UPDATE AND CALIBRATION OF THE HYDROLOGIC ENGINEERING CENTER RIVER ANALYSIS SYSTEM (HEC-RAS) MODEL

WAKULLA RIVER SYSTEM

NORTHWEST FLORIDA WATER MANAGEMENT DISTRICT
81 WATER MANAGEMENT DRIVE
HAVANA, FLORIDA 32333-4712

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LIST OF ACRONYMS AND ABBREVIATIONS

ADCP	acoustic Doppler current profiler
ATM	Applied Technology and Management, Inc.
cfs	cubic feet per second
cfs/ft	cubic feet per second per foot of reach length
cm	centimeter
CO-OPS	Center for Operational Oceanographic Products and Services
CRISPS	Collaborative Research Initiative on Sustainability and Protection of Springs
ECT	Environmental Consulting & Technology, Inc.
ft	foot
ft-NAVD88	North American Vertical Datum of 1988
GIS	geographic information system
HD	Hydrodynamic Station
HEC-DSS	Hydrologic Engineering Centers Data Storage System
HEC-RAS	Hydrologic Engineering Centers River Analysis System
LiDAR	light detection and ranging
MDH	mean daily high
MDHW	mean daily high for the winter months November – March
MFLs	Minimum Flows and Levels
MFLs	minimum flows and levels
mm/yr	millimeter per year
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe Efficiency
NWFWMD	Northwest Florida Water Management District
PBIAS	percent bias
R^2	coefficient of determination
RMSE	root-mean-square-error
RSR	observations standard deviation ratio
SAV	submerged aquatic vegetation
SJRWMD	St. Johns River Water Management District
USGS	U.S. Geological Survey
WGI	Wantman Group, Inc.
WRV	water resource value

1.0 INTRODUCTION

The study area for the development of minimum flows for Wakulla and Sally Ward springs includes the Sally Ward Spring and spring run, and the Wakulla Springs and spring run, which extends from the Wakulla Springs pool to the confluence of the Wakulla and St. Marks rivers. This report documents the update and calibration of the Hydrologic Engineering Centers River Analysis System (HEC-RAS) model of the Wakulla River System. The focus of the model update was to extend the model to include Sally Ward Spring and its spring run. The model update also incorporated a recent survey on the Wakulla River that included additional cross-sections and re-surveying of previously surveyed areas to document potential changes in river bathymetry due to Hurricane Michael, which made landfall on October 10, 2018, near Panama City, Bay County, Florida. The intended use of this HEC-RAS model is to support minimum flows development for Wakulla Springs and Sally Ward Spring. The general study area for the model is shown on Figure 1.

Overview of Report

Applied Technology and Management, Inc. (ATM) previously refined and calibrated a HEC-RAS model of the Wakulla River system for analysis of the St. Marks River Rise Minimum Flows and Levels (MFLs) in 2017-2018. The simulation period for this model was May 3, 2017 through November 27, 2017. Since the previous model refinement, additional hydrodynamic and survey transect data have been collected along Wakulla River and the Sally Ward Spring Run. Additionally, significant effort has been made to further refine the Wakulla Springs and Sally Ward Spring discharge time series. The purpose of this effort was to further refine and calibrate the HEC-RAS model utilizing this recently collected data. The model will be used to support the determination of MFLs for Wakulla Springs and Sally Ward Spring. The following tasks were performed to achieve these goals:

- Review available data for use in performing the model update
- Modify model geometry, including extension of spatial domain
- Develop input flow files and boundary conditions using available hydrodynamic monitoring data and U.S. Geological Survey (USGS) flow data
- Perform model testing and calibration
- Convert the unsteady flow model to a steady-state model for MFL analysis

The existing model was updated to HEC-RAS 5.0.7. All model updates were performed using HEC-RAS 5.0.7 and RAS Mapper.

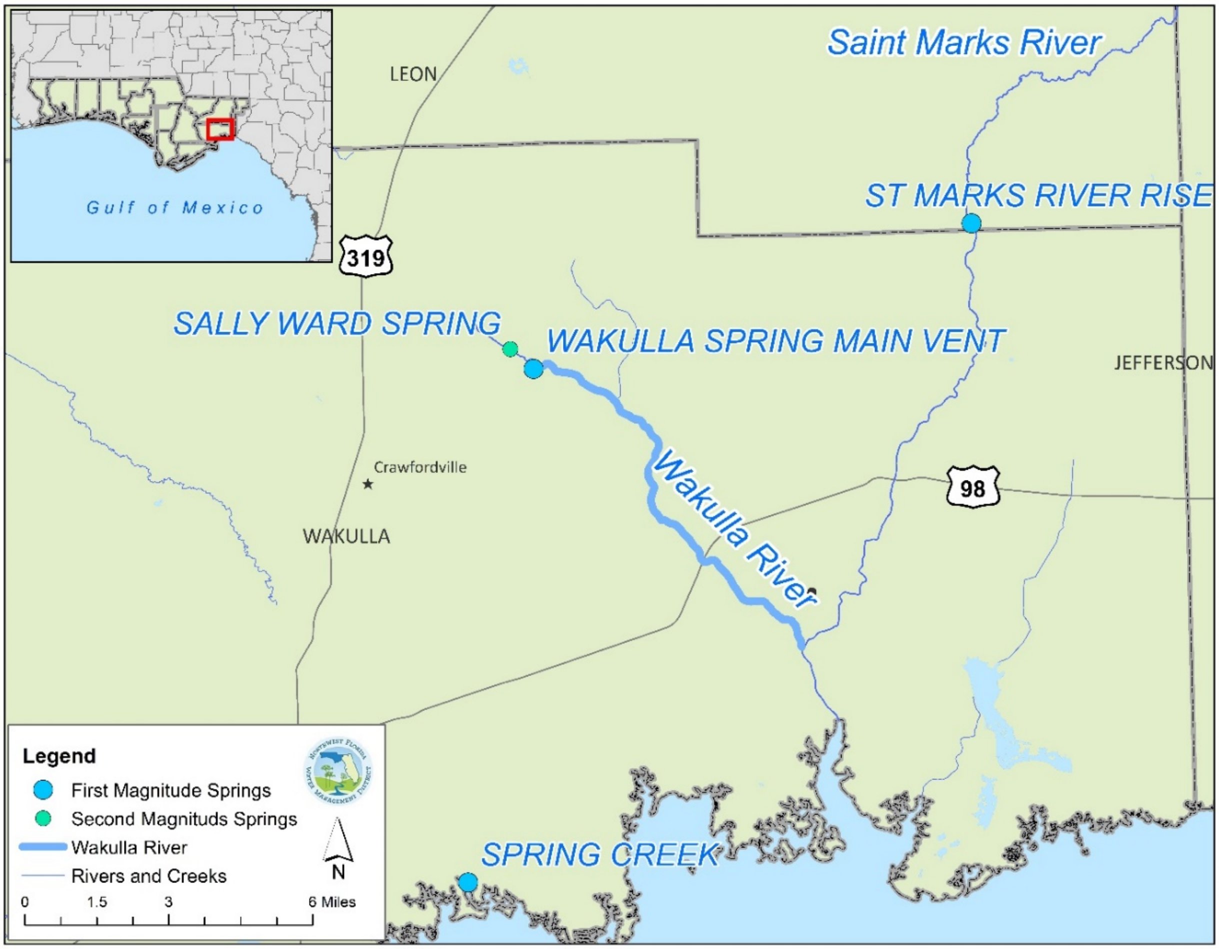


Figure 1. General Study Area for the St. Marks/Wakulla River HEC-RAS Model

2.0 MODEL GEOMETRY, CONSTRUCTION, AND MODIFICATIONS

The model geometry was updated to include additional transect and bathymetric data from 2019, reflecting post-Hurricane Michael conditions. The data consisted of eight Sally Ward Spring Run transects, a survey of the pedestrian bridge across Sally Ward Spring Run and 12 Wakulla River transects [Wantman Group, Inc. (WGI), 2019]. The survey work was completed in August 2019. Figure 2 presents the location of the 2019 survey transects. The Sally Ward Spring Run transects extended from the upland edge through the floodplain, to the water's edge, across the river and through the floodplain to the upland edge. The survey included identification of the location and elevation of the main-channel top-of-bank. Survey transects were used to extend the model to include Sally Ward Spring Run. Available light detection and ranging (LiDAR) data from 2007 [vertical accuracy +/- 8.5 centimeters (cm) per geographic information system (GIS) metadata] were used to extend the transects in the model as needed to fully encompass the potential inundation area. More recent LiDAR was flown and processed during this model update effort. That data will be incorporated into future model updates.

The 12 Wakulla River transects consisted of both transects in new locations and transects in previously surveyed locations. Three transects were co-located with previously surveyed areas. Five of the new transects, while not co-located with previously surveyed transects, were close enough to allow for assessment of channel bathymetry that may have changed as the result of storm surge from Hurricane Michael in 2018 and high spring flows through December 2018 (Figure 3). The eight transects available for comparison are listed in Table 1. Figure 3 presents the stage time series at USGS gage 02327022 (Wakulla River Nr Crawfordville). Evidence of the bathymetric changes is seen in Figure 3, which indicates a different tidal signal is being recorded post-Hurricane Michael at the 02327022 gage located approximately 3 miles downstream from the Wakulla Springs vent at Shadeville Road (Figure 2). Tidal elevations are approximately 1 foot (ft) lower following the passage of Hurricane Michael in October 2018 than were measured before its arrival. These lower elevations suggest possible scour in the channel near and downstream of Shadeville Road following hurricane Michael. The existing model geometry was compared to the additional transect and bathymetric data collected in 2019 at locations where there were co-located transects. Upon review, each of these transects was found to contrast with the existing model geometry.

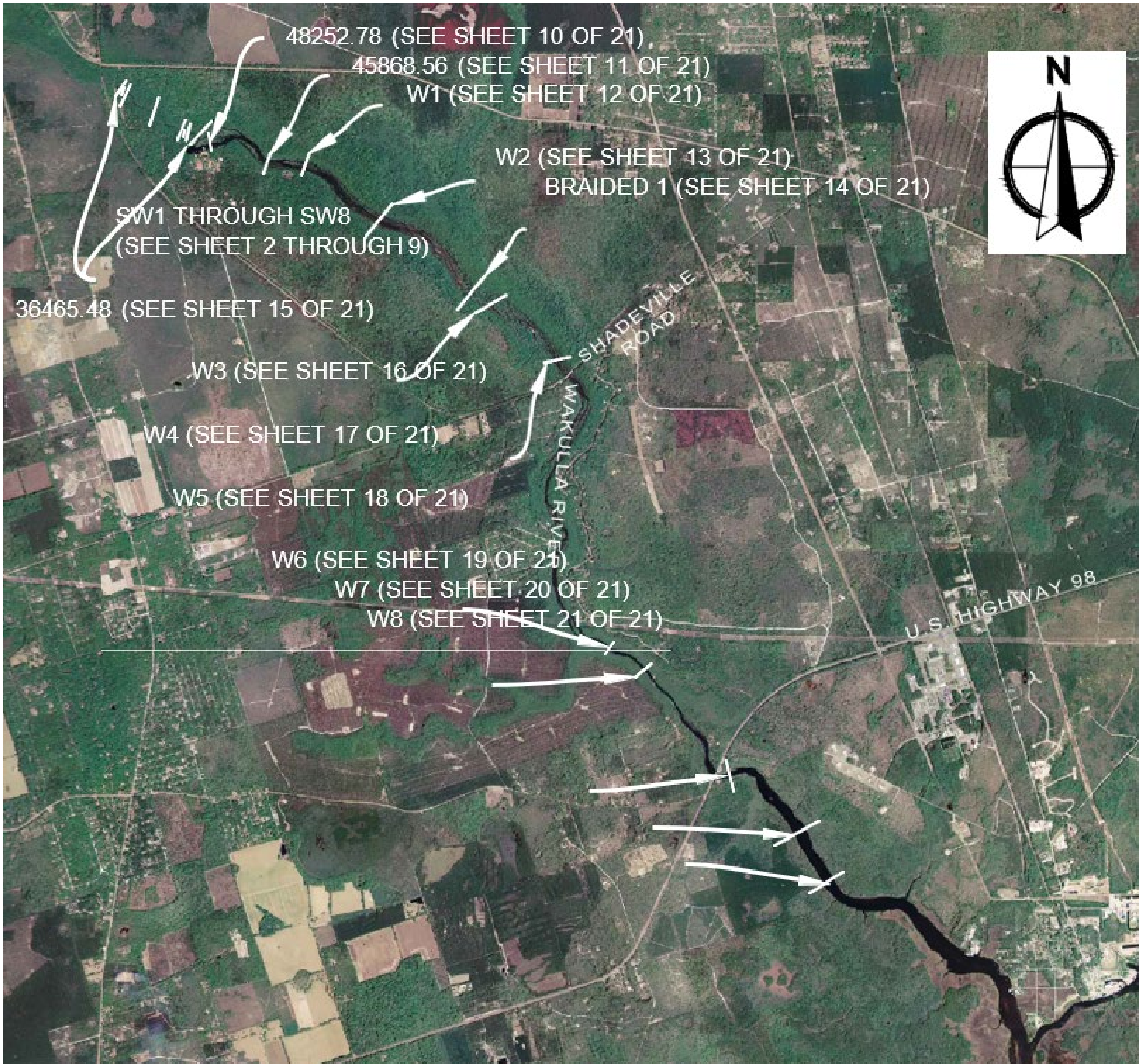


Figure 2. Location of 2019 Survey Transects (Survey Performed July 15 through August 9, 2019). (Source: WGI, 2019)

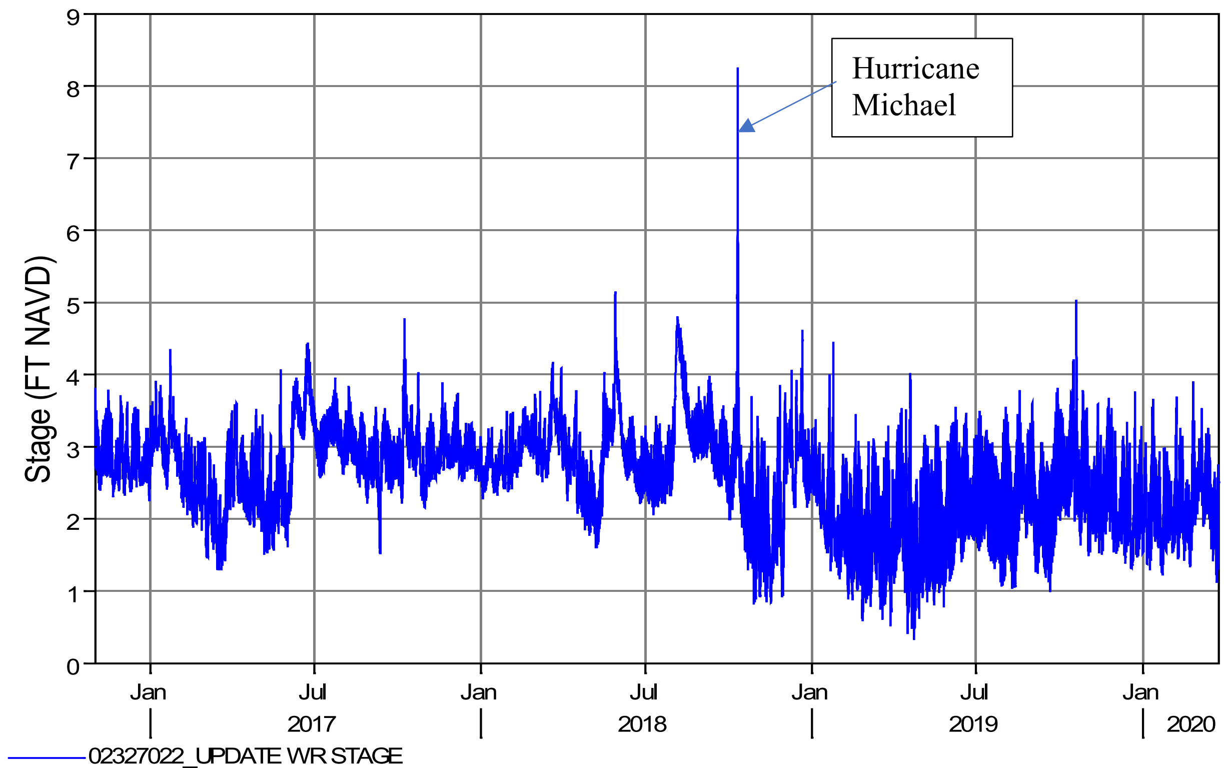


Figure 3. Stage Time Series for USGS Gage 02327022 Wakulla River near Crawfordville (September 2016 to September 2019). Note the passage of Hurricane Michael in Fall 2018 as evidenced by the fall of water level in the Wakulla River.

Table 1. Locations of Transects Available for Comparison of In-Channel Geometry in the Wakulla River Model Reach

HEC-RAS Model Cross-Section Reconfigured	2019 Bathymetric Transect Source Data
48252	48252
45868	45868
41707	W2
36465	36465
19817	W5
14877	W6
11661	W7
8591	W8

Figure 4 presents a comparison of the channel profile from the prior existing model and that using the 2019 survey information. Each point represents a transect thalweg elevation. Review of Figure 4 indicates that some significant changes in the Wakulla River channel profile occurred as the result of Hurricane Michael. A greater than 4-ft storm surge and flow reversal was recorded at USGS Gage 02327022 (Figure 3), which is located approximately 6 miles above the mouth of the Wakulla River.

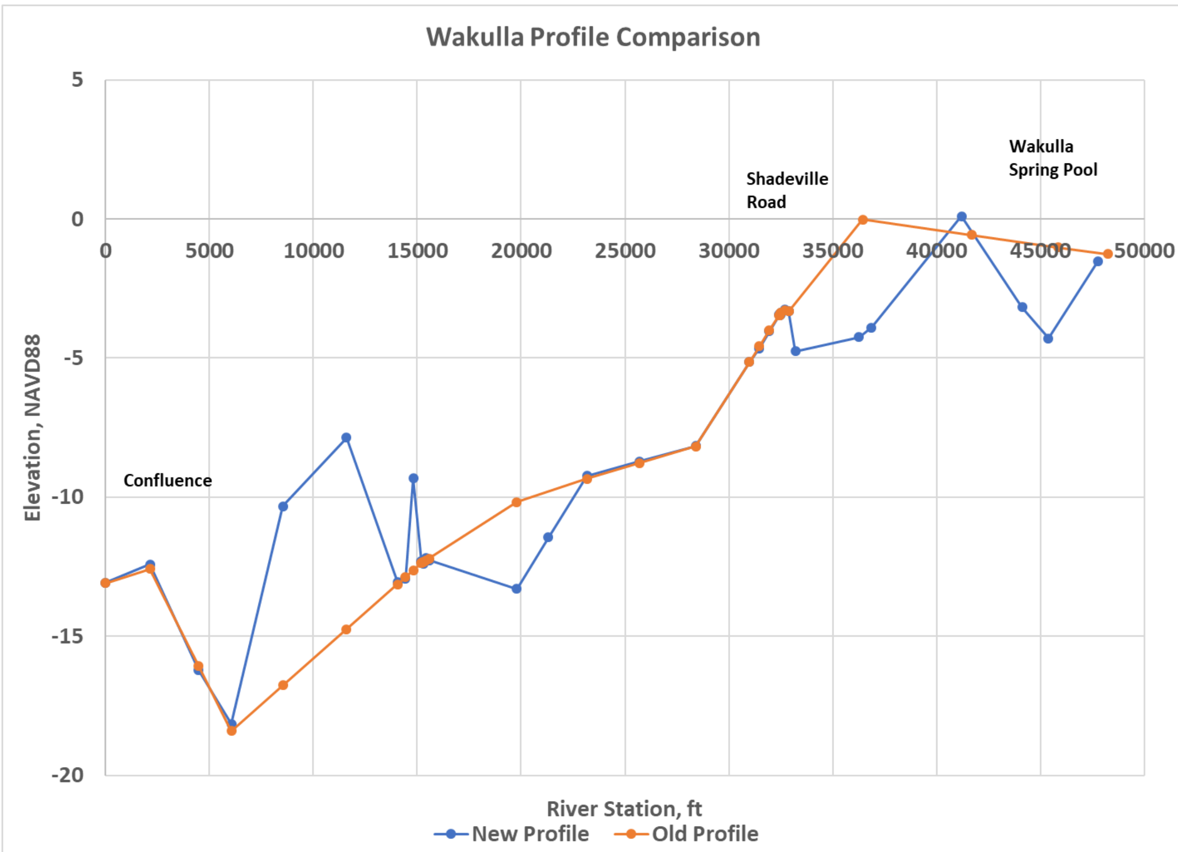


Figure 4. Comparison of Channel Profiles (transect thalweg elevations) Pre- (August 2016) and Post-Hurricane Michael (August 2019) in the Wakulla River

Inspection of Figure 4 reveals locations of deposition and scour in response to the storm surge. In the upper Wakulla River, thalweg elevations are generally lower post-hurricane at coincident locations, indicating scour, whereas in the lower Wakulla river, thalweg elevations are generally higher post-hurricane at coincident locations indicating deposition. It is likely that the Wakulla River channel is continuing to change, albeit at a more gradual rate, as it moves toward a new stasis. Because of the observed changes in the Wakulla River channel following Hurricane Michael, all survey information collected in the WGI 2019 survey was incorporated into the Wakulla River model geometry. Where updated survey information was collected near existing model cross-sections, the updated survey was used to create a new model cross-section that replaced the nearby model cross-section from the existing model.

In summary, the following model geometry modifications were performed.

1. The model extents were expanded to include the Sally Ward Spring Run.
2. In-channel geometry was reviewed and refined for 12 cross-sections in the Wakulla River using field survey data obtained by WGI (2019) and provided by Northwest Florida Water Management District (NWFWMD).

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

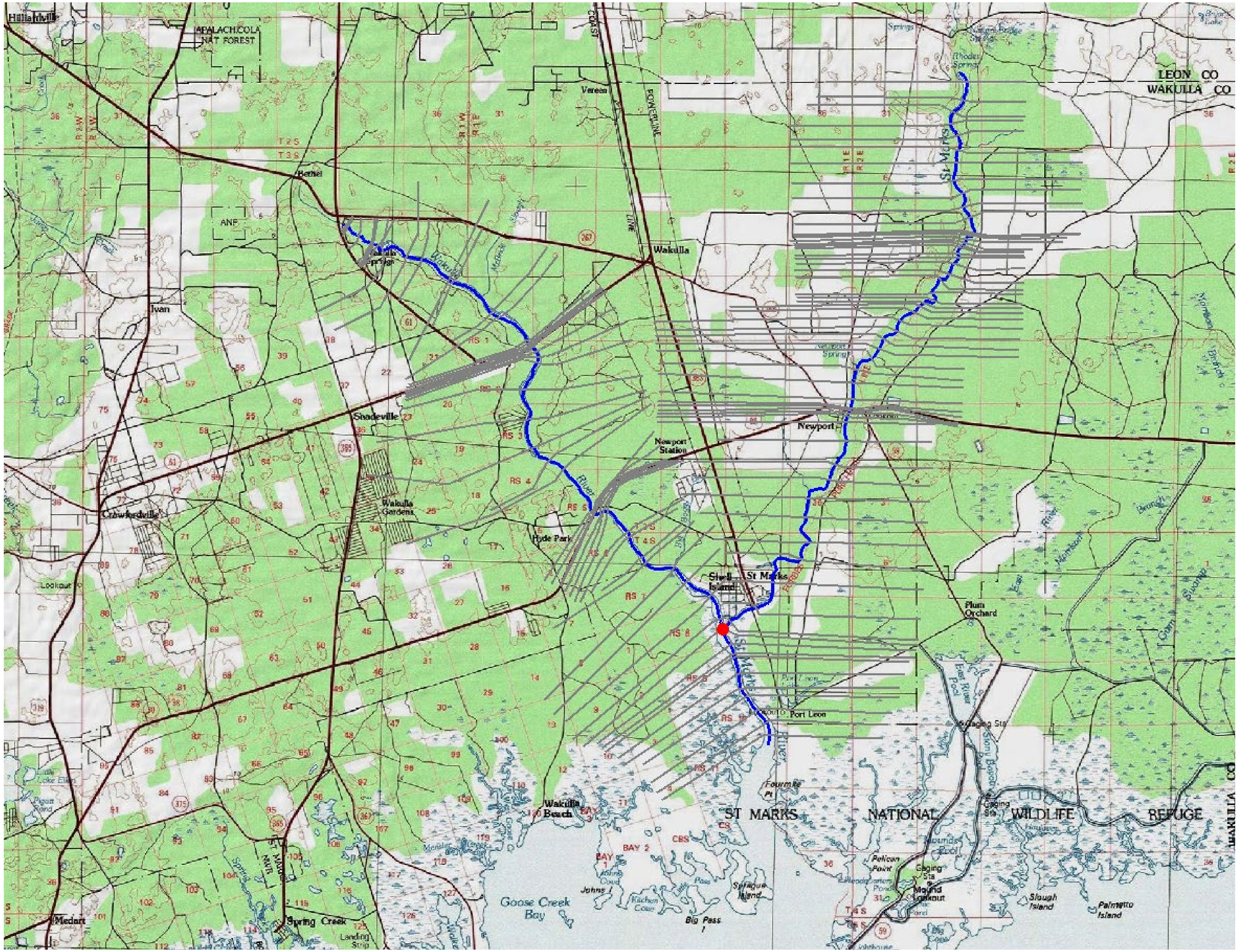


Figure 5. St. Marks/ Wakulla/Sally Ward Springs HEC-RAS Model Schematic

3.0 SIMULATION TIME PERIODS

Morphological changes were observed in the Wakulla River following Hurricane Michael, as evidenced by survey data comparisons and review of available stage time series in the river reach. Therefore, it was determined that the use of data before Hurricane Michael was not appropriate for use in testing and calibrating the updated HEC-RAS model. The period from January 7, 2019, to September 9, 2019, was used for model testing and initial calibration since this was the data period available following the passage of Hurricane Michael at the time of model update and testing. For testing and initial calibration assessment, the updated HEC-RAS model was run using the unsteady flow analysis option due to the tidal influence on the lower portions of the river systems.

4.0 BOUNDARY CONDITIONS

Boundary conditions for the St. Marks/Wakulla River/Sally Ward Spring HEC-RAS model consisted of the upstream flows from the St. Marks River Rise, Wakulla Springs, and Sally Ward Spring; 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, described in more detail in Section 4.2. Figure 6 presents those basins contributing surface water flow to the St. Marks and Wakulla River systems.

Figure 6. Surface Water Basins that Contribute Flow to the St. Marks – Wakulla System

The time series data were transferred into a Hydrologic Engineering Centers Data Storage System (HEC-DSS). The boundary conditions were stored in the “SMR_WR_SWS.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. The following sections describe the boundary data used and associated data processing in more detail.

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

4.1 DOWNSTREAM STAGE BOUNDARY CONDITION

For model refinement and calibration, 5-minute Hydrodynamic Station (HD)-3 stage data in feet referenced to the North American Vertical Datum of 1988 (NAVD88) were provided by NWFWMD and initially reviewed as the downstream boundary for the updated model. The previous model used data from HD-4, a hydrodynamic monitoring station located near the terminus of the HEC-RAS model. This station has been inactive since December 2017. Further investigation on the HD-3 data record indicated issues with the post-Hurricane Michael data record since the station came back online in January 2019, as a result of station inundation during Hurricane Michael. Therefore, it was not appropriate to use the HD-3 data post-Hurricane

Michael as a boundary condition in the model update. As a result, the tide predictions at St. Marks Lighthouse located at mouth of the St. Marks River and approximately 3.5 miles south of the terminus of the HEC-RAS model domain were considered best available information and were used as the model downstream boundary condition in the model calibration.

The National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) makes a prediction of tides at the St. Marks Lighthouse. The location of this lighthouse in relation to the model spatial domain is presented on Figure 7. This was the closest location found for available tide information. Figure 8 presents the predicted tides corresponding to the December 2018 to January 2020 simulation period, which included model calibration and validation simulation periods.

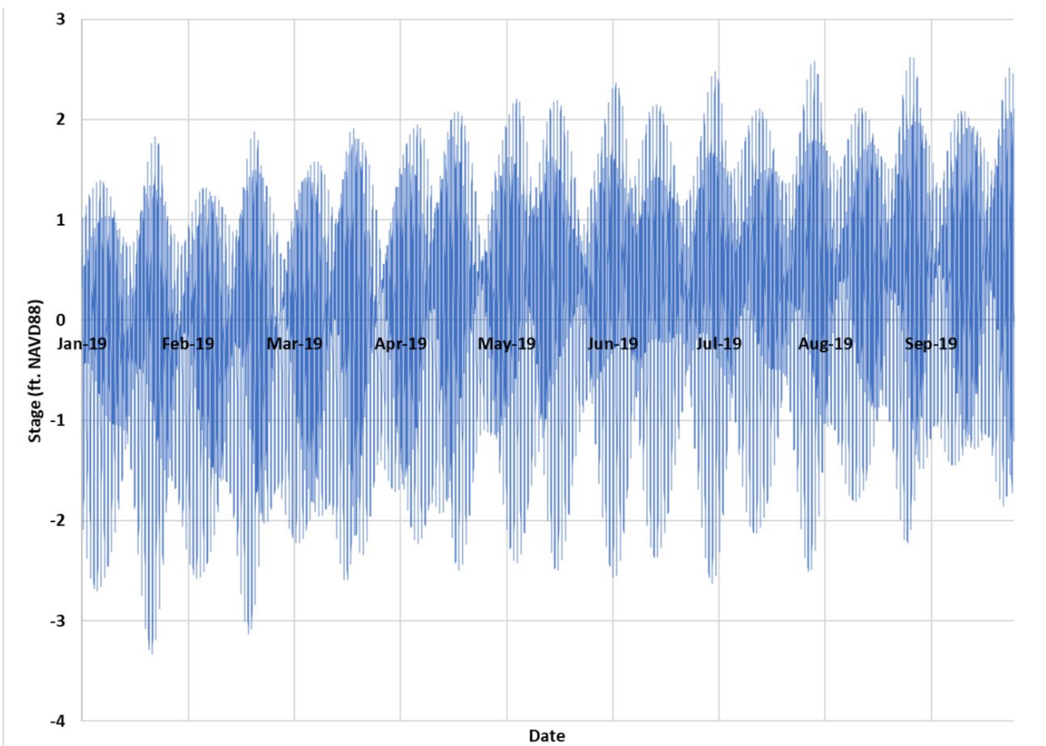


Figure 8. Predicted Tides at the St. Marks Lighthouse for the Simulation Period (Source NOAA Tides and Currents)

A tide prediction can differ from the actual sea level that will be observed as a result of the tide. Predicted tidal heights are those expected under average weather conditions. When weather conditions differ from what is considered average, corresponding differences between predicted levels and those actually observed will occur. Generally, prolonged onshore winds (wind towards the land) or a low barometric pressure can produce higher sea levels than predicted, whereas offshore winds (wind away from the land) and high barometric pressure can result in lower sea levels than predicted. Figure 9 presents a comparison of St. Marks Lighthouse predicted tides and HD-4 measured tides for May 2017 through November 2017 (previous model calibration period), which illustrates the differences in the stage records. Figure 10 presents a comparison of St. Marks Lighthouse predicted tides and HD-4 measured tides for a subset of available data, June 7, 2017, through June 14, 2017, to better illustrate differences between St. Marks Lighthouse predicted tides HD-4 measured tides. As shown in Figure 10, differences in the magnitudes of high and low tide elevations are apparent, as well as a difference in the timing of these high and low tides with the Lighthouse high and low tides occurring earlier than at the HD-4 location. This reflects the tidal propagation from the mouth of the St. Marks River to the terminus of the model domain. The differences in tidal magnitude and timing of the tidal boundary will result in timing and magnitude differences in model stage predictions when compared to water level observations at other locations up the Wakulla River.

A 15-minute time interval for both flow and stage boundary conditions in the HEC-RAS model was used to be consistent with available resolution of USGS flow and stage records at USGS 02327022 (Wakulla River near Crawfordville) and USGS 02326900 (St. Marks River near Newport). St. Marks Lighthouse predicted tides were downloaded from NOAA Tides and Currents as a 15-minute time series for use as a downstream boundary in the HEC-RAS model.

4.2 WAKULLA RIVER FLOW BOUNDARY CONDITIONS

The Wakulla River system inflows included: (1) the upper boundary inflow at Sally Ward Spring, which includes inflow from Indian Spring Run; (2) the upper boundary inflow at the Wakulla Springs vent; (3) the lateral inflow from Basin 2, which includes McBride Slough as well as groundwater contributions from small springs along the Wakulla River; and (4) the lateral inflow from Basin 3.

Flow data from USGS Station 02327022, Wakulla River near Crawfordville was obtained from the USGS National Water Information System: Web Interface. The USGS states in its remarks that flow is affected by tide, requiring filtering to remove the effects of the tides so that the net flow of the gaged location could be determined (Figure 11). Filtering was applied to 15-minute flow data from USGS 02327022 using a Godin filter routine consistent with USGS methodology (USGS 2011).

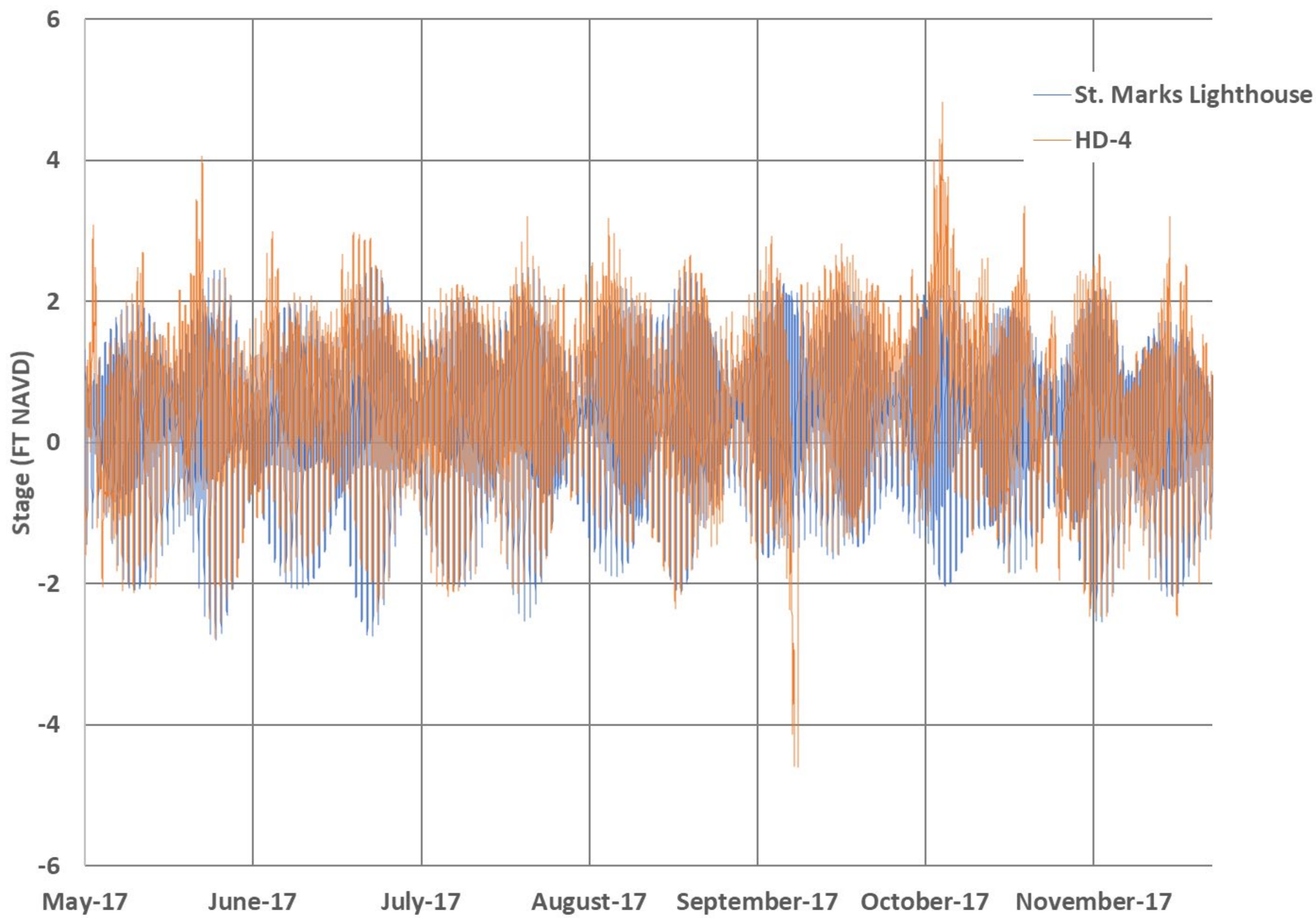


Figure 9. Comparison of St. Marks Lighthouse Predicted Tides and Station HD-4 Observed Tides for the Period of Record, 5/2017-11/2017

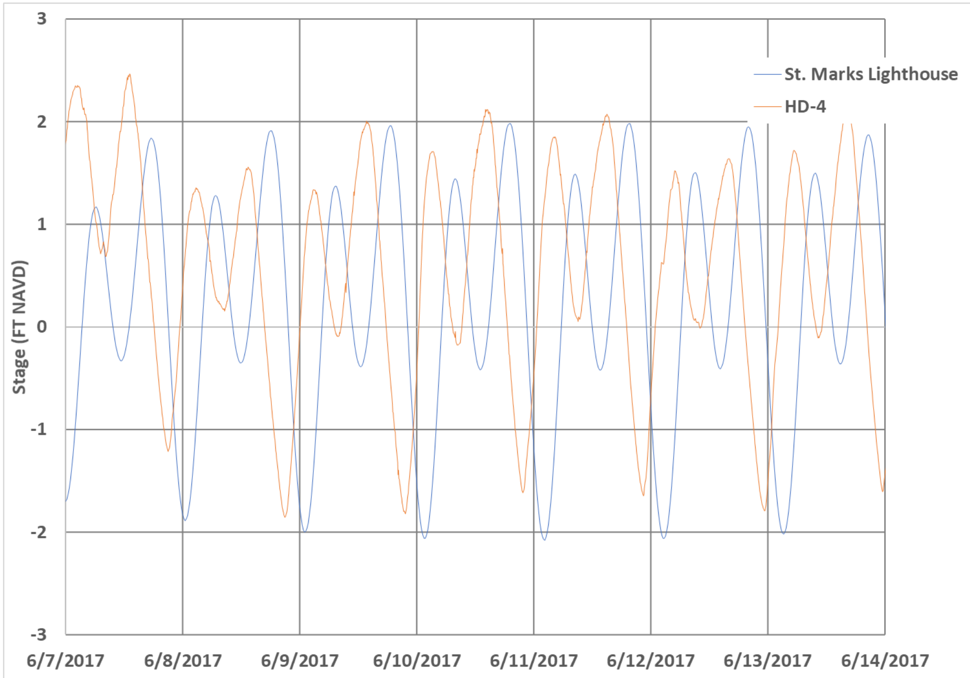


Figure 10. Comparison of St. Marks Lighthouse Predicted Tides and Station HD-4 Observed Tides for the Period of Record, 6/7/2017-6/14/2017

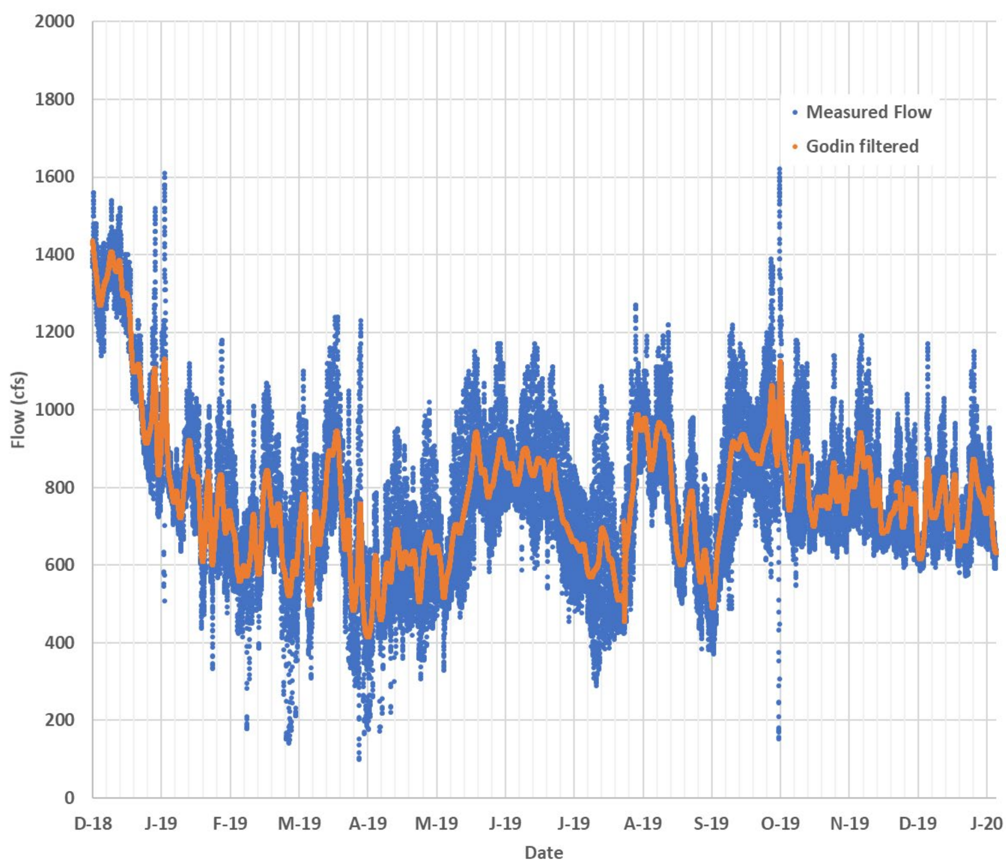


Figure 11. USGS Gage 02327022 Filtered Results for the Period of Record, 12/2018 – 1/2020

NWFWMD provided the 15-minute flow records for both Wakulla Springs vent, which is measured in the Wakulla Springs vent (Figure 12) and Sally Ward Spring, which is measured at the Sally Ward Spring Run pedestrian bridge (Figure 13). Small data gaps occurring during the model calibration period were filled using linear interpolation. Gap filling is necessary since unsteady HEC-RAS simulations require a continuous record (no gaps) for boundary conditions. Details regarding Wakulla and Sally Ward Spring discharge data collection are presented in Appendix A of the Wakulla and Sally Ward Spring MFL Technical Assessment.

