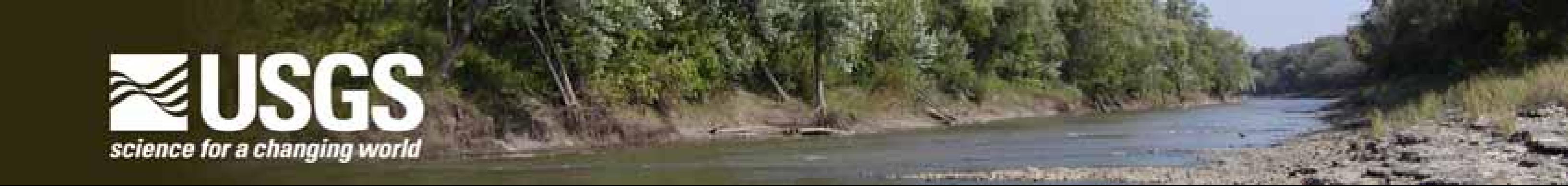

Use of Numerical Simulations in Surface-Water Studies by the U.S. Geological Survey in Missouri

—David C. Heimann, Paul H. Rydlund, Jr., and Susan S. Licher

Introduction

Numerical simulations of surface-water systems can be a useful tool to predict and understand a variety of physical, chemical, and ecological processes. A number of applications have been conducted by the U.S. Geological Survey Missouri Water Science Center in conjunction with ecological and flood studies in Missouri. Numerical simulations can provide a physically based method to predict natural processes in situations where it is impractical to measure the results directly as a result of cost, time, or infrequent occurrence.

Numerical simulations provide a means of analyzing “What if?” scenarios. For example, a simulation can be used to estimate the effects of reservoirs in a basin on the timing and magnitude of downstream streamflows. Simulations also may provide a better understanding of a complex process, such as sediment transport and deposition during a large flood. Alternatively, numerical simulations can be used to quantify aquatic habitat that is defined by the hydraulic (depth and velocity) characteristics of streamflow. This report provides information on recent applications of numerical simulations of hydraulic, floodplain, and watershed processes.

Numerical Simulation of Riverine Processes

Technological advancements in computer capabilities have made computationally intensive modeling applications, including two-dimensional simulations, more feasible for widespread application. Two-dimensional simulations often replace one-dimensional simulations to determine hydraulic processes in stream channels, and thereby provide hydraulic information at a greater level of detail. The two-dimensional hydraulic simulations use a developed computation mesh to represent stream channel geometry and solve calculations for water depth (fig. 1) and velocity at each mesh

