CONSTRUCTION, REFINEMENT AND CALIBRATION OF THE HYDROLOGIC ENGINEERING CENTERS RIVER ANALYSIS SYSTEM (HEC-RAS) MODEL

ST. MARKS AND WAKULLA RIVERS

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1.0 INTRODUCTION

This report documents the construction, refinement and calibration of the Hydrologic Engineering Centers River Analysis System (HEC-RAS) model of the St. Marks and Wakulla Rivers. The intended use of this HEC-RAS model is to support minimum flows development for the St. Marks River Rise. The general study area for the model is shown on Figure 1.

Overview of Report

The report describes the development and refinement of a single HEC-RAS model for the St. Marks and Wakulla River system. The goal of the model development effort was to utilize existing HEC-RAS models for the Wakulla River and St. Marks River constructed for Federal Emergency Management Agency (FEMA) flood map updates and construct a single HEC-RAS model using these FEMA models and recently acquired information. The model would be used to support the determination of minimum flows and levels (MFLs) in the Wakulla/St. Marks River system. The first application of this model was for the St. Marks River Rise minimum flows determination. This report describes the initial model development as related to the following:

- Model geometry modifications, including extension of spatial domain
- Input flow files and boundary conditions using available hydrodynamic monitoring data and USGS flow data
- Model testing, initial model calibration, and final model calibration
- Conversion of the unsteady flow model to a steady-state model
- Scenario runs to support the development of minimum flows for the St. Marks River Rise

The model and report were evaluated by an independent, scientific peer review panel who provided comments related to the limited calibration period available at the time of initial model construction and calibration and the need for additional discussion in the report clarifying the calibration process, assumptions implemented and uncertainty. To address these comments, additional model testing and calibration were performed using an expanded data set that included an additional four-month data period-of-record. In addition to a qualitative evaluation of model performance, quantitative model performance metrics were calculated. Scenario runs to support the development of minimum flows for the St. Marks River Rise and effects of sea-level rise using the final model were performed. The report includes a discussion of the additional model testing, calibration and performance including quantitative model performance metrics.

The report also includes additional discussion of model parameter development, assumptions and uncertainty.

Figure 1. General Study Area for the St. Marks/Wakulla River HEC-RAS Model

2.0 MODEL GEOMETRY, CONSTRUCTION, AND MODIFICATIONS

The Northwest Florida Water Management District (NWFWMD) provided separate, existing HEC-RAS floodplain models that had been used for independent Federal Emergency Management Agency (FEMA) floodplain assessments on the Wakulla and St. Marks Rivers. Those models were used as starting points for the development of a single HEC-RAS model to support minimum flows and levels (MFL) development.

The two models were combined, and the geometry data merged into one model project. In addition, the two river systems were joined with a junction feature at the confluence of the two rivers near the City of St. Marks. With the two HEC-RAS models combined into one, the respective settings and coefficients were reviewed for general appropriateness. Both models were found to have been appropriately configured.

The model geometry was updated to include additional transect and bathymetric data from 2015. Three sets of additional survey data were reviewed. The first set of data consisted of 11 St. Marks River transects (Southeastern Surveying, 2015) and eight Wakulla River transects [Wantman Group, Inc. (WGI), 2015]. Each transect extended from the upland edge through the floodplain, to the water's edge, and across the river. Most extended through the floodplain on the opposite river bank to the upland, but some transects included only one side of the river floodplain.

The existing model geometries were compared to the additional transect and bathymetric data from 2015 at locations where there were co-located transects. Figure 2 presents an example of co-located transect data. Upon review, each of these transects was found to be consistent with the existing model geometry. When compared to topographic light detection and ranging (LiDAR) data, the existing cross-sections had done a sufficient job of describing the river geometry, and the incorporation of additional cross-section data from the recent surveys was deemed unnecessary.

Figure 2. Examples of Co-Located Transect Data

The second set of survey data was obtained by Southeastern Surveying, Inc. in 2015. While comparing the Southeastern Surveying 2015 surveyed cross-sections, it was noted that the existing St. Marks River model transect data (circa 2010) agreed in the floodplain, but that on survey transects SM8, SM9, SM10 and SM11, there was substantial disagreement with the (existing) model transect depths in the channel, as shown in Table 1.

Table 1. Locations of Inconsistent Channel Geometry in the St. Marks River

2015 Survey		*2010 HECRAS Model*	
Transect Number	**Lowest Surveyed Elevation**	**Transect Number**	**Lowest Modeled Elevation**
SM8	-18.4	*22436*	-9.6
SM9	-14	*20240*	-9.8
SM11	-20	*16060*	-11.3
SM10	-18	*14427*	-11.7
Elevations in ft. NAVD88			

In addition to the surveys performed by Southeastern Surveying, Inc. in 2015, a bathymetric survey was performed by Wantman Group, Inc.in 2016 for the tidally influenced portions of the St. Marks and Wakulla Rivers (WGI 2016). Comparison of the bathymetric transect data from the NWFWMD-supplied bathymetric survey (WGI, 2016) confirmed the in-channel elevation errors in the original model. It is likely that these errors were not critical in the original floodplain analysis application but, for minimum flows evaluations, adjustments to the channel bottom elevations were deemed necessary. Both rivers were checked against the 2016 bathymetric transect data, and several cross-sections on the St. Marks River were improved and reconstructed using the 2016 bathymetric transect data supplied by NWFWMD. For those transects (Table 2), the bathymetric transect data were used to replace the concurrent transect channel data in the model by manual entry of station and elevation data.

Table 2. Locations of Improved In-Channel Geometry in the St. Marks Model Reach

HEC-RAS Model Cross-Section Reconfigured	2016 Bathymetric Transect Source Data
24105	SM1
22436	SM6
20240	SM11
18845	SM15
16060	SM22
14427	SM25
11898	SM32
10215	SM37
5936	SM47
3011	SM57
529	SM63

In addition to the 11 transect reconstructions listed in Table 2, all eight-surveyed channel and floodplain transects on the Wakulla River (WGI, 2015) were checked against the model data and found to be consistent with the original model. Accordingly, no modifications were made to the Wakulla River model geometry.

NWFWMD provided an additional set of survey data, in addition to the two prior Southeastern Surveying surveys and the WGI bathymetric survey. This survey data consisted of five additional transects of known shoal areas along the St. Marks River. These five transects were originally designed to be used to support instream habitat modeling using the System for Environmental Flow Analysis (SEFA). However, tidal influence and dense vegetation at these sites precluded the use of SEFA or similar instream habitat modeling. Knowing that these sites represented specific shoal locations within the St. Marks River, it was important to include them for probable future hydraulic analysis locations, particularly for evaluating minimum flow metrics, where depth at low flow is important. The new transect numbers are provided in Table 3, and the shoal transect locations are presented in Figure 3.

Table 3. Shoal Transect Locations

Shoal Transect	HEC-RAS Model Cross-Section (NEW)
T-1	37716
T-2	43299
T-3	43959
T-4	44415
T-5	45415

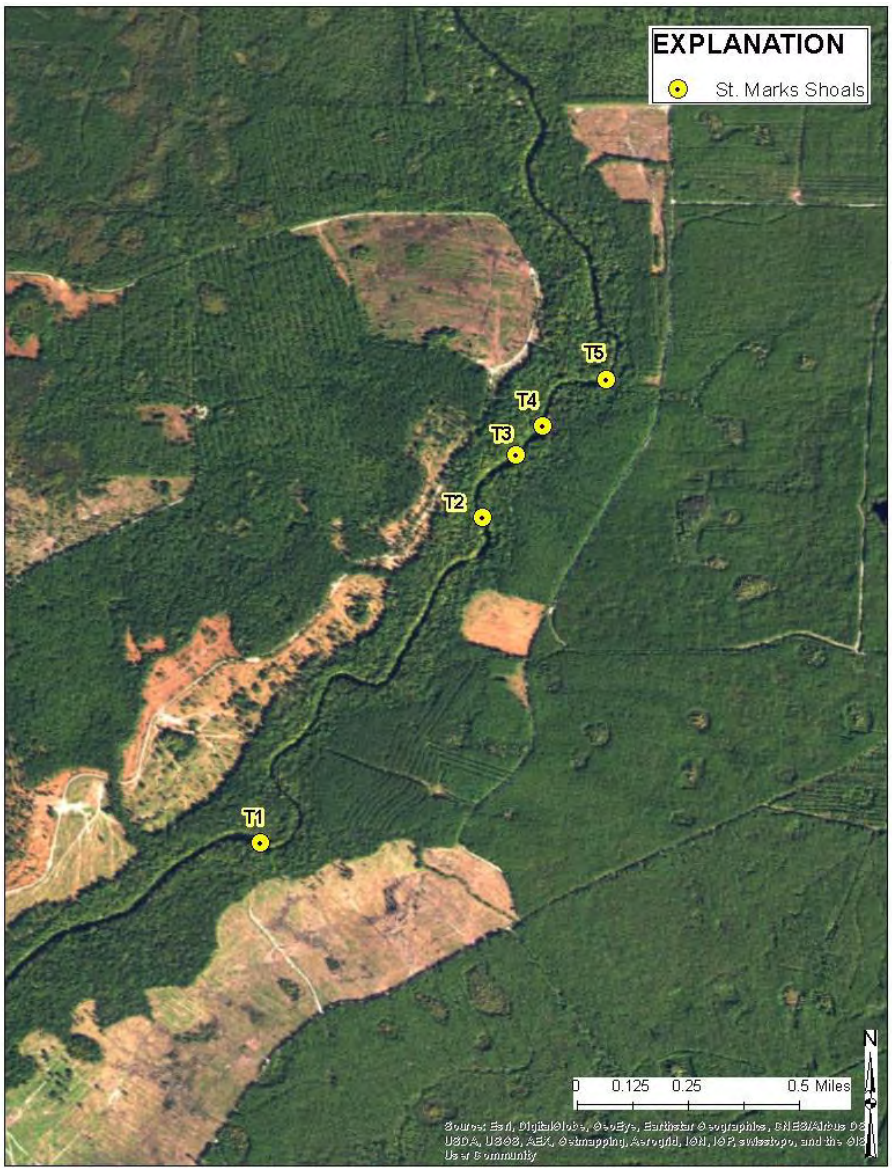


Figure 3. Shoal Transect Map (Amec Foster Wheeler Technical Memo 11/17/2016)

In addition to the St. Marks River and Wakulla River reaches, a third reach was added, extending from the confluence of the two rivers (NWFWMD monitoring station HD-3) downstream to monitoring station HD-4. Figure 4 presents the location of hydrodynamic monitoring stations along the Wakulla and St. Marks Rivers, including NWFWMD stations HD-3 and HD-4.

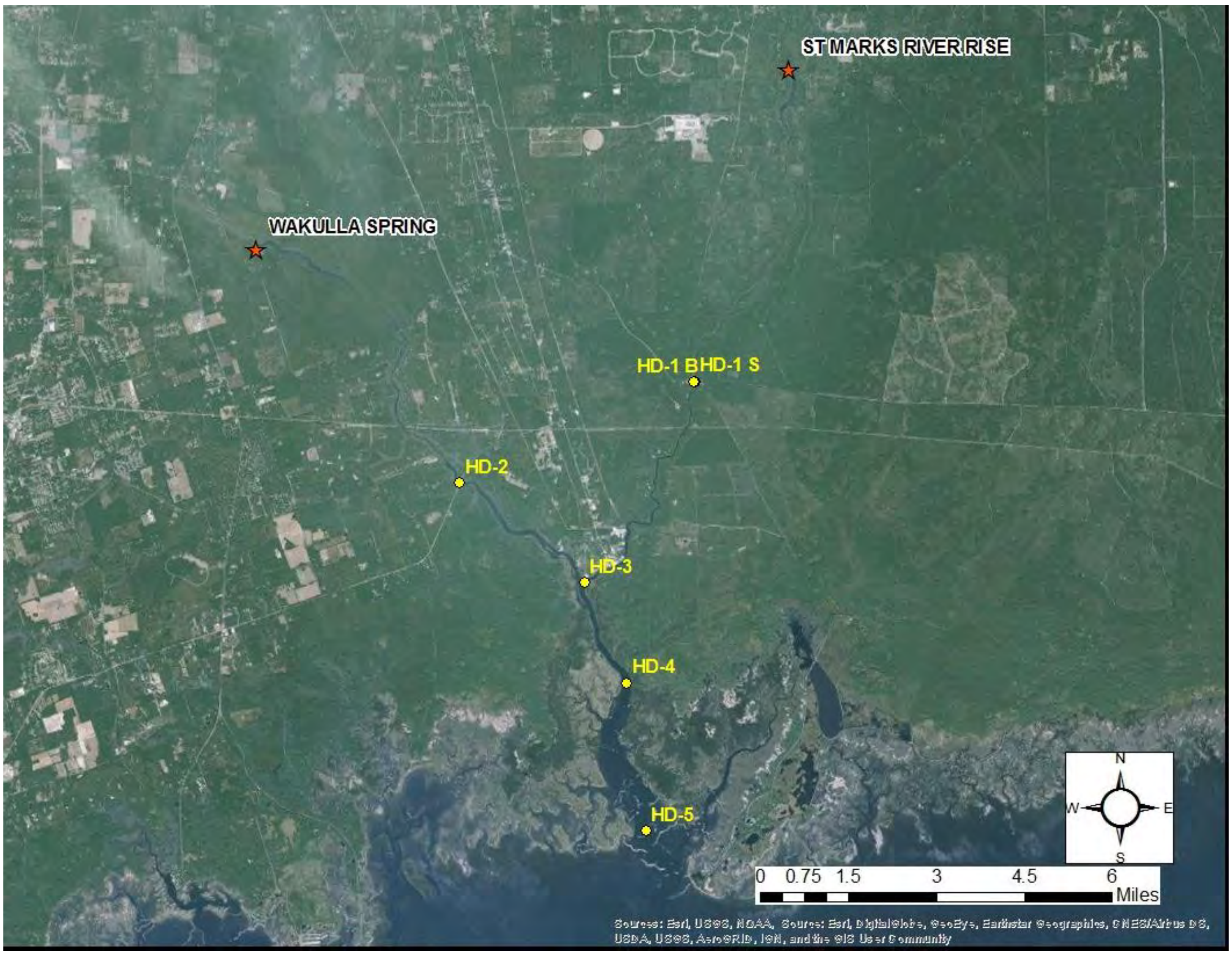


Figure 4. Location of Hydrodynamic Monitoring Stations along the Wakulla and St. Marks Rivers.

Ten cross-sections were added to this new lower reach to represent the transitions in the in-channel and overbank flow paths. Cross-section geometry in the floodplain areas was defined using available topographic LiDAR. The in-channel geometry was defined using available cross-section survey data from WGI (2016). Station and elevation data from the survey were manually entered to complete the cross-section geometry. The cross-sections used to define the lower river reach are listed in Table 4.

Table 4. Cross-Sections Added to Define the Lower HEC-RAS Model Reach.

HEC-RAS Model Cross-Section	WGI (2016) Cross-Section Source Data
10562	CO3
9237	CO9
8492	CO11
8161	CO12
6773	CO16
5495	CO20
4730	CO22
3303	CO26
2000	CO30
907	CO34

In summary, the following model geometry modifications were performed.

1. The two models for the Wakulla River and the St. Marks River were combined, and the geometry data were merged into one model project.
2. The two river systems were joined with a junction feature at the confluence of the two systems.
3. The model extents were increased to include the lower reach between NWFWMD stations HD-3 and HD-4.
4. In-channel geometry was reviewed and refined for 11 cross-sections in the St. Marks River using field survey data provided by NWFWMD.
5. Five additional cross-sections of shoal areas along the St. Marks River were incorporated.
6. Ten cross-sections were added to define in-channel and floodplain areas in the lower St. Marks River.

The refined HEC-RAS model schematic is provided in Figure 5.

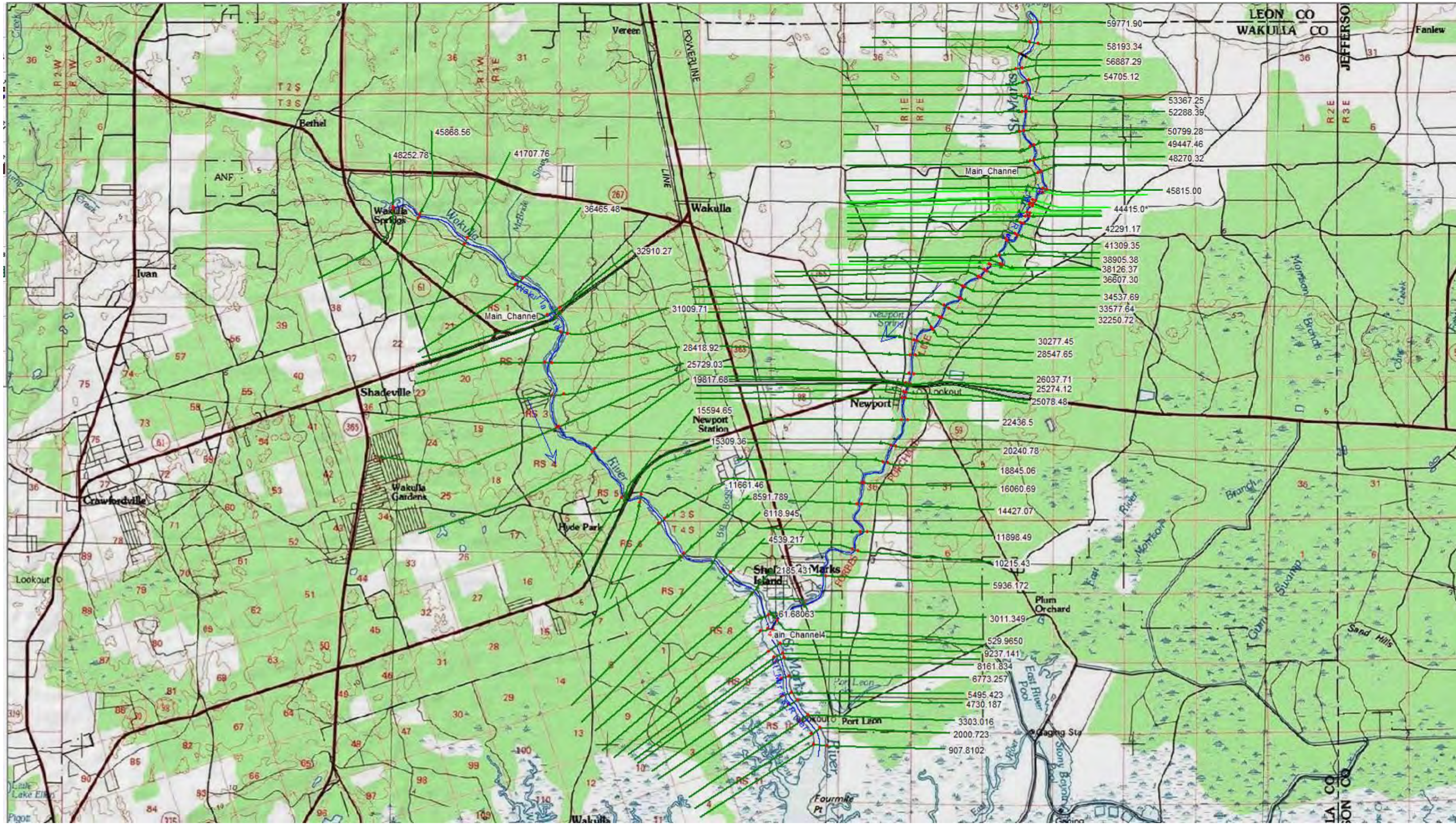


Figure 5. St. Marks/ Wakulla HEC-RAS Model Schematic

3.0 SIMULATION TIME PERIODS

The period from June 2016 to the beginning of December 2016 was used for model setup and initial testing. The period from May 13, 2017, to July 20, 2017, was used for initial calibration since this was the period for which water level data from the hydrodynamic monitoring station, HD-4, had been verified as most reliable at the time of model development. For initial testing and calibration assessment, the HEC-RAS model was run using the unsteady flow analysis option due to the tidal influence on the lower portions of the two river systems. Model calibration by means of unsteady-state forcing is suitable for both steady and unsteady-state scenario analyses applications.

4.0 BOUNDARY CONDITIONS

Boundary conditions for the St. Marks/ Wakulla River model consisted of the upstream flows on the St. Marks and Wakulla Rivers, downstream stage on the St. Marks River near the Gulf of Mexico, and internal lateral inflows (both uniformly distributed and point inflows) on both rivers.

The model input time series or boundary conditions were stored and processed in Microsoft Office Excel. The processing included calculations to develop the lateral inflows or reach pickup and surface water contributions from contributing basins. Figure 6 presents those catchments contributing surface water flow to the St. Marks and Wakulla River systems.

Figure 6. Surface Water Catchments That Contribute Flow to the St. Marks – Wakulla System

The time series data were then transferred into a HEC-DSS (HEC Data Storage System). The boundary conditions were stored in the “smr_wr_cal_V2b.dss” file. An appropriate DSS pathname was selected every time a boundary condition was specified in the model. The locations of the model boundary conditions and calibration points for the completed model are presented in Figure 7.

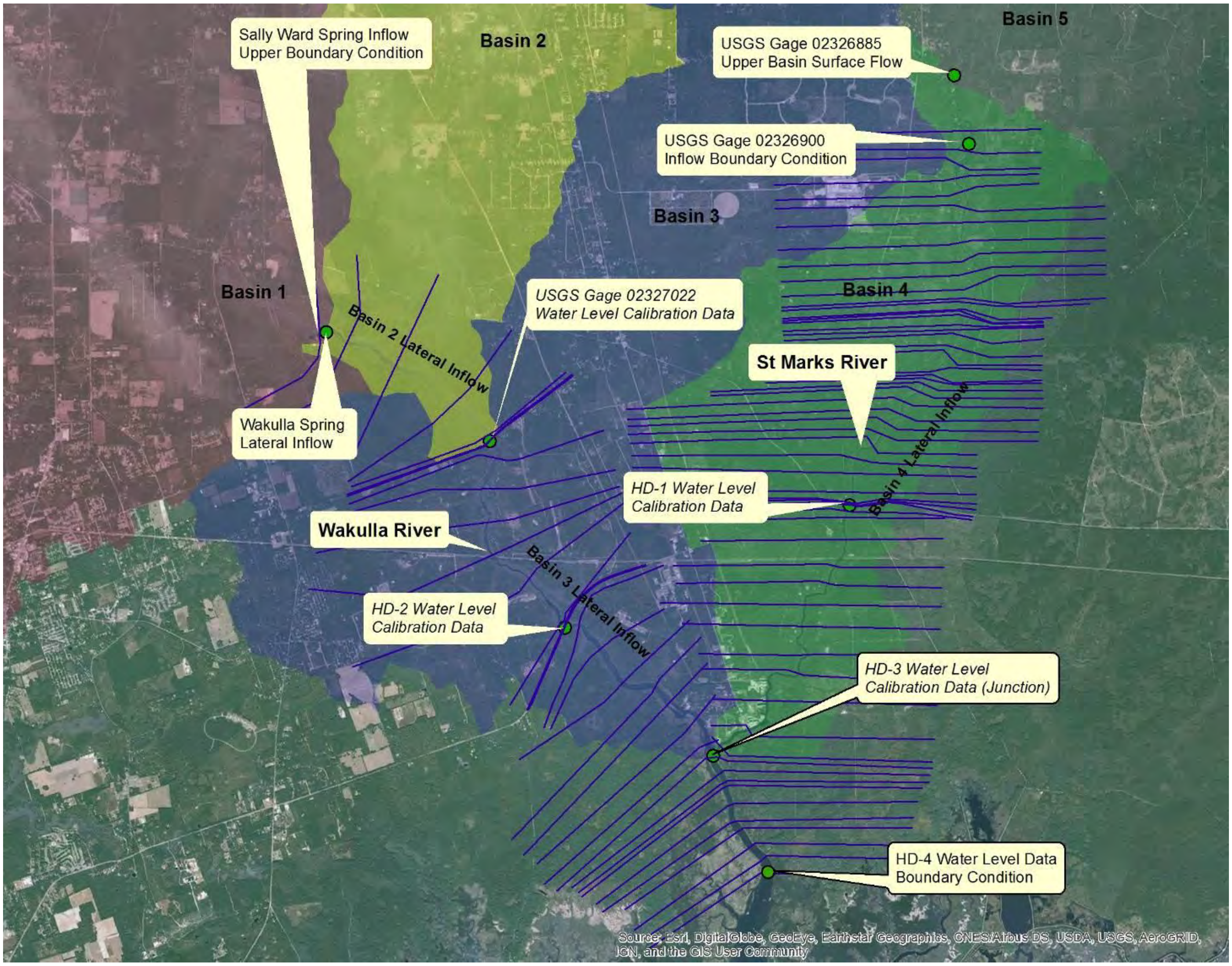


Figure 7. Components of the Model Boundary Conditions and Calibration Points

4.1 DOWNSTREAM STAGE BOUNDARY CONDITION

The 5-minute HD-3 stage data in feet referenced to the North American Vertical Datum of 1988 (NAVD88), was converted to a 15-minute time series and used for the downstream boundary condition during initial testing. For model refinement and calibration, 5-minute HD-4 stage data in feet referenced to NAVD88 was used as the downstream boundary for the model. The use of a 15-minute time interval for both flow and stage boundary conditions was done for consistency with U.S. Geological Survey (USGS) flow and stage records at USGS 02327022 (Wakulla River near Crawfordville) and USGS 02326900 (St. Marks River near Newport) and for the selected model output interval. NWFWMD provided a file containing refined and corrected data at HD-4. An initial calibration period of May 13, 2017 to July 20, 2017, was chosen since the period of record of HD-4 monitoring station was the shortest and most limiting of all boundary conditions.

4.2 ST. MARKS RIVER FLOW BOUNDARY CONDITIONS

The St. Marks River portion of the model uses the flow time series from the USGS Newport Gage 02326900 as an inflow upper boundary condition. The flow at this gage location includes spring discharge from the St. Marks River Rise and the river flow originating upstream of the rise. For the initial modeling period (May 3 – July 20, 2017), flows at USGS 02326900 ranged from 344 cubic feet per second (cfs) (P2) to 1390 cfs (P95).

Lateral ungaged inflows to the St. Marks River system from Basin 4 (see Figure 7) were estimated by examining the recent St. Marks River flux measurements collected on August 25, 2017. The acoustic Doppler current profiler (ADCP) transect for this measurement event was located in the St. Marks River approximately 1.7 miles upstream of the confluence with the Wakulla River. The measurement of net flow from the August 25, 2017, ADCP work was 567 cfs. The corresponding flow at the Newport gage on August 25, 2017, was 440 cfs, resulting in an estimated lateral inflow of 127 cfs between the Newport gage and the downstream flux measurement location. This quantity of flow is indicative of a significant groundwater contribution, given the karst characteristics of Basin 4 and the lack of a significant surface water tributary in this reach. Given that the flow at the Newport gage was approximately 3.5 times greater than the estimated lateral flow on August 25, the Newport gage flow time series was divided by 3.5 to estimate the synthetic flow time series for the Basin 4 lateral inflow. The series is named “LI_BASIN4_REV” in the DSS file, smr_wr_cal_V2b,

4.3 WAKULLA RIVER FLOW BOUNDARY CONDITIONS

The Wakulla River system required a more complex process to define the boundary conditions and associated input data. The inflows estimated included: (1) the upper boundary inflows at the Wakulla Spring pool, which represent flows from Wakulla Spring and the Sally Ward Spring run; (2) lateral inflow from Basin 2; (3) lateral inflow from Basin 3; and (4) lateral inflow between HD-3 and HD-4.

Flow data from USGS Station 02327022, Wakulla River near Crawfordville, is heavily influenced by tidal energy and required that it be filtered to remove the effects of the tides so that the net flow of the gaged location could be determined (Figures 8 and 9). Filtering was applied to 15-minute flow data from USGS 02327022 using a Butterworth digital filter routine in MATLAB, with a cutoff frequency of 4 days.

