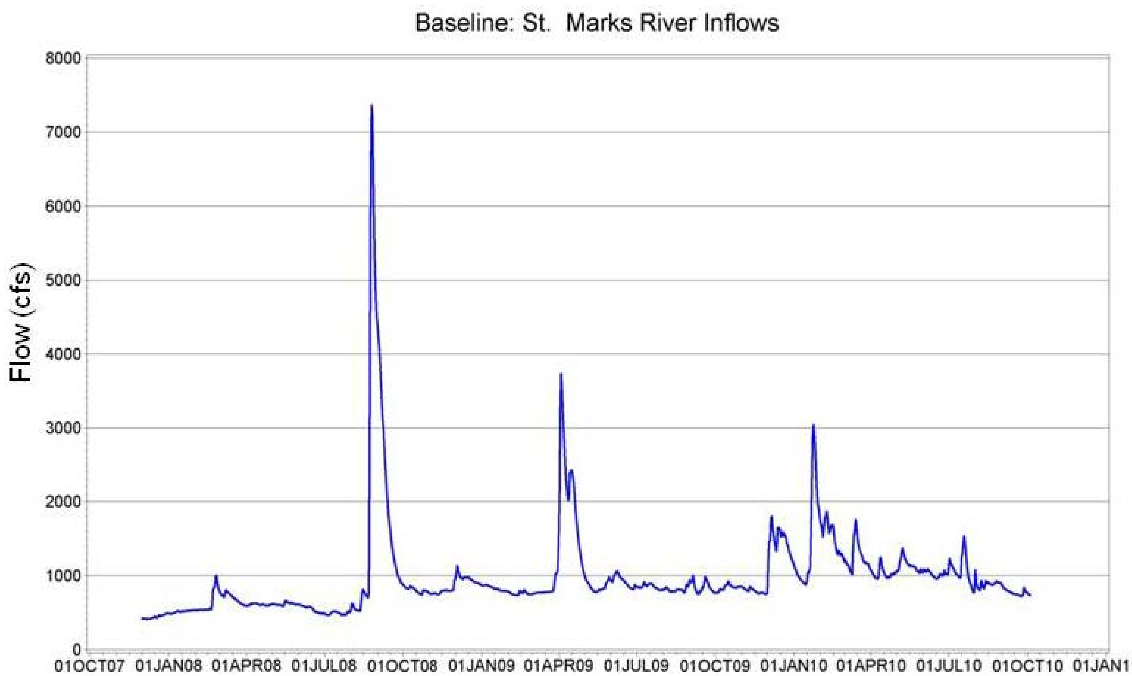

Figure 21. **Freshwater flows to upstream baseline model in St. Marks River.**

4 Definition of Water Resource Values (WRVs)

Multiple metrics were evaluated for Estuarine Resources, including the volume, bottom surface area, and shoreline length for a set of oligohaline (i.e. low salinity) zones, including ≤0.5 ppt, ≤1 ppt, ≤2 ppt, ≤3 ppt, and ≤4 ppt. This set of metrics is the same as that utilized for the Estuarine Resources evaluation of the St. Marks River Rise MFL (NWFWMD, 2019). Volume was considered as a metric to protect fish species habitat, bottom surface area to protect benthic species habitat, and shoreline length for the protection of shoreline floodplain vegetation communities.

5 Evaluation of Flow Reduction Scenarios and Sea Level Rise Scenario

Two flow reduction scenarios were evaluated for the potential impacts on the Estuarine Resource WRVs for the Wakulla and Sally Ward Spring evaluation. In the first, a flow reduction of 30% was applied at the USGS Wakulla River gage (02327022). This 30% flow reduction scenario was selected to evaluate whether such a large flow reduction would result in reduction of any of the selected WRVs to the 15% level, and is considered an upper bound flow reduction scenario that is unlikely to occur. The second flow reduction evaluated was a 36% reduction, also applied at the Wakulla River gage, and selected following output evaluation from the 30% flow reduction scenario (see results below), in an effort to determine the flow reduction percentage needed to get to a 15% reduction in any of the selected WRVs. Both flow reductions were directly applied to the input flows to the upstream end of the model domain for the Wakulla River. The evaluation of WRVs was made for the estuarine portion of the Wakulla River, between the US 98 crossing of the Wakulla River and the downstream conjunction with the St. Marks River.

