**Transitioning NWS Operational Hydraulics Models from FLDWAV to HEC-RAS**

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**Abstract**

The NOAA National Weather Service (NWS) Office of Hydrologic Development (OHD) is investigating two approaches to transition NWS operational hydraulic models from FLDWAV to HEC-RAS: (1) transform existing FLDWAV and DWOPER models into HEC-RAS and (2) modify and calibrate existing HEC-RAS models created for a purpose other than real-time forecasting. We evaluated these two approaches in the lower part of the Tar River, NC, and the lower Columbia River, OR. We also developed procedures and utility programs to assist with model conversions. The results are mixed. For the relatively simple Tar River, direct duplication of FLDWAV cross-sections and Manning's roughness specifications within HEC-RAS resulted in similar simulations. Also, a model built with more detailed cross-sections but the same roughness parameters from FLDWAV model could produce comparable simulation with some simple Manning's *n* adjustments. For the lower Columbia, approximate duplication of geometry requires more Manning's *n* adjustments, but still offers a viable pathway toward model conversion. Further work on the lower Columbia model is needed to see whether more precise representation of storage areas will improve results.

Key words: St. Venant Equations, calibration of hydraulics model, Tar River, Columbia River. FLDWAV, HEC-RAS

# 1 Introduction

In 2007, a team of National Weather Service (NWS) hydrologists reviewed several well-known hydraulic models to identify methods to improve hydraulic modeling capabilities for NWS operational forecasting (NWS, 2007). NWS forecasters currently use Flood Wave Dynamic Model (FLDWAV) and Dynamic Wave Operation (DWOPER) (Fread, 1998) for operational hydraulic modeling. NWS (2007) recommends including the United States Army Corps of Engineers (USACE) Hydrologic Engineering Center-River Analysis System (HEC-RAS) in the operational environment, testing FLDWAV and HEC-RAS on identical data sets, and developing methods to transform FLDWAV models to HEC-RAS. Compared to FLDWAV, the study found that HEC-RAS offers a much more user friendly GUI, better documentation, training, and the option to specify more detailed cross-section and hydraulic structure information. Based on those conclusions, NWS managers have decided to replace FLDWAV and DWOPER with HEC-RAS. This

proposal is based on two basic assumptions: (1) HEC-RAS can provide equivalent functionality capable of replacing existing FLDWAV and DWOPER models (with relatively minor HEC-RAS enhancements), and (2) through collaboration with HEC, it will be more economical to maintain and enhance HEC-RAS alone, rather than independently maintaining HEC-RAS and FLDWAV. Efforts are underway to include the HEC-RAS software in the NWS Community Hydrologic Prediction System (CHPS). CHPS is the software infrastructure intended to replace the NWS River Forecast System (NWSRFS). Because the NWS has defined an aggressive schedule to transition from NWSRFS to CHPS, River Forecast Centers (RFCs) need simple and inexpensive procedures to convert or replace DWOPER and FLDWAV models with HEC-RAS models.

Here we report on investigations into two approaches to meet this need: (1) transform existing FLDWAV and DWOPER models into HEC-RAS and (2) modify and calibrate existing HEC-RAS models created for a purpose other than real-time forecasting (e.g. HEC-RAS models for Federal Emergency Management Agency (FEMA) flood insurance rate maps). In this study, we developed and compared HEC-RAS models for the lower part of the Tar River, NC, and the lower Columbia River, OR, using these two approaches.

During the evaluation, we developed procedures and utility programs to assist with model conversions. Some model conversion challenges included determining equivalent hydraulic representations for cross-section geometry, ineffective areas, bridges, and specifying channel roughness factors. The procedures described here include an expeditious calibration strategy for RFC implementations when needed. This paper presents a subset of finding from a larger, ongoing Office of Hydrologic Development (OHD) project to facilitate the transition from FLDWAV to HEC-RAS. Additional information and a more detailed report can be found at http://www.weather.gov/oh/hrl/hsmb/hydraulics/index.html.

# 2 Models

## *2.1 FLDWAV*

DWOPER is the initial model developed by Fread (1978). Later, in an effort to combine DWOPER with a stand alone NWS dam break program (DAMBRK), FLDWAV emerged as a comprehensive dynamic hydraulic model that can be used to simulate network of rivers with several hydraulic structures including an option to simulate dam failure or series of dam failures. FLDWAV is being used in day to day forecasting on over two dozen of large rivers over the United States and several rivers elsewhere in the world. The model is based on the implicit finite difference solution of the complete one-dimensional Saint-Venant equations of unsteady flow.