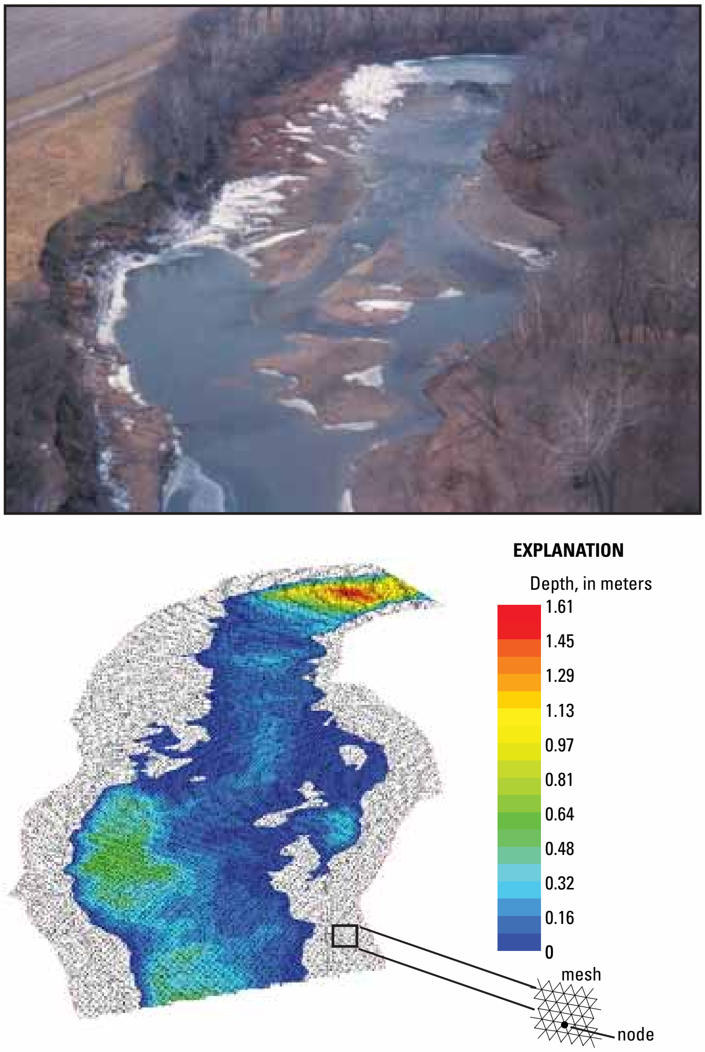

Figure 1. (A) A natural site (undetermined streamflow) simulated by a two-dimensional model. (B) Model mesh and simulated depths at the same site, at a streamflow of 16.4 cubic meters per second.

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node. Hydraulic characteristics are determined for either steady-state (streamflow and water level conditions do not vary with time) or transient (streamflow and/or water levels vary with time) conditions depending on the simulation objective. General input requirements for two-dimensional models include topography/bathymetry, channel roughness, upstream discharge, and downstream stage. Observed depth and velocity information are required for calibration and validation of the hydraulic simulations. Accurate representation of the channel topography in the model mesh is the most time-consuming, yet most critical, of the input requirements. Simulation output consists of two horizontal velocity components and a depth at each computational model mesh node providing a planar view of flow direction. The number and placement of the computational nodes in the simulation mesh are dependent on the scale of the reach being simulated and the scale of desired hydraulic information.

To obtain accurate and reliable output data from a two-dimensional model application, the simulation velocity and depth results need to be compared to observed measurements. This is achieved through a calibration and validation process. Calibration is the process by which the differences between observed and simulated velocity and depth characteristics for a particular streamflow are minimized through adjustment of model parameters. Ideally, model calibration is conducted for a range of streamflows including the working range of flows desired in the application. Model validation is an important step by which the calibrated model is applied to an independent flow condition (other than calibrated streamflows) to test the reliability of the model and to see if the differences between observed and simulated data are within acceptable limits.

One application of two-dimensional streamflow models has been to determine the location and size of fish habitat areas. Fish habitat in the upper Osage River Basin in Missouri has been simulated using the two-dimensional model River2D (Ghanem and others, 1995, 1996; Steffler and Blackburn, 2002). Fish habitat area is calculated based on the distribution of water velocity, depth, and channel bottom material characteristics compared to known species' requirements for these physical attributes (Heimann and others, 2005; fig. 2).

