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A Risk Based Framework for Evaluating Gated Spillway Operations

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ABSTRACT

Gated spillways are often necessary to provide both operational flexibility and discharge capacity to pass large flood events. However, gated spillways present operational challenges to dam owners and operators, often necessitating development of a flood operations plan (FOP) that is used in tandem with the dam's emergency action plan (EAP). Even a well-intentioned and robust FOP/EAP can require personnel to predict flooding, use judgment particular to the requirements of the plan, and react quickly. In addition, all of the equipment required to operate the gates needs to function as designed and be operated in accordance with the FOP.

This paper presents a framework for evaluating the risks related to gate operations during floods, considering operations in accordance with the FOP, as well as operations that deviate from the FOP/EAP due to operator (human) error or system (mechanical/electrical/structural) malfunction. Case studies are presented to evaluate the downstream impacts of gate operations (or misoperation) for a range of flood events. A basis for quantitative evaluation of risks is included. Considerations for improving operation plans and replacement of spillway gates with more reliable passive systems are presented in the context of risk framework.

Keywords: *Risk Management, Risk Analysis, Spillway Gates, Flood Operations*

1. INTRODUCTION

Gated spillway systems are often necessary for dams where regulation of the pool level is required, outflows must be controlled to prevent downstream flooding, and when significant discharge capacity is required to pass large inflow flood events. According to the National Inventory of Dams (USACE 2015), there are over 8,500 dams in the United States with "controlled" spillways. This is about 10 percent of the dams included in the inventory. A similar search indicates that about 20 percent of the 3,800 Federal dams have controlled spillways. Of the 8,500 dams with "controlled" spillways, nearly 3,500 (about 40 percent) have a primary purpose of "Flood Control" or "Hydroelectric."

Spillway gates include both underflow gates (examples include radial or Tainter gates and vertical lift gates) and overflow, or crest, gates. Underflow gates result in larger "surges" in outflow when operated under full head, whereas crest gates are typically better suited to control outflows.

Gated spillways offer specific advantages over fixed crest spillways, including significant discharge capacity within a given spillway width and the ability to provide surcharge (flood) storage with little to no outflow until the gates are operated to provide discharge capacity. The primary disadvantage of gated spillway systems is their vulnerability and reliability, particularly during large storms.

The US Army Corps of Engineers (USACE) acknowledges the advantages of a fixed crest spillway, noting "the value of an uncontrolled fixed crest spillway in providing an extremely reliable operation and a very low cost maintenance facility is undeniable" (USACE, 1990). However, USACE (1990) also recognizes the need for spillway gates in certain circumstances and provides guidance for these scenarios, noting that fixed crest spillways should be incorporated into designs when watershed response time (time of concentration) is relatively short (less than 12 to 24 hours), and they also suggest the use of at least two gates to "satisfy safety concerns." The latter requirement is likely to provide redundancy for situations where a gate cannot be operated.

As presented in Paxson et al. (2015), dam safety and flooding risks related to spillway gates can result from two primary sources:

1. Unintended and/or uncontrolled releases resulting from
    a. accidental or improper gate operations
    b. structural failure of the gate(s)
    c. inability to close gate(s) after operation
2. Reduction in spillway capacity, resulting in overtopping failure of the dam from
    a. Inability to properly operate the gates
    b. Blockage of spillway gate openings from debris

Item 2 is often addressed in traditional dam safety potential failure mode and risk analyses; the risks related to item 1 can be more difficult to quantify. Effective use of spillway gates during floods often requires actions by the dam owner/operator. This not only includes operating the gates, but also making decisions to predict flooding and the impacts of gate operations.

1.1. Impacts of Gated Spillway Operations

The National Performance of Dams Program (NPDP 2016a) website includes documentation of 65 dam safety incidents related to gated systems, including structural failure, operator error, and issues with gate operation systems (mechanical, hoisting, cables, and chains). Incidents could include an uncontrolled release resulting from structural failure of the gate (e.g., Folsom Dam, see ASDSO/EPRI 2000), failure of the dam during a flood due to inability to operate gates (e.g., Delhi Dam, see Fiedler et al. 2011), or unintended releases due to gate misoperation. This paper focuses on the issues related to gate operations as opposed to failures of the dam or components of the dam.

