MODELING THE OHIO RIVER: NOT JUST FOR FLOODS ANYMORE

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Abstract: The Great Lakes and Ohio River Division Water Management Team of the U.S. Army Corps of Engineers is responsible for reducing flood stages along the lower Ohio and Mississippi Rivers during flood events. Over the past 22 years, the Team has developed a real-time data management and modeling system to support its mission. The keystone of the system is an unsteady flow model of the Ohio River and its junction with the Mississippi River. The model, called Cascade, has proven to be a valuable and effective tool for flood management. Updated and operated on a daily basis, the model has lent itself to several other operational river management tasks such as modeling the effects of lock and dam operations during low flows, forecasting river stages and flows during barge salvage operations and wicket dam repairs, providing hydraulic information to a contaminant transport model, and computing natural river flows for distribution of flood damage reduction benefits to individual reservoirs. The data management system that supports the model draws upon many separate data sources including the National Weather Service, GOES satellite downlinks, the OMNI navigation data system, our District offices and the Tennessee Valley Authority. Presently based upon the Hydrologic Engineering Center's Data Storage System, the data management system is being migrated to an ORACLE database with the implementation of the new Corps Water Management System. An overview of this complex data management and modeling system is presented, along with examples of its application.

INTRODUCTION

The Ohio River drains America's heartland, stretching more than 981 miles from Pittsburgh, PA to Cairo, IL where it joins the Mississippi River. Its 204,000 mi^2 watershed stretches north to south from New York to Alabama and east to west from Pennsylvania to Illinois. 14 major tributaries and 11 minor tributaries supply the river, along with runoff from 43,490 mi^2 of local drainage area. Ohio River flows vary over three orders of magnitude at its confluence with the Mississippi River. Flows at the outlet (1933 to 1999) range from a low of about 425 m^3s^{-1} (15,000 cfs) to the 1937 flood peak of about 52,380 m^3s^{-1} (1,850,000 cfs) and have an annual average of 7,500 m^3s^{-1} (265,000 cfs) (unpublished USACE computed flows).

The Ohio River has been extensively modified to support inland navigation. Due to the navigation structures (locks and dams), the river's profile is that of a staircase during low to moderate flows. As flows increase, the dams' gates are opened. At high flows, the dams' gates are fully opened and a natural river profile returns. The navigation structures do not afford any flood control. Figure 1 illustrates the river's profile and location of the navigation locks and dams.

Figure 1 The Ohio River and its profile (locks and dams are denoted by the ⊥ symbol).

The Water Management Team has several responsibilities related to Ohio River management. The Team is responsible for reducing water level stages along the lower Ohio and middle Mississippi Rivers during significant flood events, producing and issuing daily USACE internal river flow and stage forecasts and coordinating public National Weather Service river forecasts, issuing low flow guidance, coordinating interagency (Tennessee Valley Authority and USACE) flows for lower Ohio River safety concerns during lock and dam operation and maintenance, providing flow characteristics for real time spill monitoring, and computing mainstem flood reduction benefits for the Annual Flood Damage Report (AFDR) to Congress. To conduct these responsibilities, the Team must know the detailed hydrologic and hydraulic conditions of the watershed and its river, and be able to produce a reliable near-term (3-5 day) forecast of river conditions. In support of the AFDR, river hydraulic simulations are required to compute benefits and to assign them to the appropriate Districts and respective projects. Because of the river's complex hydraulics (staircased pools at low to moderate flows, Mississippi River and tributary backwater effects, overbank flow at high flows, dynamic tributary and local inflows, and flow fluctuations due to lock and dam operations and reservoir peaking and ponding), traditional hydrologic routing techniques are insufficient to accurately model and forecast the river dynamics. Hydrodynamic modeling is required, conducted on a daily basis at an hourly computational timestep.