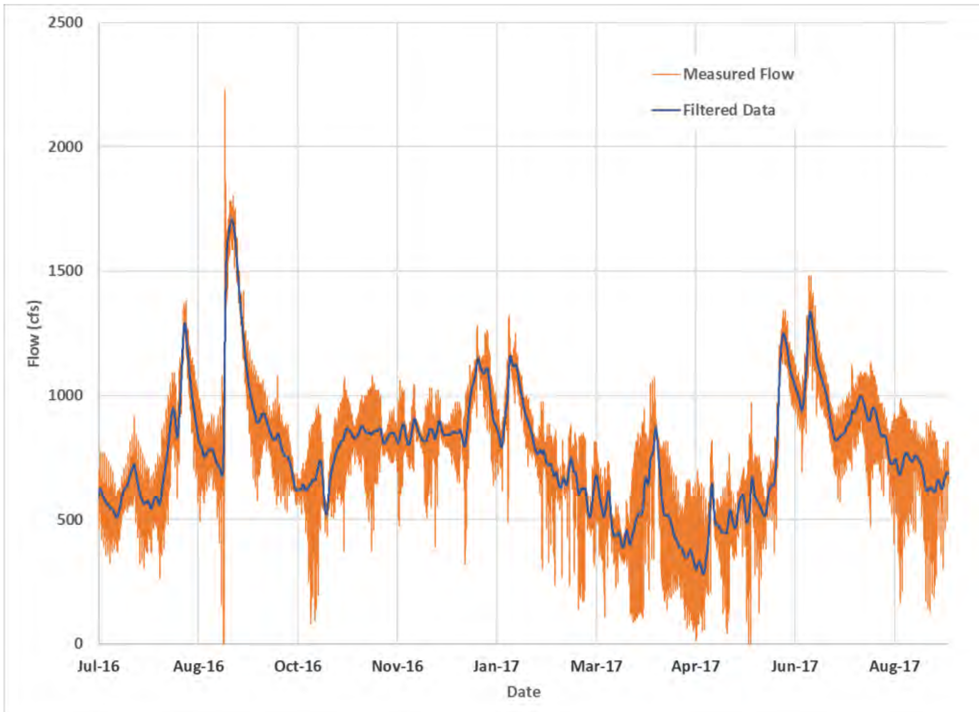


Figure 8. USGS Gage 02327022 Filtered Results for the Period of Record, 6/2016 – 8/2017

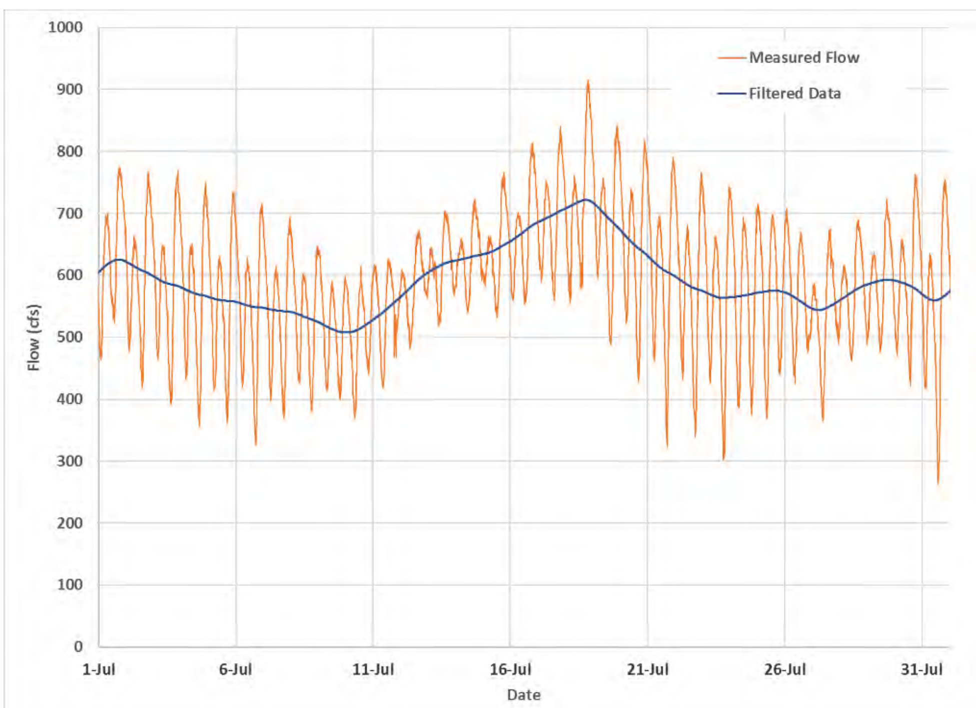


Figure 9. USGS Gage 02327022 Filtered Results for the Period of Record, 7/2016 – Detail

NWFWMD provided the flow records for both Wakulla Spring (Figure 10) and Sally Ward Spring (Figure 11). Wakulla spring flow for the initial calibration period was estimated based on a relationship between measured Wakulla spring daily discharge from 1997-2015 and daily groundwater levels from a nearby conduit well from 2014 to present, with an adjusted R^2 value of 0.78. NWFWMD installed a new vent discharge meter in November 2017 to directly measure the Wakulla Spring discharge for future evaluations. Linear interpolation was used to convert the provided daily time series of Wakulla Spring flow to 15-minute increments. Sally Ward discharges are computed using the Index Velocity Method. The method consists of two separate ratings: the index velocity rating and the stage-area rating. The outputs from each rating are then multiplied together to compute the discharge. Sally Ward Spring flow is available from December 2016 to present.

The net flow from Basin 2 into the Wakulla River model was estimated by the following:

> USGS 02327022 Filtered Flow – Wakulla Spring Vent Flow – Sally Ward Spring Vent Flow = Net Inflow from Basin 2.

The net inflow from Basin 2 was input as a uniform lateral inflow. Negative flow values were set to zero.

Lateral ungaged inflow to the Wakulla River system from Basin 3 was estimated by first examining the recent Wakulla River flux measurements collected on August 23, 2017. The ADCP transect for this measurement event was located on the Wakulla River in the vicinity of the San Marcos de Apalache Historic State Park just upstream of the confluence with the St. Marks River. The measurement of net flow from the August 23, 2017, ADCP work was 695 cfs. Inspection of flow data on August 23, 2017, for the upstream USGS Gage 02327022 Wakulla River Near Crawfordville, FL showed a tidally influenced and variable range of 900 to 200 cfs during the day, with a filtered average daily flow of 631 cfs per USGS records. This is consistent with the measured net flow and indicates that lateral inflow from Basin 3 is not a significant portion of the Wakulla River flow

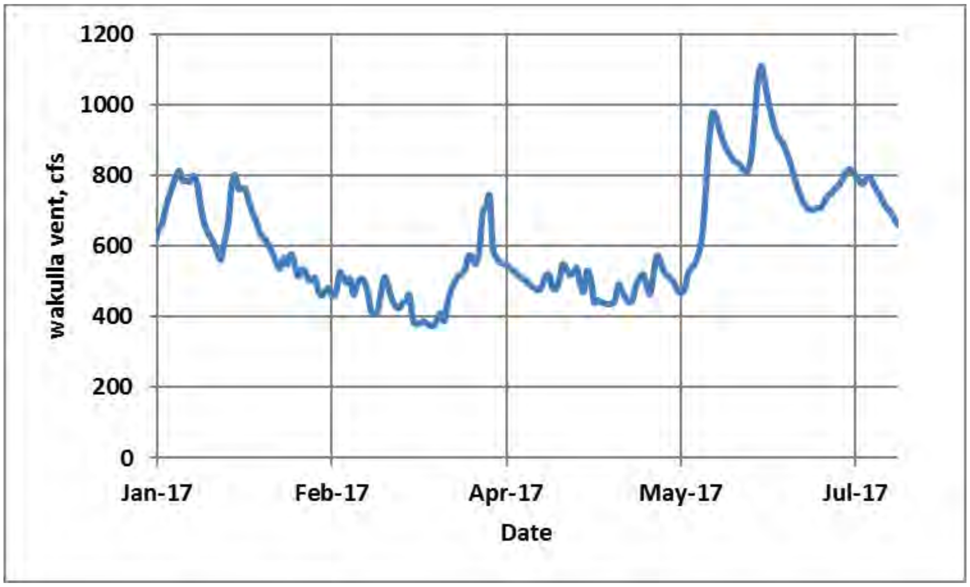


Figure 10. Wakulla Spring Flow Time Series

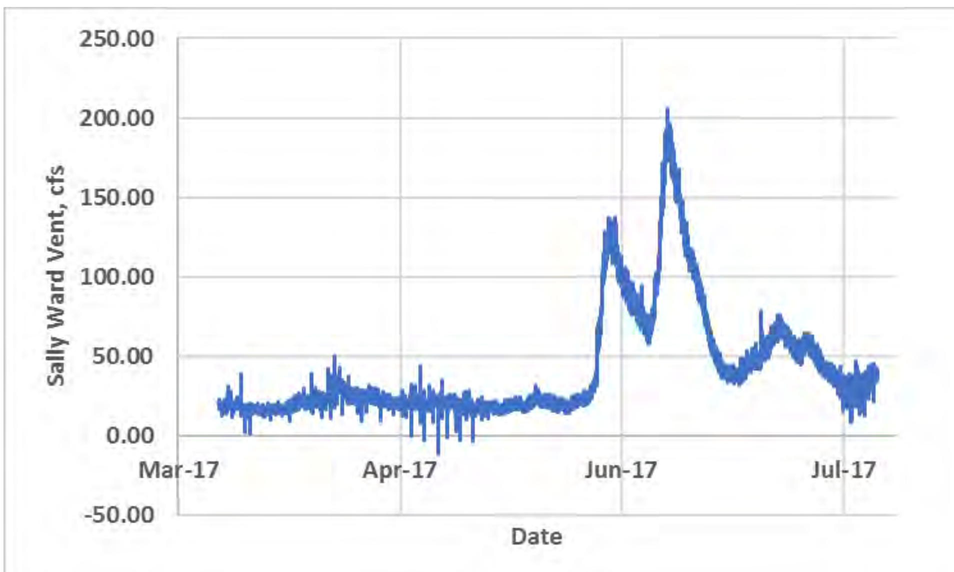


Figure 11. Sally Ward Spring Flow Time Series

Lateral ungaged inflow to the St. Marks–Wakulla river system for the reach extending from HD-3 to HD-4 was estimated by first examining the recent Wakulla River flux measurements collected on April 11, 2017. The ADCP transect for this measurement event was located in the St. Marks River Estuary, approximately 1.5 miles downstream of the St. Marks–Wakulla confluence. The measurement of net flow from the April 11, 2017, ADCP work was 1,096 cfs. Inspection of flow data for the upstream USGS Gage 02327022 on the Wakulla River showed an average flow for April 11, 2017, of 563 cfs. Inspection of flow data for the upstream USGS Gage 02326900 on the St. Marks River showed an average flow for April 11, 2017, of 420 cfs. This results in an estimated ungaged flow between the gages and the lower reach near HD-4 of approximately 112 cfs. As noted, the estimated flow for the ungaged portion of the St. Marks River was 127 cfs, for a measured flow at the USGS Gage 02326900 (St. Marks River near Newport) of 440 cfs. This would imply that most of the ungaged flow in the St. Marks–Wakulla system is from the St. Marks River. Since this flow has already been taken into account in the lateral inflow estimate for Basin 4, no additional flow was added to the river reach between HD-3 and HD-4.

5.0 INITIAL MODEL SETUP

The first evaluation runs of the model system showed that both models were stable and that the model performed quite well for an initial run. The St. Marks River inititally presented an issue with the simulated water surface elevations, in the upper reaches especially, being 1.5 to 2 feet too low compared to available data at USGS 02326900 (St. Marks River near Newport).

Further examination revealed a detail that was not present in the original 2010 floodplain model. Inspection of the 2015 floodplain transects and measurements of visible channel width from 2016 aerials suggested that the St. Marks River modeled channel in the original model was two to four times too large along most of the upper St. Marks River reach. Analysis of the the aerial, the digital elevation model (DEM) and the surveyed cross-sections revealed that the river channel is very wide but includes significant vegetation coverage across most of the channel expanse. As an example (Figure 12), the DEM shows that the inundated channel is actually 400 feet wide, while only 100 feet or less is open and free of trees and shrubs.

Further inspection of the 2010 floodplain model shows that the whole 400-foot channel is being modeled as low resistance (0.039 Manning's n) and functioning as the primary conveyance area, whereas only about 90-foot of the channel width is functioning as primary conveyance. This was confirmed during site reconnaissance via canoe at these locations. Figure 13 illustrates the comparison of the 2010 floodplain model and the current MFL model with respect to differences in the Manning's n parameterization.

All 49 St. Marks transects were reviewed for this issue, and adjustments to Manning's n coefficients were made as needed. Typically, this required reducing the width of main channel zone from approximately 400 feet wide to about 90 feet wide (Manning's n = 0.04), while expanding the higher resistance 0.20 Manning's n zone from the east bank by a corresponding amount.

Subsequent preliminary model runs were conducted where water surface comparisons were made at HD-1 and HD-2, and residuals between modeled and observed data were evaluated Typically, the in-channel Manning's n remained at 0.04, with cross-sections in the lower half of the St. Marks River reach receiving a Manning's n ranging from 0.03 to 0.1.

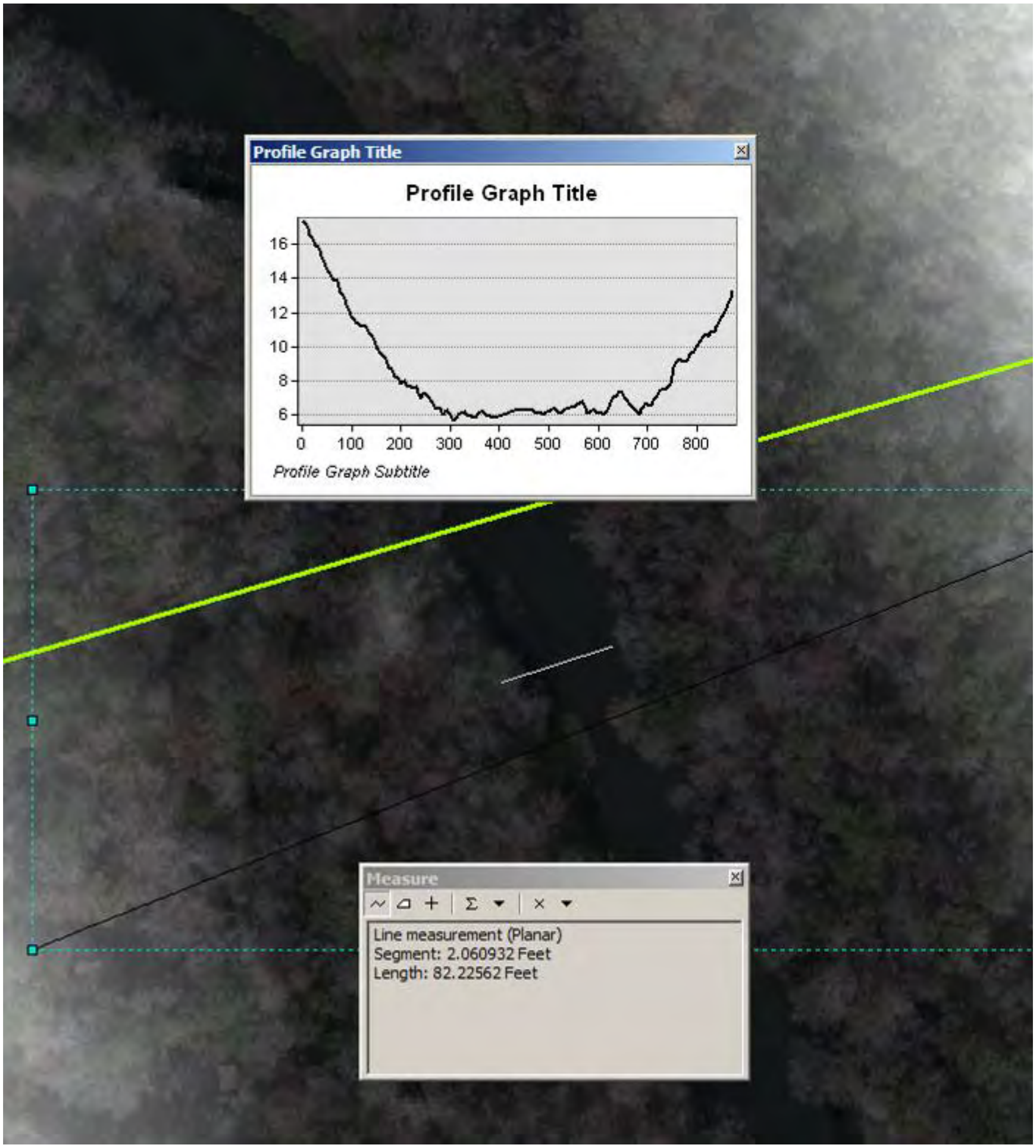
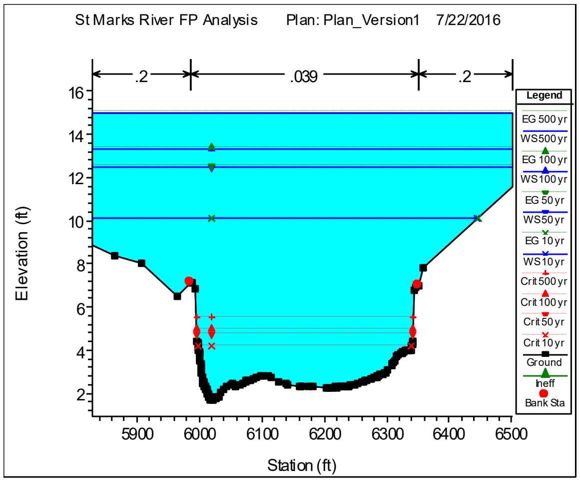
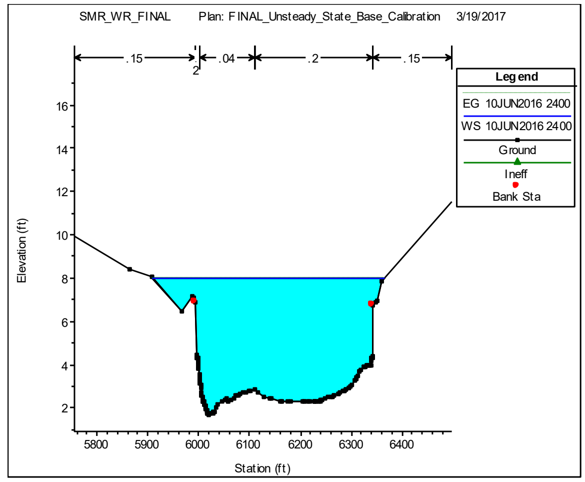


Figure 12. Example of the DEM Showing the Inundated Channel is Actually 400 Feet Wide, While Only 100 Feet or Less is Open and Free of Trees and Shrubs



2010 Floodplain Model



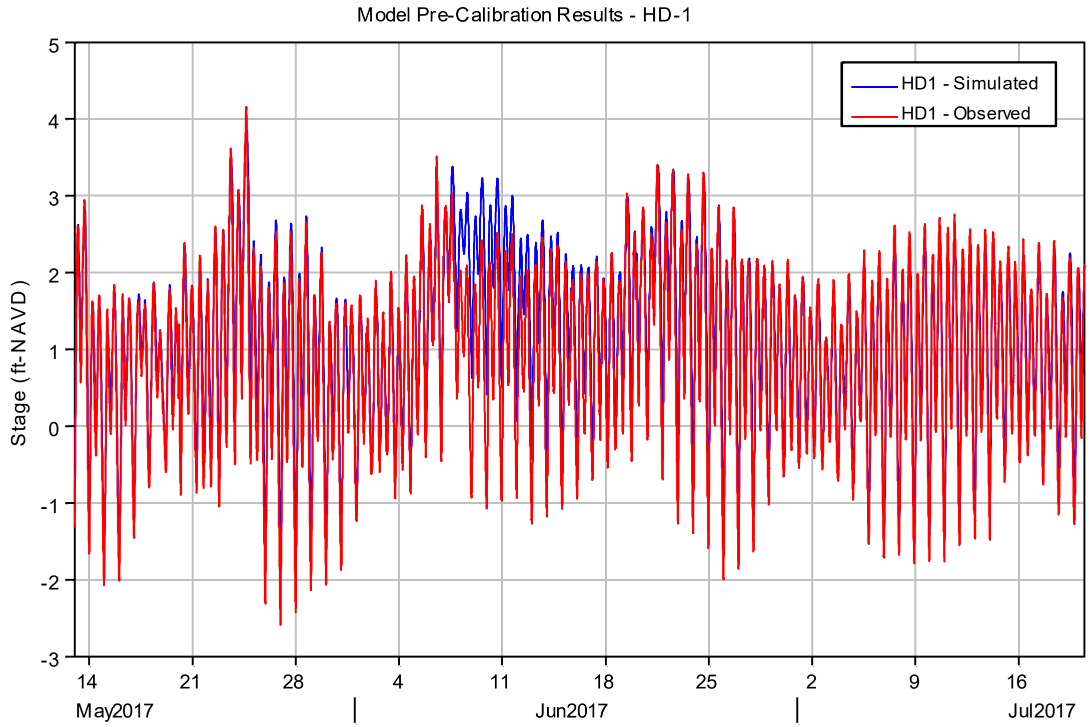
2017 MFL Model

Figure 13. Comparison of the 2010 Floodplain Model and the Current MFL Model with Respect to Differences in the Manning's n Parameterization

6.0 MODEL PRE-CALIBRATION RESULTS

The HEC-RAS model was run using the identified parameterization. The results of the initial simulation at the five calibration locations are presented in Figures 14a through 14e. The figures present both the stage time series and stage duration curves for the initial calibration period (May 13, 2017 to July 20, 2017). The uncalibrated setup achieved reasonably good results except at USGS gage 02326900 in the upper St. Marks River. The results indicate that the model consistently overestimated stage at HD-1 (Figure 14a) and underestimates stage at HD-2 (Figure 14b). In both cases, the model predictions were generally within 0.5 foot or less. Model predictions of stage at HD-3 (Figure 14c) were excellent, based on comparison to HD-3 stage data. This is not surprising given that the tide is the primary driver for stage here. The comparison of the model results with the USGS 02326900 water level data (Figure 14d) indicated that the model was not matching the observed data well, both in the magnitude and in the pattern of the observed hydrograph. Analysis of the hydrograph indicated that this was a period in which flows were in the 5th percentile range, and the observed data was indicating a stage from 2 feet to 3 feet higher than the model was predicting, indicating a likely issue with the model geometry in the upper reach of the model near the USGS gage. The observed hydrograph was also more attenuated than the model prediction hydrograph, indicating a potential issue with roughness (Manning's n). The resolution of these issues will be discussed in Section 7. Figure 14e presents the comparison of the initial model predicted stage with the observed water level at the USGS 02327022 gage on the Wakulla River. The model was consistently underpredicting the water level but was still within 0.5 foot of the observed water levels.

Figure 15 compares the initial modeled flow with the flow record at USGS 02327022 and indicates a good match, even though the location has significant tidal influence.



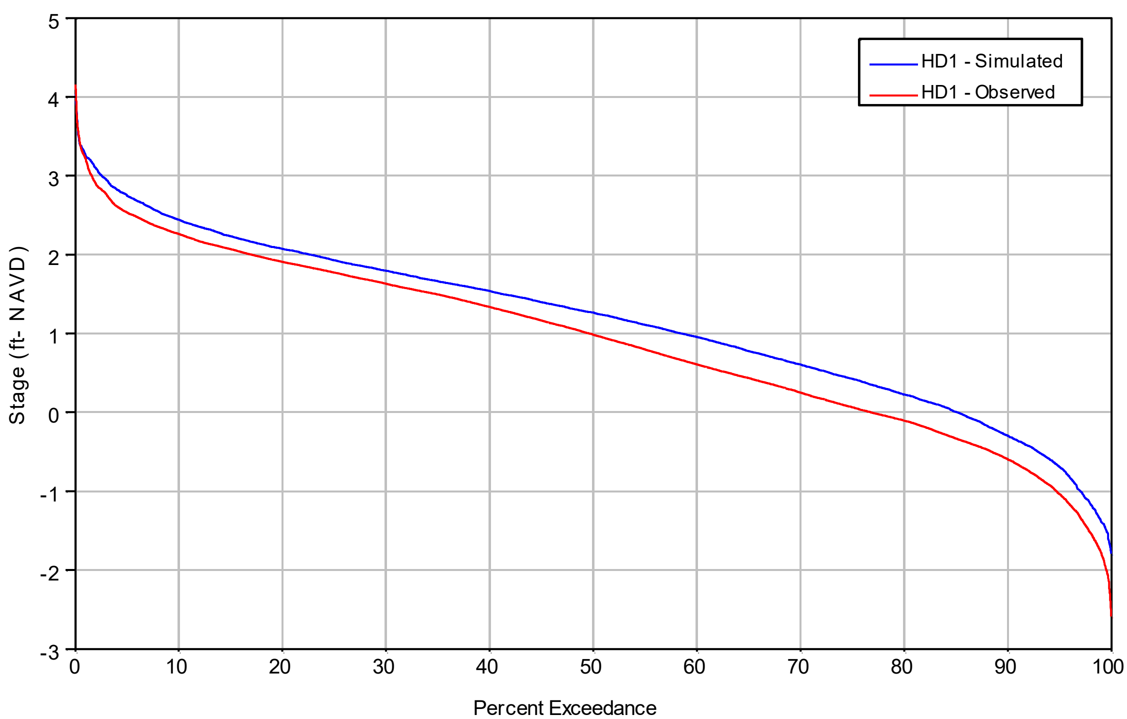
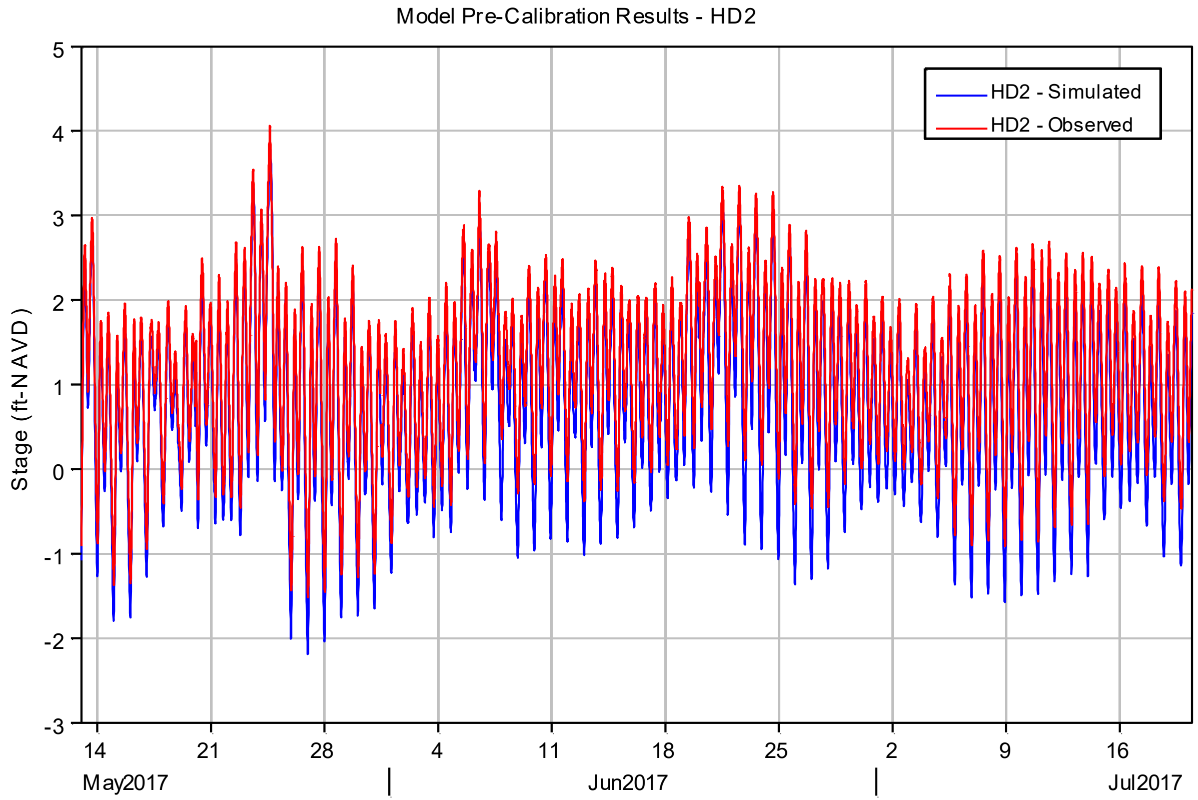


Figure 14a. Model Pre-Calibration Results at HD-1, St. Marks River at US 98, May 13, 2017 to July 20, 2017



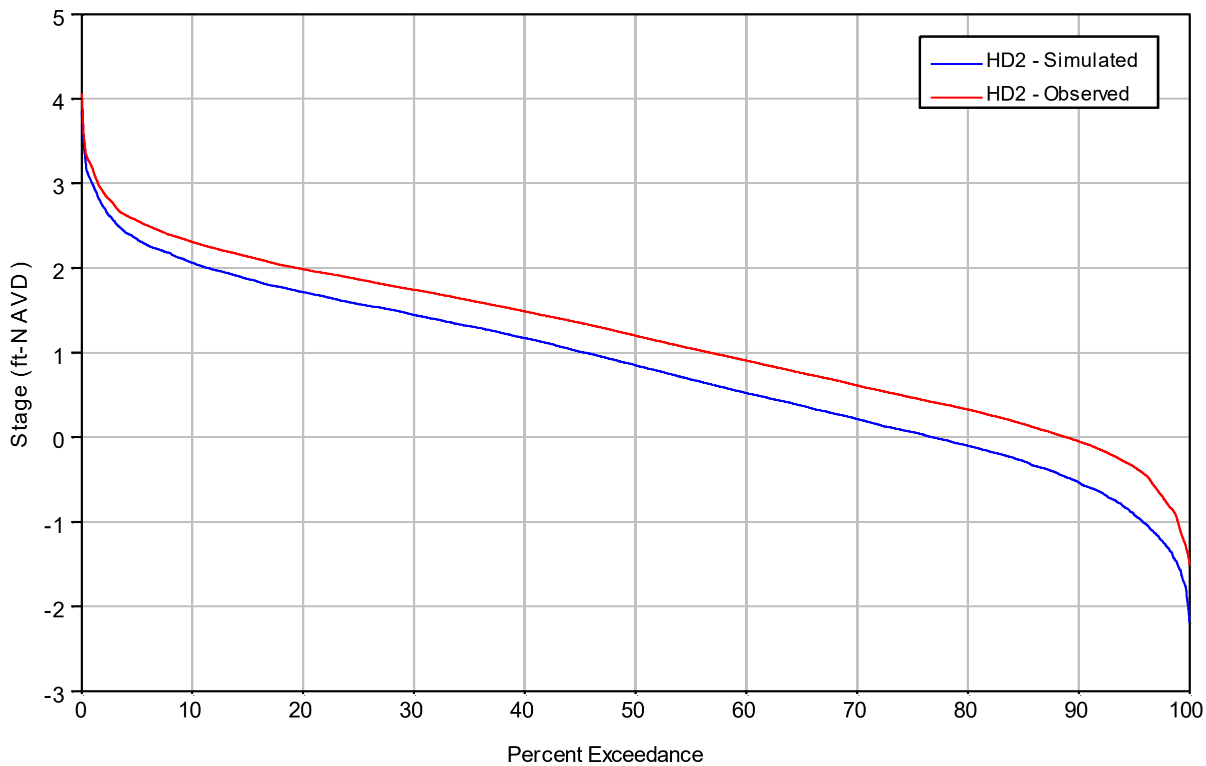
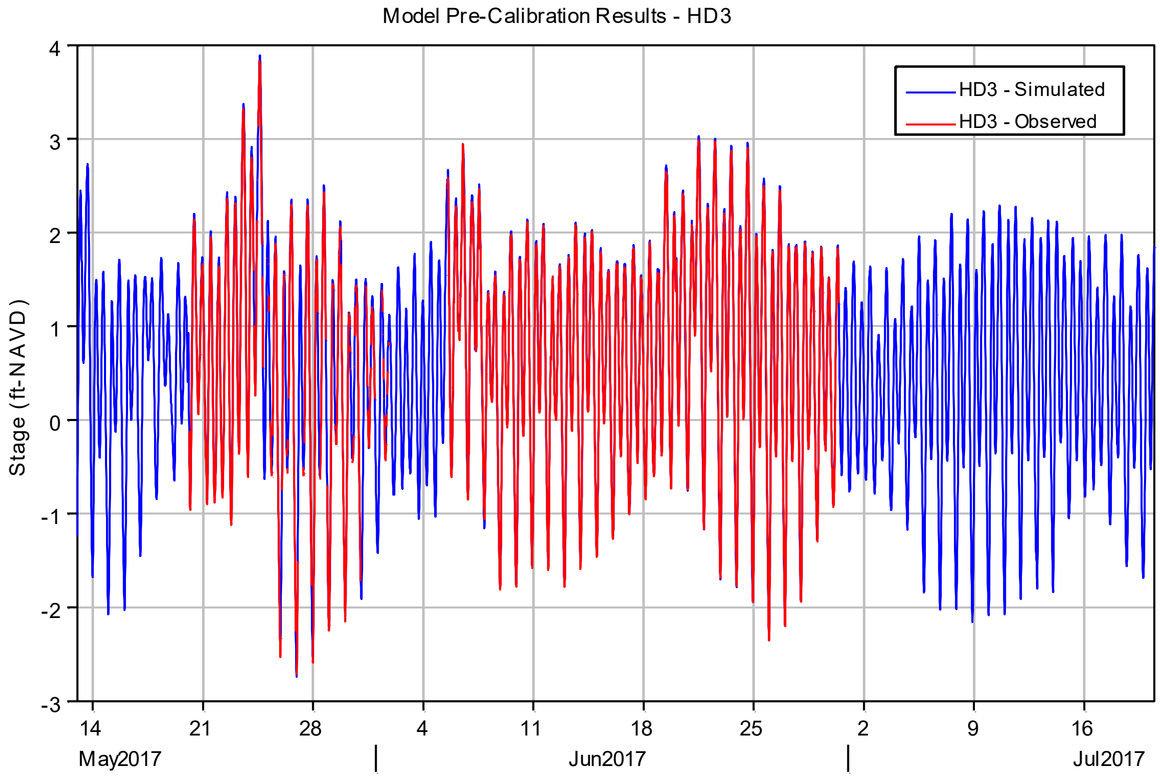


