Lower Ohio and Middle Mississippi Rivers Flood Management

Abstract

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 our mission, we direct the flow releases from Barkley Lake on the Cumberland River and issue regulation instructions to the Tennessee Valley Authority for the operation of Kentucky Lake on the Tennessee River. An effective management tool in coordinating the reservoir releases is a dynamic, one-dimensional unsteady flow model called "Cascade". Cascade routes Ohio River and upper Mississippi River flows to determine the impact of reservoir releases on flood levels. We present an overview of our water management operations, the complex issues and constraints, and Cascade. We conclude with a summary of recent past flood operations.

Introduction

Initial attempts to manage the Ohio and Mississippi Rivers were for the purpose of improving navigation, followed later by the desire for flood control (Robinson, 1983). During the 1920's, comprehensive river plans that considered benefits from navigation, flood control, hydroelectric power, and irrigation were initiated. In 1927, Congress authorized a massive agenda of surveys to assess major watersheds for potential navigation, hydropower, flood control, and other uses. The 1927 Mississippi River flood, and the Ohio River floods of the 1930's, galvanized the new focus on river management for flood control. The Flood Control Act of 1928 authorized flood control works for the Mississippi River and its junction with the Ohio River (the Mississippi River and Tributaries Project). In 1933, Congress created the Tennessee Valley Authority (TVA) to stimulate regional economic growth via development, including flood control of the Tennessee River, the largest Ohio River tributary. The 1936 Flood Control Act authorized the U.S. Army Corps of Engineers (USACE) to construct flood control reservoirs on many of the other major Ohio River tributaries. The extensive development of tributary reservoirs between 1937 and 1966 by the 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 USACE Great Lakes and Ohio River Division does this operationally by issuing regulation instructions to the Tennessee Valley Authority for the operation of Kentucky Lake on the Tennessee River. The Division also directs flow releases from its Nashville District's Barkley Lake on the Cumberland River, and coordinates releases from its other tributary reservoirs as necessary.

System Description

Figure 1 illustrates the Ohio River watershed, and Figure 2 highlights the river's junction with the Mississippi River. As shown in Figure 2, the Ohio River joins the Mississippi River at Cairo, IL. Upstream of Cairo 74 km and 93 km (46 mi and 58 mi) respectively, the Tennessee and Cumberland Rivers enter the Ohio River. These major tributaries have watersheds that are 20% (Tennessee River) and 9% (Cumberland River) of the Ohio River watershed's 522,102 km^2 (203,946 mi^2). Kentucky Lake reservoir on the Tennessee River and Barkley Lake reservoir on the Cumberland River provide significant flood control storage [10 km^3 (8,300,000 acre-ft)]. Under ideal conditions and experienced operation, Kentucky Lake reservoir alone can enable the reduction of flood crests at Cairo 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). The reservoirs are linked via an uncontrolled navigation canal, requiring their joint operation to control canal velocities.

Below the junction, on the west bank of the Mississippi River is the Birds Point - New Madrid floodway. The floodway consists of front line and back line levees and was built as part of the flood control works authorized by the Flood Control Act of 1928. It encompasses an area of about 544 km^2 (210 mi^2) of natural flood plain, stretching from the junction of the Mississippi and Ohio Rivers to New Madrid, Missouri. During minor to moderate floods, the levees protect the encompassed agricultural land. During major floods, the front line levee maybe crevassed, allowing excess Mississippi River flow to enter the floodway. The diverted flow relieves stress on the downstream levee system and reduces backwater effects at the junction. For Mississippi Project Flood conditions (the USACE flood control design standard), floodway capacity is estimated to be 15,570 m^3s^{-1} (550,000 cfs) (Mississippi River Commission, 2002). The floodway is maintained and operated by the USACE Mississippi Valley Division's Memphis District and has only been utilized during the Great Flood of 1937.