The two basic equations are the continuity and momentum equations 2.1 and 2.2, respectively.

$$\frac{\partial Q}{\partial x} + \frac{\partial s_{co}(A + A_o)}{\partial x} - q = 0 \qquad 2.1$$

$$\frac{\partial (S_m Q)}{\partial t} + \frac{\partial (\beta Q^2 / A)}{\partial x} + gA\left(\frac{\partial h}{\partial x} + S_f + S_e + S_i\right) + L - W_f B = 0 \qquad 2.2$$

Where $Q$ is the flow, $h$ is the water-surface elevation, A is the active cross-sectional area of flow, $A_o$ is the inactive off channel storage area, $S_{co}$ and $S_m$ are sinuosity factors, x is longitudinal distance along the rive channel, $t$ is the time, $q$ is the lateral inflow or outflow, $\beta$ is the momentum coefficient for velocity distribution, $g$ is the acceleration due to gravity, $S_f$ is the channel flood-plain boundary friction slope, $S_e$ is the expansion-contraction slope, $S_i$ is addition friction slope for viscous fluids and debris flow, $B$ is that active low top width and $W_f$ is the effect of wind resistance on the surface of flow.

Among the slopes that are listed in the above equation, it is important to describe the $S_f$ as it is central to the model parameterization.

$$S_f = \frac{n^2 |Q| Q}{\mu^2 A^2 R^{4/3}} = \frac{|Q| Q}{K^2} \qquad 2.3$$

In Equation 2.3 $n$ is the Manning's $n$ coefficient of frictional resistance, $M$ is a unit conversion factor *1.49* for English units and *1.0* for SI units, $R$ is the hydraulic radius and $K$ is the conveyance. The equations are solved using the well known four-point implicit box finite difference schemes documented by (Fread,1988).

## *2.2 HEC-RAS*

Hydrologic Engineering Center-River Analysis System (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). Though the system has several modules, in this paper we focus only on the unsteady flow simulation.

The unsteady flow model solves essentially the same equations as FLDWAV (Equations 2.1 and 2.2), except that the current version of HEC-RAS does not include the wind effects term, the expansion and contraction slope term ($S_e$), or the viscous fluid term ($S_i$). Similar to FLDWAV, HEC-RAS uses a four-point implicit finite difference scheme to generate a set of finite difference equations. However, HEC-RAS solves the finite difference equations using linearization and a sparse matrix linear algebra solver while FLDWAV applies a Newton-Raphson iteration technique to solve the nonlinear equations.

## *2.3 Major differences between HEC-RAS and FLDWAV*

Although the two models solve the same basic hydrodynamic equations, there are many differences in the model parameterization and solution techniques. Our detailed report

will describe these differences. Here we focus on a few major differences that have the biggest impacts on simulations.

Both models include different options to describe the physical characteristics of the system (Gee and Brunner, 2005). For example, FLDWAV represents cross-section geometry using elevation-top width pairs, which results in a symmetric channel for most FLDWAV implementations. HEC-RAS cross sections can be symmetric but are most often irregular to match the natural landscape. Also, FLDWAV and HEC-RAS differ in the methods available to calculate the friction slope $S_f$. Both FLDWAV and HEC-RAS compute a composite conveyance $K$ in each cross section to solve for $S_f$, however, the available methods to calculate the composite $K$ differ. Differences in how Manning's $n$ values are specified and differences in the definitions of left and right overbanks result in conveyance differences.

# 3 Methodology

## *3.1 Study Areas and Models*

Two rivers were used to evaluate differences between FLDWAV and HEC-RAS water level simulations: the lower Tar River in North Carolina and the lower Columbia River which forms the border between Oregon and Washington.

### 3.1.1 Tar River

Tides influence water levels in the lower Tar River starting form its inlet at Pamlico Sound upstream to USGS Gauge 02083893 at Rock Springs, NC (approximately 30 miles) (Figure 1). Because of the tidal influence, the NWS needs to run dynamic hydraulic models to provide water level forecasts at locations such as Washington and Greenville, NC. Use of a dynamic hydraulic model is also a pre-requisite for eventually providing dynamic flood mapping services.

