The Ohio River Community HEC-RAS model

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Abstract

In this paper we describe the Ohio River Community HEC-RAS Model (Model) and include some preliminary results. The Model is a cooperative effort involving the U.S. National Weather Service (NWS), Ohio River Forecast Center (OHRFC) and the U.S. Army Corps of Engineers (USACE), Great Lakes and Ohio River Division (LRD), Water Management Division. Initial planning to develop a community unsteady flow model for the mainstem of the Ohio River using the USASE HEC-RAS model began in late 2006. The purpose of collaborating on the development of the joint model was that, when completed, both agencies could independently use the model for operational/forecast purposes, yet share in the development effort, which is substantial. While the Model is now complete, continued enhancements and extensions are anticipated, such as modeling reaches of major tributaries like the Cumberland and Kanawha Rivers. Subsequent changes by one agency will be passed back to the other agency in order to maintain consistency, so that future development can be easily shared.

The scope of the modeling effort includes 20 locks and dams on the Ohio River, with storage areas and lateral structures such as levees, as well as bridges. The Model is comprised of over 2800 cross-sections, spanning approximately 1300 miles of modeled reach. The downstream boundaries are Chester, IL for the upstream portion on the Mississippi River and Carruthersville, MO for the downstream portion on the Mississippi River. The upstream boundaries include Braddock Lock and Dam, WV on the Monongahela River and Natrona, PA on the Allegheny River. The Model requires lateral and tributary inflows and is run in real-time; for the OHRFC the lateral and tributary inflows result from runoff produced by both observed and forecasted precipitation. Laterally, Model cross-sections extend to the 500-year floodplain limits, except for Mississippi River reaches that only extend to the USACE levees.

Model development involved substantial geographic information system (GIS) data preparation to obtain consistent vertical and horizontal datums between the various data sets used. Digital elevation model (DEM) data sources included U.S. Geological Survey (USGS) 10 meter DEM, and Lidar data provided by the USACE, and local and state agencies. Bathymetric and in-channel cross- section data were provided by the USACE. Every effort was made to include the best available data, and. it is anticipated that substantial improvements will be made in the future by the use of higher resolution data sets.

Background

The National Oceanic and Atmospheric Administration (NOAA), U.S. National Weather Service (NWS), Ohio River Forecast Center (OHRFC) and the U.S. Army Corps of Engineers (USACE), Great Lakes and Ohio River Division (LRD), have public forecast responsibilities for the mainstem of the Ohio River with local NWS Weather Forecast Offices (WFOs) having the responsibility of disseminating the official public forecast. For the OHRFC, forecast responsibilities are focused on public safety and protection of personal property, whereas LRD's focus is management of flood control structures to prevent or mitigate flooding. These responsibilities will be elucidated below.

Due to limited staffing and financial resources, the OHRFC and LRD reached an agreement in late 2006 to co-develop, on an unfunded basis, an unsteady 1-dimensional hydraulic model of the Ohio River mainstem — the *Community Ohio River HEC-RAS Model* — using the USACE Hydrologic Engineering Center River Analysis System (HEC-RAS) model (USACE HEC, 1995). Development of the model has the following goals:

(1) that the model would serve both agencies' real-time operational needs to improve forecasts;
(2) to add hydraulic reaches from the major tributaries in Phase 2 development (such as the Wabash, Kentucky, Green, Muskingum, Kanawha Rivers, etc.) as channel bathymetric data becomes available and the mainstem model is complete and operational;
(3) to use the best available data at the time of development and to enhance the model as higher quality data becomes available;
(4) to share model enhancements between the USACE LRD & NWS OHRFC;
(5) to distribute the model freely to other agencies, individuals, and organizations (with the stipulation that the OHRFC & LRD be credited for model development);
(6) to make possible the generation of real-time flood inundation maps;
(7) greatly improve visualization capabilities of flow dynamics.