Figure 14b. Model Pre-Calibration Results at HD-2, Wakulla River at US 98, May 13, 2017 to July 20, 2017



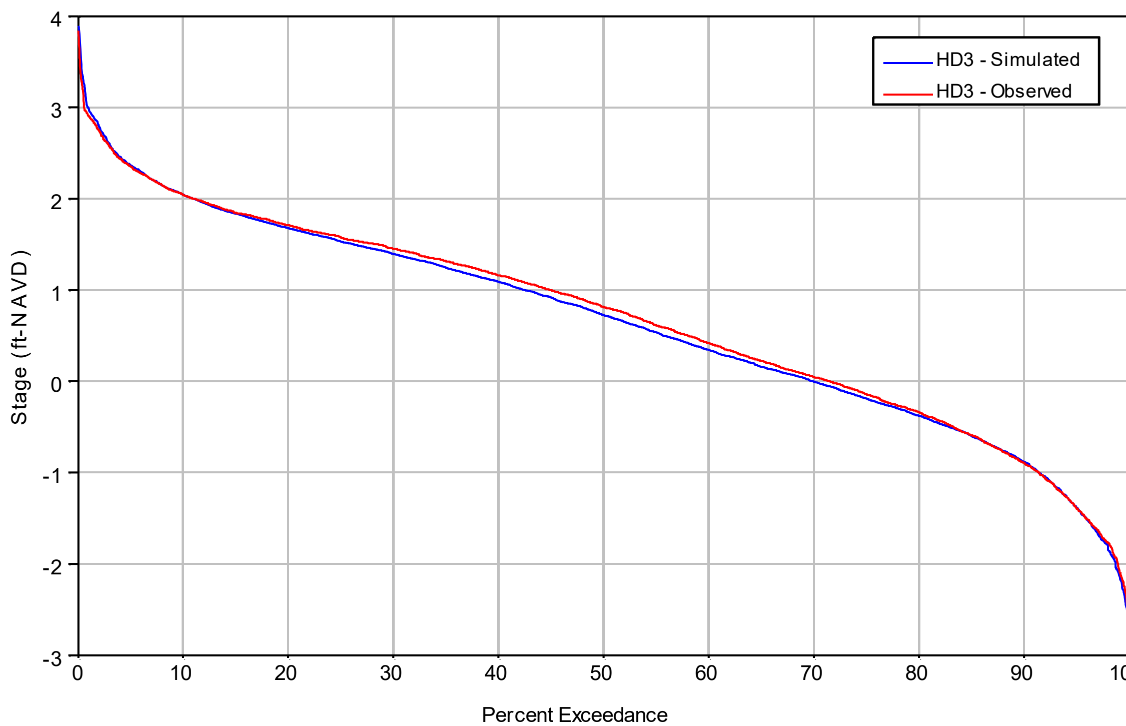


Figure 14c. Model Pre-Calibration Results at HD-3 May 13, 2017 to July 20, 2017
Note: Stage duration curve was for the period May 20, 2017 to June 30, 2017 due to missing HD3 data

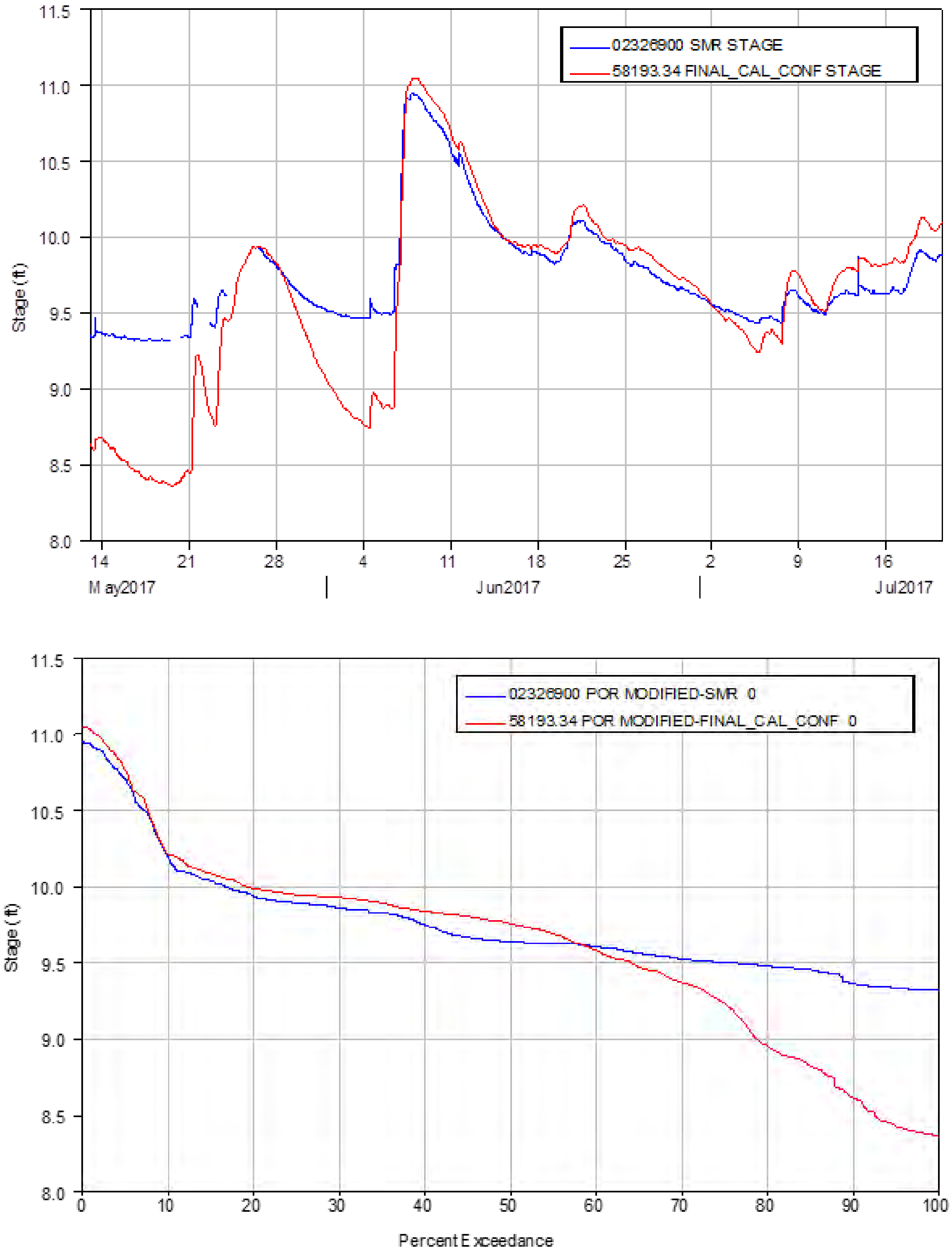
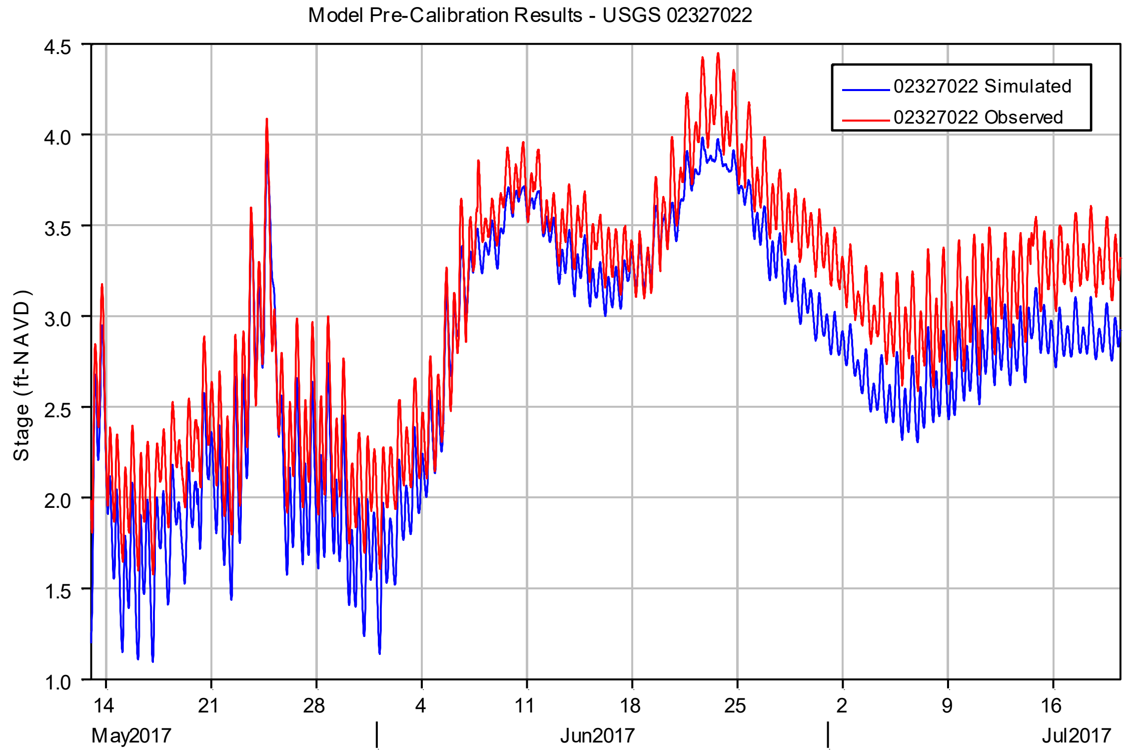


Figure 14d. Model Pre-Calibration Results at USGS 02326900, May 13, 2017 to July 20, 2017



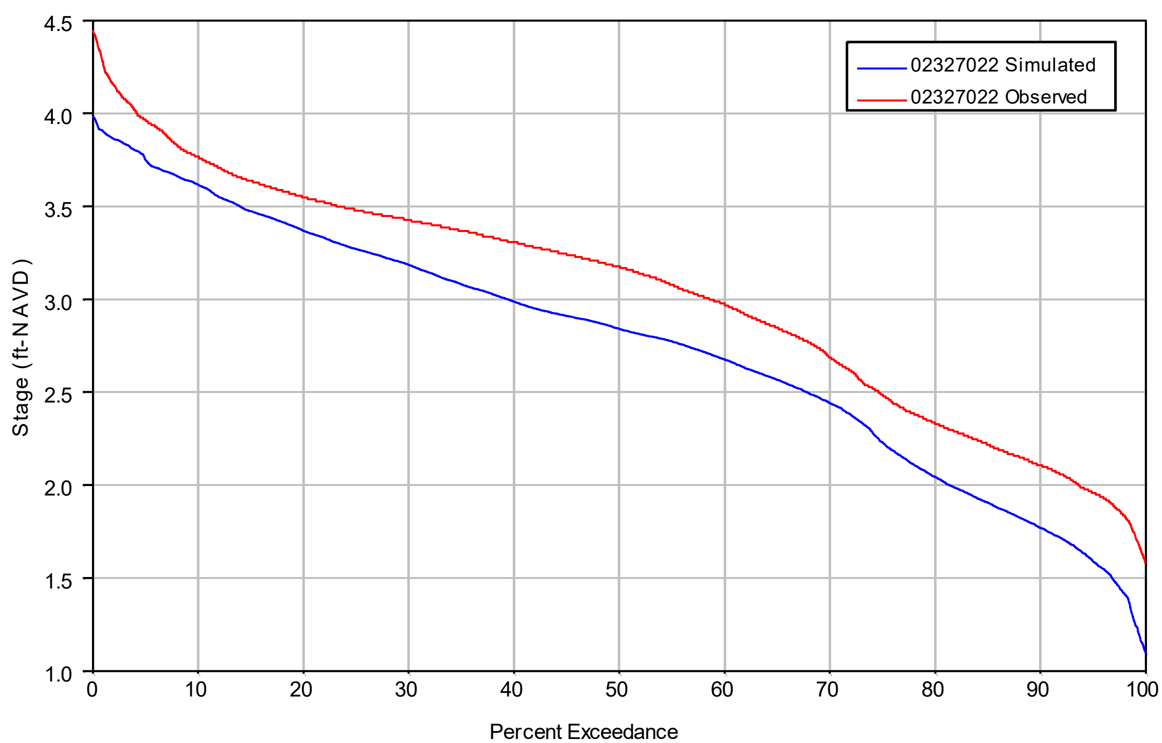
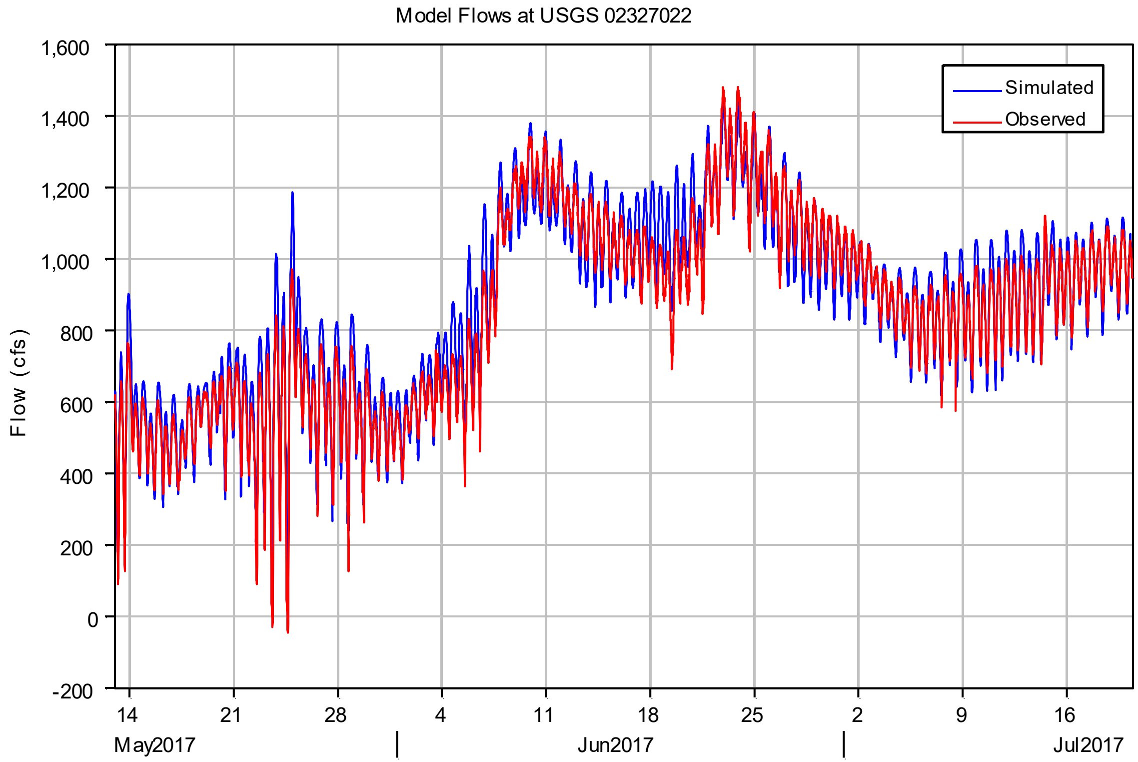


Figure 14e. Model Pre-Calibration Results at USGS 02327022, May 13, 2017 to July 20, 2017



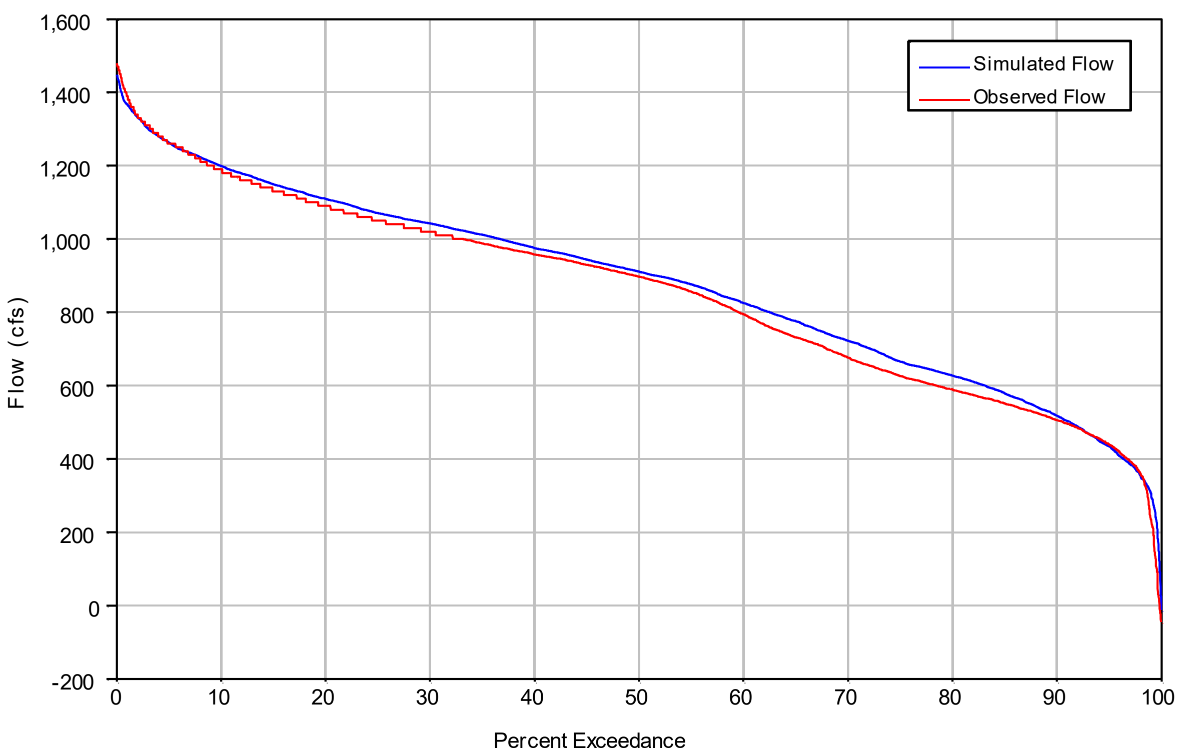


Figure 15. Model Pre-Calibration Result for Flow at USGS 02327022
May 13, 2017 to July 20, 2017

7.0 INITIAL MODEL CALIBRATION

The HEC-RAS model of the St. Marks and Wakulla Rivers was calibrated primarily by adjusting the channel Manning's n friction factors. Consistency in the friction factors was maintained, avoiding point calibration and increasing the model's predictive capability.

The pre-calibration results indicate that the model consistently overestimated stage at HD-1 (Figure 14a). The in-channel Manning's n was reduced in the lower St. Marks River from 0.04 to 0.03. Also, at simulated stages above approximately elevation 2.5 feet, which occur in response to storm events, the model was predicting higher stages and more attenuated tidal fluctuations than was indicated by the HD-1 data. This occurred in the June 2017 period. Manning's n values adjacent to the channel above elevation 2.5 feet were adjusted down to 0.03 to reduce simulated stages and to produce a less attenuated simulated tidal fluctuation.

The pre-calibration results indicated that the model underestimates stage in the Wakulla River at HD-2 (Figure 14b) and USGS gage 02327022 (Figure 14e). In both cases, the model predictions were generally within 0.5 foot or less. The in-channel Manning's n values were increased in the lower reach from 0.04 to 0.65 and from 0.04 to 0.045 in the upper reach. Model predictions of stage at HD-3 (Figure 14c) were excellent, based on comparison to HD-3 stage data. This is not surprising given that the tide is the primary driver for stage here.

The comparison of the pre-calibration model results with the USGS 02326900 water level data (Figure 14d) indicated that the model was not matching the observed data well, both in the magnitude and in the pattern of the observed hydrograph. Analysis of the hydrograph indicated that this was a period in which flows were in the 5th percentile range and the observed data was indicating a stage from 2 feet to 3 feet higher than the model was predicting, indicating a likely issue with the model geometry in the upper reach of the model near the USGS gage. The observed hydrograph was also more attenuated than the model prediction hydrograph, indicating a potential issue with roughness (Manning's n). The calibration of the model in the upper reach of the St. Marks River required adjustments to both Manning's n values and channel geometry.

The long-term gage height and daily discharge at USGS 02326900 (St. Marks River near Newport) are presented in Figures 16 and 17. There is a noticeable long-term upward trend in gage height but no trend in discharge. Part of the apparent increase in stage may be due to relocation of the stage recorder site 0.4 mile upstream in July 2004. During discussions with NWFWMD staff regarding this issue, USGS staff indicated that the flow at this site is very prone to being affected by dense vegetation growing in the channel. Over the years, some very large shifts in the flow rating have been required to try to account for the changes in the density of the grass beds. While USGS does not quantify grass growth or grass density at the site, this observation prompted an increase in the in-channel Manning's n from 0.07 to 0.34. This adjustment was made in the very upper St. Marks River reach from Station 59771 to Station 55840. This Manning's "n" adjustment resulted in a more attenuated simulated hydrograph that better matched the observations at the USGS 02326900 gage. However, during the low flow periods that were in the 5th percentile range of observed flows at the USGS 02326900, the observed water levels would approach 9.3 ft NAVD and stabilize, similar to the pattern that is seen for a hydrograph over a weir, or sill. The model was allowing a continued decrease in water level below this elevation. It was hypothesized that dense vegetation growth or a sill downstream of the gage may be creating a damming effect on in-channel flow that is not accounted for in the construction of the HEC-RAS model geometry. NWFWMD staff have noted shallow areas in the very upper reach of the St. Marks River. This was confirmed during site reconnaissance via canoe and has been confirmed by previous field observations (Light et al. 1993). The damming effect as a result of dense vegetation was tested by placing a channel obstruction downstream of the USGS gage. This greatly improved the model predictions. The final model geometry shows an obstruction to elevation 5.35 ft-NAVD (3.5 feet high at the thalweg). While the model in its current configuration does a good job of predicting hydraulic response in this part of the river, it is recommended that an additional survey be performed in this part of the river to better define the river geometry for incorporation into the HEC-RAS model as a future model refinement during the next re-evaluation of the MFLs.

The changes discussed above improved the initial calibration and model predictions as is seen in Figure 18a through 18e. The improved stage values are within 0.2 foot of observed values at all stations.

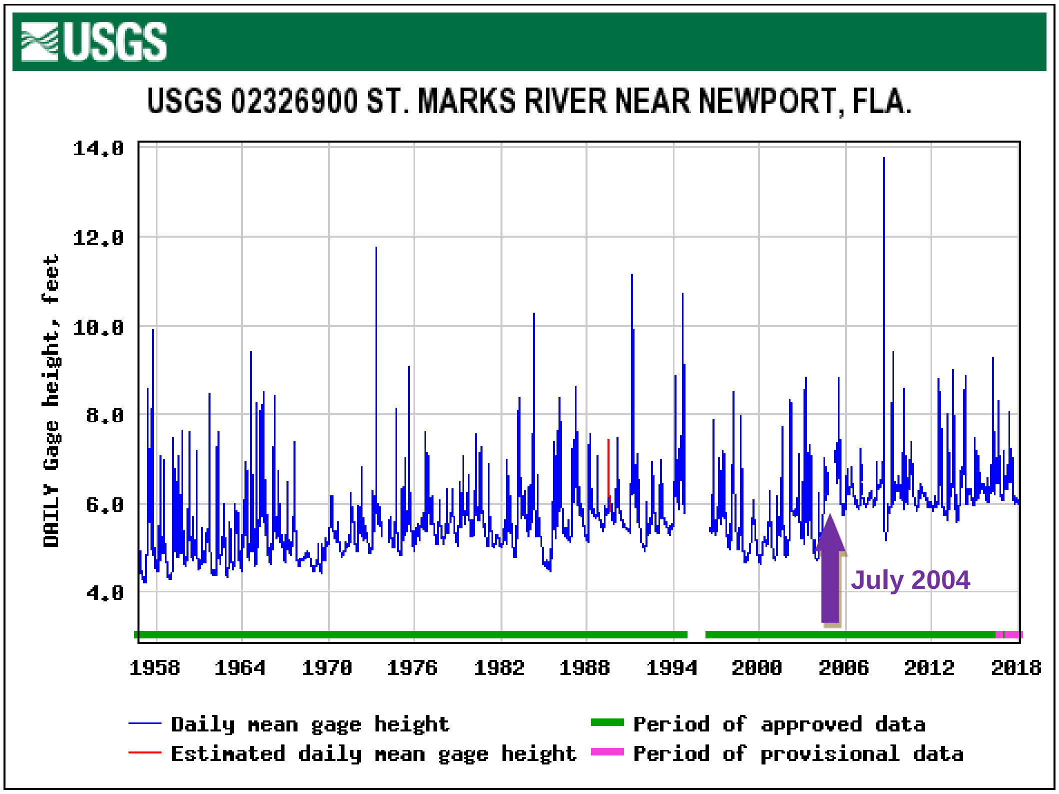


Figure 16. Daily Gage Height at USGS 02326900

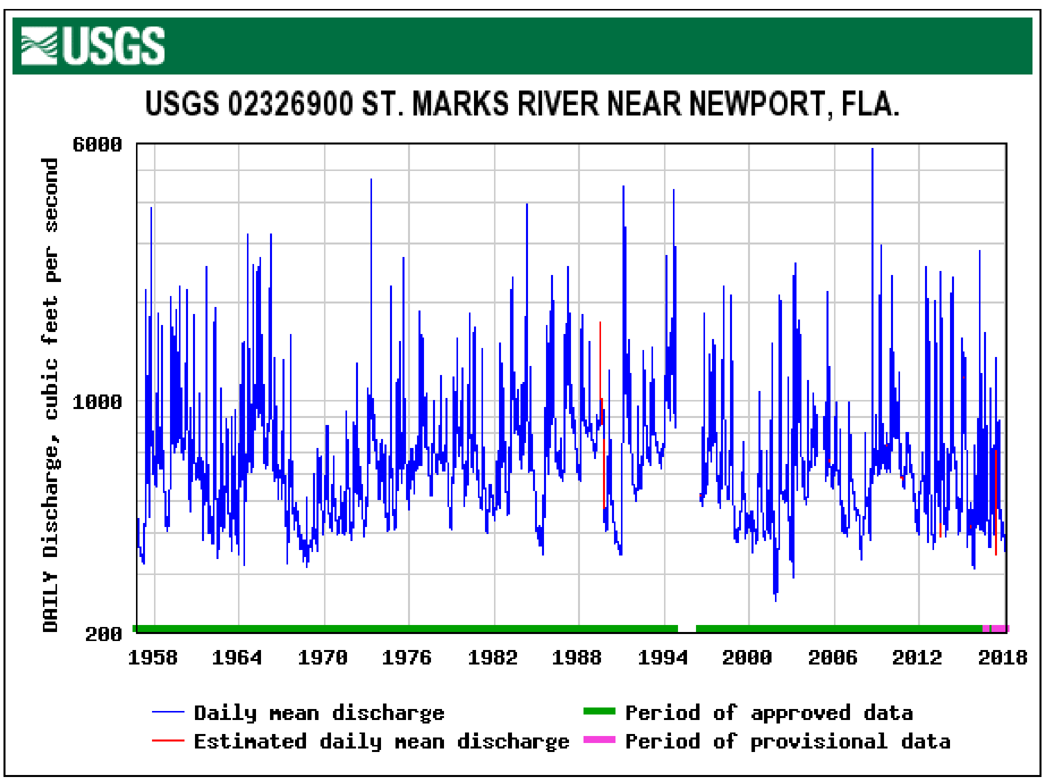
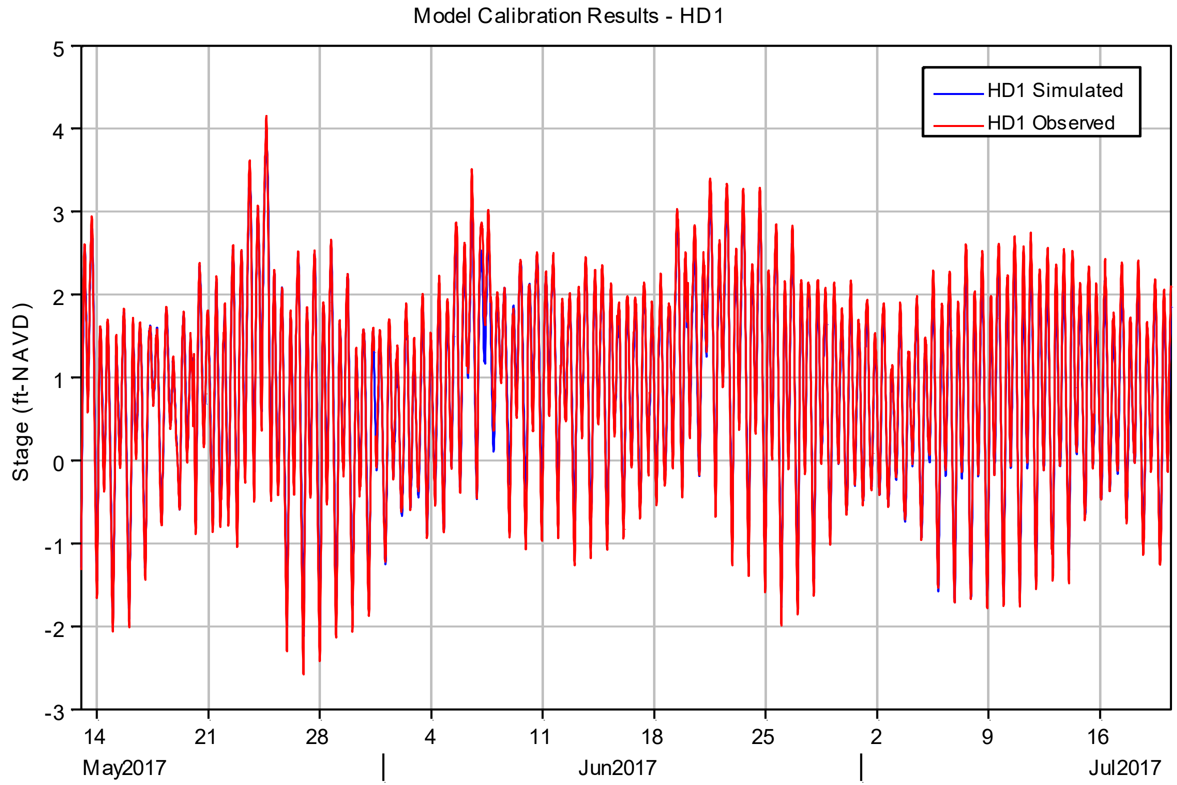