In this study, we model a single reach of the Tar River between Tarboro and Washington, NC. Riverside Technology (RTi) set-up and calibrated a FLDWAV model for this reach (RTi, 2007). The simulated reach covers of 48 miles with 102 cross-sections spaced at about 0.5 miles on average. RTi derived cross-sections for FLDWAV using cross-section data obtained from the North Carolina Floodplain Mapping Program and originally derived by the North Carolina US Geological Survey (USGS). The model accounts for the impacts of ten bridges. Four of these are modeled explicitly using bridge geometry while the other six are modeled approximately using constricted cross sections along with expansion and contraction coefficients. The parameters used in FLDWAV for the four bridges were used directly in HEC-RAS. However, for those bridges approximated by the expansion and constriction coefficients, we used the cross-sections without coefficients since HEC-RAS does not use these coefficients in the unsteady flow model. The lateral flows were originally generated using a distributed hydrologic model (Koren et al., 2004) on 4-km grid cells but later aggregated into seven inflows. We converted this FLDWAV model to HEC-RAS as described below.

We also took the steady flow HEC-RAS model with more detailed channel geometry developed by the NC USGS and converted it to an unsteady flow model. To cover the same domain as the FLDWAV model, the detailed model was modified to include five additional cross-sections from Grimesland to Washington. The channel geometry for these five sections was duplicated from FLDWAV and the overbank elevations derived from LiDAR elevation data.

The boundary condition and internal calibration/validation points on the Tar River are plotted in Figure 1. The discharge record at the Tarboro site is used as the upstream boundary condition, while the stage record at the Washington gauge is used as the downstream boundary condition. Tar River simulations are run from July 1, 1999, to August 31, 2005. This period includes a wide range of hydrological conditions, with noticeably high stage cases during Hurricanes Floyd (Sept 1999) and Isabel (Sept 2003). All simulations were run at an hourly time step using hourly input data.

Figure 1. Lower Tar River Modeled Reach

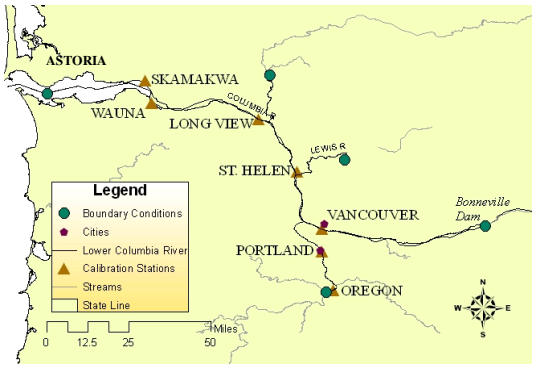


Figure 2. Lower Columbia

### 3.1.2 Columbia River

The NWS Northwest River Forecast Center operational DWOPER model of the lower Columbia River extends from Bonneville Dam to Astoria, OR (Figure 2). The model includes three major tributaries: the Willamette River, the Cowlitz River, and the Lewis River. The main channel of the lower Columbia River covers 127.5 miles, while the Willamette, Cowlitz, and Lewis segments cover 32 miles, 23 miles, and 19 miles respectively. The main river has 22 cross-sections with an average spacing of 6 miles. The Willamette, Cowlitz, and Lewis have 33, 20, and 26 cross-sections respectively. The boundary condition and internal calibration/validation points on the Columbia River and tributaries are plotted in Figure 2. For the Columbia River, discharge records from Bonneville dam define the upstream boundary condition and tide observations at Astoria, OR, define the downstream condition. Discharge records are also used at the upstream boundaries for the three simulated tributaries. A lateral inflow is applied at the river-mile 114.7 on the Columbia River and a second lateral inflow is applied at the river-mile 25.3 on the Willamette River. These two lateral flows are applied to represent tributaries, which are not modeled as rivers. An internal boundary condition represented as a rating

curve on the Willamette River at Oregon City was used to represent a 50 ft fall. The simulation runs are from Feb 1, 1995 to Feb 28, 1996.

Although NWRFC uses DWOPER for operational runs, we created a nearly identical FLDWAV model of the lower Columbia model as a reference to facilitate study over our year long calibration period. We then created a symmetric HEC-RAS model duplicating the DWOPER/FLDWAV parameterization and model layout.

