4.6 MODELING COASTAL RIVERS OPERATIONALLY: A CASE STUDY OF THE ST. JOHNS RIVER, FLA.

Reggina Cabrera Garza[1], Janice Sylvestre[2], and Michael Watts[2]
[1] NOAA, National Weather Service, Southeast River Forecast Center, Peachtree City, Ga.
[2] NOAA, National Weather Service, Office of Hydrologic Development, Silver Spring, Md.

1. Introduction

Forecasting river levels in the Southeastern United States is responsibility of the National Weather Service (NWS) Southeast River Forecast Center (SERFC). Most river forecasts in this area are generated using hydrologic models defined within the National Weather Service River Forecast System (NWSRFS). In 2001, the SERFC began forecasting water levels for a reach in the middle section of the St. Johns River in Florida, between Lake Harney and the city of Deland.

Rivers in coastal areas with mild channel bottom slopes, backwater effects, and/or tidal influence cannot be modeled properly using only hydrologic techniques. Therefore, there is a need to implement a hydraulic model that can be used in rivers with such characteristics. The NWS has developed a one-dimensional, dynamic, generalized flood wave routing model (FLDWAV), which is currently a component within NWSRFS and is being used for the St. Johns River.

When National Oceanic and Atmospheric Administration (NOAA) started the Coastal Storm Initiative (CSI), the St. Johns River was selected for a demonstration project to showcase improved forecasting capabilities in coastal river systems. The NWS Office of Hydrologic Development (OHD) and the SERFC have worked toward the development of the St. Johns River model envisioned by CSI. The combined effort involved improvements to and expansion of the existing hydraulic model from the city of Deland toward the mouth of the river in the Atlantic Ocean at Mayport, Fla. In addition, based on the simulation of the water levels provided by the hydraulic model, flood forecast maps could be generated to provide an improved method for forecast visualization.

2. Model Description

Hydrologic and/or hydraulic models of the river system are developed within NWSRFS and used on a daily basis. At the River Forecast Centers (RFCs), hydrologic models and routing techniques are used unless the characteristics of the river system are such that a hydrologic routing would not handle the dynamics involved in the movement of water.

If it is determined that the system is dynamic, the hydraulic model is developed, mainly to perform the routing. In this case, it is necessary to obtain the local flows from the output of the hydrologic model and incorporate them into the hydraulic setting; then the model is executed with the dynamic routing scheme.

The hydrologic model is a lumped model composed of sub-basins linked toward the outlet of the main river system. Each of the sub-basins is characterized in the setting as a segment, which includes the outlet position, sub-basin delineation, rainfall-runoff model, and unit hydrograph. In addition, if it is not a headwater, a routing scheme is defined.

In the hydraulic model, the system is defined by a reach along the river, bounded by upstream and downstream boundaries and with selected locations for generating output. These sites may or may not coincide with the segments. If they coincide, the local flow computed by the hydrologic model for that sub-basin is added as input into the hydraulic model.

The main challenges in setting up a forecasting model for the St. Johns River (Fig. 1), which flows from South to North, were not only the existence of lakes

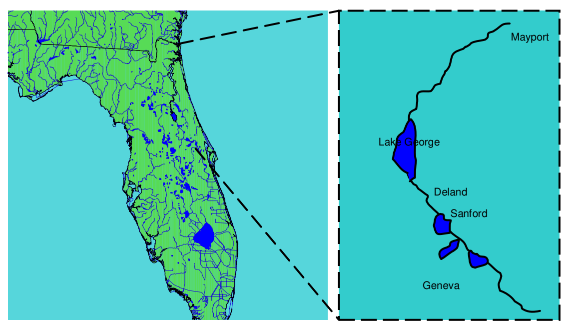

Figure 1. Study area for the St. Johns River System.

along the river but also the tidal influence in the main stem and backwater on some of the tributaries. The original hydrologic model for the St. Johns River included four segments, and a forecast was provided at three of them. The final hydrologic setting includes thirteen segments located between Lake Harney and the city of Jacksonville, six of which will be forecast sites (Fig. 2 and Tab. 1).