Two 2014 events in India demonstrate the potentially catastrophic impacts of spillway gate operations. In June, at the Larij Hydropower Project, the spillway gates were operated, reportedly increasing spillway outflows from 20 cubic meters per second (cumecs) to 450 cumecs over the course of an hour (NDTV 2014). The flooding resulted in the deaths of 24 students and a tour guide on an excursion in the Beas River downstream of the dam. An inquiry into the incident led blame to the dam authorities for the tragedy, noting that standard procedures for releasing water were ignored. Less than a month after this incident, ten boys were nearly drowned after gate operations at Tenughat Dam, which reportedly caused significant flooding (The Telegraph 2014).

In addition to cases where downstream flooding occurs as a result of releases associated with gate operations, there are many situations where the dam operator was criticized for the gate operations even though the releases may not have caused the downstream flooding or certainly did not increase flooding over what would have occurred if the dam were not in place. In July 2014, the US Army Corps of Engineers was criticized for operations at Coralville Reservoir in Iowa, which included allegations from residents of 1) not releasing enough water prior to the flood and 2) releasing too much water during the flood (O'Leary 2014).

The Washington Suburban Sanitary Commission (WSSC) came under similar scrutiny related to flooding in Laurel, Maryland, downstream of Duckett Dam during a storm in April 2014. Residents and politicians suggested that WSSC had "manufactured" the flood (Shaver 2014) and questioned whether releases at the dam could have been controlled to reduce the flooding (Pichaske 2014). WSSC and residents defended the operations, noting that the gate operations were necessary to address a potential dam safety concern (Johnson 2014). It should be noted that unlike Coralville Dam, the Duckett Dam was not constructed to provide downstream flood risk reduction; the structure impounds a water supply reservoir. Nonetheless, the dam likely provides some level of flood protection.

The 2015 floods in South Carolina were reported to have been roughly a 1,000 year event, and more than 30 dams failed (NPDP 2016b). South Carolina Electric and Gas (SCE&G) owns and operates Saluda Dam (impounding Lake Murray) to provide hydroelectric power. During the 2015 floods, SCE&G operated the spillway gates, resulting not only in criticism, but lawsuits from downstream residents (Ham 2015). Claims from residents ranged from, "[SCE&G] mishandled the rain event," to, "[they] had no right to create a flood," and had "no easement to flood [neighborhoods]." In addition to claims that SCE&G caused the flooding, the utility was criticized for not providing sufficient warning, even though they reportedly issued press releases noting the need to open the gates as much as two days prior (Smith, 2015). Of note, SCE&G faced a lawsuit in the 1960s related to releases in June 1965; the federal judge dismissed the lawsuit with a conclusion that the flooding would have occurred even without the dam (Smith 2015).

These, and numerous other case histories, document not only the potential for loss of life or property damage resulting from gate operations, but also the likelihood that the owner will face criticism and lawsuits for gate operations, resulting in significant costs to defend themselves against claims.

1.2. Flood Operations Plans

Most dams with gated spillways commonly have some type of flood operations plan (FOP) that is used to assist the operator during flood events. Even projects without a formal FOP usually have set up some guidance to maintain the reservoir pool at a target elevation by opening gates as inflow increases. More formal plans may require monitoring precipitation forecasts, stream gauge data, and lake levels. Based on observed conditions, the operator opens or closes gates and continues monitoring. In addition to reliable electrical, mechanical, and structural systems, the effective execution of an FOP requires an available operator who may need to make difficult decisions during an emergency situation in which he/she may have other responsibilities.

2. EVALUATING SPILLWAY GATE OPERATIONAL RISKS

A framework for evaluating the risks related to spillway gate operations needs to consider a variety of systems and scenarios, including management decision-making and operator actions with regard to operations and implementation of the FOP. Each project is different, and the flood scenarios that may be experienced could have a complex sequence of events during a flood. An example project is used to illustrate such a scenario.

