Lessons Learned from Transitioning NWS Operational Hydraulic Models to HEC-RAS

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Seann Reed[1]
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[1]NOAA, National Weather Service, Office of Hydrologic Development, 1325 East-West Highway, Silver Spring, MD 20910; PH: 301-713-0640 x161; email: seann.reed@noaa.gov

ABSTRACT

NOAA's National Weather Service (NWS) is in the process of replacing our Flood Wave Dynamic Model (FLDWAV) and Dynamic Wave Operational (DWOPER) hydraulic models with HEC-RAS (Hydrologic Engineering Center – River Analysis System) models. NWS forecasters will run these new unsteady HEC-RAS models within the Community Hydrologic Prediction System (CHPS) being implemented to replace the National Weather Service River Forecast System (NWSRFS). This process provides us with an excellent opportunity to revisit old model calibrations, gain perspective on expected simulation accuracies, identify potential enhancements to existing models, and consider where to implement new models. Approximately 25 models covering 5,500 river miles are being converted at NWS River Forecast Centers throughout the country to meet the initial transition goals. A simple analysis of CONUS river slopes suggests that at least 20,700 more river miles should be considered for new dynamic hydraulic model development and implementation. We also present a high level analysis of five hydraulic models from different parts of the country that have been converted to HEC-RAS. Statistical simulation results suggest no trend in simulation accuracy among different size rivers. Results suggest model builders should strive for less than five percent RMSE between simulated and observed stages at calibration points (where percent RMSE is defined as RMSE divided by the stage range). Results also highlight the importance of considering both hydraulic and hydrologic model improvements concurrently; as lateral inflow errors caused 49% of the total RMSE error in one of our examples. Among the models examined, one model contains much more detail than the others. Further work is planned to objectively assess the benefits of adding more detail to NWS hydraulic forecast models than what has been traditionally used.

INTRODUCTION

The NOAA National Weather Service (NWS) is in the process of replacing our Flood Wave Dynamic Model (FLDWAV) and Dynamic Wave Operational (DWOPER) hydraulic models with Hydrologic Engineering Center – River Analysis System (HEC-RAS) models (Moreda et al., 2009; Reed et al., 2009). Although there are many similarities in the DWOPER, FLDWAV, and HEC-RAS software, the transition to HEC-RAS will offer more hydraulic modeling functionality to forecasters, the facility for greater collaboration with the broader engineering community, more training opportunities, and software that is easier to support. NWS forecasters will run new unsteady HEC-RAS models within the Community Hydrologic Prediction System (CHPS) being implemented to replace the National Weather Service River Forecast System (NWSRFS). Approximately 25 NWS River Forecast Center (RFC) hydraulic model implementations are being converted to HEC-RAS to meet the initial transition goal of replicating current capabilities in the new software environment. This process provides us with an excellent opportunity to revisit old model calibrations, gain perspective on expected simulation accuracies, identify potential enhancements to existing models, and consider where to implement new models.

This paper presents lessons learned from model conversions and describes new analyses intended to assist in making cost-effective choices on new hydraulic forecast model development and implementation. In doing so, the following questions are considered:

Where should we consider replacing hydrologic routing models with dynamic hydraulic models?

What accuracy should we expect from dynamic, hydraulic river forecast models?

We have also begun work to understand the relative magnitude of hydraulic model errors compared with hydrologic inflow errors and the marginal benefits of more complex model (not only considering accuracy, but other operationally important issues such as timeliness and model stability). Analyses pertaining to these issues cannot be included in this short paper but will be presented at the conference.

WHERE SHOULD WE CONSIDER REPLACING HYDROLOGIC ROUTING WITH HYDRAULIC ROUTING?

