TOWARD MODELING OF RIVER-ESTUARY-OCEAN INTERACTIONS TO ENHANCE OPERATIONAL RIVER FORECASTING IN THE NOAA NATIONAL WEATHER SERVICE

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Abstract NOAA's Coast, Estuary, River Information Services (CERIS) activity has recently been initiated to provide an integrated suite of water information for coastal communities to assist with hazard mitigation, water resources management, and ecosystem management. Improved river-estuary-ocean hydrologic and hydraulic models will provide the foundation for providing these enhanced services. As we move towards implementing improved river-estuary-ocean forecast models, we need to evaluate several approaches: e.g., implementing or extending 1D river hydraulic models downstream, extending operational estuary-ocean models upstream, or building new dynamically coupled 1D, 2D, and 3D models. In this paper we explore the first approach by developing an unsteady HEC-RAS model for the tidal Potomac River. This model runs with time series of observed and forecast discharge at upstream boundaries and a time series of observed and forecast stage at the downstream boundary. In operational forecasting, the downstream boundary condition could be obtained from 2D/3D estuary-ocean models such as the Chesapeake Bay Operational Forecast System (CBOFS) or the Extratropical Water Level Forecast. Initial calibration and validation results indicate that this one-dimensional HEC-RAS model of the tidal Potomac River is capable of simulating water levels from its mouth at the Chesapeake Bay to Washington, D.C. near the Little Falls pump station.

INTRODUCTION

Coastal communities use critical water information about their watersheds, rivers, estuaries and coasts to mitigate natural hazards, and manage water resources and ecosystems. NOAA's Coast, Estuary, River Information Services (CERIS) activity has been initiated to provide this critical water information to end users in a way that is understandable, useable, and easily accessible (NOAA, 2009).

Users of hydrologic information have needs that cut across NOAA's organizational lines. CERIS is a "one-NOAA", cross-cutting strategy to ensure these needs are met. CERIS does not imply or require a new information technology system. Rather, CERIS leverages and coordinates existing NOAA capabilities. The focus areas for CERIS include:

- Link models to provide a more comprehensive understanding of coastal and estuarine areas (e.g., freshwater inflows with coastal and estuarine physical and ecosystem models)
- Expand services to coastal watersheds without existing freshwater forecasts
- Coordinate the delivery and dissemination of freshwater products and services.

NOAA's National Weather Service (NWS) uses hydrologic models and one-dimensional (1D) hydraulic routing models to forecast river flows and stages at over 4,000 locations in the United States (http://www.nws.noaa.gov/ahps/). Despite these extensive services, coastal areas without existing freshwater forecasts still exist. New and enhanced water information will be valuable for decision makers in these areas. Figure 1 shows the approximate extent of gap areas along the Atlantic and Gulf Coasts. Freshwater runoff forecasts from the red coastal watersheds are not routinely provided by the NWS. For major inland watersheds, the furthest downstream NWS forecast points are upstream of the red zones.

Fig. 1. Service gap areas along the Gulf of Mexico and the Atlantic coast (source NOAA, 2009).

River-estuary-ocean models will provide the foundation to address the first two CERIS focus areas. In this study, we begin examining options to develop and implement the most effective operational river-estuary-ocean models. Specifically, this paper focuses on a simple linkage between a 1D river hydraulics model of the Potomac River and existing NOAA estuary-ocean models. Figure 2 shows the tidal Potomac River reach near Washington, D.C. not covered by either the NWS River Forecast Center (RFC) freshwater forecasts, NWS Extratropical Storm Surge Forecasts (http://www.nws.noaa.gov/mdl/etsurge/), or the National Ocean Service's (NOS) Coast Survey Development Laboratory's (CSDL) Chesapeake Bay Operational Forecast System (CBOFS) (http://www.nauticalcharts.noaa.gov/csdl/CBOFS.html). Similar gaps exist for the James, York, and Susquehanna rivers in the Chesapeake Bay region.

Recent research has shown that accurate water level forecasts for the Washington, D.C. area along the Potomac River can be achieved by running a research 2D/3D river-estuary and ocean model (Stamey et al. 2007). Stamey et al. (2007) show that the combined effects of storm surge and river flow were important for emergency management decision making in the region during Hurricane Isabel. A 2D/3D Eulerian Circulation (ELCIRC) model was used for the hydrodynamic simulations described by Stamey et al. (2007). The flexible mesh feature of this model allows calculations to be efficiently extended into the riverine environment. Extending a 2D/3D estuary/ocean model upstream is one way to bridge the gap shown in Figure 1; however, there is little research providing guidance on where the 2D/3D estuary model should end and where a 1D hydraulic river model should begin. In the case of the Chesapeake Bay Rivers, an alternative to extending estuary-ocean models upstream is to implement operational 1D river hydraulic models to bridge the gap. Bridging the gap in this manner requires model coupling. A simple coupling approach used here is to select water level forecast information from an estuary or ocean model as the downstream boundary condition. Estuary models can also receive inflows from the river model, improving their accuracy. In future work we plan to investigate the benefits of a more sophisticated dynamic coupling approach. Also, the scale at which local inflows from the red zones in Figure 1 can and should be included in the modeling framework is another issue that deserves further investigation

