

Application of an Optimization/Simulation Model for Real-Time Flood-Control Operation of River-Reservoirs Systems

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Abstract Application of an optimization/simulation model for the simulated real-time flood control for river-reservoir systems to the catastrophic May 2010 flood on the Cumberland River at Nashville, Tennessee is described. The optimization/simulation model includes five major components, including a hydrologic rainfall-runoff model, a hydraulic unsteady flow model, a short-term rainfall forecasting model, a reservoir operation model, and a genetic algorithm optimization model. The model application revealed that the reservoir upstream of Nashville was more contained and that an optimal gate release schedule could have decreased the floodwater levels in downtown Nashville below the 100-year flood stage. The application is for demonstrative purposes only, but does reflect the suitability of the optimization/simulation model for real-world application.

Keywords Flood control operation · Real-time operation · Optimization · Genetic algorithms · Rainfall-runoff models · Unsteady flow routing · Rainfall forecasting · Flood forecasting · Reservoir operation · Cumberland River system

1 Introduction

Che and Mays (2015) and Che (2015) presented the development of an optimization/simulation model that can be used to help make real-time operation decisions (release schedule

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of reservoirs) for a river-reservoir system during flooding conditions by incorporating a real-time precipitation and stream flow data and forecasted rainfall throughout the system. The known real-time rainfall input is used as the actual rainfall up to the time of decision-making. The model consists of (1) a short-term rainfall forecasting model for generating rainfall over the next time period for which decisions on reservoir releases (gate operations) are made based upon using NEXRAD data and/or real-time rain gage data, (2) a hydrologic rainfall-runoff model (HEC-HMS) (USACE 2000, 2010b), (3) an unsteady flow routing model for the river-reservoir system (HEC-RAS) (USACE 2010a), (4) a reservoir operation model for each of the dams in the system, and (5) an optimization model (genetic algorithm) that uses projected information from the rainfall-runoff and the unsteady flow routing model for determining reservoir releases. The overall model uses MATLAB to communicate among the model components.

Che and Mays (2015) describe this model in detail along with an example application to test the development of the modeling framework, also illustrating the use of the model. Each model component and its interface in the modeling framework was tested for quality assurance. Che and Mays (2015) also presented a detailed summary of previous optimization/simulation models reported in the literature, including a state-of-the-art summary of flood operation/forecasting.

The purpose of the optimization/simulation models is to determine the releases of reservoirs in a river-reservoir system which minimizes flood stages and/or flood discharges subject to following constraints: (a) hydrologic constraints such as precipitation-watershed runoff relationships solved by HEC-HMS; (b) unsteady flow equations and other relationships which describes the flow in varies components in a river-reservoir system solved by HEC-RAS; (c) maximum and minimum allowable reservoir releases and flow rates at specified locations; (d) maximum and minimum allowable water surface elevations at specified locations in the system, including reservoir surface elevations; and (d) rules of operation, water level targets, storage capacities, limitations. The state variables used in the optimization/simulation model are: water surface elevations at control points and discharges at all computational points. The control or decision variable are the reservoir (spillway) gate openings (releases) at all reservoirs.

Che and Mays (2015) applied the optimization/simulation model to a simple example using the objective function to minimize the discharges $Q_{i,t}$ at all control points i at all times,

$$\text{Min } Z = \sum_{i=1}^I \sum_{t=1}^T [C_i Q_{i,t}].$$

Demonstration of the optimization/simulation model reported herein was performed using the May 2010 flood event on a portion of the Cumberland River system upstream of Nashville, Tennessee. A different objective function of minimizing flood stages at the control points in Nashville is used in the application for the Cumberland River described herein. The objective function to minimize the maximum stage considering all control points i at all-times t is:

$$\text{Min } Z = \text{Min}(\text{Max } h_{i,t}) \quad (1)$$

in which $h_{i,t}$ are the respective stages.

2 Cumberland River Basin

This paper describes the application of the new optimization-simulation model (Che and Mays 2015) for the real-time operation of river-reservoir systems. The application was to a portion of

the Cumberland River upstream of Nashville, Tennessee for the May 2010 flood event. The Cumberland River Basin lies entirely within the states of Kentucky and Tennessee and has a total area of 17,914 mile², of which 10,695 mile² (60%) are in the state of Tennessee as shown in Fig. 1. The topography of the basin varies from rugged mountains in the eastern upstream portion to rolling low-plateaus in the western, or downstream sector. Elevations range from 4150 ft above mean sea level (msl) in the Cumberland Mountain to 302 ft in the pool at the mouth of the river (USACE 2010c).