The NWS runs snowmelt, frozen ground, and continuous rainfall-runoff models to generate simulated and forecast time series of surface and subsurface runoff in watersheds throughout the Nation. Various overland and channel routing techniques are then used to translate these runoff depth time series into flow time series at forecast points of interest along the river network. In most locations, flow time series are then converted to stage time series using rating curves. Watershed and channel routing techniques that predict only flow (not stage) are referred to as *hydrologic* routing techniques. Hydrologic routing techniques often simplify representation of the channel geomorphology with conceptual parameters (e.g. power law cross-

sections or linear storage coefficients). Examples of hydrologic routing techniques used by NWS RFCs include Unit Hydrograph, Tatum, Streamflow Simulation and Reservoir Regulation System (SSARR) Routing, Lag-K, Layered Coefficient, and Muskingum (NWS, 2009). The alternative to the use of hydrologic routing and rating curves is to use a hydraulic model (e.g. FLDWAV or HEC-RAS).

Most commonly, forecasters use single-valued rating curves in conjunction with hydrologic routing to define a unique relationship between stage and discharge at a river cross-section. However, in many rivers, natural or man-made conditions result in non-single-valued rating curves. Backwater from downstream influences such as a tributary, dam, abrupt change in slope, or tide can create a variable, 'looped,' rating curve within an event. Even without a downstream influence, rapidly changing discharge in low gradient streams also causes dynamic loops in rating curves (Fread, 1973; 1975). The magnitude of the dynamic loop caused by changing discharge in low gradient streams can vary substantially from location to location and from event to event. Some conditions can produce large loops. For example, Fread (1973) reports on a looped rating for the Mississippi River at Red River Landing for which the difference in stage for the same discharge (450,000 cfs) during the rising and falling limbs reached 9 feet.

Methods do exist to account for looped ratings without implementing a dynamic hydraulic model. Rantz et al. (1982) describe 'stage-fall-discharge' rating techniques that can be used to convert stage to flow (or flow to stage) during backwater conditions, and the 'Boyer' method that can be used to adjust stage-discharge estimates for dynamic loop conditions. More recently, the U.S. Geological Survey (USGS) has moved towards equipping sites that have non-single-valued rating curves with acoustic Doppler velocity meters to more efficiently gather the information necessary to define the ratings at these sites (Phil Turnipseed, personal communication). All of these methods rely on extensive field measurements. Fread (1973) and Fread (1975) suggest an alternative dynamic stage-discharge estimation approach that requires fewer measurements and may be applicable to ungauged locations. The Fread (1973) approach is equivalent to implementing a dynamic hydraulic model at a single cross section.

Implementing a dynamic hydraulic model offers several advantages over hydrologic routing-rating curve approaches. A single hydraulic model implementation can cover numerous forecast points, does not rely as heavily on at-a-site empirical data (particularly for sites with non-single-valued ratings), and provides predictive capabilities for floods beyond the range of empirical observations. A well-calibrated hydraulic model can also more easily account for seasonal changes in hydraulic properties due to vegetation or water temperature changes. Using either a rating curve or hydraulic modeling approach, dealing with changes in channel geometry caused by scour and deposition accurately will require collection of new bathymetry data; however, less new data will be required with the hydraulic modeling approach.

The St. Venant equations describing mass and momentum conservation provide the mathematical foundation for DWOPER, FLDWAV, HEC-RAS and other one-dimensional river hydraulics models. Following the notation from Chow et al. (1988), Equation 1 is a simplified form of the momentum equation. It is useful to examine the terms in Equation 1 to understand various recommendations in the science and engineering literature about what type of model to implement for different rivers.

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g(S_o - S_f) = 0 \qquad \text{Equation 1}$$

The first two terms in Equation 1 are the local and convective acceleration terms arising from flow changes with time and location. The third term is the pressure term accounting for differences in water depth along the river. The fourth term represents the gravity force and the fifth term represents the friction force of the channel bottom acting on the fluid. A model that uses only the 4th and 5th terms is often referred to as a kinematic wave model. A model that uses the 3rd, 4th, and 5th terms is referred to as diffusion wave (or non-inertial wave), and a model that uses all the terms is referred to as dynamic wave (Chow et al., 1988).