OHRFC forecast responsibility for the mainstem of the Ohio River ends at Smithland Dam, KY, some 63 miles (~101 km) from the confluence with the Mississippi River. However, LRD responsibility includes protection of Cairo, IL, management of the Birds Point - New Madrid floodway and Kentucky Lake reservoir on the Tennessee River and Barkley Lake reservoir on the Cumberland River, which provide significant flood control storage for the protection of New Orleans and intervening points. Figure 1 shows the scope of the model area, with principle upstream boundaries including Braddock Lock and Dam, WV on the Monongahela River, Natrona, PA on the Allegheny River, and downstream flow boundary at Chester, IL for the upstream portion on the Mississippi River and rating curve boundary at Carruthersville, MO for the downstream portion on the Mississippi River.

Figure 2 is a schematic of the Ohio River mainstem profile showing the USACE Locks and Dams. The Lock and Dam operations, particularly during low flows, significantly affect the propagation of waves on the Ohio River as described by Lee et al (2002). Duplication of the Lock and Dam operations at low flows in real-time is highly problematic, as results (below) will show. The unpredictable nature of the Lock and Dam operations are due to human (dam operators) control of gate settings to regulate pool levels.

NWS/Ohio River Forecast Center

By U.S. Congressional mandate, the mission statement of the NWS is to "…provide[s] weather, hydrologic, and climate forecasts and warnings for the United States, its territories, and adjacent waters and ocean areas for the protection of life and property and the enhancement of the national economy. NWS data and products form a national information database and infrastructure which can be used by other government agencies, the private sector, the public, and the global community." As such, the OHRFC currently has the responsibility of issuing flood forecast and river stage forecast guidance for 274 locations located in the Ohio River basin and U.S. drainage into Lake Erie, including the Maumee River basin (see Figure 1). The OHRFC area of responsibility does not include the Tennessee River basin. The OHRFC maintains 43 forecast locations on the Ohio River mainstem.

OHRFC real-time operations are 16 hours per day, 365 days per year, which is extended to 24-hour operations during periods of flooding or significant threat of flooding. Tributary and lateral inflows to the HEC-RAS model are computed in real-time using the Sacramento Soil Moisture Accounting (SAC-SMA) model (Anderson, 2002; Burnash, 1973; Burnash, 1995) and SNOW-17 model (Anderson, 1973) within the NWS River Forecast System (NWSRFS) (U.S. Department of Commerce, 1972). Inputs to the SAC-SMA and SNOW-17 models utilize observed NEXRAD radar derived precipitation estimates and temperature station data and locally estimated forecast precipitation, known as quantitative precipitation forecasts (QPF), and forecast temperatures from NWS weather forecast offices (WFOs) National Digital Forecast Database (NDFD). Due to the lumped hydrologic routing schemes currently used, such as layered coefficient and Tatum, the OHRFC is unable to make *ad hoc* forecasts at intermediate points between forecast locations on the Ohio River. The HEC-RAS model will make possible forecasts at intermediate locations where the existing methods could not due to dynamic conditions.