A HEC-RAS model with more detailed channel geometry for the Columbia River system was obtained from the Hydrologic Engineering Center (HEC). The model was originally developed by the USACE Portland District and later modified by HEC. The initial model contains 604 cross-sections of which 330 describe the lower Columbia River from Bonneville to Astoria, 86 the Willamette River, and 3 the Cowlitz tributary; the remaining 185 are located in distribution channels along the river. There are no bridges specified in the model; however, ineffective areas are specified in 61 river cross-sections.

The detailed HEC-RAS model was modified to cover the exact same domain as the DWOPER and symmetric HEC-RAS models. We extended the Cowlitz tributary and added the Lewis Tributary. These additions used the cross-section information from the symmetric model.

## *3.2 FLDWAV to HEC-RAS Parameter Conversions*

### 3.2.1 Cross-sections

The representation of the cross-section is different in the FLDWAV and HEC-RAS models. In the FLDWAV models, a river cross-section is approximated by a predefined number of pairs of top width (BS) and elevation (HS). The total number of pairs in FLDWAV (NB) is fixed for a given model and typically five to eight pairs are required to define a cross-section. HEC-RAS represents cross-sections using station-elevation (X-Z) pairs. Figure 3 shows a FLDWAV and HEC-RAS representation of the same cross-section from our Tar River model. The validity of using simplified cross-sections for large river routing has been established (Fread, 1998; Hicks, 1996). The complexity of the channel is fully represented in the detailed cross-section, which may be advantageous in areas where there are flood mapping needs. We compare simulations from the symmetric and detailed cross-section models to assess the added value of having detailed cross-sections for modeling at NWS river forecast points.

In order to represent the symmetric cross-sections of FLDWAV in HEC-RAS, the BS versus HS pairs are translated to station versus elevation. To facilitate the conversion of the cross-sections from FLDWAV to HEC-RAS, we developed a program called *fld2ras*. In addition to converting top width-elevation pairs to station-elevation pairs, *fld2ras* (1) reorders station numbering (if necessary) to be compatible with the HEC-RAS convention to decrease from upstream to downstream, (2) converts distances between cross-sections from miles to feet, (3) assigns default bank station locations required by HEC-RAS, (4) modifies the cross-section shape to account for the FLDWAV AS

parameter (explained below), (5) creates HEC-RAS ineffective areas to approximate FLDWAV ineffective areas defined by the FLDWAV BSS parameter (optional, explained below), and (6) creates a text file formatted for import into HEC-RAS.

An important feature in the FLDWAV/DWOPER model of the lower Columbia River is a parameter that represents the active channel cross-sectional area below the lowest HS elevation. This parameter helps to define the area subject to the deposition and scour processes below the river line, in lieu of using the exact cross section. The parameter is known as *AS*. In HEC-RAS, this *AS* parameter is not available. Therefore to account for the area, at each cross-section, an additional active area is added by assuming a rectangular bottom with same width as the lowest HS value. The depth of the additional area is calculated using *Depth = AS/BS(1).* The elevation of the lowest point is then calculated as *Lowest Elevation= HS(1)- Depth.*

### 3.2.2 Roughness

The FLDWAV model has the option in which the user can define a stage or flow versus Manning's *n* relationship. Flow is preferred to stage because the calibration of Manning's *n* for different flow levels is relatively straightforward for long reaches, and the geomorphology literature supports the assumption that breaks in channel properties occur at consistent flow levels along a reach. If calibration causes Manning's *n* values to depart from published ranges, the modeler knows to check other parts of the model for errors.

In typical HEC-RAS applications, Manning's *n* values vary horizontally along a cross-section with higher values typically assigned in the floodplain. This can produce a similar effect to the typical FLDWAV application of defining composite Manning's *n* values that tend to increase when high flows reach the floodplain, reflecting the physical presence of brush, trees, or man-made structures in the floodplain. Assigning fixed Manning's *n* values that do not vary with depth or flow can be reasonable for design applications (e.g. when models are calibrated against only single events using high water marks); however, this approach cannot properly represent the physics for unsteady modeling across a range of flows. Therefore, HEC-RAS also provides the option to specify flow roughness factors as a function of flow. Using this feature we reproduce FLDWAV Manning's *n* parameterizations within HEC-RAS. Note that in HEC-RAS 4.0 specification of flow roughness factors is limited to uniform flow increments. Through a Memorandum of Agreement between HEC and NWS, HEC has added the option to define non-uniform flow increments and made this capability available for this study via HEC-RAS 4.0.1 Beta.