Most frequently, the Ohio River is the main contributor to flooding at the junction. 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

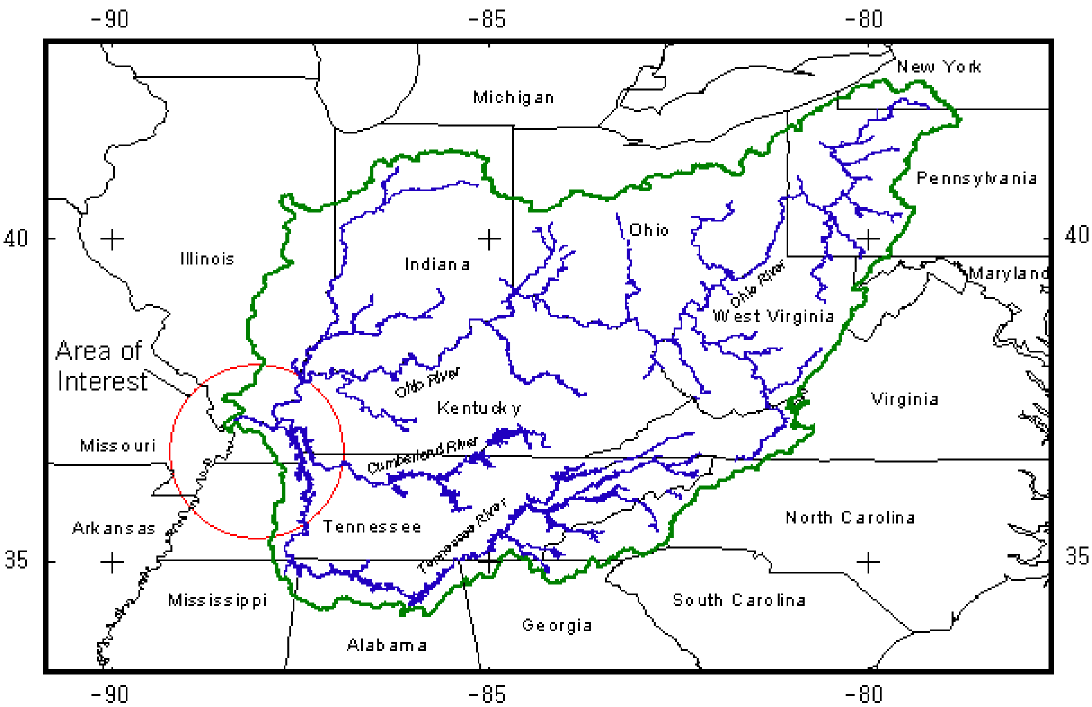

Figure 1. The Ohio River watershed.