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

- USGS 02327022 Filtered Flow – Wakulla Springs Vent Flow – Sally Ward Spring Run Flow = Net Inflow from Basin 2.
- The net inflow from Basin 2 was input as a uniform lateral inflow. The uniform lateral inflow boundary condition allows the user to evenly distribute a single flow hydrograph between an upstream and downstream cross-section. Negative net inflow values were set to zero, affecting approximately 38 percent of the record. This was done since contributions from Basin 2 are expected be zero or greater. Negative net inflows are likely due to measurement precision, the precision of the Godin filter to represent actual net flow at the USGS 02327022 station and differences in the timing of flows between the Wakulla Springs vent and the USGS 02327022 monitoring station.

Figures 14a and 14b present the resultant net inflow time series, Figure 14a presents the resultant time series before negative values were set to zero. Figure 14b presents the time series with negative inflow values set to zero. The Basin 2 net inflow time series illustrated in Figure 14b was input as a uniform lateral inflow in the HEC-RAS model.

The unsteady HEC-RAS model dynamically calculates flow at all cross-sections based on the boundary inflows and hydraulic gradients. The results of this calculation at the Shadeville Road Bridge for the inflow boundaries above the USGS 02327022 gage should approximate the measurements from the USGS 02327022 gage. The quality of this comparison of simulated and measured flows at this location is assessed as part of the model calibration and assessment process, which is discussed in Section 6 and 7.

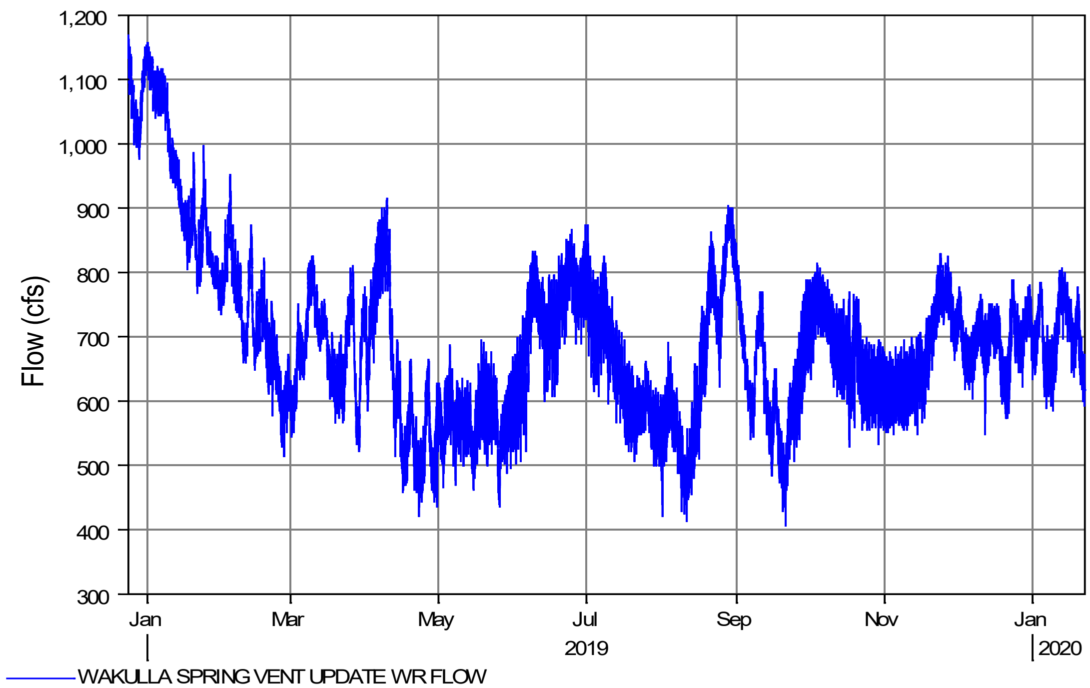


Figure 12. Wakulla Springs Vent Flow Time Series

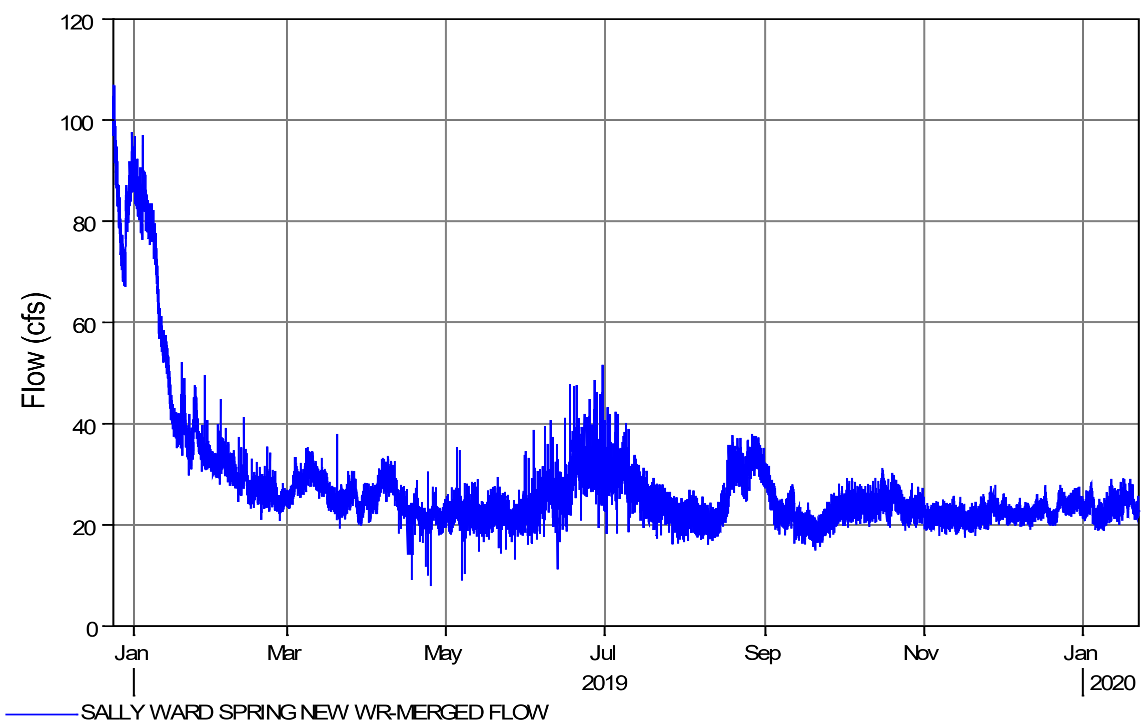


Figure 13. Sally Ward Spring Run Flow Time Series

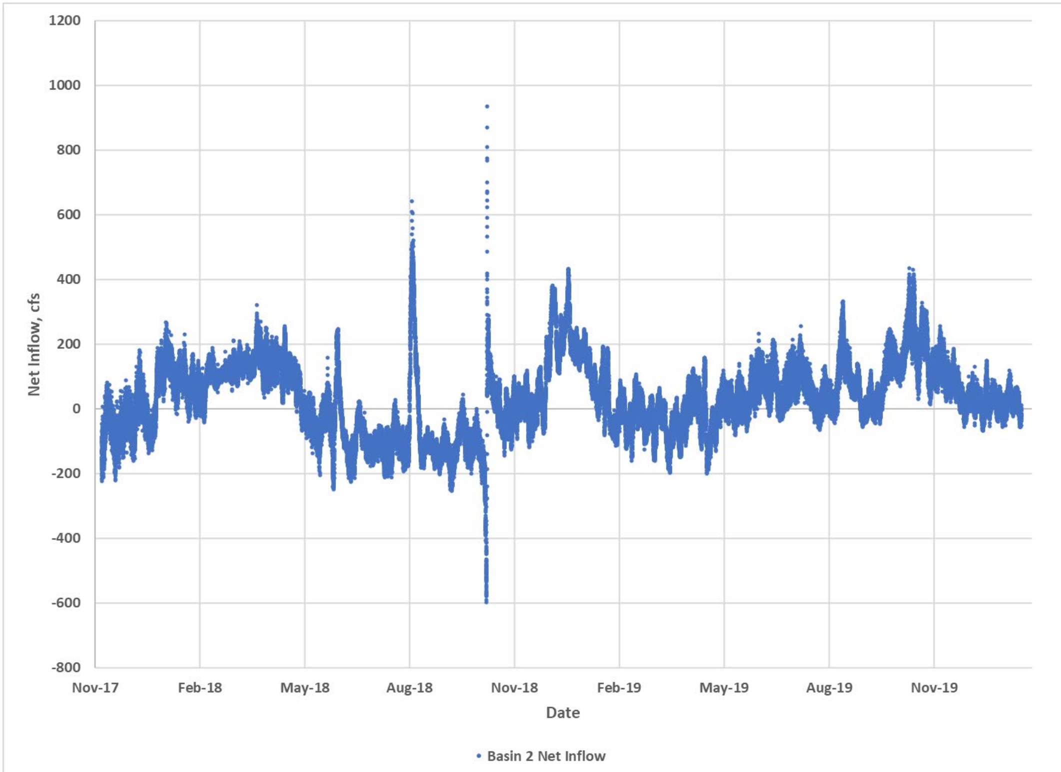


Figure 14a. Basin 2 Net Inflow Time Series Before Negative Inflow Values Were Set to Zero

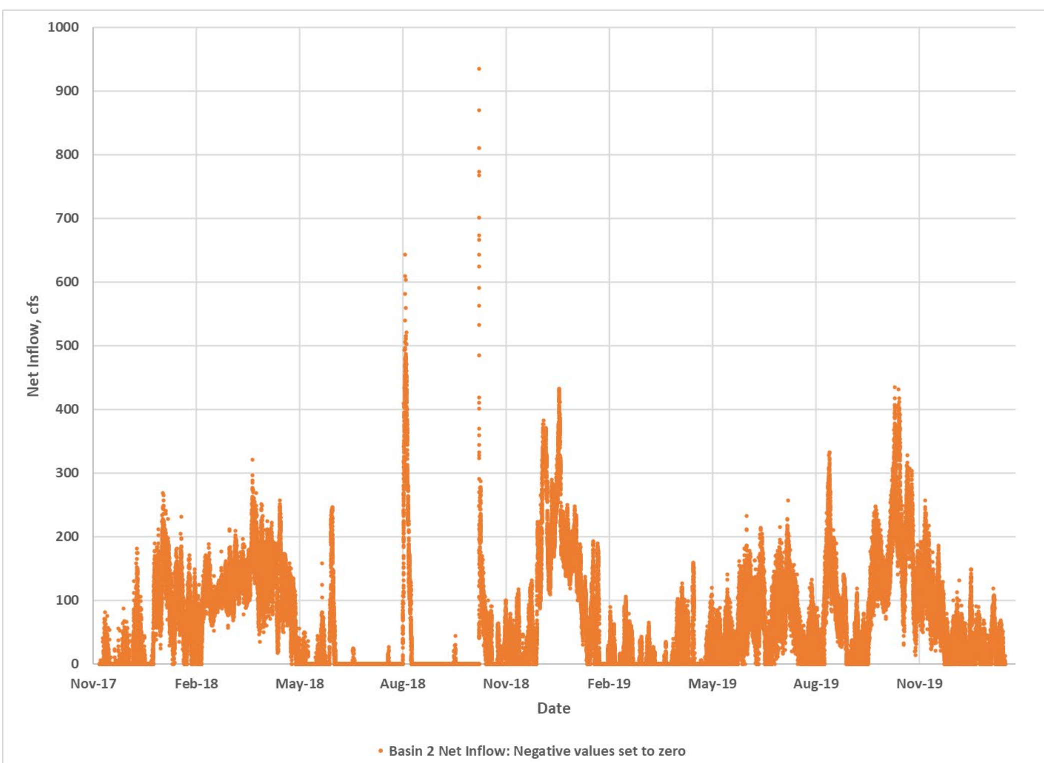


Figure 14b. Basin 2 Net Inflow Time Series After Negative Inflow Values Were Set to Zero

Lateral ungaged inflow to the Wakulla River system from Basin 3 was estimated by first examining the Wakulla River flux measurements collected on August 23, 2017. The acoustic Doppler current profiler (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 cubic feet per second (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. Based on the tidal flux measurement below the St. Marks-Wakulla confluence (discussed in Section 4.4), no lateral inflow from Basin 3 was added to the model since most of the ungaged flow in the St. Marks–Wakulla system appears to be from the St. Marks River, based on that and other river-specific measurements (Section 4.3).

4.3 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 calibration period (January 7 – September 9, 2019), flows at USGS 02326900 ranged from 386 cfs (P6) to 1,350 cfs (P95). The flow percentiles are based on the period of record October 1956 to present daily flows at USGS 02326900.

Lateral ungaged inflows to the St. Marks River system from Basin 4 (Figure 6) were estimated by examining St. Marks River flux measurements collected on August 25, 2017. The 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, 2017, 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 “Basin 4 Lateral Inflow” in the DSS file, SMR_WR_SWS. This flow was input into the HEC-RAS model as a uniform lateral inflow from the USGS 02326900 gage to the location of the ADCP measurement.

4.4 ST. MARKS RIVER BELOW CONFLUENCE

Lateral ungaged inflow to the St. Marks–Wakulla River system for the reach extending downstream from the confluence was estimated by first examining the 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 uniform lateral inflow estimate for Basin 4, no additional flow was added to the river reach downstream of the confluence.

4.5 MODEL CALIBRATION DATA

Stage and flow data available for use as calibration was obtained from the USGS and NWFWMD. The calibration data used included:

- USGS 02327000 Wakulla Spring Nr Crawfordville (stage)
- USGS 02327022 Wakulla River Nr Crawfordville (stage and flow)
- NWFWMD Station 010822 (Boat Tram) (stage)
- NWFWMD Station 000774 Sally Ward Spring Run (stage)
- USGS 02326900 St. Marks River Nr Newport (stage)

5.0 MODEL SETUP

An existing HEC-RAS model was updated and set up using a recently acquired survey (discussed in Section 2) and updated inflow and downstream stage boundary conditions (Section 4). Updates on model geometry were performed only in the Wakulla River reach. Updated inflow and downstream stage boundary conditions were added to both the Wakulla and St. Marks River reaches.

The geometry of the Wakulla River Reach was modified to include extending the spatial domain of the model upstream to Sally Ward Spring and its spring run. This involved the incorporation of the eight survey transects performed by WGI (WGI, 2019) and the pedestrian bridge that spans Sally Ward Spring Run and its floodplain. A berm that parallels the spring run for most of its reach length is located on the right edge of water looking downstream towards the confluence with the Wakulla River (Figure 15). There are few connections to the spring run, but the area may contain water following rainfall events and backwater from the Wakulla Springs pool. Manning's n values were initially set at 0.02 in the channel and 0.15 in the floodplain areas, based on field reconnaissance in March 2019. Figure 16 illustrates typical conditions along Sally Ward Spring Run.

The geometry of the Wakulla River Reach was modified to incorporate the 12 survey transects performed by WGI (WGI, 2019). This included eight cross-sections that were co-located with existing model cross-sections or were near cross-sections in the existing model and four new cross-sections. Manning's n values were initially set at 0.02 in the deeper channel areas, 0.045 in the shallower channel areas, and 0.15 in the floodplain areas, based on field reconnaissance in March 2019.

Another observation during the March 2019 field reconnaissance was that some areas downstream of the Wakulla Springs pool are covered with dense vegetation (Figure 17). These areas are typically located in the middle of the river, with deeper portions of the channel located on either side. The presence of dense vegetation can affect conveyance capacity, with some portions of the channel having reduced ability to convey flow due to increased vegetative drag and an effective reduction in channel cross-sectional area.

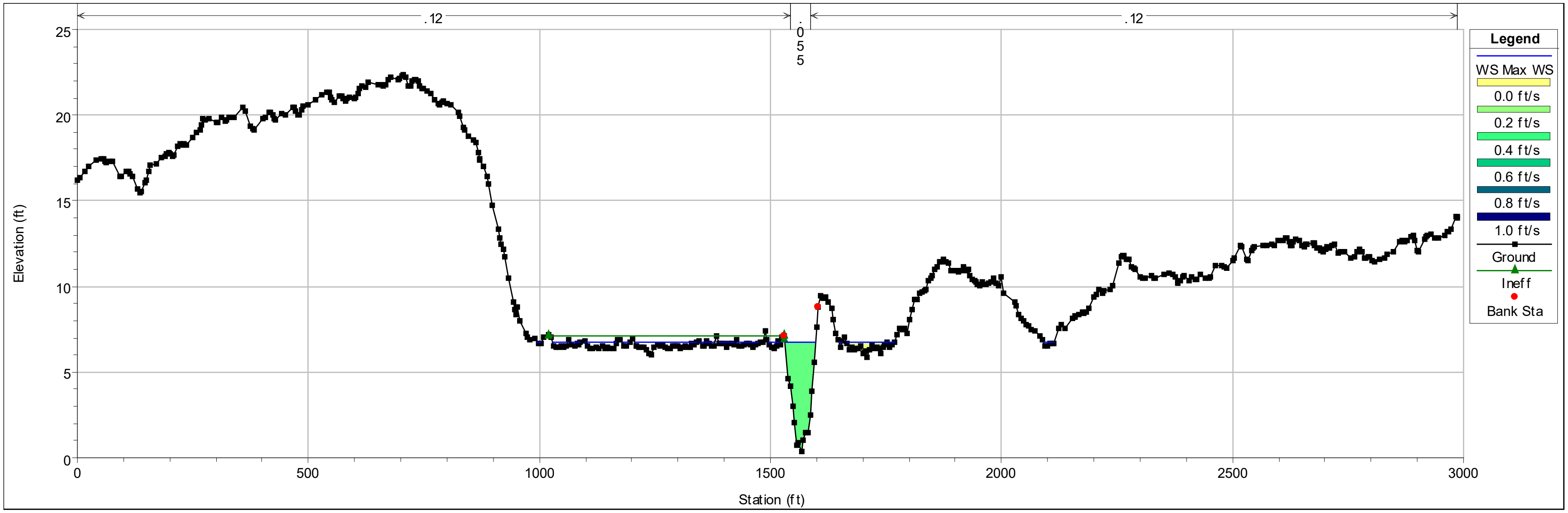


Figure 15. Typical Sally Ward Spring Run Cross-Section Looking Downstream Illustrating the Berm Parallel to the Run. Note the Berm is Located at Cross-Section Station 1600

Figure 16. Typical Sally Ward Spring Run Conditions in the Channel and the Adjacent Floodplain Areas.

Figure 17. Typical Conditions in the Wakulla River Downstream of the Spring Pool.

The Collaborative Research Initiative on Sustainability and Protection of Springs (CRISPS) Final Report, 2014-2017 (Reddy et al.,, 2017)found a range of shifting stage-discharge relationships for Silver River that evidently resulted from reach-scale changes to submerged aquatic vegetation (SAV) coverage and density. This phenomenon has also been observed in the St. Marks River, where rating curve shifts are routinely made for the 02326900 gage due to vegetation growing and dying off in the channel (Ron Knapp (USGS), Personal Communication). To account for the effects of this vegetation on flow conveyance, ineffective flow areas were incorporated into the channel areas in the upper portion of the Wakulla River. Ineffective flow areas are often used in HEC-RAS to describe portions of a cross-section in which water will pond and the velocity of that water in the downstream direction is close to zero. This water is included in the storage calculations and other wetted cross-section parameters, but it is not included as part of the active flow area. Adjustments to the elevations of the ineffective flow areas along with Manning's n values were the primary parameters used in model calibration.

The St. Marks River Reach contains 49 transects. Manning's n in the channel typically ranges from 0.02 to 0.04, with floodplain areas having a Manning's n of 0.2.

6.0 MODEL TESTING AND INITIAL CALIBRATION

The results of the model testing and initial calibration at the five calibration locations are presented in Figures 18 through 22. The figures present both the stage time series, stage residuals (simulated-observed) and stage duration curves for the initial calibration period (January 7, 2019, to September 9, 2019). Flows during the calibration period encompassed a wide range of flows. At the Wakulla Springs vent, daily flows ranged from the 20th percentile up to the 99th percentile of the available flow record (Period of Record October 2004 through December 2018). At USGS 02327022 (Wakulla River Nr Crawfordville), tidally filtered daily flows ranged from the 7th percentile up to the 98th percentile of the available flow record. The HEC-RAS model of the St. Marks and Wakulla Rivers was calibrated primarily by adjusting the channel Manning's n friction factors and elevations of the ineffective flow areas. Adjustments to friction factors were performed throughout each river reach. By maintaining consistency throughout the reach with this parameter and avoiding point calibration near locations of observed data, the model's predictive capability throughout the system is improved.

Simulated and observed stages and flow were compared graphically at each water level station in Figures 18 through 22. Residuals (differences between simulated and observed values) across the simulated flow range and time period were also presented graphically. The various graphical and statistical model performance measures employed for assessing model performance are discussed in more detail in Section 6.1. Generally, model predictions of stage are within 0.2 to 0.3 ft of measured stage, except at USGS 02327022 (Wakulla River Near Crawfordville) (Figure 21). Differences there appear to be due largely to timing differences from tidal propagation between the simulated and observed stages since the comparison of the respective stage and flow duration curves (Figure 21) show a good match graphically across the range of water elevations and flow conditions indicating that the model simulates the magnitude and frequency of tidal fluctuations appropriately. Duration curves are cumulative frequency curves that show the percent of time specified stages or discharges were equaled or exceeded during a given period. It combines in one curve the flow characteristics of a stream throughout the range of discharge, without regard to the sequence of occurrence (Searcy, 1959). By removing the timing, or sequence of occurrence, duration curves provide a graphical way to assess how well the percent of time specified stages or discharges were equaled or exceeded during a given period as predicted by a model simulation compares to the percent of time specified stages or discharges were equaled or exceeded during a given period for the observed data, without regard to sequence or timing of occurrence.

Comparison of simulated to observed stage in Figure 21a indicates that the timing of high and low tides is not coincident, which is the likely cause of model error and larger residuals at this location. Considering the use of a predicted tide instead of tidal observations for the downstream boundary condition, and the timing differences of high and low tides associated with using the St. Marks Lighthouse predicted tides as described in Section 4.1, the unsteady state model proved to be a good predictor of water levels across low, medium and high flow conditions in the Wakulla River.

The initial calibration results for Sally Ward Spring are presented on Figure 18. The results indicate that the model generally underestimated stage even when the in-channel Manning's n was increased to 0.1. The underprediction was more pronounced in the May through August period. This phenomenon was also observed at the other calibration locations on Wakulla River. At this location and at the other calibration locations, the predicted water levels converged with the observed water levels in the latter part of the calibration period. A possible explanation for this phenomenon is that the Wakulla River is still transitioning following the passage of Hurricane Michael in October 2018, which resulted in some large changes in river morphology. It is also possible that summer vegetation growth may contribute to the discrepancy during the May-through-August period. Seasonal roughness factors to account for changes in vegetation can be used in HEC-RAS. Based on limited data following Hurricane Michael, it is not clear that a regular seasonal signal is present, so seasonal roughness factors are not considered to be appropriate remedies in this case. Predicted stages at Sally Ward Spring were generally within 0.4 ft. It was noted that the model overpredicted at the higher flows in the early part of the simulation indicating that additional floodplain connectivity and conveyance may be present beyond what was apparent in the field survey and reconnaissance.

The initial calibration results for USGS 02327000 (Wakulla Spring Nr Crawfordville) are presented on Figure 19. The results indicate that the model generally predicts the spring pool stage well but began to underpredict in the May-to-August period, similar to the pattern at Sally Ward Spring. Predicted stages at Wakulla Springs pool were generally within 0.2 to 0.4 ft of the observed data.

The initial calibration results for the Wakulla River Boat Tram station are presented on Figure 20. The results indicate that the model generally predicts stage well but began to underpredict in May. Observed data were not available until the later part of the simulation period, but it is likely that the same pattern seen at Sally Ward Spring and USGS 02327000 would be seen at this location. Predicted stages at the Wakulla River Boat Tram station were generally within 0.2 to 0.4 ft of the available observed data.

The initial calibration results for USGS 02327022 (Wakulla River Nr Crawfordville) are presented on Figure 21. This location is the most downstream calibration point on the Wakulla River and is most affected by tide and the use of predicted tide as the downstream boundary condition. The results indicate that the model generally predicts stage and its variability well. The high residuals seen in Figure 21b may stem from using the St. Marks Lighthouse predicted tide, which is located approximately 3.5 miles south of the end of the model domain, instead of observed tides at the end of the model domain. The May-to-August period predicted the central tendency of the tidal signal well but was not predicting the tidal variation as measured at USGS 02327022. It was also noted that the simulated tidal signal was somewhat dampened as compared to the observed data, which is expected when using a predicted tide for the downstream boundary condition. This also affected the model’s predictions of flow (Figure 21e), in which the central tendency was captured but range over the tidal cycle was not. The model is dynamically calculating the flow at this point based on the simulated energy gradient. Therefore, if the tidal signal is dampened, that will also affect calculated flow range.

The comparison of the model results with the USGS 02326900 water level data on the St. Marks River (Figure 22a) 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 observed data indicates that the observed rating has shifted over the simulation period (Figure 22f). USGS routinely applies adjustments to the rating curve at this monitoring location based on field measurements to account for changes in vegetation coverage and density. It would be possible to adjust roughness over the year through the use of seasonal roughness factors to account for changes in vegetation in the upper St. Marks River. Based on data reviewed in this effort, it is not clear that a regular seasonal signal is present, so seasonal roughness factors were not applied. It should be noted that based on previous modeling efforts on the Wakulla-St. Marks system, flow in the St. Marks River has a minimal effect on water levels in the Wakulla River.

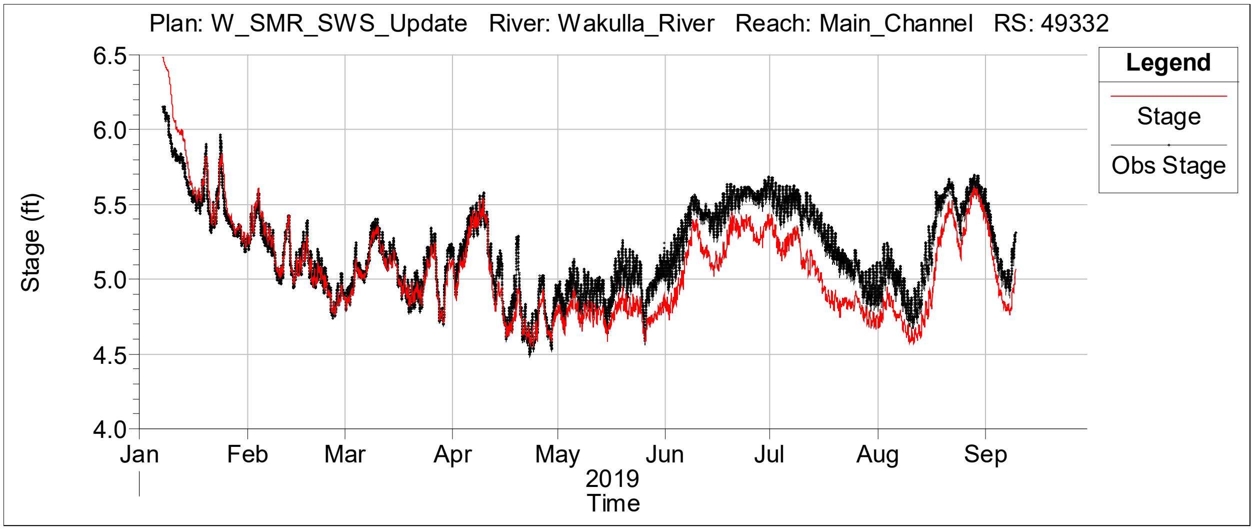


Figure 18a. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Run: Comparison of Simulated and Observed Stage Time Series

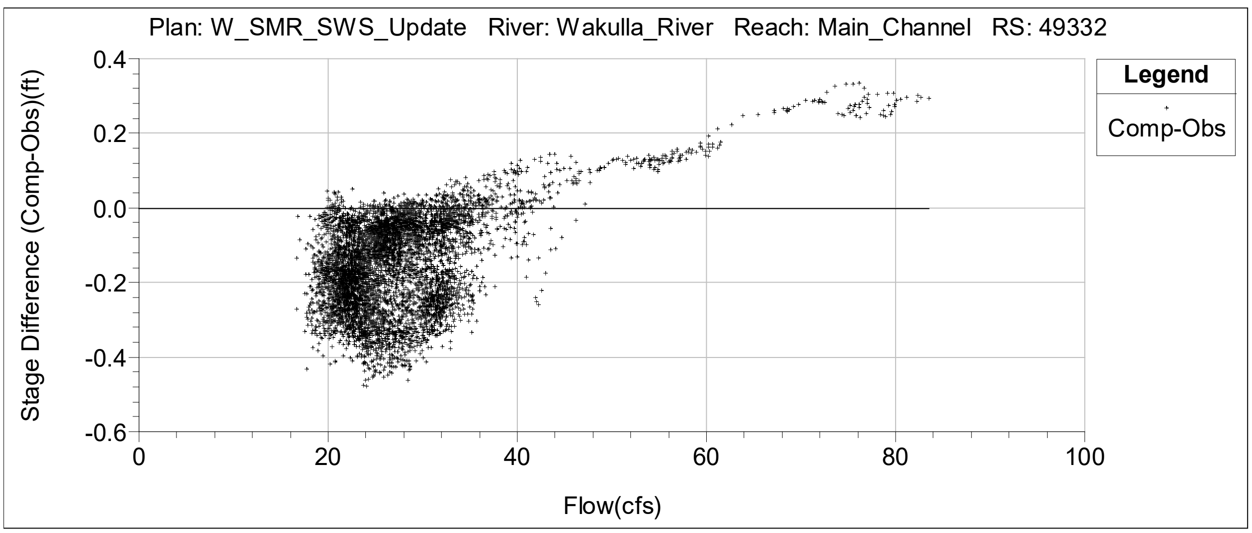


Figure 18b. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Run: Residuals (Simulated – Observed) vs Flow

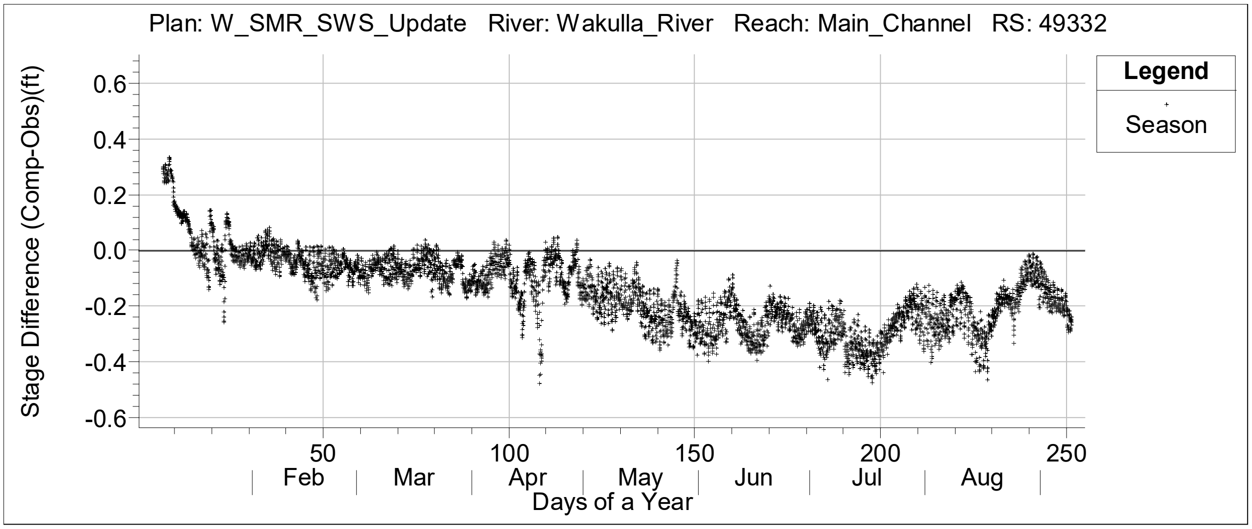


Figure 18c. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Run: Residuals (Simulated – Observed) over Time

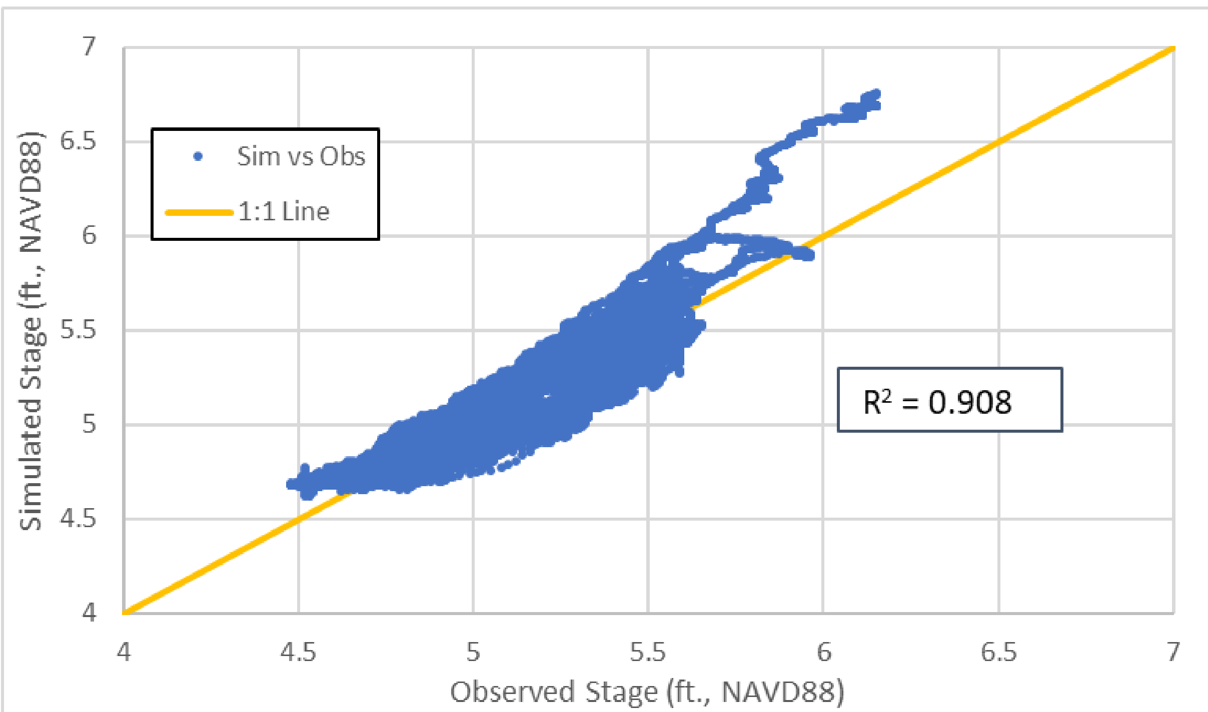


Figure 18d. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Run: Scatter Plot of Observed and Simulated Stages

