A 1D River Hydraulic Model for Operational Flood Forecasting in the Tidal Potomac: Evaluation for Freshwater, Tidal, and Wind Driven Events

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Abstract The National Oceanic and Atmospheric Administration (NOAA) is working towards improving water forecasts in the river-estuary transition zone. One operationally viable method is to extend one-dimensional (1D) hydraulic models downstream well into the tidal estuarine environment. Recent advances in NOAA’s National Weather Service (NWS) operational software infrastructure have made this method easier to implement using the Hydrologic Engineering Center River Analysis System (HEC-RAS). Here, we evaluated the strengths and limitations of an unsteady HEC-RAS implementation for the tidal Potomac River. We calibrated the HEC-RAS model for harmonic tides and major historic freshwater flood events and validated the model on recent freshwater and storm surge events, focusing on water level gauges near Washington, D.C. Root mean squared error for tide simulation at the Washington Waterfront gauge was 0.05 m (0.16 ft) with a phase error of about 2 hours. For historic flood events, simulated peak water level error varied from -0.40 m (-1.34 ft) to 0.40 m (1.34 ft) with a mean absolute error of 0.25 m (0.82 ft) at the Wisconsin Avenue gauge. While HEC-RAS shows considerable potential to improve upon an existing empirical forecast technique for freshwater, tidal, and freshwater-tidal events, HEC-RAS did not adequately model wind-driven events because it does not include an explicit wind forcing term.

Therefore, to further understand the influence of wind on Potomac water levels, we developed both a SOBEK 1D model and a ADCIRC 2D model for Hurricane Isabel. With storm-specific calibration, wind driven simulations from SOBEK and ADCIRC improved peak water level simulation for Hurricane Isabel over HEC-RAS. HEC-RAS without wind forcing missed the Hurricane Isabel peak at the Washington Waterfront by 0.66 m while SOBEK and ADCIRC came within 0.08 and 0.01 m respectively. Interestingly, little improvement was seen over HEC-RAS in prediction of peak time. While SOBEK results show that a wind term in a 1D hydraulic
model can account for observed high water levels, our simple wind reduction factor calibration technique should be replaced by a more physically-based approach to achieve more robust implementations in the future.

**Key Words:** hydraulic modeling, HEC-RAS, SOBEK, ADCIRC, flood forecasting, river-estuary transition zone, tidal river
1 INTRODUCTION

1.1 Motivation

The National Oceanic and Atmospheric Administration’s (NOAA’s) vision for Coast, Estuary, River Information Services (CERIS) (NOAA 2009) includes providing enhanced water information in coastal areas, and identifies improved river-estuary-ocean model linkages as a key mechanism to achieve this goal. The CERIS vision covers a range of forecast services including flow, water level, current, water quality, and ecosystem health. In this paper, we focus on methods to improve water level forecasts in the river estuary transition zone.

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. Through the National Ocean Service (NOS), NOAA also produces estuary and ocean forecasts of tides, storm surge, waves, and estuarine circulation for a variety of users. Despite extensive modeling by both NWS and NOS, various gaps exist in the forecast services, particularly for the riverine-estuarine transition zone where the water elevation can be substantially influenced both by freshwater flows as well as tides and other open ocean effects. Because of these multiple influences, complex modeling is necessary to fully understand and forecast the water behavior in the river-estuary transition zone.

The riverine hydraulic model described in this paper fills the long standing gap in operational model coverage shown in Fig. 1. Prior to this work, the NWS Middle Atlantic River Forecast Center (MARFC) ran dynamic hydrologic models on the Potomac River only as far as the Little Falls Pump station above Washington, D.C. The upstream-most forecast from the NOS Chesapeake Bay Operational Forecast System (CBOFS) (Lanerolle et al. 2009) (described
below) is downstream of the confluence of the Anacostia and Potomac rivers. This left a fifteen kilometer (nine mile) gap where neither the NWS nor NOS operational forecast models provided water level simulations. This gap area includes nationally significant areas such as the National Mall, Parks and Georgetown’s Washington Harbor, where local businesses need more accurate flood forecasts to guide decisions on when and where to erect movable flood walls. While MARFC forecasters have had utilized empirical guidance curves to forecast water levels at one point along this stretch for many years (Wisconsin Avenue near Washington, D.C.), they desired an automated, dynamic hydraulic model with continuous spatial coverage.

1.2 Rationale for Using HEC-RAS to Forecast Water Level on the Lower Potomac River

Historically, NWS one-dimensional (1D) hydraulic models have proven to be a viable option for generating accurate water level forecasts in coastal rivers (Fread and Lewis 1985). Working closely with the US Army Corps of Engineers (USACE), the NWS has recently added the USACE’s Hydrologic Engineering Center River Analysis System (HEC-RAS) (Brunner 2000) computational engines to the suite of modeling tools available for operational river forecasting (Moreda et al. 2009). The unsteady module of the HEC-RAS 1D hydraulic model is used for river forecasting and is accessible to NWS forecasters through the Community Hydrologic Prediction System (CHPS) (Roe et al. 2010). NWS adoption of HEC-RAS has stimulated renewed interest at River Forecast Centers (RFC) to implement hydraulic models for operational forecasting, particularly in coastal rivers.

In addition to the tidal Potomac River, we are aware of four other new, coastal HEC-RAS implementation projects in progress at RFCs: (1) the Colorado River, TX; (2) a joint model of several rivers in the Houston, TX, metropolitan region; (3) the Pascagoula River, MS; and (4) the Waccamaw River, SC. Implementing new HEC-RAS models in the transition zone is a relatively
simple and cost-effective method for RFCs to improve the accuracy of forecasts at existing forecast points and to expand water level forecast services to new locations.

Several operational estuary-ocean models which produce water level and flow data are candidate sources for downstream boundary conditions for operational HEC-RAS implementations in the Chesapeake Bay and elsewhere in the United States, including the Sea, Lake and Overland Surges from Hurricanes (SLOSH) (Jelesnianski et al. 1992), Extratropical Surge (ETSurge) (Kim et al. 1996), and Extratropical Surge and Tide Operational Forecast System (ESTOFS) (NOAA Coast Survey Development Lab (CSDL) 2011). Table 1 summarizes the available operational estuary-ocean models considered for this research.