The U.S. Army Corps of Engineers (USACE) Nashville District maintains and operates five projects on the Cumberland River main stream and five projects on its tributaries. The five USACE tributary projects, which are Dale Hollow, Center Hill, Martin's Fork, Laurel, and J. Percy Priest are congressionally authorized for flood risk management (USACE 2010c, 2012); whereas Old Hickory, Cordell Hull, upstream of Nashville are not.

In May 2010, portions of the Cumberland River Basin experienced a 36-h rainfall that produced record flooding (USACE 2010c, 2012). Officials estimated the two-day storm to be far greater than a 1000-year rainfall event. Catastrophic flooding occurred in greater Nashville, western Kentucky, and central Tennessee during May 1 to 4, 2010. The rainfall event began with heavy rainfall on Saturday, May 1 followed by second period of heavy rainfall on Sunday May 2nd, resulting in flooding to record levels in Nashville (USACE 2010c, 2012; NWS 2011).

Throughout that weekend into the following Monday morning, the Cumberland River at Nashville gage rose more than 33 ft, cresting at 52 ft on Monday night and Tuesday May 3rd. This crest stage was approximately 4 ft higher than any other previous peak, the highest of which was 48 ft in 1975 and 10 ft higher than the original forecast issued Sunday morning.

Consequently, record releases were made at the USACE projects in the Cumberland River Basin, including those at Cordell Hull, Old Hickory (just upstream of Nashville), Cheatham, and Barkley. Sadly, 26 people lost their lives due to flooding, and property damage estimates in Greater Nashville alone were over \$2 billion (USACE 2010c, 2012). Figure 2 shows the flood discharges and stages illustrating the severity of the flood event that showed that the flood stage was well above the major flood stage at the Nashville gage.

2.1 Operation of the old Hickory dam during the Flood Event

The primary control location for the release from the Old Hickory Dam is Nashville, Tennessee, which is about 25 miles downstream of the dam (USACE 2010c).



Fig. 1 Cumberland River Basin showing location of Nashville, Tennessee and the dam projects (Martins Fork, Laurel River, Wolf Creek, Dale Hollow, Center Hill, and J. Percy Priest) and the lock and dam projects (Cordell Hull, Old Hickory, Cheatham, and Barkley). There is no flood risk management at Laurel River, Cordell Hull, Old Hickory, and Chatham. (USACE 2010c)

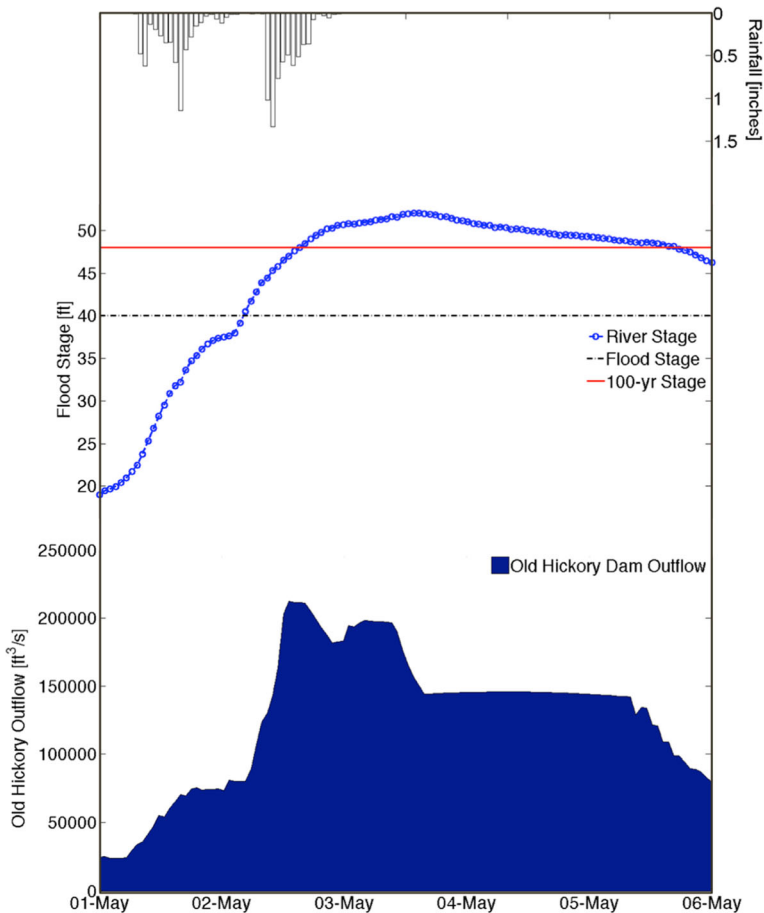


Fig. 2 Discharge and flood stage as a function of time in Nashville, Tennessee during the April 29 – May 7, 2010 event. (USACE 2010c)