Figure 17. Daily Discharge at USGS 02326900



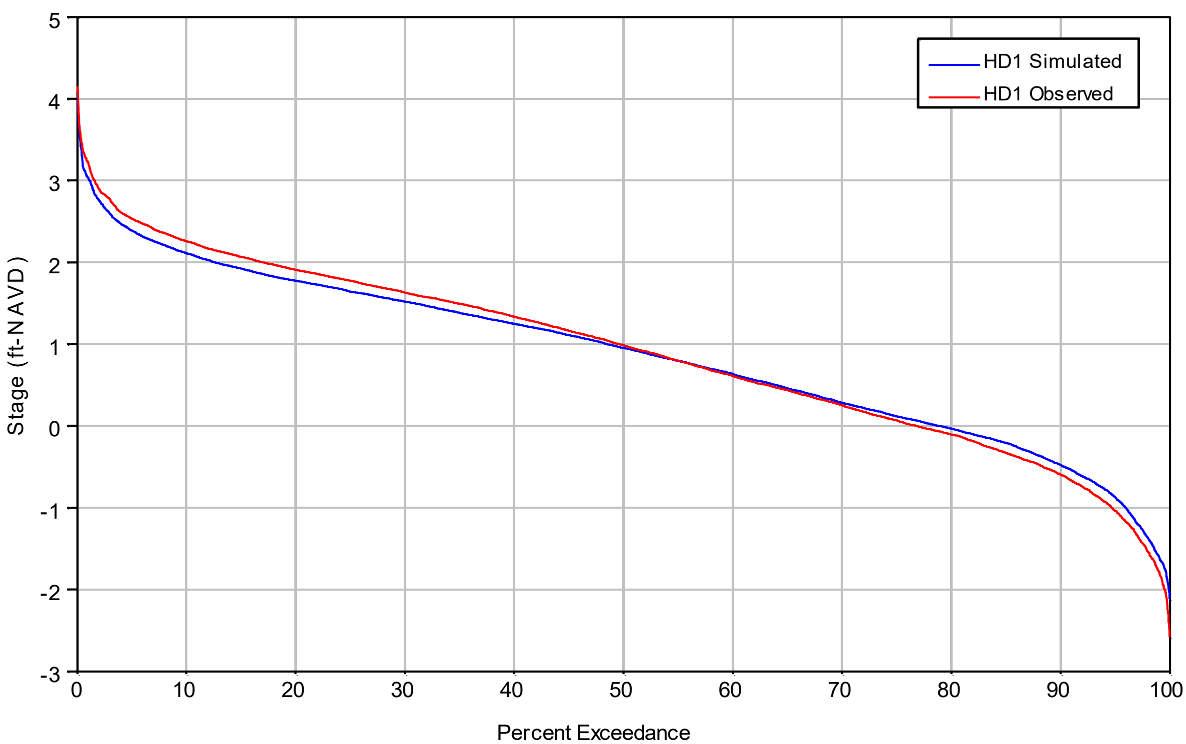
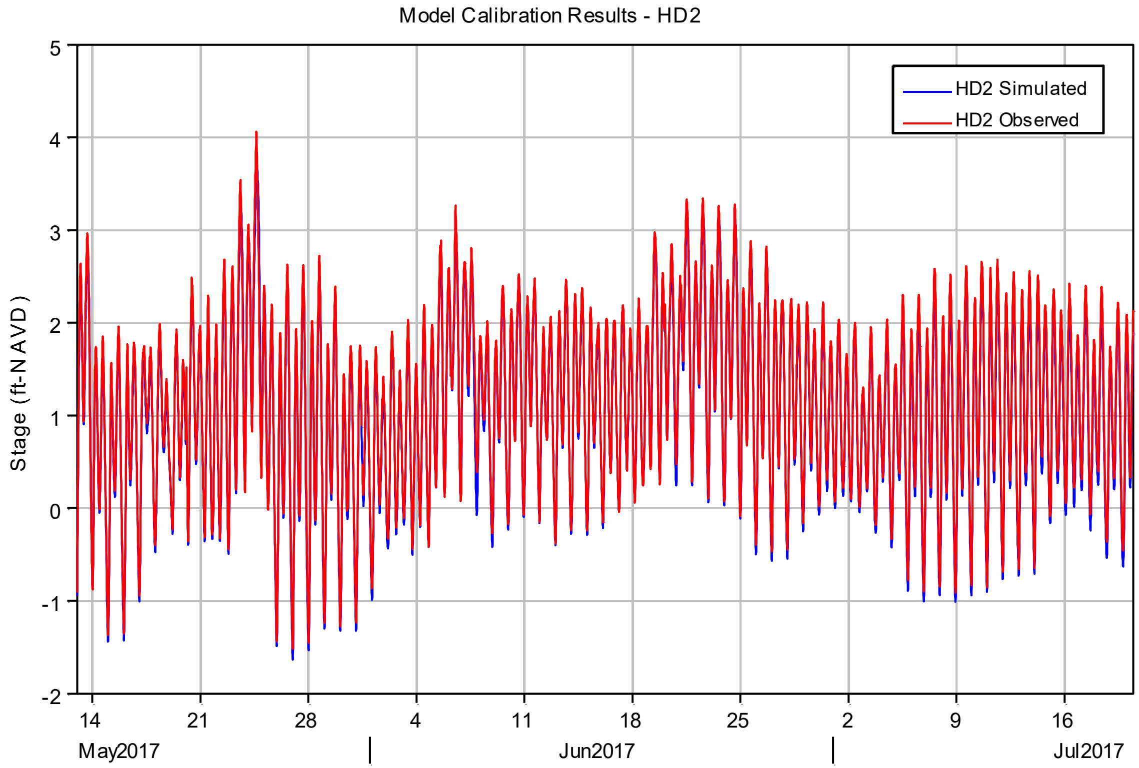


Figure 18a. Model Calibration Results at HD-1, St. Marks River at US 98,
May 13, 2017 to July 20, 2017



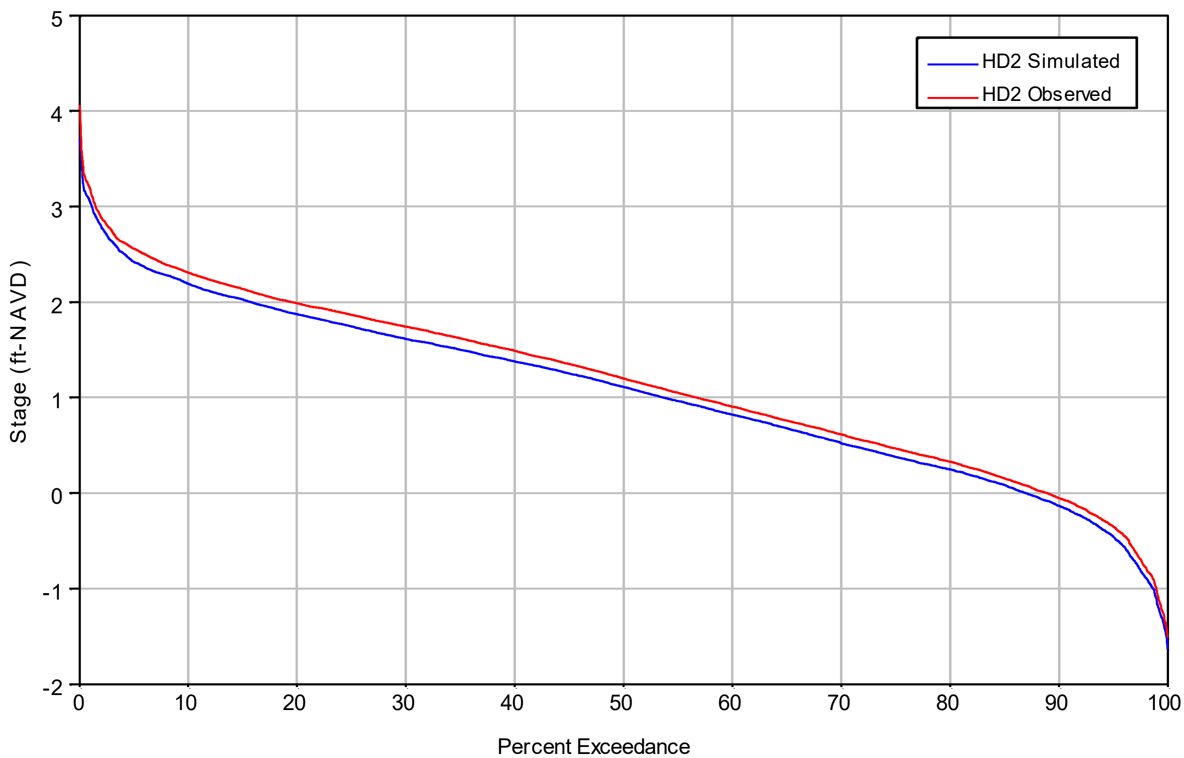
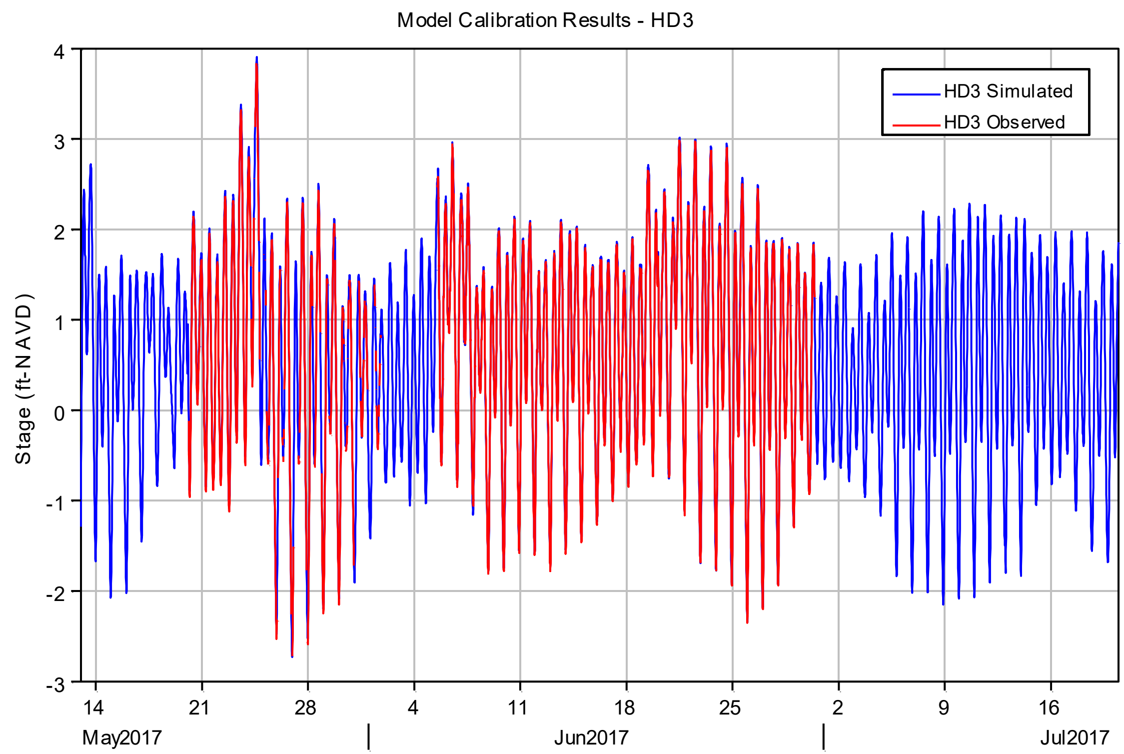


Figure 18b. Model Calibration Results at HD-2, Wakulla River at US 98, May 13, 2017 to July 20, 2017



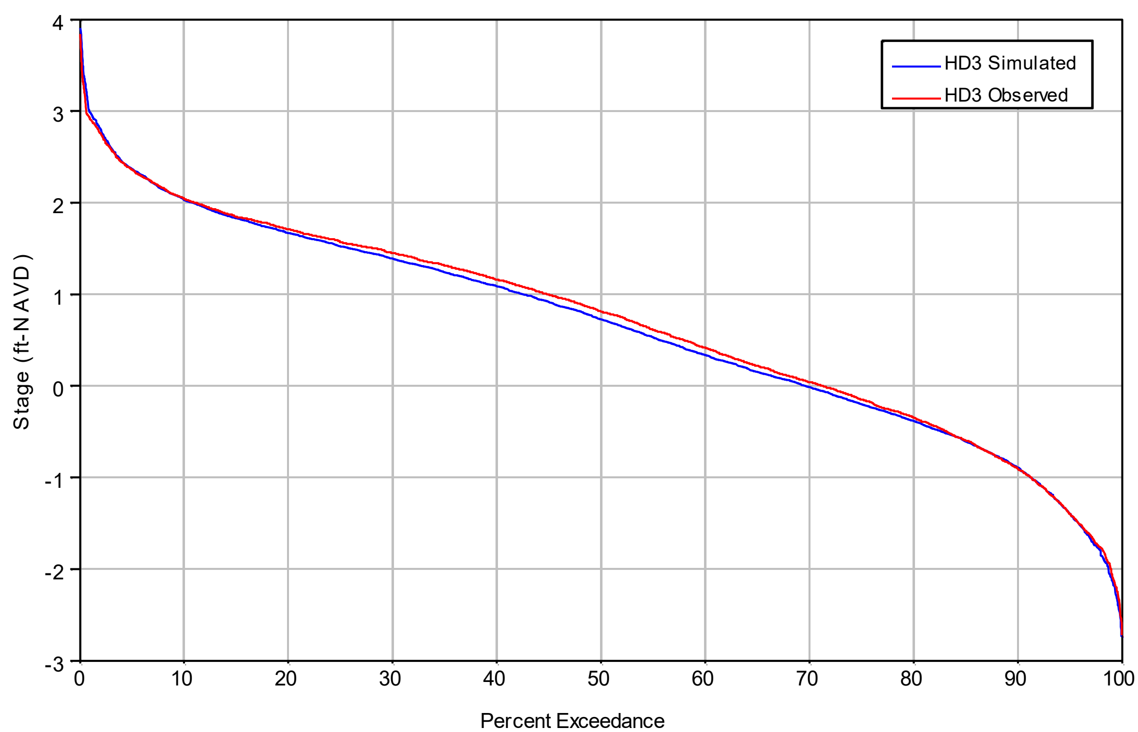
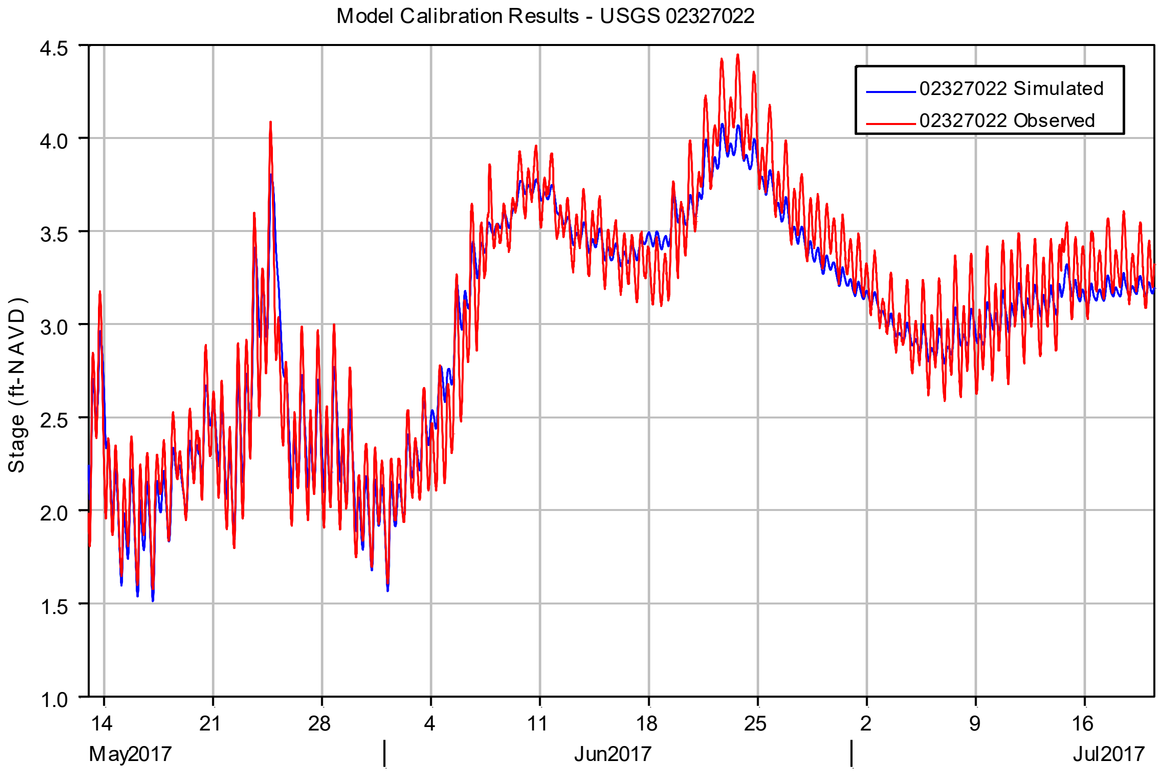


Figure 18c. Model Calibration Results at HD-3, May 13, 2017 to July 20, 2017



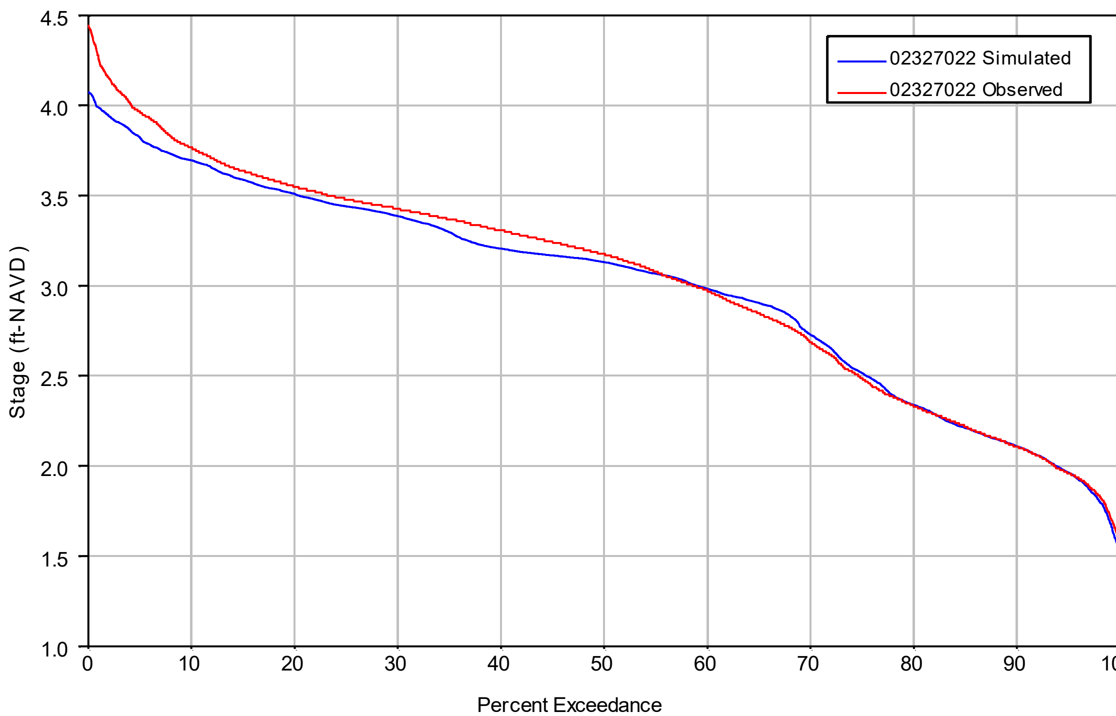
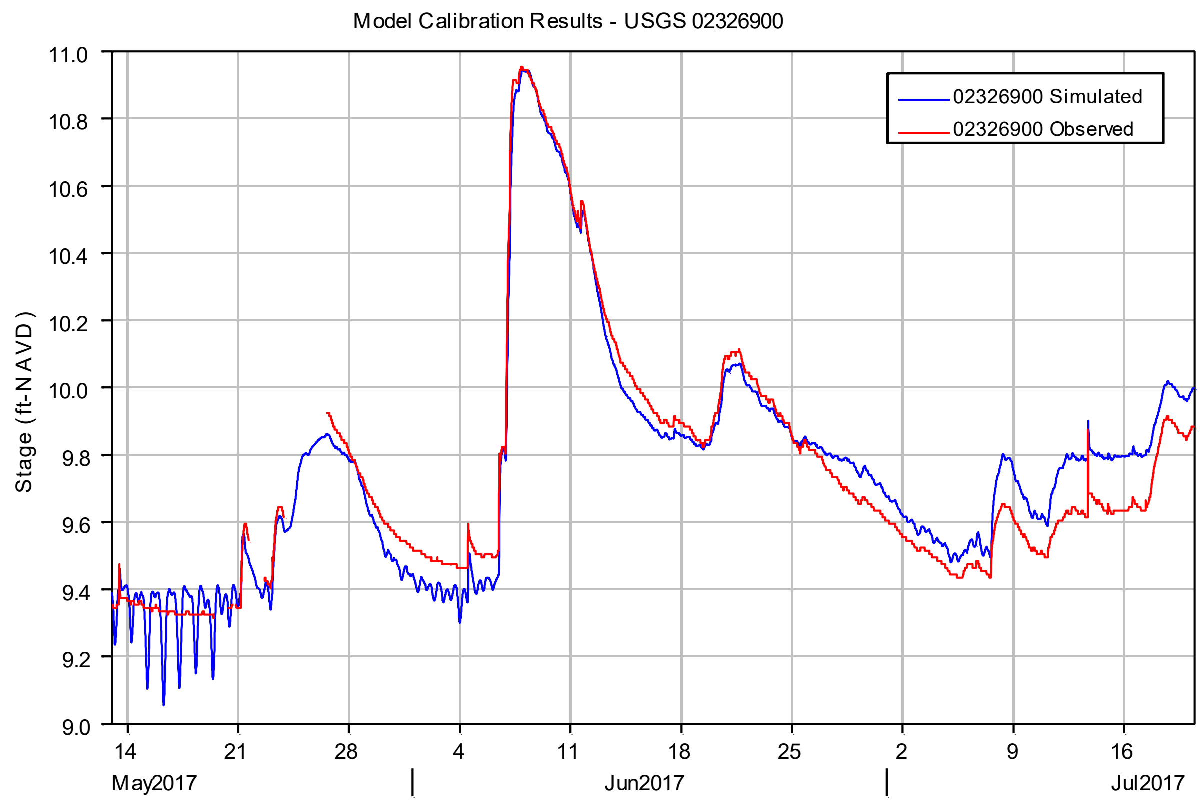


Figure 18d. Model Calibration Results at USGS 02327022,
May 13, 2017 to July 20, 2017



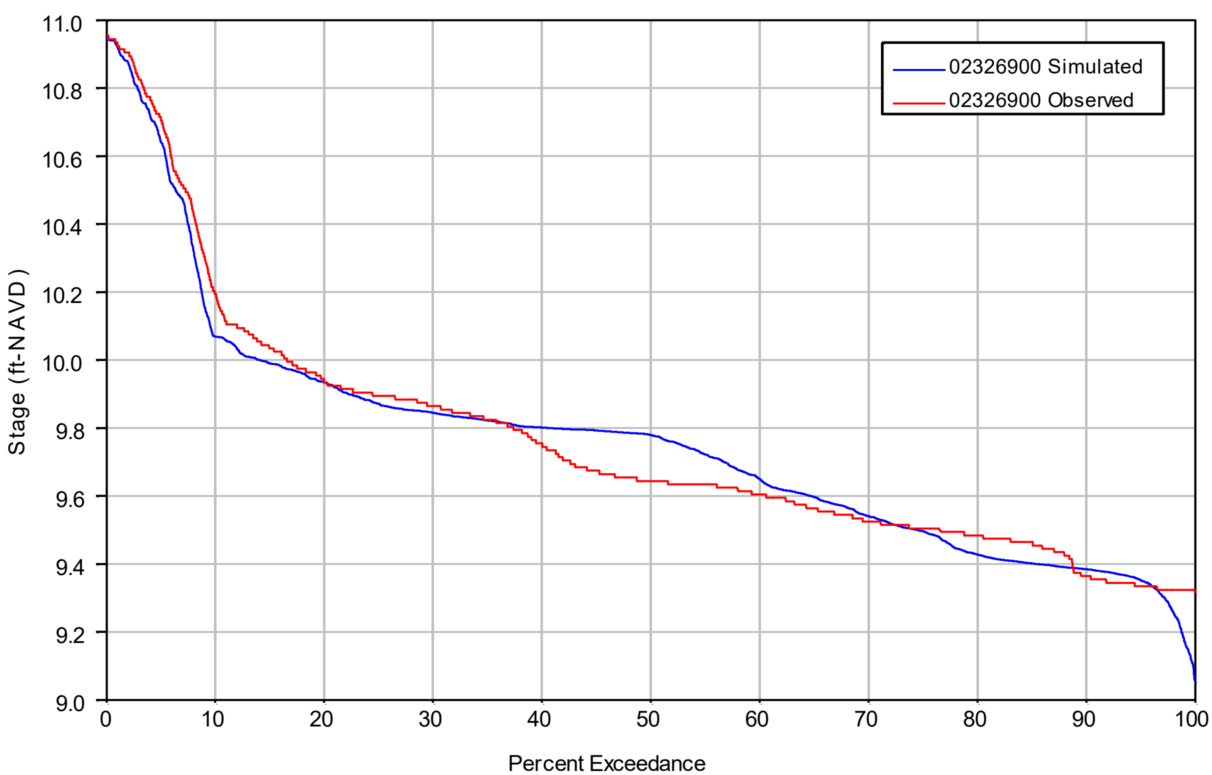


Figure 18e. Model Calibration Results at USGS 02326900

8.0 FINAL MODEL CALIBRATION

NWFWMD provided additional data from the HD stations that were deployed in the St. Marks/ Wakulla system that were not available during the initial model calibration. The period-of-record for this data is May 3, 2017, through November 27, 2017. This provided an additional period of approximately four months, from late July 2017 to late November 2017, to further test and calibrate the model beyond what was used originally. Typically, a calibrated model will be tested in a validation phase in which the results of model predictions are compared to observations for a separate and unrelated portion of the available period-of-record. There was not sufficient data available to perform a separate model validation, but extension of the calibration period allowed for the model to simulate a broader range of flow conditions and patterns. Review of the updated HD data indicates some significant tidal variation occurring in response to Hurricanes Irma and Nate. This period was also characterized by relatively low flows in the St. Marks River as measured by USGS Gage 02329000 as well as low and relatively stable water levels in the upper St. Marks River when the dense vegetation present has the greatest influence on flows and resultant stages.