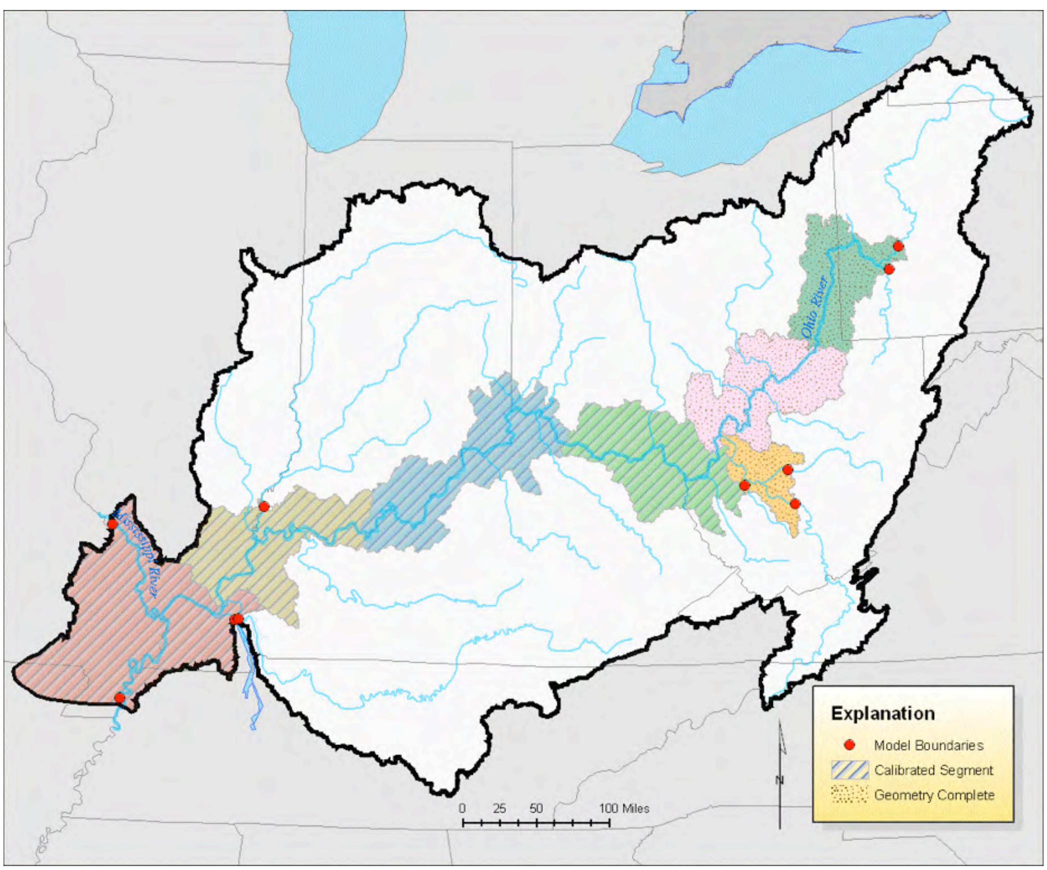

Figure 1. Scope of the Community Ohio River HEC-RAS model. Local runoff areas to the Ohio River mainstem are shown in color. Model boundaries are depicted as red dots. The OHRFC area of responsibility is shown by the black outline, with the exception of the area downstream of Smithland Dam near the confluence with the Mississippi River.