Beyond operational modeling, recent research focused specifically on the Chesapeake Bay Region makes the lower Potomac River an excellent test bed for transition zone modeling and model evaluation since we can compare operational model results to research model results. Two modeling efforts of particular interest are enhancements to the CBOFS operational forecast system (Lanerolle et al. 2009) and an implementation of the Eulerian Circulation (ELCIRC) model (A. Zhang et al. 2010; Y. Zhang et al. 2004) as part of the Chesapeake Bay Inundation Prediction System (CIPS) demonstration project (Cho 2009; Cho et al. 2011). The CBOFS estuary model, based on the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams 2005), was developed primarily to produce operational tide and current forecasts for the navigational community and has recently been enhanced to include three-dimensional water quality as part of the forecast output. The current CBOFS model grid extends close to the Anacostia – Potomac confluence as shown in Fig. 1.

An alternative to using a 1D river hydraulic model to model the transition zone and bridge forecast gaps is extending an estuary-ocean model farther upstream. Cho et al. (2011)
worked toward this capability, showing accurate water level forecasts for the Washington, D.C. area from ELCIRC simulations for Hurricane Isabel event in 2003. The flexible mesh feature of their model allows calculations to be efficiently extended into the riverine environment.

However, while the Cho et al. (2011) model has been tested under some freshwater flood conditions, it has not been tested with or calibrated to extreme freshwater flood conditions such as the Potomac River flood of 1936, when peak flow was about 13,450 cubic meter per second (cms) (475,000 cubic feet per second (cfs)). Also, the Cho et al. (2011) model is only available in demonstration mode at an academic institution and therefore less likely for immediate use in an operational environment.

The low computational demands of 1D river models offer additional advantages for operational use. Existing NWS RFC hardware can easily run and re-run 1D river models to accommodate changing weather and water conditions in a matter of minutes on a workstation as compared to hours on a super computer for complex 2D models. Forecasters have expressed a preference to re-run HEC-RAS using different boundary conditions available in operations (Table 1) and this option is easily configurable within CHPS. Ensemble forecast runs including 1D river hydraulic models are also feasible with existing hardware. More generally, riverine models such as HEC-RAS provide advanced tools for modeling the impacts of bridges, locks and gates and other river obstructions, which are generally not included in the currently operational or research 2D/3D estuarine models. Despite the advantages of 1D models, operational HEC-RAS implementations are limited due to the lack of a wind forcing term in the momentum equation.
1.3 Objectives

This paper describes creation, calibration, and validation of a HEC-RAS unsteady state model for forecasting water level in the river-estuary transition zone for the lower Potomac River. Building a model for operational forecasting requires some different considerations than the more common steady-state HEC-RAS applications for engineering design. Therefore, we expect documenting this study to provide useful lessons learned for future operational forecasting implementations. We evaluate the model performance over a wide range of conditions relevant to the transition zone, including events where freshwater runoff, tides and wind play an important role. We also compare the model performance to MARFC’s empirical guidance curves for the Wisconsin Avenue gauge.

To understand the significance of wind directly on the hydraulics of the transition zone in the Potomac, we construct two other models covering the lower Potomac that include explicit wind forcing and compare results to HEC-RAS results for Hurricane Isabel. The first wind model is a 1D implementation of SOBEK (Deltares 2011) and the second is an implementation of ADCIRC 2D (Westerink et al. 1992). We identify several practical issues to consider when implementing wind forcing in an operational 1D model including availability and consistency of observed and forecast wind fields and effectiveness of available approaches to spatially and temporally translate wind forces onto the 1D model geometry.

2 Methodology

This section describes how the HEC-RAS, SOBEK1D and ADCIRC 2D models were built or applied to explore the dynamic influences on water level in the transition zone. We first provide detail on the HEC-RAS model calibrated and validated first for tidally dominated events,
then for freshwater events. Our results will help forecasters understand what range of accuracies to expect when using this model.

We subsequently describe the SOBEK 1D and ADCIRC 2D model implementations and associated modeling experiments designed to better understand the impacts of including a wind forcing term in the hydraulic computations during simulations of the Hurricane Isabel event in 2003.

2.1 Lower Potomac HEC-RAS Model

The tidal Potomac River unsteady HEC-RAS model domain covers about 183.4 km (114 miles) of the main stem of the Potomac and contains 89 cross-sections beginning where the river enters Washington, D.C. just below Little Falls and extending to the mouth of the Potomac at the Chesapeake Bay near Lewisetta, Virginia (Fig. 2). This domain includes the NWS service gap area of about fifteen kilometers (nine miles) from SW Washington, D.C. to near Little Falls.

About eleven kilometers (seven miles) of the Anacostia River comprising 15 cross-sections are included in the model as a tributary to the Potomac River. Although a study by the Maryland Department of the Environment (MDE - D.C. DE-NRA 2007) indicates that there are tidal influences farther upstream in the Anacostia River, we did not have the necessary bathymetry information to extend the model. Other minor tributaries and lateral flows are not included in the model. These tributaries account for about 14% of the total drainage area above Lewisetta; however, most of this additional tributary drainage is below our primary forecast locations of interest near Washington, D.C.
Observed or synthetic inflow time series defined the upstream boundary conditions of the different model scenarios, while the downstream boundary condition at Lewisetta was a water level time series.

We developed the Potomac HEC-RAS model cross-section geometry based on both bathymetry data provided by NOS Coast Survey Development Laboratory (CSDL) and a georeferenced HEC-RAS model of the Potomac River from Little Falls to the Anacostia-Potomac confluence developed for the Federal Emergency Management Agency (FEMA) Region 3. The FEMA cross sections were used unmodified and new HEC-RAS cross sections were developed downstream of the FEMA model domain using NOS-CSDL data. Where necessary, the USGS 7.5-minute Digital Elevation Model (DEM) (nominally 30- by 30-m data spacing) was used to determine the bank and flood plain elevations. The vertical datum for time series plots and cross section elevations are in mean sea level (MSL). Where applicable, elevations were converted to MSL. Greenwich Mean Time (GMT) is used as the reference time frame.