* *Corresponding author address*: Reggina Cabrera Garza, NOAA/NWS, Southeast River Forecast Center, 4 Falcon Dr. Peachtree City, GA 30269
email: Reggina.Cabrera.Garza@noaa.gov

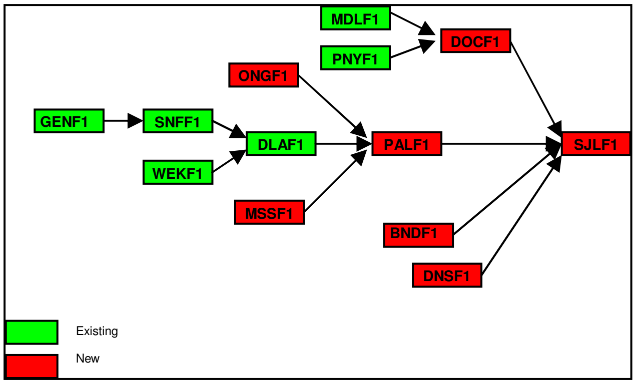

Figure 2. St. Johns River Hydrologic Model.

Table 1. Site ID for segments included in the hydrologic model.

Site	ID	Forecast Site
St. Johns River above Lake Harney near Geneva	GENF1	X
St. Johns River near Sanford	SNFF1	X
Wekiva River near Sanford	WEKF1	
St. Johns River near Deland	DLAF1	X
Orange Creek at Orange Springs	ONGF1	
Ocklawaha River at Moss Bluff	MSSF1	
St. Johns River at Buffalo Bluff	PALF1	X
North Fork Black Creek near Middleburg	MDLF1	X
South Fork Black Creek near Penney Farms	PNYF1	
Black Creek near Doctor's Inlet	DOCF1	
Etonia Creek at Bardin	BNDF1	
Dunns Creek near Satsuma	DNSF1	X
St. Johns River at Jacksonville	SJLF1	

Within the St. Johns River setup, the NWSRFS hydrologic model was implemented with the purpose of computing local and lateral flows and providing the upstream boundary of the hydraulic model, FLDWAV. If there are tributaries of the main stem of the river which, given their characteristics, do not require to be modeled in a dynamic fashion, then the flows entering the main stem are also computed with the hydrologic model. They are referred to as lateral flows and incorporated in the hydraulic model as well.

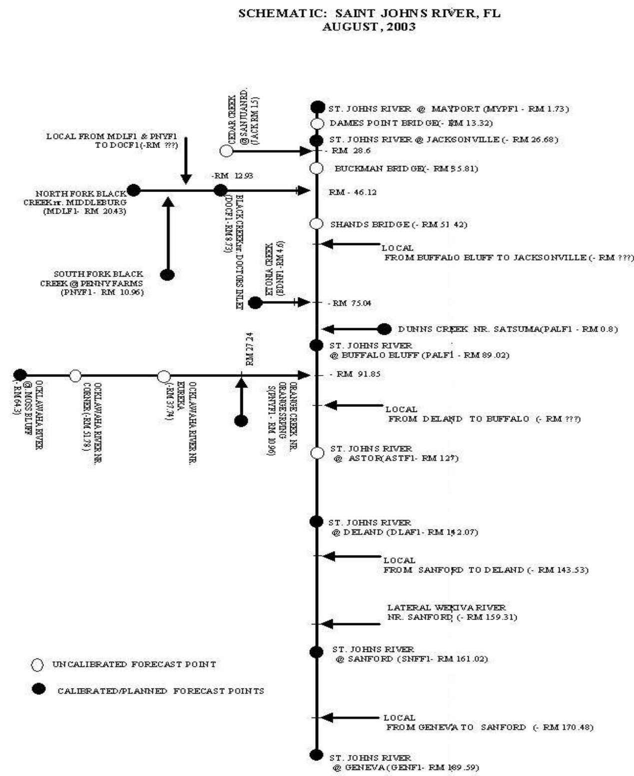

Figure 3. Setting for the Hydraulic Model.

The boundaries selected for the FLDWAV model include the discharge hydrograph at the St. Johns River above Lake Harney near Geneva (as the upper boundary) and the tides at Mayport (as the downstream boundary). Although the current hydraulic model incorporates the effects of the astronomic tides, the final model would also be defined to account for storm surge effects.

The St. Johns hydraulic model (Fig. 3) consists of seven dynamic reaches, the main stem plus six tributaries (Ocklawaha River, Orange Creek, Dunns Creek, Etonia Creek, South Fork Black Creek, and North Fork Black Creek). There are also a lateral inflow that corresponds to the contribution of the Wekiva River and a total of five local inflows.

The main stem of the St. Johns River, extends for about 312 kilometers from above Lake Harney to its mouth in the Atlantic Ocean at Mayport, Florida. Five stream gages and a tide gage are used in this reach. Each of the five stream-gage sites with observed data were used during calibration.