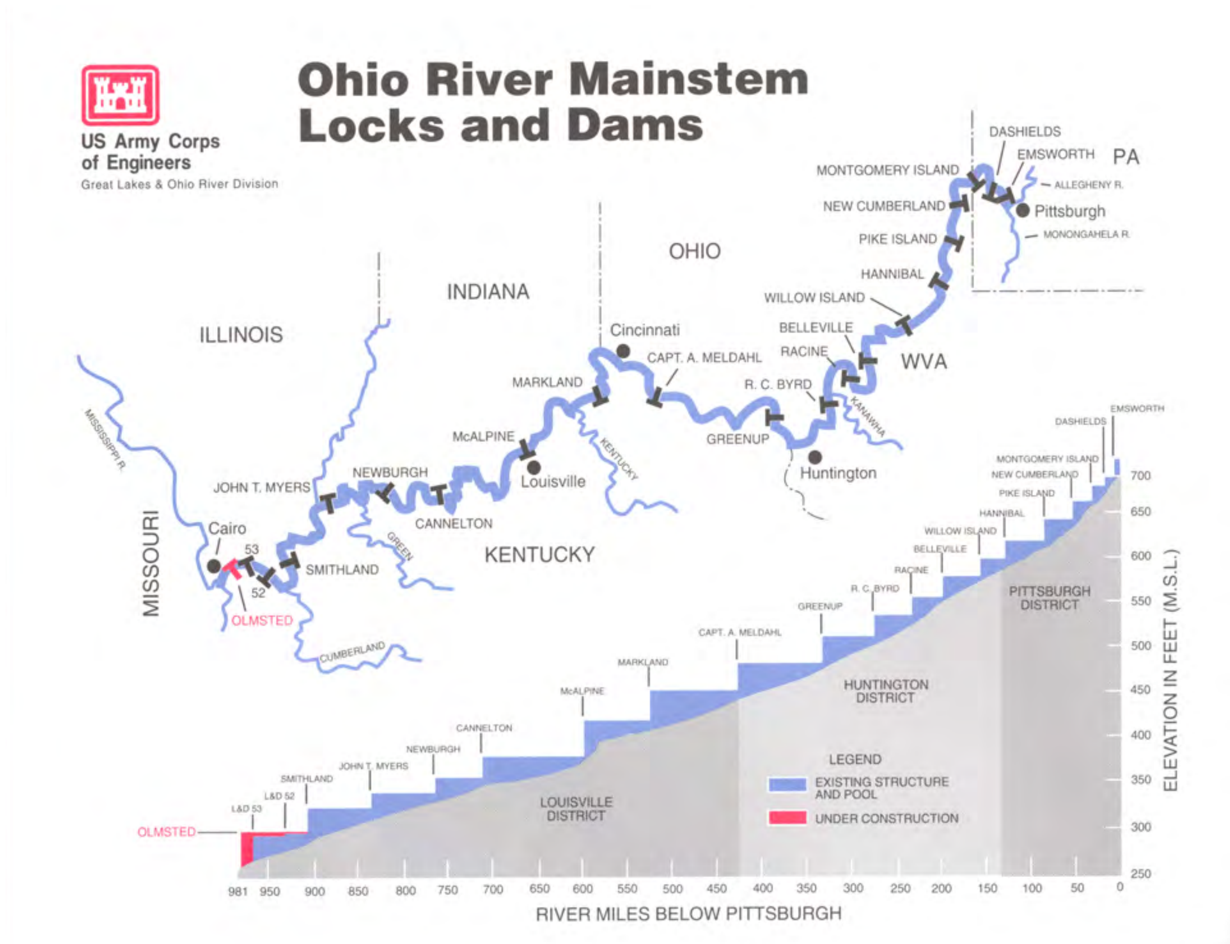

Figure 2 Location of the Ohio River Mainstem Locks and Dams (USACE), showing the Ohio River profile from Pittsburgh to Smithland Dam.

USACE/Great Lakes and Ohio River Division

The Great Lakes and Ohio River Division Water Management Team of the U.S. Army Corps of Engineers (USACE) is responsible for reducing water level stages along the lower Ohio and middle Mississippi Rivers during significant flood events. To accomplish this mission, LRD directs the flow releases from Barkley Lake on the Cumberland River and issues regulation instructions to the Tennessee Valley Authority for the operation of Kentucky Lake on the Tennessee River. LRD currently utilizes a dynamic, one-dimensional unsteady flow model called “Cascade”, which has proven to be an effective management tool in coordinating the reservoir releases. Cascade routes Ohio River and upper Mississippi River flows to determine the impact of reservoir releases on flood levels. A complete description of LRD operations is described in Lee et al (2002).

Continued use of Cascade is problematic due to on-going code maintenance and difficulty of integrating the model into the USACE Corps Water Management System (CWMS) (Fritz et al, 2002). Consequently, LRD is emphasizing migration from Cascade to HEC-RAS for operations.

Description of the model

The best freely available data sources were used to construct channel cross-sections, using a combination of previously existing channel cross-section data, bathymetric data, lidar, and digital elevation model (DEM) data, as Table 2 indicates. The original data were produced using a differing vertical and horizontal datums and geographic projections. Consequently, the data had to be transformed to a common datum and projection in order to minimize distortions. One issue is that, due to the length of the greater than 1300 miles modeled on the curved surface of the Earth and with the desire to have geographically registered channel cross-sections for future real-time flood inundation mapping, some distortion of the channel length is unavoidable. One can only hope to minimize map distortions by choosing an appropriate map projection that preserves areas and minimizes horizontal distortions.

Table 1 indicates the steps taken to transform the various data sources to Albers Equal Area projection using NAD 83 and NAVD 88 within ESRI ArcGIS™ and with the National Geodetic Survey VERTCON software (http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html).

Model calibrations proceeded in a stepwise fashion, beginning with downstream reaches and progressively moving upstream. A reach would be calibrated and new cross-sections would be added upstream, followed by re-calibration of the entire model, including the new and old reaches. The calibration period spans September 25, 2004 to July 1, 2008.

Table 1. Data processing steps to transform data from all sources to the Albers Equal Area projection using NAD 83 and NAVD 88.