2.1. Example Project

The example project is a 40-m (130-ft) high dam impounding a water supply reservoir. The spillway is a concrete chute equipped with three Tainter gates, each about 5.5 m (18-ft) high, located in 5.5 m (18-ft) wide bays. This is the only spillway at the dam, which is located on a 56.8 square km (22 square mile) mountainous watershed. A city with a population of about 90,000 is located 19 km (12 miles) downstream of the dam. The dam is classified as "high hazard," and the regulatory spillway design flood (SDF) is the Probable Maximum Flood (PMF). The gated spillway was found to have a capacity of about 65 percent of the PMF, assuming a starting reservoir elevation of 791.9 m (2,598 ft). The gates are operated to maintain this elevation until they are fully opened. If the gates are inoperable (closed), flow would overtop the gates at reservoir EL 792.9 m (2,601.5 ft) and the spillway would have capacity to pass a flood with an estimated return period of about 1,250 years without overtopping the embankment dam (top of dam EL 796.3 m (2,612.5 ft)). The PMF has been estimated to have a return period between 100,000 and 200,000 years. Based on the requirement to pass the PMF, the owner is constructing a new auxiliary spillway through an abutment, requiring significant investment. As part of this project, the owner is considering options to reduce reliance on the gated spillway to pass floods.

2.1.1. Flood Operations

This project has a formal FOP, which includes guidance for gate operations that is tied to precipitation forecasts, upstream stream gauge data, and reservoir level before and during the flood event, as follows:

- The FOP includes monthly target "normal" reservoir levels, selected based on anticipated water supply needs balanced with reducing reliance on gate operations.
- The operator may be required to open gates when significant rainfall (greater than 15.2 cm (6 inches) over 24 hours) is predicted, depending on the reservoir elevation.
- If the reservoir is below EL 789.4 m (2590 ft), the gates remain closed.
- If the reservoir is above EL 789.4 m but below the monthly target, one to three of the gates are opened between 0.15 and 0.3 m (0.5 to 1.5 ft) based on flows reported at a stream gauge located upstream of the reservoir.
- If the reservoir is above the monthly target, one to three of the gates are opened between 0.15 and 0.46 m (0.5 to 1.5 ft) based on the rate of rise in the reservoir.
- The gates are opened such that the gates do not overtop.
- The FOP includes guidance to enact the dam's EAP if rainfall, inflow, or reservoir rise reach given threshold values related to anticipated flooding of downstream structures.

To follow the FOP guidance, the gate hoisting systems (mechanical, electrical, structural) must be operational and the onsite operator is required to make decisions based on predicted and actual flooding conditions.

2.1.2. Risk Analysis Framework

To support the owner's efforts to reduce reliance on a gated spillway system, a risk-informed evaluation is carried out. The first step in this process is the development of a risk model for the project in its current configuration with the gated spillway system. A component of the risk model is an event tree that is used to evaluate the possible sequence of events that may occur during inflow floods and the outflows that may occur as a result of these sequences that may include overtopping and failure of the dam, unplanned releases due to operator error, or gate system failure. The development of the event tree was guided by the steps and guidance in the FOP. Of particular interest are the flood releases during events significantly smaller than the PMF, particularly since the PMF is estimated to have such a low probability.

For purposes of this evaluation, failure modes (structural, geotechnical, etc.) associated with the dam are not explicitly evaluated. Instead, a "dam fails" event was included to consider all failure modes. The general sequence of events evaluated is presented in Figure 1.

Each of the events shown in Figure 1 can have multiple branches to simulate conditions and result in different estimates of outflow and reservoir stage. Some examples include:

- If the precipitation forecast is greater than the actual rainfall, it is possible the gates would be opened more than needed, resulting in a greater outflow than if the forecast were accurate.
- The stream gauge that is used for flood prediction only represents a portion of the watershed; therefore, it is possible that actual inflow could be lower or higher than anticipated, representing uncertainty in flow releases.
- Gate operations require interpretation of several factors, including estimating reservoir rise and anticipating whether overtopping of the gates is imminent. In addition, decision making during a large flood is stressful, and an operator may elect to deviate from the FOP.