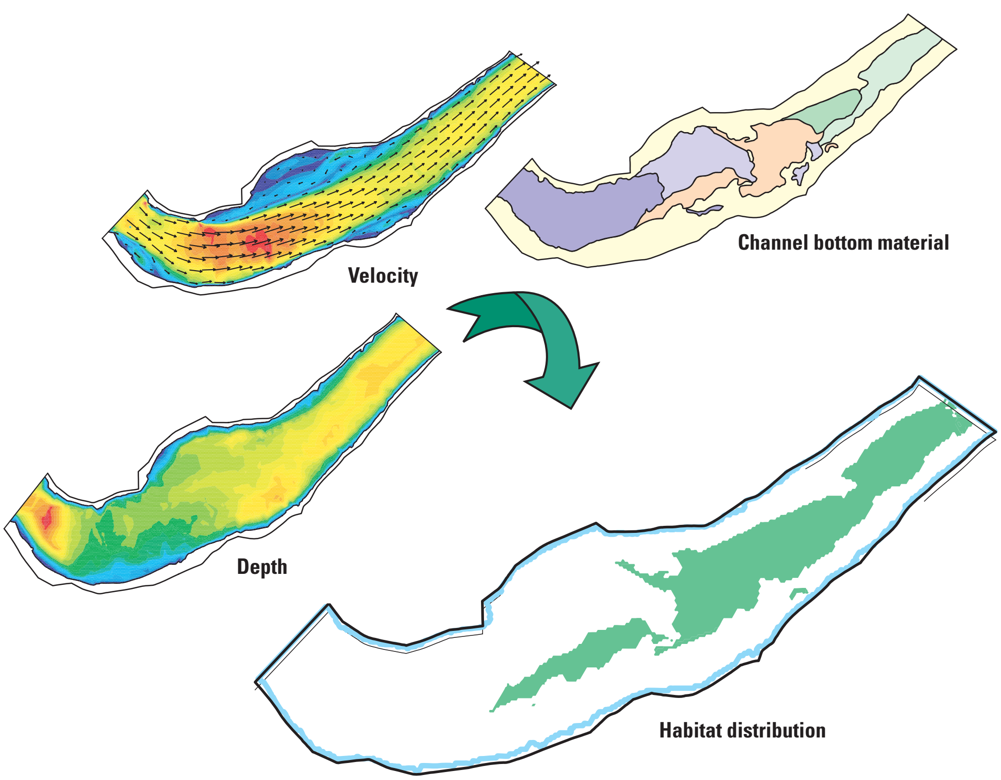

Figure 2. Velocity, depth, and substrate layers are combined using Geographic Information System software to produce a habitat distribution map for paddlefish based on known habitat requirements.

The Federal Highway Administration's Finite Element Surface-Water Modeling System (FESWMS) (Froehlich, 1989) has been used to simulate the movement of water and sediment in rivers, lakes, and coastal waters. FESWMS is a two-dimensional streamflow model that provides water-surface elevation and velocity information around buildings (fig. 3), levees, bridge abutments, spur dikes, and meander bends, and also has been used to provide flow distributions at confluences of rivers. FESWMS commonly is used at highway river crossings where complex flow conditions exist (Froehlich, 1989). In addition, the model has utilities that allow detailed analysis of flow over roadway embankments, as well as pressure flow through bridges, culverts, gate structures, and drop-inlet spillways. One of the more important aspects of modeling flow through structures is the potential for backwater. Backwater (elevated water-level conditions) can be caused by structures, hydraulic inefficiencies, or channel constrictions and may contribute to road inundations and flood damage. Knowing when backwater exists and the extent can be difficult to measure in a complex river reach.

Example of complex riverine flow that can be modeled by the Finite Element Surface-Water Modeling System.

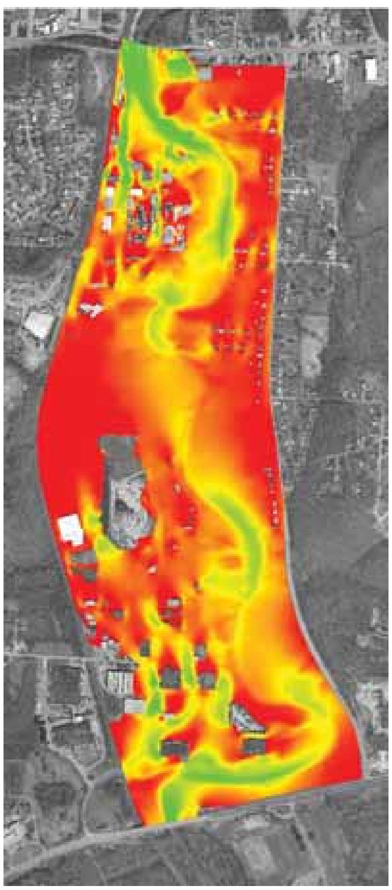

Figure 3. Visualization of numerical model output for a flood along the Blue River in Kansas City, Missouri, as simulated by the Finite Element Surface-Water Modeling System. (Red represents the slowest water velocities and green represents the fastest water velocities).