Figure 4, shows the FLDWAV Tar River model calibrated Manning's *n* values versus flow for calibration reaches defined in the model. The calibration strategy used to subdivide the reaches and change Manning's values manually or automatically is described by Fread et al. (1986) and RTi (2007).

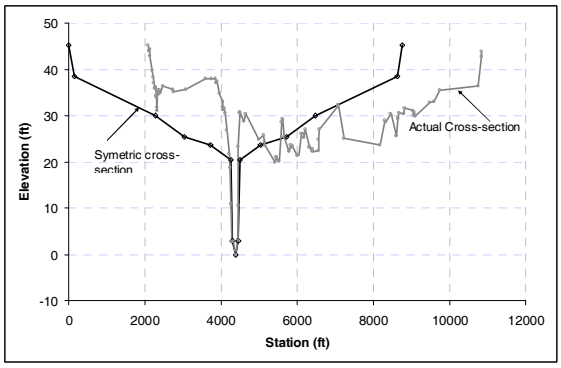


Figure 3. A symmetric and detailed representation of a cross-section of Tar River. While the detailed cross-section is obtained from 105 survey points, the symmetric cross-section is represented by only 16 points which were derived from FLDWAV (eight pairs of top width (BS) and elevation (HS)).

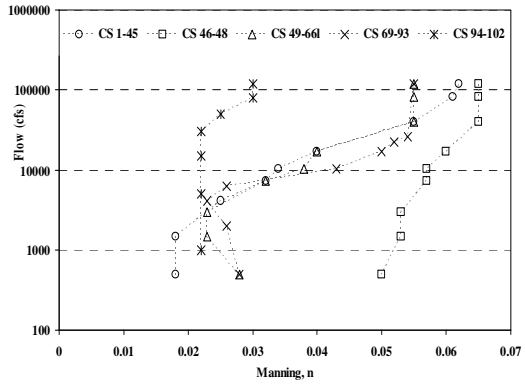


Figure 4. Variation of Manning's *n* versus flow for five cross-section reaches that are designated by the calibration gauges for the Tar River.

### *3.3 Experiments*

For the Tar River we simulated five sets of stages using 1) the FLDWAV model, 2) the HEC-RAS symmetric model with FLDWAV Manning's *n*-flow parameters (SYM), 3) the HEC-RAS detailed model with raw Manning's *n* values from the USGS steady flow analysis (DET_RAW_n), 4) the HEC-RAS detailed model with Manning's *n*-flow parameters from FLDWAV (DET_FLDWAV_n), and 5) the detailed model with calibrated Manning's *n* values (DET_CAL_n).

Similarly, for the Columbia River, we simulated five sets of stages using 1) the FLDWAV model, 2) the HEC-RAS symmetric model with FLDWAV Manning's *n*-flow parameters (SYM), 3) a calibrated version of the HEC-RAS symmetric model (SYM_CAL), 4) the HEC-RAS detailed model with FLDWAV Manning's *n*-flow parameters (DET_FLDWAV_n), and 5) the HEC-RAS detailed model with some additional calibration (DET_CAL_n). In both the Tar and lower Columbia, the calibrated Manning's *n* values were determined through manual calibration by comparing observed and simulated stages at several points along the rivers.

## 4 Results

Table 1 summarizes statistical results for four validation stations on the Tar River. The FLDWAV and symmetric HEC-RAS model (SYM) exhibit similar overall bias and RMSE and examination of the hydrographs (not shown here) showed acceptable results over all flow ranges. This result was achieved through direct conversion of model geometry and FLDWAV Manning's *n* parameters and no further calibration. We did not attempt further calibration of the HEC-RAS symmetric model, although additional fine tuning can be easily done within HEC-RAS. On the other hand, the detailed HEC-RAS model with raw Manning's *n* values specified for steady state applications

(DET_RAW_n) produced much higher RMSE statistics compared to the other two models. It therefore required more additional work. To achieve a more reasonable result with the detailed model, we first replaced the Manning's *n* values with those from FLDWAV (DET_FLDWAV_n). This yielded some improvements, but additional calibration was necessary to produce acceptable results comparable to those from FLDWAV (DET_CAL_n).