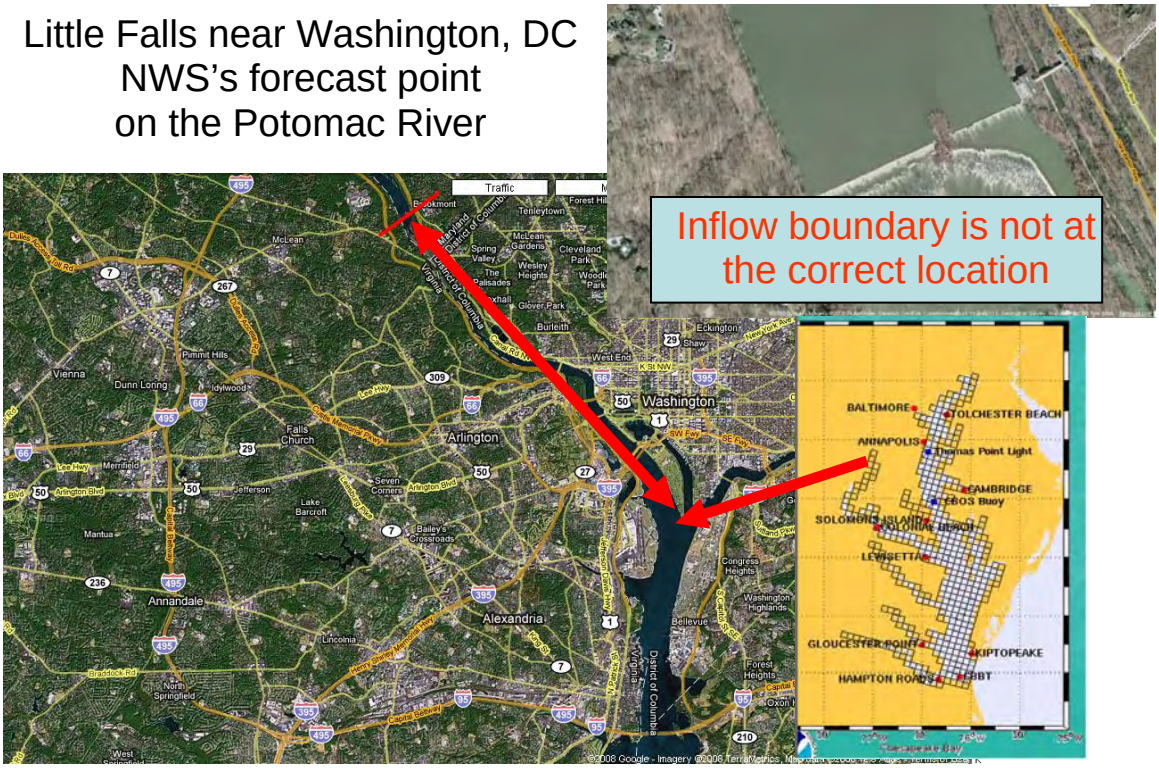

Fig. 2. Example location of a service gap area near Washington, D.C. showing the upper part of the tidal Potomac River and existing NOS CBOFS model domain. Inset figure shows the CBOFS model domain. The operational service gap exists because the CBOFS freshwater inflow boundary is about seven miles downstream of the NWS forecast location (service gap is shown by the arrow).

Historically, 1D hydraulic models have proven to be a viable option for generating accurate water level forecasts in coastal rivers (Fread and Lewis, 1985). Despite advances in 2D/3D modeling and computational power, 1D models are likely to remain an important component of a 1D/2D/3D estuarine forecasting system for years to come. Because of their computational efficiency, 1D models can be easily run in the NWS RFC operational environment with existing hardware. 1D models can be easily re-run in a matter of minutes as weather and water conditions change. Most 1D models provide advanced tools for modeling the impacts of bridges and other riverine obstructions, which are generally not included in the currently operational or research 2D/3D models.

In this paper, we describe one step towards building an enhanced 1D/2D/3D River-Estuary-Ocean (REO) forecast system for the Chesapeake Bay Region. We have built a 1D Hydrologic Engineering Center River Analysis System (HEC- RAS) model for the Potomac River. This model will run with time series of observed and forecast discharge at upstream boundaries and a time series of observed and forecast stage at the downstream boundary. In operational forecasting, the downstream boundary condition could be obtained from 2D/3D estuarine or ocean models such CBOFS or the Extratropical Water Level Forecast. We plan to examine the model behavior using different boundary conditions. Receiving the elevation downstream boundary condition from 2D/3D estuary model is similar to what is currently used for other major rivers in the United States (e.g. Columbia River, Mississippi River, Hudson River), but is new for the Chesapeake Region. This 1D model can serve as a baseline and building block for examining the benefits of more complex approaches (such as extending 2D/3D model upstream or adding 1D elements in 2D/3D models).

In this paper, the tidal Potomac River is defined as the reach that begins about one mile below Little Falls near Washington, D.C. and ends at its mouth in the Chesapeake Bay near Point Lookout, Maryland or near Lewisetta, Virginia (Fig. 3). The Anacostia River is the major tributary and flows into the Potomac River near the Southwest (SW) Waterfront in Washington, D.C.