FESWMS has been used by the USGS in Missouri to simulate a complex 2-mile reach along the Blue River in Kansas City, Missouri, in 2005 to determine water levels and areas of inundation associated with various streamflows (Kelly and Rydlund, 2006). FESWMS is a useful tool for simulating water levels, turbulence parameters, and pressure flow through bridge openings, and was used to analyze three bridge structures in the reach. In addition to analyzing bridge structures, the two-dimensional approach was beneficial in defining flow directions and velocities in sharp meander bends and at tributary junctions.

Flood simulations from the FESWMS model produced water-surface elevations that were used in the development of flood profiles and inundation maps for the Blue River in Kansas City, Missouri (Kelly and Rydlund, 2006). A library of inundation maps for selected water-surface elevations are available on the internet (http://mo.water.usgs.gov/indep/kelly/blueriver/index.htm), which allows the user to identify the estimated extent of flood inundation by selecting the appropriate inundation map for the water-surface elevation measured at the stream gage (fig. 4).

If river-channel sediments are characterized, the FESWMS flow results can determine the effects of flow on river channel bed and banks. Bottom shear stress in natural channels and those constricted by waterway crossings are analyzed to aid in stream-bank stability and abutment protection countermeasures. An additional utility that allows for the computation of erosion or "scour" in bridge openings during floods also is available.

RMA2 is a two-dimensional hydraulic model (U.S. Army Corps of Engineers, 1996) that has been used to simulate steady-state and transient streamflow conditions in Missouri rivers. RMA2 has been used in conjunction with the U.S. Army Corps of Engineers model SED2D (Roig and others, 1996) to simulate sediment transport and flood plain deposition (fig. 5) along Long Branch Creek in northeast Missouri (Heimann, 2001). In this application the two-dimensional distribution of water velocity, direction, and depth derived from