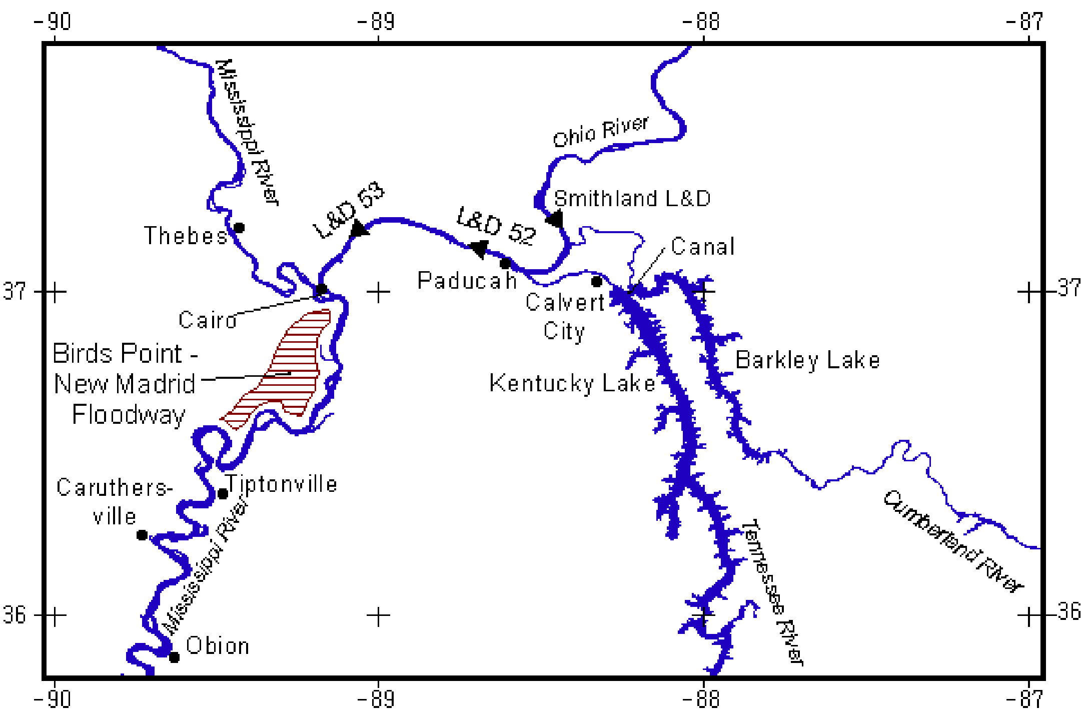

Figure 2. The lower Ohio River and its junction with the Mississippi River.

Mississippi floods tend to occur in the late spring and early summer, after the Ohio River flood season. The Mississippi Project Flood reflects these characteristics with Ohio River flows of 63,700 m^3s^{-1} (2,250,000 cfs) and Mississippi River flows above the junction of 6,800 m^3s^{-1} (240,000 cfs) (Mississippi River Commission, 2002). The Lower Ohio flood of record occurred January-February, 1937 with the crest measuring 18.14 m (59.5 ft) at Cairo.

Flood Operations

The Great Lakes and Ohio River Division 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). (Note that operations are conducted in Imperial Units and that the metric equivalents presented here are approximate.) 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. Figure 3 illustrates Barkley and Kentucky Lakes' normal operating curve and critical elevations. The effect of the 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