Step	DEM/Lidar	USACE cross-sections	Channel bathymetry	Gauge datum
1	Obtain DEM data — geographic projection (latitude-longitude), NAD 83, NAVD 88	Obtain USACE cross-section data	Obtain bathymetry data	Obtain gauge zero elevations for modeling ponts
2	Convert vertical units (meters to feet)	Project to NAD 83, Albers feet	Project cross-sections to NAD 83, Albers feet	Determine correction factor (ORD to NGVD 29)

Step	DEM/Lidar	USACE cross-sections	Channel bathymetry	Gauge datum
3	Mosaic DEM tiles	Determine correction factor (ORD to NGVD 29)	Define cross-sections by connecting bathymetry points	Determine correction factor (NGVD 29 to NAVD 88)
4	Project DEM from Geographic to Albers	Determine correction factor (NGVD 29 to NAVD 88)	Assign river mile locations to cross-sections	Apply gaude zero correction factors in HEC-RAS
5	•	Apply cross-section correction factors in HEC-RAS	Determine correction factor (ORD to NGVD 29)	•
6	•	•	Determine correction factor (NGVD 29 to NAVD 88)	•
7	•	•	Reduce the number of cross-sections	•
8	•	•	Apply correction factors to bathymetry cross-sections	•

Table 2. Data types and sources used to construct HEC-RAS cross-sections.

Data Type	Data Source
Surveyed Cross-section and Bathymetry Data	USACE Pittsburgh District USACE Huntington District USACE Louisville District USACE St. Louis District USACE Memphis District USGS
National Elevation Dataset (NED) (10 m and 3 m horizontal resolution)	USGS
Indiana DEM data (5 ft and 10 ft horizontal resolution)	USACE Louisville District
Lidar Data	USACE Memphis District PASDA: Pennsylvania OGRIP: Ohio
Elevation Datum Correction Factor Data (Ohio River Datum to NGVD29)	USACE Huntington District USACE Louisville District
Elevation Datum Correction Factor Data (VERTCON program to derive NVGD29 to NAVD88 correction factors)	NOAA National Geodetic Survey
USACE Levee Database Data	USACE Huntington District USACE Louisville District
Lock and Dam Geometry	USACE Navigation Charts USACE Pittsburgh District
National Hydrography Dataset (NHD)	USGS
Historic and Real-time Stage and Streamflow Data	USGS USACE LRD NWS OHRFC and LMRFC
Streamflow forecasts	NWS OHRFC and LMRFC

Data Type	Data Source
In-house Digitized Data (Levee line data and elevations) (Storage Area geometry)	NWS OHRFC
Ancillary/Miscellaneous Data	Internet Sources

Table 3. Model details, listing reach length modeled, numbers of bridges, storage areas, lateral structures, locks & dams, and cross-sections defined in the model.

River Name	River miles modeled	Bridges	Storage Areas	Lateral Structures	Locks & Dams	Cross Sections
Alleghaney R	24.30				2	263
Monongahela R	11.00					64
Ohio R	981.00	17	43	20	20	2194
Upper Mississippi R	110.00			16		246
Lower Mississippi R	107.00			18		119
Wabash R	45.00					22
Tennessee R	18.21					13
Cumberland R	29.36					21
Subtotal	1325.87	17	43	54	22	2942
Kanawah R	94.00	3			2	346
Elk R	25.67	5				151
Coal R	11.96	1				60
Subtotal	131.63	9			2	557
Total	**1457.50**	**26**	**43**	**54**	**24**	**3499**

Discussion

Initial results show very acceptable calibration statistics with R^2 values better than 0.98, except for the Pittsburgh location ($R^2 = 0.86$), where model calibrations are preliminary. Also, the Pittsburgh pool is controlled at low flows by Emsworth Dam, which has experienced operational difficulties over the calibration period. Figures 3 and 4 show the effect of downstream control of the Pittsburgh pool by Emsworth Dam, which has a target pool elevation of approximately 710.5 ft (MSL). Model results, in general, are expected to vary by location due to differences in the quality of the tributary flow and lateral inflow estimates. So, these selected results should not be considered universal; local conditions involving structural and natural controls can be problematic to duplicate in our HEC-RAS model implementation. However, model improvements will be an on-going process and will be implemented following a review and validation process.

Operational results are not expected to match calibration statistics due to errors with real-time lateral and tributary inflow estimation. Also, with the use of forecast precipitation (also known as quantitative precipitation forecast or, QPF) in real-time operations, HEC-RAS model errors will also reflect QPF error as well, which are often substantial. No comparison between existing lumped hydrologic routing methods at the OHRFC or CASCADE routing at LRD have yet been attempted. So, no conclusions can be drawn with respect to operational improvements.