Both the Potomac and Anacostia Rivers are highly influenced by freshwater inflow and storm tides, and either of these or combinations of both are the major causes of flooding along the tidal Potomac and the Anacostia River at Washington, D.C. and the City of Alexandria, Virginia (Cho 2009; FEMA 2010). In the vicinity of Washington, D.C., the variation in the river’s water surface elevation over a normal tidal cycle ranges from 0.9 m to 1.2 m (3 ft to 4 ft) (mean sea level, MSL). As shown in Table 2, during flooding events, water levels at Wisconsin Avenue have reached nearly to 5 meters above MSL (16 ft) and can be as high as 3.7 m (12 feet) above mean sea level near Washington, D.C. (FEMA 2010). To attain predictive skill over the wide range of possible conditions, we calibrated the HEC-RAS model to tidal forcings representative of low flow conditions and then to historical record flood conditions. The
calibrated parameters were validated with recent low-flow periods as well as storm surge and freshwater flood events.

2.1.1 Calibration to Tidal Boundary with HEC-RAS

Baseline calibration of the HEC-RAS Manning’s n roughness parameters was performed to evaluate the model’s ability to reproduce harmonic constituents estimated by the NOAA’s Center for Operational Oceanographic Products and Services (CO-OPS). The harmonic constituents are the amplitude and phase parameters of various cosine functions which when added, give the total tidal variation at a particular coastal location independent of the effects of wind, freshwater flows, and other deviations from the pure astronomical tide (Schureman 1941).

The tidal evaluation used 29 days of astronomical tide at Lewisetta (NOAA’s CO-OPS Station ID 8635750) as the downstream boundary condition. A minimal 0.3 cms (10 cfs) flow was used for the upstream boundary conditions.

HEC-RAS simulated water level was compared with predicted astronomical tide at Washington D.C. Waterfront (NOAA’s CO-OPS Station ID 8594900). Initial Manning’s n values were assigned based on the calibration provided in the FEMA HEC-RAS model for the upper portion of the model. For the lower portion, we started with a constant Manning’s n from the literature (0.025) and then made adjustments until we reached values closer to the NOAA’s CO-OPS published tidal amplitudes. In addition to full time series statistical analysis, harmonic analysis of tidal constituents was performed using T_TIDE (Pawlowicz et al. 2002) on HEC-RAS simulated water levels at the Washington Waterfront.

2.1.2 Calibration to Historic Floods and High Water Marks with HEC-RAS

HEC-RAS was further calibrated for various historic freshwater events that caused extensive flooding at Wisconsin Avenue at Washington, D.C. Although flooding on the Potomac
has occurred every month of the year, most Potomac River floods occur in spring due to heavy rainfall, sudden or rapid snowmelt and usually last for several days (Doheny 1997). Detailed flow hydrographs are not available for the historic flooding events and only peak flows were available in the literature. Inflow hydrographs for the HEC-RAS model were developed starting with an assumed base flow followed by a symmetric three-day linear rise to the observed peak and subsequent three-day linear fall back to the assumed base flow requiring a total of six days of simulation for each historic flood event. Rise and fall of the Potomac floods over six days are a reasonable approximation of the observed flow hydrographs reported by Doheny (1997).

We adjusted the Manning’s n values in the upper Potomac channel sections and overbank areas to produce a good fit for the peak stages at Wisconsin Avenue. This final set of calibrated roughness coefficients was used for all subsequent HEC-RAS simulations.

2.1.3 January, 2010 Low Flow Event Validation

The first validation run used 10 days of observed flow and stage data from a low-flow period from January 3, 2009 through January 12, 2009 when water level fluctuation was due almost entirely to tidal effects to validate the simulated propagation of tide. No model parameters (such as roughness) were adjusted during this simulation.

2.1.4 Hurricane Isabel Event in 2003

Additional model validation was performed for the Hurricane Isabel event in 2003. During Isabel, a 1.8 m to 2.4 m (6 to 8 ft) storm tide reached the Washington, D.C. area via the Potomac River, causing flooding in Old Town Alexandria and requiring closure of flood gates at the Washington Harbour Center in Georgetown. Two days later, a second flood wave caused by heavy rain upstream in the Potomac River watershed (NOAA 2009) arrived at Washington
Harbor Center. We simulated the Isabel event from September 18, 2003 to September 22, 2003 to include both the storm tide and subsequent high river discharge through the Potomac River.

2.1.5 Development of Forecast Guidance Curves
Historically, during high river flow, MARFC utilized empirical guidance curves for forecasting at Wisconsin Avenue. The HEC-RAS model was used to generate forecast guidance curves that were similar to the empirical guidance curve but based on simulated dynamic tide and river flow. The new curves show the ability of the dynamic model to reduce uncertainty compared to the empirical forecasting approach and also show the relative importance of tides at two points of interest in the Washington, D.C. area.

2.2 Wind Modeling Experiments for Hurricane Isabel
Although the HEC-RAS model accounts for the propagation of the surge-created water level from the Potomac mouth at Lewisetta, the further amplification of that surge by the along-axis winds in the channel itself is not considered in HEC-RAS.

2.2.1 SOBEK 1D Model
To examine the effects of direct wind forcing implemented in a 1D model, we used the SOBEK-Rural 1D-FLOW module, we created the SOBEK implementation by importing the HEC-RAS model into the SOBEK software package. No modifications were made to the bathymetry or model parameters such as friction coefficients. To verify the HEC-RAS to SOBEK conversion, we ran a SOBEK simulation without any wind forcing for the 2003 Hurricane Isabel with boundary values and the simulation period all identical to the HEC-RAS model.