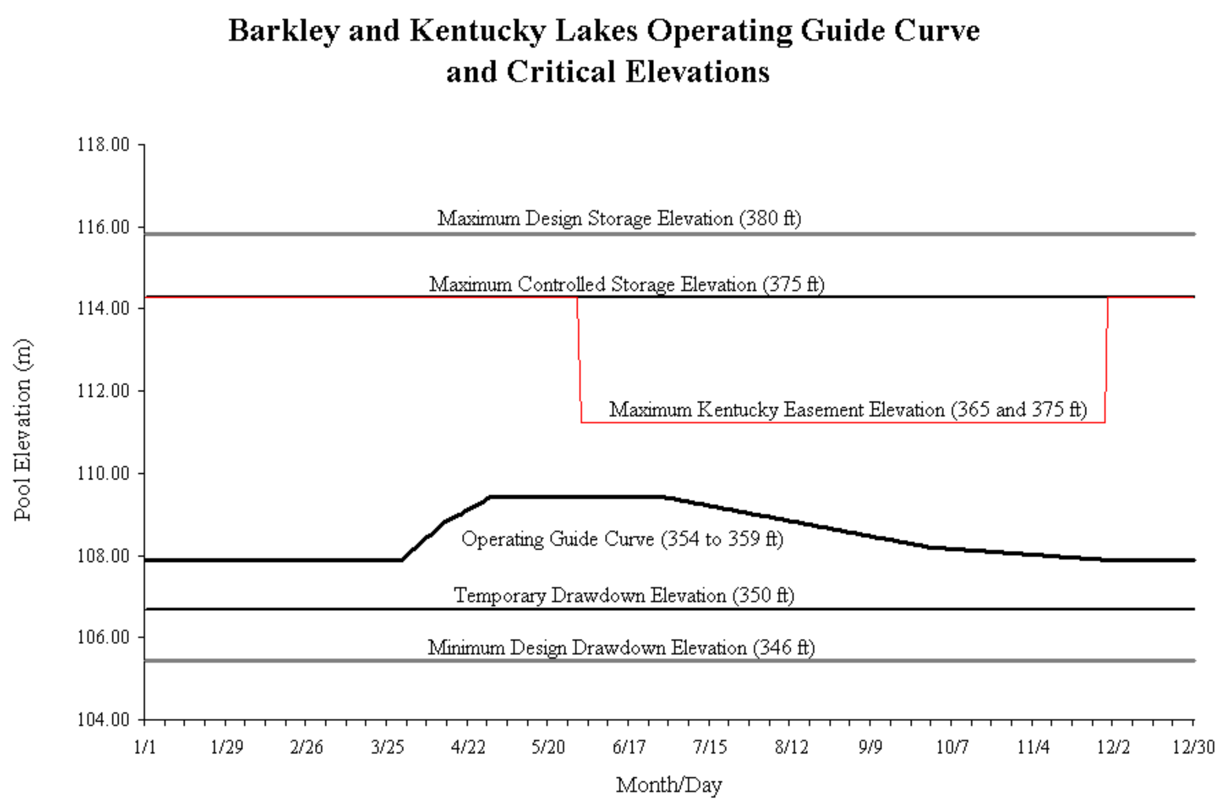

Figure 3. Barkley and Kentucky Lakes operating guide curve and critical elevations.

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 and Cairo.

As a guide to regulation of Kentucky and Barkley Lakes to meet the operating objectives, critical stages as measured at Cairo have been established. The stages are those at specific control points above which breaching or overtopping of protection works is imminent, or damage to unprotected areas becomes serious. The control points and critical stages are shown in Table 1. A stage of 18.3 m (60.0 ft) observed at the Cairo gage is the critical stage for possible operation of the floodway. With a rising stage at Cairo, Mississippi Valley Division directs its Memphis District to implement a graduated response as shown in Table 2.

Secondary objectives in the operations of the Kentucky and Barkley Lakes are (USACE and TVA, 1999):

(1) whenever possible, reservoir releases following flood storage periods should not create secondary crests higher than previously observed at Paducah or other secondary control points,
(2) when rare meteorological conditions cause local flooding along the lower Cumberland, Tennessee and Ohio Rivers but Cairo is below flood stage, operate the reservoirs so as to reduce flooding,
(3) if during the rising limb of the Cairo hydrograph, the Arkansas City stage equals or exceeds 14.6 m (48 ft), reduce reservoir releases to protect the White River backwater levee, and
(4) protect Calvert City industrial development below the 100-year flood level [elevations 104.2-105.2 m (342-345 ft)] downstream of Kentucky Lake.

The secondary objectives are met whenever possible but they do not take precedence over the primary objectives.

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

Table 1. Critical stages at Cairo, IL (USACE and TVA, 1999).

Control Points	Critical Stage - Cairo Gage
Cairo, IL	16.5 m (54.0 ft) - Dec 1 to Apr 30
	13.4 m (44.0 ft) - May 1 to Nov 30
	19.0 m (62.5 ft) - Mississippi Project Flood
	19.8 m (65.0 ft) - Top of Flood Protection
Birds Point-New Madrid Floodway	18.3 m (60.0 ft)
Tiptonville-Obion Extension Levee	16.0 m (52.5 ft)

Table 2. USACE response to rising Cairo, IL stages (USACE and TVA, 1999).

Cairo Stage	USACE Action
15.8 m (52.0 ft)	Memphis District placed on alert.
16.5 m (54.0 ft)	Barges loaded with equipment and explosives.
16.8 m (55.0 ft)	Restrict Kentucky and Barkley releases without regard to easement elevations at direction of Division Commander.
17.1 m (56.0 ft)	To safely clear Mississippi River bridges, barges sail to Birds Point-New Madrid levees.
17.7 m (58.0 ft)	Lowest stage at which floodway can be crevassed if crest of 18.3 m (60 ft) or more is forecast.
18.0 m (59.0 ft)	Explosives planted at Birds Point-New Madrid levees in anticipation of using the floodway if stages continue to rise.
18.3 m (60.0 ft)	If hydrologic conditions warrant, the stage at which explosives could be detonated, allowing water to flow into the floodway.

conservatively at the beginning of a minor flood to ensure adequate available storage should a major flood evolve. As a guide, the Division follows a winter strategy (January 1 to April 1) or a summer strategy (May 1 to December 1) as shown in Table 3. These periods differentiate between agricultural damages during the non-growing and cropping seasons. April and December are transition periods.