CASCADE

An effective management tool central to the Water Management Team's mission is a dynamic, unsteady flow model called "Cascade". Cascade is a fully implicit model using finite difference approximations of the one-dimensional Saint-Venant differential equations for the conservation of mass and momentum. Cascade is a fully object-oriented program written in C^{++} for Windows, Unix and Linux platforms, developed by Mr. Stan Wisbith of the Water Management Team. The model became operational in the early fall of 2000, replacing an older unsteady flow program called Flowsed. Cascade was designed to be 'plug compatible' with Flowsed, using the same input/output format and based on the same finite difference equations.

We believe that Cascade is unique among other existing unsteady flow models as it is composed of a hierarchy of object classes referenced by a system of linked lists. This arrangement provides an organizational and computational system that is much more flexible than the traditional matrix methods. The resulting model structure very closely parallels an actual river system. The numerical solution scheme combined with the object oriented approach produces solutions extremely quickly, allowing the Team to evaluate multiple reservoir operation alternatives during flood operations to support decision-making.

The physical system modeled by Cascade includes approximately 2,600 km (1,616 mi) of rivers. The main stem portion is comprised of 1,580 km (982 mi) of the Ohio River (Pittsburgh, PA to Cairo, IL) and 173 km (107 mi) of the lower Mississippi River (Cairo, IL to Caruthersville, MO). Tributaries include 70 km (44 mi) of the upper Mississippi River (Thebes, IL to Cairo, IL) and 777 km (483 mi) of other tributaries. Included in the model are 21 locks and dams, 20 on the Ohio River and 1 on the Kanawha River in West Virginia. There are 12 major tributary rivers, including the upper Mississippi River, and 9 minor tributaries. In addition, local runoff is input at 53 locations. The model uses 403 computational points or 'nodes' with an average distance between nodes of approximately 8 km (5 mi). The time step used by Cascade is 1 hour. Figure 2 illustrates the modeled river system.

DATA COLLECTION AND MANAGEMENT SYSTEM

The data collection and management system that supports the model draws upon many separate data sources including the National Weather Service (NWS), GOES satellite downlinks, the OMNI navigation data system, our District offices and the Tennessee Valley Authority (TVA). Precipitation data, including surface observations and gridded hourly Multi-sensor Precipitation Estimates (MPE) are received from the NWS to support the locals runoff modeling. The NWS also provides the Upper Mississippi River observed and forecast flows. Lock and dam headwater and tailwater stages, other river stages, gate openings, and precipitation data are received via OMNI. The four river District offices (Pittsburgh, Huntington, Louisville and Nashville) and TVA provide tributary observed and forecast flows and tributary stages. NWS, OMNI, Districts, and TVA stage and flow data are used by Cascade for establishing initial and boundary conditions. The GOES downlink provides a redundant data source. The data management system is presently based upon the Hydrologic Engineering Center's Data Storage System (DSS). A data server, called FLOWCON, manages the data exchange between the DSS databases and Cascade.