Data processed for inclusion into the final model included:

- HD-4 water level data (Downstream boundary condition)
- HD-1, HD-2, HD3 Water level data (calibration and validation)
- USGS Gage - St. Marks River Near Newport flow data (upstream inflow boundary)
- Wakulla Springs (Daily), Sally Ward Springs (Daily and 15-minute) Flow Data (upstream inflow boundary)
- St. Marks and Wakulla River lateral inflows (inflow boundaries)
- USGS gage water level data for Wakulla River and St. Marks River (calibration and validation)

The processed data were evaluated, and outliers or suspect values identified. Review of the HD data revealed an issue during the September 10-11, 2017 period when Hurricane Irma passed the study area (east of St. Marks and the Gulf). Figure 19 presents plots of the HD data. Inspection of the plots indicates the following:

- HD1 (calibration gage on St. Marks River-SMR) appears to have the only complete record during this extreme tidal event

- HD4 (downstream boundary condition) is missing data during most extreme part of the outgoing tide (from September 10 at 2100 hrs to September 11 at 1130 hrs)
- HD2 (calibration gauge on Wakulla River-WR) and HD3 (calibration gage at the confluence) appear to "bottom out" during the most extreme part of the outgoing tide.

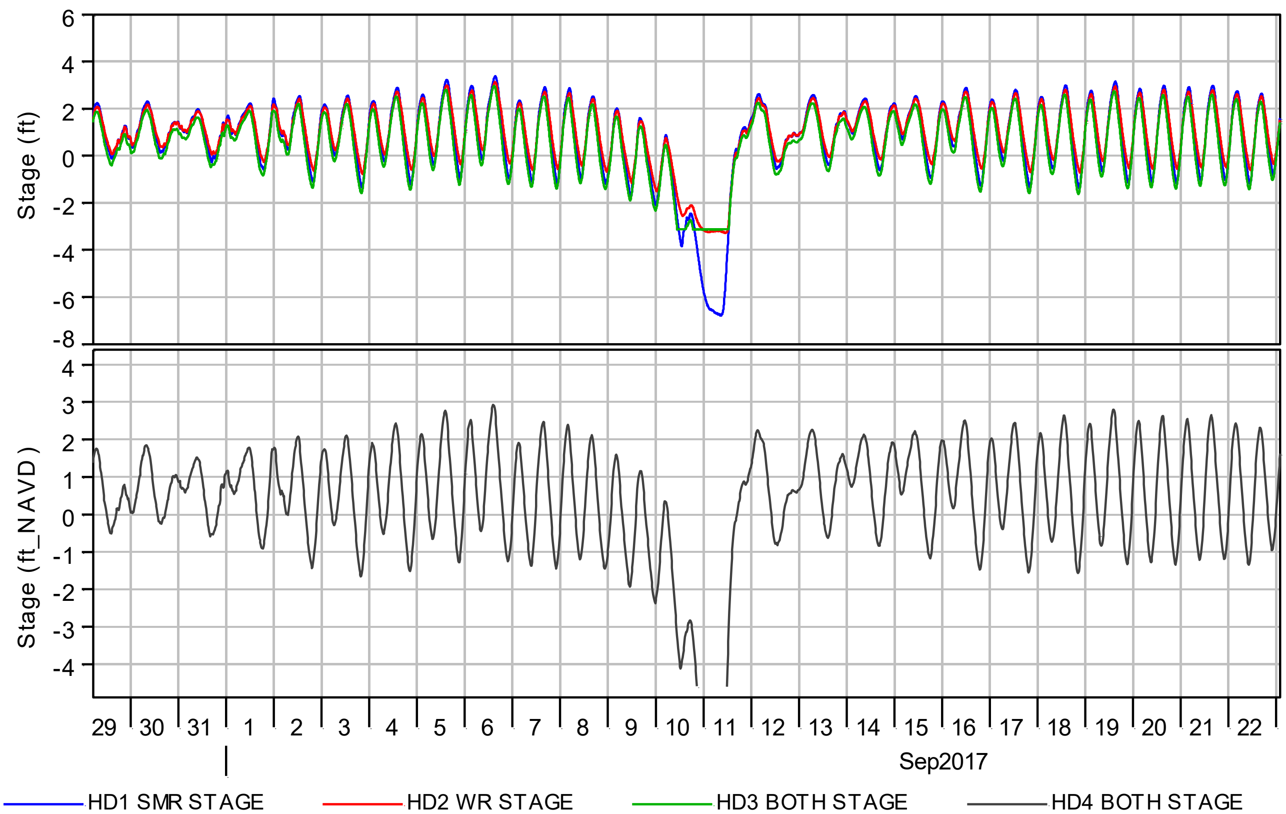


Figure 19. Comparison of HD Data around Hurricane Irma

The suspect data from HD2 and HD3 were discarded. The data gap (from September 10 at 2100 hrs to September 11 at 1130 hrs) in HD4 (downstream boundary condition) was filled with the data from HD1 to allow for model execution.

Inflow boundary time series were constructed using the data provided by the NWFWMD and downloaded from the USGS Water Data site. For the St. Marks River, 15-minute flow data were used to develop the upstream flow boundary at the top of the model and the uniform lateral inflow boundary. For the Wakulla River, 15-minute flow data provided by NWFWMD were input as the upstream flow bound at the top of the model. Because only daily flow data were available for Wakulla Springs, the daily data time series was converted to a 15-minute time series. The net inflow from Basin 2 (see Figure 7) was estimated using daily flow data using the following formula:

> USGS 02327022 Daily Flow – Wakulla Spring Vent Daily Flow – Sally Ward Spring Vent Daily Flow = Net Inflow from Basin 2.

The net daily inflow from Basin 2 was converted to a 15-minute time series and input as a uniform lateral inflow. Negative flow values were set to zero. The use of daily data for the development of flow time series may result in some minor mass balance issues in the Wakulla River. However, previous simulations have shown that water levels in the lower St. Marks River are not sensitive to Wakulla River flows but are driven primarily by tide. Flows at the USGS Gage 02326900 are presented on Figure 20. For the initial calibration period (May 3 – July 20, 2017), flows ranged from 344 cfs (P2) to 1390 cfs (P95). For the extended calibration period, the flow record shows an extended low-flow period with flows ranging from 392 cfs (P7) to 850 cfs (P80) with flows below 500 cfs (P30) observed approximately 60 percent of the time from late July to the end of the modeling period.

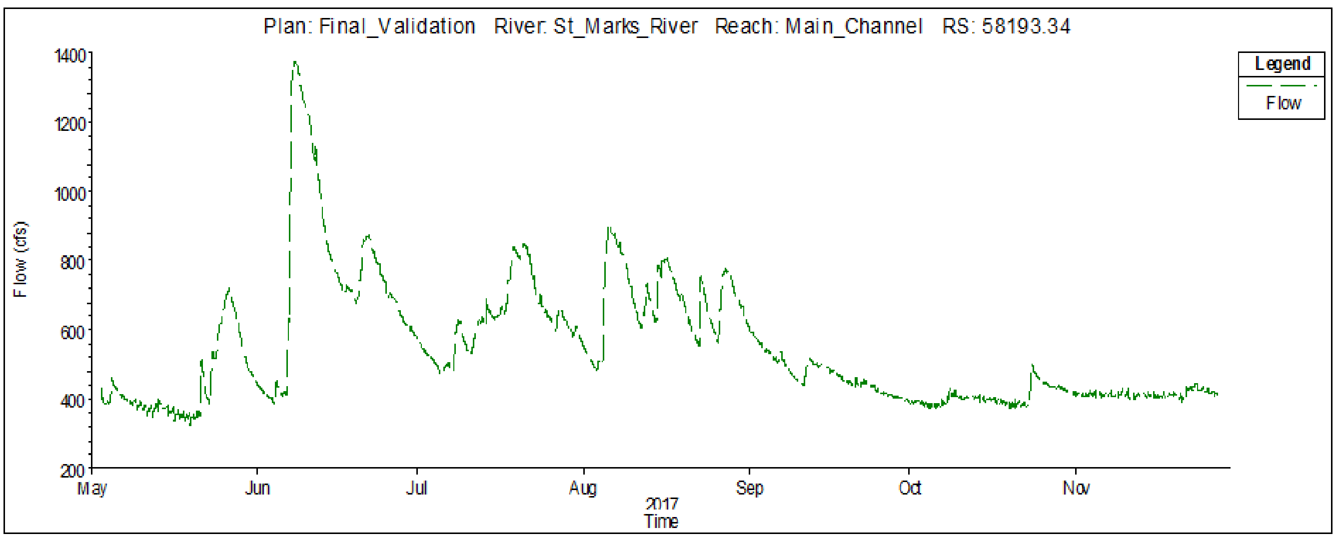


Figure 20. USGS 02326900 Flow Hydrograph for the Extended Model Period-of-Record.

8.1 EXTENDED CALIBRATION PERIOD SIMULATION

The HEC-RAS model was modified to incorporate the expanded data record. Model boundary conditions as identified in the DSS file contain “UPDATE” in the series name to reflect the updated and extended modeling period. Simulations were performed with the updated model inputs to confirm the initial calibration of the model. The model simulation for the period from

May 3, 2017 through November 27, 2017 period used the model parameterization from the May 3, 2017 through July 20, 2017 initial calibration run (Section 7). To initially assess the model performance for the extended simulation period, qualitative comparisons of simulated and observed water level time series and comparison of simulated and observed water level stage duration curves were performed.

The results of this effort are presented on Figure 21 at USGS Gauge 02326900. The model calibrated to the May 3, 2017, to July 20, 2017 period predicts water levels to within 0.2 ft at all locations where data are available for comparison up to the middle of August 2017. At this time, stages begin to diverge with differences toward the latter part of the extended simulation period between +0.4 - 0.5 ft, which corresponds to the extended low flow period. Inspection of Figure 21, particularly when comparing the beginning and end of the extended simulation period indicates that the flow rating curve at the 02326900 gage has shifted down approximately 0.5 ft.

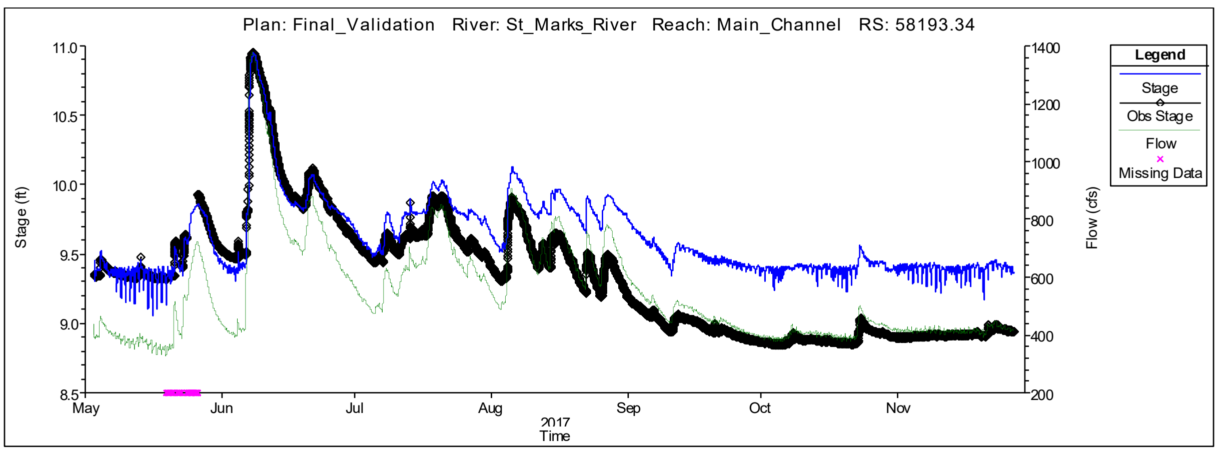


Figure 21. Simulated and Observed Time Series at USGS 02326900

It has been documented during discussions by NWFWMD staff with USGS staff that the flow at this site is very prone to being affected by vegetation growing in the channel. Over the years, some large shifts in the flow rating have been required to try to account for the changes in the density of the grass beds. During the extended modeling period of May 3, 2017, to November 27, 2017, five (5) rating shifts were made for the 02326900 gage due to vegetation growing and dying off in the channel (Ron Knapp (USGS), Personal Communication). Figure 22 is a plot of published gage height and flow for the extended modeling period of May 3 to November 27, 2017, that illustrates the flow rating shifts. The blue reflects the period from May 3, 2017, to July 20, 2017 (initial calibration period) while the orange reflects the period from July 21, 2017 through November 27, 2017. Figure 23 presents a photo of the St. Marks River near the USGS gage 02326900 which shows the vegetated condition typical of the reach downstream of St. Marks River Rise.

It is possible to account for phenomena such as the growing and dying of vegetation in channel in HEC-RAS unsteady flow simulations through the use of seasonal roughness factors if systematic changes in growth and decay patterns can be discerned. At this point, a systematic pattern has not been discerned. Also, the migration of the unsteady flow model to a steady-state version for use in MFL analyses would render this adjustment moot. Therefore, it was decided to adjust the height of the sill so that the model predictions would result in an “average” condition during the extended modeling period in which predictions would split the difference to achieve a best fit across the various flow rating relationships. The sill was adjusted down 0.55 ft to elevation 4.8 ft NAVD88 to achieve this goal.

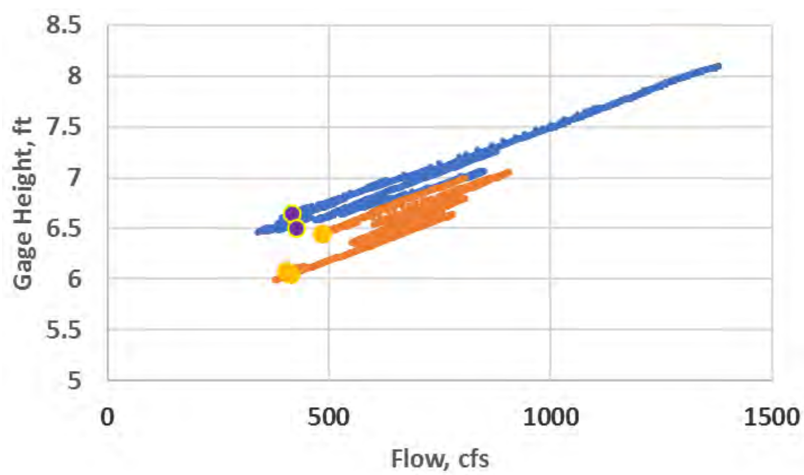


Figure 22. Published Gage Height Versus Flow at USGS 02326900 for the Modeling Period of May 3 to November 27, 2017

Figure 23. St. Marks River near USGS 02326900 on June 22, 2018. (Photo by Paul Thurman)

Figures 24 through 27 present comparisons of the simulated and observed stages at Stations HD1, HD3, USGS 02327022 and HD 2 respectively. Inspection of the graphs indicate that the model is performing well in the extended modeling period. At USGS 02327022 on the Wakulla River (Figure 8), the model is underpredicting stage 0.3-0.5 ft. during the August to November 2017 period.

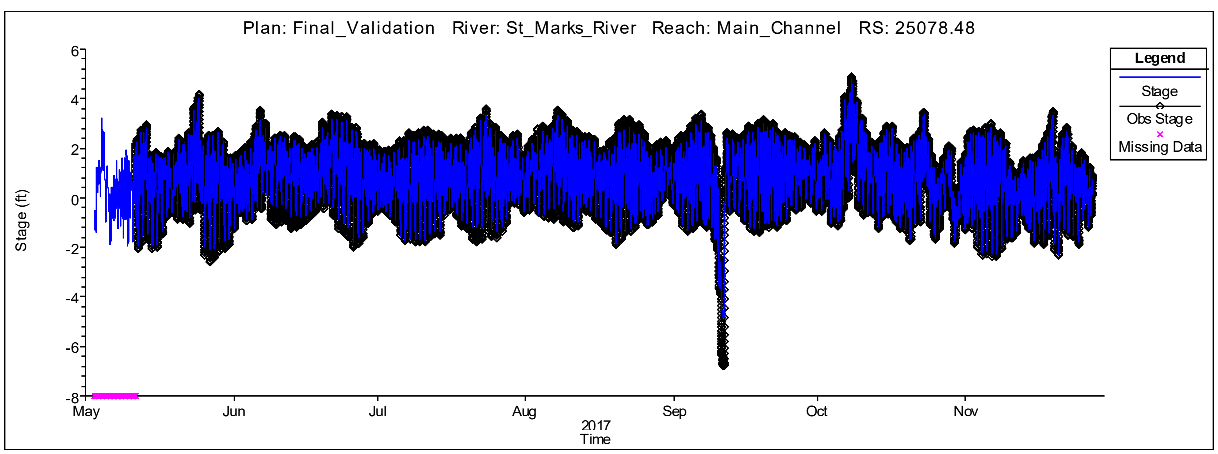


Figure 24. HD1 Stage Hydrograph

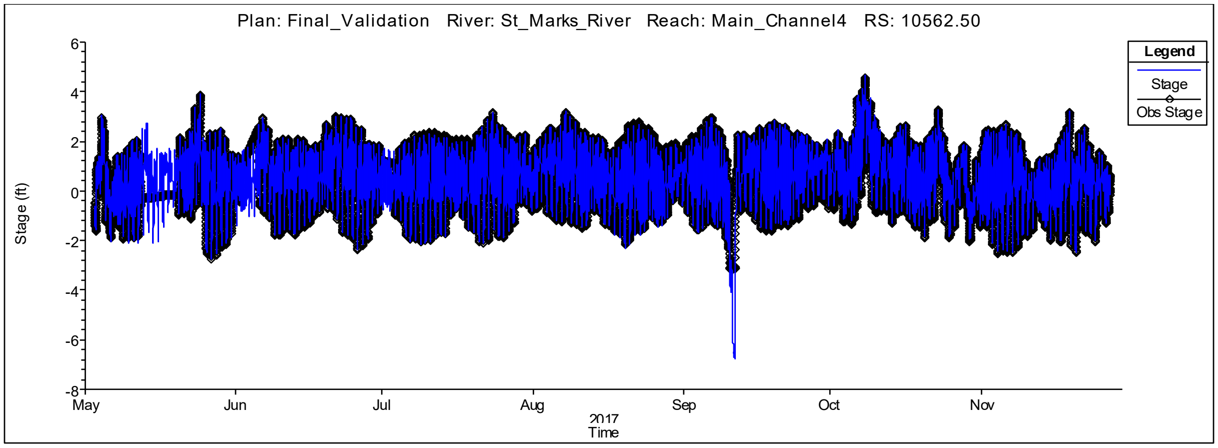


Figure 25. HD3 Stage Hydrograph

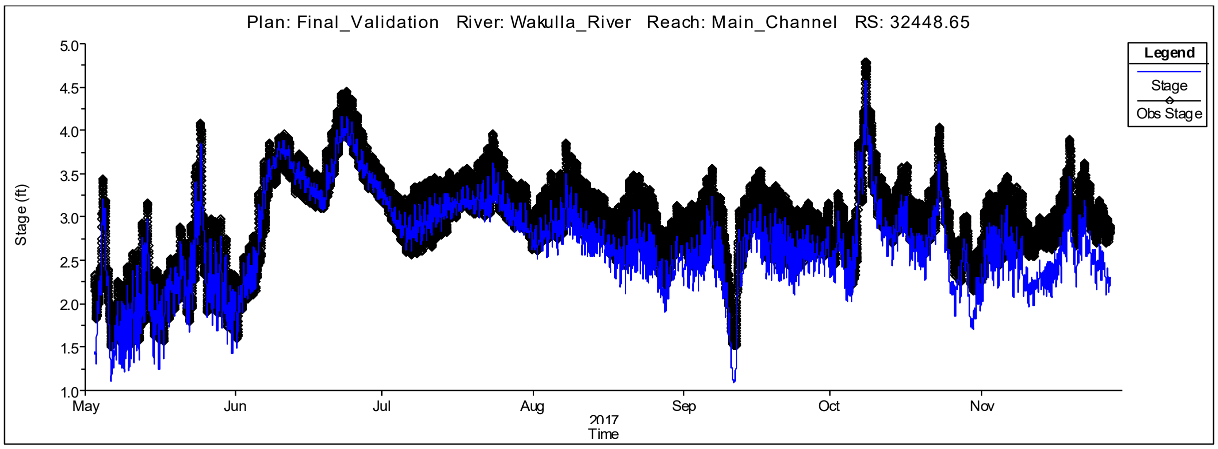


Figure 26. USGS 02327022 Stage Hydrograph

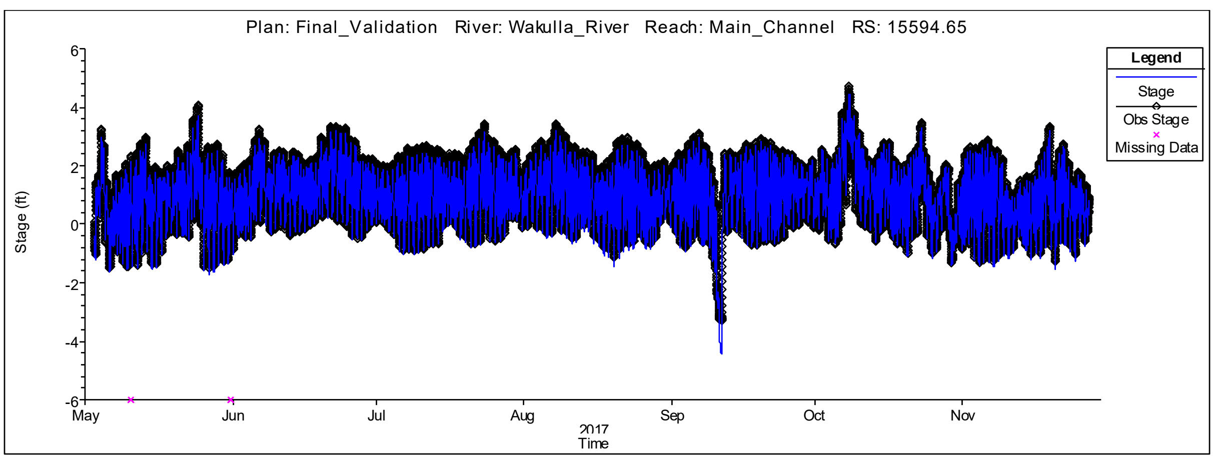


Figure 27. HD2 Stage Hydrograph

8.2 MODEL PERFORMANCE AND ADDITIONAL ADJUSTMENTS AT THE ST. MARKS RIVER SHOALS

The model's performance at the St. Marks River shoals was examined during the extended calibration period of May 3, 2017, to November 27, 2017. Figure 28 presents the stage hydrograph at Shoal Transect 5 (see Figure 3 – Shoal Transect Map), which is located upstream of the shallowest shoal transect (Shoal Transect 4). It is during this period that flows are relatively stable. It is at these locations during low flows where flow transitions between sub-critical and critical flow may be expected to occur, depending on the tidal condition. Inspection of the figure shows what at first appears to be an instability. Zooming in on a portion of Figure 28, a regular pattern based on tidal condition is apparent (Figure 29). The periods of higher stages correspond to periods of low tide. This is a result that is consistent with the concept of "specific energy". When this concept is applied to a condition where there is an upward step in the channel bottom, such as occurs at Shoal Transect 4, the depth over the transition decreases with an approaching subcritical flow. For super-critical flow, depth over the transition will increase. The results in the model do not indicate a condition of super-critical flow (maximum Froude number of 0.6) but does confirm conditions approaching critical flow near the shoals.

The model appears to make the appropriate predictions in following the pattern of greater depths as you approach critical flow and shallower depths in the sub-critical flow region. HEC-RAS is providing warnings that energy loss between the current and previous cross-sections is greater than 1 ft. In such instances, this may indicate the need for additional cross-sections in these regions. This would be accomplished with the insertion of interpolated cross-sections to provide better resolution. While the model's pattern appears to be appropriate, additional cross-sections were added in this reach to improve computational resolution and improve the water depth calculations.

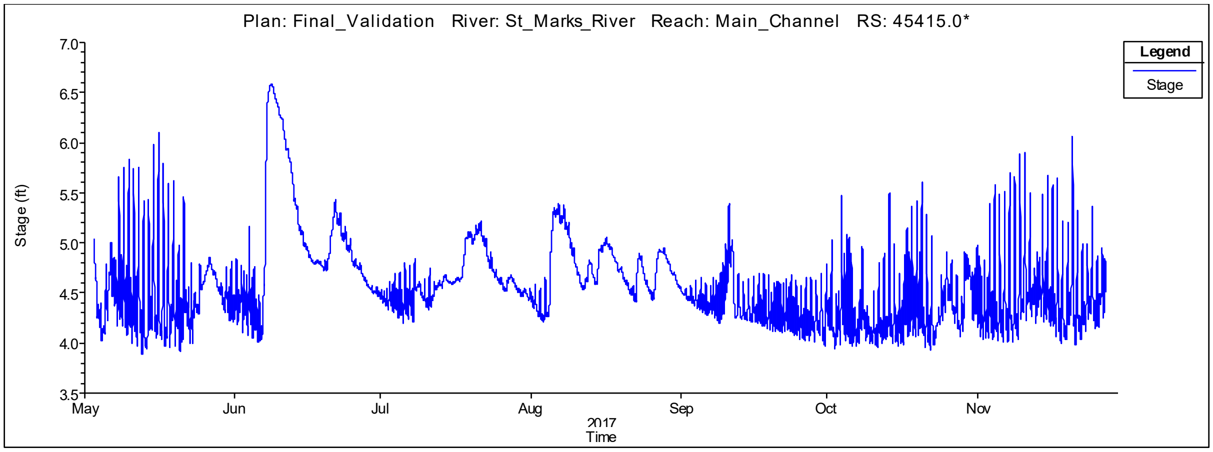


Figure 28. Stage Hydrograph at Shoal Transect 5 for the Model Period-of-Record.

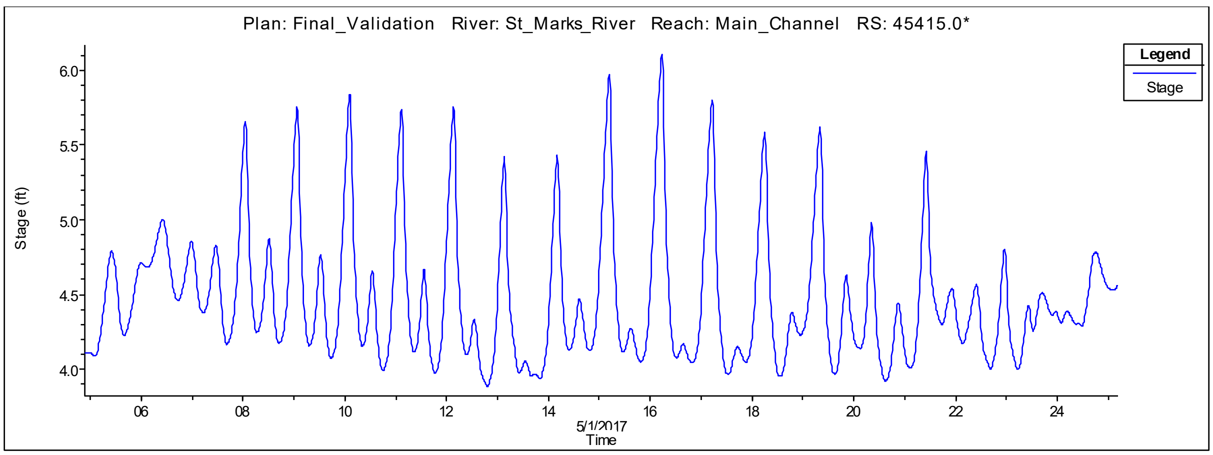


Figure 29. Stage Hydrograph at Shoal Transect 5 for May 5 to May 25, 2017

8.3 MODEL PERFORMANCE EVALUATION

In order to calibrate and validate the models and for comparison purposes, some quantitative information is required to measure model performance. In this study, the stage data measured at the five (5) calibration locations (USGS 02326900, USGS 02327022, HD1, HD2 and HD3) were used to assess the model performance. In this study, the HEC-RAS model results were evaluated with statistical measures of coefficient of determination (R^2), percent bias (PBIAS), and RMSE-observations standard deviation ratio (RSR) as well as visual comparison of observed and simulated flow time series and flow duration curves.

The Root-mean-square-error (RMSE) (Equation 1) indicates a perfect match between observed and predicted values when it equals 0 (zero), with increasing RMSE values indicating an increasingly poor match. Singh et al. stated that RMSE values less than half the standard deviation of the observed (measured) data might be considered low and indicative of a good model prediction.

The coefficient of determination (R^2) (Equation 2) describes the degree of collinearity between simulated and measured data ranging from 0 to 1, where N is the total number of data; Q is observed stage; P is simulated or predicted stage; and the over bar denotes the mean for the entire evaluation time period. R^2 of 1 means a perfect linear relationship between two variables, while an R^2 of zero represents no linear relationship.

The percentage of bias (PBIAS) (Equation 3) represents the overall agreement between two variables. A PBIAS of zero means there is no overall bias in the simulated output of interest compared to the observed data. Positive and negative PBIAS values indicate over-estimation and under-estimation bias of the model, respectively (Gupta, H.V. et al, 1999).