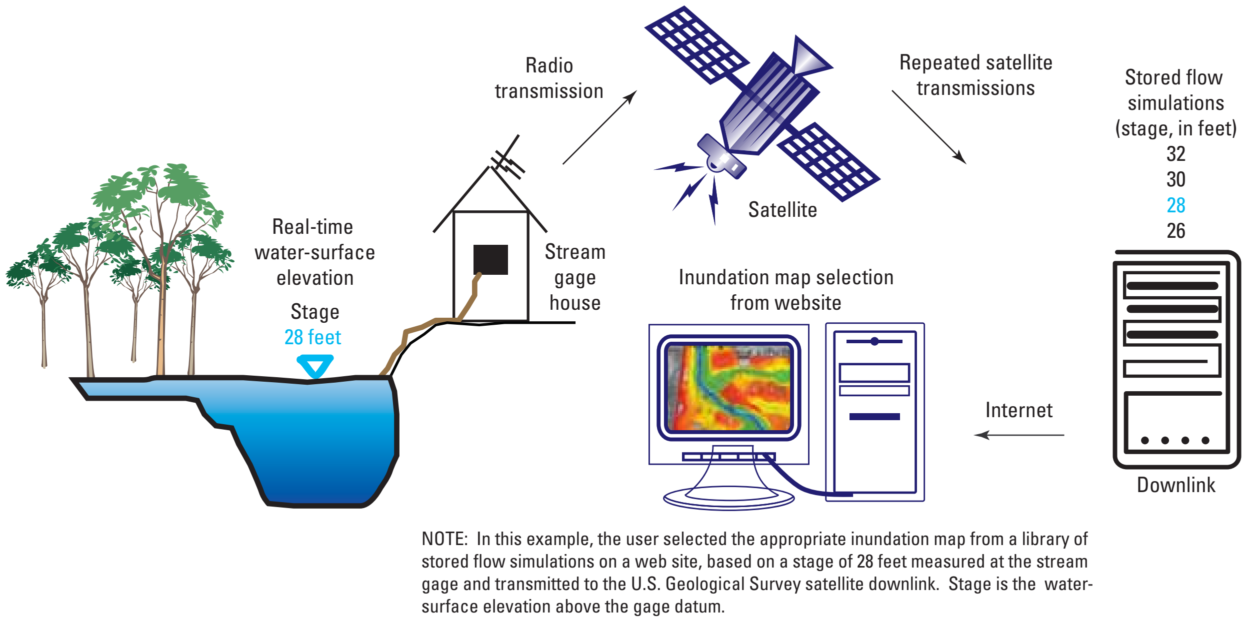

Figure 4. Schematic depicting communication links that occur when accessing estimated flood inundation maps from the internet.

RMA2 was used as the input to determine sediment transport and changes in bed elevation in SED2D simulations (fig. 5). Data requirements for SED2D included sediment concentration time series and streambed characteristics such as bottom material particle size, water depth, and spatial distribution of bottom material.

Numerical Simulation of Watershed Processes

Precipitation-runoff models are used to simulate the quantity and timing of streamflow or the quality of stream water at select points in a watershed resulting from the cumulative effects of precipitation, land use, soils, and topography. The key inputs of a watershed model are precipitation, temperature, land-use information, topog-