The need to include different terms in the solution to achieve accuracy depends strongly on the magnitude of the channel slope (4th term) and the rate of rise of the flood, which impacts the magnitudes of the first three terms. USACE (1994) cites a rule-of-thumb that the kinematic wave equations should only be applied to channels with slopes greater than 10 ft/mile (0.001894). In these channels, the slope term typically dominates the calculations to the extent that the first three terms in the equation can be ignored. USACE (1994) also states that the diffusion wave approximation may be applicable to “extremely flat” slopes, but suggests diffusion wave applications should be limited to slopes approximately 1 ft/mile (0.0001894) or greater where rapidly rising flood waves occur.

Fread (1983) shows that NWS hydrologic routing techniques listed above theoretically belong in the same category as the kinematic wave simplification of the momentum equation, so it is reasonable to infer that the combination of hydrologic routing and rating curves will be less accurate and more difficult to apply as one moves from high gradient to low gradient channels. In low slope rivers, the use of a dynamic rating can improve the flow to stage conversion but cannot correct for inaccuracies in timing due to the flow routing itself.

Figure 1 shows rivers in the conterminous United States classified into three slope regimes corresponding to the USACE (1994) rule-of-thumb criteria. The slopes in Figure 1 were calculated using information in the National Hydrography Dataset Plus (NHDPlus) (http://www.horizon-systems.com/nhdplus/). NHDPlus provides detailed digitized maps of surface water bodies in the United States at the 1:100,000 scale. Each NHDPlus streamline contains a slope attribute computed from high resolution Digital Elevation Models (DEM). Because the full NHDPlus data set is far too

detailed for this analysis, only river segments draining more than 2000 km^2 were retained to create Figure 1. In addition, the length-weighted average slopes for major river segments within each USGS 10 digit Hydrologic Unit Code were computed for this high level assessment, reducing the number of line segments in the data set by a factor of about 2000. CONUS-wide, the total number of river segments with average slope estimates presented in Figure 1 is 1892, with an average length of 60.5 mi (97.3 km). While the NHDPlus DEM-based slopes will not necessarily be equal to the true channel bottom slope, these DEM-based slopes computed are an adequate surrogate for purposes of this discussion.

As one would expect, most NWS hydraulic models (thick blue lines in Figure 1) have been implemented on rivers in the lowest slope regime (green lines). However, Figure 1 also shows that there are many rivers throughout the country where implementing new hydraulic models should be considered. There is a high potential to improve upon hydrologic routing models in the low slope regime (green line), and also in the medium slope regime (brown line) where at least diffusion wave approaches are recommended. Table 1 summarizes the approximate length of streams modeled hydraulically by the NWS and the length of streams that are rule-of-thumb candidates for diffusion and dynamic wave modeling. The 5501 miles of rivers modeled hydraulically represent only 21% of the rivers with average slopes less than 1 ft/mile (0.000189) and 6% of the rivers with average slopes less than 10 ft/mile (0.00189).

Table 1. Length of streams in different categories from Figure 1

Category	**Length (mi)**	**Rule-of-thumb Model Type**
Length covered by NWS hydraulic models	5501	
Slope <= 1 ft/mile	26236	Dynamic
1 ft/mile < Slope <= 10 ft/mile	71063	Diffusion
Slope > 10 ft/mile	17116	Kinematic