The RMSE-observations standard deviation ratio (RSR) (Equation 4) is calculated as the ratio of the RMSE and standard deviation of measured data. RSR varies from the optimal value of 0, to a large positive value. The lower the RSR, the lower the RMSE and the better the model simulation performance.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{n}}$$

(1)

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}\sqrt{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}}\right] \qquad 0 \le R^2 \le 1$$

(2)

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(O_i - P_i\right)*100}{\sum_{i=1}^{n}\left(O_i\right)}\right]$$

(3)

$$RSR = \frac{RMSE}{STDEV_{obs}} = \left[\frac{\sum_{i=1}^{n} \left(O_i - P_i\right)^2}{\sqrt{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)^2}} \right]$$

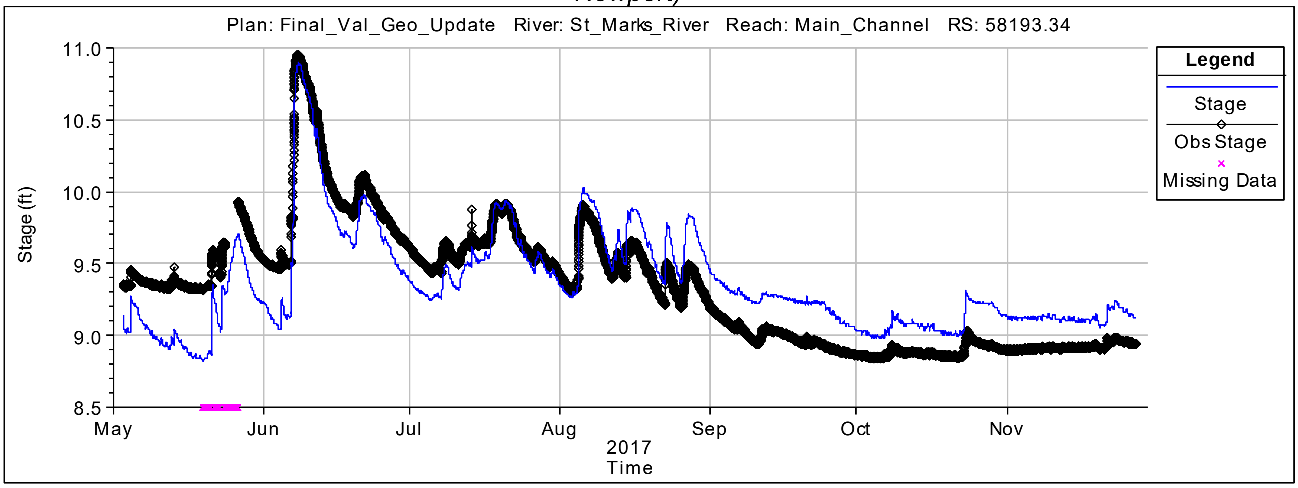
(4)

where, n is the number of observations in the period under consideration, Oi is the i-th observed value, O is the mean observed value, Pi is the i-th model-predicted value and P is the mean model-predicted value.

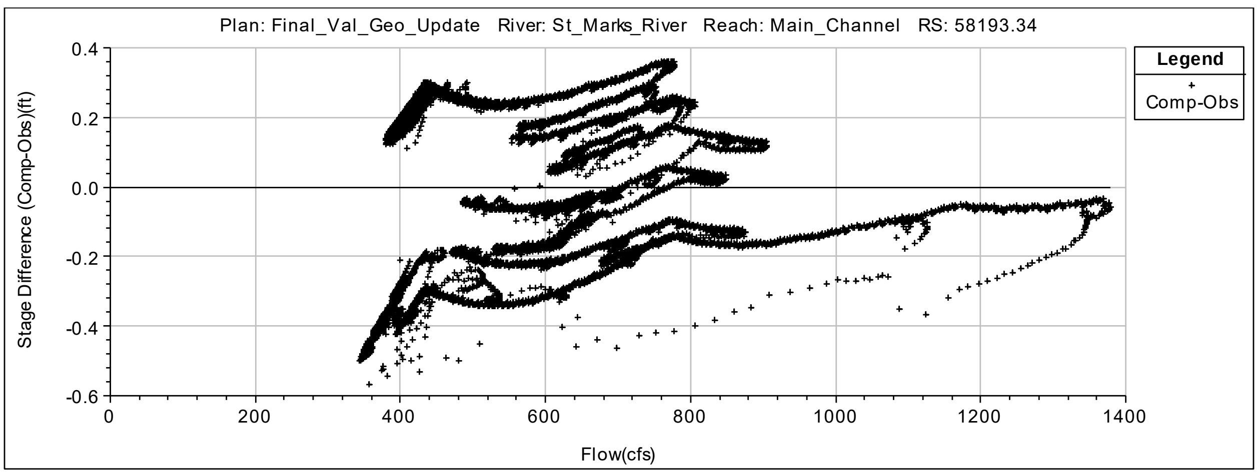
8.4 FINAL MODEL CALIBRATION RESULTS

The results of the final calibration simulation are presented below. Simulated and observed water stages were compared at each water level station in Figures 30 through 34. Table 5 presents a summary of the statistical measures of model performance. The results for the USGS Gage 02326900 (St. Marks River at Newport) are presented in Figures 30a through 30e. Figure 30c presents a plot of residuals over time which reflects the shifting flow rating over the modeling period of record. The model appears to balance the positive and negative residuals (PBIAS = 0.334) which was a goal of the final calibration effort. R^2 and RSR were worse at this location but are still considered good even with the shifting flow rating performed by the USGS. Discrepancy in average stages ranged from 0.03 (at USGS 02326900) to 0.08 ft (at HD2). Water level predictions at the St. Marks River shoals are also improved as can be seen in Figure 35. Overall, the unsteady state model proved to be a good predictor of water levels in low, medium and high flow conditions.

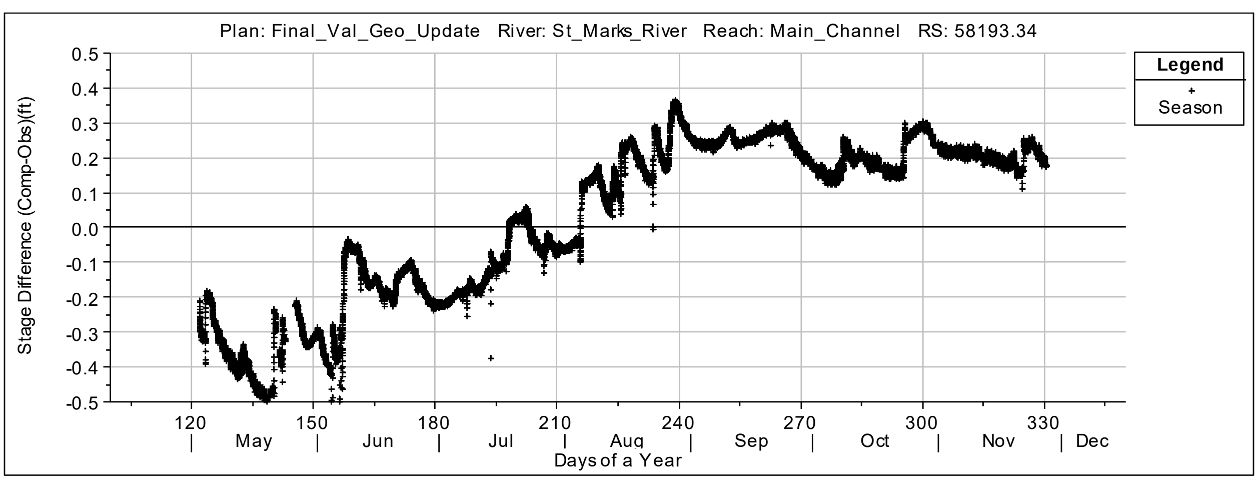
Figure 30. Comparison of Observed and Simulated Water Levels - Station 02326900 (St. Marks River nr Newport)



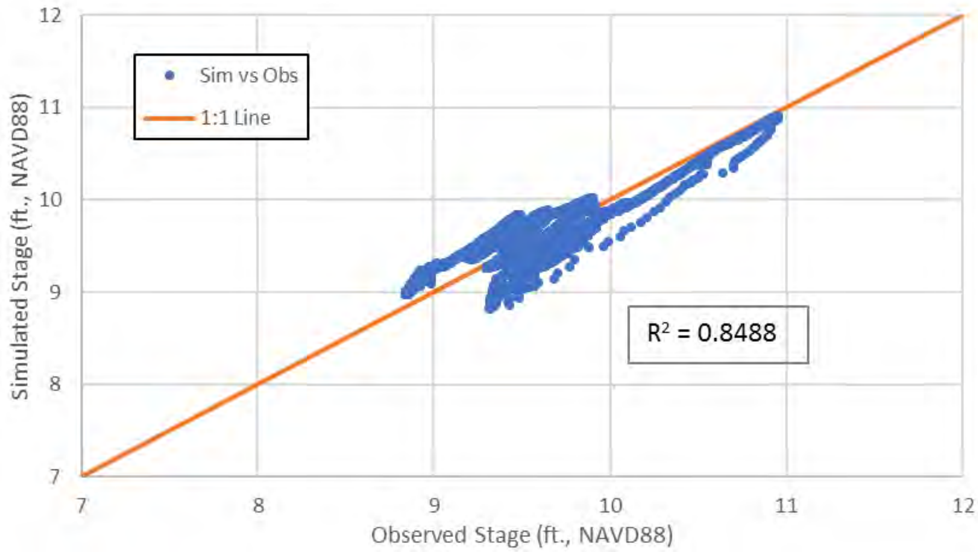
(a) Comparison of Simulated and Observed Stage Time Series



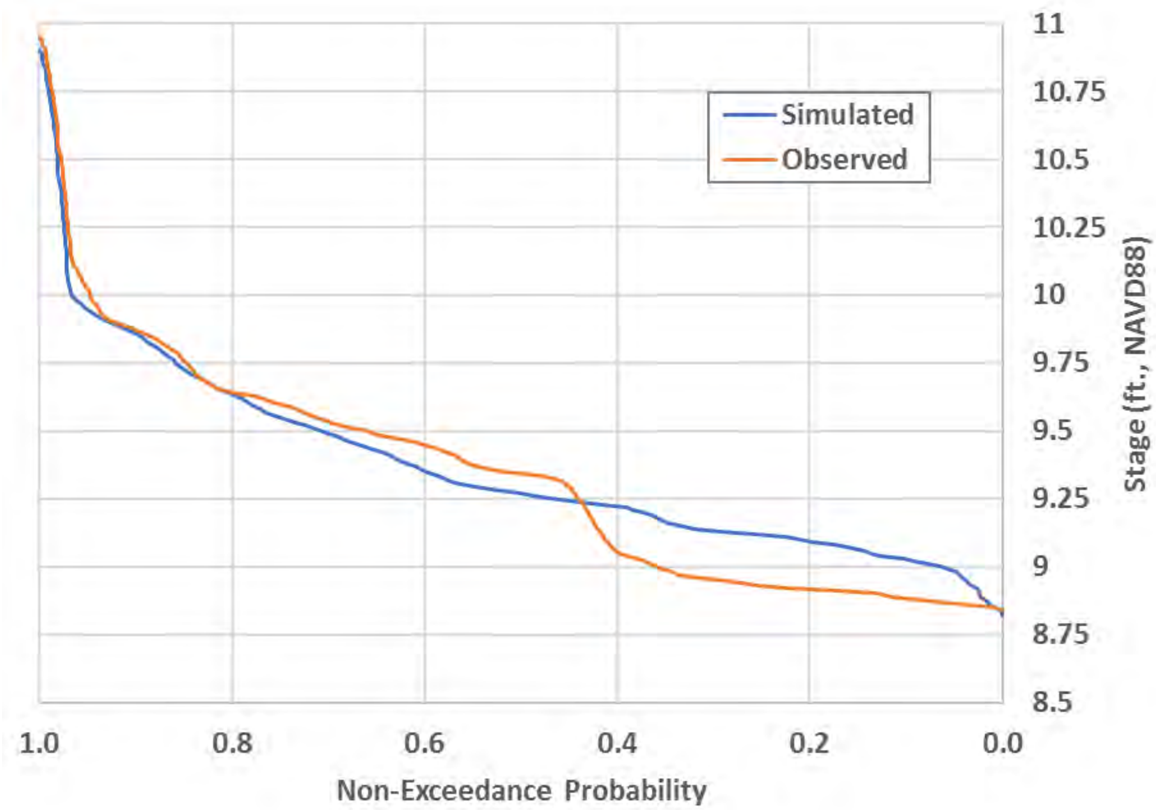
(b) Residuals (Simulated – Observed) vs Flow



(c) Residuals (Simulated – Observed) over Time

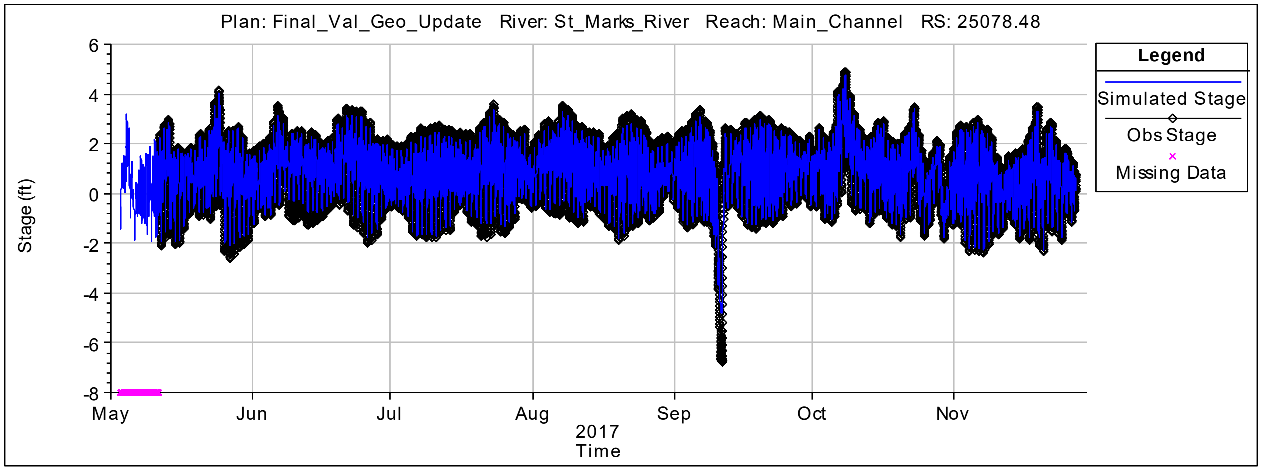


(d) Scatter Plot of Observed and Simulated Stages

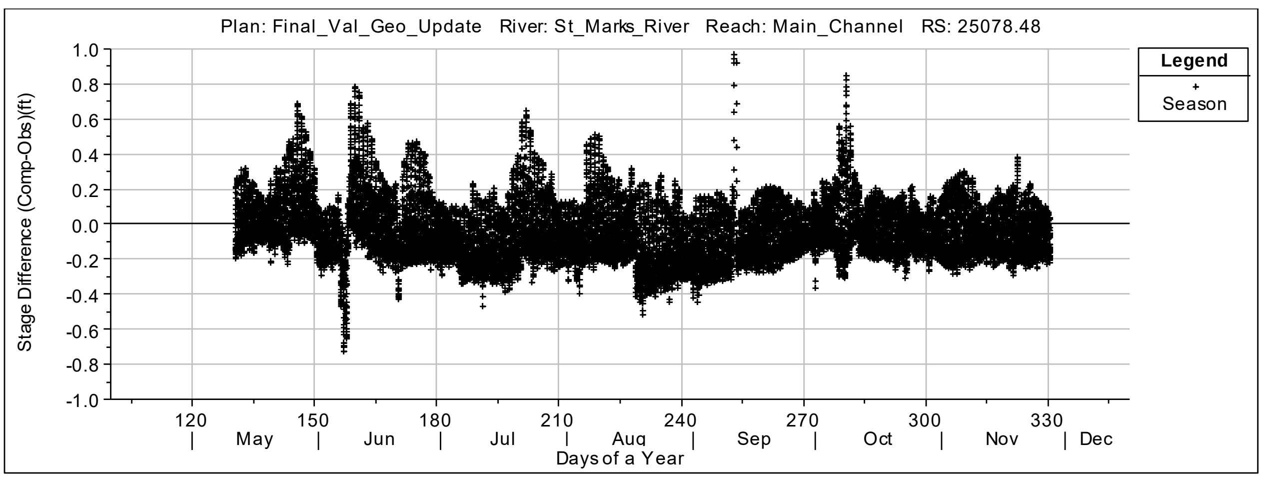


(e) Non-Exceedance Curves for Observed and Simulated Stages

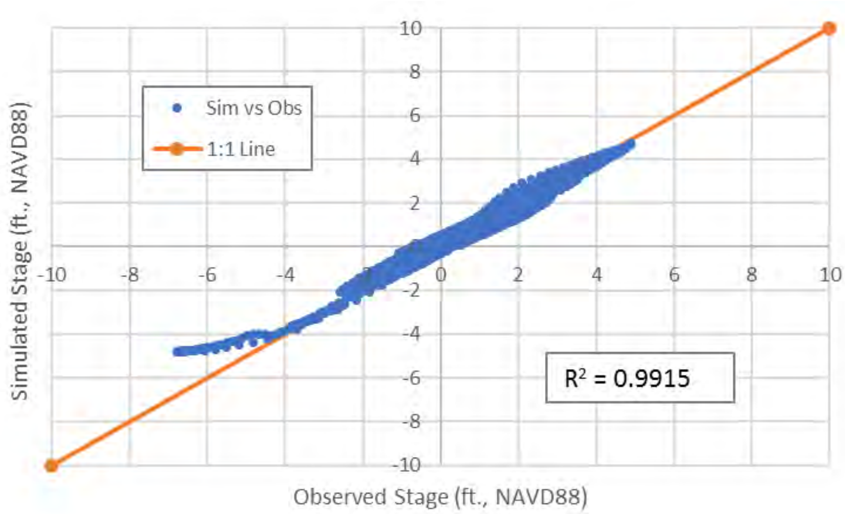
Figure 31. Comparison of observed and simulated water levels - Station HD1



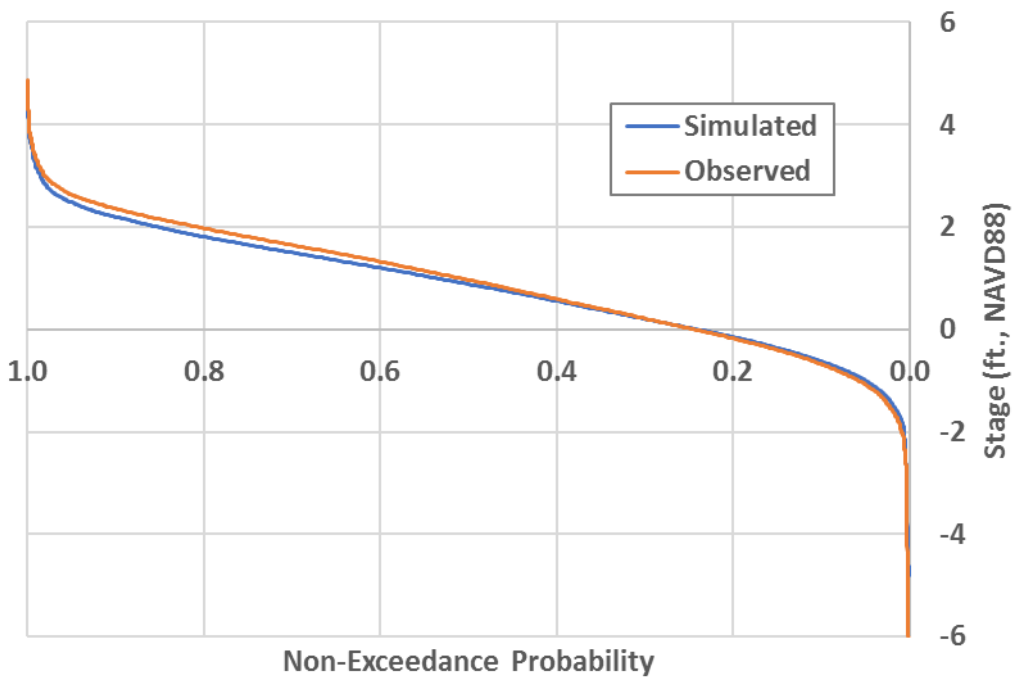
(a) Comparison of Simulated and Observed Stage Time Series



(b) Residuals (Simulated – Observed) over Time

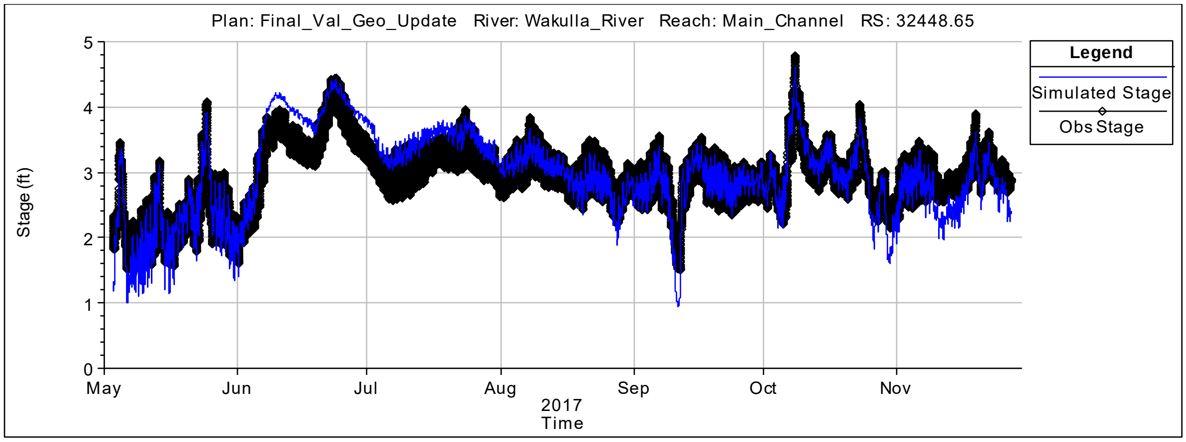


(c) Scatter Plot of Observed and Simulated Stages

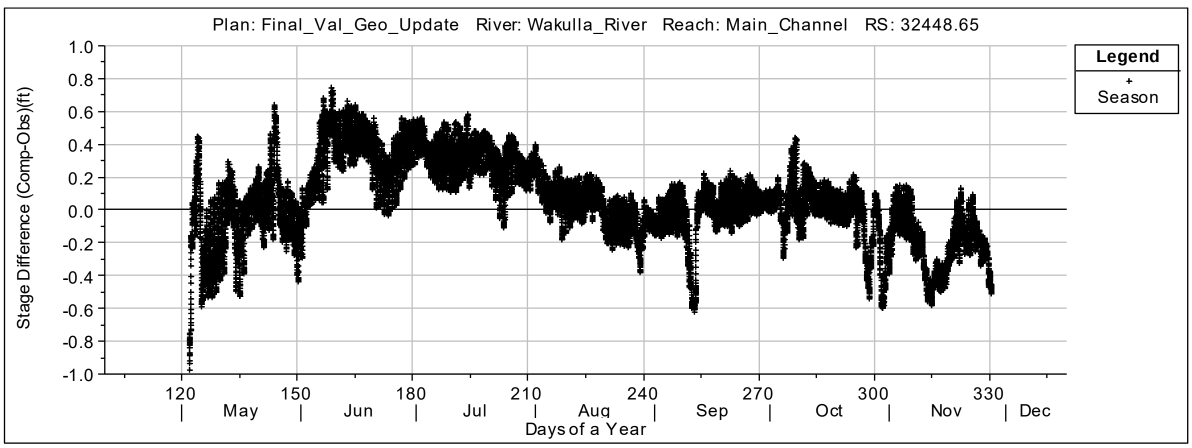


(d) Non-Exceedance Curves for Observed and Simulated Stages

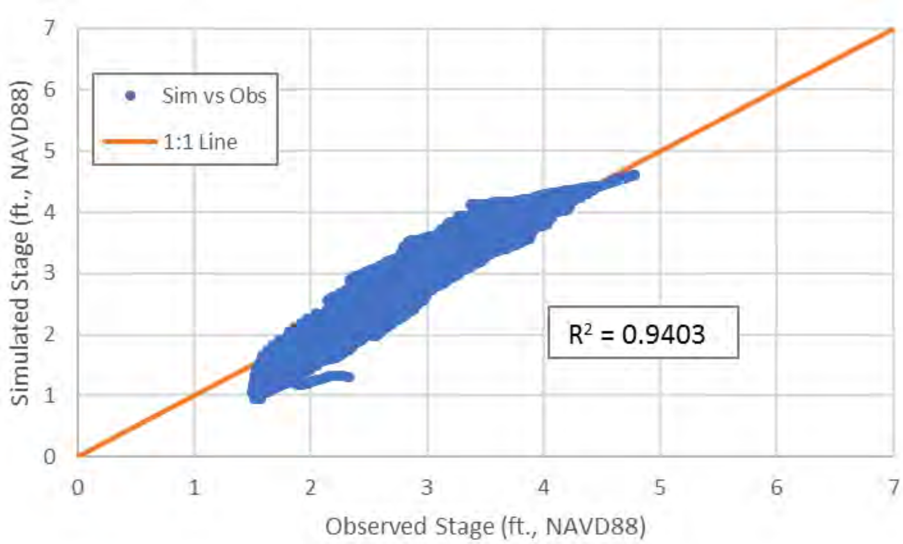
Figure 32. Comparison of Observed and Simulated Water Levels - Station 02327022 (Wakulla River Nr Crawfordville)



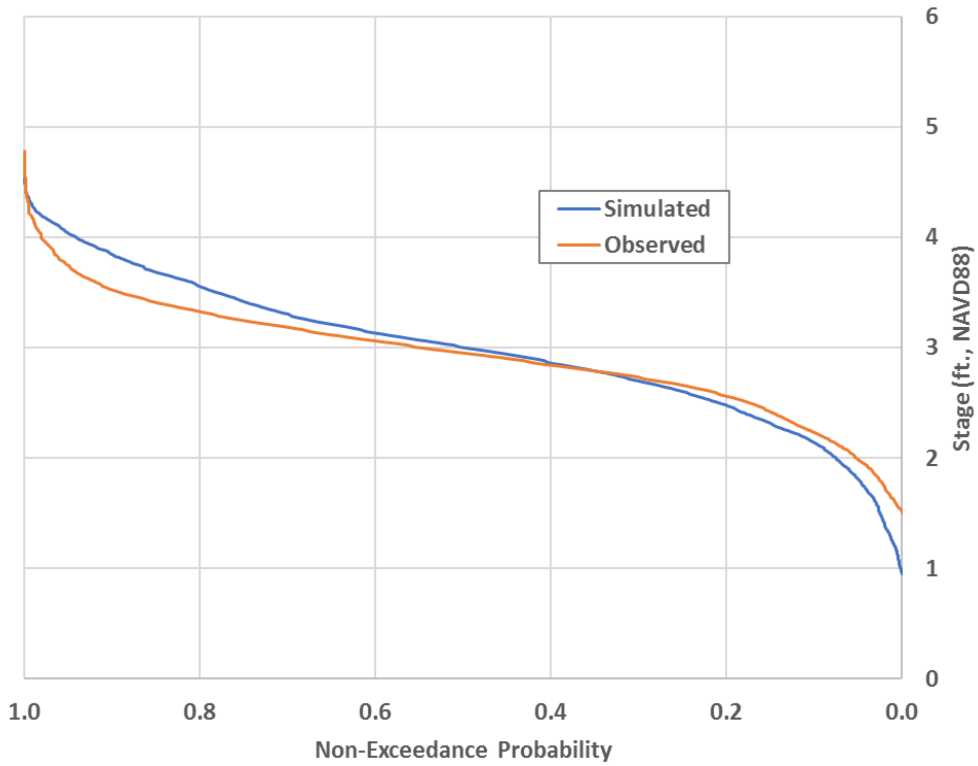
(a) Comparison of Simulated and Observed Stage Time Series