For this WRV metric comparison, two different analyses were completed. First, the average daily volumes, bottom areas, and shoreline lengths of each salinity envelope (≤0.5 ppt, ≤1 ppt, ≤2 ppt, ≤3 ppt, and ≤4 ppt) were calculated over the 01/01/08-10/03/10 period for each scenario (the last day of the model period, 10/04/10, was not completed for the full 24-hour period due to an incomplete wind data input file, which was short by 4 fours due to correction of the timestamp from UTC to EST). Then, both the median and mean metric values for each salinity envelope over the full period were calculated. The daily frequency for this analysis was selected as commensurate with the minimum period of likely responses in the estuarine biota to changes in salinity due to flow reductions, as shifts in benthic community locations and composition do not occur at very short timescales. In addition, boundary conditions associated with low or high tides are likely to display extreme conditions representative of upstream (low tide) or offshore (high tide) conditions. Since the average salinity conditions during a typical day are of interest compared to short term extreme values, the average and median water levels were assessed.

Table 3 below provides these results comparing the baseline scenario and the 30% Wakulla River flow reduction run for the Wakulla River portion of the model domain (that area from the confluence upstream to the US98 bridge crossing of the Wakulla River), using the median of the daily average values for comparison. Table 4 similarly shows comparison results, based on the average (not the median) of the daily average values. As shown in both Tables 3 and 4, the reduction in WRV metrics within the estuarine Wakulla River (confluence upstream to the US98 Bridge) for a 30% river flow reduction never reached 15%. This results because the mean flow of 676 cfs for the baseline period when reduced by 30% is still more than 470 cfs mean daily flow.

The average river volume for the baseline flow record between the confluence and the US 98 bridge is 1.02 million m^3. The average flow rate of 676 cfs for the baseline is equivalent to 1.65 million m^3/day. The average daily flow through the river between the confluence and the US 98 bridge is thus 1.6 times the average river volume, so that most of the river in this region is relatively fresh (<4 ppt) (Table 3). The flow reduction of 30% still results in the total daily flow volume being greater than the river volume in this region (1.1 times), so that even at this flow reduction level most of the river volume here is <4 ppt.

An additional scenario with a 36% flow reduction to the estuarine Wakulla River was implemented to determine if this large reduction would result in exceedance of the 15% habitat reduction level for any of the metrics. Tables 5 and 6 below contain the results of this effort, with Table 5 providing a comparison of the medians of the daily average values, and Table 6 the average of the daily average values. Based on this scenario, a reduction of >15% was found for the ≤1 ppt extent of bottom area (Table 4), as well as reductions >15% for the ≤0.5 ppt metrics.

Time series plots of the resultant habitat metrics from the baseline and two flow reduction scenarios are provided in Appendix 1, along with those of the Sea Level Rise scenario (described below).

Table 3. Comparison of WRV metrics for median volume, bottom area, and shoreline length in estuarine Wakulla River for baseline (Base) and flow reduction (30%) scenarios.						
Scenario	**Volume ≤ 0.5 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 0.5 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 0.5 ppt (m)**	**Percent Reduction**
Base	852,096	14.6	529,980	13.6	9,675	8.3
30% Reduction	727,709		458,054		8,870	
Scenario	**Volume ≤ 1 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 1 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 1 ppt (m)**	**Percent Reduction**
Base	908,972	11.4	571,531	12.6	9,863	2.9
30% Reduction	805,273		499,659		9,572	
Scenario	**Volume ≤ 2 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 2 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 2 ppt (m)**	**Percent Reduction**
Base	962,040	6.5	605,710	7.3	9,863	0.0
30% Reduction	899,514		561,270		9,863	
Scenario	**Volume ≤ 3 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 3 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 3 ppt (m)**	**Percent Reduction**
Base	985,263	3.9	637,117	6.2	9,863	0.0
30% Reduction	947,326		597,919		9,863	
Scenario	**Volume ≤ 4 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 4 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 4 ppt (m)**	**Percent Reduction**
Base	1,000,640	3.0	646,681	4.1	9,863	0.0
30% Reduction	970,173		619,954		9,863	