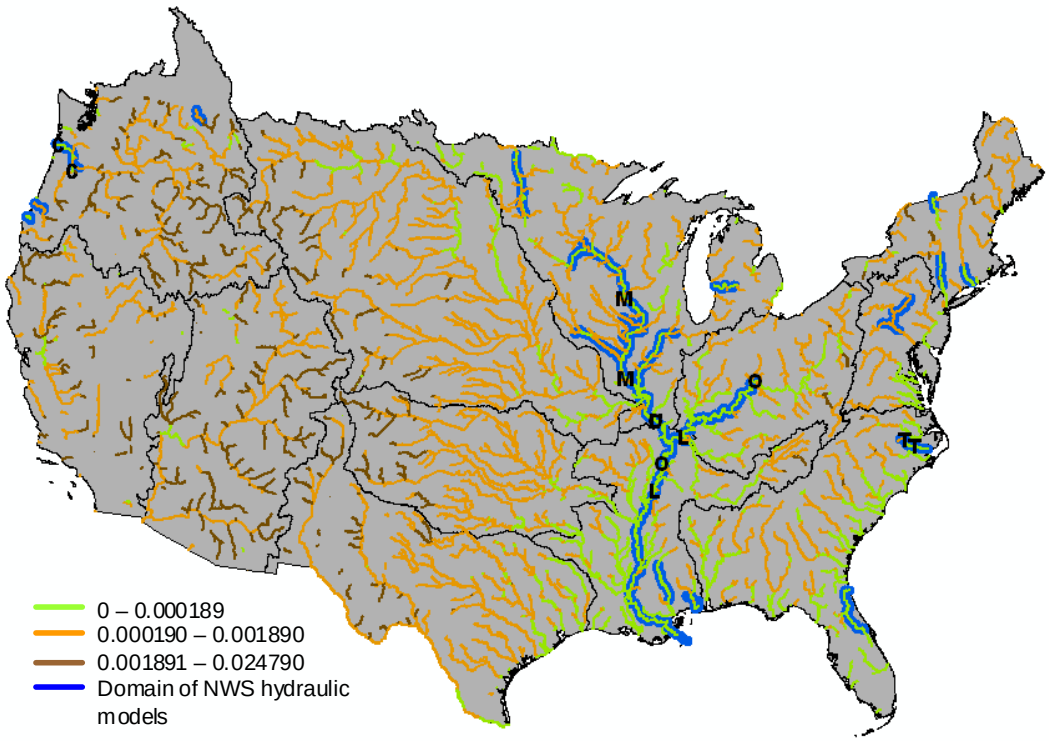

Figure 1. ***Average slopes of CONUS rivers > 2000 km2.***

As mentioned previously, both slope and rate of flood rise strongly influence the size of the dynamic loop and the need for a hydraulic model. Therefore, Figure 1 only provides an initial screening of candidate rivers for hydraulic model implementation. Figures 2a and b show how two very different dynamic loops can occur at the same location depending on how rapidly the flood is rising. The data for Figure 2 were generated using the Lower Mississippi-Ohio model described in the next section. It would be valuable to be able to estimate the magnitude of this loop prior to incurring the expense of developing a complete hydraulic model. Therefore, as an extension of the work described in this paper, we are proposing to develop new software tools to support the dynamic rating curve analysis described by Fread (1973) and Fread (1975).

The information in Figure 1 and Table 1 suggest potential benefits of more widespread hydraulic model implementation. Why haven't hydraulic models been implemented more widely for operational forecasting? Hicks and Peacock (2005) suggest two reasons. First, there have not been adequate studies to convince forecasting agencies to invest more funds in hydraulic modeling. Second, forecasters are hesitant to use hydraulic models because they have "a reputation for being difficult to learn and apply." Hydraulic models can be more difficult to implement compared to hydrologic models because set-up is relatively complex and work must be done to ensure model stability. Moving forward, advances in computing power,

improved modeling tools, and improved topographic and bathymetric data are making implementation easier. A third reason may be that forecasters have developed techniques to adjust hydrologic routing parameters in real-time to compensate for model inaccuracies. In 1996, it took 15 minutes to run a quarter of a year simulation on the Lower Columbia model described below. Today, a year long run for the same model takes less than a minute (Joanne Salerno, Northwest RFC, personal communication). Fifteen years ago, paper USGS 7.5-minute topography maps were the only practical source for deriving cross-section information. Today, cross-section information can be obtained easily in digital format (e.g. USGS DEMs) and with higher resolution and accuracy in some cases (e.g. LIDAR).