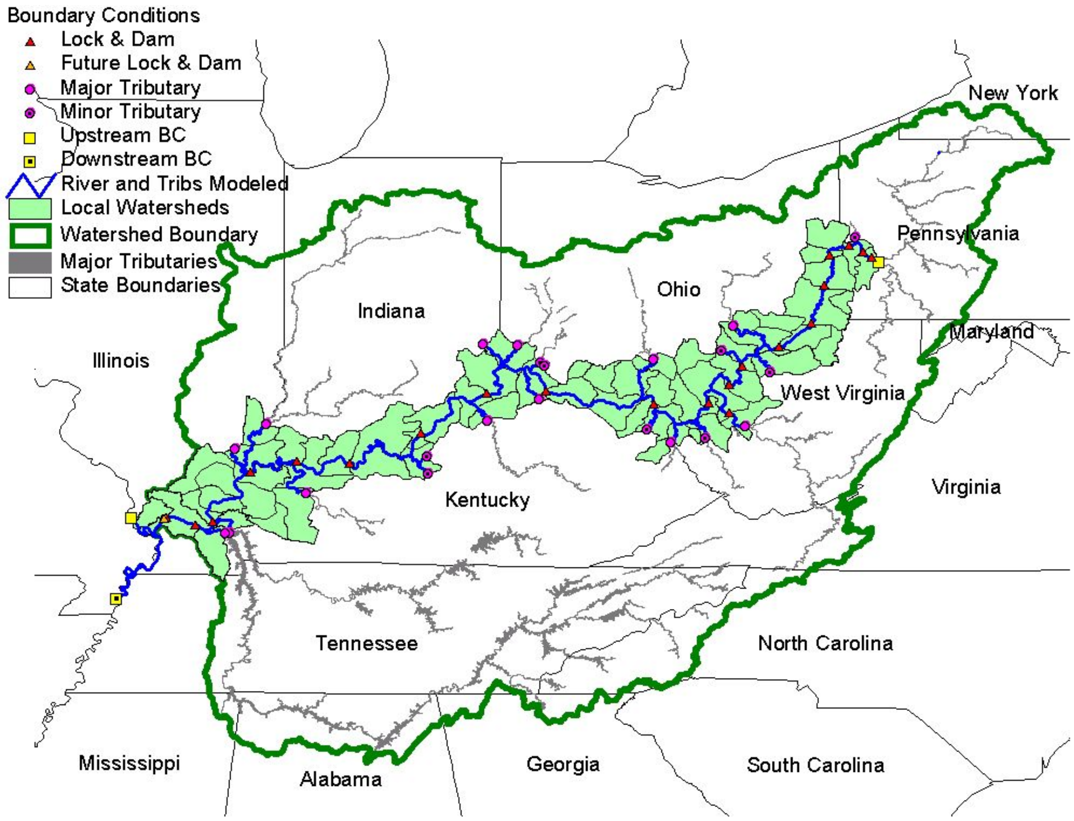

Figure 2 The physical system modeled by Cascade.

OHIO AND MISSISSIPPI RIVER FLOOD CONTROL OPERATIONS

Extensive development of tributary reservoirs between 1937 and 1966 by the U.S. Army Corps of Engineers (USACE) and the TVA necessitated coordinated operation to obtain full flood control benefits on the lower Ohio and Mississippi Rivers. Coordination between the two agencies was legislated in the Flood Control Act of December 1944. Section 7 of this legislation directs the USACE to assume regulation of Tennessee River discharges during flood events on the lower Ohio and Mississippi Rivers. The Water Management Team does this operationally by issuing regulation instructions to TVA for the operation of Kentucky Lake on the Tennessee River. The Team also directs flow releases from Nashville District's Barkley Lake on the Cumberland River, and coordinates releases from its other tributary reservoirs as necessary.

Kentucky Lake reservoir and Barkley Lake reservoir provide significant flood control storage [10 km^3 (8,300,000 acre-ft)] and jointly control runoff from nearly 30% of the Ohio River watershed. Under ideal conditions and experienced operation, Kentucky Lake reservoir alone can enable the reduction of flood crests at Cairo, IL by 0.5 to 1 m (1.5 to 3 ft) and peak flows by more than 5,660 m^3s^{-1} (200,000 cfs) (TVA, 1951). Cairo is located at the junction of the Ohio and Mississippi Rivers (see Figure 1) and is the site of a key indicator gage. The two reservoirs are linked via an uncontrolled navigation canal, requiring their joint operation to control canal velocities.