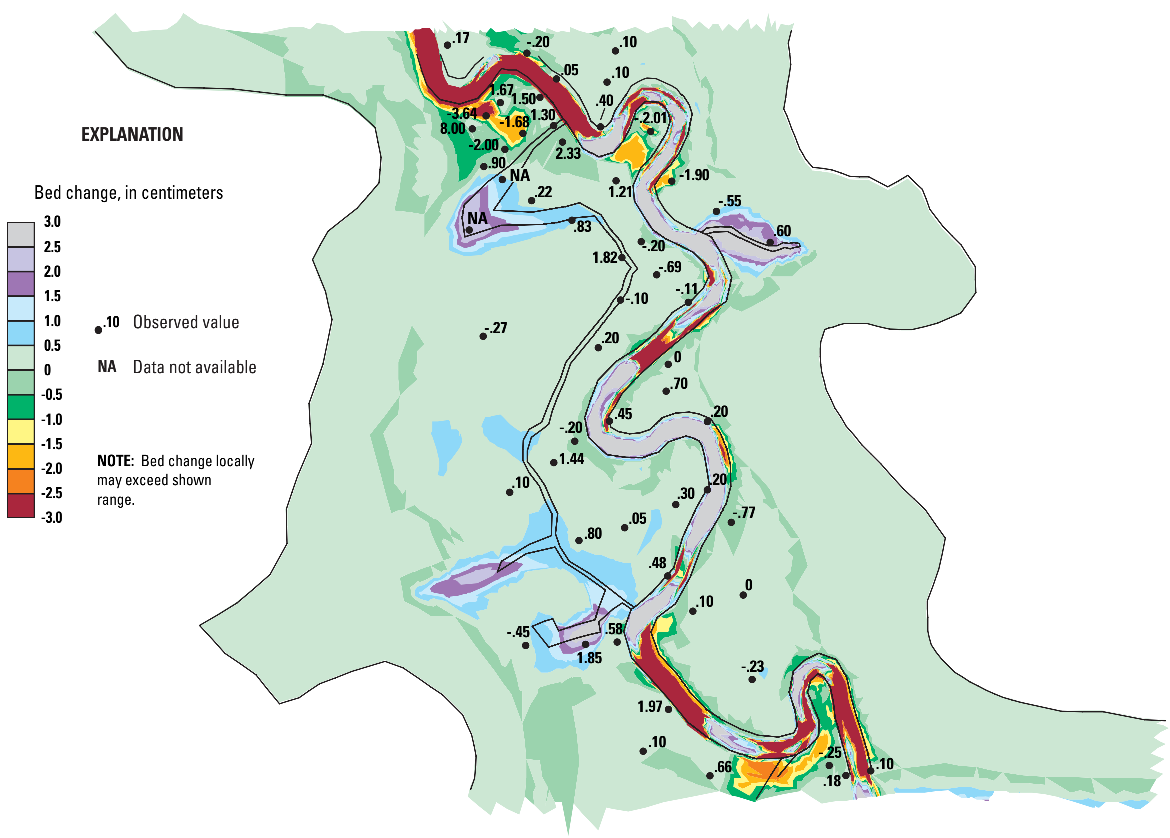

Figure 5. Comparison of observed and simulated spatial distributions of changes in bed elevation along Long Branch Creek (northwest Missouri) following a 2-year recurrence interval flood.

raphy, soils, and point-source discharges and withdrawals. Additional data required for modeling sediment transport and water-quality variables are temperature, dissolved oxygen, total nitrogen, total phosphorus, pesticides, and other constituents. Simulation outputs may include total streamflow (fig. 6), the proportions of run off, interflow, and baseflow that contribute to the total streamflow, sediment transport and deposition, and water-quality constituent concentrations. To ensure that precipitation-runoff models are reliable, the model output must be calibrated to observed data. Parameters that help determine the model output are adjusted within realistic bounds to improve the match between simulated output and observed data. Once model parameters have been adjusted to minimize differences, an independent set of observed data are compared to simulated output to validate that the model will correctly simulate different conditions.

The Hydrologic Simulation Program-Fortran (HSPF) is a precipitation-runoff model that can be used to simulate the hydrologic (streamflow quantity and timing) and water-quality processes within a watershed (Bicknell and others, 2004). HSPF is being used in 2006 within the USGS Missouri Water Science Center to understand the effect of many small flood-retarding impoundments on streamflow at selected downstream locations. Some other applications of HSPF (and similar numerical models) include predicting flow at ungaged locations, extending missing record, understanding how land-use changes affect hydrology and water quality (Duncker and others, 1995; Duncker and Melching, 1998; Coon, 2003), how wetland restoration affects hydrology (Jones and Winterstein, 1999), the effects of withdrawals on hydrology (Zarriello and Ries, 2000), and simulation of water quality and nutrient loads (Stigall and others, 1993; Laroche and others, 1996).

In conclusion, a number of different numerical models have been used by the USGS Missouri Water Science Center to simulate hydraulic and hydrologic conditions in surface-water systems in Missouri. Increases in computing capabilities have resulted in a greater prevalence of two-dimensional numerical simulations, and for some applications, three-dimensional numerical simulations may provide the most appropriate means of obtaining suitable answers. These