SOBEK includes a wind friction term in the momentum equation with user specified wind friction coefficients and “wind hiding” factors (to be discussed later). Wind data are input
as direction and speed for each time step and may be specified for the entire model or individual reaches. The angle between each river reach and the wind direction is used to calculate the wind shear stress along the river.

2.2.2 ADCIRC 2D Model

We also simulated storm surge during Hurricane Isabel using the two-dimensional ADvanced CIRCulation (ADCIRC) hydrodynamic model (Westerink et al. 1992). ADCIRC simulations were performed using the model domain developed by the NOS VDatum project for the Chesapeake Bay, Delaware Bay, and adjacent coastal water areas (Fig. 3) (Yang et al. 2008). This model grid represents the domain with 318,860 nodes and 558,718 triangular elements and resolves various rivers and small tributaries in the Chesapeake and Delaware Bay.

We started with the calibrated ADCIRC model parameters from the VDatum project changed bottom friction coefficients to match surge at the Washington D.C. area. We used lateral viscosity as a constant, 25.0 m s$^{-2}$, throughout the model domain and a quadratic friction scheme with specified spatially-varying coefficients to calculate bottom friction. The five most significant astronomical tidal constituents ($M_2$, $S_2$, $N_2$, $K_1$ and $O_1$) derived from the Western North Atlantic Ocean tidal model (WNATM) provided open-ocean boundary tidal forcing as was specified in the VDatum project (Mukai et al. 2002).

For Hurricane Isabel simulations, wind and pressure fields were generated using the Holland parametric wind model (Holland 1980, 2008) included within ADCIRC. The Holland model calculated wind stress and barometric pressure for the ADCIRC simulations based on the best track estimate and cyclone parameters obtained from the National Hurricane Center (NHC).
Hindcast surge simulations were for the 4.375 days from September 15, 2003 15:30 GMT to September 20, 2003 0:00 GMT with 40 days of tidal spin up. Time series of wind and water levels were saved at 30 minute intervals.

2.2.3 Wind Data Sources

Operational implementation of a wind forcing term in riverine hydraulic models, will require both observed and forecast wind data. Thus, for Hurricane Isabel simulations we examined the use of two separate sources of wind data: 1) observed wind speed and directions at the CO-OPS stations at Lewisetta and 2) forecast wind speed and direction output from the ADCIRC model. Because the available CO-OPS observed data were limited to point observations, we applied a single direction and speed time series to the entire SOBEK model rather than separate time series to sub-reaches. For consistency between the observed and forecast-based simulations, only the wind time series at a node located near Lewisetta, VA, was extracted from ADCIRC output. Table 3 summarizes the modeling experiments to examine wind effects during Hurricane Isabel. We tested the SOBEK model with no wind, CO-OPS observed wind, CO-OPS observed wind with a “wind hiding” factor of 0.75, and wind produced from ADCIRC runs. The factor of 0.75 was applied to instantaneous (non-averaged) wind observations taken every hour at Lewisetta, VA and was derived purely based on calibration to reproduce the peak surge at Washington Waterfront. Westerink et al. (2008) discuss two physical reasons for needing to reduce observed or simulated wind in hydrodynamic model implementations to predict surge near the coast. One reason relates to the wind temporal averaging scale used to derive surface drag law coefficients. For example, Westerink et al. (2008) report that a 10 minute wind averaging period is suitable for application of Garratt’s drag formula (Garratt 1977). Therefore, they adjusted 1 minute winds from a parametric wind model
by a factor of 0.893 (from Powell et al. 1996) to apply the drag law correctly. This reduction accounts for the fact that 10-minute temporal averaging produces smaller peak wind values relative to 1-minute averaging. A second physical reason to modify observed wind for use in a model is that wind observed near open water or wind simulated for the open ocean is often reduced by land roughness elements such as trees, topography, buildings, etc. so that the overall effect on water movement is lessened at points farther inland.

Although it is unclear from the literature precisely how the instantaneous hourly observations at Lewisetta should be adjusted to apply drag formulas used in SOBEK1D, it seems clear that some adjustment is required. Since Lewisetta, VA, is situated close to the wide Potomac mouth and open water of the Chesapeake Bay, it is likely that our calibrated reduction factor accounts for the effects of land roughness elements found in the more upstream reaches of the model domain.

3 Results and Discussion

3.1 Calibration Results

3.1.1 Tide Propagation

Fig. 4 presents comparisons of the CO-OPS predicted and HEC-RAS simulated water level at Potomac River at Washington D.C. Waterfront (NOAA’s CO-OPS Station ID 8594900) for the pure astronomical tide simulation. Comparison of the model simulated water level to CO-OPS predicted tide indicate that tidal amplitude, phase and spring and neap tide modulations were captured by the HEC-RAS model fairly accurately except that HEC-RAS peak simulations precede observed tide peaks by about two hours. We shifted the HEC-RAS time series before statistical analysis to determine series mean differences, root mean square error (RMSE), mean
error (ME) and standard deviation (SD) of error at Potomac River at Washington Waterfront.
The series mean difference (CO-OPS minus HEC-RAS) was 0.01 m (0.05 ft) and the RMSE was 0.05 m (0.16 ft). Table 4 summarizes all of the computed statistics.

The T_TIDE analysis showed that the three largest harmonic constituents of tidal variation at Washington Waterfront were the M2 (Principal lunar semidiurnal), S2 (Principal solar semidiurnal) and N2 (Larger lunar elliptic semidiurnal) constituents. Table 5 gives the amplitude difference and phase shift for these constituents and shows close agreement with the CO-OPS observed tides. The largest contribution to the variation in the observed tide is from the M2 constituent with amplitude of 0.41 m (1.35 ft). This is close to the simulated time series M2 amplitude of 0.44 m (1.46 ft), a difference of 0.03 m (0.11 ft). The simulated M2 phase is shifted two hours early from the observed.

The amplitude and phase differences between HEC-RAS and CO-OPS are similar to the differences reported by Lanerolle et al. (2009) for CBOFS. Both the HEC-RAS model and the CBOFS model have phase errors of about 2 hours (predicting early high tides). More investigation will be required to determine the cause of the phase error in both of these models.