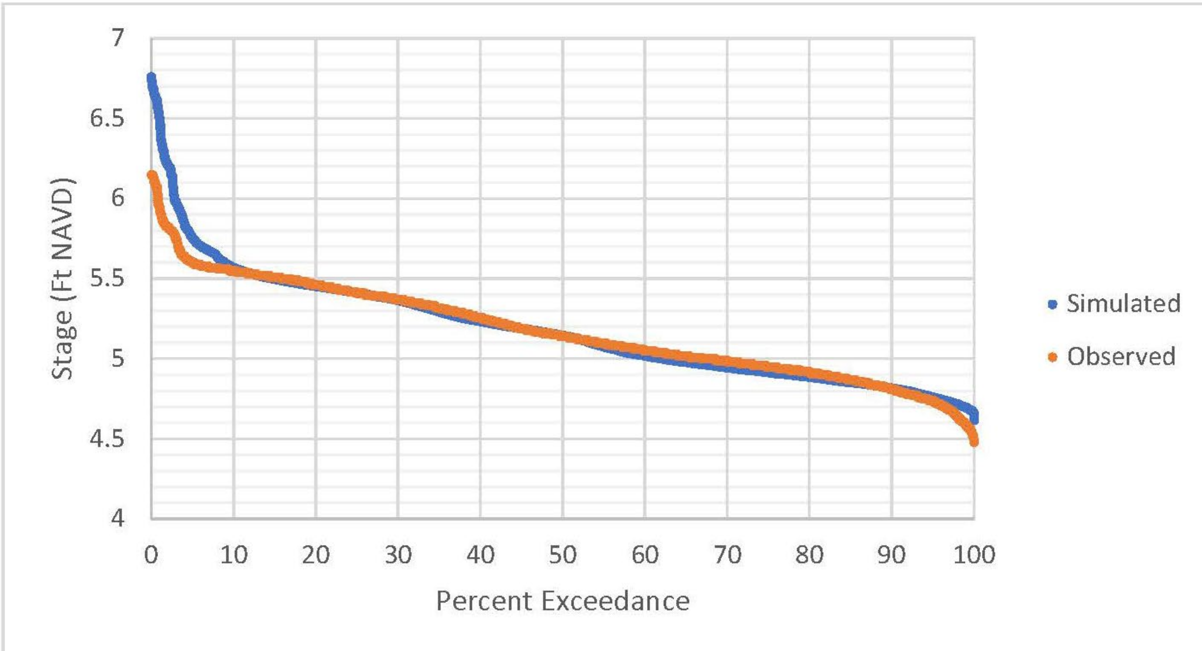


Figure 18e. Comparison of Observed and Simulated Water Levels – Sally Ward Spring: Exceedance Curves for Observed and Simulated Stages

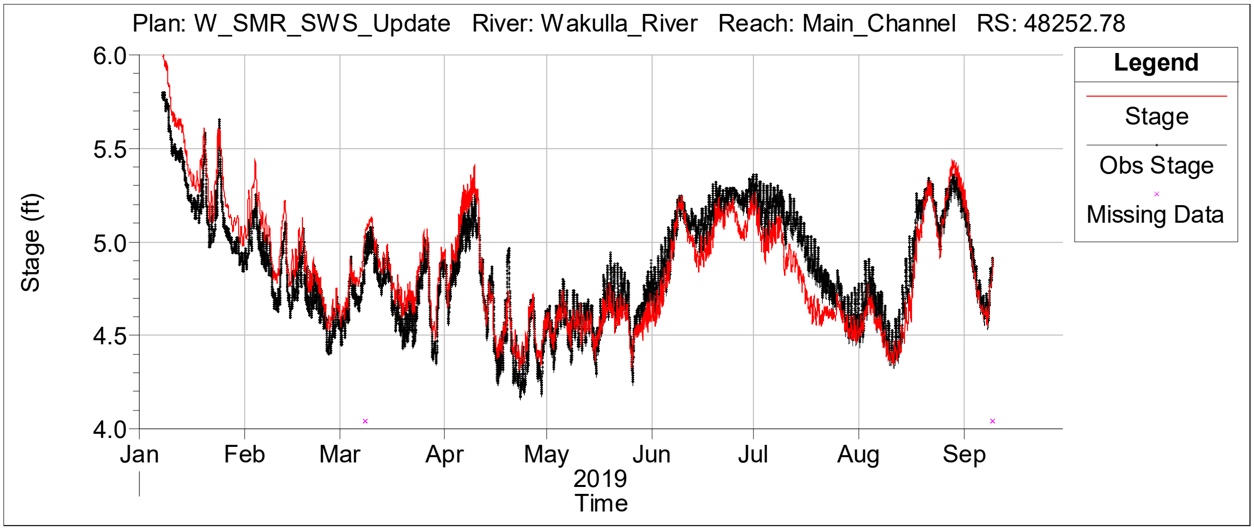


Figure 19a. Comparison of Observed and Simulated Water Levels – USGS 02327000 (Wakulla Springs Pool)

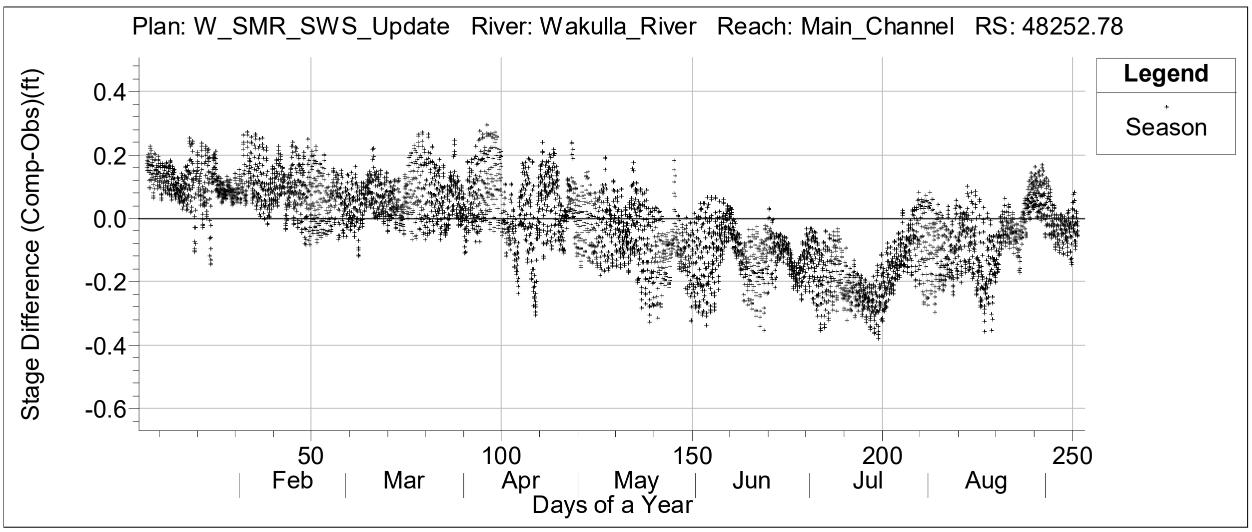


Figure 19b. Comparison of Observed and Simulated Water Levels – USGS 02327000: Residuals (Simulated – Observed) over Time

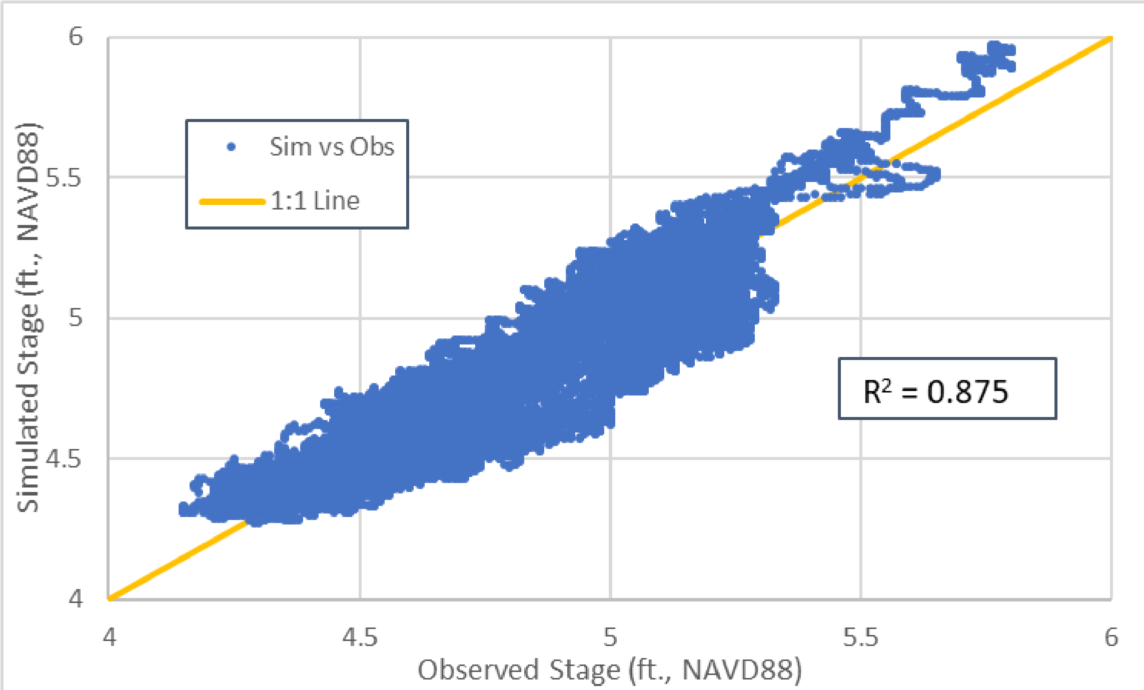


Figure 19c. Comparison of Observed and Simulated Water Levels – USGS 02327000: Scatter Plot of Observed and Simulated Stages

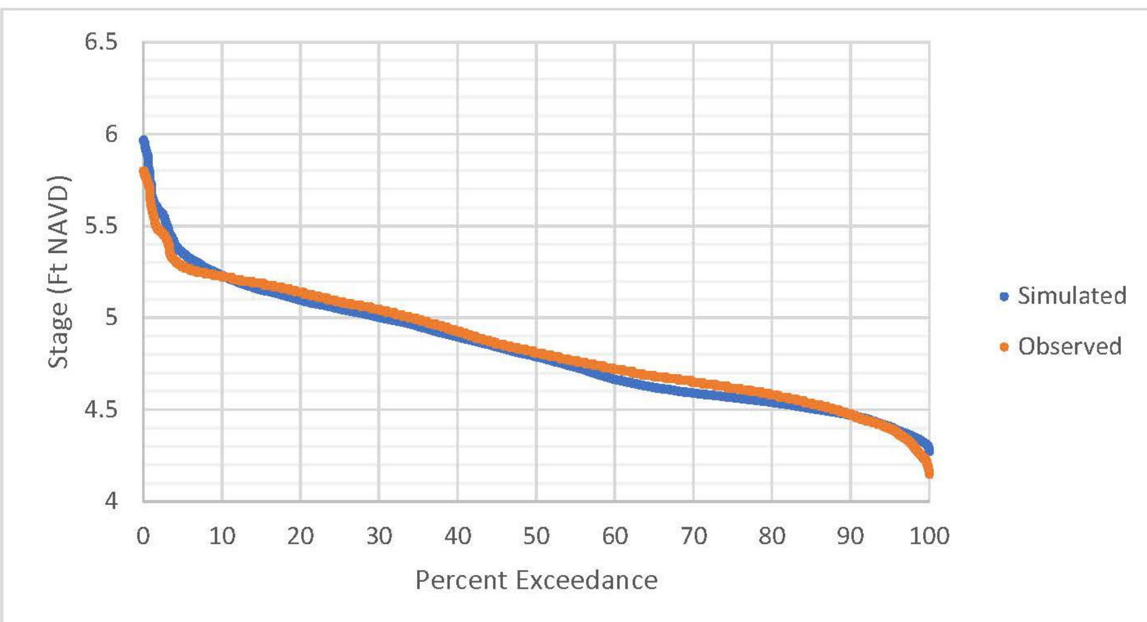


Figure 19d. Comparison of Observed and Simulated Water Levels – USGS 02327000: Exceedance Curves for Observed and Simulated Stages

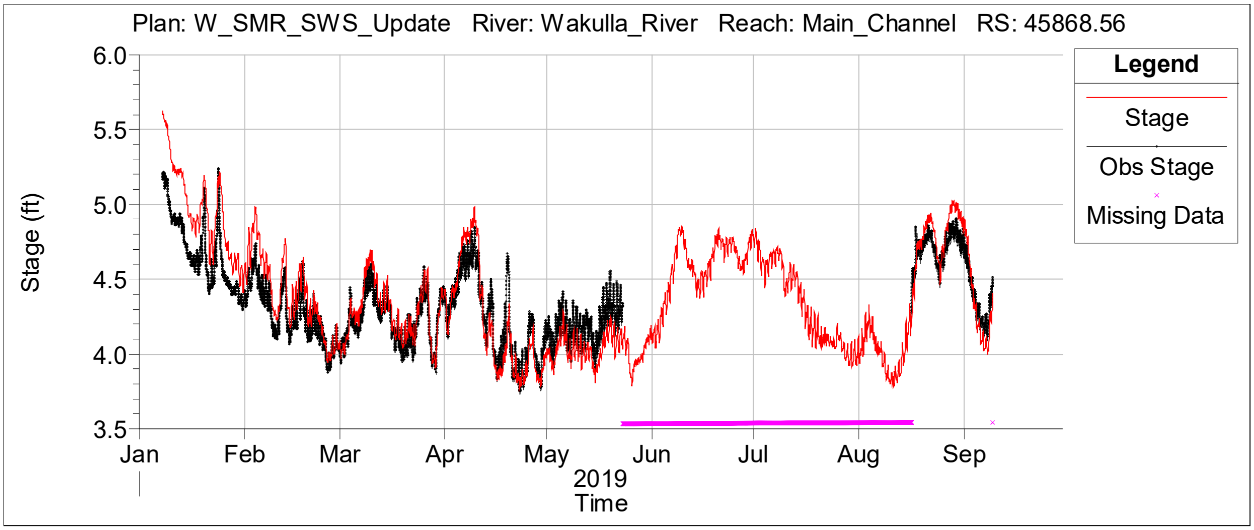


Figure 20a. Comparison of Observed and Simulated Water Levels – Boat Tram (Wakulla River): Comparison of Simulated and Observed Stage Time Series. Note the purple line represents a period of missing data.

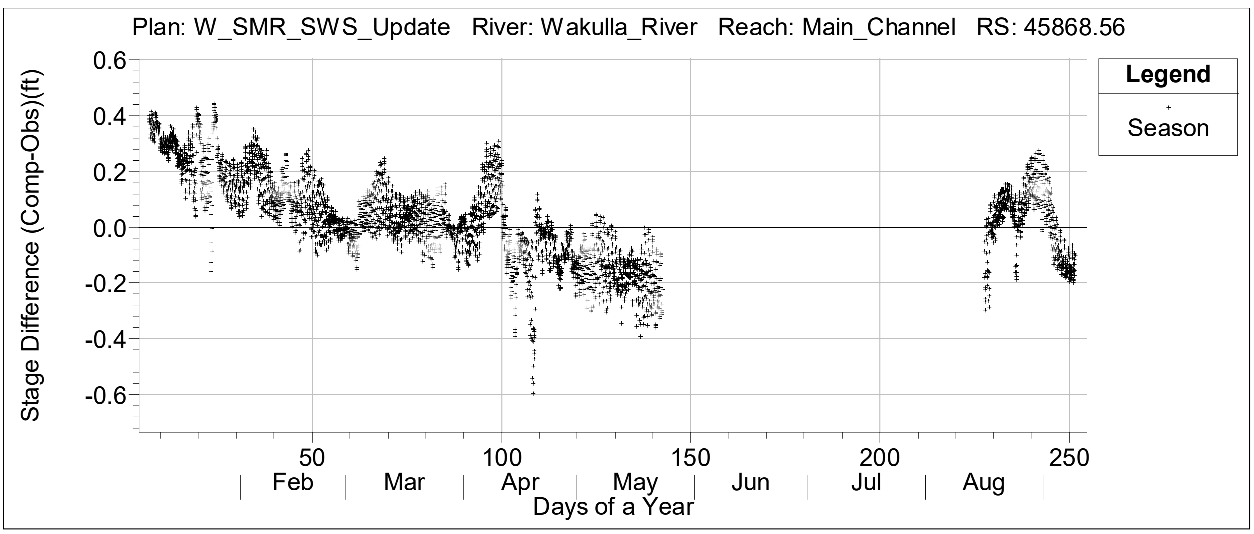


Figure 20b. Comparison of Observed and Simulated Water Levels – Boat Tram (Wakulla River): Residuals (Simulated – Observed) over Time

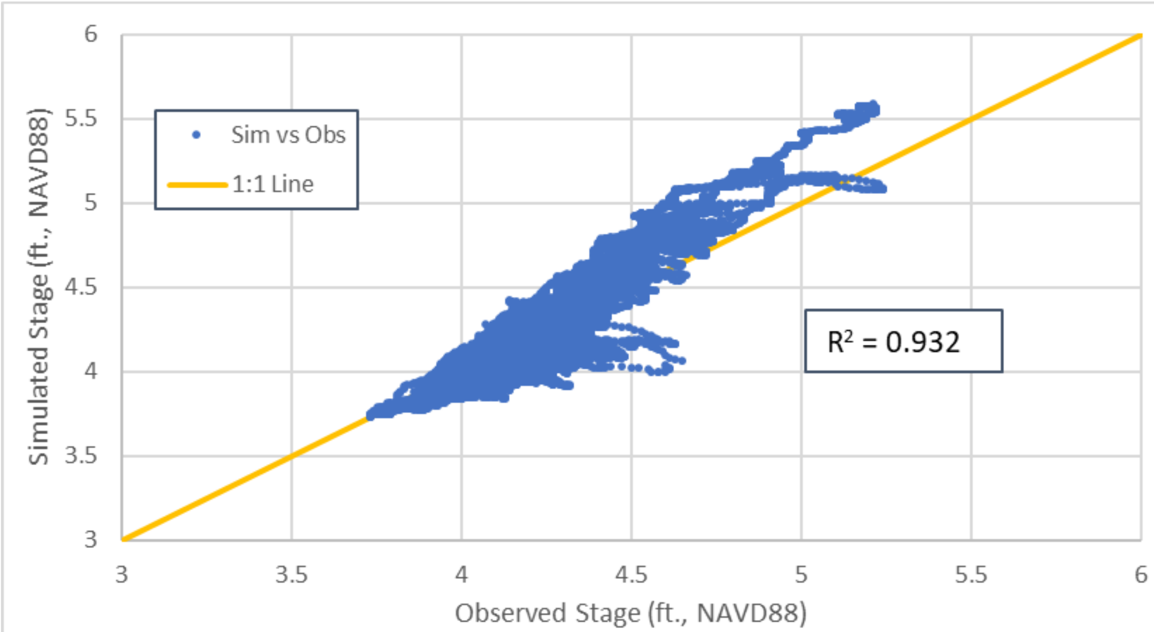


Figure 20c. Comparison of Observed and Simulated Water Levels – Boat Tram (Wakulla River): Scatter Plot of Observed and Simulated Stages

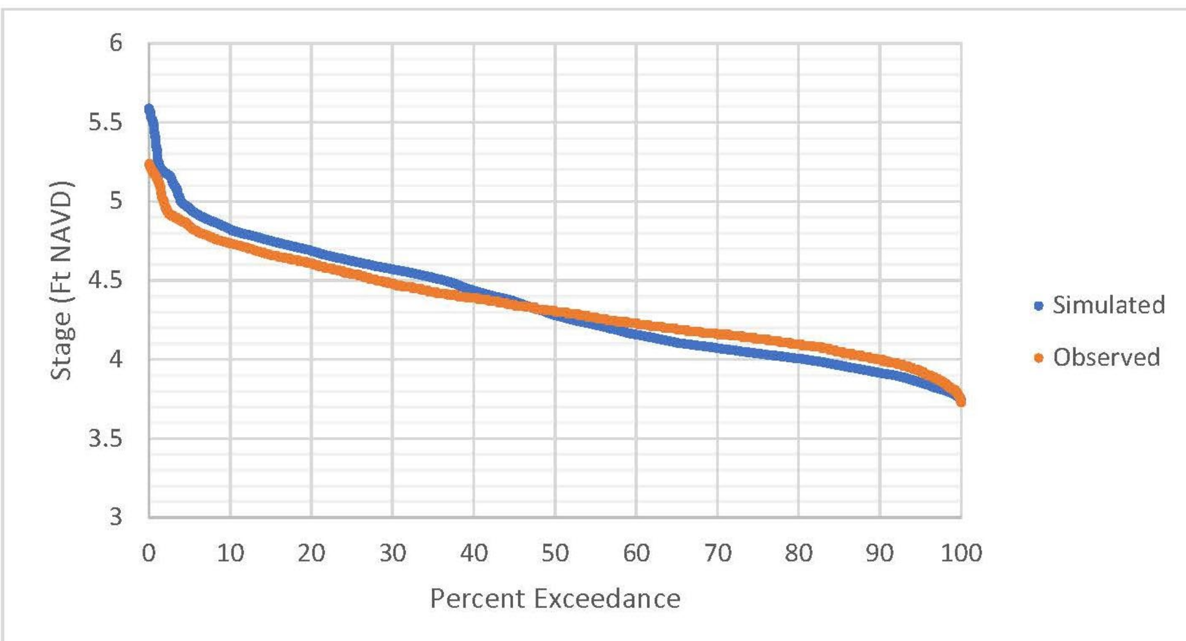


Figure 20d. Comparison of Observed and Simulated Water Levels – Boat Tram (Wakulla River): Exceedance Curves for Observed and Simulated Stages

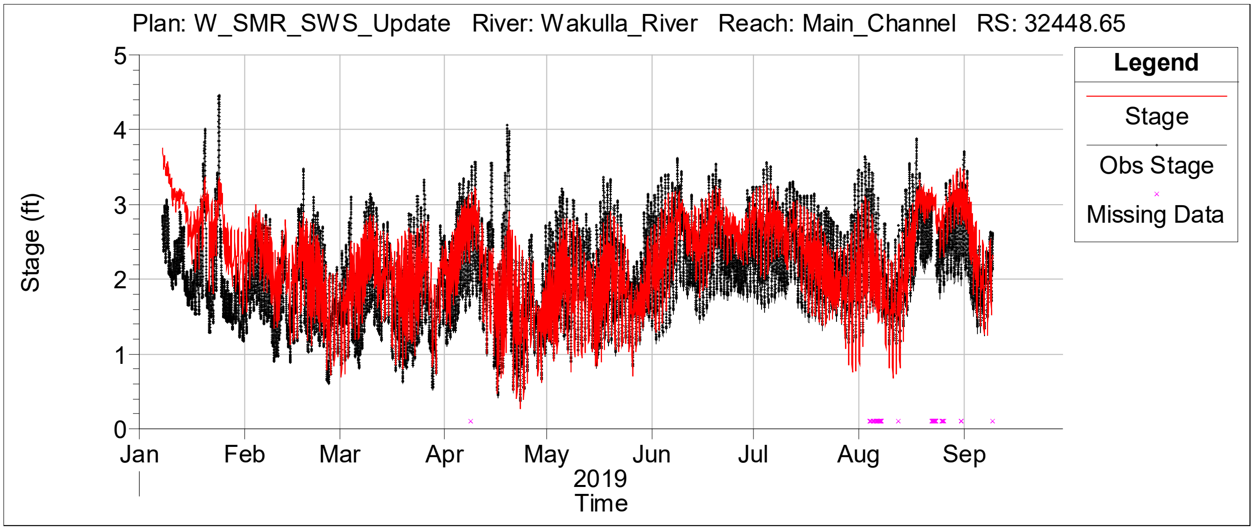


Figure 21a. Comparison of Observed and Simulated Water Levels – USGS 02327022 (Wakulla River Nr Crawfordville): Comparison of Simulated and Observed Stage Time Series

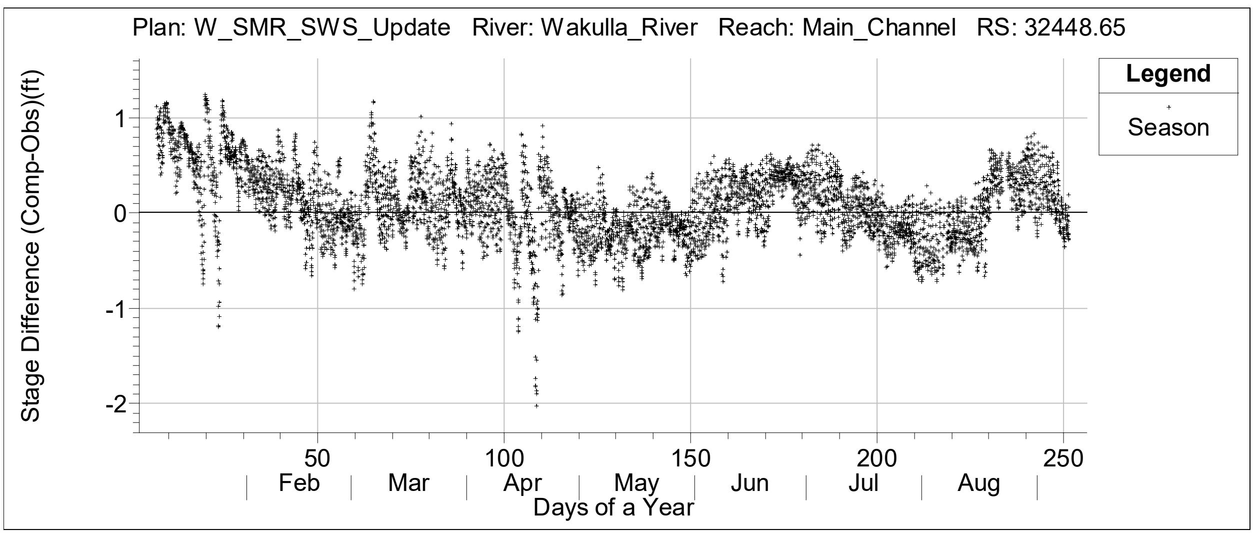


Figure 21b. Comparison of Observed and Simulated Water Levels – USGS 02327022 (Wakulla River Nr Crawfordville): Residuals (Simulated – Observed) over Time

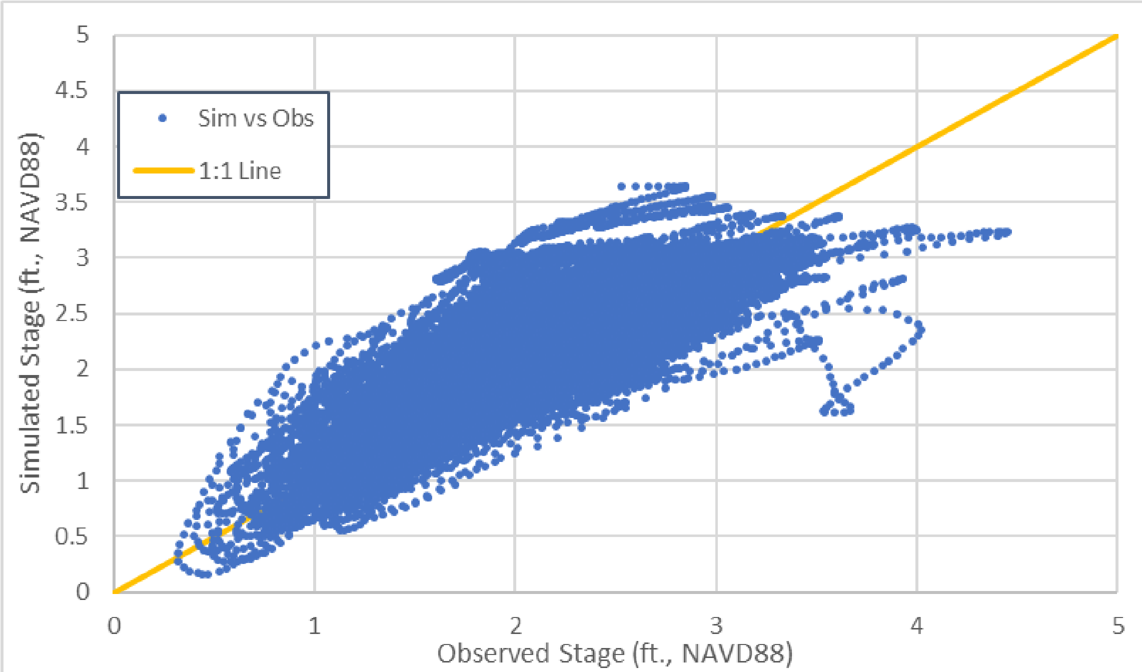


Figure 21c. Comparison of Observed and Simulated Water Levels – USGS 02327022 (Wakulla River Nr Crawfordville): Scatter Plot of Observed and Simulated Stages

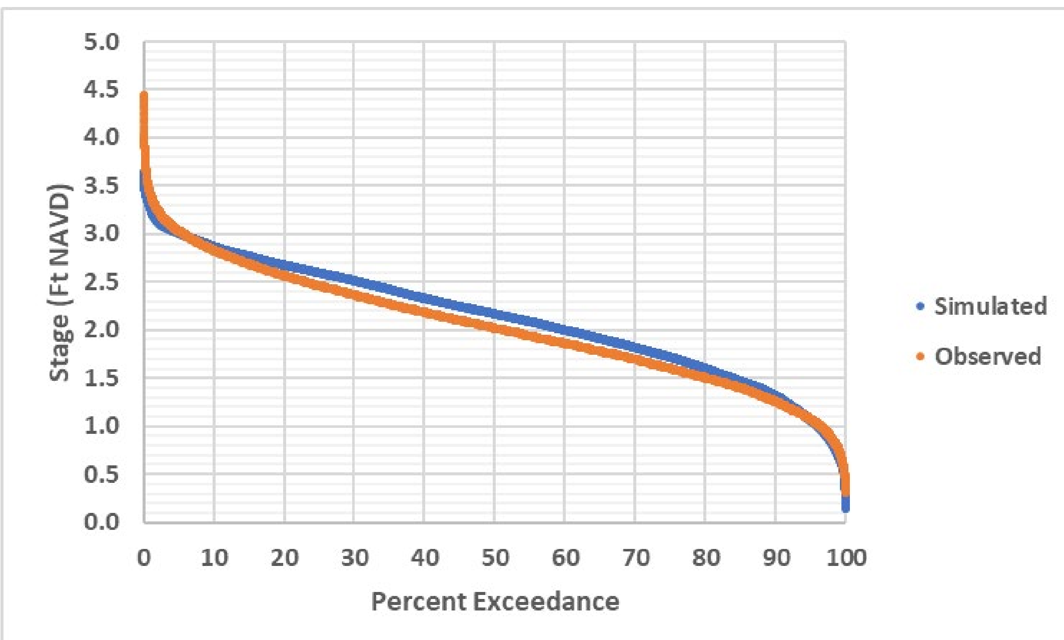


Figure 21d. Comparison of Observed and Simulated Water Levels – USGS 02327022 (Wakulla River Nr Crawfordville): Exceedance Curves for Observed and Simulated Stages

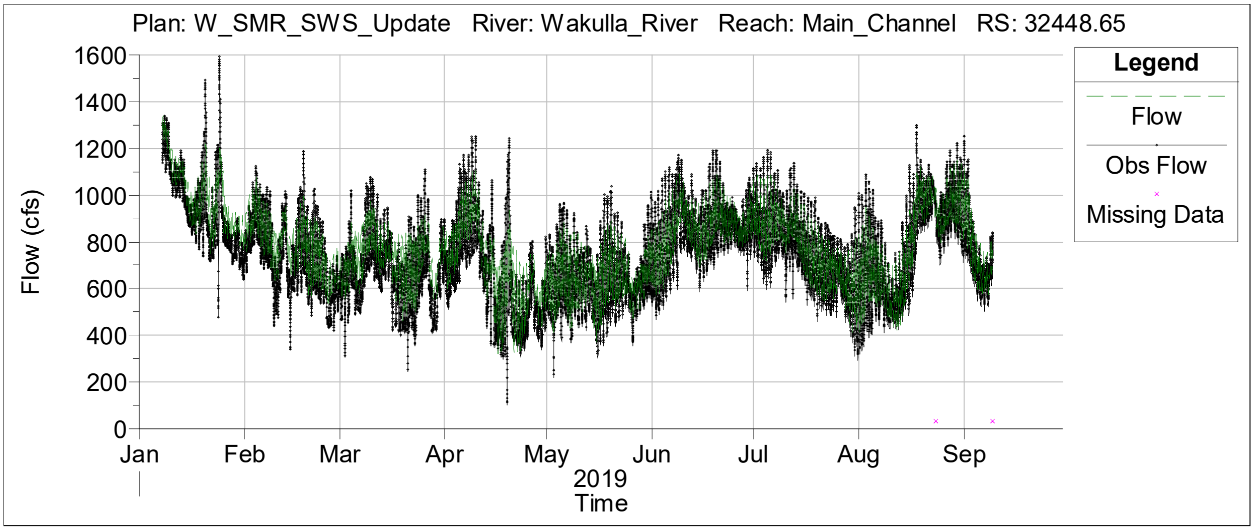


Figure 21e. Comparison of Observed and Simulated Flows - USGS 02327022 (Wakulla River Nr Crawfordville): Comparison of Simulated and Observed Stage Time Series

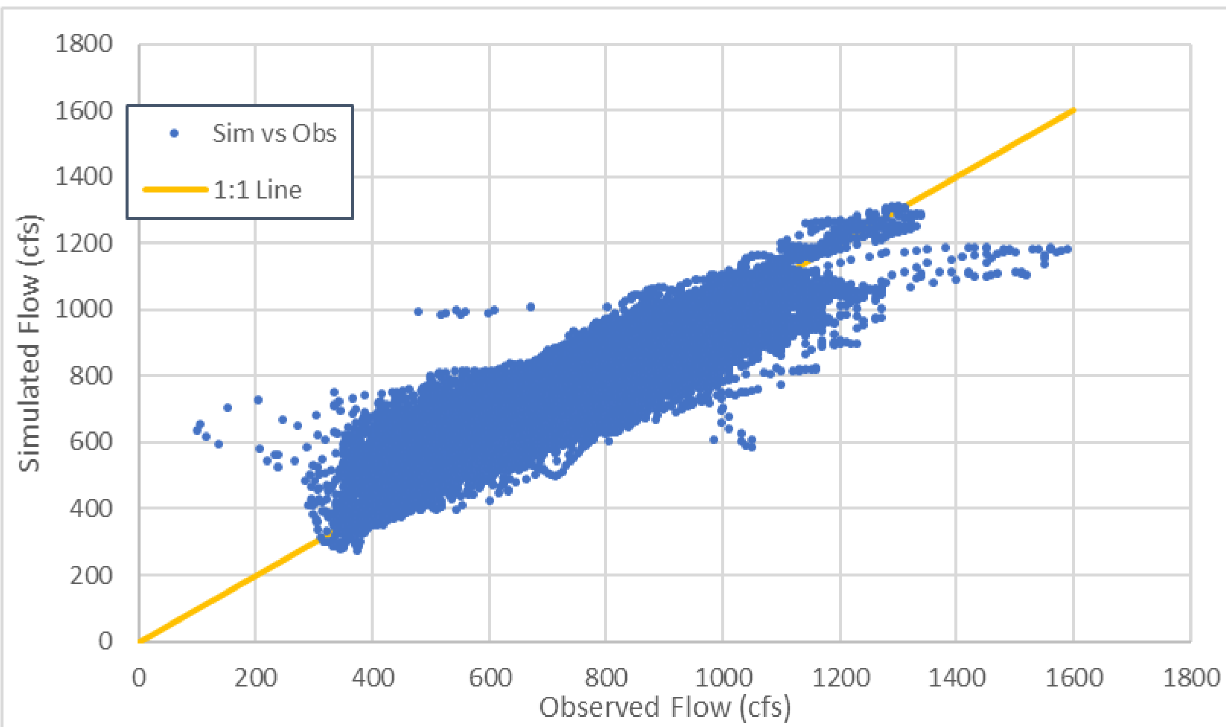


Figure 21f. Comparison of Observed and Simulated Flows - USGS 02327022 (Wakulla River Nr Crawfordville): Scatter Plot of Observed and Simulated Flows