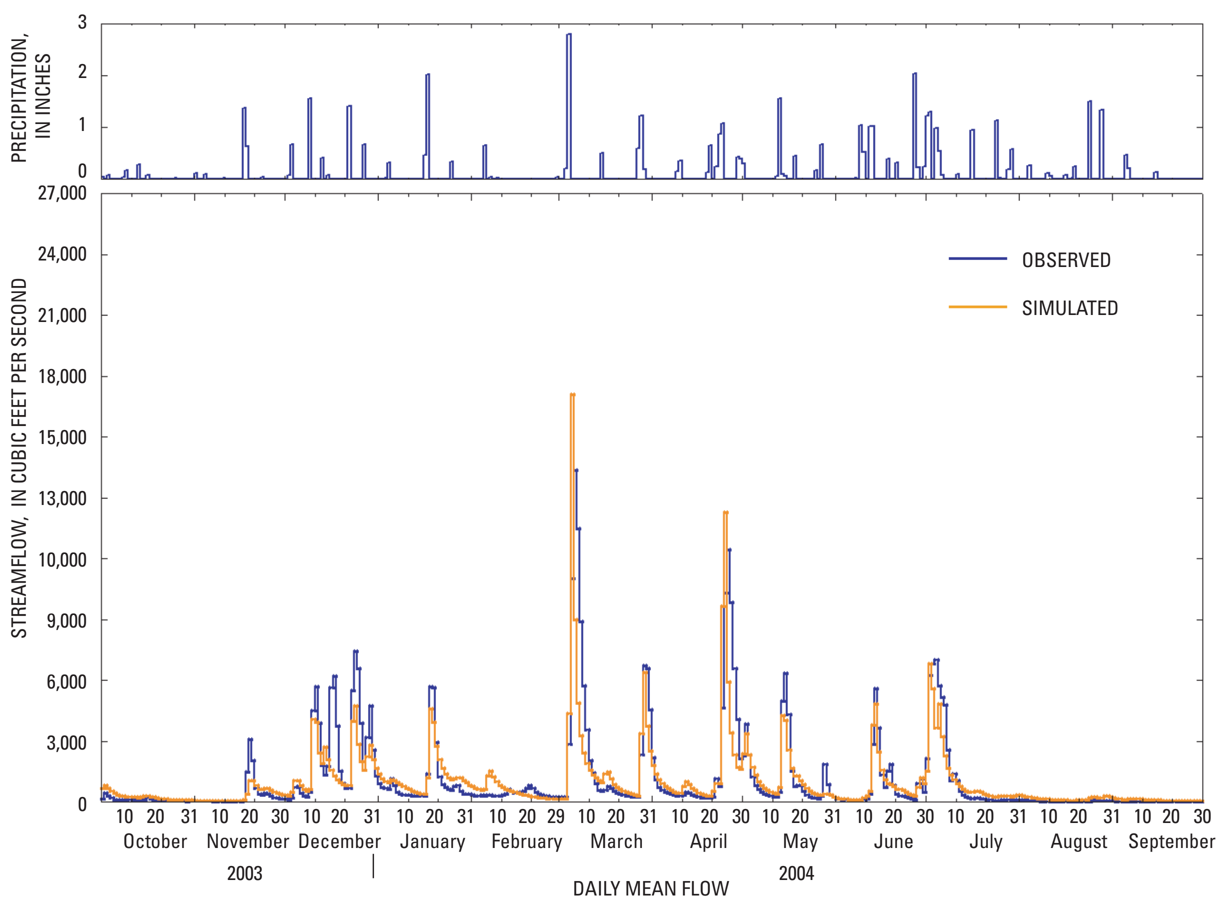

Figure 6. Comparison of observed and simulated streamflow as predicted by the Hydrologic Simulation Program-Fortran.

tools continue to undergo further development and enhancements in capabilities and will continue to provide an effective means for the USGS to answer "What if ?" questions regarding the surface-water resources of Missouri.

Selected References

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Jobes, T.H. and Donigian, A.S., Jr., 2004, Hydrological Simulation Program-Fortran, users manual version 12.1: Athens, Ga., U.S. Environmental Protection Agency Research Laboratory, 885 p.

Coon, W.F., 2003, Simulating land-use changes and stormwater-detention basins and evaluating their effect on peak streamflows and stream-water quality in Irondequoit Creek Basin, New York: U.S. Geological Survey Open-File Report 03–136, 96 p.

Duncker, J.J., and Melching, C.S., 1998, Regional rainfall-runoff relations for simulation of streamflow for watersheds in Du Page County, Illinois: U.S. Geological Survey Water-Resources Investigations Report 98–4035, 80 p.

Duncker, J.J., Vail, T.J., and Melching, C.S., 1995, Regional rainfall-runoff relations for watersheds in Lake County, Illinois: U.S. Geological Survey Water-Resources Investigations Report 95–4023, 71 p.