3. System Setup

The system setup was chosen based on the following criteria: volume contribution of the tributaries, possible forecast sites, backwater effects due to tides, backwater effects due to mild channel slope, and channel storage due to variation in topography. The first two aspects determined whether or not to include a tributary, and the last three were used to determine whether to model these tributaries as lateral flows or as dynamic tributaries.

Within the St. Johns River System, 68% of the total volume comes from local flow, with 32% coming from the upstream boundary of the system, above Lake Harney near Geneva, Florida. This accounts for 80% of the total river volume. The remaining volume corresponds to the tributaries, each of which contributes less than 10% of the volume. Table 2 indicates the criteria in the different tributaries that determine them to be defined as dynamic.

Table 2. Criteria to determine dynamic definition of the tributaries.

Site	Backwater due to tides	Backwater due to slope	Storage
Ocklawaha River	X	X	
Orange Creek		X	
Dunns Creek	X		
Etonia Creek		X	
North Fork Black Creek	X		X
South Fork Black Creek	X		X

4. Calibration

Model calibration of the NWSRFS hydrologic model must be performed first; then the local flows generated during this process are used to perform the calibration of the hydraulic model.

The hydrologic calibration is performed on the rainfall-runoff parameters for the model in use. In this case, the Sacramento Soil Moisture Accounting model (SAC-SMA) was used. The evaluation of such calibration is based on overall simulation error statistics as well as a close examination of the simulated hydrographs versus the observed ones. Unit hydrographs need to be derived, and for downstream reaches the existence of a routing technique is necessary. A good “fit” between the observed and simulated flows is expected to occur in headwater basins, mainly because there are no additional difficulties from routing parameters. For downstream areas, the additional calibration of routing parameters makes the simulation more complex, therefore increasing the chance for simulation errors. The complexity of the hydrologic environment in Florida—the existence of numerous lakes in an otherwise swampy terrain and a flat river channel—add difficulty to the calibration of the model.

The calibration periods were selected based on the availability and quality of data. The hydrologic model was calibrated for a period from 1967 to 1998, and in some cases data was available until 2001. The data considered included precipitation, flows computed based on observed stages and available ratings, and evaporation. The precipitation was used to compute mean areal precipitation for each of the sub-basins, which is the forcing mechanism for the generation of the local flows.

A water mass balance was computed for the St. Johns River Basin, and it was determined that there was a high level of stream-aquifer interaction (Riverside Technology, Inc., St. Johns River, Florida, March 2004). This prompted the use of techniques within the calibration to adjust flows in several sub-basins to account for this condition. In addition, based on the same reference, at the lower reaches of the basin there were suggestions of a sub-surface hydraulic connection between the river and the ocean.

Although the annual percentage bias of the purely hydrologic model at all sites was less than 1%, visual examination of the simulated versus observed flows suggested the existence of limitations in the hydrologic setting. Therefore, this model could not be expected to forecast accurately when used by itself. It was decided that the river system would be better represented and the results would be more accurate if the hydrologic model was used in combination with the hydraulic model (Fig. 3).

The hydraulic calibration followed the hydrologic calibration. In order to use the local flows, the period selected for the hydraulic calibration was within the period of the hydrologic calibration. Note that the calibration of the hydraulic model simulates selected events, but the operational model should be able to simulate any circumstances that might arise during daily operations. Thus, it is advisable to include a high-flow scenario as well as a low-flow scenario to assure the performance of the model under both extreme conditions.

The time period selected for low flow conditions extended from September 25, 1996, to February 2, 1997. Overall, the simulations matched reasonably well with the observed water surface profile. The Root Mean Square Error (RMSE) during the calibration process was computed to be less than 0.15 meters for all the sites (Table 3).

The high-flow calibration included the period from November 29, 1997, to May 28, 1998. In this case, the RMSE was also less than 0.15 meters for all sites (Table 3). For this scenario, the individual RMSEs were slightly higher than those for low flows.

Major challenges during calibration included the determination of the channel slope, reasonable simulations at the lower end of the St. Johns River reach, and backwater effects. Regarding the latter, model results and observed data suggested the existence of backwater up to about 145 kilometers upstream of the mouth of the St. Johns River system, near Buffalo Bluff, Florida. The backwater on the Saint Johns River was due to mild slope and tidal effects from the Atlantic Ocean. Tidal effect was also present at some of the tributaries: North Fork Black Creek during low-flow events and Dunns Creek during low- and high-flow events.