Fig. 3. Map of the Potomac River and the Anacostia River within the Chesapeake Bay estuary indicating the extent of the HEC- RAS model.

Both rivers are integral parts of the Chesapeake Bay estuary system and highly influenced by the freshwater inflow, tide and other hydrometeorological forcing. Around the Washington, D.C. locations, the variation in the river's water surface elevation over a normal tidal cycle ranges from 3-4 feet. Freshwater flow, storm surge or the combination of the both are the major causes of flooding along the tidal Potomac and the Anacostia River.

HEC-RAS MODEL

The National Weather Service is including the United States Army Corps of Engineers (USACE) HEC-RAS in its operational forecast environment and replacing existing 1D hydraulics models with HEC-RAS models (Moreda et al., 2009). HEC-RAS is an integrated system of software comprised of a graphical user interface (GUI), separate hydraulic analysis component, and data storage management (Brunner, 2002). The model is based on the implicit finite difference solution of the complete one-dimensional Saint-Venant equations of unsteady flow. HEC-RAS uses a four-point implicit finite difference scheme to generate a set of finite difference equations and solves the finite difference equations using linearization and a sparse matrix linear algebra solver. For detailed information and technical manuals please see http://www.hec.usace.army.mil/software/hec-ras/.

STUDY AREA AND METHODOLOGY

The tidal Potomac River unsteady HEC-RAS Model domain consists of the Potomac River from Little Falls, near Washington, D.C. to its mouth at the Chesapeake Bay near Lewisetta, Virginia (Fig. 3 and Fig. 4). The main stem model covers about 114 miles (from River mile 4.42 to 118.25) and contains 89 cross-sections. In this model the gap area of about 7 miles from SW Washington, DC to near Little Falls pump station was included which was outside the CBOFS model domain (Fig. 2 and 3).

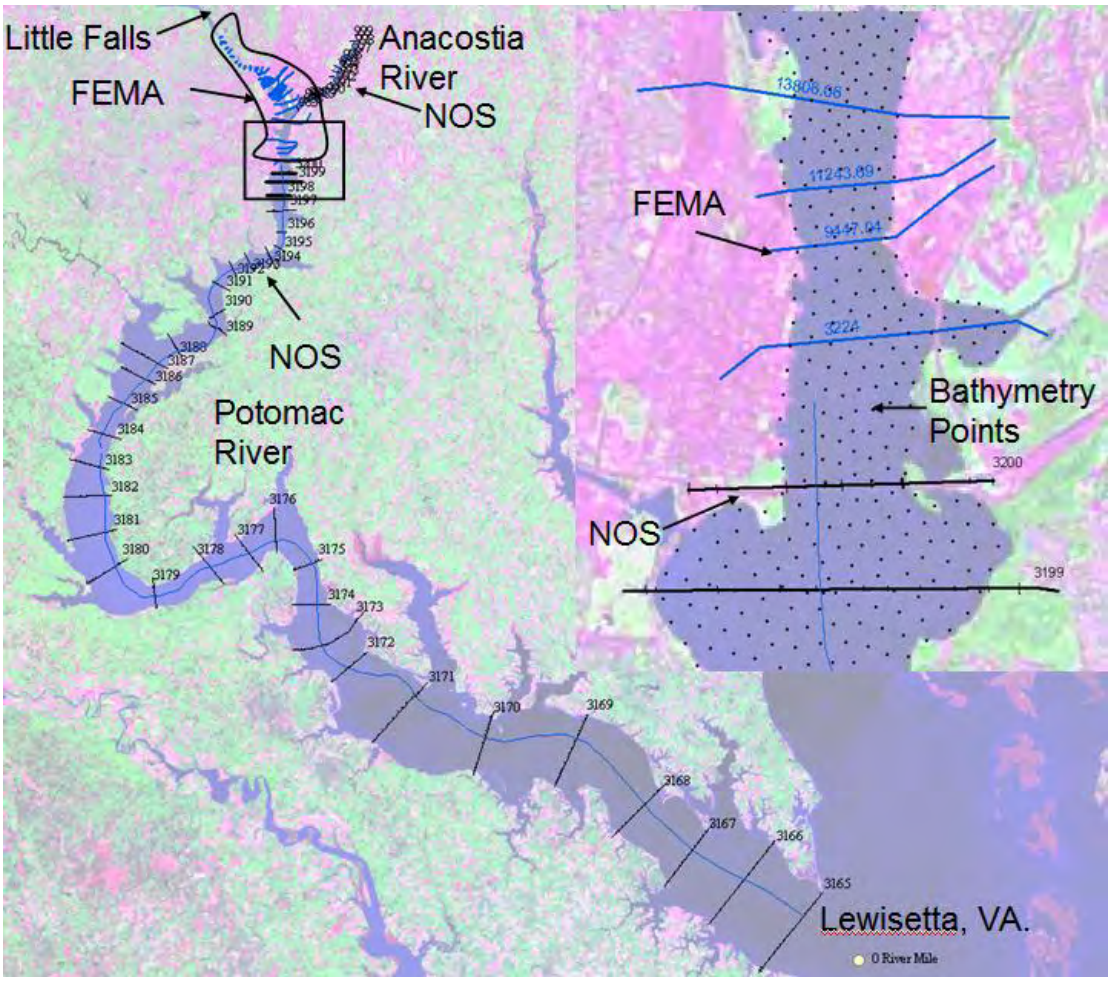

Fig. 4. The Potomac-Anacostia River HEC-RAS model domain with bathymetry data sources. The inset figure shows the transition locations of NOS and FEMA data sources and black dots represents bathymetry points obtained from NOS.