Most frequently, the Ohio River is the main contributor to lower Mississippi River flooding. Major Ohio River floods generally occur during the fall to spring period. Fall floods are often the result of intense precipitation events from inland-moving tropical systems from the Gulf of Mexico or the Atlantic seaboard. Winter and spring floods are due to extended periods of excessive precipitation and/or rapid snowmelt. Flows at the outlet (1933 to 1999) range over three orders of magnitude, from a low of about 425 m^3s^{-1} (15,000 cfs) to the 1937 flood peak of about 52,380 m^3s^{-1} (1,850,000 cfs) and have an annual average of 7,500 m^3s^{-1} (265,000 cfs) (unpublished USACE computed flows). By contrast, Mississippi flows at Thebes (1933 to 1999) range from about 700 m^3s^{-1} (24,700 cfs) to the 1993 flood peak of 28,200 m^3s^{-1} (996,000 cfs) and have an annual average of 5,920 m^3s^{-1} (209,100 cfs) (USGS, 2002). In addition, large Mississippi floods tend to occur in the late spring and early summer, after the Ohio River flood season. The lower Ohio River flood of record occurred January-February, 1937 with the crest measuring 18.14 m (59.5 ft) at Cairo. It is of interest to note that the remnants of three major tropical systems (Dennis, Katrina, and Rita) passed over the Ohio River watershed in this year of record tropical activity (2005); yet despite wreaking havoc elsewhere, the systems resulted in no appreciable Ohio River or tributary flooding. Moderate rainfall from the systems, ameliorated by watershed drought conditions, resulted in flow increases that remained below flood stages.

The Water Management Team initiates a flood operation when the Cairo stage rises to 10.7 m (35 ft) and is forecast to rise above 12.2 m (40 ft). Simply stated, a flood operation consists of optionally lowering Kentucky and Barkley pool levels to increase available storage ahead of a flood crest, utilizing the available storage during the crest by increasing the pool levels, then eliminating the excess storage and returning the pools to their normal elevations after the crest has past. Generally, the effect of a flood operation is to increase Ohio River flows above natural flows on the rising and falling limbs of the flood hydrograph but to reduce peak flows (and stages) during the crest. The effectiveness of a flood operation depends upon the Tennessee and Cumberland Rivers natural (unregulated) flows being significant contributors to a flood event, accurately forecasting the timing and magnitude of the flood crest, and sufficient available storage in Kentucky and Barkley pools. A flood operation is terminated when Cairo stage falls to 12.2 m (40 ft) and further recession is forecast.

The three primary objectives in the operations of Kentucky and Barkley Lakes for lower Ohio and Mississippi Rivers flood control, in order of priority, are as follows (USACE and TVA, 1999):

(1) safeguard the Mississippi River levee system,
(2) reduce the frequency of use of the Birds Point-New Madrid floodway, and
(3) reduce the frequency and magnitude of flooding of lands along the lower Ohio and Mississippi Rivers not protected by levees.

In the event use of the floodway or overtopping/failure of the Mississippi River levee system cannot be prevented, the reservoirs will be operated with the primary objective of safeguarding the floodwalls at Paducah, KY and Cairo, IL.

Although conceptually simple, the operation of Kentucky and Barkley Lakes to meet the primary and secondary objectives is quite complex. The operation involves balancing the amount of storage utilized with the magnitude of downstream flooding. Storage must be used conservatively at the beginning of a minor flood to ensure adequate available storage should a major flood evolve. Often, flood control strategies must be revised as a flood event unfolds.

Cascade serves as the primary tool used in developing flood control strategies. Alternative reservoir operations' impacts on river stages and flows can quickly be assessed by experienced model operators. The previous day's decision can be evaluated in light of model updates the following day. Flood control operations have been conducted each year following the closure of Kentucky Dam in 1944 with the exceptions of 1953, 1954, 1992 and 2000 when no operations were required. Figure 3 illustrates the effect of a flood control operation at Cairo, IL.