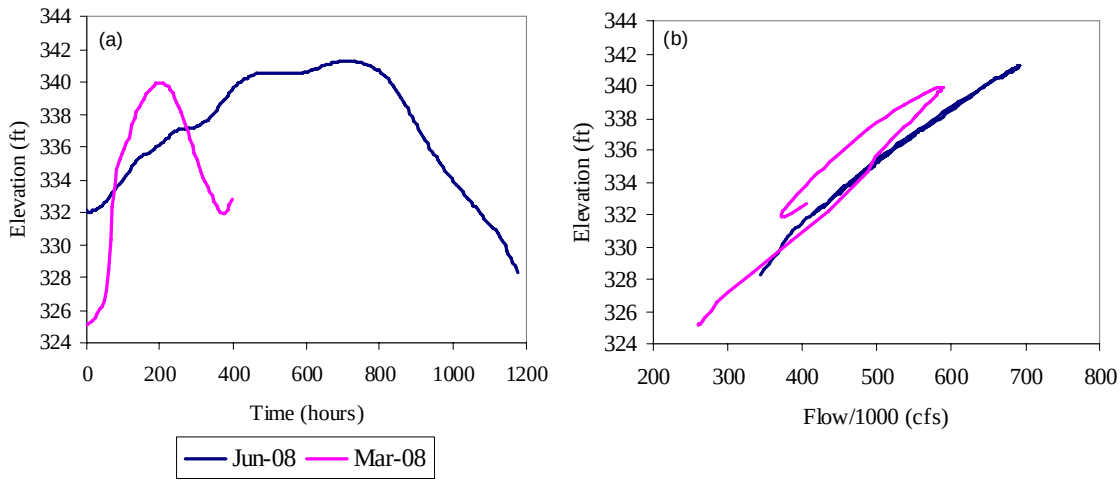

Figure2. (a) Elevation hydrographs for two selected events at Thebes, IL, on the Mississippi River. (b) Dynamic rating curves for the same two events.

Costs and expected benefits will drive decisions about hydraulic model implementation. There is a wide range in the amount of effort that can go into building a hydraulic model and hence a wide range in model development costs. Although not an exact analog for developing hydraulic forecast models, the costs for FEMA flood insurance map studies can range anywhere from $250 per mile to $25,000 per mile depending on the level of detail (NRC, 2009, Table 2.1). In building new hydraulic forecast models, it may be possible to offset a large portion of the cost by using cross-section data already developed for other hydraulic modeling applications such as flood insurance studies (often already in HEC-RAS format). However, there is still a clear need for informative studies to assess the incremental benefits of including more detail in a hydraulic model, collecting more data, or working more on model calibration.

WHAT ACCURACY SHOULD WE EXPECT FROM HYDRAULIC RIVER FORECAST MODELS?

For this study, we examine simulation results from four NWS hydraulic models that have been converted to HEC-RAS and one forecast model built in HEC-RAS. Letters on the Figure 1 map indicate the approximate starting and ending locations for

these models (the correspondence between letter symbols and models is provided in the first column of Table 2).