Table 4. Verification statistics from model calibration, showing mean absolute error (MAE), mean error (ME), mean square error (MSE), and R^2 for selected locations.

Location	MAE	ME	MSE	R^2
Pittsburgh, PA (PTTP1)	0.2096	-0.0180	0.0847	0.8585
Evansville, IN (EVVI3)	0.7365	0.0587	0.9830	0.9842
Cairo, IL	0.8253	0.0277	1.0830	0.9935
Chester, IL	0.3677	0.1516	0.3269	0.9960
Cruthersville, MO	0.8634	0.2003	1.3260	0.9887

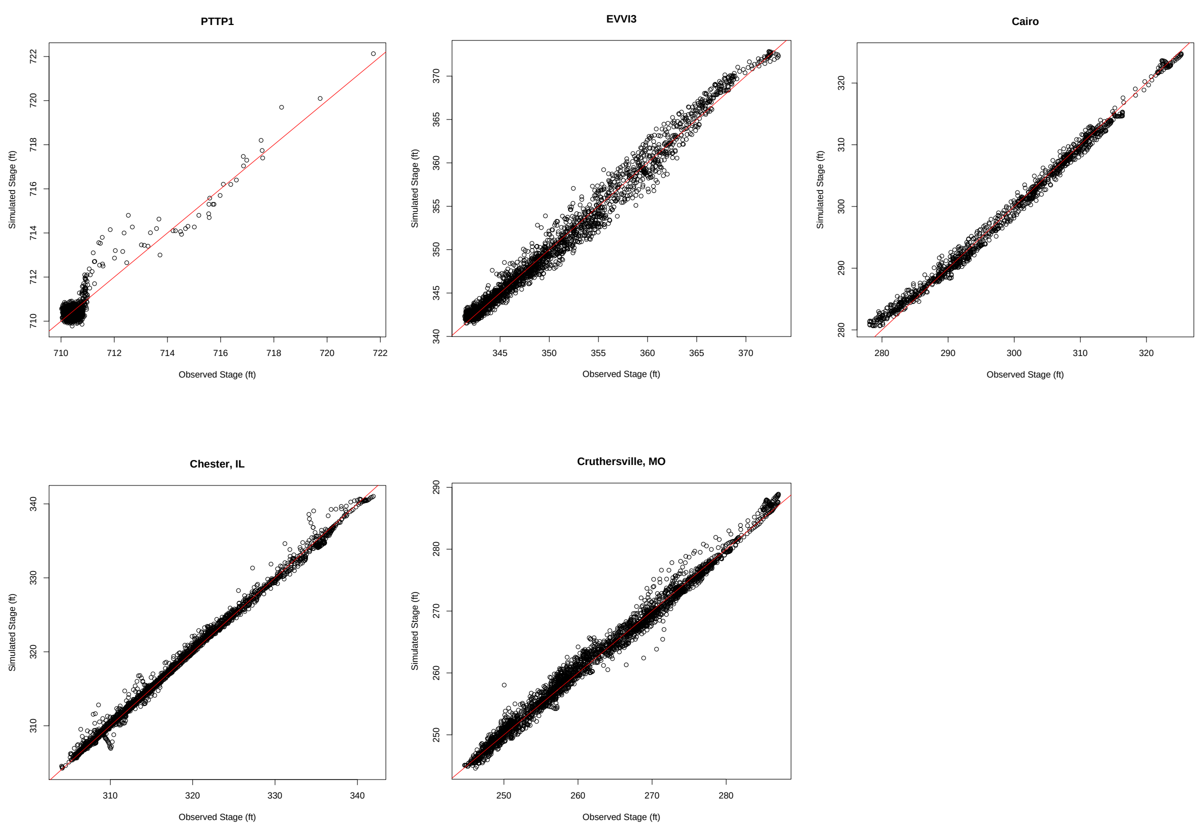

Figure 3. Scatterplots for selected modeling points for the calibration period. The *red* line indicates 1-to-1 agreement.