Flood flows through Nashville is directly affected by the releases from the two immediate upstream reservoirs, Old Hickory and the J. Percy Priest. The J. Percy Priest is a flood control structure having a much greater capacity than Old Hickory. The J. Percy Priest dam is located on the Stone River, which is a tributary river to the main Cumberland River. Neither the Old Hickory nor the Cordell Hull (upstream of Old Hickory) have any significant flood control storage and therefore are not flood risk management projects. The local drainage area to Cordell Hull is 1372 mi² and the local drainage area for Old Hickory is 1404 mi², making the total uncontrolled drainage area upstream of Old Hickory for major floods to be 2776 mi². Keeping in mind that Nashville is downstream of Old Hickory, which basically says that the uncontrolled drainage area for Nashville is well over 3000 mi². The total drainage area to Old Hickory is 11,647 mi².

Old Hickory is permitted to have pre-flood drawdown prior to the arrival of the flood waters with certain guidelines for operation during a storm event (USACE 2010c, 2012). For instance, according to the Old Hickory Water Control Manual, the six gates must be opened uniformly as soon as the headwater rises above 447 ft. as shown in Table 1 (USACE 1998).

Flood operations at the Old Hickory Dam are based on the peak stage and the rate of water level rise in Nashville. The Old Hickory Dam is operated in conjunction with the J. Percy Priest to limit the increase in combined releases to 5000 cfs/h, which in effect limits the rate of rise at Nashville to about one foot per hour. If the headwater elevation in Old Hickory reaches 450 ft. (top of the surcharge pool) then releases can be increased as necessary to maintain the water surface at 450 ft. During the May 2010 event the maximum headwater elevation of Old Hickory reached 451.45 ft. (USACE 2010c) resulting in very large releases from Old Hickory (see Fig. 2). According to the USACE (2010c) After-Action Report “Old Hickory set a new pool record and came within 6.6 inches of overtopping the upstream lock wall.” This obviously emphasizes the severity of the manner in which the system was operated.

The Cumberland River basin flood control system above Nashville, which is by far the largest drainage in the basin, is operated to limit the flow at Nashville to a maximum of 90,000 cfs (stage of 35 ft) during flood season and 54,000 cfs (stage of 26 ft) during the crop season. Crop season is generally defined as April 15 through December 15, however, actual conditions in the fields are more important than these dates. Flood season is defined as any time other than crop season, but is generally December 15 through April 15.

Hourly changes in combined spillway releases from the Old Hickory Dam and the J. Percy Priest are limited to a total of 5000 cfs for increase and 10,000 cfs for decrease. It is desirable that the limit for decrease is 5000 cfs per hour as well, and whenever practical, this limit is directed by the USACE Nashville District Water Management Section. The purpose of these restrictions is to reduce sudden surges downstream, reduce stream bank station erosion, and minimize impacts on navigation.

According to the control manual, as flooding progresses, the Old Hickory discharges are increased and flow rates in Nashville are allowed to reach control levels before any storage is used. Once the control flows are reached, the J. Percy Priest discharge is then reduced to maintain the control flow in Nashville. If the Nashville control flow cannot be maintained, then the flood storage of Old Hickory is utilized (USACE 1998).

Prior to the May 2010 storm event, the U.S. Corps of Engineers did not conduct any substantial pre-flood drawdown from the Old Hickory. As seen in Fig. 2, there were not any significant releases from the Old Hickory Dam until the afternoon of May 1, even though the storm had started in the early morning hours that day. The dam releases increased substantially on May 2, as the storm entered the second major phase of the event. Towards the end of the storm event, the Old Hickory releases were nearly 200,000 cfs, and the reservoir levels were close overtopping the dam, which could have resulted in a complete failure of the Old Hickory (USACE 2010c, 2012). Throughout the event, there was minimal application of real-time strategies for

Table 1 Old Hickory Dam spillway releases for various headwater levels (USACE 1998)

Headwater	Minimum	Minimum
Elevation (feet)	Gate Opening (feet)	Spillway Discharge (cfs)
445	0	0
446	0	0
447	0	0
448	1	7500
449	2	14,880
450	3	22,440

the reservoir's management, and there was minimal utilization of rainfall and flood forecasting information.