The Anacostia River is included in the model as a tributary to the Potomac River, covers about 7 miles, and includes 15 cross-sections. Other minor tributaries and lateral flows are neglected because of their relatively small discharge contribution. For the purposes of HEC-RAS modeling, a junction was created at the location where the Anacostia River meets the Potomac River at river mile 110 (Fig. 5).

Junctions in HEC-RAS are locations where two or more reaches join together or split apart. The tidal Potomac River is divided into two hydraulic reaches, which are labeled as upper reach and lower reach. The Anacostia River extends from Colmar Manor Park near the US Highway 50 to the confluence with the Potomac (Fig. 5 and 6). The upper reach of the Potomac River is the portion that begins at Little Falls to the junction, and the lower reach is the portion of the river from the junction to the mouth at the Chesapeake Bay near Lewisetta, VA.

The unsteady HEC-RAS model described in this paper has been developed based on the bathymetry data provided by NOS-CSDL and a geo-referenced HEC-RAS model of the Potomac River from Little Falls to Haines Point Gage developed for FEMA Region 3. The geo-referenced HEC-RAS cross-sections were imported into ArcGIS along with the geo-referenced NOS-CSDL bathymetry data and satellite imagery. New HEC-RAS cross sections were developed from the downstream section of the FEMA model based on NOS-CSDL data. FEMA and NOS-CSDL data boundary locations are shown in Fig. 4. The inset of Fig. 4 shows the border location between FEMA and NOS-CSDL data and the density of the bathymetry points.

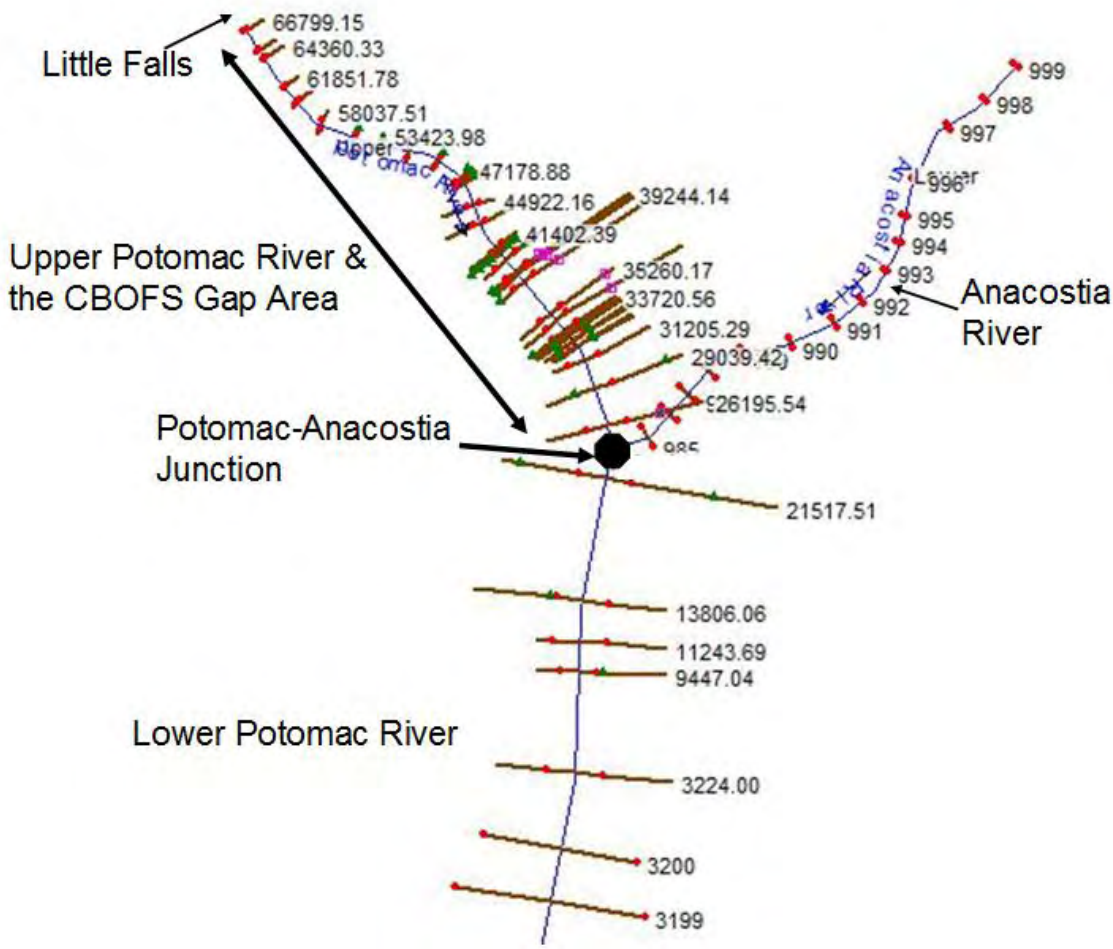

Fig. 5. The upper part of the Potomac River HEC-RAS model showing cross section locations, part of the Anacostia River main channel, Potomac-Anacostia junction location and a portion of the lower Potomac Reach.