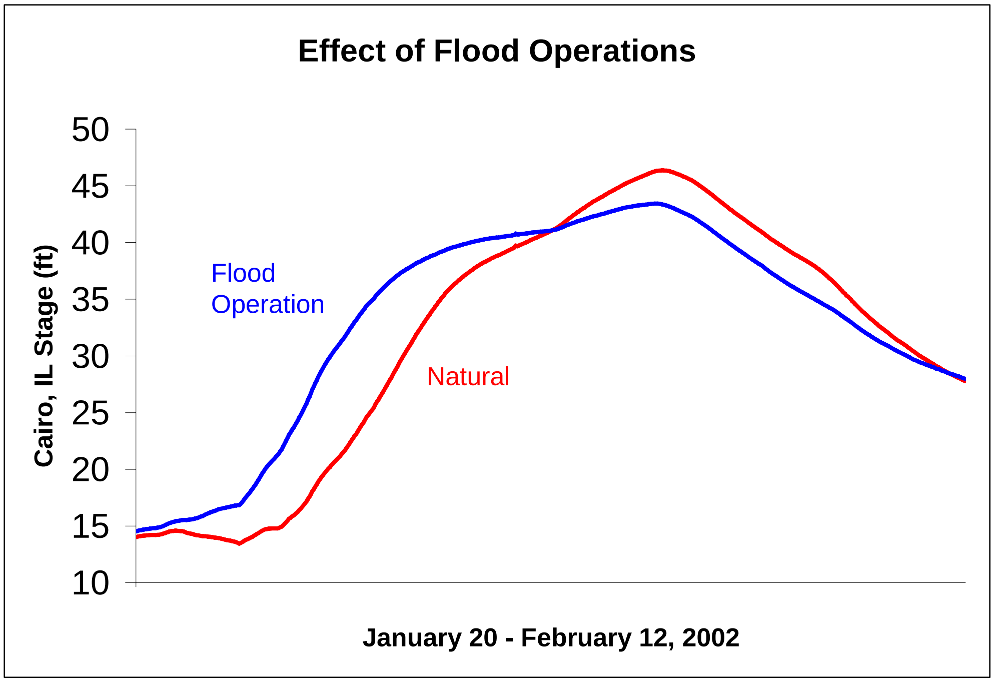

Figure 3 Regulated (blue) versus unregulated or natural (red) stages at Cairo, IL.

OTHER APPLICATIONS

The successful use of Cascade as a decision tool in flood control management has been extended to other useful applications and management situations, described as follows.

Distribution of Flood Damage Reduction Benefits: The Energy and Water Development Appropriation Act of 1984 requires that information on storm events and associated flood damages be published annually. In compliance, the USACE produces an annual report that is submitted to Congress. Within the Great Lakes and Ohio River Division (LRD), each of its Districts submits information on damages prevented by USACE reservoirs, levees and emergency operations. LRD Ohio River tributary projects prevent damages not only on the tributary streams, but also along the Ohio River and lower Mississippi River. Cascade is used as the definitive tool to compute the Ohio and Mississippi Rivers flood control stage reductions and apportion them back to the individual tributary systems.

In order to assess damages prevented along the Ohio and lower Mississippi Rivers, natural river stages (without the effects of reservoir regulation) must be computed for each flood event. The four river Districts and TVA routinely provide "holdouts" (the difference between natural and regulated flows) for each of 23 tributaries (there are 25 tributaries in all, but the Allegheny and Monongahela Rivers and two minor tributaries are combined for model purposes). The holdouts are applied to the observed tributary inflows input to Cascade. Natural stages are then computed throughout the Ohio River's length. The natural stages are passed back to District and USACE Mississippi River Division economists who convert stage reductions to dollar damages prevented along damage reaches. The Districts then distribute the damages prevented back to each individual project (McKee, 2005). This requires a complete Ohio River system model run for each of the 23 tributaries to assess their individual contributions to stage reductions. In Fiscal Year 2004 (coincides with the water year 2004), LRD Ohio River tributary reservoir projects prevented $3,279,220,000 in damages, a record year. The reservoir flood control operations were in response to several winter storms, summer convective events (high precipitation producing thunderstorms), and the remnants of Hurricanes Frances and Ivan. The Pittsburgh District experienced its wettest year on record with more than 143 cm (57 inches) of annual precipitation (Ryan, 2005).