Figure 3 shows a comparison of actual flood stage in Nashville during the May 2010 event and the simulation of a hypothetical condition that Old Hickory did not exist. The conclusion here is that the fact that Old Hickory existed and the manner in which it was operated during the May 2010 flood event caused greater flood elevations than if the dam did not exist. During the May 2010 event the maximum headwater elevation of Old Hickory reached 451.45 ft., within 6.6 in. of overtopping the upstream lock wall, emphasizing the severity of the system operation and the need for a real-time optimal operation model.

3 Optimization/Simulation Model Components

3.1 HEC-HMS Model

Both the HEC-HMS and the HEC-RAS models for the Cumberland River system were developed by the U.S. Army Corps of Engineers. The hydrologic model HEC-HMS covers approximately 14,160 mi² of the Cumberland River Basin, starting from the headwater of the basin, and ends at the Cheatham Dam, 32 miles downstream of Nashville, Tennessee. The HEC-HMS model consists of 69 sub-basins and 66 reaches; basin areas range from 7 mi² to 1700 mi², with the average area of 205 mi². The hydrologic process methods used in the Cumberland River Basin HEC-HMS model include: the Clark unit hydrograph method, Muskingum method for channel routing, deficit constant method for losses, and bounded recession method for base flow. The high resolution gridded rainfall forcing used in the hydrologic model HEC-HMS to simulate the May 2010 storm event is a product generated by Next-Generation Radar (NEXRAD). The HEC-HMS Cumberland River Basin model has been validated with a model efficiency of 0.853.

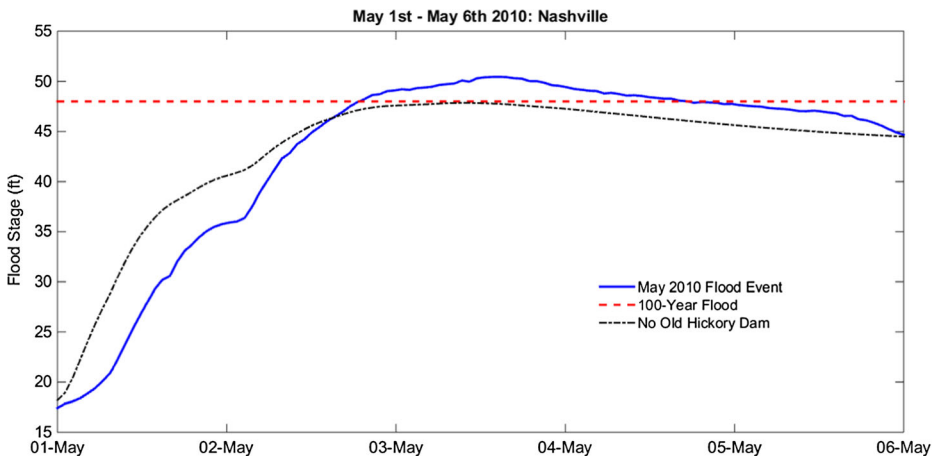


Fig. 3 Comparison of actual flood stage in Nashville during the May 2010 event and the hypothetical condition that Old Hickory did not exist

3.2 HEC-RAS Model

The HEC-RAS model for the Cumberland River application contains 801 computational nodes. These include 675 cross-sections, 1 bridge, 8 inline structures, and 117 lateral structures. The HEC-RAS model also has been calibrated and validated for the May 2010 storm event. Calibration parameters are mainly the roughness values. The roughness values are increased in locations where unreasonable high velocity flows were detected in the model. The root mean square error (RMSE) at the Nashville for this HEC-RAS model is 14,550 cfs, which is acceptable considering the magnitude of the storm event and the nature of unsteady flow simulation. The root mean square error (RMSE) at the Nashville stage for this simulation is 1.777 ft. The validated model efficiency for the HEC-RAS model is 0.890, implying that the unsteady flow model is well calibrated and validated.

3.3 Short-Term Rainfall Forecasting

The short term rainfall forecasting procedure, explained by Che and Mays (2015), was utilized using both NEXRAD and rainfall depths measured using rain gauges for the recent past. For this application, an approach using area-weighted rainfall forecasting was utilized to make the rainfall forecasting process efficient. First, for each grid cell, rainfall up to current time step, t , was extracted to form a hyetograph (a time series). For each subbasin, the weights of grid cells, w , that are overlaying the subbasin were calculated using ArcGIS 10.1. Then, a time series of rainfall up to current time t for the i -th sub-basin can be determined by:

$$P_{i,t} = \sum_j w_{i,j} P_{j,t} \quad (2)$$

where $P_{i,t}$ = time series of rainfall up to current time, t , for the i -th subbasin, $w_{i,j}$ = weight of the j -th grid overlaying the i -th subbasin, and $P_{j,t}$ = time series of rainfall up to current time, t , for the j -th grid.