(b) Residuals (Simulated – Observed) over Time

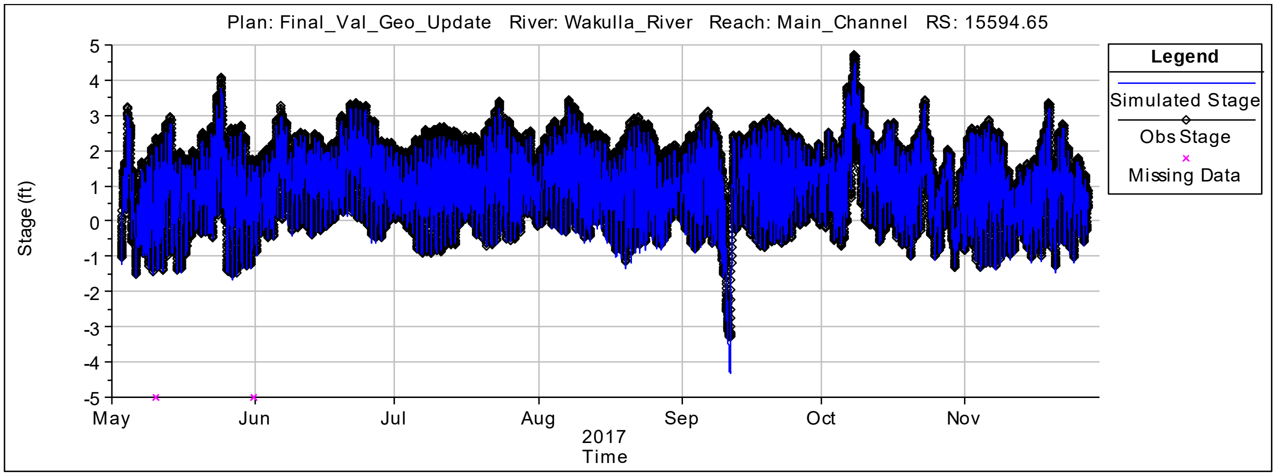


(c) Scatter Plot of Observed and Simulated Stages

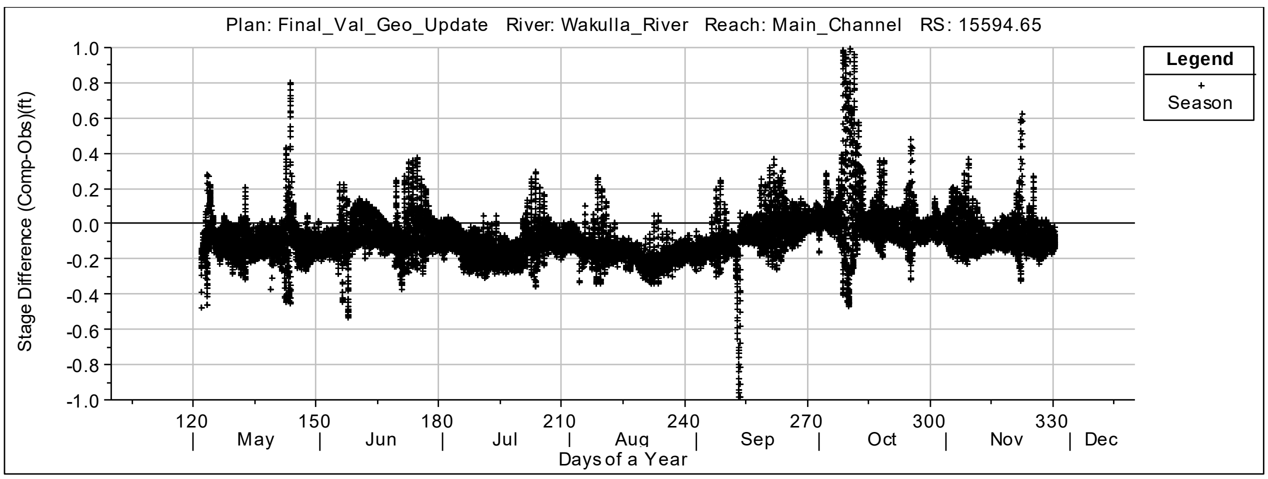


(d) Non-Exceedance Curves for Observed and Simulated Stages

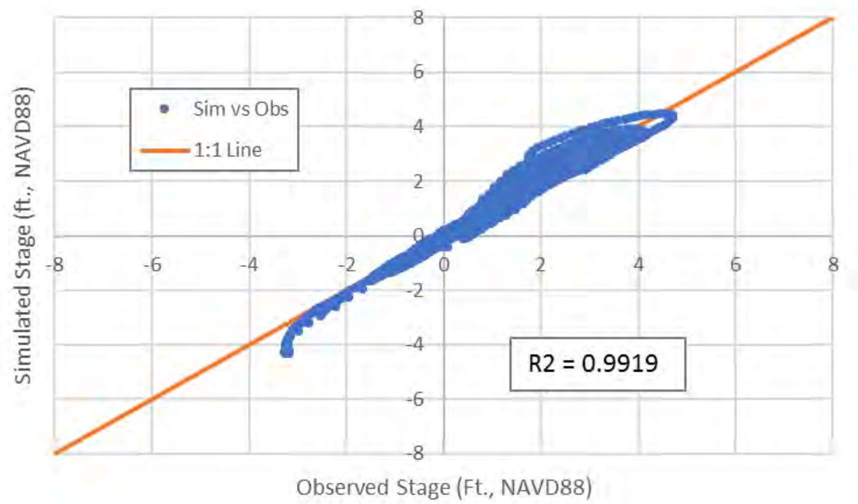
Figure 33. Comparison of Observed and Simulated Water Levels - Station HD2



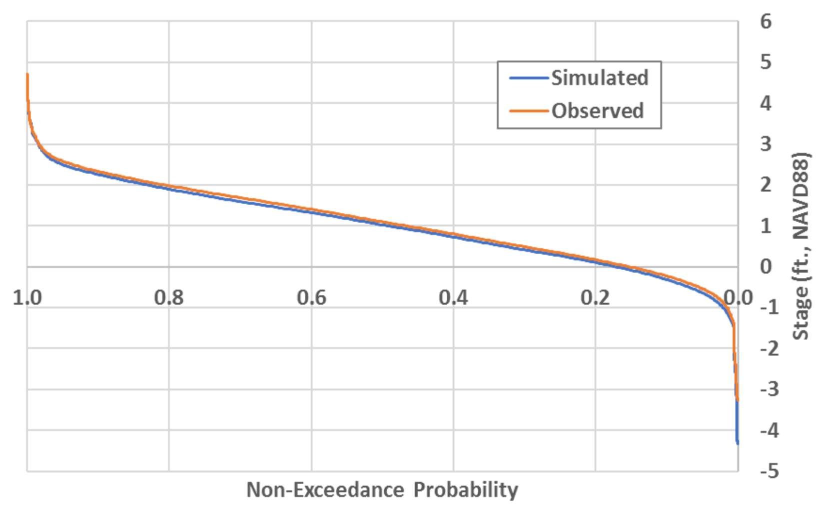
(a) Comparison of Simulated and Observed Stage Time Series



(b) Residuals (Simulated – Observed) over Time

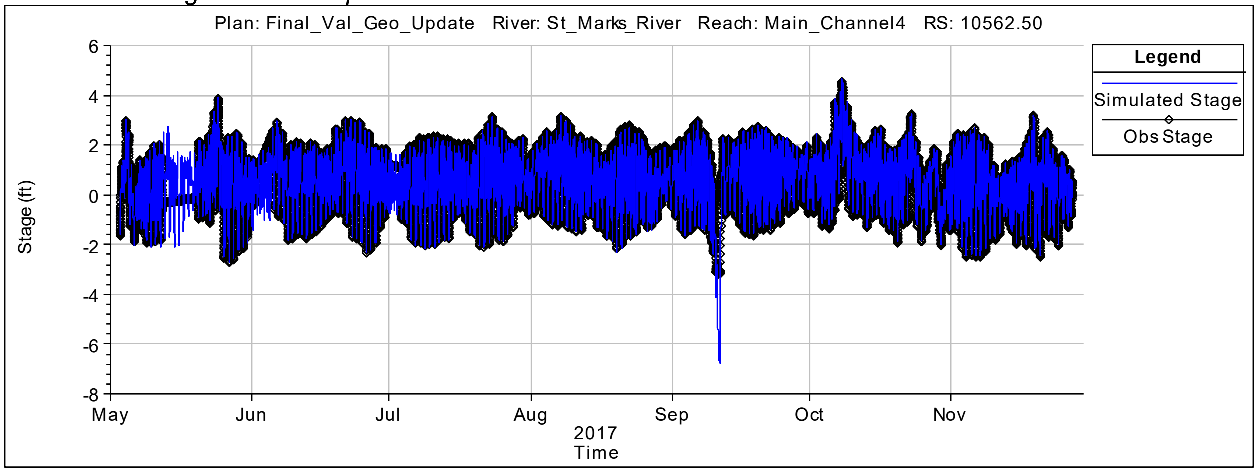


(c) Scatter Plot of Observed and Simulated Stages

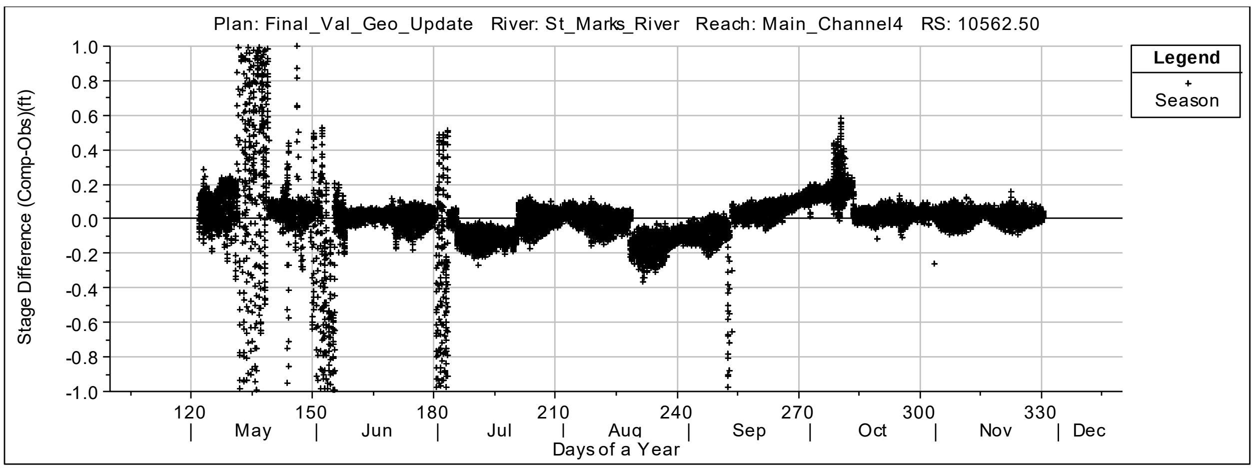


(d) Non-Exceedance Curves for Observed and Simulated Stages

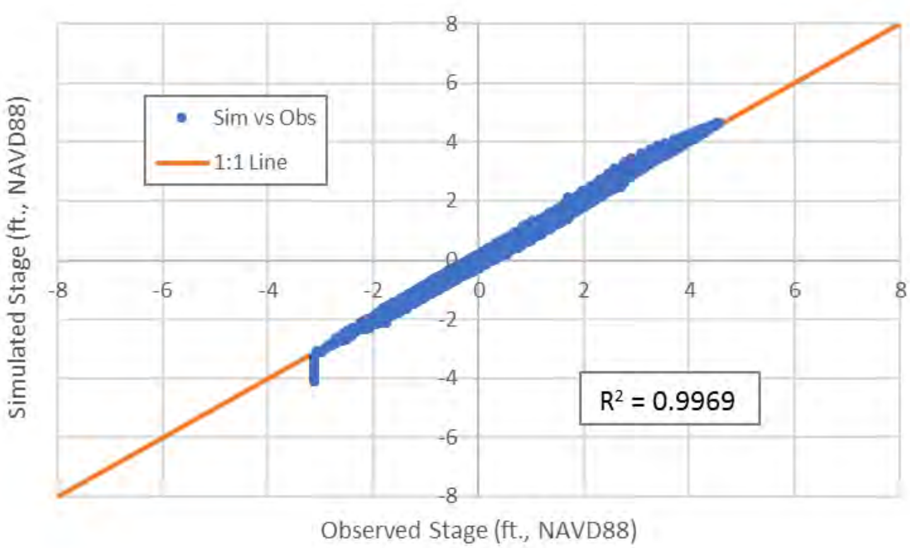
Figure 34. Comparison of Observed and Simulated Water Levels - Station HD3



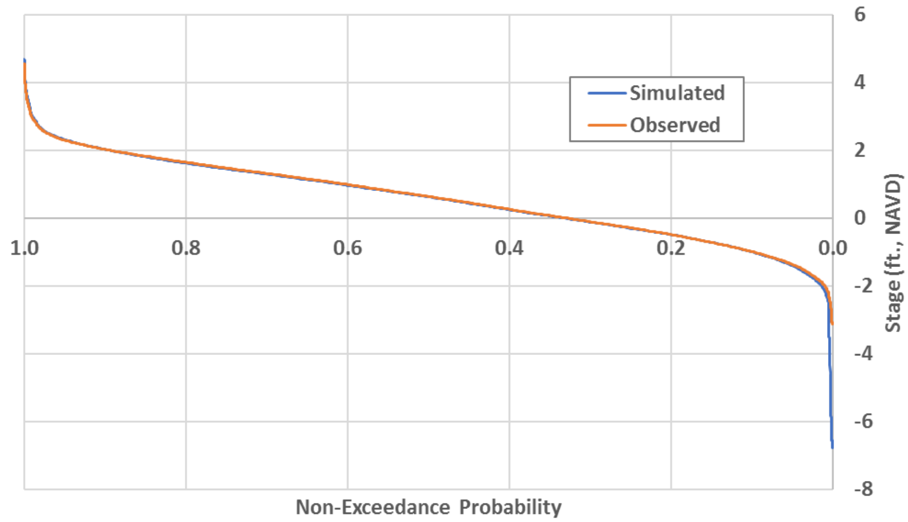
(a) Comparison of Simulated and Observed Stage Time Series



(b) Residuals (Simulated – Observed) over Time



(c) Scatter Plot of Observed and Simulated Stages



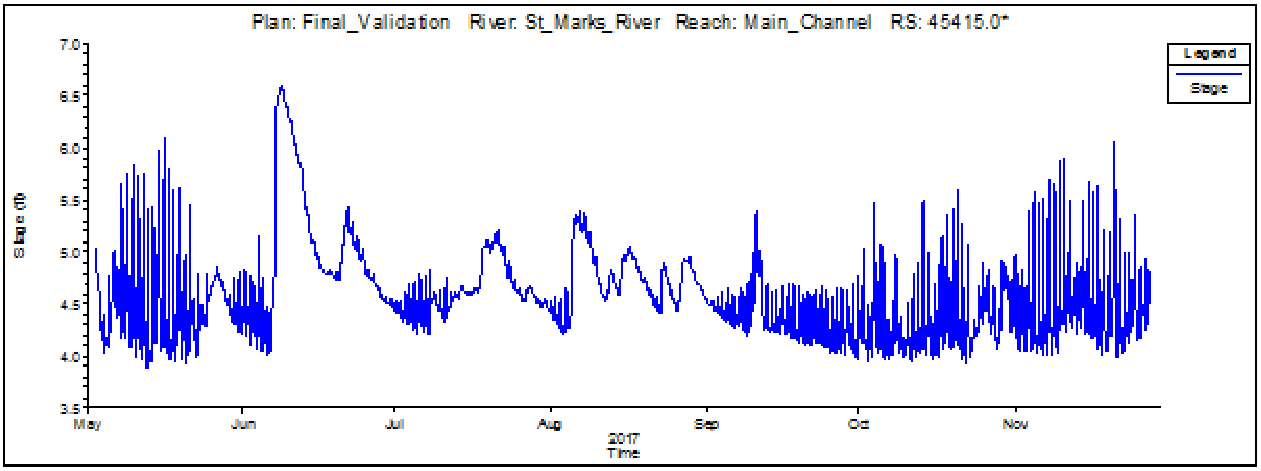
(d) Non-Exceedance Curves for Observed and Simulated Stages

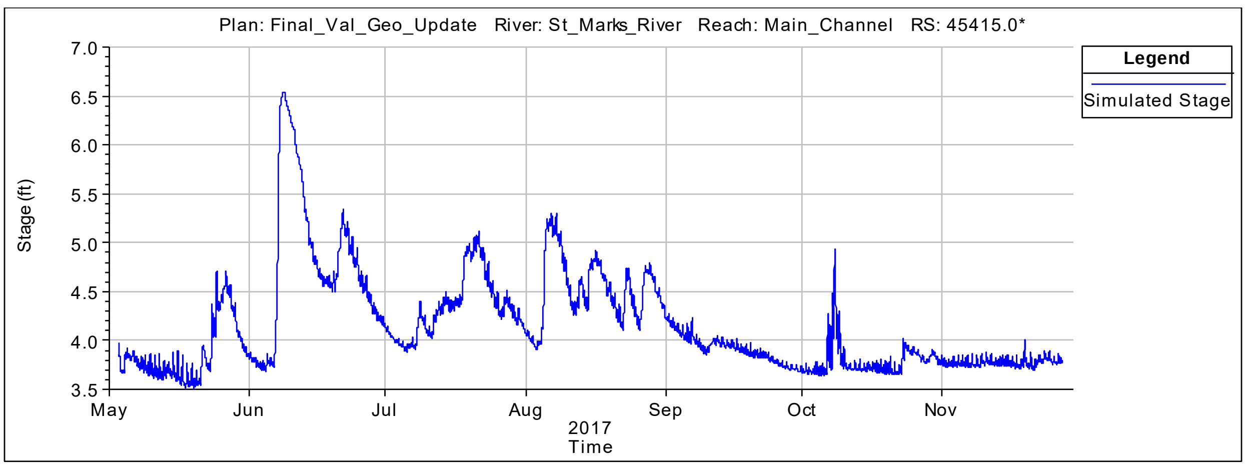
Table 5. Summary Statistics of Model Performance – St. Marks River/Wakulla River HEC-RAS Model

River	Station	Statistics	Mean (ft-NAVD88)	Max (ft-NAVD88)	Min (ft-NAVD88)	R2	RMSE	PBIAS	RSR
St. Marks River	2326900	Obs	9.33	10.95	8.84	0.849	0.228	0.334	0.534
		Sim	9.36	10.9	8.82				
		Diff	-0.03	0.05	0.02				
	HD1	Obs	0.87	4.88	-6.77	0.992	0.191	-4.472	0.154
		Sim	0.81	4.74	-4.8				
		Diff	0.06	0.14	-1.97				
Wakulla River	2327022	Obs	2.93	4.78	1.5	0.940	0.253	1.655	0.495
		Sim	2.98	4.61	0.95				
		Diff	-0.05	0.17	0.55				
	HD2	Obs	1.06	4.71	-3.27*	0.992	0.154	-7.675	0.152
		Sim	0.98	4.48	-4.32				
		Diff	0.08	0.23					
Confluence	HD3	Obs	0.57	4.56	-3.13*	0.997	0.088	1.029	0.076
		Sim	0.55	4.68	-6.76				
		Diff	0.03	-0.12					

*Gage appeared to bottom out during Hurricane Irma

Figure 35. Comparison of Simulated Water Levels at Shoal T5 Following Incorporation of Additional Cross-Sections





9.0 STEADY-STATE MODEL AND PREDICTIVE SIMULATIONS

After model calibration in unsteady state, the steady-state model was developed. The steady-state model was utilized for predictive simulations and for use in the evaluation of water resource values for determination of minimum flows for the St. Marks River Rise.

9.1 STEADY-STATE MODEL DEVELOPMENT

Changes to the boundary conditions of the calibrated unsteady model were made to develop a steady-state model. A steady-state model requires a known discharge value at every flow change location. Where point inflows are present, the flow is entered at the appropriate location, in this case, the HEC-RAS cross-section. Because the unsteady model had regions of uniform lateral flow (no point inflows), this required developing a flow regime where discharge values were defined at multiple locations along the reach to approximate the uniform inflows along this reach. Unlike the transient model, which adds flows as part of its calculation, thus maintaining a mass balance, the steady-state model requires that flows are defined in a cumulative fashion moving downstream. For example, the flow at USGS 02326900, St. Marks River near Newport is specified at the top of the model (Station 59771.9). The increase in flow estimated as the lateral ungaged flow in St. Marks River was calculated as a flow per reach length. This was added to the USGS 02326900 flow at discrete locations shown in Table 5. Predictive simulations were run for every 2nd incremental percentile flow, from the 2nd percentile through the 98th percentile, including every 5th percentile and the 1st and 99th percentiles. For summary purposes, Table 6 provides steady-state input percentile flows at every flow change location for every 5th percentile. Steady-state HEC-RAS input 10th percentile flow refers to the low flow or the flow that is exceeded 90 percent of the time.

To run predictive simulations, downstream stage boundary conditions are needed. The stage time series from monitoring location HD-4 for the period May 13, 2017 to July 20, 2017 was utilized to develop a probability distribution of stage at the downstream boundary (Figure 36).

Table 6. Steady-State Input Flow Percentiles at the Flow Change Locations: St. Marks River/Wakulla River

Station	Reach									Flow Percentile										
	St. Marks River	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
59771.9		376	403	421	445	475	504	530	560	585	611	635	659	690	730	784	845	916	1050	1300
54705.12		387	415	433	458	489	519	546	576	602	629	654	678	710	751	807	870	943	1081	1338
48270.32		401	430	449	475	507	537	565	597	624	652	677	703	736	778	836	901	977	1120	1386
42291.17		414	444	463	490	523	555	583	617	644	673	699	726	760	804	863	930	1008	1156	1431
36607.3		426	457	477	505	539	571	601	635	663	693	720	747	782	828	889	958	1038	1190	1474
30277.45		440	472	493	521	556	590	620	655	685	715	743	771	807	854	917	989	1072	1229	1521
26037.71		449	481	503	532	568	602	633	669	699	730	759	787	824	872	937	1010	1094	1254	1553
20240.78		462	495	517	547	583	619	651	688	718	750	780	809	847	897	963	1038	1125	1290	1597
14427.07		474	508	531	561	599	636	669	707	738	771	801	832	871	921	989	1066	1156	1325	1640
10215.43		484	518	541	572	611	648	682	720	752	786	817	848	887	939	1008	1087	1178	1350	1672
5936.17		493	528	552	583	623	661	695	734	767	801	832	864	904	957	1028	1108	1201	1376	1704
	Wakulla River																			
48252.78		137	173	210	251	286	322	354	390	427	468	511	551	587	622	645	667	695	740	801
32526.33		197	237	280	323	357	391	418	453	492	529	575	617	650	685	729	773	826	887	997
	Confluence																			
10562.5		690	765	832	906	980	1052	1113	1187	1259	1330	1407	1481	1554	1642	1757	1881	2027	2263	2701

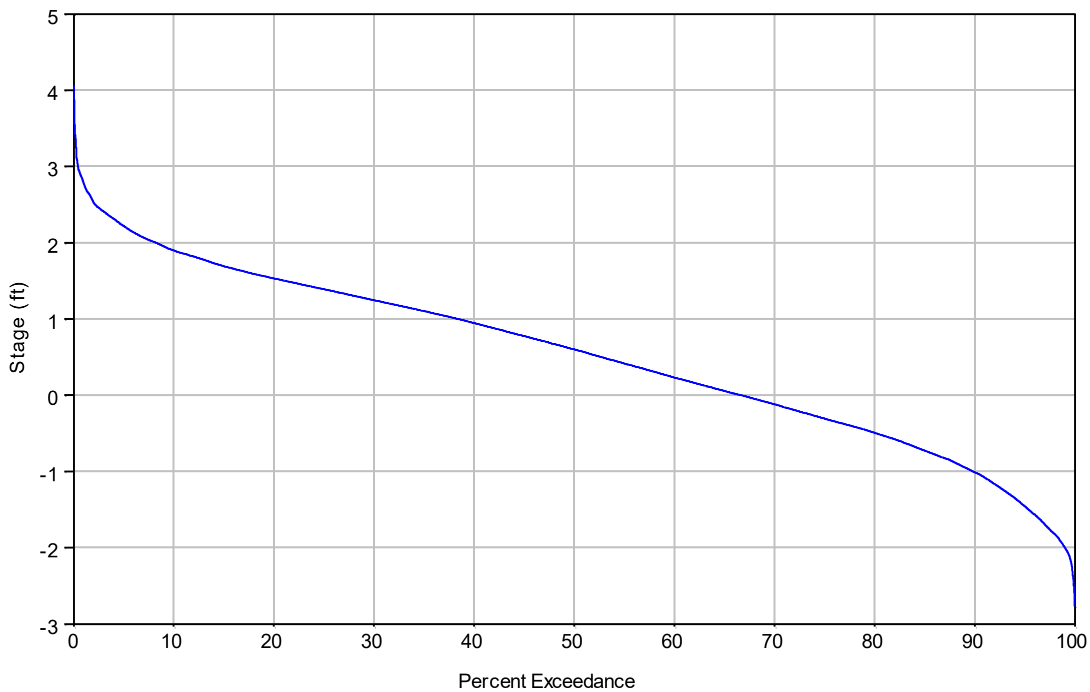


Figure 36. Probability of Exceedance – Downstream Boundary Stage,.
Station HD4 - Period of Record May 13, 2017 to July 20, 2017

Scenarios were evaluated under a low, mean and high tide condition. The mean tide elevation for the period of record is 0.52 NAVD. Based on the limited period of data at HD-4 and the probability distribution in Figure 36, the following elevations were used to represent the three tide conditions used for the downstream boundary condition (rounded to the nearest 0.1 foot):

Low Tide	-2.0 ft-NAVD (99 percent exceedance probability)
Mean Tide	0.5 ft-NAVD
High Tide	2.5 ft-NAVD (2 percent exceedance probability)

9.2 STEADY-STATE MODEL RESULTS

Each of the 2nd and 5th percentile flows and the 1st and 99th percentile flows for low, mean and high tide downstream boundary stage condition was run in the constructed steady-state HEC-RAS model. The resulting HEC-RAS simulated stages in the St. Marks River for every 10th percentile flow (Table 6) and each boundary condition (low tide, mean tide, and high tide) are shown in Tables 7 through 9. The resulting water surface profiles for the St. Marks River are shown in Figures 37 through 39.

The results indicate that changes in stage at many locations below the shoals are tidally driven and insensitive to changes in river or spring flow. Table 10 compares the fluctuation in stage at each ecological transect due to river flow versus tide. The fluctuations in stage between low (P10) and high (P90) river flows are compared to the fluctuations in stage at the same locations due to high and low tide. River stage above the shoals is largely driven by river flow, whereas stage below the shoals is largely driven by tide. This has implications regarding the mechanisms influencing floodplain inundation. Below the shoals, model results indicate that inundation is insensitive to changes in river flow, and less so to spring flow, which is component of the river flow.

9.3 EVALUATION OF SEA-LEVEL RISE

Additional scenario runs were performed to evaluate the effect of sea-level rise on predicted water levels in the St. Marks River. Per discussions with District staff, the sea-level rise condition that was evaluated was a sea level rise of 2.82 inches total by 2038. This is the average of Apalachicola and Cedar Key medium projections from 2018-2038. The downstream boundary condition in the steady-state HEC-RAS model was adjusted up 2.82 inches for the low, mean and high tide conditions. The results of these runs indicate that the effect of a sea-level rise of this magnitude is largely confined to the river reach below the St. Marks River shoals within the area of the model domain where tidal effects predominate.

9.4 DISCUSSION OF MODEL UNCERTAINTY

Following data evaluation, model construction, calibration and testing activities, it is concluded that there are two primary areas of uncertainty that affect model predictions of water level in the St. Marks River. The first area is related to the estimate of lateral flow contributions along the entire St. Marks River reach. The estimate of lateral inflows is based on a limited number of tidal flux measurements. Because of the limited number of measurements, a simple linear relationship between flow as measured at USGS gage 02326900 (St. Marks River near Newport) was developed to account for the additional flow contributions and was applied evenly along the entire river reach. Review of data and site reconnaissance indicate both groundwater and surficial flow contributions exist. Additional flow measurements along the river reach would provide a better definition of the relationship of lateral inflows to the long-term flow record at USGS gage 02326900 and the distribution of these lateral inflows along the river reach. While lateral inflows appear to occur along the entire river reach, their effect is more important in the river reach at the shoals and upstream where stages are primarily driven by spring flow. While the model developed utilizes the best available information, better definition of lateral inflows would increase confidence in model predictions of water levels in future MFL evaluations.

The second area of uncertainty is related to the shifting flow-stage relationship in the upper St. Marks River near the USGS gage 02326900 and the St. Marks River Rise. The patterns of vegetative growth, death and decay require the USGS to make frequent shifts in the flow-stage rating curve to account for this phenomenon. Preliminary evaluation of the data does not reveal a systematic, or seasonal pattern of "shifts". Further evaluation of these shifts, likely through the implementation of signal processing techniques, should be performed to identify whether there are regular, or even seasonal patterns of ratings shifts as the result of vegetative growth and death. If such patterns are found, the HEC-RAS model can be set-up to account for this in future MFL evaluations. Also, additional reconnaissance in the upper St. Marks River reach should be performed to identify whether there are additional shallow areas and areas of channel constrictions which could act as control points for flow. The incorporation of additional survey for these locations would improve the representation of the physical area in the model's geometry. Currently, a sill, in the form of a channel obstruction has been incorporated into the upper St. Marks River reach to allow the HEC-RAS model to replicate the hydraulic response observed in the USGS data. The incorporation of the sill is supported by field observations (Light et al. 1993).

The vegetative growth patterns and available channel survey in the upper reach contribute to uncertainty in the model's predictions for water levels. This phenomenon has been occurring for many years. Consequently, the ecosystem in the upper St. Marks River has adapted to this shifting and has developed natural resiliency to the shifting flow-stage relationship. This resiliency helps to mitigate the uncertainty contained in the model's prediction of water level in this area. While the recommendations provided may improve future modeling efforts, the current model developed utilizes the best available information.