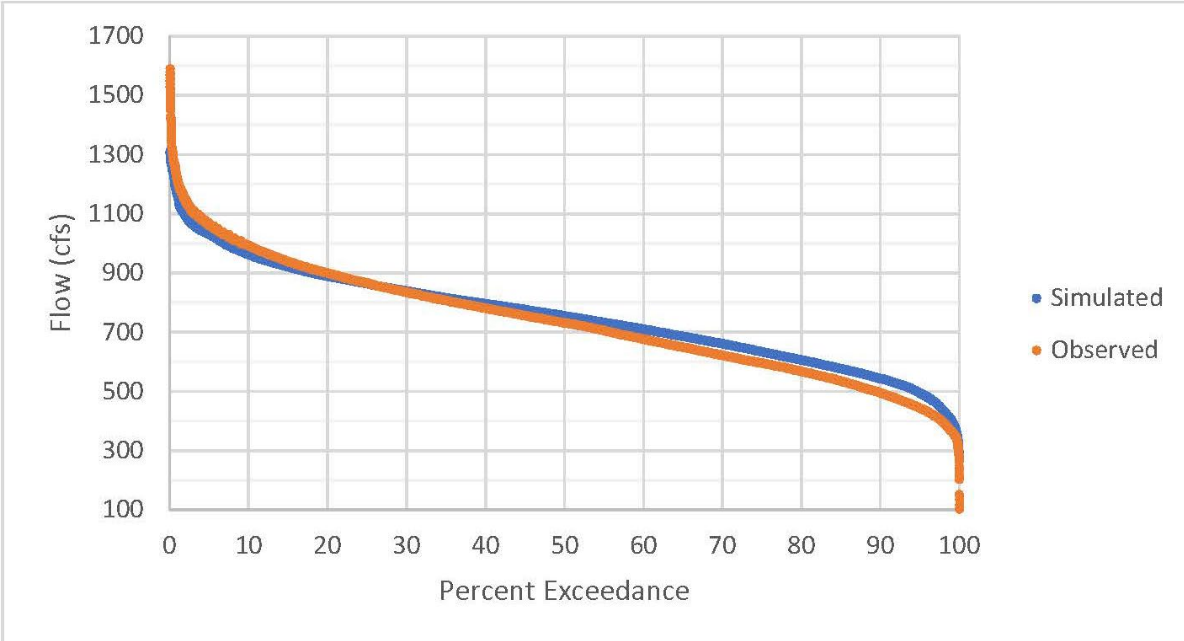


Figure 21g. Comparison of Observed and Simulated Flows - USGS 02327022 (Wakulla River Nr Crawfordville): Exceedance Curves for Observed and Simulated Flows

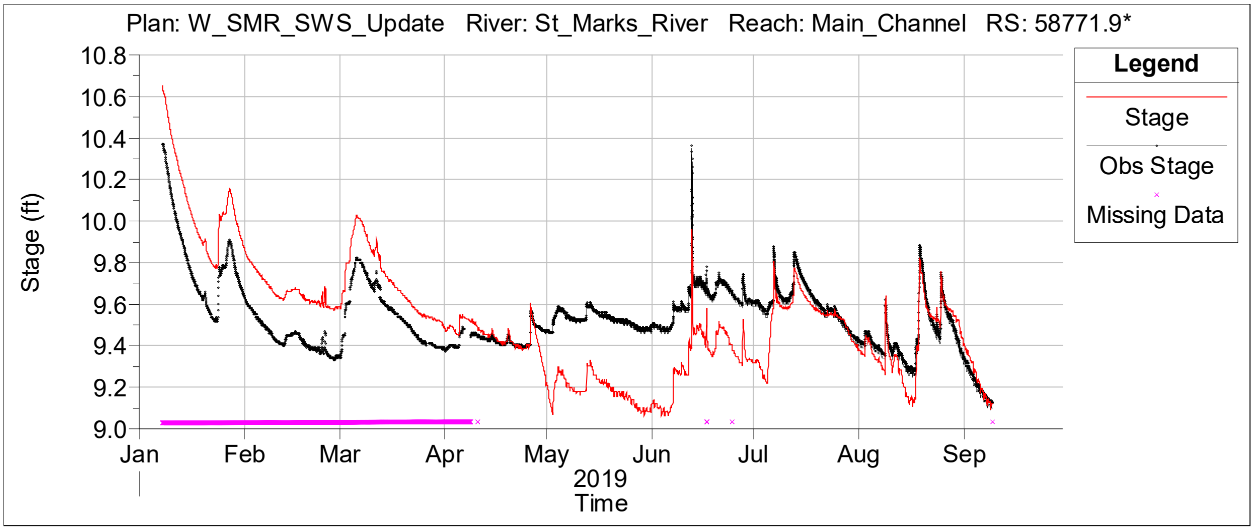


Figure 22a. Comparison of Observed and Simulated Water Levels - Station 02326900 (St. Marks River nr Newport): Comparison of Simulated and Observed Stage Time Series

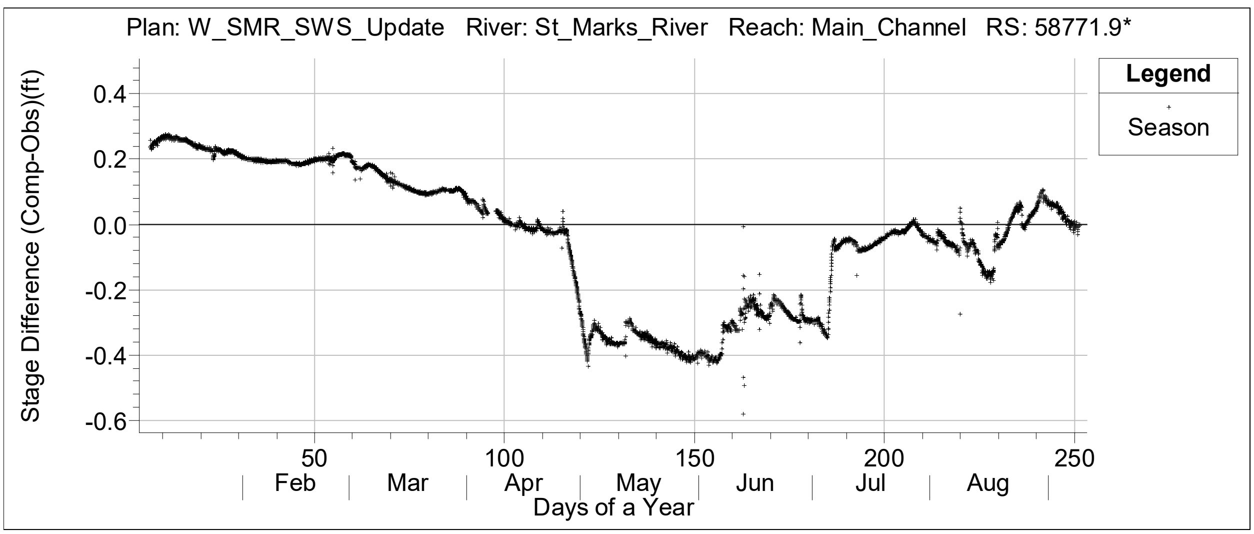


Figure 22b. Comparison of Observed and Simulated Water Levels - Station 02326900 (St. Marks River nr Newport): Residuals (Simulated – Observed) over Time

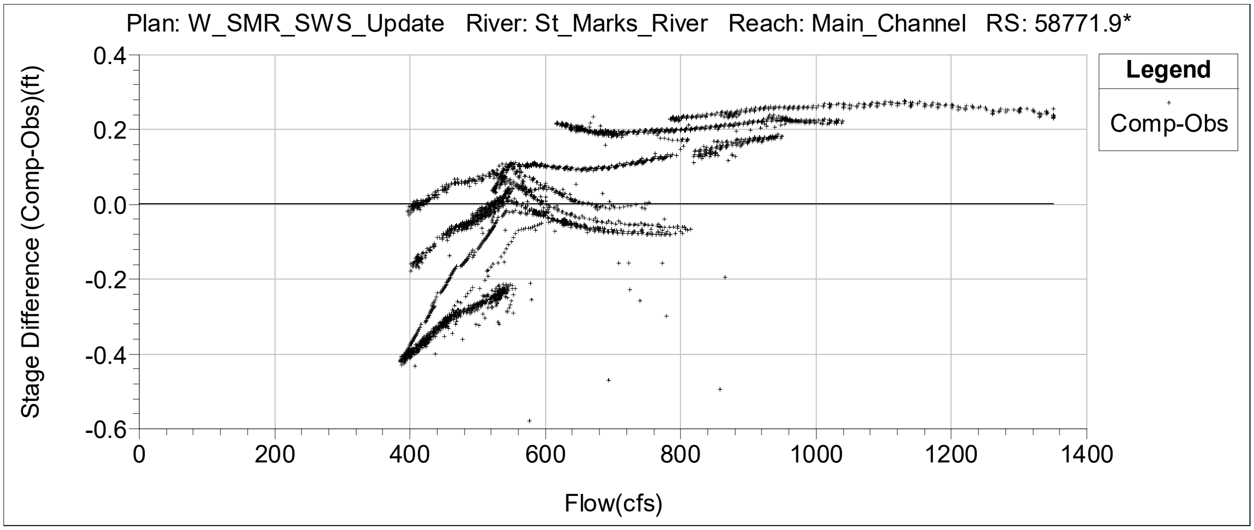


Figure 22c. Comparison of Observed and Simulated Water Levels - Station 02326900 (St. Marks River nr Newport): Residuals (Simulated – Observed) vs Flow

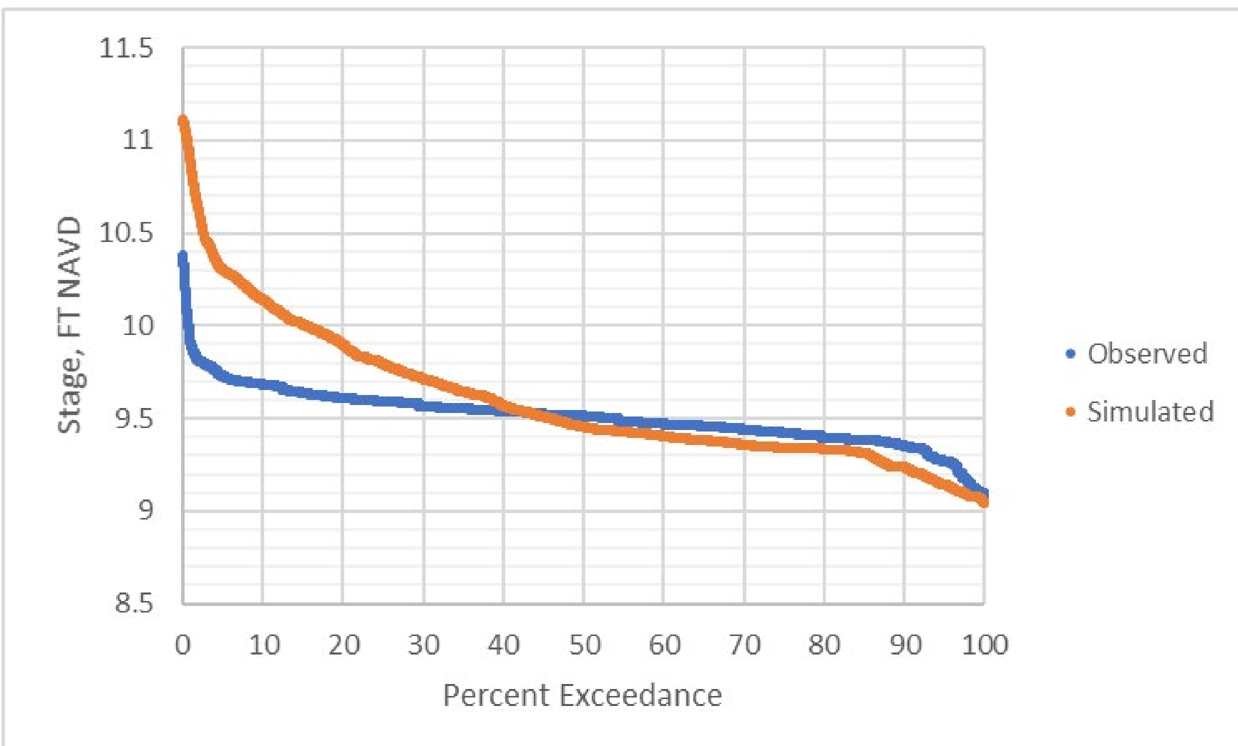


Figure 22d. Comparison of Observed and Simulated Water Levels - Station 02326900 (St. Marks River nr Newport): Exceedance Curves for Observed and Simulated Stages

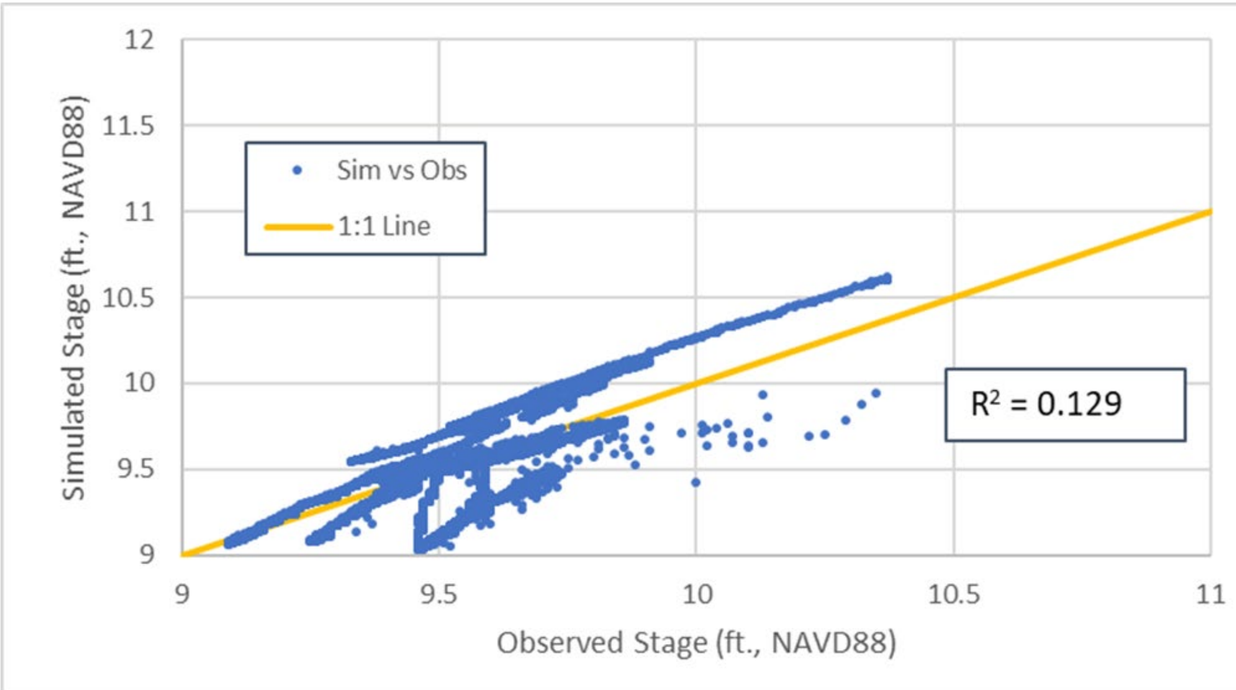


Figure 22e. Comparison of Observed and Simulated Water Levels - Station 02326900 (St. Marks River nr Newport): Scatter Plot of Observed and Simulated Stages

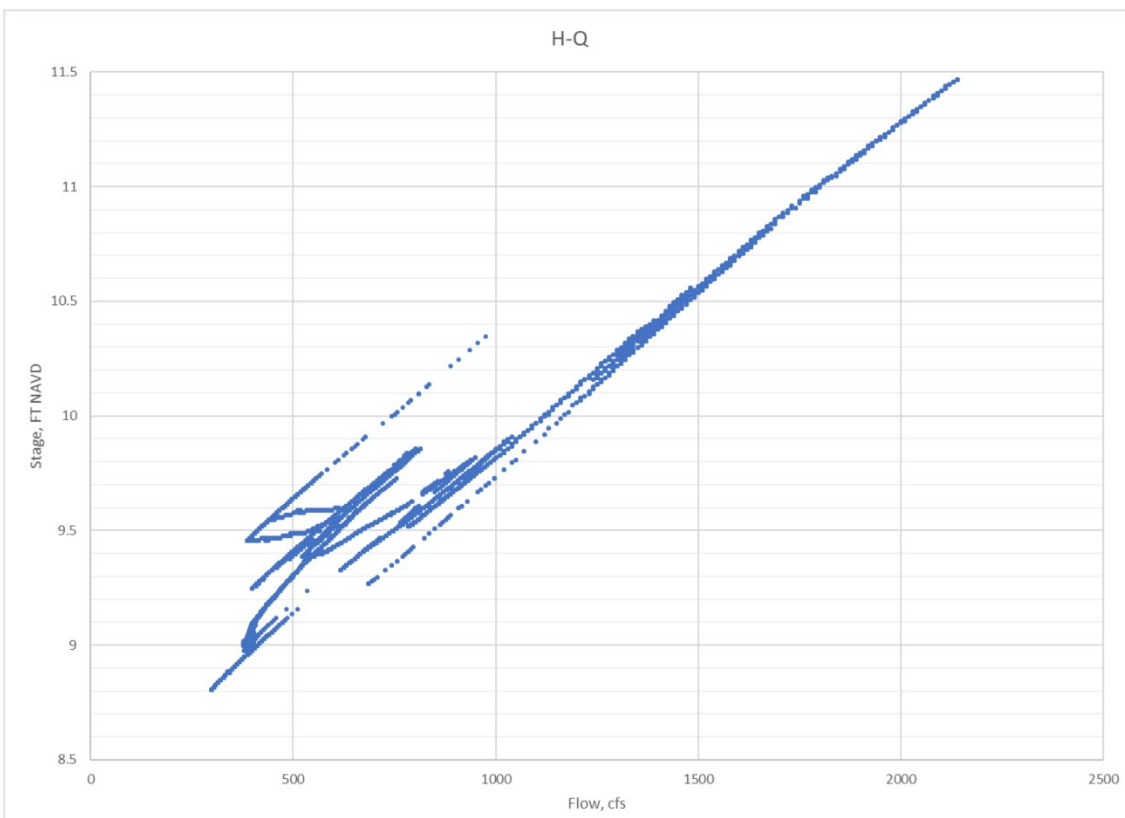


Figure 22f. Comparison of Observed and Simulated Water Levels - Station 02326900 (St. Marks River nr Newport): Rating Curve of Published Stage and Flow

6.1 MODEL PERFORMANCE EVALUATION

To calibrate and validate the models for comparison purposes, model performance statistics were determined. In this study, the stage data measured at the five calibration locations (Sally Ward Spring, USGS 02327000, Boat Tram, USGS 02327022 and USGS 02326900 and flow at USGS 02327022) were used to assess the model performance. Due to varied strengths of the different performance measures, Moriasi et al. (2015) recommend the use of multiple graphical and statistical performance measures. Graphical performance measures allow visual comparison of simulated and measured output response data, help identify model bias, identify differences in timing and magnitude of peaks (e.g., peak flows) and shape of recession curves, and illustrate how well the model reproduces the frequency of measured daily values (Pfannerstill et al., 2014). Both direct and derived graphical performance measures are recommended in determining model calibration and validation performance. For shorter periods and coarse temporal resolutions (e.g., monthly calibration for one to three years), time series and scatter plots are most effective for data visualization and demonstration of model performance. With increasing data points, an inconsistent understanding of model performance may result from direct graphical performance measures. Under such circumstances, derived measures such as cumulative distributions or duration curves should be employed (Moriasi et al.,2015).

Statistical performance measures with varied complementary strengths recommended by Moriasi et al. (2015) included coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and root-mean-square-error (RMSE) observations standard deviation ratio (RSR). HEC-RAS model results were evaluated with these statistical performance measures as well as with graphical comparison of observed and simulated stage and flow time series, stage and flow duration curves and residuals.

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. (2004) 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.

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

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; O 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, whereas an R^2 of zero represents no linear relationship.

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

Equation 2

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 et al, 1999).

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

Equation 3

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. Singh et al. (2004) 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.

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

Equation 4

In these equations, 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.

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared to the measured data variance (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE varies from negative infinity to an optimal value of 1.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

Equation 5

Table 2 presents a summary of performance evaluation criteria for recommended statistical performance measures for watershed models. While these criteria relate to daily flow in Moriasi et al (2015), they do provide a means of assessing whether model performance, based on statistical performance measures in this application is satisfactory or not. Engel et al. (2007) note that typically, model performance is poorer for shorter periods than for longer periods (e.g., daily versus monthly versus yearly).

Table 2. Summary of Performance Evaluation Criteria for Recommended Statistical Performance Measures for Watershed Models. (after Moriasi et al. 2015)

	Performance Evaluation Criteria			
Measure	Very Good	Good	Satisfactory	Not Satisfactory
R^2	R^2>0.85	0.75<R^2<0.85	0.60<R^2<0.75	R^2≤0.60
NSE	NSE>0.80	0.70<NSE<0.80	0.50<NSE<0.70	NSE≤0.50
PBIAS(%)	PBIAS<±5	±5<PBIAS<±10	±10<PBIAS<±15	PBIAS≥±15

Table 3 presents the model statistics for the initial model calibration based on 15-minute observed and simulated time series. For the performance measures listed, model performance can be classified as good to very good at all locations except at USGS 02327022, Wakulla River near Crawfordville. For stage, model performance can be classified as satisfactory to good at this location. This location is the most downstream calibration point on the Wakulla River and is most affected by tide and the use of predicted tide as the downstream boundary condition. Additional model calibration was performed (described in Section 7) to try to improve model performance at all locations, and specifically at USGS 02327022.

Table 3. Summary Statistics of Model Performance – St. Marks River/Wakulla River HEC-RAS Model Initial Calibration (Based on 15-minute simulated and observed time series)

River	Station	Statistics	Mean (ft-NAVD88)	Max (ft-NAVD88)	Min (ft-NAVD88)	R^2	RMSE	RMSE/ Range	PBIAS(%)	RSR
Sally Ward Spring	SWS	Obs	5.18	6.15	4.48	0.908	0.148	8.9%	0.244	0.501
		Sim	5.19	6.76	4.62					
		Diff	-0.01	-0.61	-0.14					
Wakulla River	2327000	Obs	4.85	5.80	4.15	0.875	0.129	7.8%	0.409	0.431
		Sim	4.83	5.97	4.27					
		Diff	0.02	-0.17	-0.12					
	Boat Tram	Obs	4.34	5.24	3.73	0.937	0.155	10.2%	0.787	0.543
		Sim	4.35	5.59	3.73					
		Diff	-0.01	-0.35	0.00					
	2327022 (Stage)	Obs	2.04	4.45	0.32	0.736	0.382	9.3%	4.311	0.635
		Sim	2.14	3.65	0.16					
		Diff	-0.10	0.80	0.16					
	2327022 (Flow)	Obs	732.45	1590.00	99.70	0.889	59.195	4.0%	1.759	0.310
		Sim	755.05	1310.62	271.33					
		Diff	-22.60	279.38	-171.63					
St. Marks River	2326900	Obs	9.51	10.37	9.09	0.129	0.220	17.2%	1.230	1.491
		Sim	9.39	10.62	9.03					
		Diff	0.12	-0.25	0.06					

7.0 MODEL FINAL CALIBRATION AND VALIDATION

Based on the results of the initial calibration, additional adjustments were made to Manning's n values and to the elevation of incorporated ineffective flow areas in the channel to further improve model accuracy. An additional ineffective flow area was placed in Sally Ward Spring Run near the confluence with the Wakulla River, based on review of photographs taken during the field reconnaissance in March 2019 indicating more dense vegetative coverage. In-channel Manning's n was increased to reflect losses occurring as the Sally Ward Spring flow enters the Wakulla Springs side channel. Also, connectivity of the Sally Ward Spring Run channel with the Sally Ward floodplain was increased through modification of the ineffective flow areas, adjustments to the floodplain Manning's n, and incorporation of flow roughness factors. These additional adjustments were made in the Sally Ward Spring Run as results from the initial model calibration showed that the model generally underpredicted stage at this location. Field reconnaissance in March 2019 revealed that a high degree of floodplain connection is present along the Sally Ward Spring Run. No parameter adjustments were made to the St. Marks River portion of the model. Table 4 presents the final Manning's n coefficients in the Wakulla River and Sally Ward Spring Run for the calibrated model.

During the construction and testing of the HEC-RAS model update, additional flow and stage data became available from NWFWMD for Sally Ward Spring and the Wakulla Springs vent. Also, an extended period of approved flow and stage data became available for USGS 02327022 (Wakulla River at Crawfordville) and USGS 02326900 (St. Marks River Near Newport). The additional data extended the model simulation period from September 9, 2019 to January 22, 2020. This allowed for a simulation period where the calibrated model could be validated. In addition, flow and stage data from December 24, 2018 to Jan 9, 2019 were added to better calibrate to high flow conditions in the early part of the simulation period. The updated simulation period ranges approximately 13 months, from December 24, 2018, to January 22, 2020.

7.1 MODEL CALIBRATION AND VALIDATION RESULTS

Simulated and observed stages and flows were compared at each water level station in Figures 23 through 28. The figures present the time series and residuals over the entire simulation period.

Table 4. Summary of Final Manning's N Values for Wakulla River

River Sta		n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	n11	n12	n13	n14	n15	n16	n17	n18	n19
52189		0.12	0.085	0.12																
52070		0.12	0.085	0.12																
51914		0.12	0.085	0.12																
50723		0.12	0.085	0.12																
49442		0.12	0.085	0.12																
49370		0.12	0.085	0.12																
49360	Bridge																			
49332		0.12	0.085	0.12																
49206		0.12	0.085	0.12																
48873		0.12	0.095	0.12																
48552.4*		0.1	0.072	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.091	0.1	0.1	0.1					
48252.78		0.1	0.03	0.03	0.035	0.04	0.035	0.035	0.03	0.1										
45868.56		0.1	0.03	0.03	0.1															
44619		0.1	0.04	0.03	0.03	0.03	0.03	0.1												
41707.76		0.1	0.04	0.04	0.04	0.1														
37105		0.1	0.055	0.1	0.04	0.1	0.055	0.04	0.055	0.1	0.065	0.06	0.06	0.1	0.06	0.1	0.06	0.1	0.06	0.1
36465.48		0.1	0.055	0.1	0.055	0.04	0.055	0.04	0.055	0.04	0.065	0.06	0.065	0.06	0.065	0.06	0.065	0.06	0.065	0.1
33245		0.1	0.052	0.048	0.052	0.1														
32910.27		0.1	0.052	0.048	0.052	0.1														
32718.3*		0.1	0.052	0.048	0.052	0.1														
32526.33		0.1	0.052	0.048	0.052	0.1														
32483.62	Bridge																			
32448.65		0.1	0.052	0.048	0.052	0.1														
31969.0*		0.1	0.052	0.048	0.052	0.1														
31489.3*		0.1	0.052	0.048	0.052	0.1														
31009.71		0.1	0.052	0.048	0.052	0.1														
28418.92		0.1	0.052	0.048	0.052	0.035	0.1													
25729.03		0.1	0.052	0.048	0.052	0.1														
23189		0.1	0.052	0.048	0.052	0.1	0.1													
21323		0.1	0.052	0.048	0.052	0.1														
19817.68		0.1	0.052	0.048	0.052	0.1														
15594.65		0.1	0.052	0.048	0.052	0.1	0.1													
15452.0*		0.1	0.052	0.048	0.052	0.1														
15309.36		0.1	0.052	0.048	0.052	0.1														
15285.02	Bridge																			
15258.24		0.1	0.052	0.048	0.052	0.1														
14877.0*		0.1	0.052	0.048	0.052	0.1	0.1													
14495.8*		0.1	0.052	0.048	0.052	0.1														
14114.64		0.1	0.052	0.048	0.052	0.1														
11661.46		0.1	0.052	0.048	0.052	0.1														
8591.789		0.1	0.052	0.048	0.052	0.1														
6118.945		0.1	0.052	0.048	0.052	0.1														
4539.217		0.1	0.052	0.048	0.052	0.06	0.1													
2185.431		0.1	0.052	0.048	0.052	0.1	0.1													
61.68063		0.1	0.052	0.048	0.052	0.1	0.1													

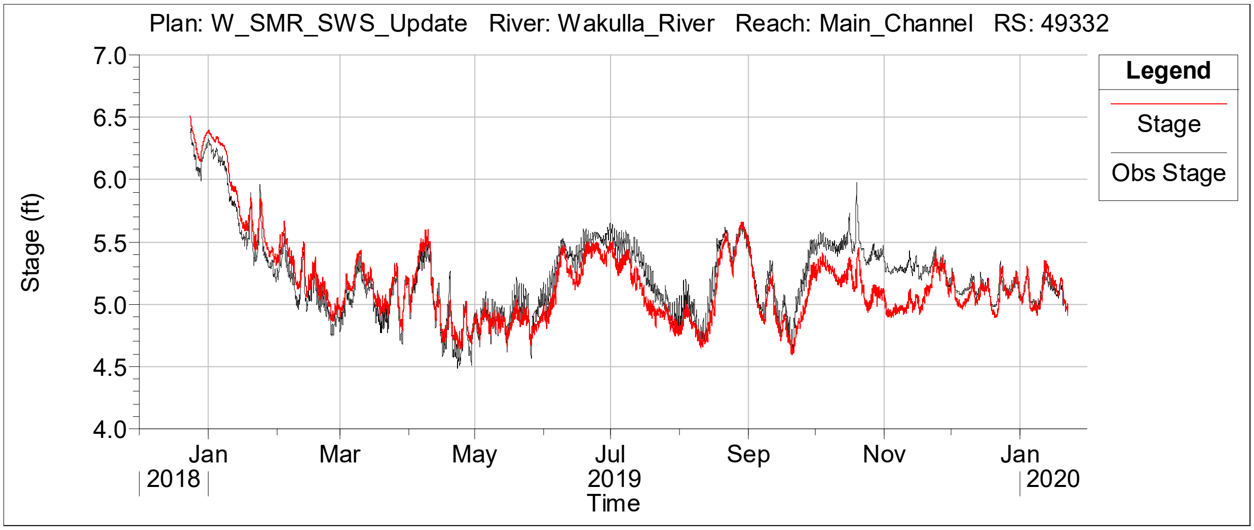


Figure 23a. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Run: Comparison of Simulated and Observed Stage Time Series

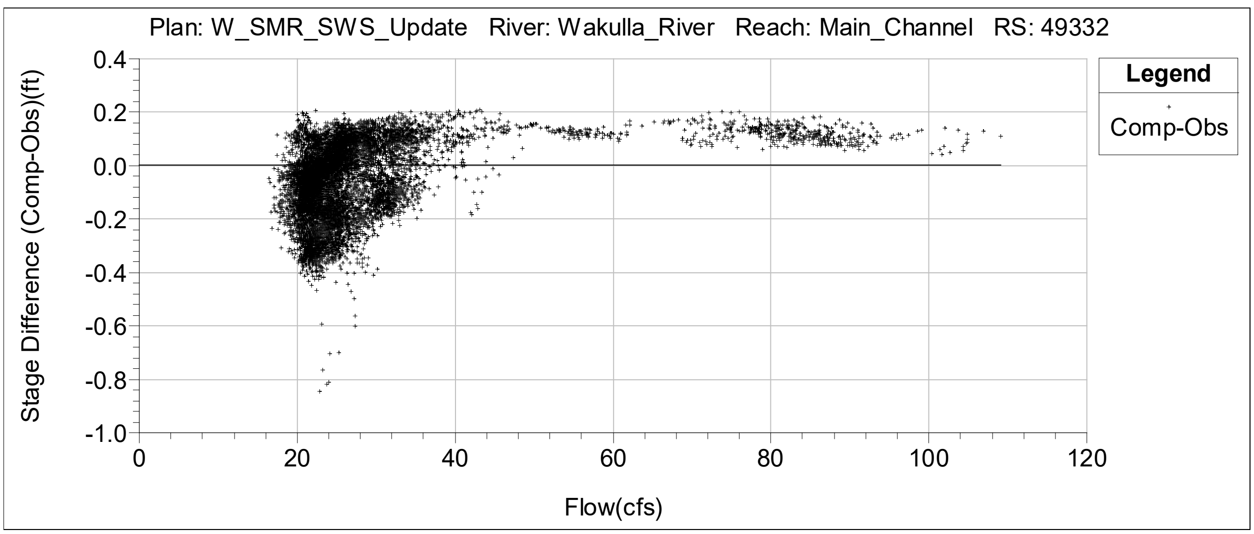


Figure 23b. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Run: Residuals (Simulated – Observed) vs Flow

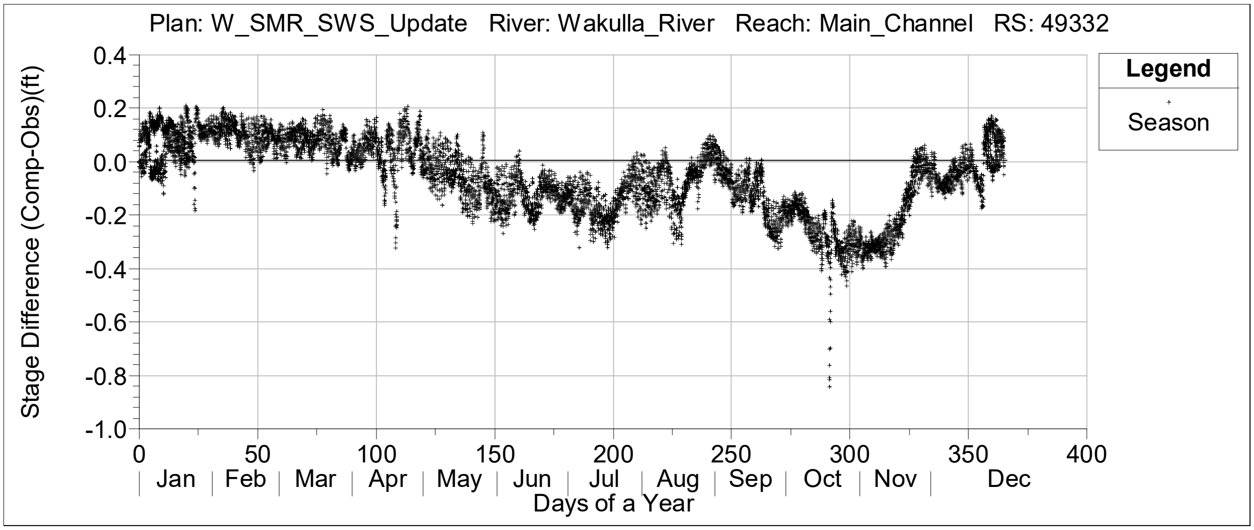


Figure 23c. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Run: Residuals (Simulated – Observed) over Time

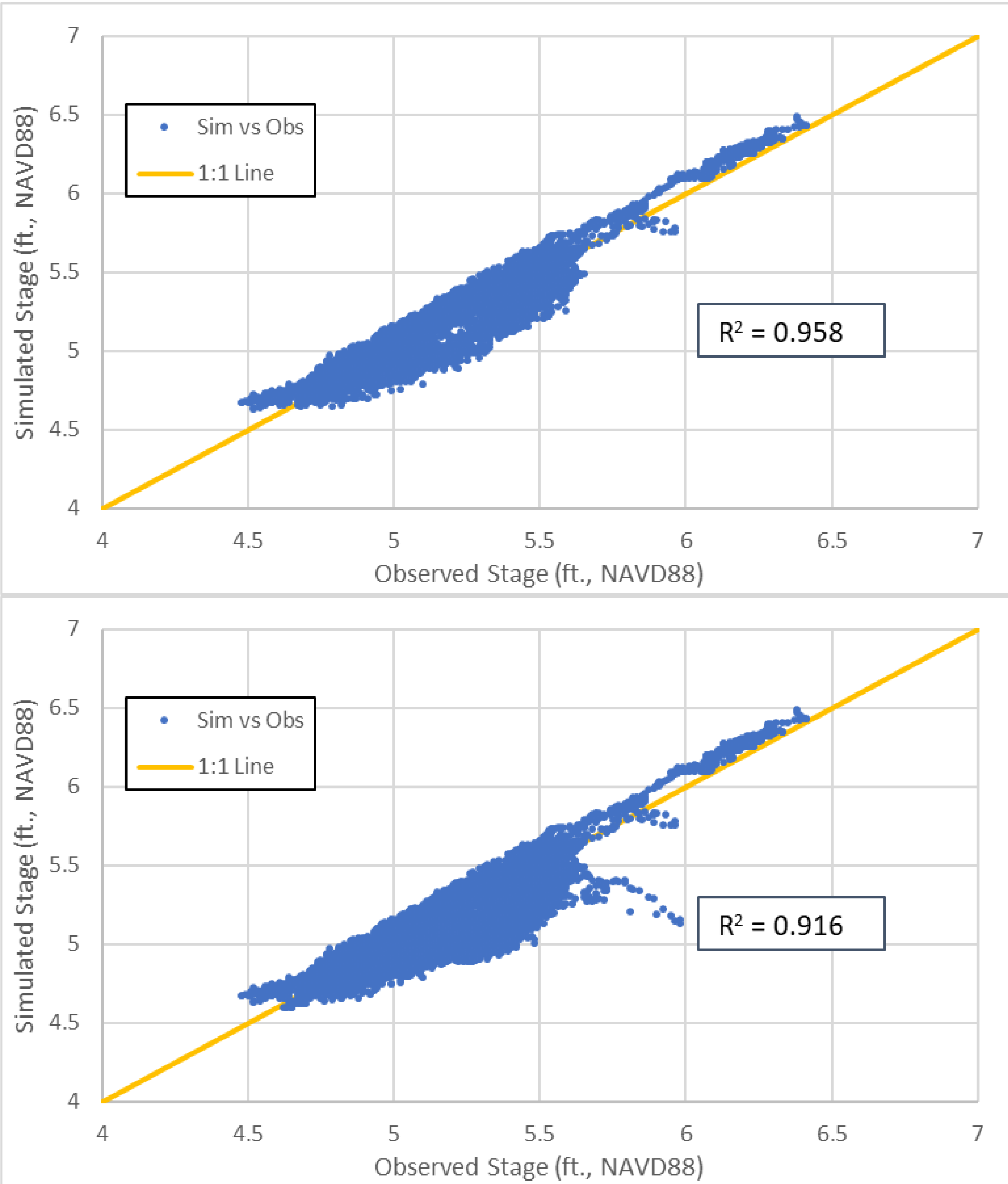


Figure 23d. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Run: Scatter Plot of Observed and Simulated Stages (Calibration-upper, Full Simulation Period-lower)