### 3.1.2 Historic Floods

In total, eight historic flooding events were simulated including the largest flood ever recorded for the Potomac River at Little Falls, the 1936 flood event which had the peak flow of 13,450 cms (475,000 cfs). Table 2 and Fig. 5 summarize performance for historical events. Simulated peak errors range from -0.4 m to 0.4 m (-1.34 ft to 1.34 ft) (Table 2). The mean absolute error for peak predictions was 0.25 m (0.82 ft). The correlation between simulated and observed peaks was 0.88 and the $R^2$ for the 1:1 fit was 0.90.
3.2 HEC-RAS Validation Results

3.2.1 January, 2010 Low Flow Event

Fig. 6 shows a historical simulation for the January validation event at the Washington Waterfront station. From January 3 to January 12, 2009, water level fluctuated from 0.6 m (2 feet) above MSL to 0.8 m (2.5 ft) below MSL and flow varied from 170 cms to 764 cms (6,000 cfs to 27,000 cfs). Similar to the tide calibration plot (Fig. 4), HEC-RAS simulates amplitude and water level peaks and troughs reasonably well, but peaks occur about 2 hours early. The difference in series means (observed minus HEC-RAS) was 0.06 m (0.18 ft) and simulation RMSE was 0.12 m (0.38 ft). Table 4 lists the remaining statistics.

3.2.2 Hurricane Isabel Event in 2003

Fig. 7 shows the observed and HEC-RAS simulated water level at the Washington Waterfront station for Hurricane Isabel in 2003. Even though the simulated water level tracked observed water level reasonably well, simulated peak storm tide due to Hurricane Isabel was 0.66 m (2.13 ft) lower than the observed data. This is well below the accuracy of surge prediction reported by Cho (2009) and Cho et al. (2011) using the 2D CIPS-ELCIRC model. Cho et al. (2011) reported peak prediction errors of 0.03 m (0.1 ft). With CBOFS we have not been able to make the same comparison at the Washington Waterfront location because CBOFS model boundary does not reach this location; however, downstream comparisons suggest that CBOFS will also predict a more accurate surge similar to CIPS performances.

3.3 Results from Forecast Guidance Curves

The dashed line in Fig. 8 is a quadratic best fit curve for the historic peaks (shown with plus marks) and is similar to the guidance curve that MARFC and the Sterling Weather Forecast
Office (WFO) used to manually estimate stage at Wisconsin Avenue as a function of flow at Little Falls prior to the availability of the HEC-RAS model. In this study, we generated the HEC-RAS based traces (gray lines) in Fig. 8 using a series of simulations with a set of constant pre-flood water levels in the tidal zone with the possible intra-tidal range of -0.92 m to 0.92 m (-3 ft to +3 ft) MSL. For each trace, the model is initialized with a low flow value at the upstream end and a fixed elevation between -0.92 m to 0.92 m (-3 and +3 ft) at the downstream end. To generate points along each trace of Fig. 8, the model is run first with a low flow until equilibrium is reached and then a storm event with a peak flow is introduced at the upstream end and the maximum predicted stage at the location of interest (e.g. Wisconsin Avenue) is recorded.

Based on these traces, we see that water levels at Wisconsin Avenue may vary substantially depending on pre-flood water level. The smaller range at higher flows indicates (intuitively) that freshwater flow dominates the river stage for high flows. At low flows, the HEC-RAS traces reasonably bound the range of uncertainty in the observed peak flows. Differences in initial tidal level may explain the scatter (uncertainty) in the observations. Using a HEC-RAS model with actual tidal data could reduce the uncertainty in water level forecast relative to the empirical curve method. At very high flows, where there is less scatter in the historic data, the benefits of running the HEC-RAS model to predict stage at Wisconsin Avenue are reduced; however, the HEC-RAS model offers additional benefits such as the ability to produce peak time and stage forecasts at many locations along the lower Potomac, and the ability to produce water surface profiles that can be used to generate flood forecast maps.

Fig. 9 compares the effect of initial water level on freshwater events at two locations: Wisconsin Avenue and the Washington Waterfront, 4.8 km (3 miles) down stream. The flatter slope and wider spread of the Washington Waterfront curves in Fig. 9 indicates a substantially
greater tidal influence on water levels compared to the Wisconsin gage despite their relatively close proximity.

### 3.4 Results from Wind Modeling Experiments for Hurricane Isabel

Fig. 10 presents hurricane surge at the Washington Waterfront simulated by the HEC-RAS and SOBEK models without using wind forcing in both models. Without wind forcing, SOBEK produces an almost identical water level peak for Hurricane Isabel. Although the models use the same geometry and roughness parameters, there are discrepancies between HEC-RAS and SOBEK results for moderate to low flows. These are likely due to differences in methods to compute conveyance and numerical solution algorithms used by SOBEK and HEC-RAS. Peak surge estimated by HEC-RAS and SOBEK without wind were 2.0 m (6.59 ft) and 2.06 m (6.75 ft), respectively. Time of peak surge estimated by HEC-RAS was 05 GMT while SOBEK was 05:30 GMT. Differences between the two peak surge heights was -0.05 m (-0.16 ft) and the time difference was about 30 min. The rising and falling shape of the surge hydrographs appear similar.

Fig. 11 presents ADCIRC simulated peak surge at Washington Waterfront. Computed peak surge was 2.6 m (8.45 ft) on 19 September 2003 at about 05 GMT compared to the 2.65 m (8.7 ft) observed peak. Time of the peak was similar to the HEC-RAS model and was about 4 hours early. Since ADCIRC simulated surge peak was close to the observed, we used ADCIRC generated wind forcing (wind speed and direction) along with ADCIRC simulated water level as another scenario to force the SOBEK model (Table 3).