4 Application to Cumberland River System

The optimization/simulation model has been applied to a portion (see Fig. 4) of the large river-reservoir system, the Cumberland River basin. The objective of the optimization/simulation model was to minimize the peak flood stage at Nashville (Eq. 1), subsequently to keep the flood stage in downtown Nashville under the 100-year stage of 48 ft during the entire simulation period. The rules of reservoir operations were set in the model according to the water control manual by USACE.

The simulation process for the river/reservoir system in Fig. 4 starts with the hydrologic modeling using HEC-HMS, which simulates the Cumberland River Basin rainfall-runoff process. The HEC-HMS model includes all sub-basins and reaches upstream to the Cordell Hull Reservoir, at which the reservoir inlet node is the outlet node of the HEC-HMS model. After the HEC-HMS model generates the Cordell Hull reservoir inflow hydrograph, the inflow hydrograph is sent to the Cordell Hull reservoir operation and optimization models for determining its operation. After the gate release decisions are determined, the information becomes the input of the unsteady flow HEC-RAS model for downstream hydraulic routing.

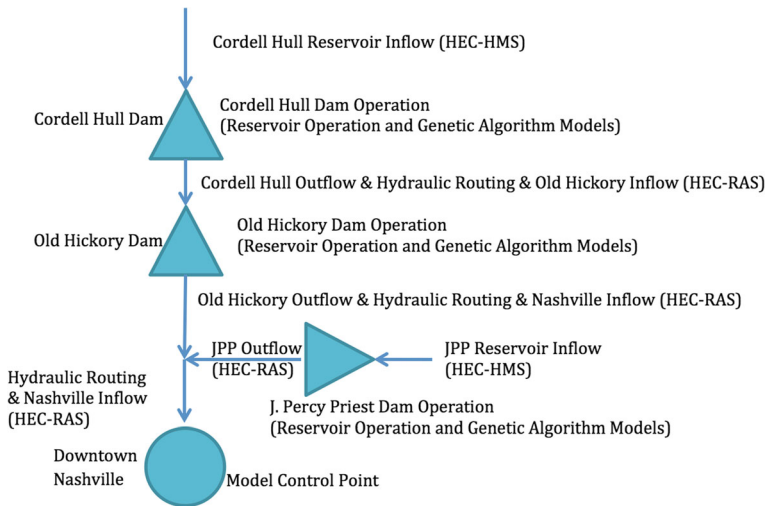


Fig. 4 Schematic of the portion of the Cumberland River Basin used in the optimization/simulation model application

Once the flow information reaches the Old Hickory Dam, the inflow hydrograph enters the Old Hickory reservoir operation and optimization models for its operation determination. Similar to the process at the Cordell Hull Dam, once the gate release decisions are determined at the Old Hickory Dam, the information becomes the input of the unsteady flow HEC-RAS model for downstream hydraulic routing. Similar procedures are applied to the J. Percy Priest Dam. The decision variables of the optimization/simulation model are determined by the condition at the system control point, downtown Nashville.

The above process is repeated if the objective is not met, or the processes move to the next forecasting period if the objective has been met. For the Cumberland River Basin application, the objective is to keep the peak flood levels at downtown Nashville below the 100-year level throughout the May 2010 storm event. In other words, the optimization/simulation model would keep the flow rate at the model control point below Q_{100} at all time, while satisfying all the model constraints. As seen in Fig. 2, which depicts the flood stage condition in Nashville during the May 2010, the 100-year flood stage (the red-solid line) is 48 ft and the corresponding flow rate is $Q_{Nashville, 100} = 172,000$ cfs. The optimization/simulation was used to determine the optimal operation at the Cordell Hull Dam and Old Hickory, to maintain the flood stage at Nashville under the 100-year level.

4.1 Model Results and Discussion

First, the operation at the Old Hickory Dam is discussed here. The simulated optimal gate operation at the dam is compared to the actual gate operation by the USACE during the event. Second, the flood condition at model control point, downtown Nashville, is analyzed. Comparisons between the actual flood condition and the flood condition simulated by the optimization/simulation model are presented and discussed. As a reminder the decision variables of the optimization/simulation model are the gate openings at the two dams as a function of time.

Due to the severity of the May 2010 storm event in the Cumberland River Basin, the optimization/simulation model would determine the gate releases on hour-to-hour basis. For each short-time forecasting period, which is the next two hours, the operation of the following two hours is determined. Figure 5 shows the gate operation determined by the optimization-simulation model, and Fig. 6 shows the Old Hickory Dam releases determined by the optimization-simulation model.