Table 2 summarizes statistical results for the validation stations on the lower Columbia River. For the lower Columbia, direct conversion of model geometry and DWOPER Manning's *n* values did not produce results as satisfactory as those for the Tar River. Although RMSE statistics (SYM) relative to observed stages come close to the FLDWAV results for most stations (the Oregon station is the big exception), examination of the hydrographs (Figure 5) shows that the HEC-RAS symmetric model and FLDWAV simulations deviate substantially from each other. One possible reason for more differences between FLDWAV and HEC-RAS SYM in the lower Columbia compared to the Tar River is that our conversion of the AS parameter is only an approximation. Independent experiments running FLDWAV with and without the AS parameter show that AS values have a very large impact on simulation results (not shown here). Table 2 also shows that some manual calibration effort with the symmetric HEC-RAS model (SYM_CAL compared to SYM) produces improved results at all stations except Portland on the Willamette tributary. We also found that using the detailed model with FLDWAV Manning's *n* parameterizations (DET_FLDWAV_n) provides a good starting point, but some manual calibration produces dramatic improvements (DET_CAL_n). Figure 5 highlights the improvements from calibration in the lower Columbia models both for a station that is highly affected by inflow hydrographs (Vancouver) and for a downstream station dominated more by tides (Wauna).

Table 1 Bias and (RMSE) both in ft (ft) for the Tar River

| | | HEC-RAS | | | |
|---|---|---|---|---|---|
| Stations | FLDWAV | SYM | DET_RAW_n | DET_FLDWAV_n | DET_CAL_n |
| Tarboro | .03 (.32) | .04 (.34) | 1.71 (2.03) | -0.15 (0.60 | 0.04 (0.38) |
| Rcksp | .12 (.51) | .16 (.63) | 0.88 (1.20) | -1.13 (1.45) | -0.43 (0.68 |
| Grnvl | .00 (.90) | .36 (1.11) | 1.86 (2.30) | -0.55 (1.05) | -0.40 (0.86) |
| Grim | .16 (.28) | .00 (.22) | 1.96 (2.25) | 0.00 (0.22) | 0.11 (0.24) |

* Note that the time period for statistical evaluation is shorter for Rock Springs and Grimesland due to a more limited duration of observed data.

**Table 2 Bias and (RMSE) both in (ft) for the Columbia River**

| | | HEC-RAS | | | |
|---|---|---|---|---|---|
| Stations | FLDWAV | SYM | SYM_CAL | DET_FLDWAV_n | DET_CAL_n |
| Vancouver | 0.72 (1.04) | -0.44 (1.06) | -0.17 (0.76) | -054 (1.17) | -0.17 (0.79) |
| St. Helen | 1.12 (1.37) | 0.63 (1.08) | 0.38 (0.91) | -0.31 (1.11) | 0.76 (1.27) |
| Long View | 0.48 (0.87) | 0.31 (0.77) | -0.08 (0.62) | -2.21 (2.53) | 0.04 (0.85) |
| Wauna | 0.19 (0.84) | 0.27 (0.86) | -0.04 (0.80) | -0.61 (1.01) | -0.51 (1.00) |
| Skamakwa | 0.35 (0.85) | 0.28 (0.74) | 0.14 (0.74) | 0.03 (0.69) | -0.00 (0.80) |
| Oregon | 0.77 (1.23) | 1.76 (2.27) | 0.04 (1.31) | -0.51 (1.09) | -026 (0.80) |
| Portland | 0.57 (0.94) | -0.58 (1.08) | -0.85 (1.24) | -0.51 (1.09) | -025 (0.82) |

# 5 Conclusions and Future Work

We investigated two approaches for replacing FLDWAV models with HEC-RAS models for use in operational forecasting. The first is conversion of existing FLDWAV models and the second is acquisition and modification of HEC-RAS models originally developed for other purposes. Both approaches can save time over building a new model from scratch because they take advantage of cross-section geometry and hydraulic feature data developed by others. The second approach requires more effort than the first because the available model domain and boundary conditions may not exactly match RFC needs, the roughness values assigned for other applications may not be suitable for continuous modeling over a wide range of flows, and the model may not be stable under all flow conditions of interest.