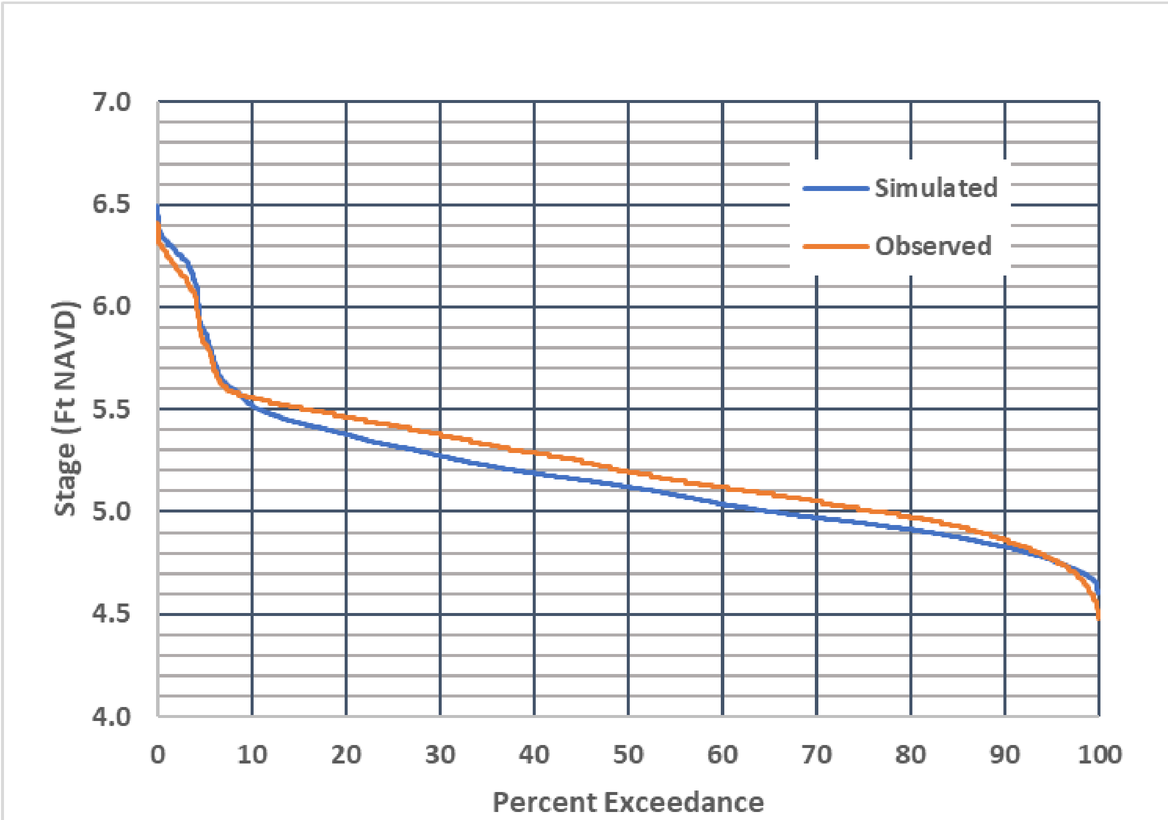


Figure 23e. Comparison of Observed and Simulated Water Levels – Sally Ward Spring Bridge: Exceedance Curves for Observed and Simulated Stages

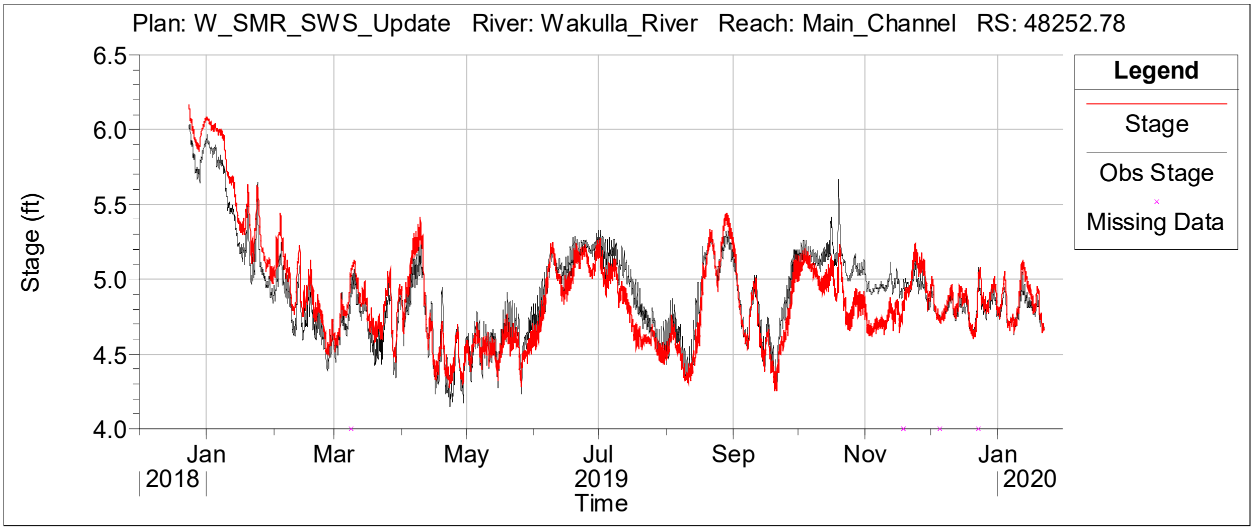


Figure 24a. Comparison of Observed and Simulated Water Levels – USGS 02327000 (Wakulla Springs Pool)

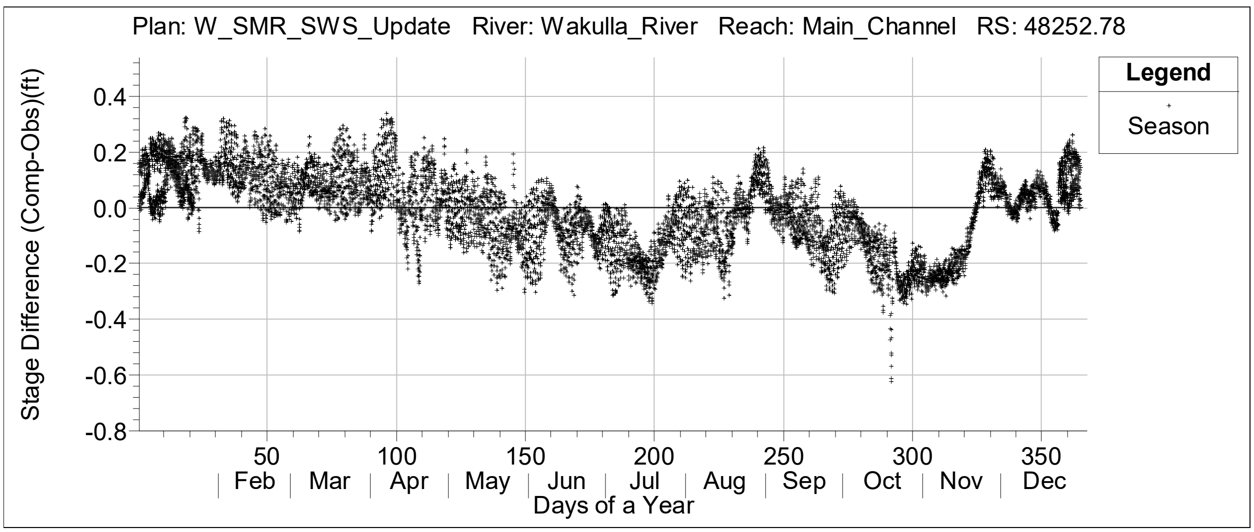


Figure 24b. Comparison of Observed and Simulated Water Levels – USGS 02327000: Residuals (Simulated – Observed) over Time

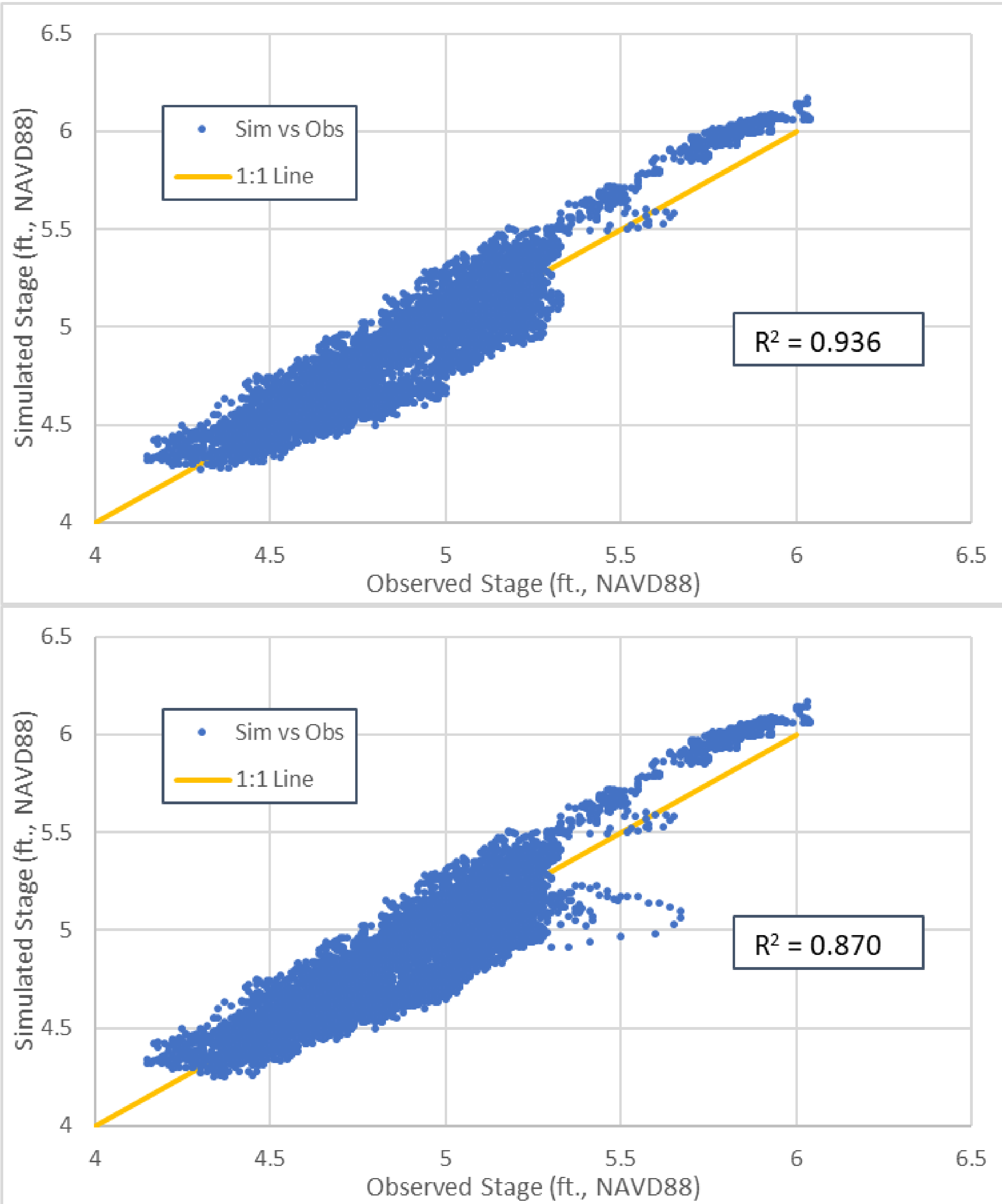


Figure 24c. Comparison of Observed and Simulated Water Levels – USGS 02327000: Scatter Plot of Observed and Simulated Stages (Calibration-upper, Full Simulation Period-lower)

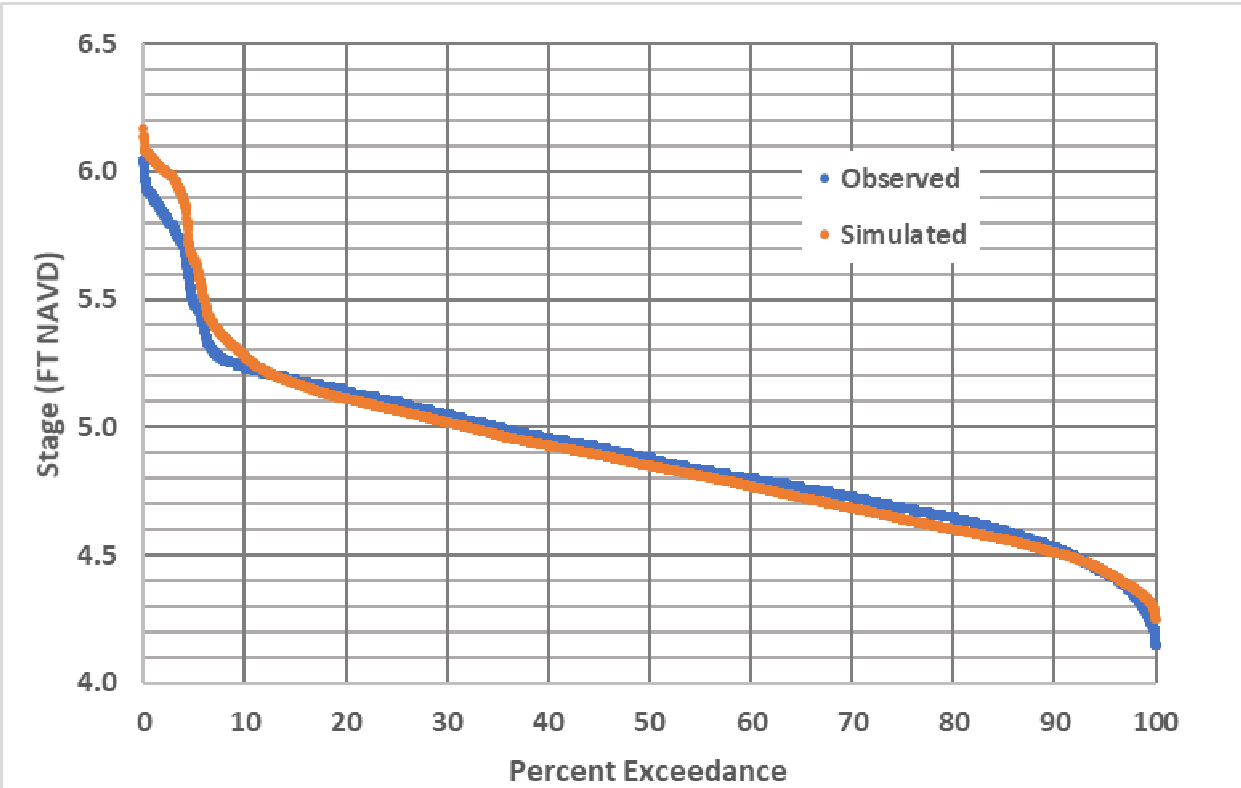


Figure 24d. Comparison of Observed and Simulated Water Levels – USGS 02327000: Exceedance Curves for Observed and Simulated Stages

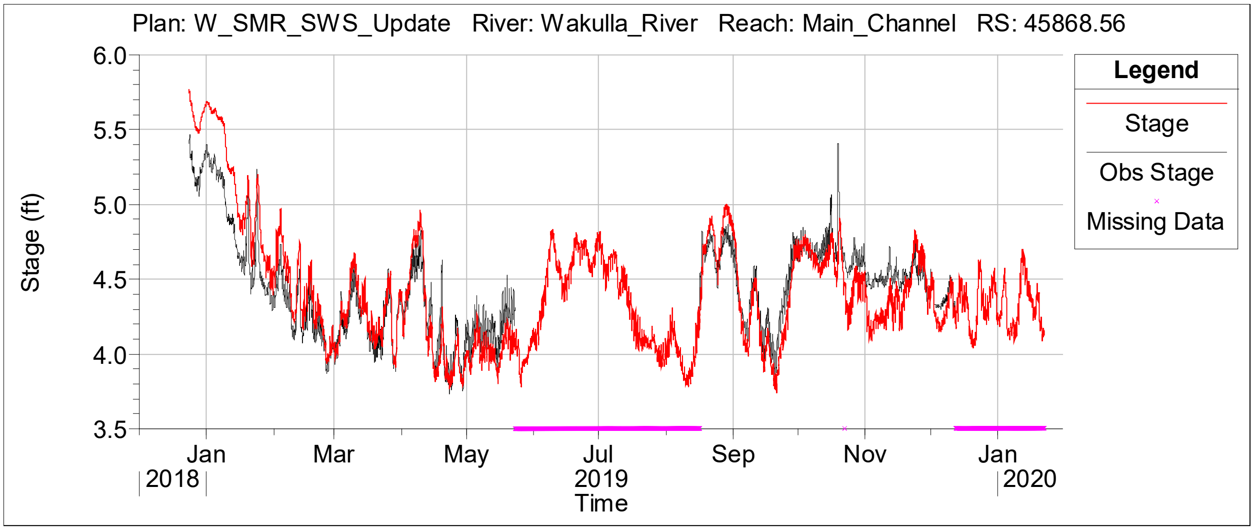


Figure 25a. Comparison of Observed and Simulated Water Levels – Boat Tram (Wakulla River): Comparison of Simulated and Observed Stage Time Series. Note purple line indicates periods of missing measured data.

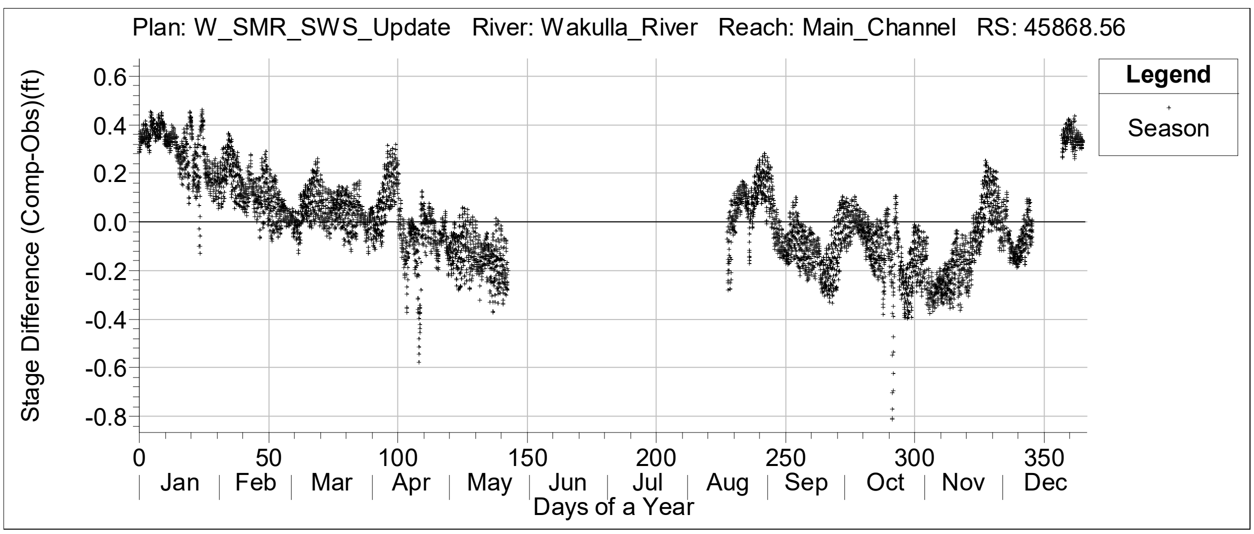
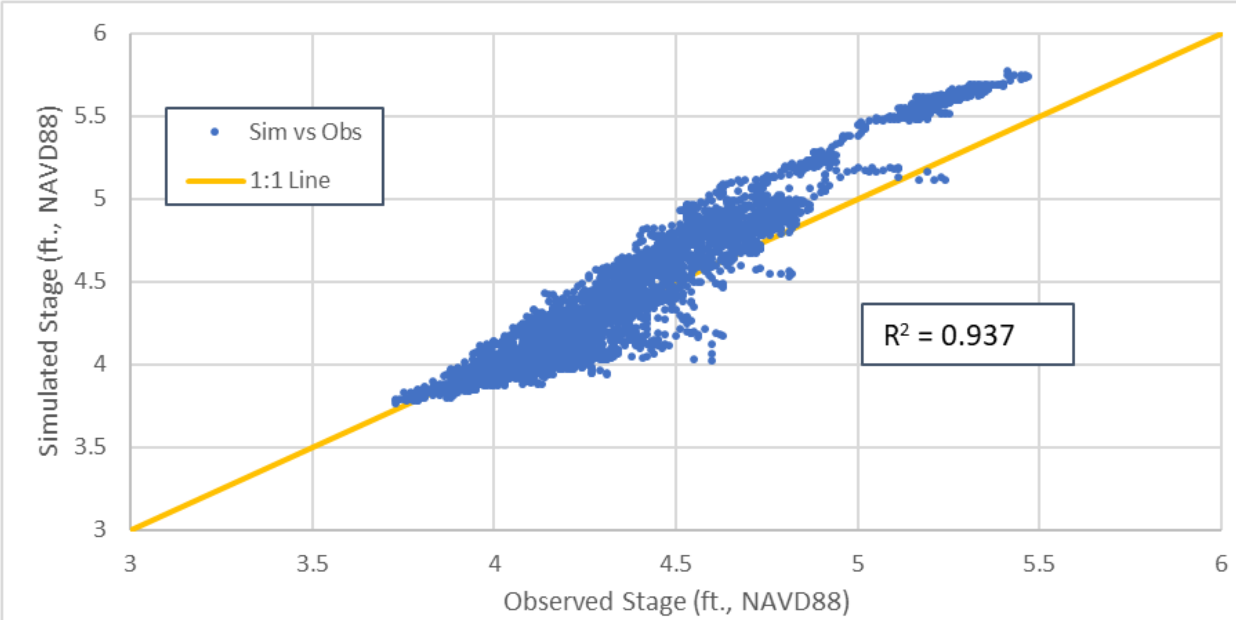


Figure 25b. Comparison of Observed and Simulated Water Levels – Boat Tram (Wakulla River): Residuals (Simulated – Observed) over Time



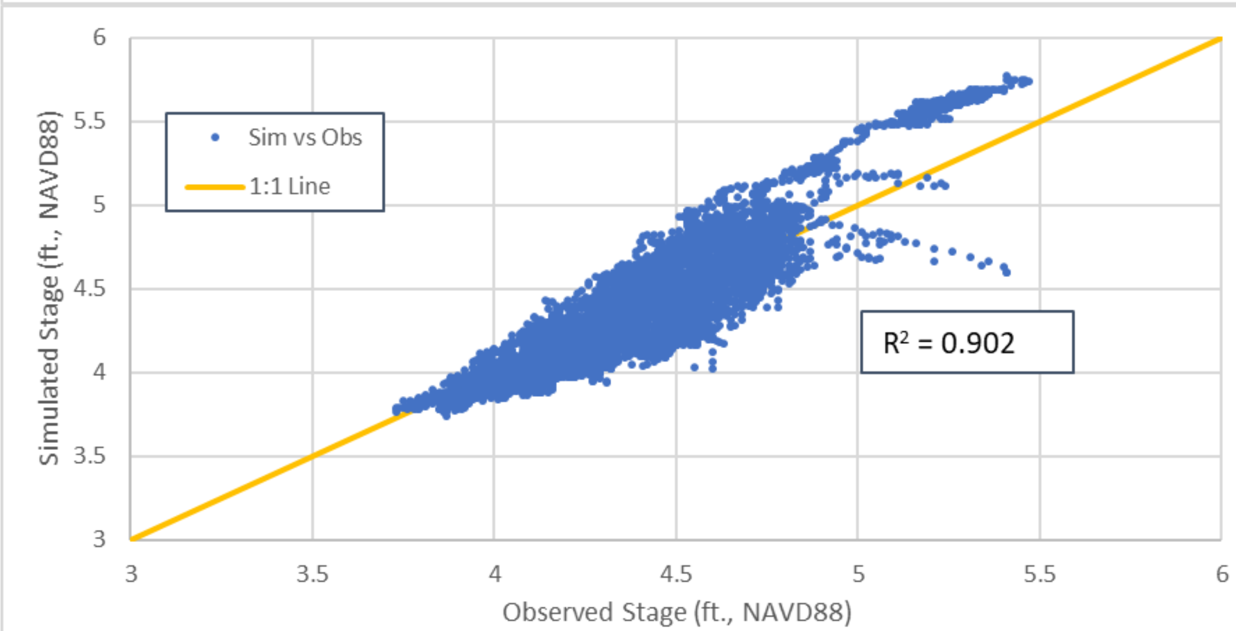


Figure 25c. Comparison of Observed and Simulated Water Levels – Boat Tram (Wakulla River): Scatter Plot of Observed and Simulated Stages (Calibration-upper, Full Simulation Period-lower)

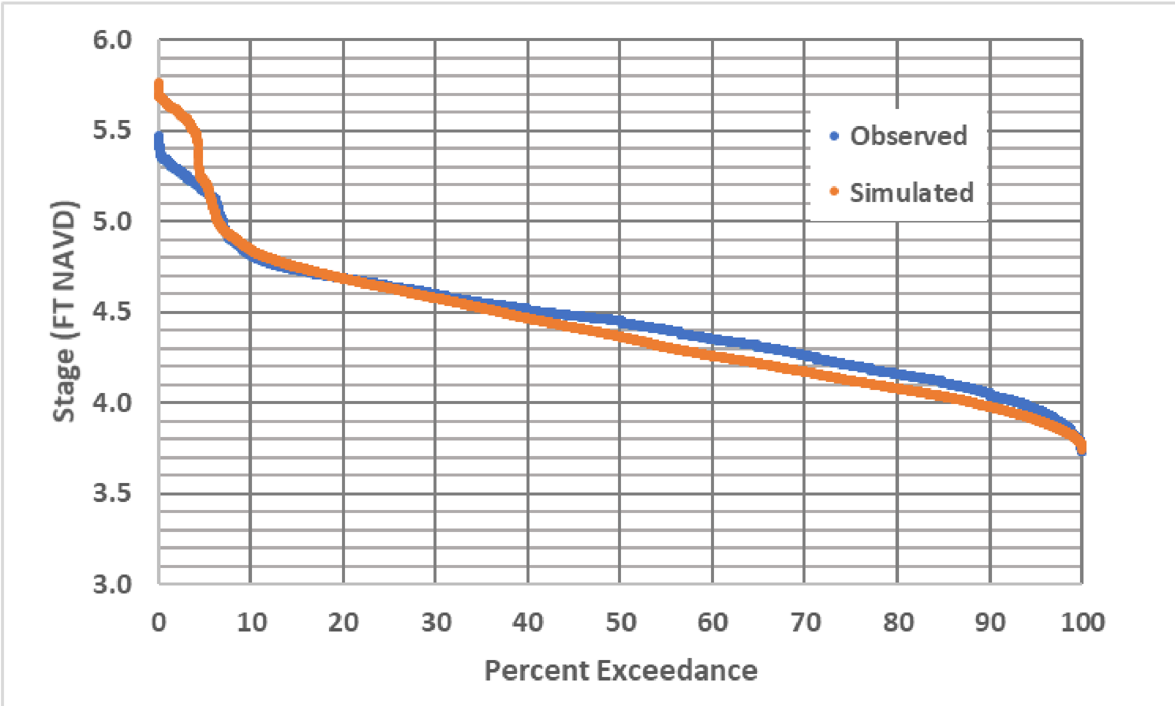


Figure 25d. Comparison of Observed and Simulated Water Levels – Boat Tram (Wakulla River): Exceedance Curves for Observed and Simulated Stages

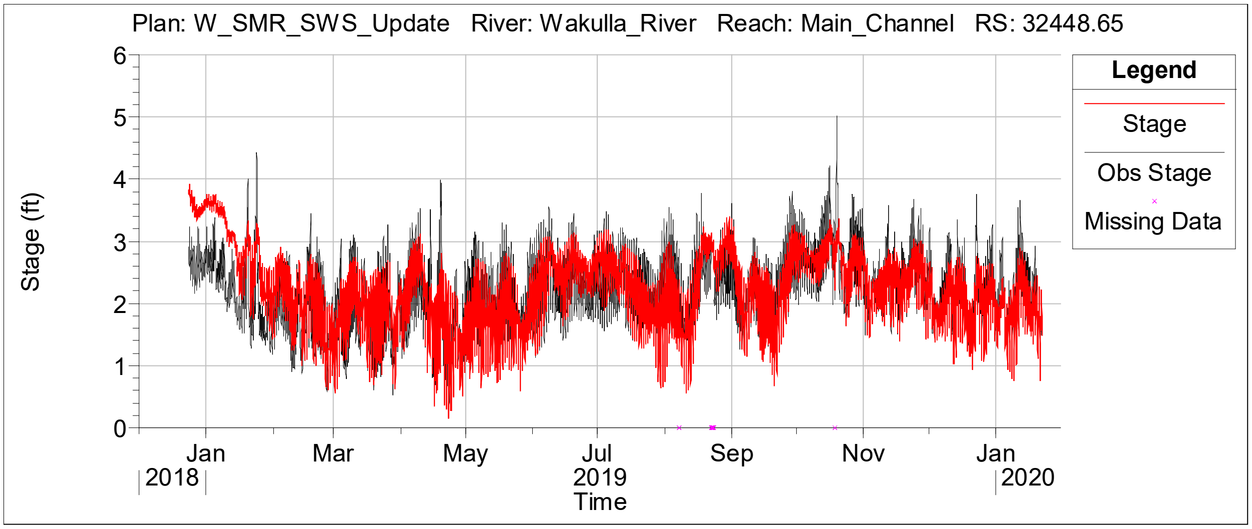


Figure 26a. Comparison of Observed and Simulated Water Levels – USGS 02327022 (Wakulla River Nr Crawfordville): Comparison of Simulated and Observed Stage Time Series

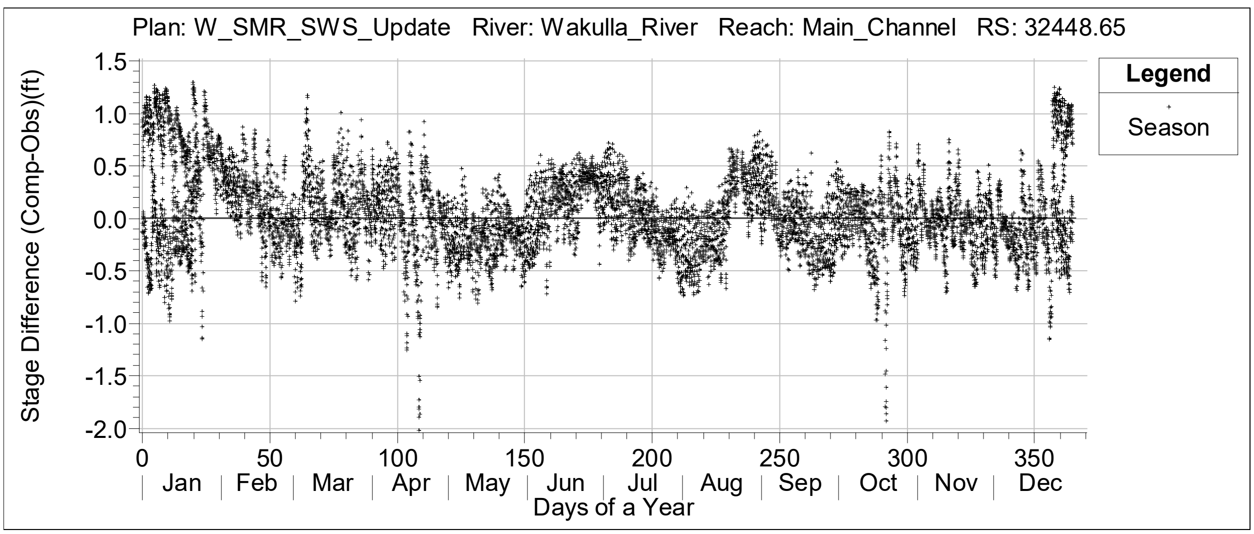


Figure 26b. Comparison of Observed and Simulated Water Levels – USGS 02327022 (Wakulla River Nr Crawfordville): Residuals (Simulated – Observed) over Time

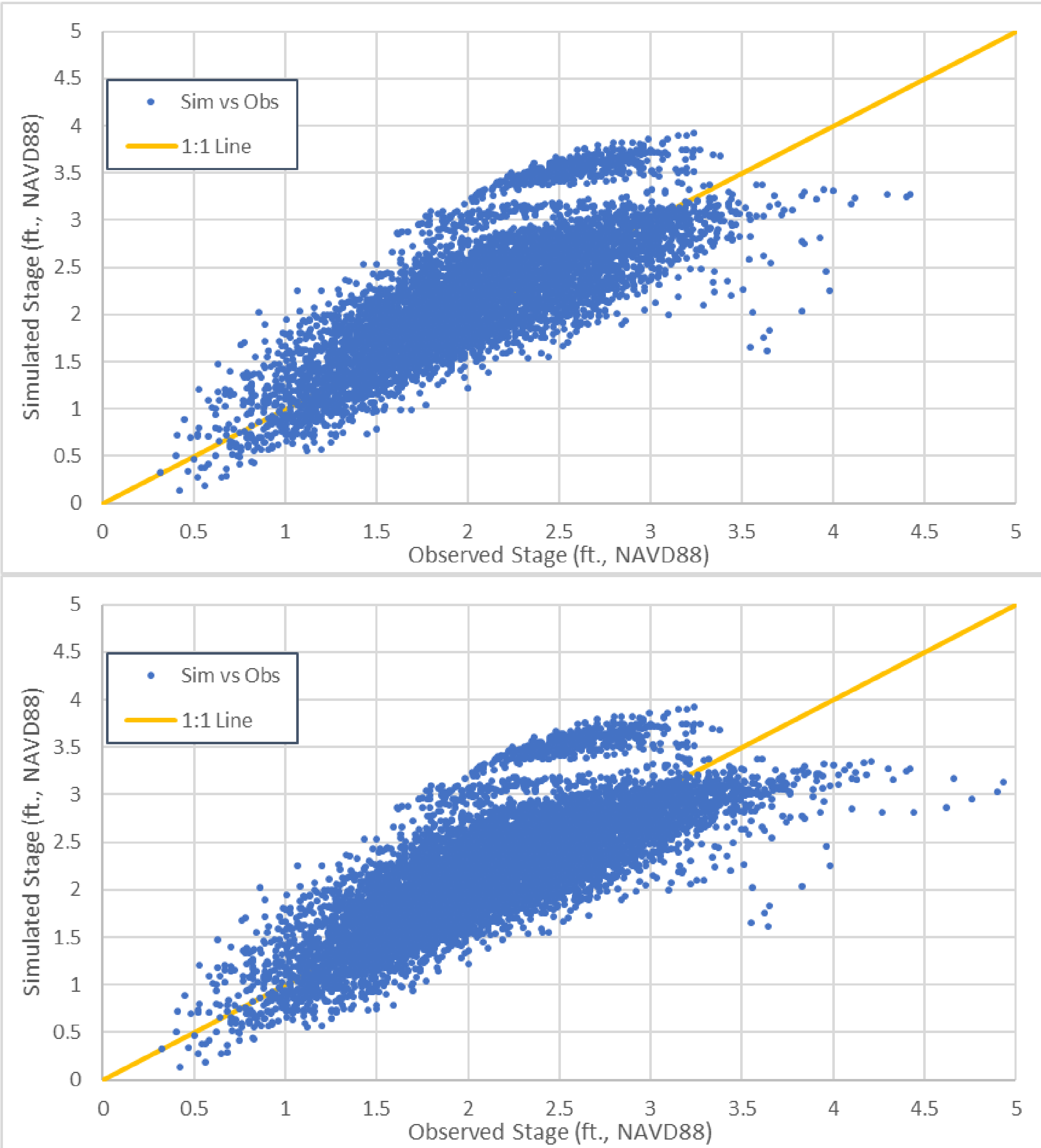


Figure 26c. Comparison of Observed and Simulated Water Levels – USGS 02327022 (Wakulla River Nr Crawfordville): Scatter Plot of Observed and Simulated Stages (Calibration-upper, Full Simulation Period-lower)

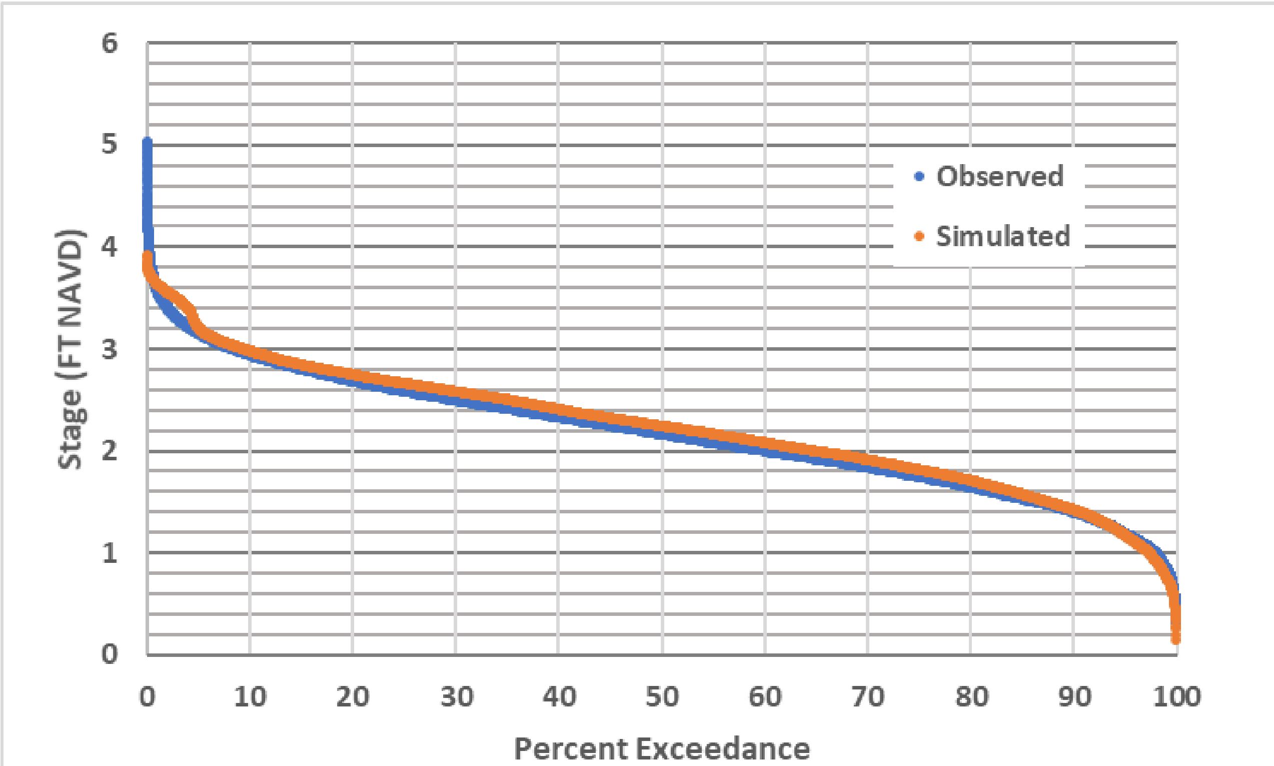


Figure 26d. Comparison of Observed and Simulated Water Levels – USGS 02327022 (Wakulla River Nr Crawfordville): Exceedance Curves for Observed and Simulated Stages