Effects of Lock and Dam Operations during Low Flows: Cascade is successfully used to illustrate the effects of lock and dam operations during low flow conditions. During low Ohio River flows, operations of the locks and dams cause relatively large fluctuations or 'waves' of flow that are magnified by downstream lock and dam operations. Flows from the Tennessee and Cumberland Rivers also fluctuate due to peaking and ponding operations of Kentucky and Barkley Lakes for hydroelectric power generation. These flow fluctuations cause significant safety and operational problems at Dam 52 and Dam 53, the remaining 1929-era wicket dams. Figure 4 illustrates the Cascade modeled flow fluctuations.

An optimization process has been included in Cascade to determine lock and dam operations to minimize the flow fluctuations. This feature is continuing to be developed for use in the future to issue operational guidance. It will become of critical importance with the completion of Olmstead Lock and Dam whose operations are expected to create significant flow fluctuations when the modern high lift wicket dam is raised and lowered.

River Level Forecasting during Lock and Dam Repair Operations: On January 6, 2005, four barges sank at the Belleville Locks and Dam (see Figure 1 for location), affecting the operation of five gates. As river flows naturally diminished, the navigation pool could no longer be maintained, and low river levels halted locking January 19 (Noel, 2005). Cascade proved itself to be flexible enough to model the changing hydraulic conditions and the Water Management Team provided stage and flow forecasts to support the Huntington District's salvage efforts. The salvage effort resulted in restoring all of the gates to operation by the end of January. Cascade's estimates of the time to refill the pool (less than 1 day) also proved reliable. Navigation resumed on February 1. Figure 5 shows some of the obstructed gate bays with the sunken barges wrapped around the gate bay piers.