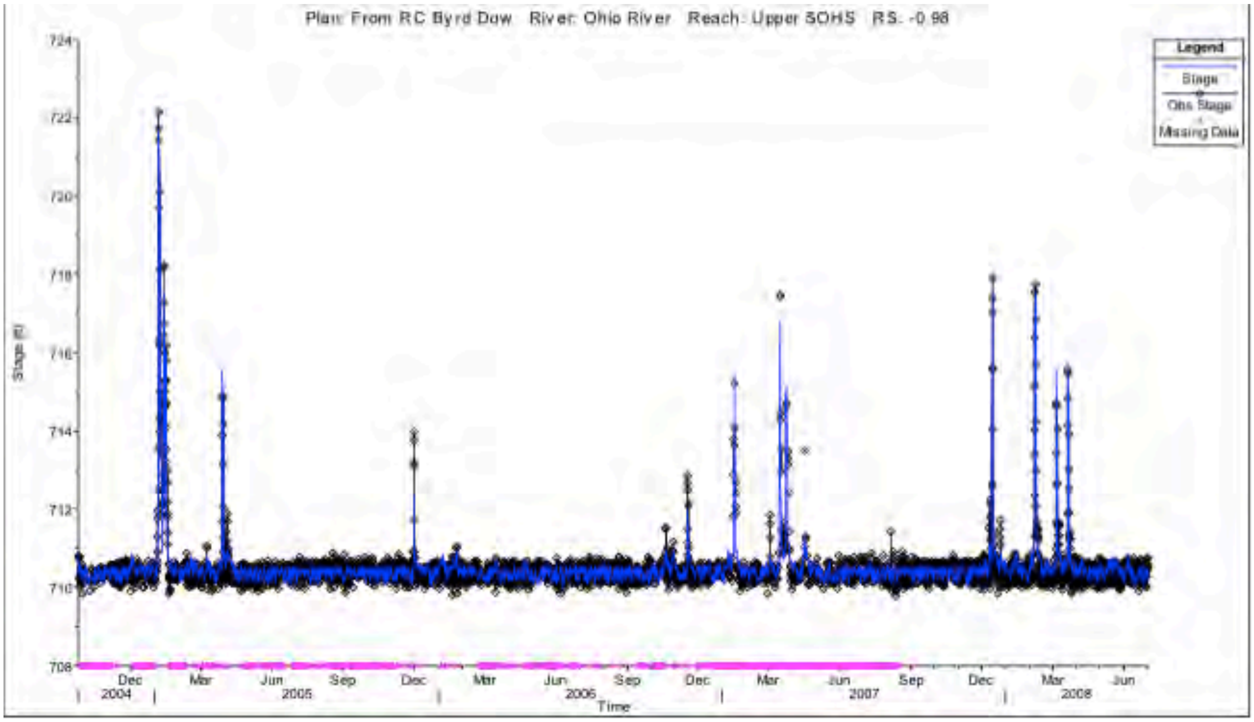

Figure 4. Stage hydrograph (ft, MSL) for Pittsburgh (PTTP1) for the calibration period, 01/01/2004 to 12/31/2008.