Fig. 12 shows a snapshot of the ADCIRC generated directional wind pattern when wind direction was favorable for propagating water into the Chesapeake Bay and into the Potomac River. Fig 13 shows the magnitude of the wind speed simulated by ADCIRC along the Potomac
River along with CO-OPS wind at Lewisetta. ADCIRC peak wind speeds at Lewisetta and Colonial Beach are similar, about 22 m/s (49.2 mile/hr). We used ADCIRC wind at Lewisetta, VA, for SOBEK applications. Wind values at Wisconsin Avenue are notably less than at the other stations with open ocean exposure, justifying our empirically reduced Lewisetta wind. Fig. 14 illustrates that the strongest winds blew during the 12 hours leading up to the peak surge. These winds were roughly aligned with the axis of the Potomac River (coming from 90 degrees to 180 degrees relative to North), allowing optimal conditions for surge propagation from the Chesapeake Bay and toward Washington D.C.

Fig. 15 shows results from the SOBEK model with three separate wind forcings. Table 3 includes peak level and timing statistics for the simulations. Simulated peak level errors for CO-OPS wind, 0.75*CO-OPS wind, and ADCIRC wind cases are +0.70 m (2.3 ft), -0.08 m and -0.18 m respectively. For all three simulations time to peak did not change more than 30 min. Therefore, while application of wind changed peak surge, no significant improvements were observed in estimating time to peak surge. Interestingly, peak surge predicted by the SOBEK implementation with no wind was closer to observed than peak surge predicted when applying raw CO-OPS wind from Lewisetta to the entire model. The SOBEK no-wind case underestimated the peak by -0.57 m (1.9 ft) and the SOBEK CO-OPS wind case overestimated by +0.7 m (2.3 ft). While these results give us confidence that the magnitude of a wind forcing term in a 1D hydraulic model is an important factor in modeling surge, it also highlights the challenges in properly implementing and parameterizing the wind term. Further work can be done to improve the physical inputs and reduce reliance on calibration. For example, a modeler could use gridded wind data for both forecast and observed time periods when available, or
estimating wind reduction factors using techniques similar to those described by Westerink et al. (2008).

The peak error from SOBEK with ADCIRC wind case was 0.18 m (0.6 ft) compared with 0.01 m (0.03 ft) for the ADCIRC simulation (Figure 11). We suspect the differences are mostly due to differences in the parameterization of the drag coefficients between ADCIRC and SOBEK and the fact that ADCIRC uses a spatially varying wind field, and not differences between 1D and 2D hydrodynamic calculations. Future work is needed to confirm this hypothesis. These results highlight the need to develop consistent wind pre-processing and parameterization procedures for both observed and forecast wind fields for operational implementation of 1D models.

For all the modeling scenarios, Table 3 reports the peak flows into the Potomac River from the Chesapeake Bay during Hurricane Isabel. While we do not have observed data to validate these flows, the flow results among models are consistent with the respective physical inputs and stage forecasts. As expected, the SOBEK simulation with observed CO-OPS wind has a much higher inflow than SOBEK simulation which uses a reduction factor of 0.75. The reductions in flow are comparable among different models when moving upstream. For example, inflows with observed CO-OPS wind are consistently higher than those from simulation which uses a shielding factor of 0.75 when moving from the mouth of the river at Lewisetta to near the midpoint at Newburg to almost the upstream end at Alexandria. On average only 3% of the peak inflow to the Potomac from storm tide reaches Alexandria, VA. Despite this dramatic inflow reduction, storm tide still plays a dominant role in water levels in the Washington, D.C region for this event.
480 4 CONCLUSIONS AND RECOMMENDATIONS

This 1D HEC-RAS model of the tidal Potomac River is capable of simulating water levels from the Potomac mouth at the Chesapeake Bay upstream past Washington, D.C. to 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 for reducing the operational flood forecast service gaps that exist for coastal rivers throughout the Nation. The NWS MARFC has begun testing this model for operational forecasting within CHPS. The HEC-RAS model offers an enhanced capability over an existing empirical technique for predicting flood stages at Wisconsin Avenue in Washington, D.C.

The HEC-RAS boundary condition requirements are relatively simple for the lower Potomac implementation: observed and forecast discharge time series at upstream boundaries and observed and forecast stage time series at the downstream boundary. At the downstream boundary, observed water level can be obtained from the Lewisetta CO-OPS station and forecast water level from one of several operational estuary-ocean models: CBOFS, ET Surge, or ESTOFS. Forecasters can configure CHPS to compare results using the different available boundary conditions in real-time. This loose coupling of operational HEC-RAS models and one or more operational estuary-ocean models provides a baseline, operational river-estuary-ocean forecasting capability which is relatively easy to implement and provides a good reference against which more advanced modeling techniques (e.g. detailed 2D/3D estuary ocean models extended farther upstream) can be measured in the future.

We calibrated and validated the HEC-RAS model over a wide range of conditions including a time period dominated by tide, a period with both tidal and freshwater flow influence, historic freshwater floods, and an extreme storm surge event. For pure tidal
simulation, RMSE for simulations at Washington Waterfront was 0.05 m. For the period with mixed tidal and freshwater flows, RMSE was 0.12 m. For eight historic flood events, peak prediction errors at Wisconsin Avenue were all less than 0.41 m and the mean absolute error was 0.25 m. Simulation error for the Hurricane Isabel peak surge at the Washington Waterfront was 0.65 m. Like the water level prediction, the peak time prediction error for the surge event (4 hours) was also larger than prediction errors for moderate flow and tidal events (2 hours).

The HEC-RAS simulations showed promising performance for freshwater and tide dominated events, but less accurate performance for the heavily wind-forced hydraulics during Hurricane Isabel. The lower performance in predicting peak surge during Hurricane Isabel is not surprising given that HEC-RAS does not include an explicit wind forcing term. We simulated “HEC-RAS plus wind” model by running SOBEK 1D model with identical geometry but incorporating wind forcing in the model. We ran a SOBEK model with several wind scenarios to confirm whether wind can account for this level of error in a 1D model. Basic runs in SOBEK using the same model geometry as HEC-RAS confirmed that the two models produced similar peaks without wind. SOBEK runs with wind showed that the observed peak surge at Washington Waterfront could be easily matched, but only after the wind reduction factor was calibrated. However, the SOBEK models with wind did not substantially reduce peak timing error for Hurricane Isabel. For these runs, SOBEK wind inputs were based on a single time-series of observed wind from the CO-OPS gauge at Lewisetta.