To quantitatively compare the operation by the U.S. Army Corps of Engineers during the flood event and the operation results of the optimization-simulation model, Fig. 7 illustrates the cumulative releases for two operations. For the actual U.S. Army Corps of Engineers operation, the total cumulative release from the Old Hickory Dam was 1,198,660 acre-ft. as compared to the total cumulative release of 1,160,631 acre-ft. from the Old Hickory Dam using the optimization/simulation model results.

The optimization/simulation model made the decisions to release water well in advance of the real storm, thus under this operation, less water was released. Due to the early response from the Old Hickory under the optimization/simulation model operation, the cumulative release was actually well above the operation under the U.S. Army Corps of Engineers operation until in the later of May 3rd, 2010, which the two cumulative releases were equal. Up to this point, the actual storm has ended (see Fig. 2); the cumulative release from the Old Hickory Dam under the optimization/simulation operation was 261,849 acre-ft. more than the cumulative release by the U.S. Army Corps of Engineers.

Figure 8 depicts the Old Hickory headwater and tailwater stage levels during the May 2010 storm event under both the U.S. Army Corps of Engineers and the optimization-simulation model operations. Under the U.S. Army Corps of Engineers operation, there was a huge difference (approximately 40-ft) in maximum and minimum tailwater stage between the start of May 1st and the end of May 3rd. Under the optimization/simulation model operation, the difference between the maximum and minimum tailwater stage was less than 30-ft and well controlled, also the tailwater stage has never reached as high as the condition under the U.S. Army Corps of Engineers operation. Figure 10 also illustrates that, the optimization/simulation model allowed emptying the reservoir early as compared to the U.S. Army Corps of Engineers' operation, this can be seen by the decrease of the headwater level.

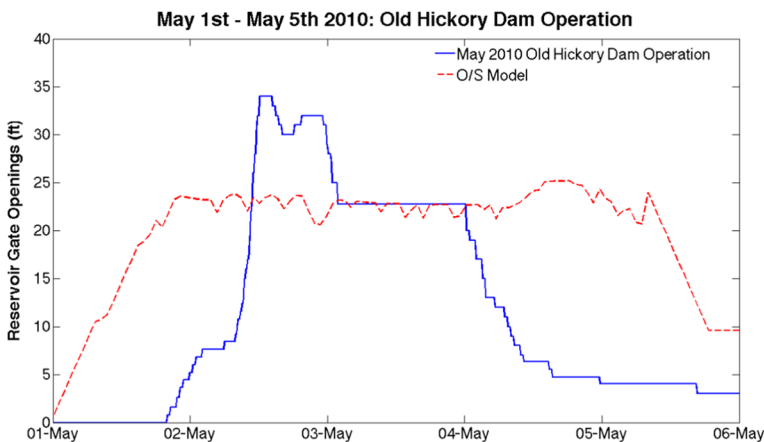


Fig. 5 Optimal Operation at the Old Hickory Dam by the Optimization/Simulation Model