The strategies reflect a 1984 Memorandum of Understanding (MOU) between the USACE and TVA establishing that the maximum Kentucky pool elevation generally be limited by seasonal elevation easements (Figure 3). The MOU reserves the right of the Division Commander to exceed the easement elevations when the Cairo stage equals or exceeds 16.8 m

Table 3. Operating guidelines (USACE and TVA, 1999).

Flooding	Cairo Stage, m (ft) Summer	Cairo Stage, m (ft) Winter	Paducah Stage, m (ft)	Kentucky Dam Pool Elevation, m (ft)
Minor	-	12.2≤15.2 (40≤50)	14.6 (48)	≤109.4 (≤359)
Intermediate	12.2≤13.4 (40≤44)	15.2≤16.5 (50≤54)	15.5 (51)	109.4≤111.2 (359≤365)
Major	13.4≤17.4 (44≤57)	16.5≤17.4 (54≤57)	16.2 (53)	111.2≤112.8 (365≤370)
Critical Flooding				
Operate Floodway	17.7≤ 18.3 (58≤60)		18.0 (59)[3]	Full Capacity[3] 114.3 (375)
Miss. Project Flood	19.0 (62.5)			Full Capacity[4] 114.3 (375)
Top of Flood Protection	19.8 (65)		19.4 (63.8)	

[3]Approximate, depends upon flow distribution in the upper Mississippi and lower Ohio Rivers.

[4]If needed, and if conditions are such that additional storms will not cause flooding to approach the Mississippi Project Flood.

(55 ft). The Division Commander may also exceed the easement elevations if the Mississippi River Commission President and the TVA Chief Operating Officer concur that full capacity is required to prevent overtopping/failure of the main stem levees, floodwalls or front-line levees along the Mississippi River and Tributaries Project. When the easements are exceeded, the USACE is responsible for paying all administrative and litigation costs and damage settlements incurred by TVA.

Cascade

An effective management tool in coordinating the reservoir releases and achieving flood stage reductions is a dynamic, unsteady flow model called "Cascade". The model is operated daily and is used to generate 5- and 30-day forecasts of Ohio River stages and flows. The flood operations described previously rely upon the model's Cairo stage forecast. 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. Computations progress along this structure of lists in a semi-autonomous manner.

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.

Boundary data for the model is comprised of main stem, local and tributary inflows and headwater elevations at each of the 21 locks and dams. The main stem and tributary information is received from 3 of the Division's district offices (Pittsburgh, Huntington and Louisville) as well as from the Tennessee Valley Authority and the National Weather Service. The Division computes the local runoff using a simplified runoff model and daily precipitation.

The initial conditions (water surface elevation, channel flows and lateral inflows) required by the unsteady flow model are not known at all nodes. In order to circumvent this problem, we perform the daily model operation by using a two-step process. The first step is to establish starting conditions for the forecast run. This is done by making a hindcast or 'update' run. Starting conditions from the last previous update run are first retrieved from the system database. Then observed boundary conditions are used to run the model to current time. This then establishes current conditions at all nodes. The system state is then saved back into the system database to be used by the forecasting step and the next day's update run. This mode of daily operation was originally started using the Flowsed program and arbitrary steady state starting conditions for October 1983. After running approximately 30 days, the Flowsed model produced realistic values uninfluenced by the initial conditions. Daily updates have been made continuously since that time. Figure 4 illustrates a continuum hydrograph of the Ohio River as hindcast by Cascade. The continuum hydrograph is a 3-dimensional plot of the river flows (vertical axis) along the river's 1,580 km (981 mi) length (x-axis) over several days (y-axis). As shown in Figure 4, Cascade is able to reproduce 'waves' of flow created by the lock and dam operations during low flow conditions.