The main channel of the Anacostia River begins near US 1 bridge in Maryland, at the confluence of its two largest tributaries, the Northeast Branch and the Northwest Branch. The main channel extends over a distance of approximately 8.4 miles before it discharges into the Potomac River in Washington, D.C. (Fig 5 and 6).

However, the Anocostia reach in the HEC-RAS model only extends about 7 miles upstream from the confluence with the Potomac. Although a study by the Maryland Department of the Environment (MDE and DC DE-NRA, 2007) indicates that there are tidal influences further upstream, we did not have the necessary bathymetry information to extend the model. If additional bathymetry data can be obtained, we will extend this model to include the entire main channel and the Northeast Branch up to USGS station 01649500 near Riverdale, Maryland and the Northwest Branch up to 01651000 near Hyattsville, Maryland.

The vertical datum for all time series plots and cross section elevations are in mean sea level (MSL). Where applicable, elevations obtained in other datum were converted to the MSL datum. Greenwich Mean Time (GMT) is used as the reference time frame.

MODEL CALIBRATION AND VALIDATION

The unsteady HEC-RAS model requires initial flows to be specified for the upstream end of the model and for all flow boundary points. For this HEC-RAS model we have used initial flow values close to the first simulation values

provided in the time series data. The flow regime is expected to be sub-critical from a few miles downstream of Little Falls all the way to the Chesapeake Bay. It was noted that about a two mile reach below the Little Falls pump station has a very narrow cross section with rocky river bottoms. This portion of the river flow may not be sub-critical all the time and during extreme flood could create a situation similar to a water fall. Flow could be super-critical during such an event. Therefore, HEC-RAS was run using the Mixed Flow Regime option.

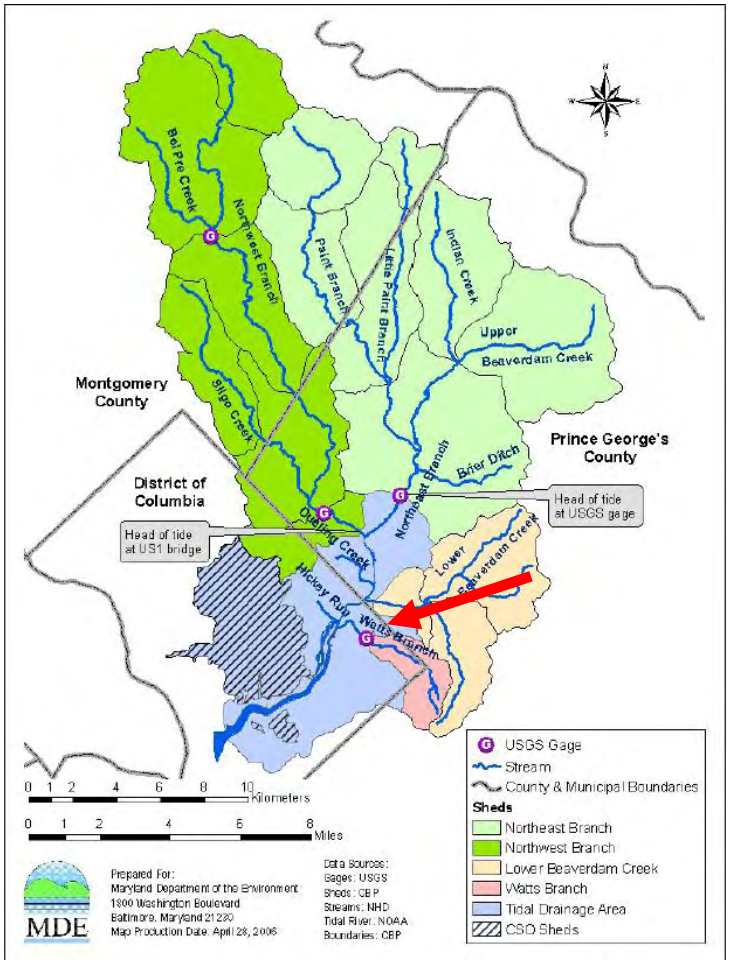

Fig. 6. Anacostia River and tributaries indicating sub-basins and two USGS gages that could be used as the boundary condition locations. This figure was modified from the report by Maryland Department of the Environment and District of Columbia Department of the Environment - Natural Resources Administration (MDE and DC DE-NRA, 2007). Arrow indicates the approximate upstream location of the Anacostia River and the location of the cross section 999, Fig 5) of the HEC-RAS model.