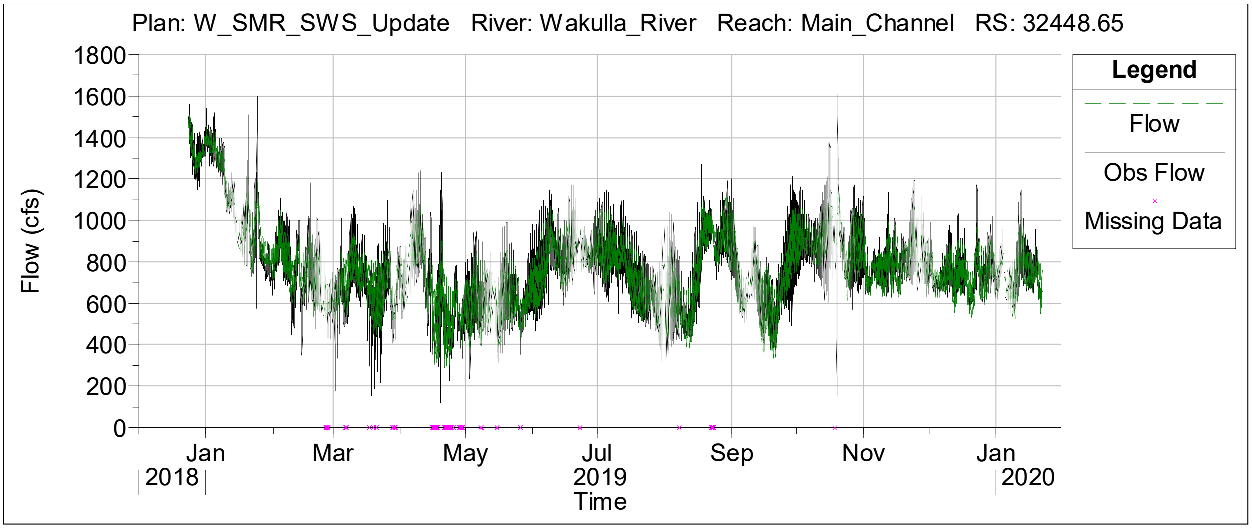


Figure 27a. Comparison of Observed and Simulated Flows - USGS 02327022 (Wakulla River Nr Crawfordville): Comparison of Simulated and Observed Flow Time Series

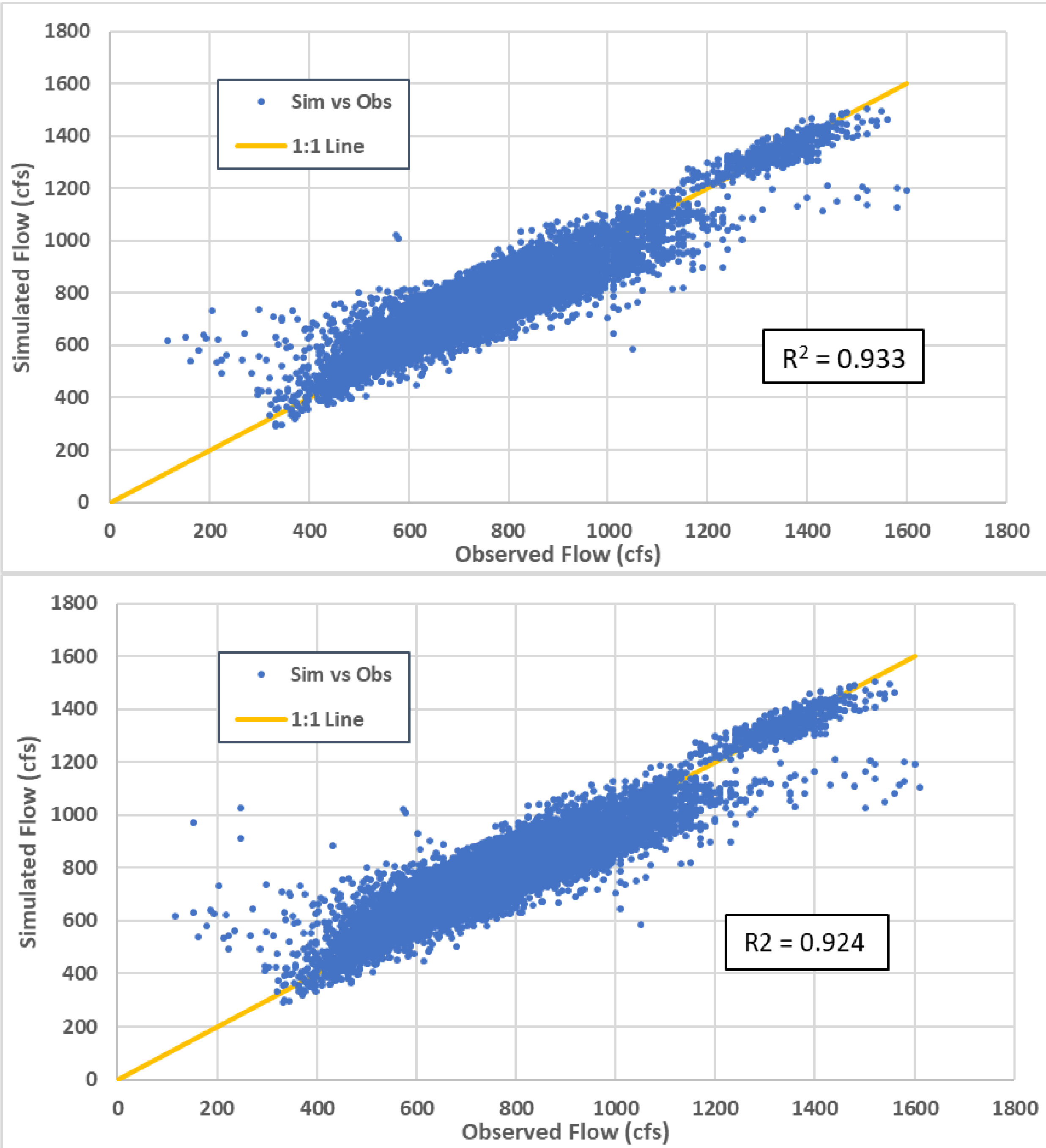


Figure 27b. Comparison of Observed and Simulated Flows - USGS 02327022 (Wakulla River Nr Crawfordville): Scatter Plot of Observed and Simulated Flows (Calibration-upper, Full Simulation Period-lower)

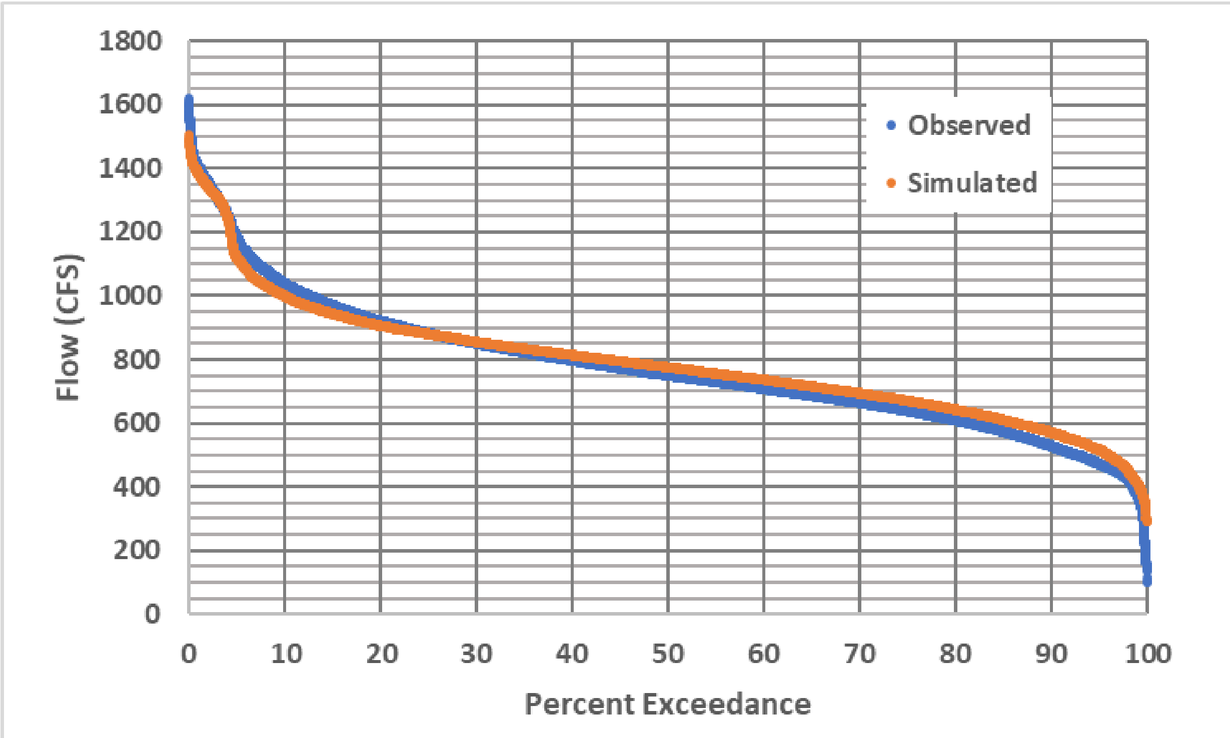


Figure 27c. Comparison of Observed and Simulated Flows - USGS 02327022 (Wakulla River Nr Crawfordville): Exceedance Curves for Observed and Simulated Flows

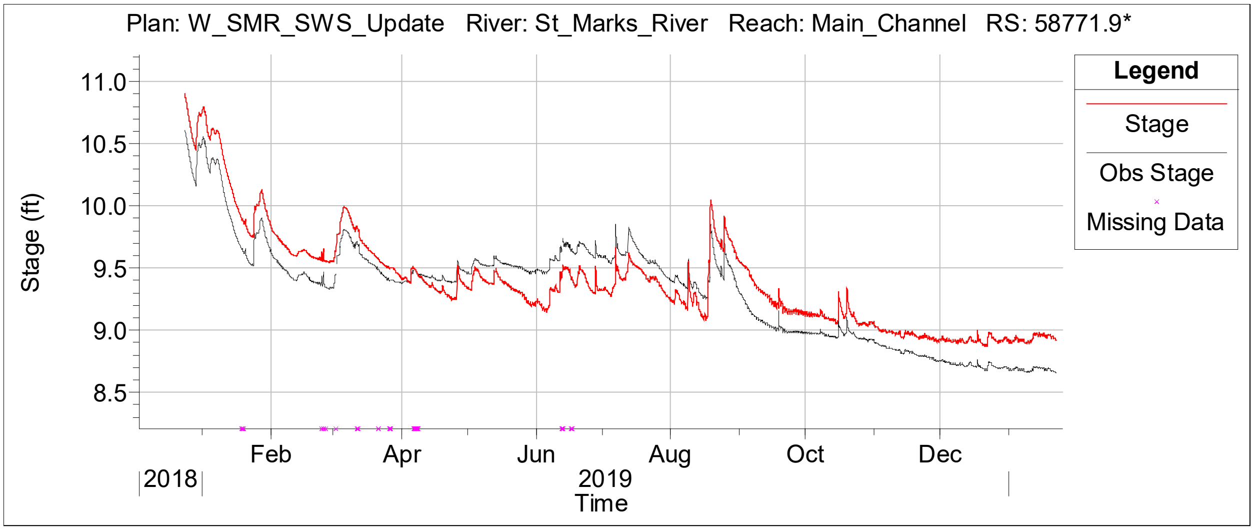


Figure 28a. Comparison of Observed and Simulated Water Levels – USGS 02326900 (St. Marks River Nr Newport): Comparison of Simulated and Observed Stage Time

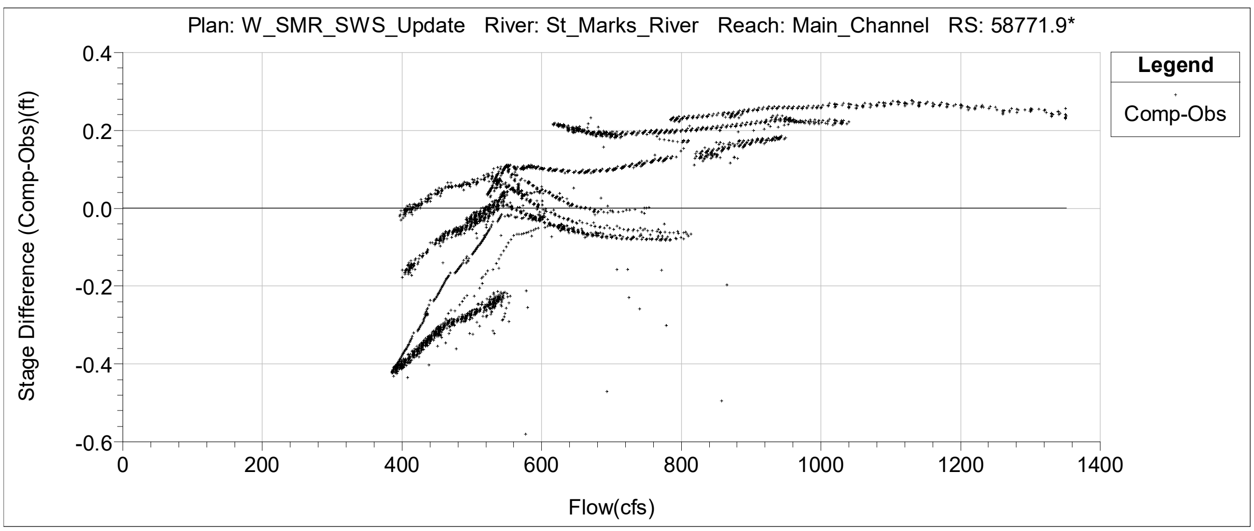


Figure 28b. Comparison of Observed and Simulated Water Levels – USGS 02326900 (St. Marks River Nr Newport): Residuals (Simulated – Observed) vs Flow

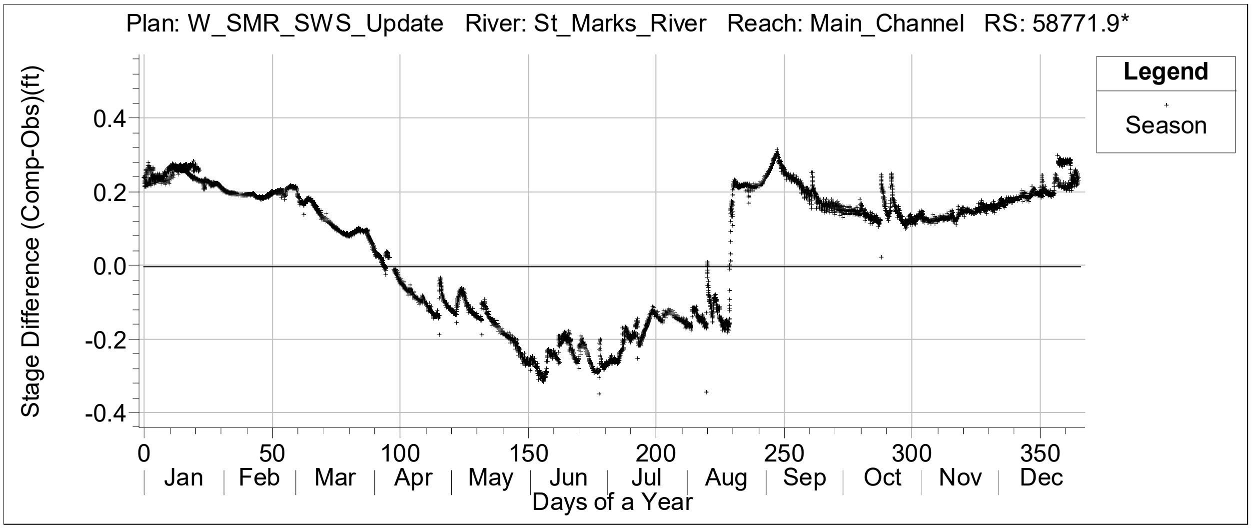


Figure 28c. Comparison of Observed and Simulated Water Levels – USGS 02326900 (St. Marks River Nr Newport): Residuals (Simulated – Observed) over Time

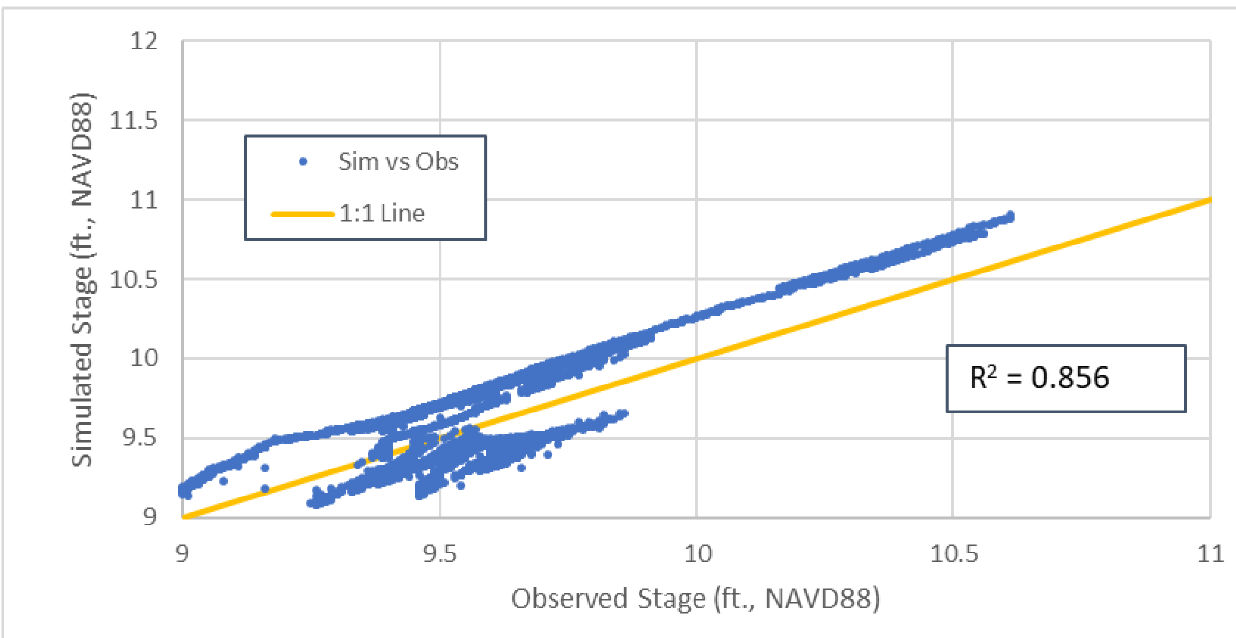


Figure 28d. Comparison of Observed and Simulated Water Levels – USGS 02326900 (St. Marks River Nr Newport): Scatter Plot of Observed and Simulated Stages

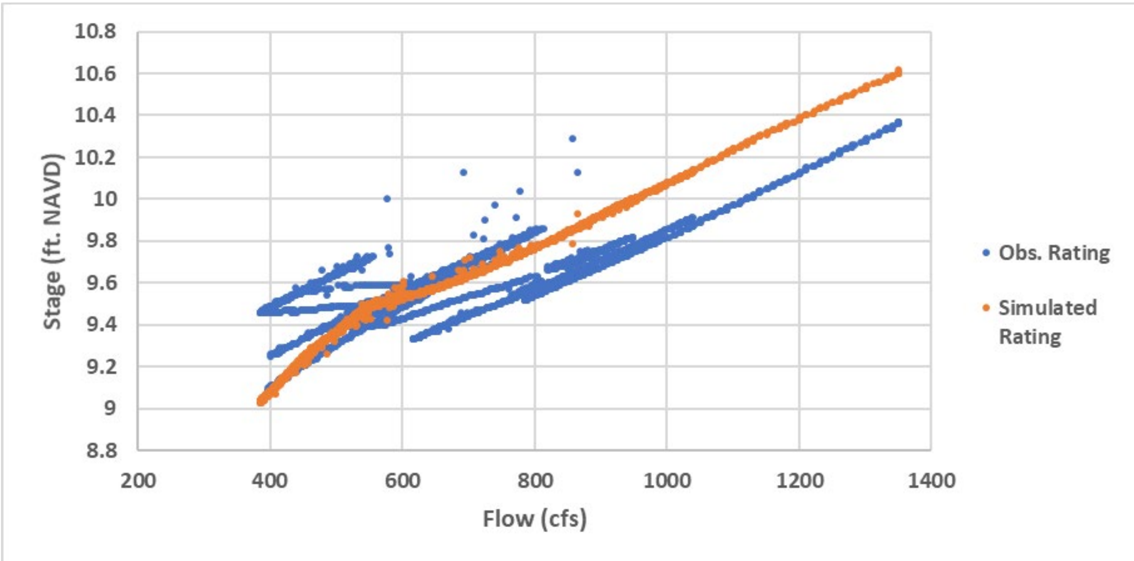


Figure 28e. Comparison of Observed and Simulated Water Levels – USGS 02326900 (St. Marks River Nr Newport): Comparison of Observed and Simulated Rating Curves at USGS 02326900

Statistical measures of model performance based on 1-hour simulated and observed time series were calculated for both the calibration period (Table 5) and the entire 13-month simulation period (Table 6). The additional adjustments to Manning's n values and ineffective flow areas improved model calibration results.

Table 5. Summary Statistics of Model Performance – St. Marks River/Wakulla River HEC-RAS Model Final Calibration (Based on 1-hour simulated and observed time series)

River	Station	Statistics	Mean (ft-NAVD88)	Max (ft-NAVD88)	Min (ft-NAVD88)	R^2	NSE	RMSE	RMSE/ Range	PBIAS(%)	RSR
Sally Ward Spring	SWS	Obs	5.23	6.41	4.48	0.958	0.91	0.11	5.9%	-0.298	0.304
		Sim	5.22	6.49	4.63						
		Diff	-0.01	0.08	0.15						
Wakulla River	2327000	Obs	4.90	6.04	4.15	0.936	0.87	0.13	7.0%	0.375	0.359
		Sim	4.92	6.17	4.27						
		Diff	0.02	0.13	0.12						
	Boat Tram	Obs	4.45	5.47	3.73	0.937	0.74	0.19	10.9%	1.165	0.579
		Sim	4.42	5.77	3.76						
		Diff	-0.03	0.35	0.03						
	2327022 (Stage)	Obs	2.08	4.42	0.32	0.790	0.46	0.44	10.8%	6.682	0.732
		Sim	2.22	3.92	0.14						
		Diff	0.14	-0.5	-0.18						
	2327022 (Flow)	Obs	780.4	1600.0	116.0	0.933	0.87	85.23	5.7%	1.663	0.365
		Sim	789.3	1506.7	289.6						
		Diff	8.9	-93.3	173.6						

Table 6. Summary Statistics of Model Performance – St. Marks River/Wakulla River HEC-RAS Model Full Simulation Period, December 24, 2018 – January 22, 2020 (Based on 1-hour simulated and observed time series)

River	Station	Statistics	Mean (ft-NAVD88)	Max (ft-NAVD88)	Min (ft-NAVD88)	R^2	NSE	RMSE	RMSE/ Range	PBIAS(%)	RSR
Sally Ward Spring	SWS	Obs	5.23	6.41	4.48	0.916	0.79	0.15	7.7%	-1.122	0.458
		Sim	5.17	6.49	4.60						
		Diff	-0.06	0.08	0.12						
Wakulla River	2327000	Obs	4.90	6.04	4.15	0.870	0.83	0.14	7.3%	-0.187	0.431
		Sim	4.89	6.17	4.25						
		Diff	-0.01	0.13	0.10						
	Boat Tram	Obs	4.45	5.47	3.73	0.902	0.70	0.18	10.6%	0.278	0.559
		Sim	4.42	5.77	3.74						
		Diff	-0.03	0.30	0.01						
	2327022 (Stage)	Obs	2.17	5.02	0.32	0.786	0.56	0.40	8.6%	2.390	0.666
		Sim	2.23	3.92	0.14						
		Diff	0.06	-1.1	-0.18						
	2327022 (Flow, cfs)	Obs	781.8	1610.0	116.0	0.924	0.85	80.3	5.4%	1.177	0.385
		Sim	788.4	1506.7	289.6						
		Diff	6.6	-103.3	173.6						
St. Marks River	2326900	Obs	9.33	10.61	8.66	0.856	0.81	0.19	9.8%	0.736	0.458
		Sim	9.39	10.91	8.87						
		Diff	0.06	0.30	0.21						

Generally, model predictions of stage are within 0.2 to 0.3 ft of measured stage, except at USGS 02327022 (Wakulla River Near Crawfordville) (Figure 26). The comparison of the respective stage and flow duration curves (Figures 26d and 27d) show a good match across the range of water surface elevations and flow conditions. As explained in the initial calibration section, differences at this location appear to be mostly due to timing differences caused by tidal propagation from the downstream boundary since comparisons of the simulated and observed stage duration curves match well, indicating agreement in stage magnitude and frequency. Flow predictions (Figure 27) also matched well in the final calibration. Considering the use of a predicted tide instead of tidal observations for the downstream boundary condition and the magnitude and timing differences that exists between the two time series, the unsteady state model proved to be a good predictor of water levels across low, medium and high flow conditions in both the Wakulla and St. Marks Rivers.

The simulation period from September 10, 2019, to January 22, 2020, served as the validation period for the model. This time period included when Tropical Storm Nestor came ashore near St. Vincent Island on October 19, 2020. During the October–November 2019 simulation period, the model underpredicted stages at all calibration locations. The underprediction is thought to be due to the use of the St. Marks Lighthouse predicted tide instead of actual tide observations. The model results began to converge in December 2019 and matched observed water levels well at all calibration locations for the remainder of the validation period. This result was encouraging as it showed that the model predicted water levels well as meteorological effects on tides diminished and the system recovered from effects from Tropical Storm Nestor.

The results in Table 6 were compared to the performance evaluation criteria listed in Table 2. Table 2 presented a summary of performance evaluation criteria for recommended statistical performance measures for watershed models. While these criteria relate to daily flow in Moriasi et al (2015), they do provide a means of assessing whether model performance in this application is satisfactory or not. Table 2 is presented below for ease of comparison.

Measure	Very Good	Good	RMSE/ Satisfactory	Not Satisfactory
R^2	$R^2>0.85$	$0.75<R^2<0.85$	$0.60<R^2<0.75$	$R^2\leq0.60$
NSE	NSE>0.80	0.70<NSE<0.80	0.50<NSE<0.70	NSE≤0.50
PBIAS(%)	PBIAS<±5	±5<PBIAS<±10	±10<PBIAS<±15	PBIAS≥±15

For the performance measures listed and including RSR, model performance can be classified as good to very good at all locations except at USGS 02327022, Wakulla River near Crawfordville. For stage, model performance can be classified as satisfactory to good at this location. This location is the most downstream calibration point on the Wakulla River and is most affected by tide and the use of predicted tide as the downstream boundary condition. Calculated model performance measures would likely improve at this location with the incorporation of observed tides for the downstream boundary condition.

7.2 DISCUSSION OF MODEL UNCERTAINTY

Following data evaluation, model construction, calibration and testing, there are three primary areas of uncertainty that affect model predictions of water level in the Wakulla River. The first area is related to the estimate of lateral flow contributions along the entire Wakulla River and St.

Marks River reaches. The estimate of lateral inflows is based on a limited number of tidal flux measurements. Review of data and site reconnaissance indicate both groundwater and surficial flow contributions exist. Additional flow measurements along the river reaches would provide a better definition of the relationship of lateral inflows to the long-term flow records and the distribution of these lateral inflows along the river reaches. Better definition of lateral inflows would increase confidence in model predictions of water level.

The second area of uncertainty is related to vegetative growth in the channel of the upper Wakulla and St. Marks River reaches. Dense vegetative growth affects flow conveyance capacity by increasing drag and friction losses. 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, could be performed to identify 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. Also, additional reconnaissance in the upper Wakulla River reach can be performed to identify shallow areas and areas of channel constrictions that act as control points for flow. The incorporation of additional surveys for these locations would improve the representation of the physical area in the model's geometry.

The third area of uncertainty is related to the use of predicted tide as the downstream boundary condition for the model. In addition to differences in the magnitudes of high and low tide elevations, there is a difference in the timing of these high and low tides with the St. Marks Lighthouse high and low tides occurring earlier than at the terminus of the HEC-RAS model. This reflects the tidal propagation from the mouth of the St. Marks River to the terminus of the model domain. The differences in tidal magnitude and timing of the tidal boundary result in timing and magnitude differences of model stage predictions when compared to water level observations at other locations up the Wakulla River. The use of observed tides for the downstream boundary condition would reduce uncertainty in the model predictions and would likely reduce simulation residuals.

8.0 REFERENCES

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Development of the Wakulla River System Hydrologic Engineering Center River Analysis System (HEC-RAS) Steady State Model

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1.0 Introduction

Applied Technology and Management, Inc. (ATM) previously refined and calibrated an unsteady-state HEC-RAS model of the Wakulla River system (ATM, 2021). The intended use of this HEC-RAS model is to support minimum flows development for Wakulla Springs and Sally Ward Spring. The general study area for the model is shown on Figure 1. The study area for the development of minimum flows for Wakulla and Sally Ward springs includes Sally Ward Spring and spring run, and Wakulla Springs and spring run, which extends from the Wakulla Springs pool to the confluence of the Wakulla and St. Marks rivers. The simulation period for this model was December 24, 2018 to January 22, 2020.

This report describes the development of a steady-state version of the previously developed unsteady-state model. The updated HEC-RAS model was previously tested and calibrated using the unsteady flow analysis option due to the tidal influence on the lower portions of the Wakulla and St. Marks River systems (ATM, 2021). A steady-state version of HEC-RAS is often developed from dynamic versions for use in MFL determinations and WRV assessments (ATM (2018), Intera, (2012), ECT (2017)).

The model schematic for the Wakulla River system HEC-RAS model is shown on Figure 2. The steady-state model will be used to evaluate critical flows and stages for water resource values and support the determination of minimum flows and levels (MFLs) for Wakulla Springs and Sally Ward Spring. Previously, a steady-state model was developed for use in the evaluation of water resource values for determination of minimum flows for the St. Marks River Rise (ATM, 2018).

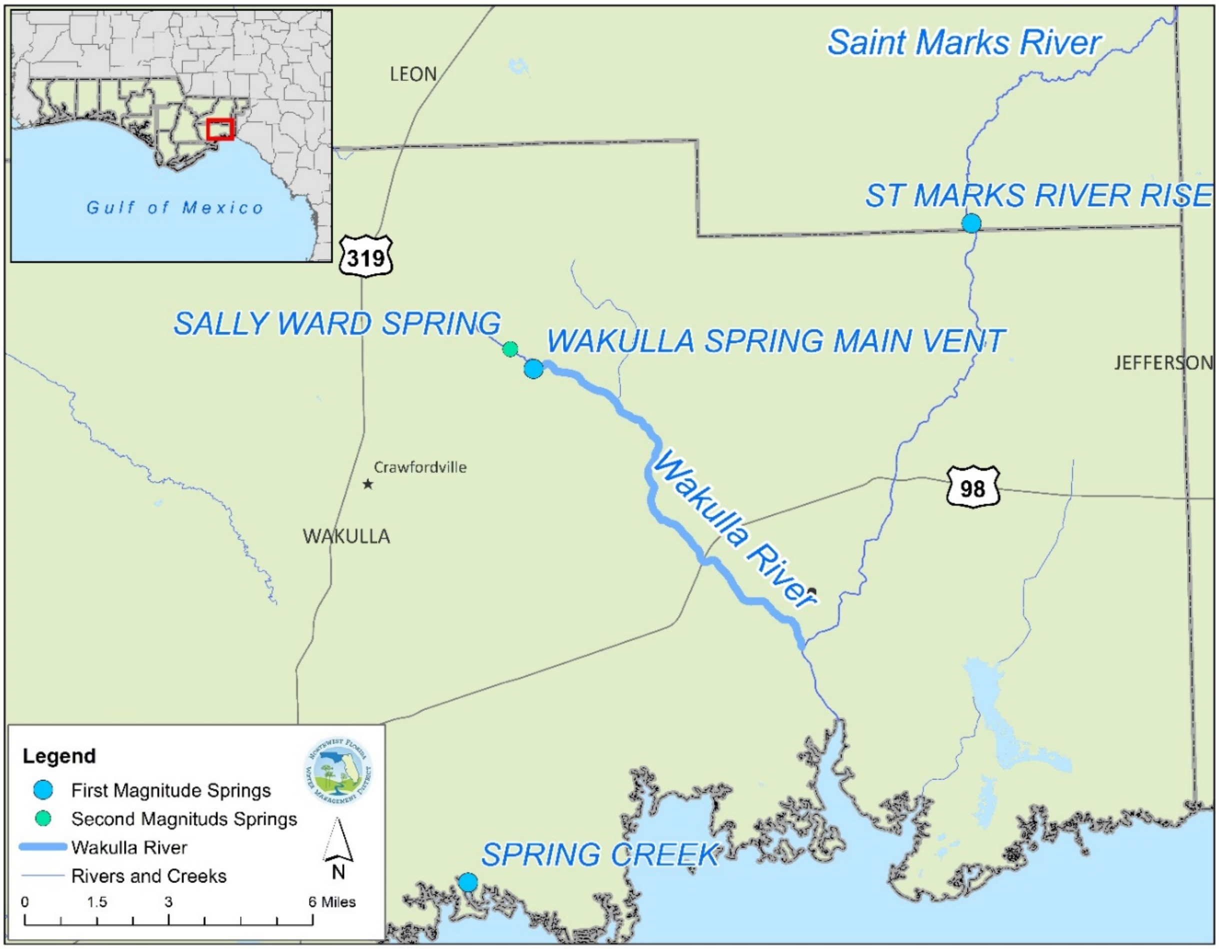

Figure 1. General Study Area for the Wakulla River/St. Marks River HEC-RAS Model

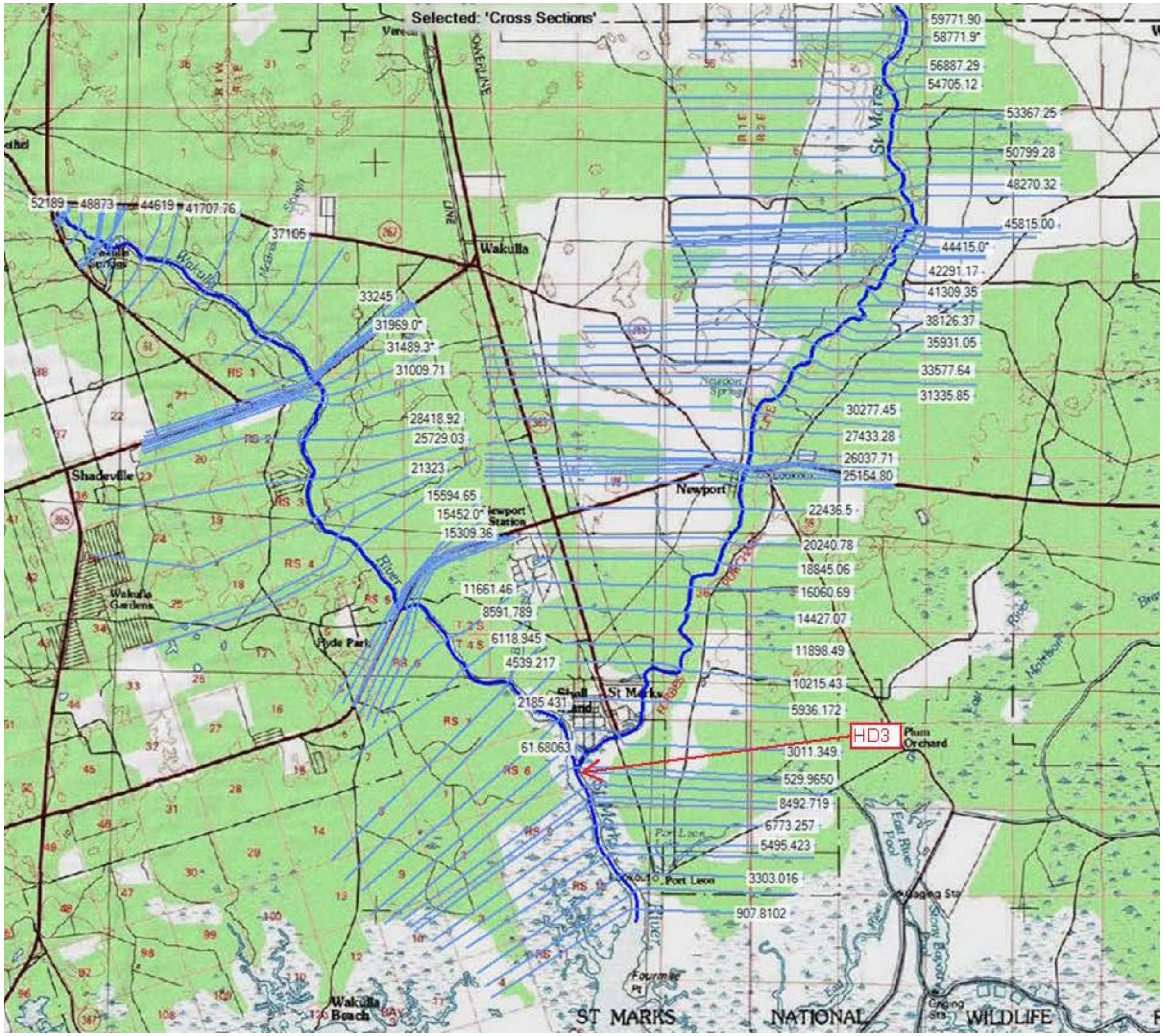

Figure 2. Model Schematic for the Wakulla River/St. Marks River HEC-RAS Model

2.0 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, 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 the Wakulla River system, the river reach requiring defined flows at multiple locations extends from Sally Ward Spring to the U.S. Geological Survey (USGS) 02327022 gage located at Shadeville Road (Figure 3).Based on evaluations of the available flow data, the selected period of record for developing flow percentiles is October 23, 2004 to December 31, 2019, corresponding to the available period of 15-minute flow measurements at USGS gage 02327022.