To gain additional understanding, we ran a 2D ADCIRC model in simulation mode for Hurricane Isabel. This model accurately predicted the peak surge level at Washington Waterfront after spatially variable bottom friction factors were calibrated. Similar to SOBEK and HEC-
RAS, the ADCIRC model also showed about a four hour peak timing error. The ADCIRC implementation uses a two-dimensional, parametric wind field rather than point observed data.

Operational implementation of a 1D hydraulic model with a wind forcing term requires both observed and forecast wind data. Our tests running SOBEK using “forecast” wind from ADCIRC output suggest that a pragmatic option to obtain forecast winds in operations is to leverage pre-processed wind fields from operational estuary-ocean models such as ADCIRC (used as the basis for ESTOFS). However, modelers must ensure that the same wind reduction factors and drag coefficient parameterizations are applied to both observed and forecast winds. To facilitate this, appropriate wind pre-processing tools need to be developed for operational implementation.

Given that NWS RFCs are already heavily invested in learning and implementing HEC-RAS models, our results suggest that adding a wind modeling capability into HEC-RAS (similar to that in SOBEK) could provide immediate benefits by enhancing NWS RFC forecasting capabilities along stretches of fourteen coastal rivers where HEC-RAS implementations are in progress or planned. The marginal benefit for each implementation will depend on a variety of factors. A key factor will be the length of river modeled. For shorter reaches, the wind effects embedded in the boundary water level data may be sufficient for surge prediction upstream. However, forecasts for longer reaches (like the lower Potomac) may be substantially improved due to wind effects along the reach.

Even given such a new wind modeling capability, more research is needed to guide operational implementation. For our Potomac River implementation, there is a high degree of uncertainty in our calibrated wind reduction factor based on only one event. Given the low computational requirements of 1D models, it should be relatively straightforward to calibrate
wind parameters using multiple-year time series of wind data. This approach, however, must be combined with other techniques for extreme events for which calibration data are limited. To improve on the approach we have taken, we recommend using spatially variable wind fields that more accurately describe wind variation over the model domain when possible or deriving wind reduction factors based on physical data, e.g. using techniques described by Westerink et al. (2008).

555 5 ACKNOWLEDGMENTS

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6 REFERENCES


Table 1. Existing NOAA Operational Models in the Chesapeake Bay Region

<table>
<thead>
<tr>
<th>Model</th>
<th>Lead Organization</th>
<th>Purpose and additional notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLOSH (Sea, Lake and Overland Surges from Hurricanes)</td>
<td>NOAA/NWS/NHC</td>
<td>Storm surge during hurricanes and tropical storms (event-based and generated for discrete basins)</td>
</tr>
<tr>
<td>ETSurge (SLOSH-based Extratropical Surge)</td>
<td>NOAA/NWS/MDL</td>
<td>Continuous water level prediction available for entire Gulf, East, and West coasts including Alaska</td>
</tr>
<tr>
<td>ESTOFS (ADCIRC-based Extratropical Surge and Tide Operational Forecast System)</td>
<td>NOAA/NWS/NCEP</td>
<td>Continuous water level prediction for East and Gulf coasts. Higher resolution in some areas than ETSurge but not currently as extensive inland.</td>
</tr>
<tr>
<td>CBOFS (ROMS-based Chesapeake Bay Operational Forecast System)</td>
<td>NOAA/CO-OPS</td>
<td>Tide and current forecasts for navigational community in the Chesapeake Bay.</td>
</tr>
</tbody>
</table>

Table 2. List of historic flood events caused by freshwater flooding and hurricanes and the corresponding HEC-RAS prediction errors.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event type</th>
<th>Peak Flow @ Little Falls [cms]</th>
<th>High Water @ Wisconsin Ave. [m MSL]</th>
<th>Prediction Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 19, 1936</td>
<td>Freshwater</td>
<td>13,450</td>
<td>4.8</td>
<td>5.2</td>
</tr>
<tr>
<td>October 17, 1942</td>
<td>Freshwater</td>
<td>11,525</td>
<td>5.0</td>
<td>4.6</td>
</tr>
<tr>
<td>June 24, 1972 (from Hurricane Agnes)</td>
<td>Freshwater</td>
<td>9,458</td>
<td>4.3</td>
<td>3.9</td>
</tr>
<tr>
<td>January 21, 1996</td>
<td>Freshwater</td>
<td>9,231</td>
<td>3.4</td>
<td>3.8</td>
</tr>
<tr>
<td>April 28, 1937</td>
<td>Freshwater</td>
<td>8,778</td>
<td>3.9</td>
<td>3.7</td>
</tr>
<tr>
<td>November 7, 1985</td>
<td>Freshwater</td>
<td>8,297</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>September 8, 1996</td>
<td>Freshwater</td>
<td>7,419</td>
<td>3.3</td>
<td>3.2</td>
</tr>
<tr>
<td>January 27, 1910</td>
<td>Freshwater</td>
<td>4,417</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>September 21, 2003</td>
<td>Hurricane Isabel*</td>
<td>4,729</td>
<td>2.7</td>
<td>2.00</td>
</tr>
</tbody>
</table>

* At the CO-OPS station at Washington Waterfront
Table 3. Description of model simulation scenarios for Hurricane Isabel along with peak surge water level, timing and inflow results.