Tidal simulation was performed to evaluate the model's capability to reproduce the tides using harmonic constituents developed by the NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) for the Lewisetta, Virginia and the SW Waterfront in Washington, D.C. stations. Using harmonic constituents, hourly time series data were generated for both stations. The Lewisetta time series was used as the tidal boundary condition to run the HEC-RAS model with a small discharge (10 cfs) at the upstream locations. HEC-RAS simulated water level near Washington, D.C. was then compared to the corresponding time series data generated by harmonic constituents for the same location.

Following the tidal simulations, we initially calibrated the model by selecting inflow and tidal boundary conditions from 01 June 2003 to 30 May 2004. This period includes storm surge and subsequent high river discharge through the Potomac River. Initial Manning's n roughness values were assigned based on information from the FEMA

HEC-RAS model for the upper portion of the model. For the lower portion, we started with a Manning's n from the literature (0.025) and then made some adjustments to get a reasonable match with the tidal amplitude.

After this initial model calibration, two validation periods were selected to further evaluate the HEC-RAS model capabilities: 1) 01 Jan 2009 to 13 Jan 2009 and 2) 07 Feb 2009 to 28 Feb 2009. Recent 2009 data were selected so that parallel analyses requiring additional forcing data (e.g. observed and modeled wind forcings) can be run for the same period.

We have also evaluated this model for the high water marks observed at Wisconsin Avenue at Washington, D.C. during critical river flood events (e.g. 1996 flooding due to sudden snow melt). In most cases, freshwater of the Potomac River is the main cause of flooding around Washington, D.C. and the City of Alexandria, Virginia areas. Historic flood records showed that high water in the Potomac River has caused major flooding along the Anacostia River and other tributaries. Potomac River floods occur rapidly in spring due to heavy rainfall, sudden or rapid snowmelt and usually last for several days. Major flooding in the Potomac basin occurred in 1889, 1936, 1937, 1942, 1954, 1955, 1972, 1975, 1985, and 1996 (Source: http://www.erh.noaa.gov/marfc/). The largest flow ever recorded on the Potomac at Little Falls near Washington, D.C. was in March 1936 when it reached 425,000 ft^3/s. The historic maximum flow through the Anacostia River was estimated to be 18,000 ft^3/s and was observed in June 1972. An operational unsteady HEC-RAS model should be capable (at a minimum) of simulating conditions observed in the past flood events. We simulated the 1996 flood event which had a peak flow of 350,000 cfs and compared the simulated elevation to the observed high water elevation at Wisconsin Avenue. We also evaluated this model for the 1936 flood peak of 426,000 cfs and found that the model is stable with this inflow. However, further high flow calibration is needed to better match observed high water marks.

MODEL RESULTS

Figure 7 shows water levels simulated by the HEC-RAS model and the corresponding time series data based on harmonic constituents for the SW Waterfront in Washington, D.C. It should be noted that high tide and low tides were within 0.5 foot but about 2-3 hours early. To provide a time frame for plotting the harmonic data, they were saved as 2003 tide, although these time series data do not represent 2003 tide.

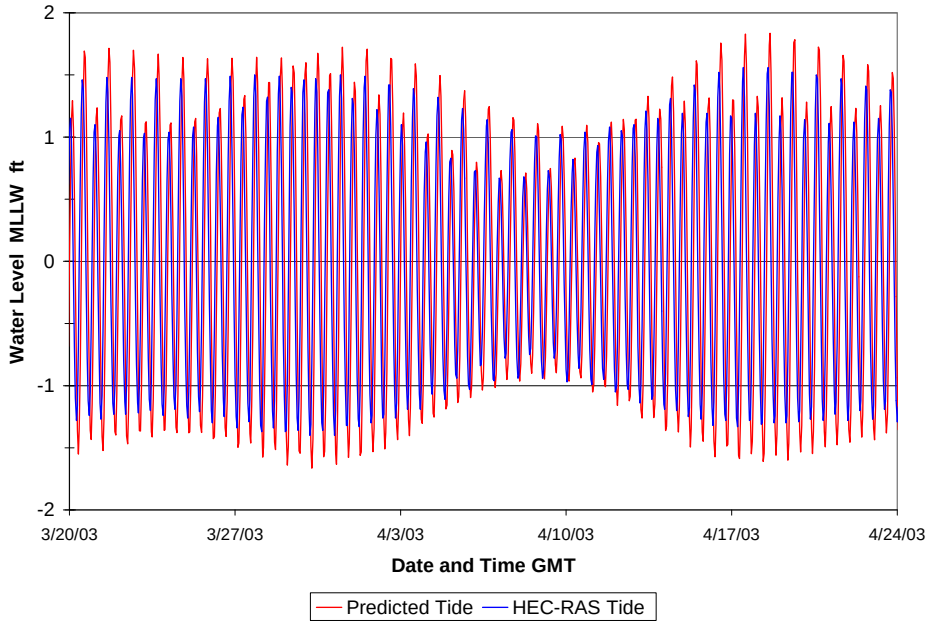

Fig. 7. HEC-RAS simulated water level (blue line) and constructed tide based on harmonic constituents (red line) at the SW Waterfront, Washington, D.C. station.