Table 4. Comparison of WRV metrics for average volume, bottom area, and shoreline length in estuarine Wakulla River for baseline (Base) and flow reduction (30%) scenarios.						
Scenario	**Volume ≤ 0.5 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 0.5 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 0.5 ppt (m)**	**Percent Reduction**
Base	848,704	12.4	537,577	12.2	9,395	7.5
30% Reduction	743,270		472,257		8,690	
Scenario	**Volume ≤ 1 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 1 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 1 ppt (m)**	**Percent Reduction**
Base	900,463	10.2	568,113	10.7	9,730	4.1
30% Reduction	808,393		507,388		9,336	
Scenario	**Volume ≤ 2 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 2 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 2 ppt (m)**	**Percent Reduction**
Base	953,935	6.7	604,736	7.4	9,849	0.7
30% Reduction	889,837		449,939		9,785	
Scenario	**Volume ≤ 3 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 3 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 3 ppt (m)**	**Percent Reduction**
Base	982,222	4.8	627,712	5.2	9,860	0.1
30% Reduction	935,537		595,172		9,849	
Scenario	**Volume ≤ 4 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 4 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 4 ppt (m)**	**Percent Reduction**
Base	998,509	3.4	642,314	3.8	9,862	0.0
30% Reduction	964,274		617,991		9,860	

Table 5. Comparison of WRV metrics for median volume, bottom area, and shoreline length in estuarine Wakulla River for baseline (Base) and flow reduction (36%) scenarios.						
Scenario	**Volume ≤ 0.5 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 0.5 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 0.5 ppt (m)**	**Percent Reduction**
Base	852,096	18.8	529,980	20.7	9,675	11.0
36% Reduction	692,080		420,172		8,615	
Scenario	**Volume ≤ 1 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 1 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 1 ppt (m)**	**Percent Reduction**
Base	908,972	14.8	571,531	15.3	9,863	3.2
36% Reduction	774,260		484,004		9,548	
Scenario	**Volume ≤ 2 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 2 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 2 ppt (m)**	**Percent Reduction**
Base	962,040	8.8	605,710	10.2	9,863	0.0
36% Reduction	877,016		543,769		9,863	
Scenario	**Volume ≤ 3 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 3 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 3 ppt (m)**	**Percent Reduction**
Base	985,263	5.3	637,117	7.5	9,863	0.0
36% Reduction	932,866		589,625		9,863	
Scenario	**Volume ≤ 4 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 4 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 4 ppt (m)**	**Percent Reduction**
Base	1,000,640	4.1	646,681	6.1	9,863	0.0
36% Reduction	959,514		607,284		9,863	

Table 6. Comparison of WRV metrics for average volume, bottom area, and shoreline length in estuarine Wakulla River for baseline (Base) and flow reduction (36%) scenarios.						
Scenario	**Volume ≤ 0.5 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 0.5 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 0.5 ppt (m)**	**Percent Reduction**
Base	848,704	15.9	537,577	16.1	9,395	9.1
36% Reduction	713,771		450,964		8,534	
Scenario	**Volume ≤ 1 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 1 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 1 ppt (m)**	**Percent Reduction**
Base	900,463	13.4	568,113	14.4	9,730	4.8
36% Reduction	780,139		486,067		9,262	
Scenario	**Volume ≤ 2 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 2 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 2 ppt (m)**	**Percent Reduction**
Base	953,935	9.0	604,736	10.5	9,849	0.5
36% Reduction	867,984		541,153		9,801	
Scenario	**Volume ≤ 3 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 3 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 3 ppt (m)**	**Percent Reduction**
Base	982,222	6.5	627,712	7.2	9,860	0.0
36% Reduction	918,572		582,440		9,861	
Scenario	**Volume ≤ 4 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 4 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 4 ppt (m)**	**Percent Reduction**
Base	998,509	4.8	642,314	5.2	9,862	0.0
36% Reduction	950,684		608,762		9,863	

In addition to the flow reduction scenario, a Sea Level Rise scenario was implemented, accounting for a potential increase in sea level of 1.87 inches. This value represents the estimated increase in sea level using the average (2.38 mm/yr) observed long-term sea level rise rates provided by NOAA for Apalachicola (2.56 mm/yr) and Cedar Key, Florida (2.19 mm/yr) (NOAA 2020). This increase was applied over the full period of the comparison run, 1/1/08-10/04/10. The resultant changes in WRV metrics are provided in Tables 7 and 8 below, for the medians of the daily average values (Table 7) and the average of the daily average values (Table 8). Time series plots of the habitat metric values are provided in Appendix 1. Results indicate that a sea level rise of 1.87 inches is likely to have an impact of some estuarine resource metrics. The effects of sea level rise in combination with Wakulla River flow reductions was not estimated.