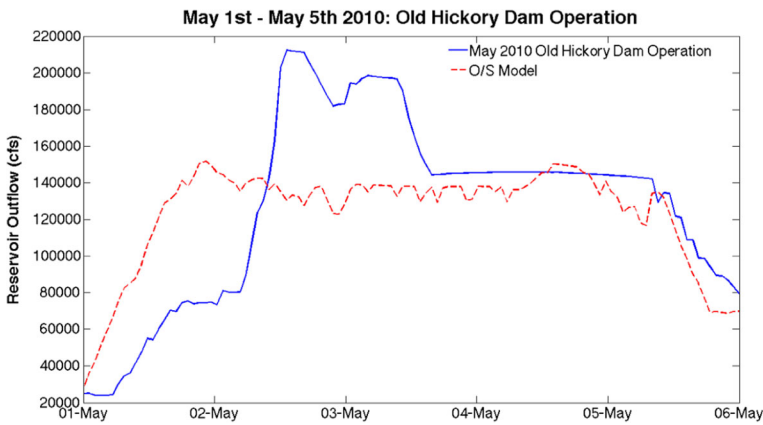


Fig. 6 Old Hickory Dam Releases by the Optimization/Simulation Model

The flow condition at downtown Nashville, being the model control point, is the most important factor of the optimization/simulation model. Figure 9 shows the flood stage at Nashville during the actual May 2010 storm event and the condition under when optimization/simulation operating rules were implemented. The objective of the optimization/simulation model was to minimize the flood stage at Nashville and the stage was constrained to maintain the flood stage at Nashville under the 100-year stage during the entire simulation period. Figure 9 illustrates that for most of the simulation period, the flow stage at Nashville is well under 100-year stage of 48 ft. The highest flood stage at Nashville under the optimization/simulation model operation was 47.26 ft, although this water surface level was close to the 100-year level, but would not have caused the devastating flooding that occurred during the May 2010. Figure 10 shows the flow rate at downtown Nashville during the actual May 2010 storm event and the condition when optimization/simulation operating rules were applied. The 100-year flow rate at the control point is $Q_{Nashville, 100} = 172,000$ cfs, and the maximum flow condition at Nashville under the optimization/simulation model was $Q_{Nashville, max} = 171,076$ cfs, and for the majority of the simulation period, the flow rate was well managed and controlled.

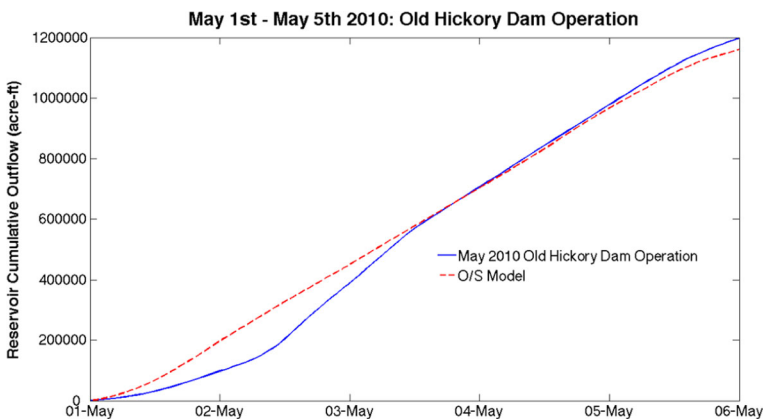


Fig. 7 Cumulative Old Hickory Dam Releases by the Optimization/Simulation Model and the USACE

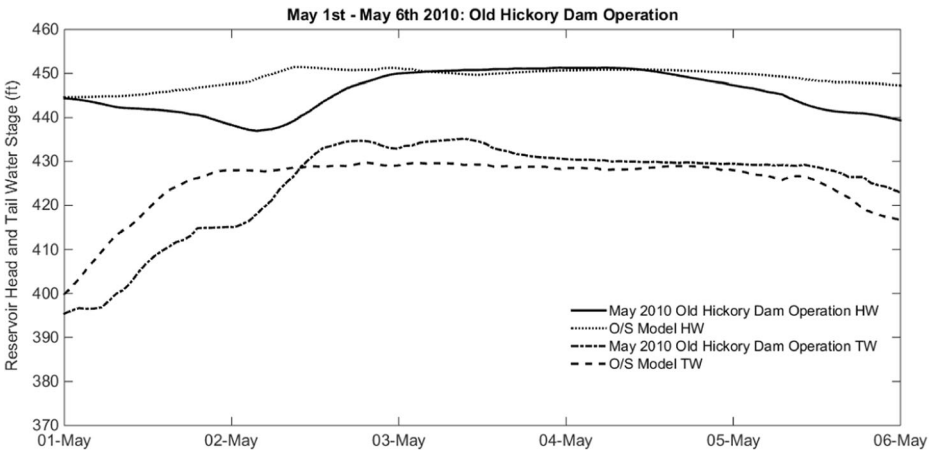


Fig. 8 Old Hickory Dam HW and TW Stage Level by the Optimization/Simulation Model and the USACE

5 Summary and Conclusions

An application of a recently proposed model is presented, aiming at the real-time operation optimization of a river reservoir system under flooding condition. It epitomizes forward-thinking and efficient approaches to reservoir operations during flooding events. The optimization/simulation includes five major components, including a mix of hydrologic and hydraulic modeling, short-term rainfall forecasting, and optimization and reservoir operation models. The optimization/simulation model is designed for ultimate accessibility and efficiency. The optimization model is based upon a genetic algorithm, which has the capability to simultaneously search for multiple optimal solutions. The dynamics of the river are simulated by applying an unsteady flow-routing method, HEC-RAS. The rainfall-runoff simulation uses the U.S. National Weather Service NexRad gridded rainfall data, since it provides critical information regarding real storm events. The short-term rainfall-forecasting model utilizes a stochastic method. The reservoir-operation is simulated by a mass-balance