Figure 8 shows the observed and HEC-RAS simulated water level at the SW Waterfront, Washington, D.C. station for the 2003-2004 simulation which includes Hurricane Isabel surge. Even though the simulated water level tracked observed water level reasonably well, simulated peak surge due to Hurricane Isabel was about 2.5 feet lower than the observed data. It should be noted that this version of the HEC-RAS model did not have the wind forcing where as Isabel surge was primarily a wind driven event. We will investigate if HEC-RAS performance for this event could be improved by using different Manning's n (e.g. as a function of flow) or adding wind forcing in the HEC-RAS model. Simulated and observed water levels for the following two validation periods: 1) 01 Jan 2009 to 13 Jan 2009 and 2) 07 Feb 2009 to 28 Feb 2009 are shown in Fig. 9 and 10, respectively.

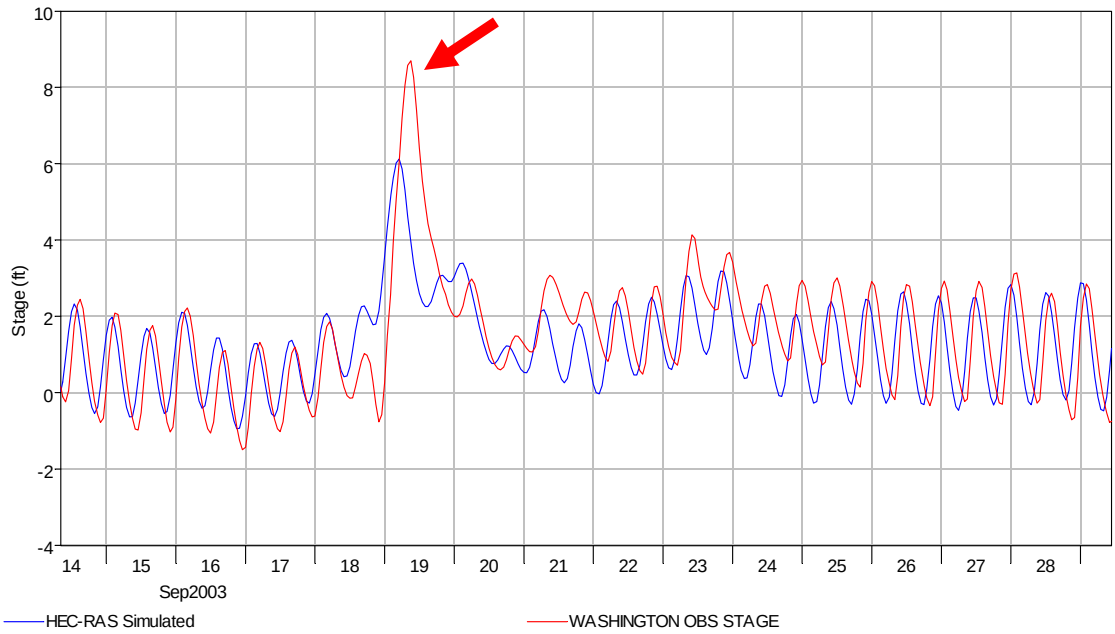

Fig. 8. HEC-RAS simulated water level (blue line) and observed water level (red line) at the SW Waterfront, Washington, D.C. station. (Peak Isabel surge is indicated by the arrow)

At Wisconsin Avenue near Washington, D.C. the HEC-RAS simulated 1996 peak flood was 11.1 ft compared to the 12.5 ft observed stage (in ft, Washington Mean Low Water datum). In this flood, river stage (~ 12ft) is entirely dominated by the freshwater flow, and tidal signal (~ 3 ft) is not present in the stage record.

We expect to improve the model through further calibration of the Manning's n roughness coefficients, in particular, by using discharge dependent roughness coefficients.

CONCLUSIONS

This 1D HEC-RAS model of the tidal Potomac River is capable of simulating water levels from its mouth at the Chesapeake Bay to Washington, D.C. near the Little Falls pump station. The simulation results suggests that implementing new 1D models with boundary conditions derived from 2D/3D models can be a technically sound and viable approach to reduce the operational service gaps that exist for coastal rivers in the Nation. However, we need to investigate further the cause of the 2-hour timing errors and the low simulation for Hurricane Isabel. Further calibration may alleviate some of this error. Also, the model does not currently include a wind forcing term. We are working concurrently on a Sobek 1D model (http://delftsoftware.wldelft.nl) that includes a wind forcing term to evaluate the impacts that wind has in this river.