The second step of the daily operation is the forecast run. The forecast run uses the previously computed system states as initial conditions, and then uses forecasted boundary data to produce the forecast run. During flood operations, Cascade is used to evaluate trial Kentucky and Barkley reservoirs releases and estimate their impact on Ohio and Mississippi river stages. TVA evaluates the impact of the trial releases on Kentucky and Barkley pools and final releases are then coordinated after consideration of the objectives and constraints described previously.

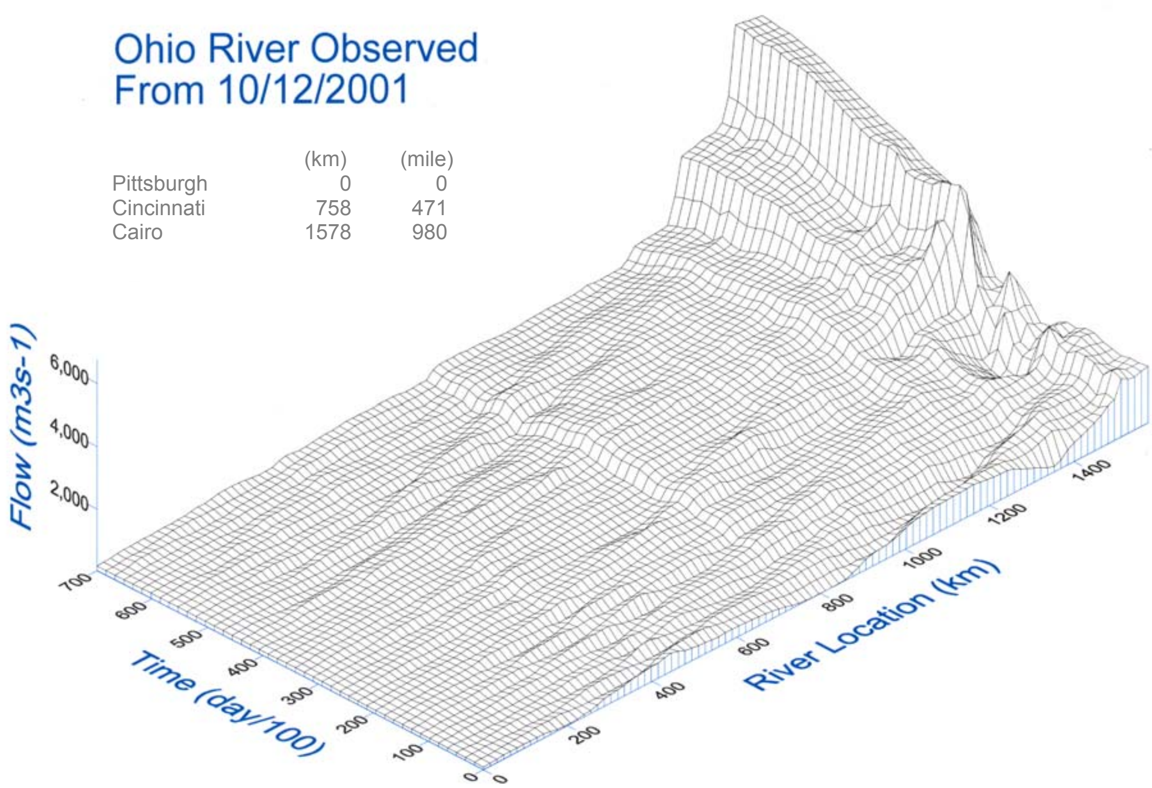

Figure 4. A continuum hydrograph of the Ohio River as hindcast by Cascade.

Past Events

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. The Division computes Ohio River stage reductions and prevented damages (lower Ohio and middle Mississippi Rivers) using stage-damage relationships and the routing of regulated and natural flows. As mandated by the Energy and Water Appropriation Act of 1984, these values are reported annually to Congress. Total prevented damages for 1984 through 2001 due to the combined operation of Kentucky and Barkley Lakes are $343,911,000 (USACE, 2001). Table 4 summarizes the Cairo stage reductions and prevented flood damages along the Ohio and Mississippi Rivers for the 6 most significant events during this period.