We have developed simple techniques to convert FLDWAV geometry and Manning's *n* parameters from FLDWAV to HEC-RAS models. For the Tar River, there is considerable value in transferring both the FLDWAV geometry and Manning's *n* parameters into HEC-RAS. After this transfer, minimal Manning's *n* adjustments are required to attain equivalent results. In a case when we use more detailed cross-section geometry data in place of FLDWAV geometry, there is still value in using previously calibrated Manning's *n* values. However, considerably more Manning's n adjustments are required. This is true even if the detailed and symmetric models were originally derived from the same elevation data.

For the Columbia River, direct conversion of model geometry and Manning's *n* was not as successful in replicating FLDWAV results. The main difference between the Tar and Columbia models is that the Columbia model includes an *AS* parameter for which there is no direct equivalent in HEC-RAS. Despite this difference, the calibrated Manning's *n* values from FLDWAV provided good initial estimates for further calibration both with the symmetric geometry from FLDWAV and the detailed HEC-RAS model.

In our two case studies, the more detailed models (e.g. more cross-sections, more detailed cross-sections, and more explicitly defined storage areas and structures) did not show substantially improved simulations or provide for easier calibration than the simpler, symmetric models. There are still potential benefits from more detailed models, but use of simpler models makes the most sense until these benefits are proven. More detailed models may be more amenable to accurate flood forecast mapping if the models are properly geo-referenced. With more study, the more detailed lower Columbia model will likely help us to more properly represent off channel storages. It may be that calibrated Manning's *n* values are compensating for physical inaccuracies in the simpler models; however, this would be difficult to prove.

Results from this study suggest that converting FLDWAV models into HEC-RAS is a viable option and likely to be less work than acquiring a more detailed HEC-RAS model from another source and modifying it. Additional work is required to rigorously evaluate stability of the models to make sure models are stable over a range of conditions for

operational needs. The model validations described here were done in simulation mode. Our next step is to validate these models in operational mode and running them side-by-side with the existing operational models. This is particularly important for the lower Columbia where we believe we can still improve the HEC-RAS model.

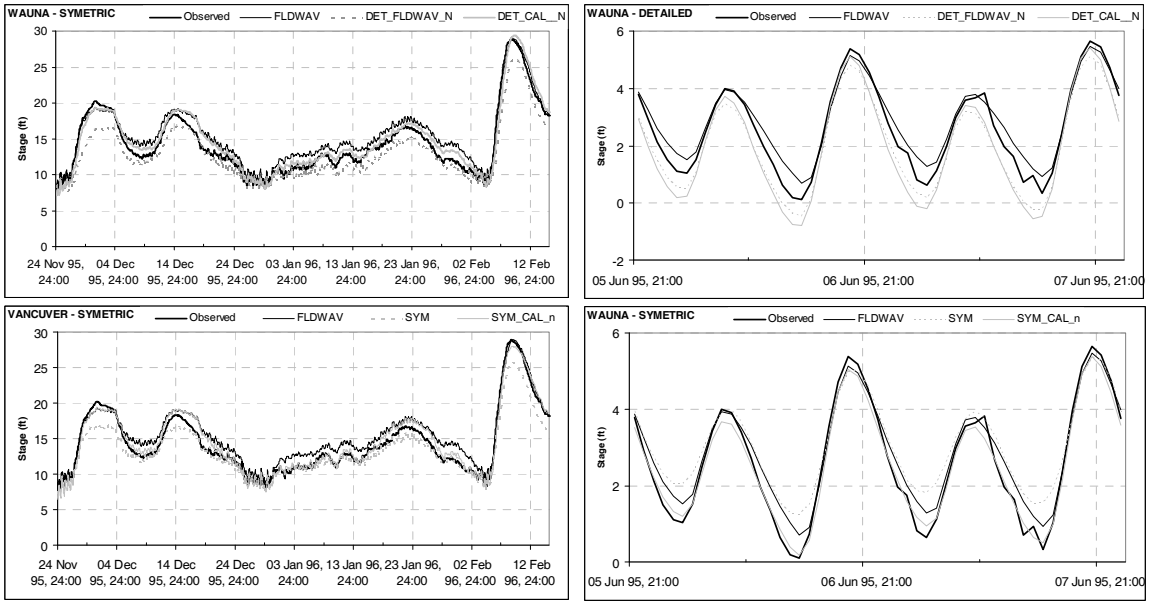


Figure 5 Example of simulated and observed hydrographs for Columbia River at Vancouver and Wauna stations

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