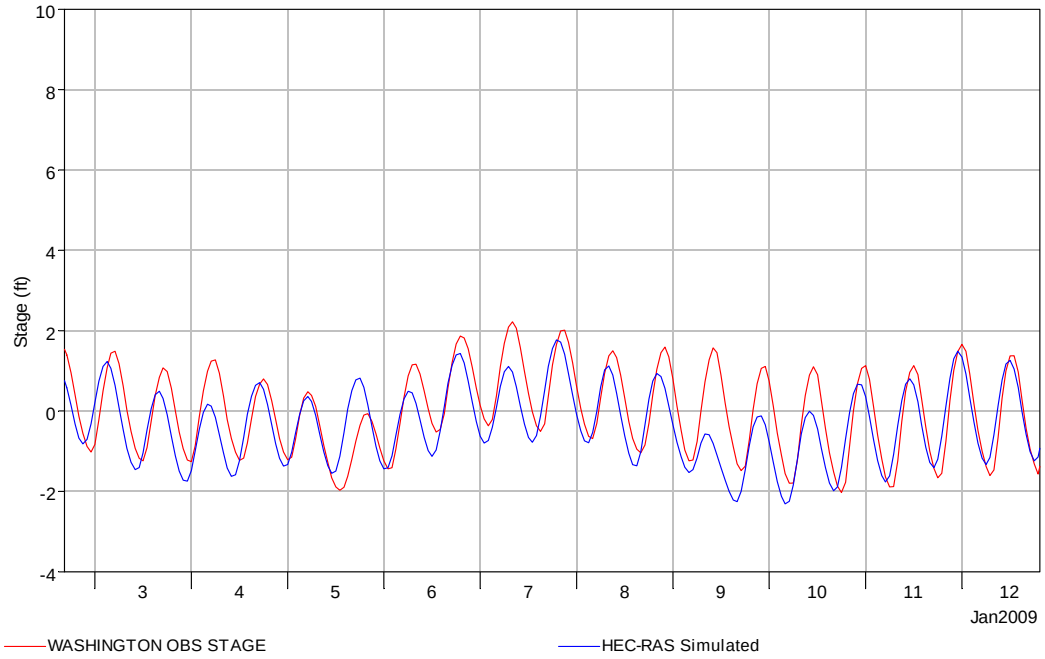

Fig. 9. HEC-RAS simulated water level (blue line) and observed water level (red line) at the SW Waterfront, Washington, D.C. station for the simulation period of 01 Jan 2009 to 12 Jan 2009.

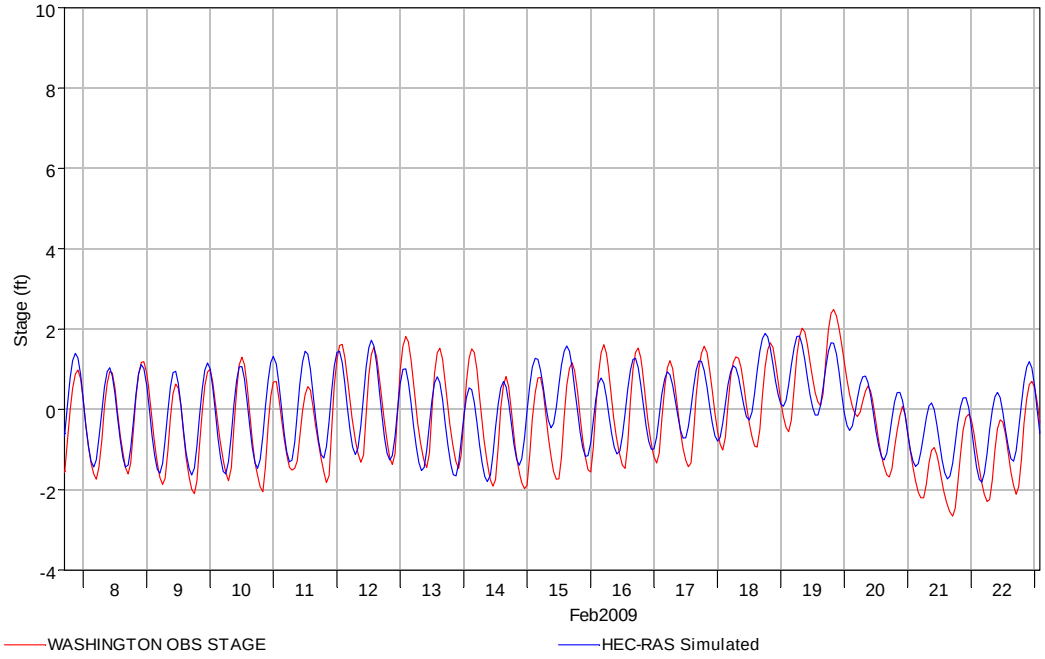

Fig. 10. HEC-RAS simulated water level (blue line) and observed water level (red line) at the SW Waterfront, Washington, D.C. station for the simulation period of 07 FEB 2009 to 28 FEB 2009.

For this unsteady model, the boundary condition requirements are relatively simple: Two time series of observed and forecast discharge at upstream boundaries and one time series of observed and forecast stage at the downstream boundary. Tidal forecast data for the Lewisetta, Virginia station could be obtained from either the Chesapeake Bay Operational Forecast System (CBOFS) or the Extratropical Water Level Forecast.

With a some additional work, the unsteady HEC-RAS model shows promise as an operationally useful forecast model for the Potomac River near Washington, D.C. that can account for the combined effects of tides, storm surge, and freshwater inflows. The NWS Mid-Atlantic River Forecast Center has begun testing this model.

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