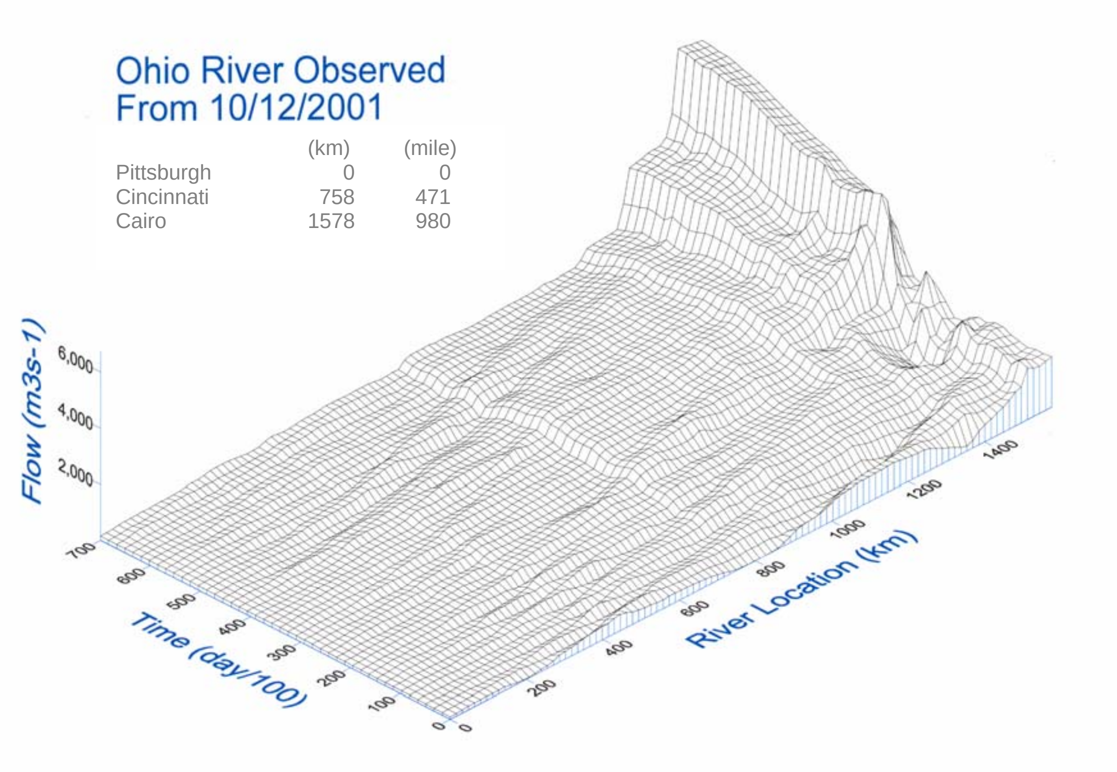

Figure 4 A continuum hydrograph of the Ohio River as hindcast by Cascade.

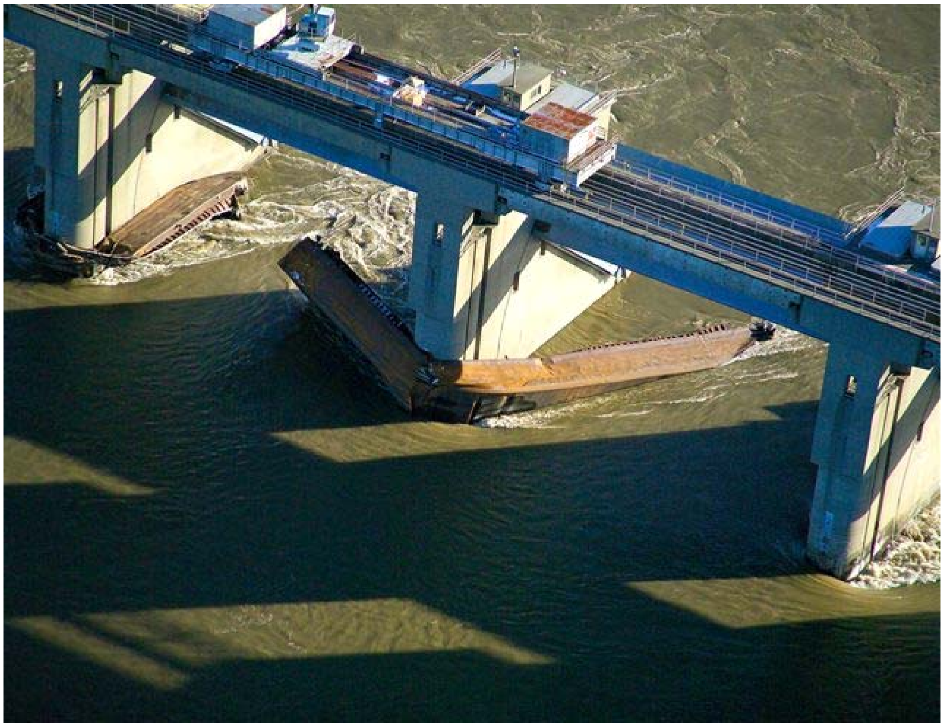

Figure 5 Belleville Lock and Dam with barge obstructed gate bays (photo provided courtesy of the Huntington District).

Hydraulic Data for Contaminant Modeling: Detailed hydraulic output (hourly instantaneous river elevations and flows at 403 model nodes) from the Cascade model is provided to the Ohio River Sanitation Commission (ORSANCO) on a daily basis. ORSANCO is an interstate commission chartered to control and abate pollution in the Ohio River Basin. The Cascade model output is used by ORSANCO to drive their contaminant spill model and for other purposes.

WHAT'S NEXT

USACE is modernizing and standardizing its water management system software with the development and implementation of the Corps Water Management System (CWMS). CWMS is an improved real-time water management framework comprised of standard corporate and centrally supported hardware and software. The Water Management Team is now working to implement CWMS for the Ohio River. Expected improvements are better visualization and geographic display of Cascade model results and observed data, improved estimates and forecast of Ohio River locals runoff, flood inundation mapping, and web dissemination of data and forecasts.

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