Flow data from USGS Station 02327022, Wakulla River near Crawfordville, is heavily influenced by tidal energy and required filtering to remove the effects of the tides so that the net flow of the gaged location could be determined. Filtering was applied to 15-minute flow data from USGS 02327022 using a Godin filter routine consistent with USGS methodology (USGS, 2011). Figure 4 presents the 15-minute time series and the filtered time series. The filtered flow time series was converted to a daily filtered time series using HEC-DSS tools to obtain a net daily flow time series at USGS 02327022. (Figure 4). Flow percentiles were determined for every 2nd incremental percentile flow, from the 2nd percentile through the 98th percentile and the 1st and 99th percentiles. Northwest Florida Water Management District (NWFWMD) provided the daily flow record for the Wakulla Springs vent and field measurements for Sally Ward Spring Run.

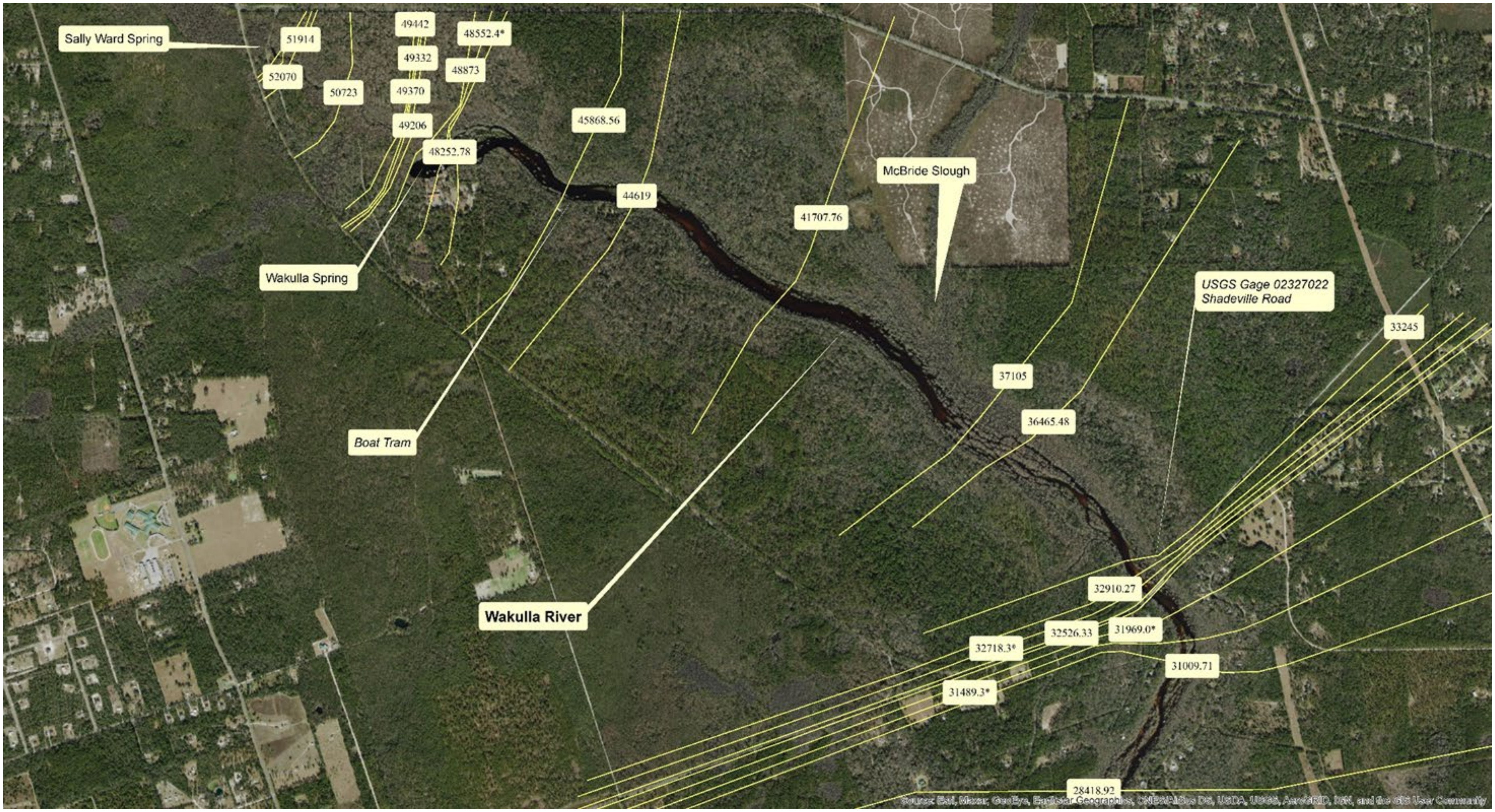

Figure 3. Wakulla River Reach Requiring Defined Flows at Multiple Locations Extending from Sally Ward Spring to the USGS 02327022 Gage Located at Shadeville Road

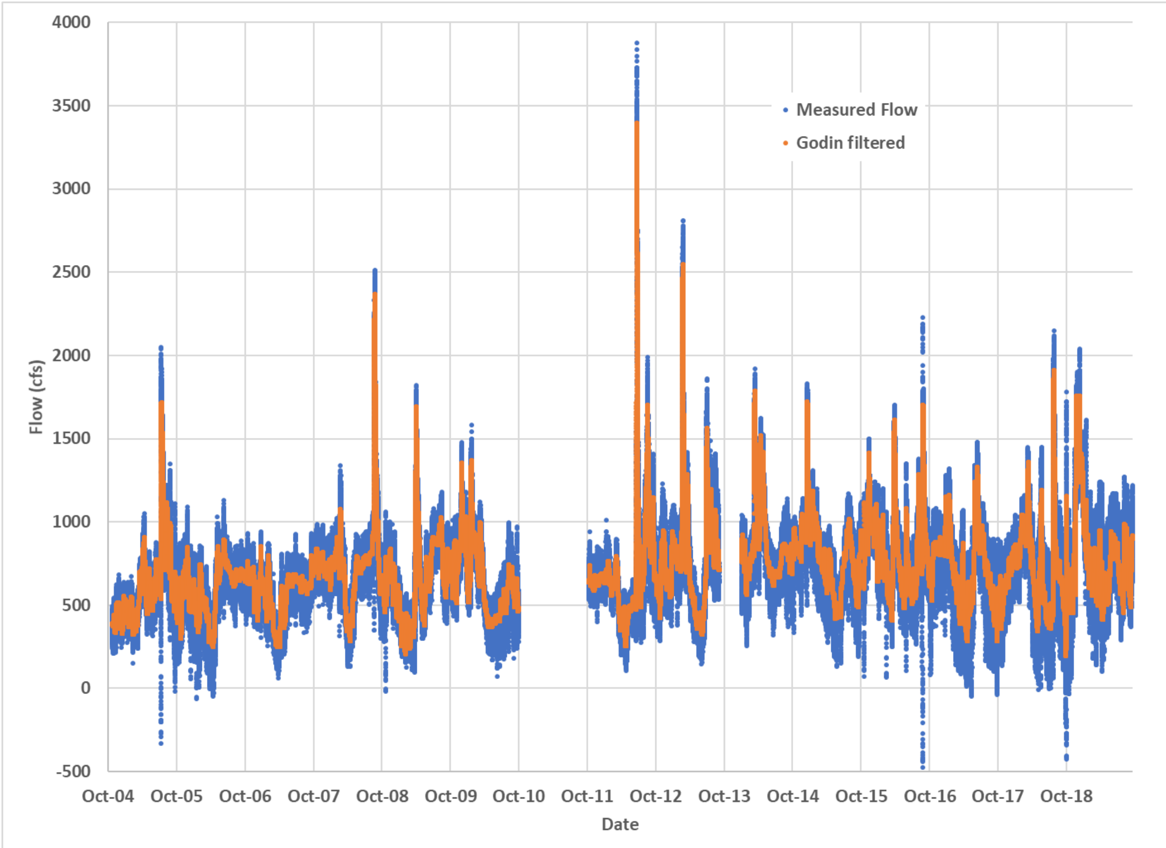

Figure 4. USGS Gage 02327022 Filtered Flow Results for the Period of Record, 10/2004 – 12/2019

The total inflow between the Wakulla Springs vent and the USGS 02327022 gage was estimated by the following, as applied to each corresponding flow percentile. The median, or 50th percentile (P50), is used as an example:

- USGS 02327022 Filtered Flow (P50) – Wakulla Springs Vent Flow (P50) – Sally Ward Spring Run Flow (P50) = P50 Inflow between the Wakulla Springs vent and the USGS 02327022 gage.

The increase in flow estimated as the lateral ungaged flow in Wakulla River between the Wakulla Springs vent and the USGS 02327022 gage was calculated as a flow per reach length for each percentile. This flow quantity was added to the Wakulla Springs vent and Sally Ward Spring flows at discrete locations (Table 1). For example, the P50 inflow quantity between USGS 02327022 and the Wakulla Springs pool is estimated to be 77 cubic feet per second (cfs).

Table 1. Steady-State Input Flow Percentiles at the Flow Change Locations: St. Marks River/Wakulla River

		Flow Percentile										
River	River Station	1%	10%	20%	30%	40%	50%	60%	70%	80%	90%	99%
St Marks River	59771.9	332	400	440	497	553	605	655	725	838	1040	2100
	54705.12	342	412	453	512	569	623	674	746	863	1070	2161
	48270.32	354	427	469	530	590	645	698	773	894	1109	2239
	42291.17	366	440	484	547	609	666	721	798	923	1145	2312
	36607.3	376	453	499	563	627	686	743	822	950	1179	2381
	30277.45	389	468	515	582	647	708	767	848	981	1217	2458
	26037.71	397	478	526	594	661	723	783	866	1001	1243	2509
	20240.78	408	491	540	610	679	743	804	890	1029	1277	2579
	14427.07	419	505	555	627	698	763	826	915	1057	1312	2650
	10215.43	427	514	566	639	711	778	842	932	1078	1338	2701
	5936.172	435	524	577	651	725	793	859	950	1098	1363	2753
Sally Ward Spring Run	52189	6.71	12.33	15.26	17.93	21.95	23.41	24.39	26.05	28.44	30.56	58.02
Wakulla River	48252.78	208	337	424	488	560	609	652	689	737	811	1242
	45868.56	221	351	438	504	573	621	666	706	757	837	1304
	44619	228	358	446	512	579	628	673	715	767	851	1336
	41707.76	245	375	464	532	595	642	690	735	791	882	1412
	37105	271	402	492	563	619	666	717	768	829	932	1532
	36465.48	275	405	495	567	622	669	721	772	834	939	1548
USGS 02327022	33245	293	424	515	589	639	686	740	795	861	974	1632
Confluence	10562.5	728	948	1092	1240	1364	1479	1598	1745	1959	2338	4385

The length of the river reach between USGS 02327022 and the Wakulla Springs pool is 15,007 ft, which results in flow per foot of reach length of 0.00513 cfs/ft for the P50 flow. The P50 flow pickup at cross-section 41707, for example, which is 6,545 ft below the Wakulla Springs pool, would be approximately 33 cfs (0.00513 cfs/ft times 6,545 ft), This would result in a P50 flow at cross section 41707 of 642 cfs (609 cfs plus 33 cfs). No additional inflows were added between USGS 02327022 and the confluence with the St. Marks River (ATM, 2020). Flow percentiles for the St. Marks River utilized those developed for the previous steady-state model construction described in ATM (2018).

For summary purposes, Table 1 provides steady-state input percentile flows at every flow change location for every 10th percentile and the 1st and 99th percentiles. Steady-state HEC-RAS input 10th percentile flow refers to the low flow or the flow that is not exceeded 10 percent of the time or is exceeded 90 percent of the time.

To run predictive simulations, downstream stage boundary conditions are needed. The stage time series from hydrodynamic monitoring location HD-3 for the period 2008-2015 was utilized to develop a probability distribution of stage at the downstream boundary (Figure 5).

The Wakulla River system is tidal, particularly at Shadeville Road and below. To account for the daily fluctuation in water levels that occur as the result of tides, scenarios were evaluated under multiple downstream boundary conditions. The boundary conditions were derived from the HD-3 monitoring station located near the confluence of the Wakulla and St. Marks rivers since it provided the longest continuous record of elevations at the terminus of the Wakulla River (Figure 2). The selected period of record was April 2008 to December 2015 (Figure 5), as there were some problems with the data logger not recording the full tidal range of stage values during 2016 to 2018. The three downstream boundary conditions selected in consultation with NWFWMD staff are as follows:

- Median elevation from full record (Median) – 0.29 feet referenced to the North American Vertical Datum of 1988 (ft-NAVD88)
- Mean daily high from full record (MDH) – 1.86 ft-NAVD88
- Mean daily high for the winter months November – March (MDHW) – 1.54 ft-NAVD88.

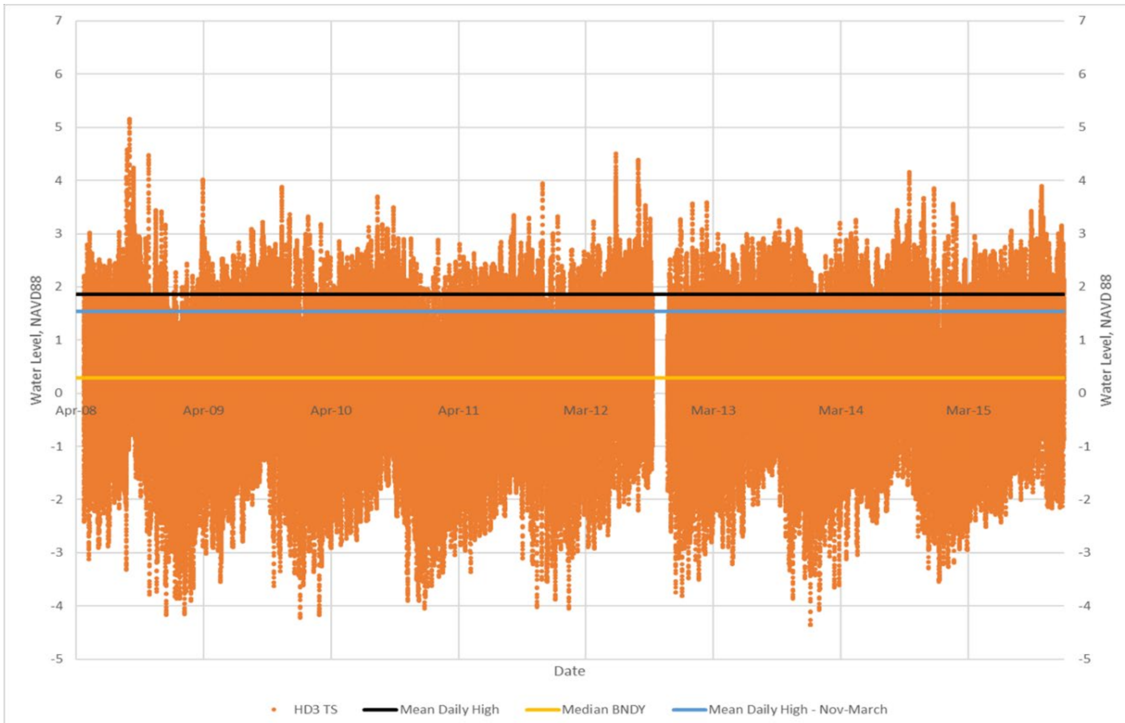

Figure 5. Station HD3 - Period of Record April 2008 to December 2015 Boundary Elevations

The record of field measurements at the USGS 02327022 gage, located in the middle portion of the Wakulla River, was used to assess how well the steady-state model predictions captured observed flow-stage dynamics. The USGS has made 144 field measurements of flow and stage from 2005 to April 2020 with 10 field measurements occurring following the passage of Hurricane Michael in October 2018. A comparison of predicted rating curves at Shadeville Road under various downstream tidal boundary scenarios from the steady state model were compared to the observed field measurements at the USGS 02327022 gage (Figure 6). Minor adjustments were made to Manning's "n" coefficients until the range of observations was largely contained by the median, mean daily high, and mean daily high winter downstream stage boundary scenarios and the median downstream boundary scenario corresponded to the central tendency of the range of observations based on visual inspection of Figure 6. Computation of calibration performance metrics is not suitable for comparing steady state model output with observed measurements at Shadeville Road since this model output does not correspond directly to specific occurrences in time when measurements were made. Visual inspection of the steady-state model results from a range of downstream stage boundary conditions to available field measurements indicates that the steady-state model captures the expected range of water levels at Shadeville Road (USGS 02327022 gage).

Based on this comparison, the steady-state model captures conditions the river system has experienced over the 2004-2019 period of record. Therefore, the constructed Wakulla River steady-state model is considered suitable for use in MFL determinations and the associated assessment of water resource values (WRVs).

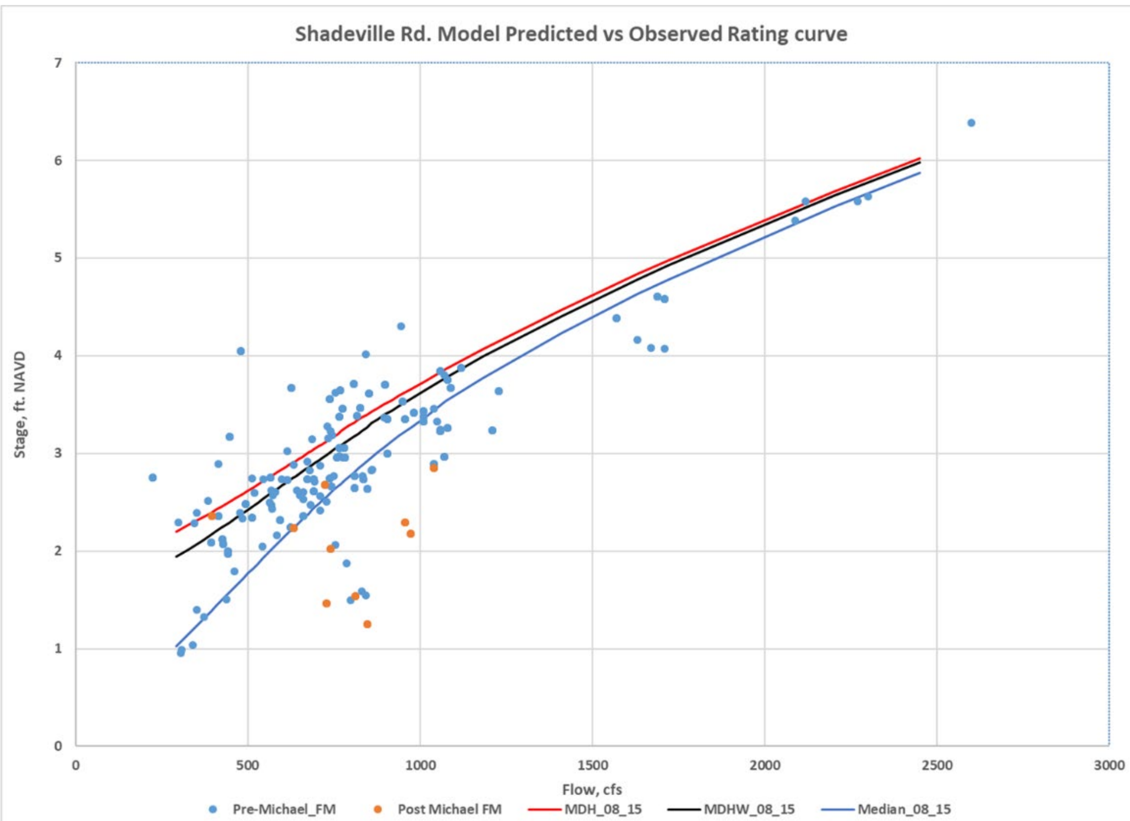

Figure 6. Comparison of Simulated Rating Curves and Field Measurements at USGS 02327022 for Specified Boundary Elevations

3.0 Steady-State Model Results

Steady-state HEC-RAS simulations using flow percentiles calculated from the 2004-2019 flow record and median, mean daily high, and mean daily high winter boundary elevations for use in WRV metric evaluations. The results of the steady-state simulations for the Wakulla River are presented in Figures 7 through 9 and Tables 2 through 4.

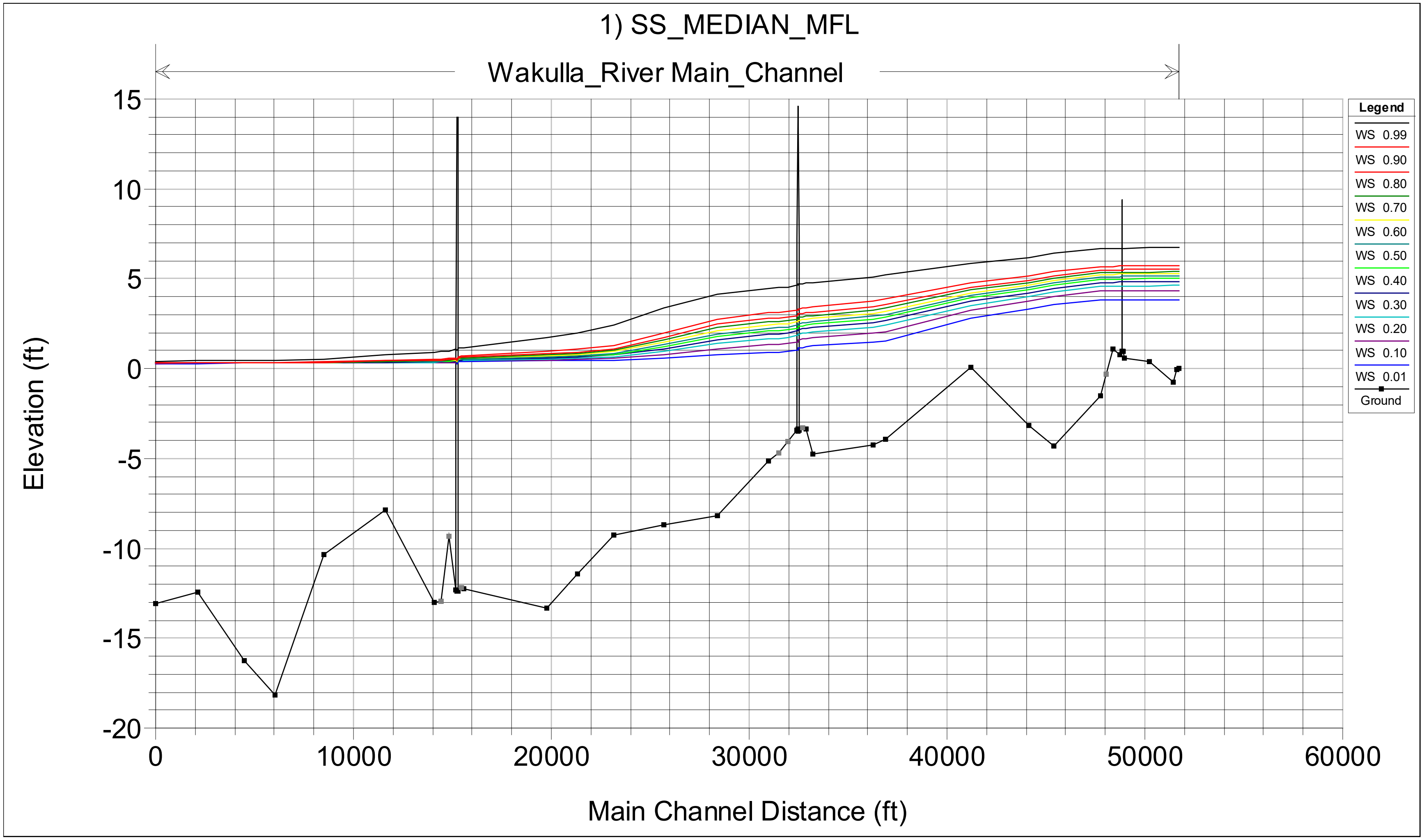

Figure 7. Water Surface Profiles for the Median Downstream Boundary Condition Simulation. Each profile represents a different percentile flow (i.e., 0.50 = 50th percentile).

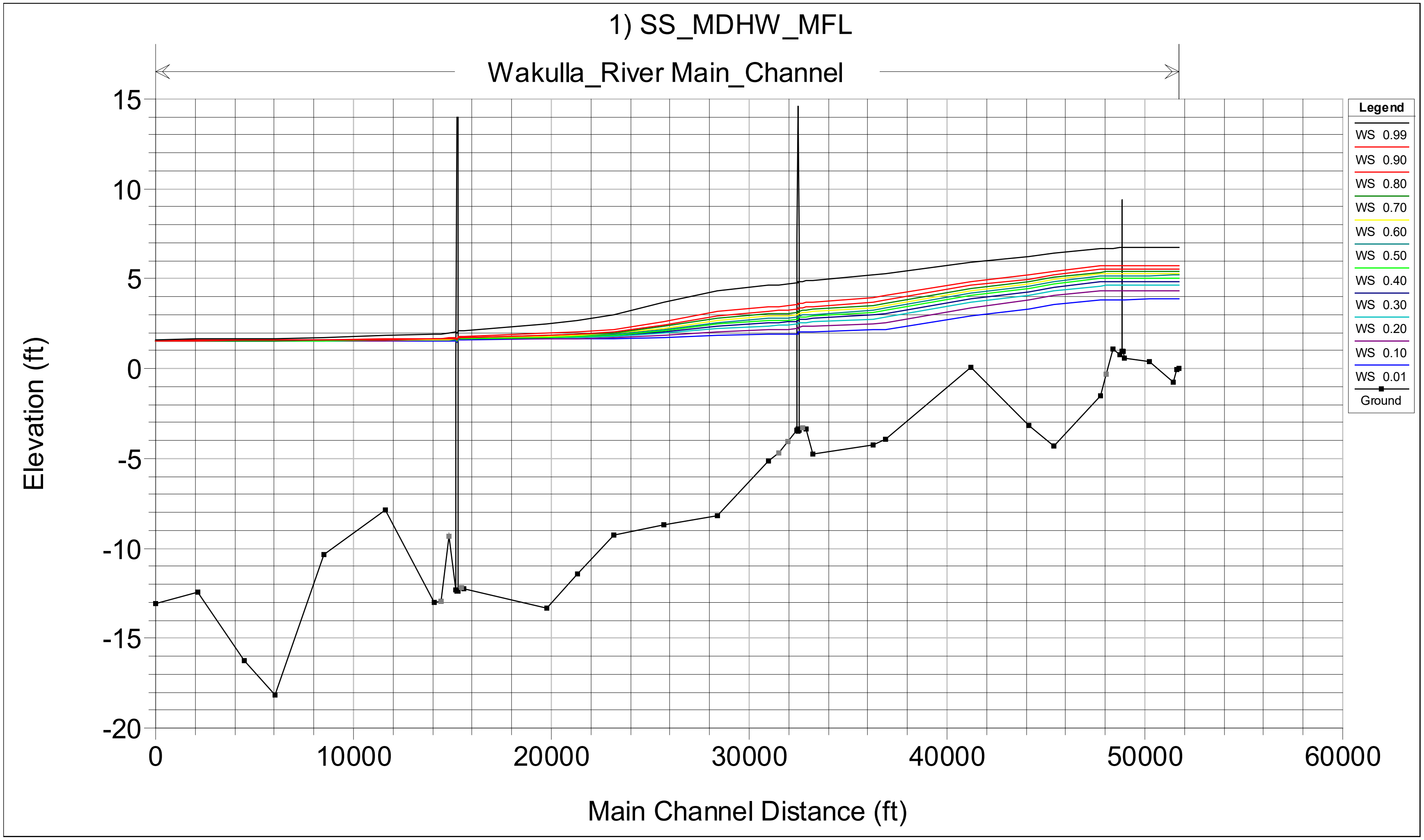

Figure 8. Water Surface Profiles for the Mean Daily High – November through March Months Downstream Boundary Condition Simulation. Each profile represents a different percentile flow (i.e., 0.50 = 50th percentile).

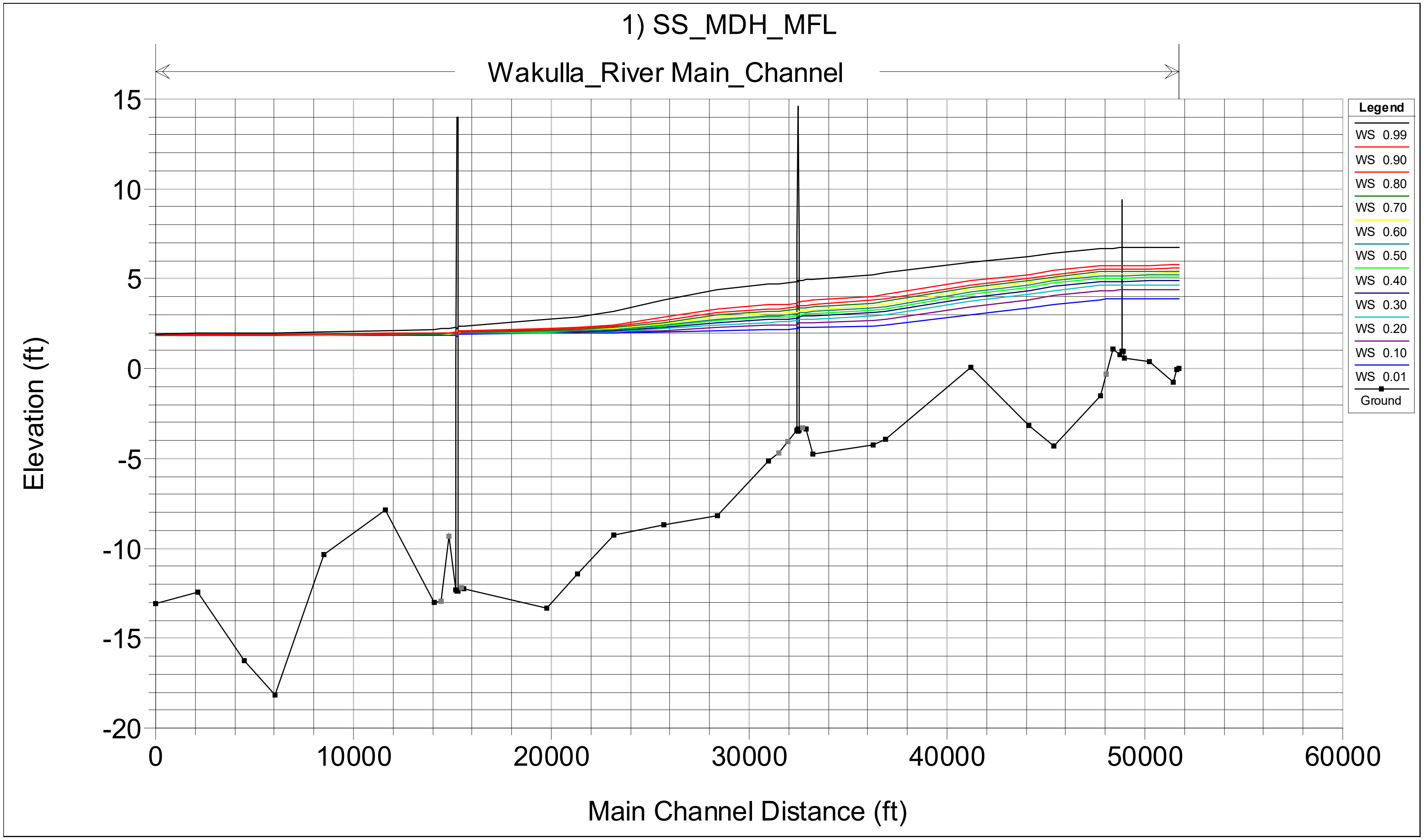

Figure 9. Water Surface Profiles for the Mean Daily High Downstream Boundary Condition Simulation. Each profile represents a different percentile flow (i.e., 0.50 = 50th percentile).