(1) Riverside Technology, Inc. developed a FLDWAV model of the Tar River from Tarboro to Washington North Carolina (RTi, 2007). The simulated reach covers 48 miles with 102 cross-sections spaced at about 0.5 miles on average. Lateral flows were initially generated using a distributed hydrologic model (Koren et al., 2004). Moreda et al. (2009) describe how this model was converted to HEC-RAS. For this study we did some additional calibration (Manning's n adjustments) on the converted model to prepare the model for use in operational forecasting.
(2) Moreda et al. (2009) also describe the conversion of the operational DWOPER model for the lower Columbia River to HEC-RAS. The main stem of the lower Columbia River extends from Bonneville Dam to Astoria, OR. The model includes three major tributaries: the Willamette River, the Cowlitz River, and the Lewis River. The main stem covers 127 miles, while the Willamette, Cowlitz, and Lewis segments cover 27, 15, and 19 miles respectively. After the initial model conversion to HEC-RAS reported by Moreda et al. (2009), the Northwest River Forecast Center (NWRFC) refined geometry for some cross-sections and performed additional calibration. The original calibration period for the DWOPER and HEC-RAS models was from Feb. 1, 1995 to Feb. 28, 1996. Additional HEC-RAS calibration was performed by NWRFC and OHD for a more recent calibration period (Sept. 2008 to Jan. 2009) as indicated in Table 2.
(3) The Upper Mississippi model we use in this study is a model from the North Central River Forecast Center (NCRFC) that extends 314 miles from Guttenberg, IA (Lock and Dam 10) to Saverton, MO (Lock and Dam 22). The model includes four dynamically modeled tributaries including the Wapsipinicon River (18 mi), the Rock River (27 mi), the Iowa River (40 mi), and the Des Moines River (51 mi). In the DWOPER model, the gate operations for the 11 lock and dam structures are not modeled explicitly. Observed pool elevations at these dams are provided as inputs to the model. In effect, this creates 11 short models because an internal elevation boundary condition is specified at each pool. For the forecast periods during non-flood conditions, it is reasonable to assume that pool elevations will remain fairly constant and near the target pool elevations. During large floods, the tailwater may begin to influence the pool elevation and gate operations will have limited impact on the water levels; therefore, the DWOPER model does not assume target pool elevations during flooding, but models the dam as a short reach with increased roughness values to account for the head loss through the dam. For the HEC-RAS results presented, we have emulated the DWOPER approach by using the same cross-section definitions and using the HEC-RAS functionality to specify observed pool elevations for internal boundary points. In future work, we plan to examine the benefits of explicitly modeling gate operations as done in the Ohio-Mississippi model discussed next.
(4) The Ohio River Community Model (ORCM) HEC-RAS model was developed by the Ohio River Forecast Center (OHRFC) in collaboration with the USACE Great Lakes and Ohio River Division (Adams et al., 2010). Unlike other models in this

study, this model was not converted from FLDWAV or DWOPER but originally built in HEC-RAS. Work on the model began in late 2006. The full ORCM spans 1291 miles. In this study, we only examine a subset of this model. Our subset covers a total of 820 miles: 510 miles on the Ohio River from Cincinnati to the Mississippi confluence, 218 miles along the Mississippi from Thebes, IL to Tiptonville, TN, 29 miles along the Cumberland River, 18 miles of the Tennessee River, and 44 miles of the Wabash River. This model contains more detail than the other models. The model includes 43 HEC-RAS storage areas (features not included in the other models). The model also explicitly represents the geometry of five navigation dams (a.k.a lock and dam) along the Ohio River and includes gate operation rules.

(5) The Lower Mississippi River Forecast Center (LMRFC) provided a FLDWAV model spanning 110 miles of the Mississippi River from Chester, IL to the junction with the Ohio River and then 222 miles from the Ohio junction to Memphis, TN. The model also includes a 60 mile reach of the Ohio River from Smithland Dam to the Mississippi junction as well as two tributaries to the Ohio, a 31 mile reach of the Cumberland River and a 22 mile reach of the Tennessee River. We converted this model to HEC-RAS following the procedures described by Reed et al. (2009) and then performed manual calibration. LMRFC has independently converted this model to prepare it for operational implementation.