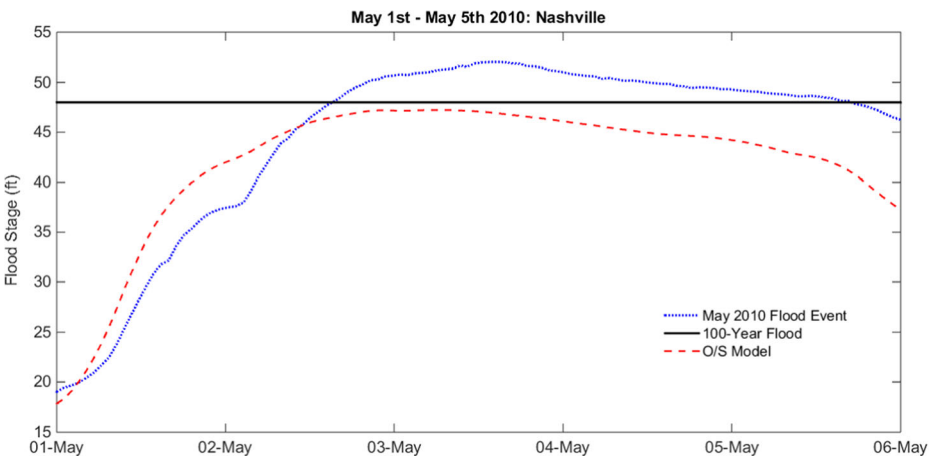


Fig. 9 Flood Stage Condition (Simulated and Observed) at Nashville during the May 2010 Storm Event

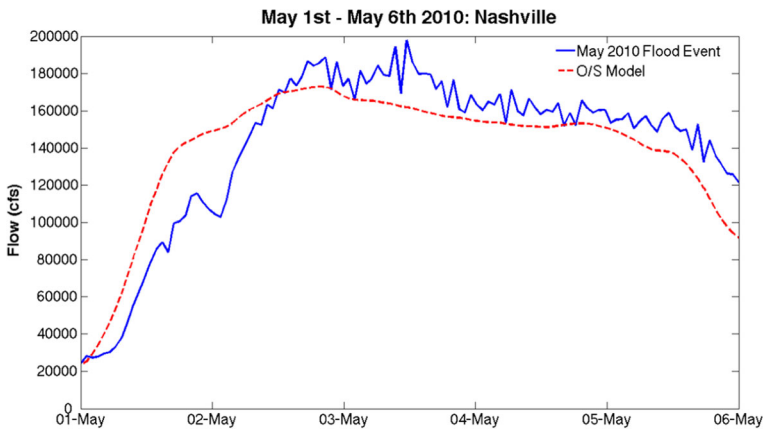


Fig. 10 Floodwater Flow Rate (Simulated and Observed) at Nashville during the May 2010 Storm Event

approach. The optimization/simulation model offers more possible optimal solutions by using the genetic algorithm approach as opposed to traditional gradient methods that can only compute one optimal solution at a time. The optimization/simulation was developed for the 2010 flood event that occurred in the Cumberland River basin in Nashville, Tennessee.

As expected, the optimization/simulation model revealed more efficient and sustainable modes of short-term reservoir operations, which reaffirmed the problematic nature of the antiquated reservoir operational procedures. Specifically, it revealed that the Old Hickory dam, the reservoir upstream of Nashville, was more contained in the model simulation than the actual reservoir during the 2010 event. During the actual event, the Old Hickory Dam was nearly overtopped. So, the model in this case, worked to create extra flood volume in the reservoir ahead of the flood event so that headwater would not approach the dam's overtopping level. This is because the model contained a built-in forecasting component that was able to project short-term rainfall.

This forecasting system could then be used to run a subsequent flood simulation to determine the necessary steps to take in order to prevent floods. One especially crucial step, for example, would be to determine an optimal gate release schedule. In the case of the Old Hickory dam, the gate was released only after the storm had accelerated. Moreover, the gate was released far too quickly rather than incrementally and at a slower pace in order to control the velocity of the floodwaters. As the model showed, had the Old Hickory dam imposed an optimal gate release schedule ahead of the actual storm, the floodwater levels in downtown Nashville could have been significantly reduced. The information gathered from the simulation model could be given to the appropriate agencies on the ground so that they may disseminate it in a way best suited for a particular community.

During the May 2010 event the maximum headwater elevation of Old Hickory reached 451.45 ft., within 6.6 in. of overtopping the upstream lock wall, emphasizing the severity of the system operation and the need for a real-time optimal operation model. The Nashville flood elevations could have been maintained below the 100 year level through the use of the model reported.

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