Table 7. Simulated Stages: St. Marks River - Low Tide Boundary Stage, ft-NAVD88

River	Flow Percentile										
Station	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
59771.90	8.41	9.01	9.32	9.66	9.86	10.04	10.19	10.40	10.70	11.16	12.99
58193.34	7.96	8.43	8.68	8.96	9.14	9.31	9.44	9.63	9.89	10.30	12.10
56887.29	6.98	7.34	7.52	7.75	7.96	8.14	8.30	8.50	8.82	9.31	11.47
55840.70	5.69	6.04	6.24	6.51	6.75	6.97	7.16	7.42	7.82	8.46	10.94
54705.12	5.18	5.52	5.72	5.97	6.20	6.41	6.59	6.85	7.26	7.90	10.43
53367.25	4.69	5.02	5.21	5.45	5.68	5.88	6.07	6.33	6.73	7.39	9.94
52288.39	4.21	4.53	4.71	4.95	5.18	5.38	5.56	5.82	6.22	6.89	9.47
50799.28	3.63	3.95	4.12	4.34	4.57	4.77	4.95	5.21	5.61	6.28	8.85
49447.46	3.38	3.69	3.86	4.07	4.29	4.49	4.67	4.93	5.33	6.00	8.54
48270.32	3.24	3.54	3.70	3.90	4.12	4.31	4.49	4.75	5.15	5.81	8.35
47237.02	3.13	3.41	3.56	3.76	3.97	4.16	4.34	4.59	4.99	5.65	8.17
45815.00	3.00	3.26	3.40	3.58	3.78	3.97	4.14	4.39	4.78	5.45	7.96
45615	2.96	3.22	3.36	3.53	3.73	3.92	4.09	4.34	4.73	5.39	7.91
45415.0*	2.89	3.13	3.26	3.42	3.62	3.80	3.97	4.21	4.60	5.26	7.81
44915	2.76	2.98	3.10	3.24	3.43	3.61	3.77	4.02	4.40	5.08	7.67
44415.0*	1.89	2.04	2.11	2.41	2.72	2.97	3.19	3.50	3.96	4.72	7.49
44179.97	1.48	1.91	2.15	2.46	2.73	2.97	3.18	3.48	3.94	4.70	7.46
43959.9*	1.44	1.87	2.11	2.42	2.69	2.93	3.14	3.44	3.90	4.66	7.42
43299.9*	1.32	1.74	1.98	2.29	2.56	2.79	3.00	3.30	3.75	4.51	7.29
43000.41	1.27	1.69	1.93	2.24	2.51	2.75	2.96	3.26	3.71	4.47	7.25
42291.17	1.13	1.55	1.79	2.10	2.38	2.61	2.82	3.12	3.58	4.34	7.12
41309.35	0.94	1.36	1.60	1.91	2.19	2.42	2.64	2.94	3.39	4.16	6.93
40227.42	0.74	1.16	1.39	1.70	1.98	2.21	2.43	2.73	3.19	3.95	6.71
38905.38	0.49	0.90	1.13	1.44	1.71	1.95	2.16	2.47	2.92	3.68	6.41
38126.37	0.35	0.75	0.98	1.28	1.55	1.79	2.01	2.31	2.76	3.52	6.25
37716.3*	0.16	0.55	0.78	1.08	1.35	1.59	1.80	2.11	2.55	3.31	6.05
36607.30	-0.35	0.03	0.25	0.54	0.80	1.04	1.25	1.55	1.99	2.75	5.59
35931.05	-0.51	-0.15	0.06	0.35	0.61	0.84	1.05	1.35	1.77	2.54	5.38
34537.69	-0.76	-0.43	-0.22	0.05	0.29	0.51	0.71	1.01	1.43	2.20	5.02
33577.64	-0.89	-0.57	-0.38	-0.12	0.11	0.33	0.52	0.81	1.23	1.99	4.79
32250.72	-1.13	-0.86	-0.69	-0.45	-0.24	-0.04	0.14	0.41	0.81	1.58	4.32
31335.85	-1.34	-1.11	-0.96	-0.75	-0.57	-0.39	-0.23	0.02	0.40	1.18	3.84
30277.45	-1.46	-1.27	-1.15	-0.96	-0.79	-0.63	-0.48	-0.25	0.10	0.88	3.50
28547.65	-1.66	-1.53	-1.44	-1.31	-1.19	-1.07	-0.95	-0.78	-0.49	0.26	2.56
27433.28	-1.74	-1.64	-1.58	-1.48	-1.39	-1.29	-1.20	-1.06	-0.83	-0.30	1.81
26037.71	-1.82	-1.75	-1.71	-1.64	-1.57	-1.50	-1.44	-1.33	-1.15	-0.81	1.26
25274.12	-1.86	-1.82	-1.79	-1.74	-1.69	-1.64	-1.59	-1.51	-1.38	-1.11	0.75
25154.80	-1.87	-1.83	-1.80	-1.76	-1.71	-1.66	-1.62	-1.54	-1.42	-1.16	0.56
25078.48	-1.91	-1.87	-1.84	-1.80	-1.76	-1.71	-1.67	-1.60	-1.47	-1.23	0.46
24837.1*	-1.93	-1.89	-1.87	-1.83	-1.79	-1.75	-1.71	-1.65	-1.54	-1.31	0.29
24595.75	-1.94	-1.91	-1.89	-1.86	-1.83	-1.79	-1.76	-1.71	-1.62	-1.43	-0.04
24105.62	-1.94	-1.91	-1.89	-1.85	-1.82	-1.79	-1.75	-1.70	-1.60	-1.41	-0.09
22436.5	-1.94	-1.92	-1.90	-1.87	-1.84	-1.81	-1.77	-1.73	-1.64	-1.46	-0.26
20240.78	-1.95	-1.93	-1.91	-1.89	-1.86	-1.84	-1.81	-1.77	-1.70	-1.55	-0.48
18845.06	-1.96	-1.94	-1.92	-1.90	-1.88	-1.85	-1.83	-1.79	-1.72	-1.58	-0.58
16060.69	-1.97	-1.95	-1.94	-1.92	-1.90	-1.88	-1.86	-1.83	-1.77	-1.66	-0.79
14427.07	-1.97	-1.96	-1.95	-1.93	-1.91	-1.90	-1.88	-1.85	-1.80	-1.70	-0.94
11898.49	-1.98	-1.97	-1.97	-1.96	-1.95	-1.94	-1.93	-1.91	-1.88	-1.82	-1.33
10215.43	-1.99	-1.98	-1.98	-1.97	-1.96	-1.96	-1.95	-1.94	-1.92	-1.87	-1.54
5936.172	-1.99	-1.99	-1.98	-1.98	-1.97	-1.96	-1.96	-1.95	-1.93	-1.89	-1.61
3011.349	-1.99	-1.99	-1.99	-1.98	-1.98	-1.97	-1.97	-1.96	-1.95	-1.92	-1.72
529.9650	-2.00	-1.99	-1.99	-1.99	-1.99	-1.98	-1.98	-1.97	-1.96	-1.95	-1.82

Table 8. Simulated Stages: St. Marks River - Mean Tide Boundary Stage, ft-NAVD88

River	Flow Percentile										
Station	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
59771.90	8.41	9.01	9.32	9.66	9.86	10.04	10.19	10.40	10.70	11.17	13.00
58193.34	7.96	8.43	8.68	8.96	9.14	9.31	9.44	9.63	9.89	10.30	12.10
56887.29	6.98	7.34	7.52	7.75	7.96	8.14	8.30	8.51	8.82	9.32	11.47
55840.70	5.69	6.04	6.24	6.51	6.76	6.98	7.17	7.43	7.84	8.48	10.95
54705.12	5.18	5.52	5.72	5.98	6.21	6.42	6.61	6.87	7.28	7.92	10.44
53367.25	4.69	5.02	5.21	5.47	5.70	5.91	6.09	6.35	6.76	7.42	9.95
52288.39	4.21	4.53	4.72	4.97	5.20	5.41	5.59	5.85	6.26	6.93	9.49
50799.28	3.63	3.95	4.13	4.38	4.61	4.82	5.00	5.27	5.68	6.34	8.87
49447.46	3.38	3.69	3.87	4.12	4.35	4.55	4.74	5.00	5.41	6.07	8.57
48270.32	3.24	3.54	3.71	3.96	4.19	4.39	4.57	4.83	5.23	5.89	8.37
47237.02	3.13	3.41	3.58	3.82	4.05	4.24	4.42	4.68	5.08	5.74	8.20
45815.00	3.00	3.26	3.43	3.66	3.87	4.07	4.24	4.50	4.90	5.55	8.00
45615	2.96	3.22	3.38	3.61	3.83	4.02	4.19	4.45	4.84	5.49	7.94
45415.0*	2.89	3.13	3.29	3.51	3.72	3.91	4.08	4.33	4.72	5.37	7.85
44915	2.76	2.98	3.13	3.34	3.55	3.74	3.91	4.16	4.55	5.20	7.72
44415.0*	1.89	2.24	2.48	2.77	3.02	3.25	3.45	3.74	4.18	4.90	7.54
44179.97	1.94	2.30	2.50	2.77	3.02	3.24	3.44	3.72	4.16	4.87	7.51
43959.9*	1.92	2.28	2.47	2.74	2.99	3.20	3.40	3.69	4.12	4.83	7.47
43299.9*	1.84	2.18	2.38	2.64	2.88	3.09	3.29	3.57	4.00	4.70	7.34
43000.41	1.81	2.15	2.34	2.60	2.84	3.06	3.25	3.53	3.97	4.67	7.30
42291.17	1.72	2.06	2.24	2.50	2.74	2.95	3.14	3.42	3.85	4.55	7.18
41309.35	1.61	1.93	2.12	2.36	2.60	2.80	2.99	3.27	3.69	4.39	7.00
40227.42	1.50	1.81	1.98	2.22	2.45	2.65	2.83	3.10	3.52	4.20	6.78
38905.38	1.37	1.65	1.82	2.05	2.26	2.46	2.64	2.90	3.31	3.97	6.49
38126.37	1.31	1.57	1.73	1.95	2.16	2.35	2.52	2.78	3.18	3.84	6.33
37716.3*	1.22	1.47	1.62	1.83	2.03	2.21	2.38	2.63	3.02	3.66	6.15
36607.30	1.05	1.25	1.37	1.55	1.72	1.88	2.03	2.25	2.61	3.22	5.71
35931.05	0.99	1.17	1.29	1.45	1.61	1.76	1.91	2.12	2.47	3.06	5.52
34537.69	0.91	1.07	1.17	1.31	1.46	1.59	1.73	1.92	2.25	2.81	5.18
33577.64	0.87	1.01	1.10	1.24	1.37	1.50	1.62	1.81	2.12	2.66	4.96
32250.72	0.80	0.92	0.99	1.10	1.22	1.33	1.44	1.61	1.89	2.38	4.52
31335.85	0.74	0.84	0.90	0.99	1.09	1.18	1.28	1.43	1.68	2.13	4.09
30277.45	0.71	0.79	0.84	0.92	1.00	1.09	1.17	1.31	1.54	1.95	3.79
28547.65	0.64	0.70	0.73	0.79	0.84	0.90	0.96	1.05	1.21	1.50	3.01
27433.28	0.61	0.65	0.68	0.72	0.76	0.80	0.84	0.90	1.02	1.24	2.53
26037.71	0.59	0.62	0.64	0.67	0.70	0.73	0.76	0.81	0.90	1.08	2.19
25274.12	0.57	0.60	0.61	0.63	0.66	0.68	0.71	0.74	0.82	0.96	1.92
25154.80	0.57	0.59	0.60	0.62	0.65	0.67	0.69	0.72	0.79	0.92	1.83
25078.48	0.54	0.56	0.57	0.59	0.61	0.63	0.66	0.69	0.75	0.88	1.76
24837.1*	0.54	0.55	0.56	0.58	0.60	0.62	0.64	0.67	0.73	0.84	1.67
24595.75	0.53	0.55	0.56	0.57	0.59	0.61	0.62	0.65	0.70	0.80	1.56
24105.62	0.53	0.54	0.55	0.57	0.58	0.60	0.62	0.64	0.69	0.79	1.52
22436.5	0.53	0.54	0.55	0.56	0.57	0.59	0.60	0.63	0.67	0.75	1.42
20240.78	0.52	0.53	0.54	0.55	0.56	0.58	0.59	0.61	0.65	0.72	1.32
18845.06	0.52	0.53	0.54	0.55	0.56	0.57	0.58	0.60	0.64	0.71	1.27
16060.69	0.52	0.53	0.53	0.54	0.55	0.56	0.57	0.59	0.62	0.68	1.16
14427.07	0.51	0.52	0.53	0.54	0.54	0.55	0.56	0.58	0.60	0.65	1.08
11898.49	0.51	0.51	0.52	0.52	0.53	0.53	0.54	0.54	0.56	0.59	0.84
10215.43	0.51	0.51	0.51	0.51	0.52	0.52	0.52	0.53	0.54	0.56	0.72
5936.172	0.50	0.51	0.51	0.51	0.51	0.52	0.52	0.52	0.53	0.55	0.68
3011.349	0.50	0.50	0.51	0.51	0.51	0.51	0.51	0.52	0.52	0.53	0.63
529.9650	0.50	0.50	0.50	0.50	0.51	0.51	0.51	0.51	0.52	0.52	0.58

Table 9. Simulated Stages: St. Marks River - High Tide Boundary Stage, ft-NAVD88

River	Flow Percentile										
Station	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
59771.90	8.41	9.01	9.32	9.66	9.86	10.04	10.19	10.40	10.70	11.17	13.00
58193.34	7.96	8.43	8.68	8.96	9.15	9.31	9.45	9.63	9.90	10.30	12.11
56887.29	6.98	7.35	7.53	7.76	7.97	8.15	8.31	8.52	8.84	9.34	11.49
55840.70	5.71	6.07	6.28	6.55	6.80	7.01	7.21	7.47	7.87	8.51	10.97
54705.12	5.22	5.57	5.77	6.04	6.27	6.48	6.67	6.93	7.33	7.98	10.47
53367.25	4.76	5.11	5.30	5.56	5.79	5.99	6.18	6.44	6.84	7.49	9.99
52288.39	4.33	4.67	4.86	5.11	5.34	5.54	5.72	5.98	6.38	7.03	9.54
50799.28	3.87	4.19	4.37	4.61	4.83	5.03	5.21	5.46	5.85	6.48	8.94
49447.46	3.69	3.99	4.17	4.40	4.62	4.81	4.98	5.23	5.61	6.23	8.65
48270.32	3.59	3.88	4.05	4.27	4.49	4.67	4.84	5.08	5.46	6.07	8.46
47237.02	3.51	3.79	3.95	4.17	4.38	4.56	4.73	4.96	5.33	5.93	8.29
45815.00	3.42	3.68	3.84	4.05	4.24	4.42	4.58	4.81	5.17	5.77	8.10
45615	3.40	3.66	3.81	4.01	4.21	4.38	4.54	4.77	5.13	5.72	8.05
45415.0*	3.35	3.59	3.74	3.94	4.13	4.30	4.45	4.68	5.03	5.62	7.96
44915	3.27	3.50	3.64	3.83	4.01	4.18	4.33	4.55	4.89	5.48	7.84
44415.0*	3.06	3.27	3.39	3.58	3.75	3.91	4.07	4.29	4.64	5.24	7.67
44179.97	3.06	3.26	3.39	3.57	3.74	3.90	4.05	4.27	4.62	5.22	7.64
43959.9*	3.05	3.25	3.37	3.55	3.72	3.88	4.03	4.25	4.60	5.19	7.61
43299.9*	3.01	3.20	3.32	3.49	3.66	3.81	3.95	4.16	4.50	5.08	7.49
43000.41	3.00	3.19	3.30	3.47	3.64	3.79	3.93	4.14	4.48	5.06	7.45
42291.17	2.97	3.15	3.26	3.42	3.58	3.72	3.86	4.06	4.39	4.96	7.34
41309.35	2.93	3.09	3.20	3.35	3.50	3.64	3.77	3.96	4.28	4.83	7.17
40227.42	2.89	3.04	3.13	3.27	3.41	3.55	3.67	3.85	4.15	4.68	6.97
38905.38	2.84	2.98	3.06	3.19	3.32	3.44	3.55	3.72	4.01	4.50	6.70
38126.37	2.82	2.94	3.02	3.14	3.26	3.38	3.49	3.65	3.92	4.40	6.56
37716.3*	2.79	2.90	2.98	3.09	3.20	3.30	3.41	3.56	3.81	4.27	6.40
36607.30	2.73	2.81	2.87	2.96	3.05	3.14	3.23	3.36	3.58	3.98	6.02
35931.05	2.71	2.79	2.84	2.92	3.00	3.09	3.16	3.28	3.49	3.88	5.86
34537.69	2.68	2.75	2.79	2.86	2.93	3.01	3.07	3.18	3.36	3.71	5.56
33577.64	2.66	2.72	2.77	2.83	2.90	2.96	3.02	3.12	3.29	3.62	5.38
32250.72	2.64	2.69	2.72	2.77	2.83	2.88	2.93	3.02	3.16	3.44	5.02
31335.85	2.61	2.66	2.68	2.73	2.77	2.82	2.86	2.93	3.05	3.28	4.68
30277.45	2.60	2.64	2.66	2.70	2.74	2.78	2.81	2.87	2.98	3.18	4.46
28547.65	2.57	2.59	2.61	2.63	2.65	2.68	2.70	2.74	2.81	2.95	3.94
27433.28	2.56	2.57	2.59	2.60	2.62	2.64	2.66	2.69	2.74	2.85	3.72
26037.71	2.55	2.56	2.57	2.59	2.60	2.62	2.63	2.65	2.70	2.78	3.56
25274.12	2.55	2.56	2.56	2.57	2.59	2.60	2.61	2.63	2.66	2.74	3.33
25154.80	2.54	2.55	2.56	2.57	2.58	2.59	2.61	2.62	2.65	2.72	3.26
25078.48	2.52	2.53	2.54	2.55	2.56	2.57	2.58	2.60	2.63	2.70	3.22
24837.1*	2.52	2.53	2.53	2.54	2.55	2.56	2.57	2.59	2.62	2.68	3.17
24595.75	2.52	2.52	2.53	2.54	2.55	2.56	2.57	2.58	2.61	2.67	3.12
24105.62	2.52	2.52	2.53	2.54	2.55	2.56	2.56	2.58	2.61	2.66	3.10
22436.5	2.51	2.52	2.53	2.53	2.54	2.55	2.56	2.57	2.60	2.65	3.06
20240.78	2.51	2.52	2.52	2.53	2.54	2.55	2.55	2.56	2.59	2.63	3.00
18845.06	2.51	2.52	2.52	2.53	2.54	2.54	2.55	2.56	2.58	2.62	2.97
16060.69	2.51	2.52	2.52	2.52	2.53	2.54	2.54	2.55	2.57	2.61	2.91
14427.07	2.51	2.51	2.52	2.52	2.53	2.53	2.54	2.55	2.56	2.60	2.87
11898.49	2.50	2.51	2.51	2.51	2.52	2.52	2.52	2.53	2.54	2.55	2.71
10215.43	2.50	2.50	2.51	2.51	2.51	2.51	2.51	2.52	2.52	2.54	2.63
5936.172	2.50	2.50	2.50	2.51	2.51	2.51	2.51	2.51	2.52	2.53	2.61
3011.349	2.50	2.50	2.50	2.50	2.51	2.51	2.51	2.51	2.51	2.52	2.57
529.9650	2.50	2.50	2.50	2.50	2.50	2.50	2.51	2.51	2.51	2.51	2.55

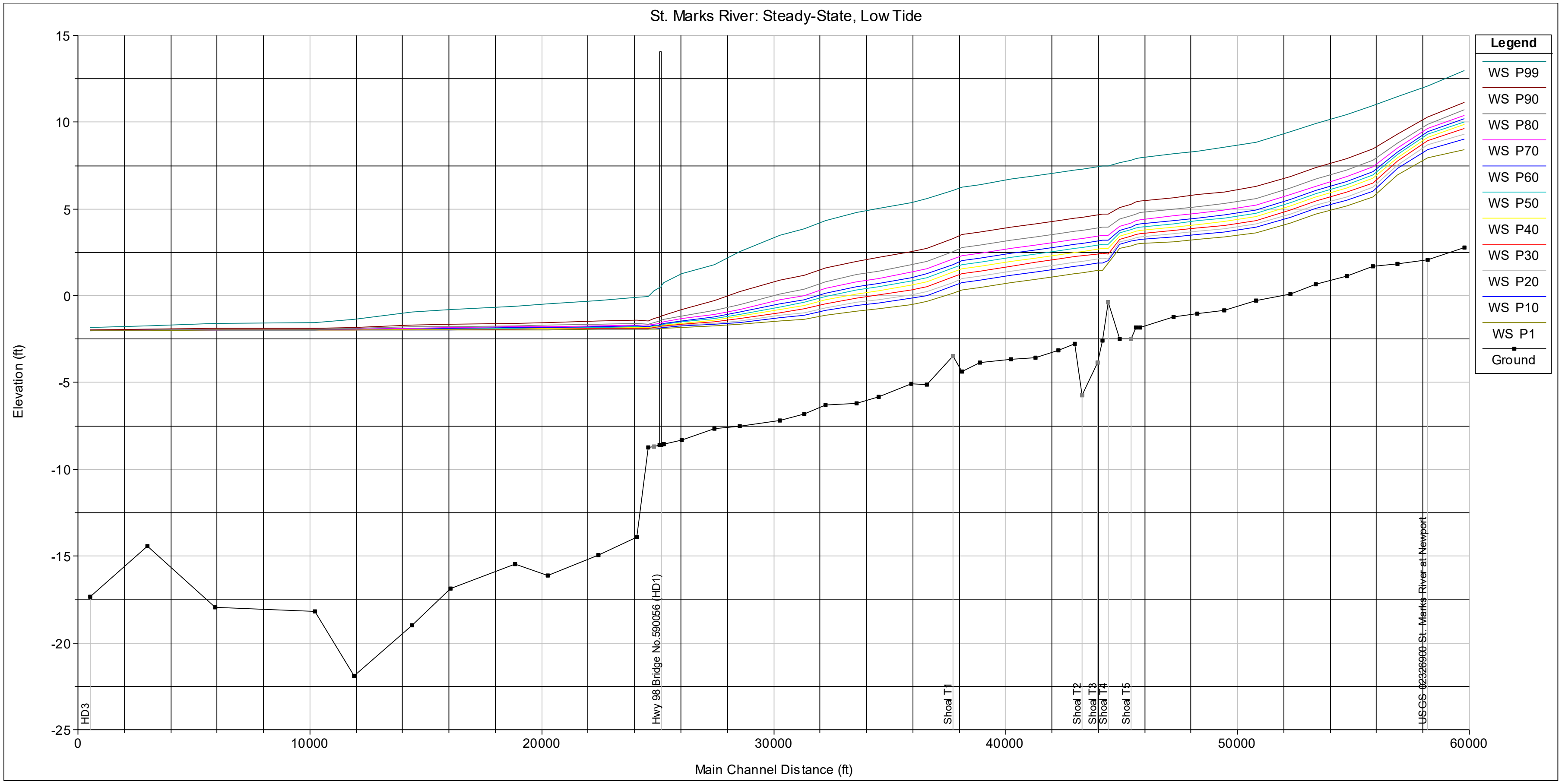


Figure 37. Water Surface Profile: St. Marks River - Low Tide Boundary Stage

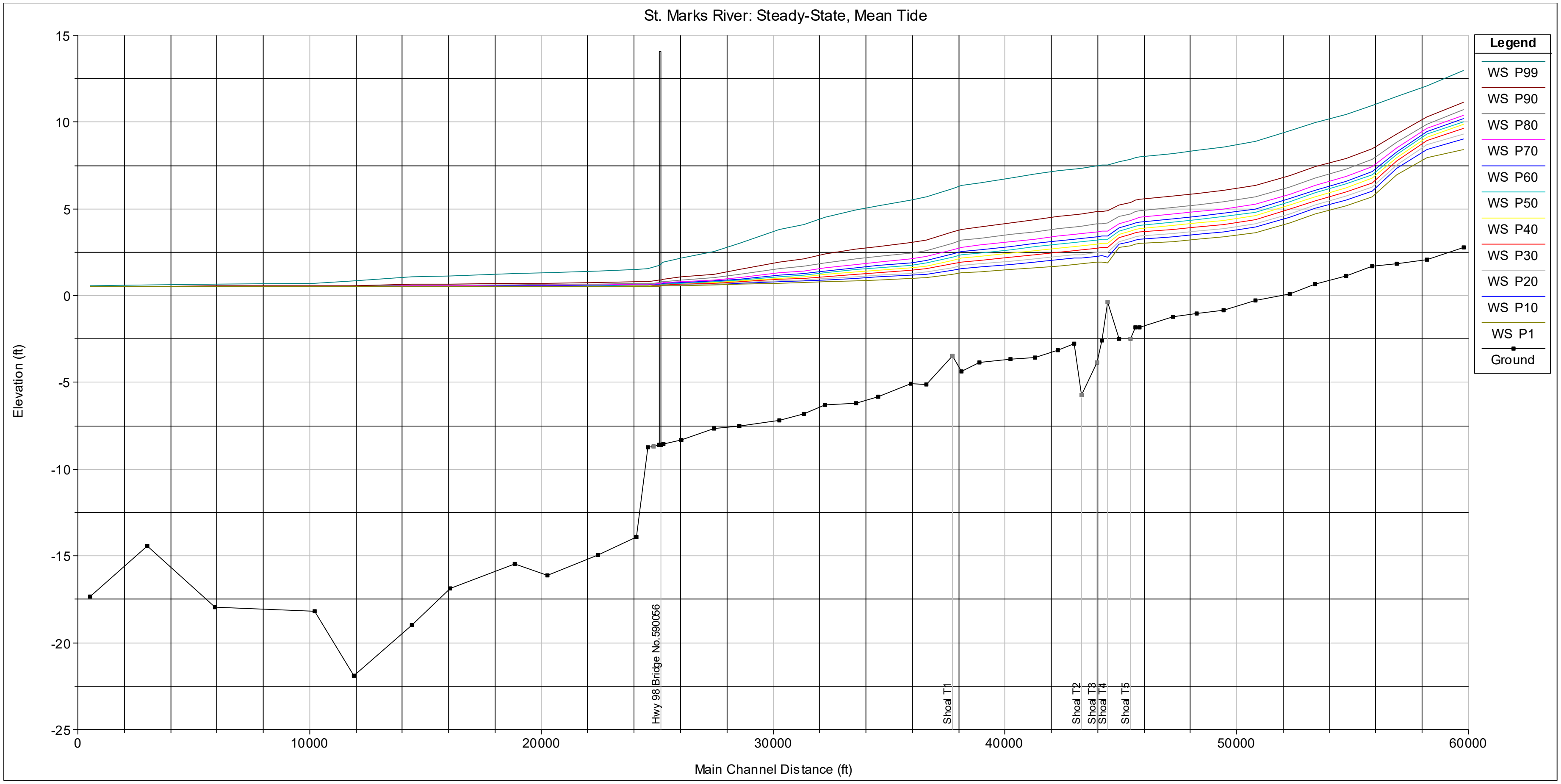


Figure 38. Water Surface Profile: St. Marks River - Mean Tide Boundary Stage

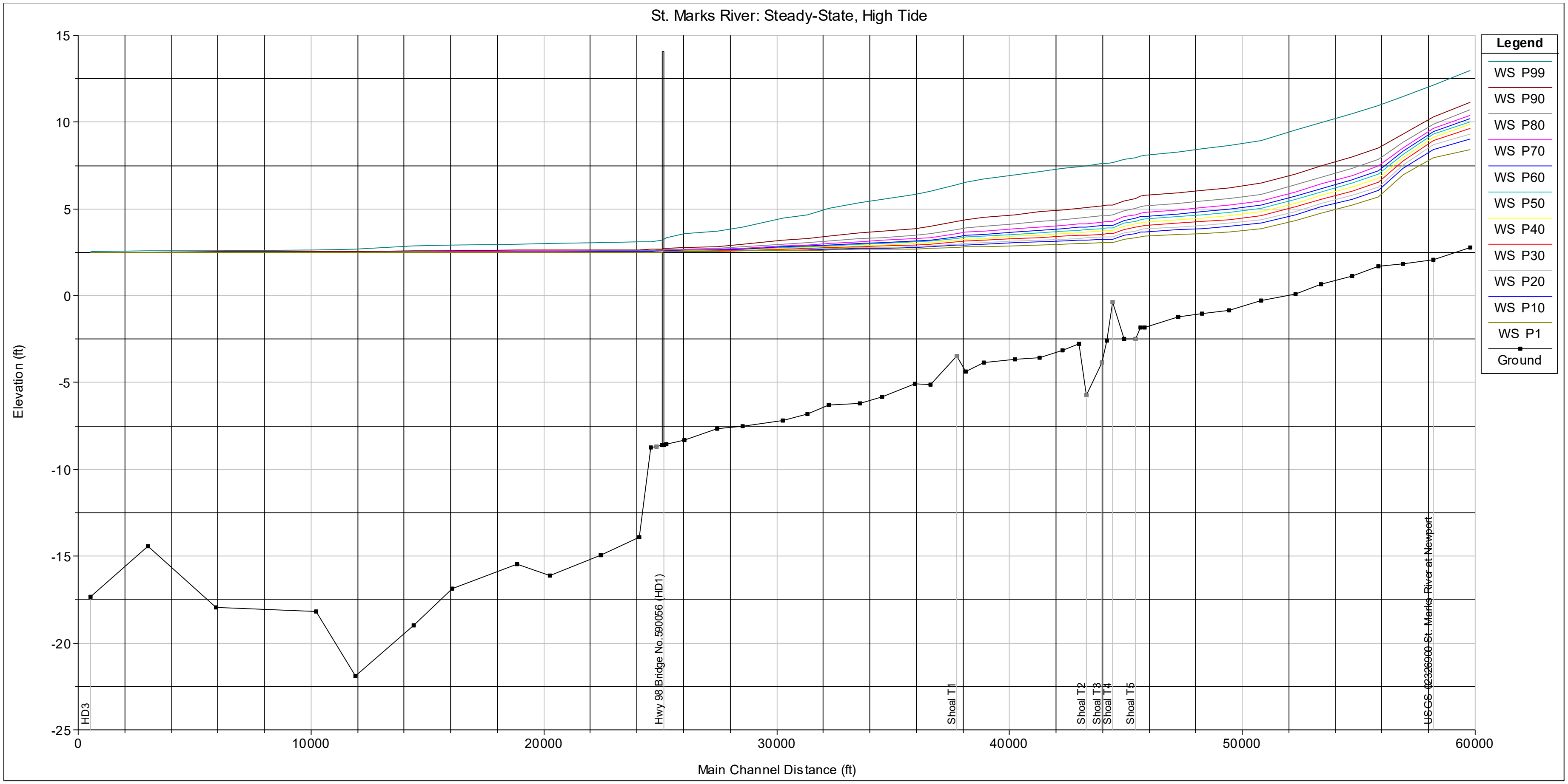


Figure 39. Water Surface Profile: St. Marks River - High Tide Boundary Stage

Table 10. Sensitivity of St. Marks River Stage to Changes in Flow and Tidal Conditions

Ecological Transect ID	Location	Nearest HEC-RAS River Station	Difference in Stage Between P10 and P90 River Flows (feet)	Difference in Stage Between High and Low Tide (feet)
SM1	Above shoals	59771.90	2.01	0.00
SM2	Above shoals	58193.34	1.72	0.00
SM3	Above shoals	53367.25	2.35-2.38	0.07-0.10
SM4	Above shoals	45815.00	2.04-2.10	0.31-0.37
SM5	At Shoals	43000.41	1.86-2.78	0.58-1.5
SM6	At Shoals	38905.38	1.52-2.78	0.82-2.08
SM7	Below shoals	28547.65	0.35-1.77	2.7-4.12
SM8	Below shoals	22436.50	0.13-0.46	4.11-4.44
SM9	Below shoals	20241.00	0.11-0.38	4.18-4.45
SM10	Below shoals	16060.69	0.09-0.29	4.27-4.47
SM11	Below shoals	14427.07	0.09-0.26	4.3-4.47

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