Table 2. General model characteristics

Model	**Analysis Period (# of months)**	**Flood Stage Reached**	**No. of Valid. Points**	**Model Length (mi)**	**Avg. cross-section spacing (mi)**
Tar River (T)	Sept 1999 - Aug 2005 (72)	Major	4	48	0.56
Columbia River (C)	Sept 2008 - Jan 2009 (5)	Action	9	189	1.7
Upper Mississippi (M)	Mar 2001 - Sept 2001 (7)	Major	20	450	2.9
Ohio-Miss Cincinnati – ORCM (O)	Oct 2004 - June 2008 (45)	Moderate	14	820	0.87
Lower Miss-Ohio Smithland (L)	Jan 2008 - Jul 2008 (6)	Major	7	445	9.3

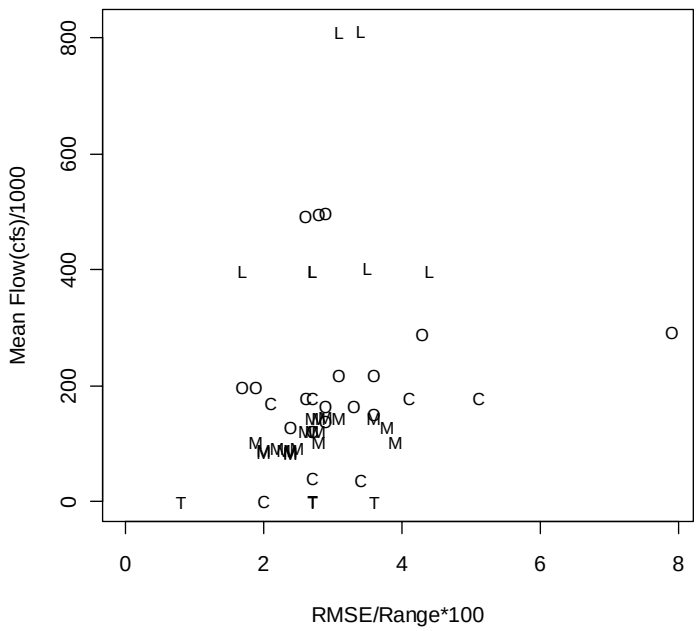

Figure 3. Summary statistics for five simulation models: T = Tar River; C = Columbia River; M = Upper Mississippi; O = Ohio-Mississippi from Cincinnati; L = Lower Mississippi-Ohio from SmithLand.

Figure 3 summarizes the statistical performance of the models at validation points where observed stage data were available. For each validation point, the Root Mean Square Error (RMSE) between simulated and observed stages was calculated for the simulation periods specified in Table 2. To compare data from different models and different levels of flooding, we compute RMSE/Range*100, where range is the difference between maximum and minimum stage. We will refer to this statistic as percent RMSE. The y-axis in Figure 3 is the mean flow during the simulation period.

While the percent RMSE can vary quite a bit from point-to-point within a single model, the range of percent RMSE values is similar from model to model. Also, there is no discernable trend in percent RMSE as a function of the flow magnitude. For all models, percent RMSE values range from 0.8 to 5.1% (ignoring the outlying point in the Ohio-Mississippi model with a percent RMSE equal to 7.9). The range of actual RMSE values (not shown) is from 0.2 to 1.57 ft (excluding the same outlier). These results are consistent with prior results reported in the literature by Fread (1985) for the lower Mississippi and the lower Columbia Rivers, and Jin and Buan (2000) for the Red River of the North. Percent RMSE values computed from figures in their publications cover a similar range, from 1.5 to 5.3%.

These results suggest that a minimum standard for model calibration performance should be about a five percent RMSE error.

OTHER LESSONS LEARNED

For the lower Columbia model, substantial changes in the Manning's n values were required to get acceptable results when moving from the original 1995-1996

calibration period to the more recent 2008-2009 period. NWRFC forecasters suspect that the changes in the Manning's n values are required to compensate for channel bathymetry changes that occurred in the intervening years but are not yet included in the model.