<table>
<thead>
<tr>
<th>Model</th>
<th>Upstream Boundary Condition (at Little Falls)</th>
<th>Downstream Boundary Condition (at Lewisetta)</th>
<th>Wind Forcing</th>
<th>Peak surge error [m]</th>
<th>Peak timing error [hours]</th>
<th>Qmax Lewisetta, VA [cms]</th>
<th>Qmax Newburg, MD [cms]</th>
<th>Qmax Alexandria, VA [cms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEC-RAS</td>
<td>Obs flow</td>
<td>CO-OPS observed stage</td>
<td>No Wind</td>
<td>-0.66</td>
<td>-3</td>
<td>34,141</td>
<td>17,245</td>
<td>1,133</td>
</tr>
<tr>
<td>SOBEK</td>
<td>Obs flow</td>
<td>CO-OPS observed stage</td>
<td>No Wind</td>
<td>-0.57</td>
<td>-4</td>
<td>35,000</td>
<td>19,000</td>
<td>1,200</td>
</tr>
<tr>
<td>ADCIRC</td>
<td>No River flow at Upstream locations</td>
<td>Ocean tide from ADCIRC database (at Ocean Boundary)</td>
<td>Holland wind Model</td>
<td>0.01</td>
<td>-4</td>
<td>47,500</td>
<td>28,100</td>
<td>1,000</td>
</tr>
<tr>
<td>SOBEK</td>
<td>Obs flow</td>
<td>CO-OPS observed stage</td>
<td>CO-OPS observed wind at Lewisetta</td>
<td>0.72</td>
<td>-4.5</td>
<td>53,000</td>
<td>28,000</td>
<td>1,700</td>
</tr>
<tr>
<td>SOBEK</td>
<td>Obs flow</td>
<td>CO-OPS observed stage</td>
<td>75% scaled CO-OPS observed wind at Lewisetta</td>
<td>0.08</td>
<td>-4</td>
<td>44,000</td>
<td>22,001</td>
<td>1,300</td>
</tr>
<tr>
<td>SOBEK</td>
<td>Obs flow</td>
<td>WL from ADCIRC</td>
<td>Wind from ADCIRC at Lewisetta (Holland Wind Model)</td>
<td>0.18</td>
<td>-5</td>
<td>49,000</td>
<td>21,000</td>
<td>1,500</td>
</tr>
</tbody>
</table>
Table 4. HEC-RAS statistics comparing simulated and reference time series for the astronomical tide calibration and January 2009 low-flow validation simulations at the Washington Waterfront station.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Peak difference [hr]</th>
<th>Series mean difference [m] (reference minus simulated)</th>
<th>RMSE [m]</th>
<th>Mean Error [m]</th>
<th>SD [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astronomical</td>
<td>-2</td>
<td>0.01</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Jan-09</td>
<td>-2</td>
<td>-0.06</td>
<td>0.12</td>
<td>0.09</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 5. Tidal harmonic analysis with amplitude referenced to mean seal level (MSL) for three major tidal constituents at Washington Waterfront. Negative sign in phase indicated peak tide in HEC-RAS model leads CO-OPS tide.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>CO-OPS (Obs.)</th>
<th>HEC-RAS simulated</th>
<th>Difference</th>
<th>Phase Difference [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>0.41</td>
<td>0.44</td>
<td>-0.03</td>
<td>-1.6</td>
</tr>
<tr>
<td>N2</td>
<td>0.08</td>
<td>0.06</td>
<td>0.02</td>
<td>-2.0</td>
</tr>
<tr>
<td>S2</td>
<td>0.05</td>
<td>0.05</td>
<td>0.00</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Figure 1. Location of river stage forecast service gap in upper part of the tidal Potomac River near Washington, D.C. The NWS forecast point at Little Falls is approximately 15 kilometers (nine miles) upstream of the existing NOS CBOFS model domain. The CBOFS inflow boundary condition is determined nominally by the Little Falls gage but the geographic location of the upstream point of the domain is not at that location.
Figure 2. Map of the tidal Potomac River and the Anacostia River within the Chesapeake Bay estuary indicating the extent of the HEC- RAS and SOBEK model domain.
Figure 3. ADCIRC Finite element grid as obtained from the VDatum Study. The open ocean boundary is modeled along the semi-circular curve along the right-hand side of the domain. The grid accurately resolves Chesapeake Bay, Delaware Bay and various coastal rivers.
Figure 4 Comparison of HEC-RAS simulated and observed tidal water level at Washington Waterfront for the December 2010 simulation.

Figure 5 HEC-RAS simulated peaks compared to observed for historic flood events.
Figure 6. Comparison of the HEC-RAS simulated and observed water levels at the Washington Waterfront for January 3, 2009 to January 13, 2009.
Figure 7. Comparison of the HEC-RAS simulated water level to observed water level at Washington Waterfront for the 2003 Hurricane Isabel.
Figure 8. HEC-RAS simulations overlaid on guidance lookup curve developed at the MARFC for forecasting stages at Wisconsin Avenue (dashed line) and historical events (plus signs).
Figure 9. Comparison of influence of initial tidal stage on final flood elevation at Washington Waterfront and Wisconsin Avenue for freshwater events.
Figure 10. Hurricane Isabel surge at the Washington Waterfront simulated by HEC-RAS and SOBEK model without wind forcing.
Figure 11. ADCIRC simulated surge during for Hurricane Isabel at Washington Waterfront.
Figure 12. Hurricane Isabel wind used by ADCIRC model at 00:00 GMT, 19 September 2003. Best-track position of hurricane Isabel passing through central VA is indicated with GMT time and maximum wind speed in knots. Note curvature of wind field around hurricane center. Also note that the wind field is generally aligned along the long axes of both Chesapeake Bay and the lower Potomac River channel.
Figure 13. Wind speed as derived from the output from the ADCIRC model at several locations along the tidal Potomac River. CO-OPS observed wind at Lewisetta is also shown.
Figure 14. Observed hourly instantaneous wind direction and intensity observed at Lewisetta CO-OPS station. Vertical line indicates time of the peak surge. Wind from is also shown. Stick plot on lower axis gives wind direction with base of stick along axis indicating time of observation. Note the prominent shift in direction when the eye passes the station on Sept 19 around 00Z.
Figure 15. SOBEK simulated Hurricane Isabel surge at Washington Waterfront based on observed tidal downstream boundary conditions and three different wind forcings.