Table 3. Root Mean Square Error in meters for Low and High Flows

Site	RMSE Low Flow	RMSE High Flow
St. Johns River above Lake Harney near Geneva	0.073	0.095
St. Johns River near Sanford	0.058	0.095
St. Johns River near Deland	0.082	0.082
St. Johns River at Buffalo Bluff	0.116	0.122
St. Johns River at Jacksonville	0.104	0.134
St. Johns River at Mayport	0.049	0.052
Ocklawaha River at Moss Bluff	0.119	0.088
Orange Creek at Orange Springs	0.070	0.058
Dunns Creek near Satsuma	0.101	0.149
Etonia Creek at Bardin	0.064	0.034
South Fork Black Creek near Penney Farms	0.052	0.061
North Fork Black Creek near Middleburg	0.070	0.110
Black Creek near Doctor's Inlet	0.107	n/a

5. **Verification**

Once the calibration for the high and low flows was completed, the calibrated parameters for channel roughness were combined into one data set that included low- and high-flow roughness. The purpose of this combination was to obtain a set of parameters that could be verified with an independent event for both types of flows. The time period used for verification was September 9, 1996, to October 1, 1996. Table 4 shows the RMSE from this event, including the comparison between the original and final models. Extending the forecast area to the mouth of the river resulted in improved values at the original forecast points. In addition, the bias for both scenarios and the verification was less than 6.0 cm at most of the gages.

6. Operational Setting

The main issue in the transition of the model from calibration into the operational forecast system resides in the assurance of the model's stability. The NWS operates NWSRFS continuously, and daily forecasts are produced independently of the magnitude of the flow in the streams. Stability of the models is essential to maintain the continuity of the simulations. The hydrologic model has proven to be stable at the lumped scale that is executed; thus, most of the effort is concentrated in ensuring the stability of the hydraulic model—in this case, FLDWAV.

Other models could be used in a similar manner as FLDWAV. However, the main reason that NWS uses FLDWAV resides in its ability to be incorporated in an operational setting, such as that existing in the NWSRFS, to provide river forecasting on a continuous basis. In addition, FLDWAV can be developed in different platforms, such as a personal computer (PC) or the NWS Advanced Weather Interactive Processing System (AWIPS). There is an advantage in using a PC in the development of the model because the availability of AWIPS during operational shifts is limited. If the model has been calibrated using a PC, it can easily be transferred into AWIPS.

Table 4. Root Mean Square Errors in meters obtained from verification
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River Kilometer	Site	Original RMSE	Final RMSE
	St. Johns River		
301.10	above Lake Harney near Geneva	0.156	0.058
259.14	near Sanford	0.125	0.049
228.78	near Deland	0.305	0.055
145.98	at Buffalo Bluff	n/a	0.131
48.88	at Jacksonville	n/a	0.131
-5.12	at Mayport	n/a	0.052
	Ocklawaha River		
105.27	at Moss Bluff	n/a	0.052
	Orange Creek		
5.00	at Orange Springs	n/a	0.110
	Dunns Creek		
	near Satsuma	n/a	0.082
	Etonia Creek		
7.71	at Bardin	n/a	0.058
	South Fork Black Creek		
17.35	near Penney Farms	n/a	0.037
	North Fork Black Creek		
31.90	near Middleburg	n/a	0.119
19.67	near Doctor's Inlet	n/a	0.134

The upper part of the system, from above Lake Harney to Deland, was tested operationally during the 2004 hurricane season. Several issues arose during this season regarding the performance of FLDWAV, mainly because since this river system was defined in 2001, there had been only one event (September 2001) that caused flooding, and it was minor. During 2004, there were three hurricanes that affected this area: Charley, Frances, and Jeanne (Fig. 4).

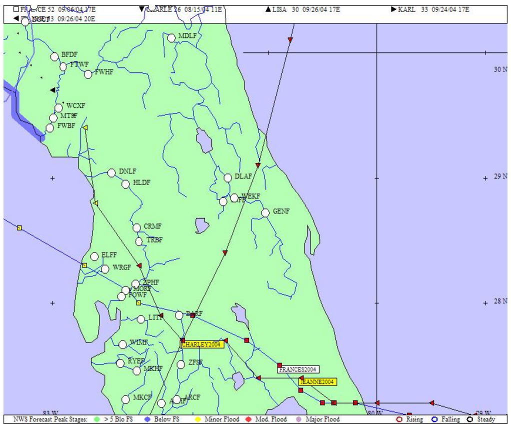

Figure 4. Paths of Hurricanes Charley, Frances, and Jeanne, 2004 (Hurrevac2000).

Rainfall produced by these systems affected the water levels in the St. Johns River. Water levels were low at the beginning of August, and the rainfall associated with Charley produced a significant rise, but it wasn't until the passage of Frances that the rises reached flood stage and remained above flood stage until the beginning of November, 2004 (Fig. 5).