The most recent major flood operation occurred in late February through early April 1997. On February 26, the Cairo stage reached 12.8 m (38.8 ft) due to December through February precipitation nearly 200 percent of normal. Mississippi River flows at Chester, IL were 14,380 m^3s^{-1} (508,000 cfs) and Ohio River flows at Cairo, IL were 10,330 m^3s^{-1} (365,000 cfs). Kentucky Lake and Barkley Lake pool elevations were 108.1 m (354.66 ft) and 108.0 m (354.35 ft), respectively. A flood operation was initiated as the Cairo stage was forecast to exceed 12.2 m (40 ft) the following day. Moderate rainfall on February 27-28 over Indiana, Illinois and Tennessee caused flooding in the Wabash basin and increased flows on the Tennessee River. Over March 1-3, thunderstorms repeatedly tracked over northern Kentucky and southern Ohio dropping 150 to 300 mm (6 to 12 inches) of rain (National Weather Service, 1998).

As a result of this extraordinary rainfall, the Cairo stage rose and crested at 17.1 m (56.21 ft) on March 12, and remained near this stage until March 17 when the flood wave began to recede. A peak flow of nearly 33,270 m^3s^{-1} (1,175,000 cfs) occurred during this period. Several subsequent moderate rainfall events slowed the recession. Kentucky and Barkley releases were increased ahead of the flood wave's arrival at Cairo from a combined 3,200 m^3s^{-1} (113,000 cfs) to a maximum of about 13,590 m^3s^{-1} (480,000 cfs) on March 5-6. Even with these releases, the Kentucky and Barkley pools rose to about 109.4 m (358.8 ft) by March 6, more than 1.2 m (4 ft) above normal winter pool (Figure 3). Releases were then progressively reduced to about 6,510-6,800 m^3s^{-1} (230,000-240,000 cfs) and held steady over March 12-19 as the flood wave reached Cairo and passed. Kentucky and Barkley pools rose to about 111.6 m (366.1 ft) on March 15 and then declined slightly to about 111.3 m (365.1 ft) on March 19. Storage in the Kentucky and Barkley reservoirs was then reduced as the flood wave recessed such that by the end of the operation, the pools were near 108.4 m (355.6 ft). On April 7, the Cairo stage fell to 12.1 m (39.80 ft) and the flood operation ended. The operation successfully prevented the need to utilize the Birds Point-New Madrid Floodway by reducing the peak natural stage by 0.7 m (2.26 ft) and prevented flood damages of $102,881,000 (Table 4).

Table 4. Cairo stage reductions and prevented flood damages due to the combined operation of Kentucky and Barkley Lakes (USACE, 2001).

Year	1991	1993	1994	1995	1997	1998
Cairo Stage, m (ft)	15.8 (51.90)	14.8 (48.64)	16.6 (54.31)	17.0 (55.67)	17.1 (56.21)	15.6 (51.26)
Reduction, m (ft)	0.6 (1.87)	0.8 (2.68)	0.8 (2.68)	0.6 (1.92)	0.7 (2.26)	0.8 (2.58)
Damages Prevented ($1,000)	36,073	34,769	53,811	34,388	102,881	22,196

Summary

The Great Lakes and Ohio River Division Water Management Team of the U.S. Army Corps of Engineers (USACE) has successfully reduced water level stages along the lower Ohio and middle Mississippi Rivers during significant flood events. Through the management of Kentucky Lake and Barkley Lake reservoir storage and releases, stages at Cairo, IL have been reduced up to 0.8 m (2.68 ft) with damages prevented totaling $343,911,000 during 1984-2001. Cascade, our unique unsteady flow model of the Ohio River and its junction with the Mississippi, is an important tool used to forecast flood events and coordinate reservoir releases.

Acknowledgements

This paper is contributed in recognition of Mr. Ronald Yates and Mr. Michael Tatum for their dedicated service to Ohio and Mississippi Rivers flood management. Mr. Yates and Mr. Tatum recently retired from the USACE Great Lakes and Ohio River Division after 33 and 28 years of service, respectively.

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