One reason for choosing the ORCM and Lower Mississippi-Ohio models in this study is to compare two overlapping models with different levels of detail. As indicated in Table 2, cross-sections for the ORCM model are ten times closer together on average. The cross-section data in this model also have considerably more detail with more precise representations of inactive and storage areas. Both models were calibrated by adjusting Manning's n, but with different levels of effort and a different number of calibration points. As the development of the more detailed ORCM model required a substantial resource investment, it is important to understand the potential benefits of doing similar work on other rivers where simpler forecast models already exist. Results from comparing overlapping sections of the ORCM and LMO models are not ready for this pre-print but will be presented at the conference.

To identify areas for forecast improvement, hydraulic model errors should not be examined in isolation but in an integrated framework that also includes analysis of precipitation observations, precipitation forecasts, and hydrologic models. In the near future, we expect new tools such as hindcasting capabilities in CHPS and the NWS Ensemble Verfication System (EVS) (Demargne et al., 2009) will provide this integrated framework. In the mean time, we do have the tools and the data (at a limited number of locations) to analyze the relative contribution of input flow errors and hydraulic model errors during simulation runs. While we don't have space in this pre-print to present the complete analysis, we were able to use USGS observed flow data for an interior point in the Tar River model to estimate the importance of accurate lateral inflow estimates to the hydraulic model. For the Tar River model station with the highest RMSE error, this analysis showed that 49% of the error in stage simulations may be attributable to errors in the lateral inflow estimates, despite the fact that lateral inflows only contribute about 17% of the average flow. It is worth noting that the lateral inflows used in this study were generated from an uncalibrated hydrologic model driven by gridded rainfall data with limited quality control so this may be an extreme case. In an operational setting, more effort would go into hydrologic model calibration and data quality control. Generating accurate lateral inflows is important not only for forecast accuracy but also for hydraulic model stability.

CONCLUSIONS AND FUTURE NEEDS

NWS one-dimensional, dynamic hydraulic river models provide essential information for forecasting flood stages on major rivers in the United States. Currently operational dynamic hydraulic models cover approximately 5,500 river miles. However, this represents only about 21% of the 26,200 miles of CONUS rivers with average slopes smaller than 1 ft/mile. Although there is no universal rule, USACE (1994) suggests use of dynamic hydraulic models may be needed on all rivers with

slopes less than 1 ft/mile if rapidly rising floods occur. There are also 71,000 river miles with slopes between 1ft/mile and 10 ft/mile where USACE (1994) recommends either diffusion wave or dynamic routing methods. Most of these rivers are currently modeled using hydrologic routing techniques (comparable to kinematic wave routing). Hydrologic methods have proven acceptable in practice, presumably because other sources of errors can overwhelm and/or manual forecaster adjustments can compensate for potential deficiencies. The simple analysis of slopes presented here suggests high potential for accuracy improvements and less manual intervention with more widespread implementation of dynamic hydraulic models. In addition to slope, the rate of flood rise is another major factor that influences when a dynamic hydraulic model will provide benefits. We propose developing a new tool to implement the Fread (1973) method for estimating dynamic loop magnitudes. This will allow rapidly assessing the potential benefits of full hydraulic model development for a site.

An analysis of five calibrated hydraulic models used for NWS forecasting reveals no systematic relation between model accuracy and the magnitude of the river flow. Results suggest that a successful calibration should yield a percent RMSE lower than five percent.

Implementation of dynamic hydraulic models can be costly, and the costs can vary widely depending on the level of detail desired. Unfortunately, there is limited objective guidance on the marginal benefits of adding model complexity. Further work is needed on this topic. New, detailed and geo-referenced models are likely to be more suitable than traditional hydraulic forecast models for flood forecast mapping applications. Including new types of data, such as LIDAR measurements of water levels during floods NRC (2009), in validation studies will make it easier to fairly evaluate models of differing complexities. The benefits of improved hydraulic models should be considered in the context of other potential forecast improvements. For example, we found that improvements in the precipitation data and lateral inflow data could improve the stage simulations at a point in our Tar River model by up to 49%. With this in mind, we strive for an integrated hindcasting system to more easily understand the interplay between hydrometeorology, hydrology, and hydraulics.

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