These events brought the stages and flows to ranges which had not been tested before; therefore, FLDWAV will need to be calibrated for higher values using the data from this season.

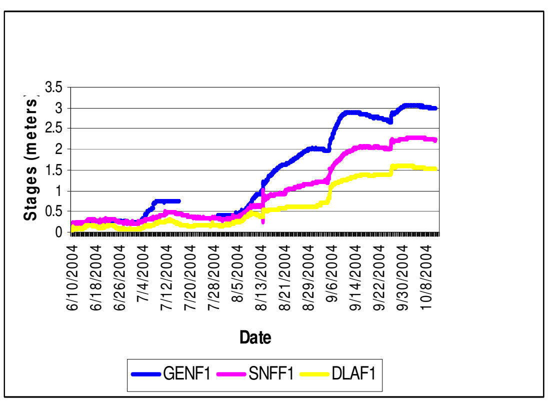

Figure 5. Water levels at three sites on the St. Johns River.

7. Flood Mapping

The maps displaying the extent of flooding are in high demand. These maps can be generated based on the forecast of the water surface profile. Two pieces of software are used by NWS: FLDWAV (Fread and Lewis, 1988) and FLDVIEW (Cajina et. al., 2002). During the development of FLDWAV for the St. Johns River, calibration outputs were used to test the generation of maps. Although the maps can be generated for any flow, they are particularly valuable during flooding events. The visualization of the area(s) affected by water level forecasts can be very useful to decision makers.

The input requirements for FLDVIEW include the water surface profile, the channel width corresponding to the known water surface elevation, the channel bottom, cross section locations, and the latitude/longitude of the end points of the flood map. The FLDWAV model exports this information into files read by FLDVIEW, and maps such as the one shown in Figure 6 are generated. This figure shows the extent of flooding from Mayport to Jacksonville during the high-flow event, depicting the inundated area during the peak flow.

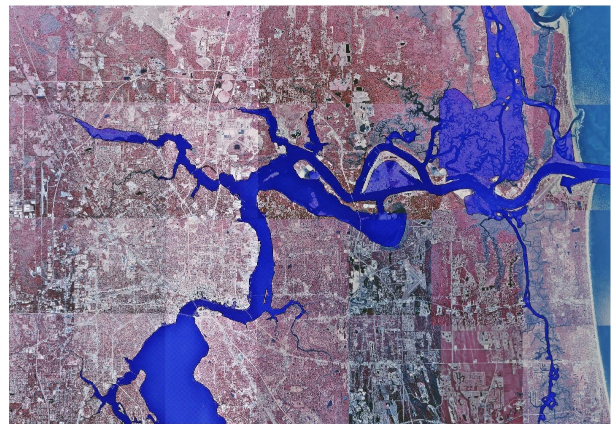

Figure 6. Inundation map in Jacksonville area

8. Summary

The development of the St. Johns River hydraulic model was accomplished by expanding the original hydrologic and hydraulic models to include the reach from the city of Deland to Mayport, Florida. Both the hydrologic and hydraulic models have been calibrated, and their implementation into the NWSRFS operational setting is scheduled to occur soon.

The 2004 hurricane season provided insight on the performance of the hydraulic model. Even though the original St. Johns River model proved to be stable, once the observed stages reached levels higher than those included in the calibration, it was necessary to recalibrate the model parameters in the hydraulic model (FLDWAV).

There are two temporary effects that need to be modified in the current version of FLDWAV: wind and storm surge. When setting up a river reach in FLDWAV, there is an option to include magnitude and direction of the wind for the whole reach of the river. Wind effect is particularly important when river basins are being affected by tropical events. Because wind effect is temporary and does not always affect the whole reach, a modification to this option is necessary. A suggested modification would be a wind turn on/off switch in the model operation.

Storm surge also has a temporary effect on the model operation. Its incorporation in the FLDWAV scheme could not be evaluated during the 2004 events because the expanded hydraulic model had not been implemented yet. However, the methodology is being developed so that in the future, when the surge is forecast, it can be added to the astronomic tides. In this case, the total tide, astronomic plus surge, will become the downstream boundary of the hydraulic model.

Consideration for future work includes: (1) evaluation of the steadiness of the upstream boundary in the St. Johns River for high flows, (2) improvement on the cross-sectional data, (3) recalibration of the roughness coefficient for high flows, and (4) generation of flood maps in the upper part of the St. Johns River, with validation using high water marks.

9. References

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