Table 2. Simulated Stages: Wakulla River - Median Boundary Stage, ft-NAVD88

River Station	Flow Percentile										
	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	3.84	4.33	4.62	4.82	5.01	5.14	5.27	5.38	5.53	5.73	6.73
52070	3.84	4.33	4.62	4.82	5.01	5.14	5.27	5.38	5.53	5.73	6.73
51914	3.84	4.33	4.62	4.82	5.01	5.14	5.27	5.38	5.53	5.72	6.73
50723	3.84	4.33	4.61	4.82	5.01	5.14	5.26	5.37	5.52	5.71	6.72
49442	3.84	4.32	4.61	4.81	5.00	5.13	5.25	5.36	5.50	5.70	6.69
49370	3.84	4.32	4.61	4.81	4.99	5.12	5.25	5.36	5.50	5.70	6.69
49332	3.84	4.32	4.60	4.81	4.99	5.12	5.25	5.36	5.50	5.70	6.69
49206	3.84	4.32	4.60	4.81	4.99	5.12	5.25	5.36	5.50	5.70	6.69
48873	3.84	4.32	4.60	4.8	4.98	5.11	5.24	5.35	5.49	5.69	6.67
48252	3.82	4.3	4.58	4.78	4.97	5.09	5.22	5.33	5.47	5.67	6.66
45868	3.56	4.01	4.29	4.49	4.66	4.79	4.92	5.04	5.19	5.39	6.4
44619	3.28	3.73	4.00	4.21	4.38	4.51	4.65	4.77	4.93	5.14	6.17
41707	2.78	3.24	3.53	3.75	3.93	4.07	4.23	4.37	4.54	4.77	5.85
37105	1.55	2.06	2.40	2.67	2.86	3.02	3.21	3.39	3.58	3.87	5.19
36465	1.46	1.96	2.30	2.56	2.74	2.90	3.08	3.26	3.45	3.75	5.08
33245	1.25	1.73	2.04	2.29	2.46	2.61	2.78	2.95	3.14	3.43	4.78
32910	1.21	1.68	2.00	2.25	2.42	2.57	2.74	2.9	3.1	3.39	4.74
32526	1.15	1.61	1.93	2.18	2.35	2.51	2.68	2.85	3.04	3.34	4.69
32448	1.03	1.49	1.82	2.08	2.26	2.42	2.59	2.76	2.96	3.27	4.63
31009	0.90	1.33	1.65	1.91	2.09	2.25	2.43	2.60	2.80	3.11	4.46
28418	0.74	1.10	1.38	1.61	1.78	1.93	2.10	2.27	2.47	2.77	4.12
25729	0.57	0.78	0.95	1.10	1.21	1.32	1.44	1.57	1.73	1.99	3.35
23189	0.46	0.57	0.66	0.74	0.8	0.86	0.93	1.01	1.11	1.29	2.39
21323	0.44	0.51	0.58	0.64	0.68	0.73	0.78	0.84	0.92	1.06	1.96
19817	0.42	0.48	0.54	0.59	0.63	0.67	0.71	0.76	0.82	0.94	1.73
15594	0.40	0.43	0.46	0.49	0.51	0.53	0.56	0.58	0.62	0.69	1.18
15309	0.40	0.43	0.46	0.48	0.50	0.52	0.55	0.57	0.61	0.67	1.15
15258	0.32	0.35	0.38	0.40	0.42	0.44	0.47	0.50	0.53	0.59	1.06
14114	0.31	0.34	0.36	0.38	0.39	0.41	0.43	0.45	0.48	0.53	0.91
11661	0.31	0.32	0.34	0.35	0.36	0.38	0.39	0.40	0.42	0.46	0.76
8591	0.30	0.30	0.31	0.32	0.32	0.33	0.33	0.34	0.35	0.37	0.53
6118	0.30	0.30	0.31	0.31	0.31	0.32	0.32	0.33	0.34	0.35	0.48
4539	0.30	0.30	0.30	0.31	0.31	0.31	0.32	0.32	0.33	0.35	0.46
2185	0.29	0.30	0.30	0.30	0.31	0.31	0.31	0.32	0.32	0.33	0.43
61	0.29	0.29	0.30	0.30	0.30	0.30	0.30	0.31	0.31	0.32	0.39

Table 3. Simulated Stages: Wakulla River – Mean Daily High (November-March) Boundary Stage, ft-NAVD88

River Station	Flow Percentile										
	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	3.86	4.36	4.65	4.86	5.05	5.19	5.31	5.42	5.56	5.75	6.76
52070	3.86	4.36	4.65	4.86	5.05	5.19	5.31	5.42	5.56	5.75	6.76
51914	3.86	4.36	4.65	4.86	5.05	5.19	5.31	5.41	5.56	5.75	6.76
50723	3.85	4.35	4.64	4.85	5.04	5.18	5.30	5.41	5.55	5.74	6.74
49442	3.85	4.35	4.64	4.85	5.03	5.17	5.29	5.40	5.54	5.73	6.72
49370	3.85	4.35	4.64	4.85	5.03	5.17	5.29	5.39	5.54	5.73	6.72
49332	3.85	4.35	4.64	4.84	5.03	5.17	5.29	5.39	5.54	5.73	6.72
49206	3.85	4.35	4.63	4.84	5.03	5.17	5.28	5.39	5.53	5.73	6.71
48873	3.85	4.34	4.63	4.84	5.02	5.16	5.28	5.38	5.52	5.72	6.70
48252	3.83	4.33	4.61	4.82	5.00	5.14	5.26	5.37	5.51	5.70	6.68
45868	3.58	4.06	4.34	4.54	4.72	4.85	4.97	5.08	5.23	5.43	6.43
44619	3.32	3.80	4.08	4.29	4.46	4.59	4.72	4.83	4.99	5.19	6.21
41707	2.92	3.39	3.68	3.91	4.07	4.21	4.35	4.47	4.63	4.85	5.91
37105	2.19	2.56	2.84	3.06	3.22	3.35	3.49	3.63	3.8	4.06	5.29
36465	2.15	2.51	2.77	2.98	3.13	3.25	3.39	3.53	3.70	3.96	5.19
33245	2.07	2.37	2.6	2.78	2.91	3.02	3.16	3.28	3.45	3.70	4.92
32910	2.05	2.35	2.58	2.76	2.88	2.99	3.12	3.25	3.42	3.67	4.89
32526	2.03	2.32	2.54	2.72	2.84	2.96	3.08	3.21	3.38	3.63	4.83
32448	1.94	2.24	2.46	2.64	2.77	2.88	3.01	3.14	3.31	3.56	4.78
31009	1.90	2.17	2.38	2.55	2.67	2.78	2.90	3.03	3.20	3.44	4.63
28418	1.82	2.04	2.22	2.37	2.47	2.57	2.68	2.8	2.95	3.18	4.33
25729	1.72	1.84	1.95	2.04	2.11	2.18	2.26	2.35	2.45	2.64	3.72
23189	1.66	1.72	1.78	1.83	1.87	1.91	1.95	2.00	2.07	2.18	2.99
21323	1.64	1.69	1.73	1.76	1.79	1.82	1.86	1.89	1.94	2.03	2.67
19817	1.63	1.67	1.70	1.73	1.76	1.78	1.81	1.84	1.88	1.95	2.49
15594	1.62	1.64	1.65	1.67	1.68	1.70	1.71	1.73	1.75	1.79	2.11
15309	1.62	1.64	1.65	1.67	1.68	1.69	1.70	1.72	1.74	1.78	2.09
15258	1.56	1.57	1.59	1.60	1.62	1.63	1.64	1.66	1.68	1.72	2.01
14114	1.55	1.57	1.58	1.59	1.60	1.61	1.62	1.63	1.65	1.68	1.92
11661	1.55	1.56	1.57	1.58	1.58	1.59	1.60	1.61	1.62	1.64	1.83
8591	1.55	1.55	1.55	1.56	1.56	1.57	1.57	1.57	1.58	1.59	1.71
6118	1.54	1.55	1.55	1.55	1.56	1.56	1.56	1.57	1.57	1.58	1.67
4539	1.54	1.55	1.55	1.55	1.55	1.56	1.56	1.56	1.57	1.58	1.66
2185	1.54	1.54	1.55	1.55	1.55	1.55	1.55	1.56	1.56	1.57	1.63
61	1.54	1.54	1.54	1.55	1.55	1.55	1.55	1.55	1.55	1.56	1.61

Table 4. Simulated Stages: Wakulla River – Mean Daily High Boundary Stage, ft-NAVD88

River	Flow Percentile										
Station	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	3.86	4.37	4.67	4.88	5.07	5.20	5.32	5.44	5.57	5.77	6.77
52070	3.86	4.37	4.67	4.88	5.07	5.20	5.32	5.44	5.57	5.76	6.77
51914	3.86	4.37	4.66	4.88	5.07	5.20	5.32	5.44	5.57	5.76	6.77
50723	3.86	4.37	4.66	4.87	5.06	5.19	5.31	5.43	5.56	5.75	6.75
49442	3.86	4.36	4.65	4.86	5.05	5.18	5.30	5.42	5.55	5.74	6.73
49370	3.86	4.36	4.65	4.86	5.05	5.18	5.30	5.42	5.55	5.74	6.73
49332	3.86	4.36	4.65	4.86	5.05	5.18	5.30	5.42	5.55	5.74	6.73
49206	3.86	4.36	4.65	4.86	5.05	5.18	5.30	5.41	5.55	5.74	6.72
48873	3.86	4.36	4.65	4.85	5.04	5.17	5.29	5.41	5.54	5.73	6.71
48252	3.84	4.34	4.63	4.84	5.02	5.15	5.27	5.39	5.52	5.71	6.69
45868	3.59	4.08	4.36	4.57	4.74	4.87	4.99	5.11	5.25	5.45	6.45
44619	3.35	3.83	4.11	4.32	4.49	4.62	4.74	4.87	5.01	5.21	6.22
41707	3.00	3.46	3.75	3.97	4.13	4.26	4.39	4.53	4.67	4.88	5.93
37105	2.40	2.74	2.99	3.20	3.33	3.46	3.59	3.73	3.88	4.14	5.33
36465	2.38	2.69	2.92	3.12	3.25	3.37	3.5	3.64	3.79	4.04	5.24
33245	2.31	2.57	2.77	2.94	3.05	3.16	3.28	3.42	3.56	3.79	4.97
32910	2.30	2.56	2.75	2.92	3.03	3.13	3.25	3.39	3.53	3.76	4.94
32526	2.28	2.53	2.72	2.88	2.99	3.10	3.22	3.35	3.49	3.72	4.89
32448	2.20	2.45	2.65	2.81	2.92	3.03	3.15	3.29	3.43	3.66	4.84
31009	2.17	2.40	2.58	2.73	2.84	2.94	3.05	3.19	3.32	3.55	4.69
28418	2.11	2.29	2.44	2.58	2.67	2.76	2.86	2.98	3.10	3.31	4.41
25729	2.02	2.13	2.22	2.30	2.36	2.42	2.50	2.57	2.67	2.84	3.84
23189	1.97	2.02	2.07	2.12	2.15	2.19	2.23	2.27	2.33	2.44	3.18
21323	1.96	1.99	2.03	2.06	2.09	2.11	2.14	2.18	2.22	2.30	2.88
19817	1.95	1.98	2.01	2.03	2.05	2.07	2.01	2.13	2.16	2.23	2.72
15594	1.93	1.95	1.97	1.98	1.99	2.00	2.01	2.03	2.05	2.09	2.38
15309	1.93	1.95	1.96	1.98	1.99	2.00	2.01	2.02	2.04	2.08	2.35
15258	1.87	1.89	1.90	1.92	1.93	1.94	1.95	1.96	1.98	2.01	2.28
14114	1.87	1.88	1.89	1.90	1.91	1.92	1.93	1.94	1.95	1.98	2.20
11661	1.87	1.88	1.88	1.89	1.90	1.90	1.91	1.92	1.93	1.95	2.12
8591	1.86	1.87	1.87	1.88	1.88	1.88	1.89	1.89	1.90	1.91	2.01
6118	1.86	1.87	1.87	1.87	1.87	1.88	1.88	1.88	1.89	1.90	1.98
4539	1.86	1.87	1.87	1.87	1.87	1.87	1.88	1.88	1.88	1.89	1.97
2185	1.86	1.86	1.87	1.87	1.87	1.87	1.87	1.88	1.88	1.89	1.95
61	1.86	1.86	1.86	1.87	1.87	1.87	1.87	1.87	1.87	1.88	1.93

4.0 Sensitivity of Water Levels in Sally Ward Spring Run to Wakulla Springs Pool Water Levels

An analysis was performed to determine the effect of Wakulla Springs pool water levels on water levels in Sally Ward Spring Run. Sally Ward Spring Run has an adverse slope (channel bottom elevations increase as you move downstream) from the springhead to the confluence with the Wakulla Springs pool, where it has an elevation of 1.06 ft-NAVD88. This contributes to a pooling effect between the pedestrian bridge and the end of the spring run and flattens the water surface profile along the spring run. It is apparent that water levels in the Wakulla Springs pool affect water levels to some extent along the entire Sally Ward Spring Run. Because of the potential effect that minimum flows established for Wakulla Springs may have on Sally Ward Spring Run, an analysis was performed to determine the impact of Wakulla Springs pool water levels on Sally Ward Spring Run and under what conditions they exhibit the most effect.

Two approaches were taken to assess water level sensitivity. Both approaches were compared to the normal calibrated simulation for the median downstream boundary condition described previously. The first approach was to shift the elevations typically observed at the Wakulla Springs pool by lowering and raising the elevation of the ineffective flow area downstream of the Wakulla Springs pool by 0.5 ft, look at the differences these modifications had on water levels at the Wakulla Springs pool in comparison to the normal, calibrated simulation, and compare those differences to the differences in Sally Ward Spring Run water levels. As the elevations of the Wakulla Springs pool serve as the tailwater boundary for Sally Ward Spring Run, the purpose was to assess whether differences in water elevations in Sally Ward Spring Run were similar to, or less than, those differences seen in the Wakulla Springs pool. In the second approach, a simulation was run where flows in Sally Ward Spring were set to 0 cfs for all flow percentiles. The resultant water levels were compared to those in the normal calibrated simulation for the median downstream boundary condition. The purpose was to assess the magnitude of changes in the Sally Ward Spring Run water surface profiles across the range of flow percentiles when a drastic change in Sally Ward Spring flows is forced on the system. Simulations were performed for these scenarios and compared to the calibrated steady-state model. Figures 10a, 10b and 11 present the stage differences for the approaches described.

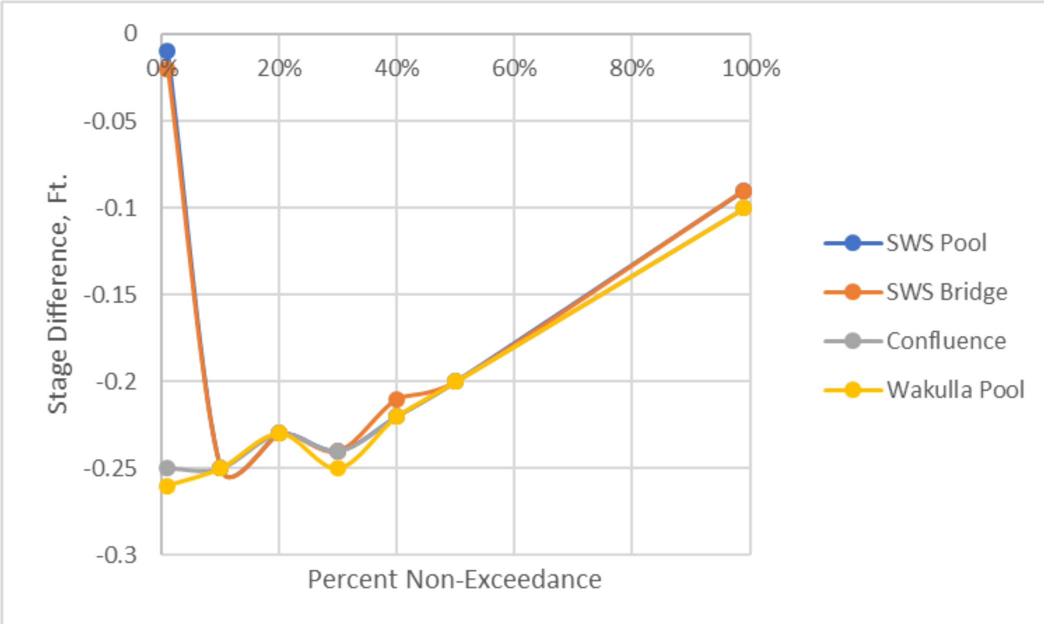

Figure 10a. Comparison of Stage Sensitivity Analysis Simulation Results for Approach 1 – Lowering Downstream Ineffective Flow Area Elevation 0.5 ft

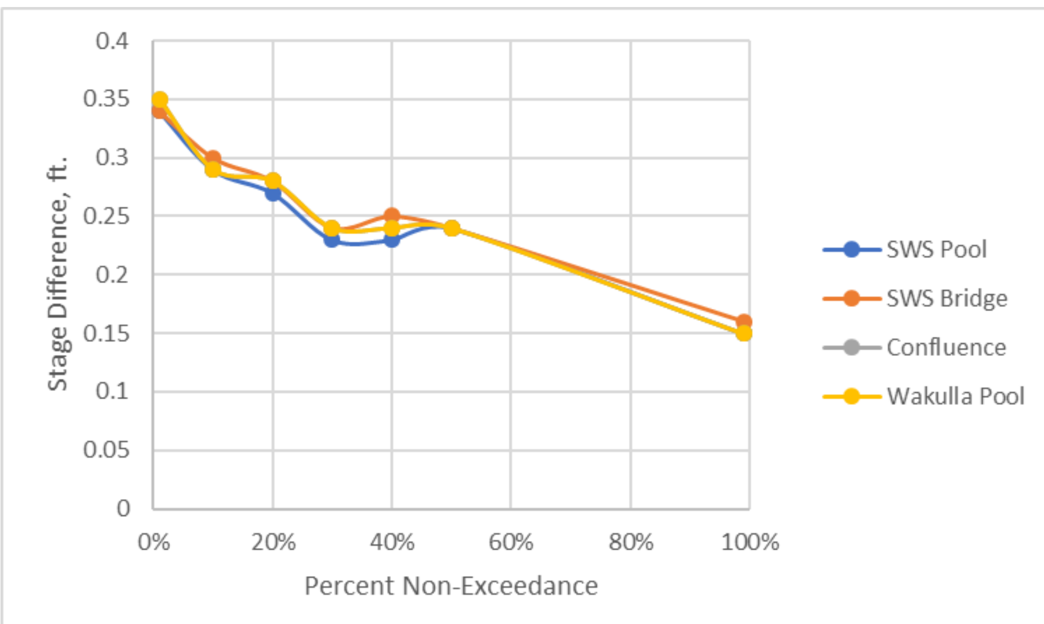

Figure 10b. Comparison of Stage Sensitivity Analysis Simulation Results for Approach 1 – Raising Downstream Ineffective Flow Area Elevation 0.5 ft

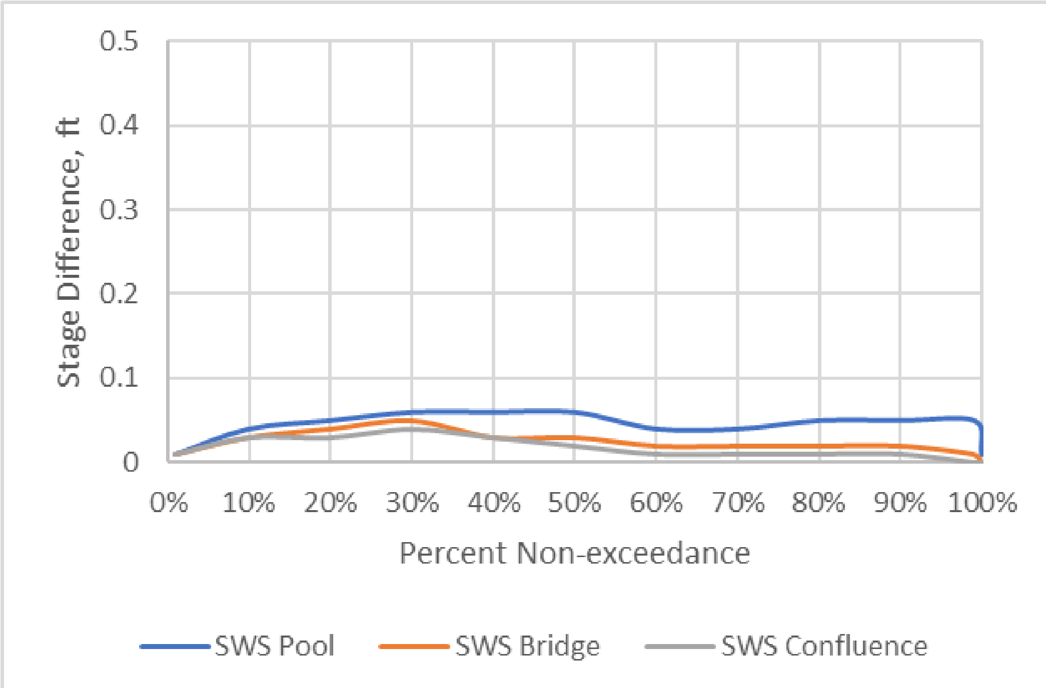

Figure 11. Comparison of Flow Sensitivity Analysis Simulation Results for Approach 2

Inspection of the results shown in Figure 10a, indicate that, at low flows and elevations at the 10 percent non-exceedance level and below, water surface elevations in Sally Ward Spring Run are not influenced by water levels in the Wakulla Springs pool when the ineffective flow area elevation is shifted down 0.5 ft. This is likely due to the adverse slope of the Sally Ward Spring Run channel and the relatively high channel elevation at the confluence with Wakulla River in comparison to the Wakulla Springs pool water elevations. It is in this low range that Wakulla Springs pool elevations do not have a backwater effect on water surface profiles in Sally Ward Spring Run. At stages above the 10-percent non-exceedance level, stage differences are of the same magnitude at all locations on Sally Ward Spring Run as they are in the Wakulla Springs pool, ranging from 0.1 ft to 0.25 ft. Inspection of the results in Figure 10b indicates that stage differences are of the same magnitude at all locations on Sally Ward Spring Run as they are in the Wakulla Springs pool when the ineffective flow area elevation is shifted up 0.5 ft across the range of flow percentiles. Wakulla Springs pool elevations have a backwater effect on water surface profiles in Sally Ward Spring Run across all flow percentiles.

Figure 11 presents the results of the second approach where a simulation was run with flows in Sally Ward Spring set to 0 cfs for all flow percentiles. The resultant water levels were compared to those in the normal calibrated simulation for the median downstream boundary condition. Inspection of Figure 11 shows that the maximum difference in water surface elevations is 0.06 ft at the Sally Ward Spring pool, with the magnitude of the difference decreasing moving closer to the Wakulla Springs pool.

Based on this analysis, water surface profiles in Sally Ward Spring Run appear to be affected more by Wakulla Springs pool water levels than by drastic decreases in Sally Ward Spring flows.

5.0 Evaluation of Sea-Level Rise

Additional scenario runs were performed to evaluate the effect of sea-level rise on predicted water levels in the Wakulla River. Per discussions with NWFWMD staff, a sea-level rise of 2.38 millimeter per year (mm/yr) or 1.87 inches total by 2040 was the condition evaluated. This is the average of Apalachicola and Cedar Key medium projections from 2020-2040. To evaluate the effect of sea-level rise, the downstream boundary conditions in the steady-state HEC-RAS model were adjusted up by 1.87 inches. Predicted water levels in the Wakulla River from sea-level rise scenarios were compared to the predicted water levels under existing conditions to evaluate the effect of sea-level rise. This approach was also used to evaluate sea-level rise in the HEC-RAS modeling for the St. Marks River Rise MFL evaluation. The focus of these scenarios is to look solely at the effects of sea-level rise on predicted water levels in the Wakulla River and not overall potential system impacts resulting from global climate change.

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 McBride Slough, within the area of the model domain where tidal effects predominate. Tables 5 through 10 present summary results of the sea-level rise runs and the water level differences between the sea-level rise and the corresponding existing condition scenarios.

Table 5. Simulated Stages: Wakulla River – Mean Daily High with Sea-Level Rise Boundary Stage, ft-NAVD88

River Station	Flow Percentile										
	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	3.87	4.38	4.68	4.89	5.08	5.21	5.33	5.45	5.58	5.77	6.77
52070	3.87	4.38	4.68	4.89	5.08	5.21	5.33	5.45	5.58	5.77	6.77
51914	3.87	4.38	4.68	4.89	5.08	5.21	5.33	5.45	5.58	5.77	6.77
50723	3.87	4.38	4.67	4.88	5.07	5.20	5.32	5.44	5.57	5.76	6.76
49442	3.87	4.37	4.66	4.87	5.06	5.19	5.31	5.43	5.56	5.75	6.74
49370	3.87	4.37	4.66	4.87	5.06	5.19	5.31	5.43	5.55	5.75	6.73
49332	3.87	4.37	4.66	4.87	5.06	5.19	5.31	5.43	5.55	5.75	6.73
49206	3.87	4.37	4.66	4.87	5.06	5.19	5.31	5.42	5.55	5.75	6.73
48873	3.86	4.37	4.66	4.86	5.05	5.18	5.30	5.42	5.54	5.74	6.72
48252	3.85	4.35	4.64	4.85	5.03	5.16	5.28	5.40	5.53	5.72	6.70
45868	3.61	4.09	4.38	4.58	4.76	4.88	5.01	5.13	5.26	5.46	6.46
44619	3.37	3.85	4.14	4.34	4.51	4.64	4.76	4.89	5.02	5.22	6.23
41707	3.05	3.50	3.79	4.00	4.16	4.29	4.42	4.55	4.68	4.9	5.94
37105	2.52	2.83	3.07	3.27	3.4	3.51	3.65	3.78	3.93	4.18	5.35
36465	2.49	2.79	3.01	3.19	3.32	3.43	3.57	3.69	3.84	4.08	5.26
33245	2.43	2.68	2.86	3.02	3.13	3.23	3.36	3.48	3.62	3.84	5.00
32910	2.42	2.66	2.85	3.00	3.11	3.21	3.34	3.45	3.59	3.81	4.97
32526	2.41	2.64	2.82	2.97	3.08	3.18	3.3	3.42	3.55	3.78	4.92
32448	2.33	2.57	2.75	2.9	3.01	3.11	3.24	3.35	3.49	3.72	4.87
31009	2.30	2.52	2.68	2.83	2.93	3.02	3.15	3.26	3.39	3.61	4.73
28418	2.25	2.42	2.56	2.69	2.77	2.85	2.96	3.06	3.18	3.38	4.45
25729	2.17	2.27	2.36	2.44	2.49	2.55	2.62	2.69	2.78	2.94	3.91
23189	2.13	2.18	2.22	2.27	2.3	2.33	2.37	2.41	2.47	2.57	3.27
21323	2.11	2.15	2.18	2.21	2.24	2.26	2.29	2.32	2.36	2.44	2.99
19817	2.10	2.13	2.16	2.19	2.2	2.22	2.25	2.27	2.31	2.37	2.83
15594	2.09	2.11	2.12	2.13	2.14	2.16	2.17	2.18	2.20	2.24	2.51
15309	2.09	2.11	2.12	2.13	2.14	2.15	2.16	2.18	2.19	2.23	2.49
15258	2.03	2.05	2.06	2.07	2.08	2.09	2.10	2.12	2.13	2.16	2.41
14114	2.03	2.04	2.05	2.06	2.07	2.08	2.08	2.09	2.11	2.13	2.34
11661	2.03	2.04	2.04	2.05	2.06	2.06	2.07	2.08	2.09	2.11	2.26
8591	2.02	2.03	2.03	2.04	2.04	2.04	2.05	2.05	2.06	2.07	2.16
6118	2.02	2.03	2.03	2.03	2.03	2.04	2.04	2.04	2.05	2.06	2.13
4539	2.02	2.03	2.03	2.03	2.03	2.03	2.04	2.04	2.04	2.05	2.12
2185	2.02	2.02	2.03	2.03	2.03	2.03	2.03	2.03	2.04	2.05	2.10
61	2.02	2.02	2.02	2.03	2.03	2.03	2.03	2.03	2.03	2.04	2.08

Table 6. Wakulla River – Water Level Difference, Ft. (Mean Daily High- Sea-Level Rise minus Existing)

River Station	Flow Percentile										
	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
52070	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
51914	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
50723	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
49442	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
49370	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00
49332	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00
49206	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
48873	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
48252	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
45868	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.01
44619	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
41707	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.01	0.02	0.01
37105	0.12	0.09	0.08	0.07	0.07	0.05	0.06	0.05	0.05	0.04	0.02
36465	0.11	0.10	0.09	0.07	0.07	0.06	0.07	0.05	0.05	0.04	0.02
33245	0.12	0.11	0.09	0.08	0.08	0.07	0.08	0.06	0.06	0.05	0.03
32910	0.12	0.10	0.10	0.08	0.08	0.08	0.09	0.06	0.06	0.05	0.03
32526	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.07	0.06	0.06	0.03
32448	0.13	0.12	0.10	0.09	0.09	0.08	0.09	0.06	0.06	0.06	0.03
31009	0.13	0.12	0.10	0.10	0.09	0.08	0.10	0.07	0.07	0.06	0.04
28418	0.14	0.13	0.12	0.11	0.10	0.09	0.10	0.08	0.08	0.07	0.04
25729	0.15	0.14	0.14	0.14	0.13	0.13	0.12	0.12	0.11	0.10	0.07
23189	0.16	0.16	0.15	0.15	0.15	0.14	0.14	0.14	0.14	0.13	0.09
21323	0.15	0.16	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.11
19817	0.15	0.15	0.15	0.16	0.15	0.15	0.15	0.14	0.15	0.14	0.11
15594	0.16	0.16	0.15	0.15	0.15	0.16	0.16	0.15	0.15	0.15	0.13
15309	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.16	0.15	0.15	0.14
15258	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.16	0.15	0.15	0.13
14114	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15	0.16	0.15	0.14
11661	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.14
8591	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15
6118	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15
4539	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15
2185	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.16	0.16	0.15
61	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15

Table 7. Simulated Stages: Wakulla River – Mean Daily High- November-March Boundary Stage, ft-NAVD88

River Station	Flow Percentile										
	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	3.86	4.36	4.66	4.87	5.06	5.19	5.31	5.42	5.57	5.76	6.76
52070	3.86	4.36	4.66	4.87	5.06	5.19	5.31	5.42	5.56	5.76	6.76
51914	3.86	4.36	4.66	4.87	5.06	5.19	5.31	5.42	5.56	5.76	6.76
50723	3.86	4.36	4.65	4.86	5.05	5.18	5.3	5.41	5.55	5.75	6.75
49442	3.85	4.36	4.64	4.85	5.04	5.17	5.29	5.40	5.54	5.74	6.72
49370	3.85	4.35	4.64	4.85	5.04	5.17	5.29	5.40	5.54	5.74	6.72
49332	3.85	4.35	4.64	4.85	5.04	5.17	5.29	5.40	5.54	5.74	6.72
49206	3.85	4.35	4.64	4.85	5.04	5.17	5.29	5.40	5.54	5.73	6.72
48873	3.85	4.35	4.64	4.84	5.03	5.16	5.28	5.39	5.53	5.72	6.7
48252	3.84	4.33	4.62	4.83	5.01	5.15	5.26	5.37	5.51	5.71	6.69
45868	3.58	4.07	4.35	4.55	4.73	4.86	4.98	5.09	5.24	5.44	6.44
44619	3.33	3.81	4.09	4.30	4.47	4.61	4.73	4.85	5.00	5.20	6.22
41707	2.95	3.42	3.71	3.94	4.10	4.24	4.37	4.49	4.65	4.87	5.92
37105	2.29	2.65	2.91	3.13	3.27	3.40	3.54	3.67	3.84	4.10	5.31
36465	2.26	2.60	2.84	3.05	3.19	3.31	3.44	3.58	3.75	4.00	5.22
33245	2.19	2.47	2.68	2.86	2.98	3.09	3.22	3.34	3.51	3.74	4.94
32910	2.17	2.45	2.66	2.83	2.95	3.06	3.19	3.31	3.48	3.71	4.91
32526	2.16	2.43	2.63	2.80	2.92	3.02	3.15	3.27	3.44	3.67	4.86
32448	2.07	2.34	2.55	2.73	2.84	2.95	3.08	3.20	3.37	3.61	4.81
31009	2.03	2.28	2.47	2.64	2.75	2.85	2.97	3.10	3.26	3.49	4.66
28418	1.97	2.17	2.33	2.47	2.57	2.66	2.77	2.88	3.03	3.24	4.37
25729	1.87	1.98	2.08	2.17	2.24	2.30	2.38	2.46	2.56	2.73	3.78
23189	1.81	1.87	1.92	1.97	2.01	2.05	2.09	2.14	2.20	2.31	3.08
21323	1.80	1.84	1.88	1.91	1.94	1.97	2.00	2.03	2.08	2.16	2.77
19817	1.79	1.82	1.85	1.88	1.90	1.93	1.95	1.98	2.02	2.09	2.60
15594	1.78	1.79	1.81	1.82	1.84	1.85	1.86	1.88	1.90	1.94	2.24
15309	1.78	1.79	1.81	1.82	1.83	1.84	1.86	1.87	1.89	1.93	2.22
15258	1.72	1.73	1.75	1.76	1.77	1.78	1.79	1.81	1.83	1.86	2.15
14114	1.71	1.72	1.74	1.75	1.75	1.76	1.77	1.78	1.80	1.83	2.06
11661	1.71	1.72	1.73	1.73	1.74	1.75	1.75	1.76	1.77	1.80	1.97
8591	1.70	1.71	1.71	1.72	1.72	1.72	1.73	1.73	1.74	1.75	1.86
6118	1.70	1.71	1.71	1.71	1.72	1.72	1.72	1.72	1.73	1.74	1.82
4539	1.70	1.71	1.71	1.71	1.71	1.72	1.72	1.72	1.73	1.74	1.81
2185	1.70	1.70	1.71	1.71	1.71	1.71	1.71	1.72	1.72	1.73	1.79
61	1.70	1.70	1.70	1.71	1.71	1.71	1.71	1.71	1.71	1.72	1.77

Table 8. Simulated Stages: Water Level Difference (ft) - Mean Daily High- November-March - Sea-Level Rise minus Existing

River Station	Flow Percentile										
	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.00
52070	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00
51914	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00
50723	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
49442	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
49370	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00
49332	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00
49206	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.01
48873	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00
48252	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01
45868	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
44619	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
41707	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.01
37105	0.10	0.09	0.07	0.07	0.05	0.05	0.05	0.04	0.04	0.04	0.02
36465	0.11	0.09	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.03
33245	0.12	0.10	0.08	0.08	0.07	0.07	0.06	0.06	0.06	0.04	0.02
32910	0.12	0.10	0.08	0.07	0.07	0.07	0.07	0.06	0.06	0.04	0.02
32526	0.13	0.11	0.09	0.08	0.08	0.06	0.07	0.06	0.06	0.04	0.03
32448	0.13	0.10	0.09	0.09	0.07	0.07	0.07	0.06	0.06	0.05	0.03
31009	0.13	0.11	0.09	0.09	0.08	0.07	0.07	0.07	0.06	0.05	0.03
28418	0.15	0.13	0.11	0.10	0.10	0.09	0.09	0.08	0.08	0.06	0.04
25729	0.15	0.14	0.13	0.13	0.13	0.12	0.12	0.11	0.11	0.09	0.06
23189	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.13	0.13	0.09
21323	0.16	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.13	0.10
19817	0.16	0.15	0.15	0.15	0.14	0.15	0.14	0.14	0.14	0.14	0.11
15594	0.16	0.15	0.16	0.15	0.16	0.15	0.15	0.15	0.15	0.15	0.13
15309	0.16	0.15	0.16	0.15	0.15	0.15	0.16	0.15	0.15	0.15	0.13
15258	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.14	0.14
14114	0.16	0.15	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.14
11661	0.16	0.16	0.16	0.15	0.16	0.16	0.15	0.15	0.15	0.16	0.14
8591	0.15	0.16	0.16	0.16	0.16	0.15	0.16	0.16	0.16	0.16	0.15
6118	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.16	0.16	0.15
4539	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15
2185	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
61	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16

Table 9. Simulated Stages: Wakulla River – Median Boundary Stage, ft-NAVD88

River Station	Flow Percentile										
	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	3.85	4.33	4.62	4.83	5.02	5.15	5.28	5.39	5.53	5.73	6.74
52070	3.85	4.33	4.62	4.83	5.02	5.15	5.28	5.39	5.53	5.73	6.73
51914	3.84	4.33	4.62	4.83	5.02	5.15	5.28	5.39	5.53	5.73	6.73
50723	3.84	4.33	4.61	4.82	5.01	5.14	5.27	5.38	5.52	5.72	6.72
49442	3.84	4.32	4.61	4.81	5.00	5.13	5.26	5.37	5.51	5.71	6.7
49370	3.84	4.32	4.61	4.81	5.00	5.13	5.26	5.37	5.51	5.70	6.69
49332	3.84	4.32	4.61	4.81	5.00	5.13	5.26	5.37	5.51	5.70	6.69
49206	3.84	4.32	4.61	4.81	5.00	5.13	5.25	5.36	5.50	5.70	6.69
48873	3.84	4.32	4.60	4.80	4.99	5.12	5.25	5.35	5.49	5.69	6.68
48252	3.82	4.30	4.58	4.79	4.97	5.10	5.23	5.34	5.48	5.67	6.66
45868	3.56	4.01	4.29	4.49	4.67	4.79	4.93	5.04	5.19	5.40	6.40
44619	3.29	3.73	4.01	4.21	4.38	4.51	4.66	4.78	4.93	5.14	6.17
41707	2.79	3.25	3.54	3.77	3.94	4.08	4.24	4.38	4.55	4.78	5.86
37105	1.61	2.11	2.44	2.71	2.89	3.06	3.24	3.42	3.60	3.88	5.20
36465	1.53	2.02	2.34	2.61	2.78	2.94	3.12	3.29	3.48	3.76	5.09
33245	1.34	1.79	2.10	2.35	2.51	2.66	2.82	2.99	3.17	3.46	4.79
32910	1.31	1.75	2.06	2.31	2.47	2.62	2.78	2.94	3.13	3.42	4.76
32526	1.25	1.69	2.00	2.24	2.41	2.56	2.72	2.89	3.08	3.36	4.70
32448	1.13	1.58	1.89	2.15	2.31	2.47	2.64	2.81	3.00	3.29	4.64
31009	1.02	1.43	1.74	1.99	2.16	2.32	2.48	2.65	2.85	3.14	4.48
28418	0.88	1.21	1.48	1.70	1.86	2.01	2.17	2.34	2.53	2.81	4.14
25729	0.71	0.91	1.07	1.21	1.32	1.42	1.54	1.66	1.81	2.06	3.39
23189	0.62	0.71	0.80	0.87	0.93	0.99	1.06	1.13	1.23	1.39	2.46
21323	0.59	0.66	0.72	0.78	0.82	0.87	0.92	0.97	1.05	1.18	2.04
19817	0.58	0.63	0.68	0.73	0.77	0.80	0.85	0.89	0.95	1.06	1.81
15594	0.55	0.58	0.61	0.64	0.66	0.68	0.70	0.73	0.76	0.82	1.29
15309	0.55	0.58	0.61	0.63	0.65	0.67	0.69	0.72	0.75	0.81	1.26
15258	0.48	0.51	0.53	0.56	0.57	0.59	0.62	0.64	0.67	0.73	1.17
14114	0.47	0.49	0.51	0.53	0.55	0.56	0.58	0.60	0.62	0.67	1.03
11661	0.47	0.48	0.49	0.51	0.52	0.53	0.54	0.56	0.58	0.61	0.89
8591	0.46	0.46	0.47	0.48	0.48	0.49	0.49	0.50	0.51	0.53	0.68
6118	0.46	0.46	0.46	0.47	0.47	0.48	0.48	0.49	0.49	0.51	0.63
4539	0.45	0.46	0.46	0.47	0.47	0.47	0.48	0.48	0.49	0.50	0.61
2185	0.45	0.46	0.46	0.46	0.46	0.47	0.47	0.47	0.48	0.49	0.58
61	0.45	0.45	0.46	0.46	0.46	0.46	0.46	0.46	0.47	0.48	0.54

Table 10. Simulated Stages: Water Level Difference– Median- Sea-Level Rise minus Existing

River	Flow Percentile										
Station	P1	P10	P20	P30	P40	P50	P60	P70	P80	P90	P99
52189	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01
52070	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
51914	0.00	0.00	00.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00
50723	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.00
49442	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
49370	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00
49332	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00
49206	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
48873	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.01
48252	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00
45868	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00
44619	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00
41707	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
37105	0.06	0.05	0.04	0.04	0.03	0.04	0.03	0.03	0.02	0.01	0.01
36465	0.07	0.06	0.04	0.05	0.04	0.04	0.04	0.03	0.03	0.01	0.01
33245	0.09	0.06	0.06	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.01
32910	0.10	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.02
32526	0.10	0.08	0.07	0.06	0.06	0.05	0.04	0.04	0.04	0.02	0.01
32448	0.10	0.09	0.07	0.07	0.05	0.05	0.05	0.05	0.04	0.02	0.01
31009	0.12	0.10	0.09	0.08	0.07	0.07	0.05	0.05	0.05	0.03	0.02
28418	0.14	0.11	0.10	0.09	0.08	0.08	0.07	0.07	0.06	0.04	0.02
25729	0.14	0.13	0.12	0.11	0.11	0.10	0.10	0.09	0.08	0.07	0.04
23189	0.16	0.14	0.14	0.13	0.13	0.13	0.13	0.12	0.12	0.10	0.07
21323	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.13	0.13	0.12	0.08
19817	0.16	0.15	0.14	0.14	0.14	0.13	0.14	0.13	0.13	0.12	0.08
15594	0.15	0.15	0.15	0.15	0.15	0.15	0.14	0.15	0.14	0.13	0.11
15309	0.15	0.15	0.15	0.15	0.15	0.15	0.14	0.15	0.14	0.14	0.11
15258	0.16	0.16	0.15	0.16	0.15	0.15	0.15	0.14	0.14	0.14	0.11
14114	0.16	0.15	0.15	0.15	0.16	0.15	0.15	0.15	0.14	0.14	0.12
11661	0.16	0.16	0.15	0.16	0.16	0.15	0.15	0.16	0.16	0.15	0.13
8591	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15
6118	0.16	0.16	0.15	0.16	0.16	0.16	0.16	0.16	0.15	0.16	0.15
4539	0.15	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15
2185	0.16	0.16	0.16	0.16	0.15	0.16	0.16	0.15	0.16	0.16	0.15
61	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.16	0.16	0.15

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