Froehlich, D.C., 1989, HW031.D—Finite Element Surface-Water Modeling System: Two-dimensional flow in a horizontal plane—users manual: Federal Highway Administration Report FHWA-RD–88–177. 285 p.

Ghanem, A.H., Steffler, P.M., Hicks, F.E., and Katopodis, C., 1995, Two dimensional finite element model for aquatic habitats: Edmonton, Alberta Canada, University of Alberta, Department of Civil Engineering, Water Resources Engineering Report 95–S1, 189 p.

Ghanem, A.H., Steffler, P.M., Hicks, F.E., and Katopodis, C., 1996, Two dimensional finite element flow modeling of physical fish habitat: Regulated Rivers: Research and Management, v. 12, pp. 185–200.

Heimann, D.C., 2001, Numerical simulation of streamflow distribution, sediment transport, and sediment deposition along Long Branch Creek in northeast Missouri: U.S. Geological Survey Water-Resources Investigations Report 01–4269, 61 p.

Heimann, D.C., Richards, J.M., Brewer, S.H., and Norman, R.D., 2005, Quantification of fish habitat in selected reaches of the Marmaton and Marais des Cygnes Rivers, Missouri, 2004: U.S. Geological Survey Scientific Investigations Report 05–5180, 58 p.

Huizinga, R.J., and Rydlund, P.H., Jr., 2001, Simulation of flow and evaluation of bridge scour at Horse Island Chute Bridge near Chester, Illinois: U.S. Geological Survey Water-Resources Investigations Report 01–4269, 28 p.

Kelly, B.P., and Rydlund, P.H., Jr., 2006, Estimated flood-inundation mapping for the lower Blue River in Kansas City, Missouri, 2003–05: U.S. Geological Survey Scientific Investigations Report 06–5089, 29 p. plus appendixes.

Jones, P.M, and Winterstein, T.A., 1999, Characterization of rainfall-runoff response and estimation of the effect of wetland restoration on runoff, Heron Lake Basin, Southwestern Minnesota, 1991–97: U.S. Geological Survey Water-Resources Investigations Report 00–4095, 48 p.

Laroche, A., Gallichand, J., Lagacé, R., and Pesant, A., 1996, Simulating atrazine transport with HSPF in an agricultural watershed: Journal of Environmental Engineering, vol. 122, no. 7, 622–630 p.

Roig, L.C., Donnell, B.P., Thomas, W.A., McAnally, W.H., and Adamec, Jr. S.A., 1996, A users manual for SED2D-WES—a generalized computer program for two-dimensional, vertically average sediment transport: Vicksburg, Miss., U.S. Army Corps of Engineers Waterways Experiment Station, 75 p.

Southard, R.E., 1997, Simulation of the effect of traffic barricades on backwater along U.S. Highway 54 at Jefferson City, Missouri—1993 flood on the Missouri River: U.S. Geological Survey Water-Resources Investigations Report 97–4213, 13 p.

Steffler, P., and Blackburn, J., 2002, Two-dimensional depth averaged model of river hydrodynamics and fish habitat: Introduction to depth averaged modeling and users manual: Edmunton, Alberta, Canada, University of Alberta, 119 p.

Stigall, E., Linker, L.C., and Donigian, A.S., 1993, Application of the Hydrologic Simulation Program-Fortran (HSPF) Model to the Potomac River Basin: Proceedings of WATERSHED '93 A National Conference on Watershed Management, March 21–24, 1993, Alexandria, Va., 776–775 p.

U.S. Army Corps of Engineers, 1996, Users guide to RMA2, version 4.3: Vicksburg, Miss., Waterways experiment Station, 226 p.

Zarriello, P.J., and Ries K.G., III, 2000, A precipitation-runoff model for analysis of the effects of water withdrawals on streamflow, Ipswich River Basin, Massachusetts: U.S. Geological Survey Water-Resources Investigation Report 00–4029, 99 p.

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