Table 7. Comparison of WRV metrics for median volume, bottom area, and shoreline length in estuarine Wakulla River for baseline (Base) and sea level rise (SLR) scenarios.

Scenario	Volume ≤ 0.5 ppt (m^3)	Percent Reduction	Bottom Area ≤ 0.5 ppt (m^2)	Percent Reduction	Shoreline ≤ 0.5 ppt (m)	Percent Reduction
Base	852,096	2.3	529,980	4.9	9,675	0.6
SLR	832,500		503,961		9,623	
Scenario	**Volume ≤ 1 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 1 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 1 ppt (m)**	**Percent Reduction**
Base	908,972	0.6	571,531	6.2	9,863	0.0
SLR	903,429		536,312		9,863	
Scenario	**Volume ≤ 2 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 2 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 2 ppt (m)**	**Percent Reduction**
Base	962,040	-0.8	605,710	1.6	9,863	0.0
SLR	969,487		596,337		9,863	
Scenario	**Volume ≤ 3 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 3 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 3 ppt (m)**	**Percent Reduction**
Base	985,263	-1.5	637,117	3.5	9,863	0.0
SLR	999,519		615,132		9,863	
Scenario	**Volume ≤ 4 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 4 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 4 ppt (m)**	**Percent Reduction**
Base	1,000,640	-1.6	646,681	1.2	9,863	0.0
SLR	1,016,341		639,258		9,863	

Table 8. Comparison of WRV metrics for average volume, bottom area, and shoreline length in estuarine Wakulla River for baseline (Base) and sea level rise (SLR) scenarios.						
Scenario	**Volume ≤ 0.5 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 0.5 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 0.5 ppt (m)**	**Percent Reduction**
Base	848,704	1.1	537,577	5.3	9,395	0.6
SLR	839,144		509,232		9,337	
Scenario	**Volume ≤ 1 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 1 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 1 ppt (m)**	**Percent Reduction**
Base	900,463	0.5	568,113	4.5	9,730	-0.2
SLR	896,374		542,442		9,745	
Scenario	**Volume ≤ 2 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 2 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 2 ppt (m)**	**Percent Reduction**
Base	953,935	-0.5	604,736	2.9	9,849	-0.1
SLR	958,580		587,014		9,860	
Scenario	**Volume ≤ 3 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 3 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 3 ppt (m)**	**Percent Reduction**
Base	982,222	-1.1	627,712	2.1	9,860	0.0
SLR	992,876		614,646		9,863	
Scenario	**Volume ≤ 4 ppt (m^3)**	**Percent Reduction**	**Bottom Area ≤ 4 ppt (m^2)**	**Percent Reduction**	**Shoreline ≤ 4 ppt (m)**	**Percent Reduction**
Base	998,509	-1.5	642,314	1.7	9,862	0.0
SLR	1,013,774		631,561		9,863	

6 Conclusions

A baseline model scenario was developed and implemented for the period 1/01/08-10/04/10, when the Wakulla River flow distributions were very similar to those for the full period of record, from 2004-2019. Two flow reduction scenarios were implemented and evaluated along with a sea level rise scenario. It required a 36% flow reduction to reach a habitat metric reduction of 15% or greater in the estuarine Wakulla River, with a 30% flow reduction resulting in no habitat metrics reduced by 15% or more relative to the baseline conditions.

The results also indicated that changes in low-salinity habitat metrics within the estuarine Wakulla River are not linear with respect to flow reductions. For example, Table 2 shows that a 30% flow reduction results in a 14.6% reduction in the volume of ≤0.5 ppt habitat compared to baseline conditions within the Wakulla River portion of the model domain, or approximately a 2.9% reduction in habitat volume per 6% reduction in flow. However, Table 4 shows that a 36% flow reduction results in an 18.8% reduction in the volume of the ≤0.5 ppt habitat compared to baseline conditions, or approximately a 3.1% reduction in habitat volume per 6% reduction in flow. Overall, salinity habitat metrics within the estuarine river show only small responses (<15% reductions) in response to large reductions (30%) in flow from Wakulla Spring.

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