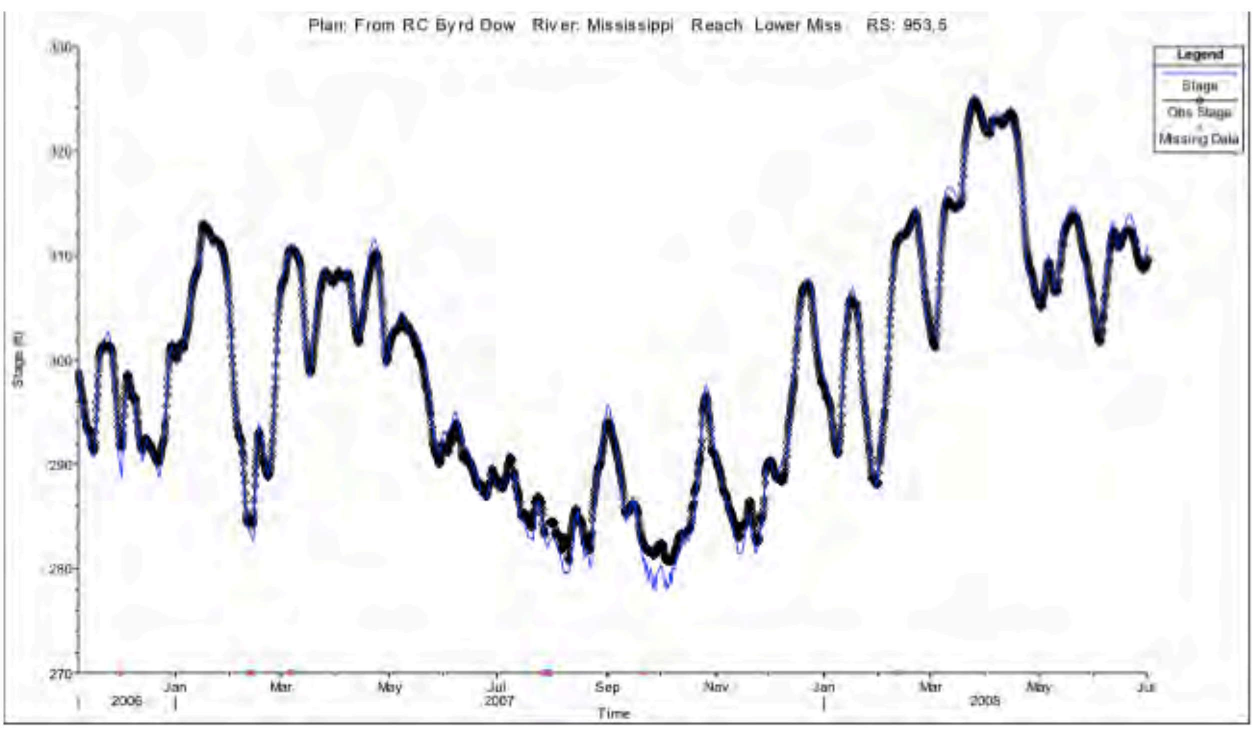

Figure 5. Stage hydrograph (ft, MSL) for Cairo, IL for the calibration period, 01/01/2004 to 12/31/2008.

Conclusion

The joint NWS-USACE cooperation in the co-development of the Ohio River Community HEC-RAS model has been successful. Real-time operations with the model will begin by mid-2010. While no model comparisons with existing routing models have been made, calibration statistics are very encouraging. Critically important to LRD operations is the ability to accurately model the confluence of the Ohio and Mississippi Rivers where Cairo, IL is located. Results presented in Table 4 and Figures 3 and 5 show promise for meeting LRD needs at Cairo, IL.

We also acknowledge Joe Heim (NOAA/NWS/OHRFC) for his significant efforts in data preparation for calibrations and preparing data pathways and procedures for operations at the OHRFC.

References

Anderson, E.A., 1973. National Weather Service River Forecast System-Snow Accumulation and Ablation Model. Technical Memo. NOAA, Silver Spring, MD, pp. 217.

Anderson, E.A., 2002. Calibration of Conceptual Hydrologic Models for Use in River Forecasting, Hydrology Laboratory.

Burnash, R.J., Ferral, R.L., McGuire, R.A., 1973. A Generalized Streamflow Simulation System: Conceptual Modeling for Digital Computers, U.S. Department of Commerce National Weather Service and State of California Department of Water Resources.

Burnash, R. J. C., 1995. The NWS River Forecast System—Catchment modeling. Computer Models of Watershed Hydrology, V. P. Singh, Ed., Water Re- sources Publications, 311–366.

Fritz, J.A., W.J. Charley, D.W. Davis, and J.W. Haines, 2002. “New water management system begins operation in US projects”, Hydropower & Dams, 3, pp. 49-53.

Lee, D.H., S. Wisbith, D. Buelow, and G. McKee (2002). “Lower Ohio and Middle Mississippi Rivers Flood Management.” In *Proceedings of the ASCE EWRI 2002 Conference on Water Resources Planning and Management, Symposium on Managing the Extremes: Floods and Droughts*, ed. D.F Kibler, Roanoke, Virginia, May 19-22, 2002, C-4-167.pdf.

USACE HEC, 1995. HEC-RAS, River Analysis System, Hydraulics Reference Manual. USACE, HEC, CPD-69. Davis, CA, pp. 152.

US. Department of Commerce (1972): National Weather Service River Forecast System (NWSRFS-Model), NOAA Technical Memorandum NWS-Hydro-14, Washington.