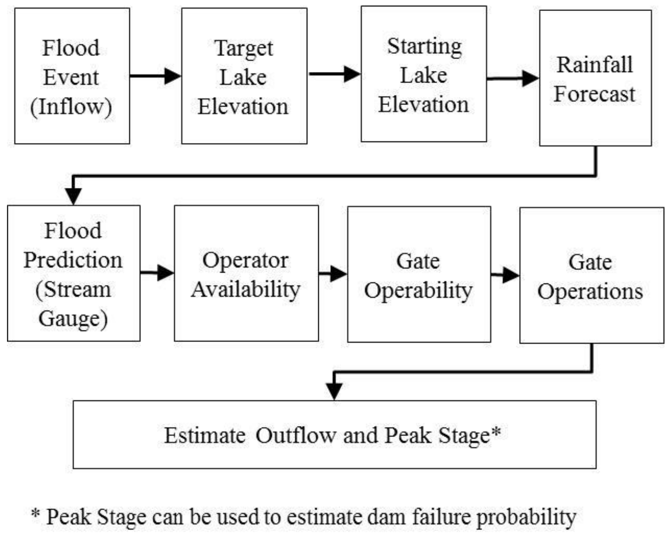

Figure 1. Event sequence, based on Flood Operations Plan

The event tree is presented in Figure 2. Three event trees were developed for each flood evaluated, corresponding to the three target reservoir elevations included in the FOP. Several branches of the event tree are not expanded. The probabilities at each node were estimated by the authors, but in a real example, these probabilities would be estimated based on statistical analysis or expert elicitation.

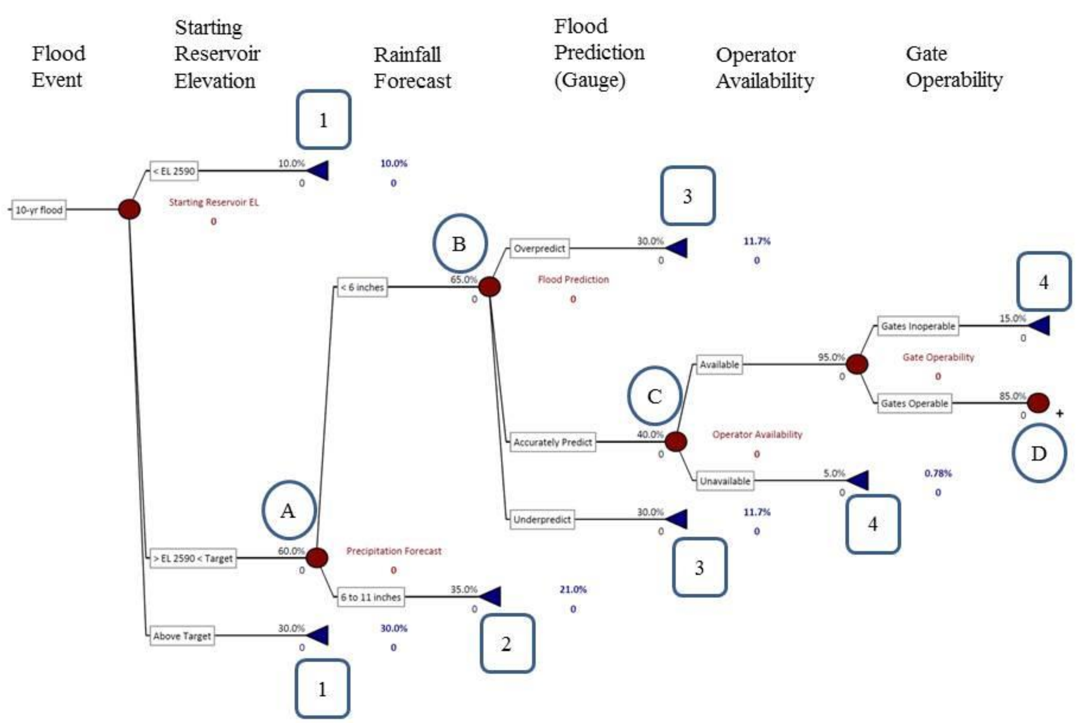

Figure 2. Gate operations event tree

The results at the various branches, quantitative and qualitative, are as follows:

1. These nodes would be expanded similar to node A. Probabilities at each node may differ.
2. If the precipitation forecast is greater than actual precipitation, the spillway gates would be opened at the start of the storm. This would result in an initial release of about 14 to 28 cumecs (500 to 1,000 cfs). This node would be expanded similar to node B.
3. If inflow is greater than predicted by the upstream gauge (underprediction), gates would be operated later in the storm. If inflow is less than predicted by the gauge (overprediction), gates would be operated earlier in the storm. These nodes would be expanded similar to node C.
4. If the operator is unavailable or the gates cannot be operated, the gates would be overtopped, resulting in an estimated peak stage of 793.8 m (2,604.3 ft) and peak outflow of about 23 cumecs (800 cfs). This node could be expanded to also include branches representing a gate failure and a dam failure.

As noted above, a "dam fails" node can be included the end of each branch of the tree. For this model, the probability of failure was explicitly related to hydrologic loading, with an estimated failure probability of 5×10^{-6} for reservoir elevation of 789.4 m (2590 ft) and 1×10-5 for reservoir elevation of 795.5 m (2610 ft). Figure 3 shows the expansion of node D, illustrating gate operation scenarios relative to the FOP.

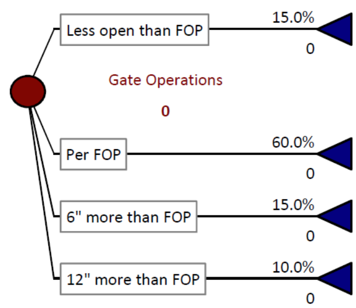

Figure 3. Gate operation scenarios event tree branches

Hydrologic modeling for various hypothetical storms (2- through 1,000-year estimated return periods) was performed using the HEC-HMS computer program. Inflow hydrographs were then input into spreadsheet model that was developed to perform reservoir storage routings, and estimate outflow and peak stage. This model can be used to simulate operations according to the FOP or manually revised to consider various scenarios, including those identified in Figure 3.

A baseline model was developed to simulate operations per the FOP, which also considers that precipitation and inflow estimates are accurate, an operator is available, and the gates can be operated according to the FOP. Three scenarios were modeled to consider each of the target reservoir elevations included in the FOP. The modeling assumes the reservoir is at the target elevation at the start of the storm. The results of the modeling of the gate operations per the FOP for these storms are presented in Table 1. The 10- and 100-year 24-hour rainfall are 13.5 cm (5.3 inches) and 20.5 cm (8.1 inches), respectively, and the estimated inflows are 171 cumecs (6,030 cfs) and 337 cumecs (11,900 cfs), respectively.

The results in Table 1 show that outflows are significantly less than the flood inflow, illustrating that the dam, while not constructed for the purpose of flood protection, provides significant reduction in outflows over what would occur without the dam in place. The results also show the sensitivity of outflow to the target elevation. The downstream area is particularly sensitive to flooding, with flooding of structures occurring at a flow of about 45 cumecs (1,600 cfs).

Table 1. Results – Gate Operations per FOP for Reservoir Targets

Storm	Parameter	Result for Target Reservoir EL:		
		790.6m (2594 ft)	791.3 m (2596 ft)	791.9 m (2598 ft)
10-year	Outflow (cumecs/cfs)	27.1 / 960	31.2 / 1100	47.3 / 1670
	Peak Stage (m/ft)	792.9 / 2601.5	793.1 / 2602.0	793.3 / 2602.6
	Gate Opening (m/ft)*	0.30 / 1.0	0.3 m / 1.0	0.46 m / 1.5
100-year	Outflow (cumecs/cfs)	80.2 / 2830	97.3 / 3440	130.2 / 4600
	Peak Stage (m/ft)	793.6 / 2603.7	793.8 / 2604.4	794.0 / 2605.0
	Gate Opening (m/ft)*	0.76 / 2.5	0.91 / 3.0	1.22 / 4.0

* Maximum gate opening per FOP or to prevent overtopping of gates

Three event trees were constructed (one for each target elevation), and outflows were estimated using the spreadsheet program for each branch of the event tree. Probability distributions were developed for each reservoir target elevation for both the 10- and 100-year flood, presented in Figure 4.

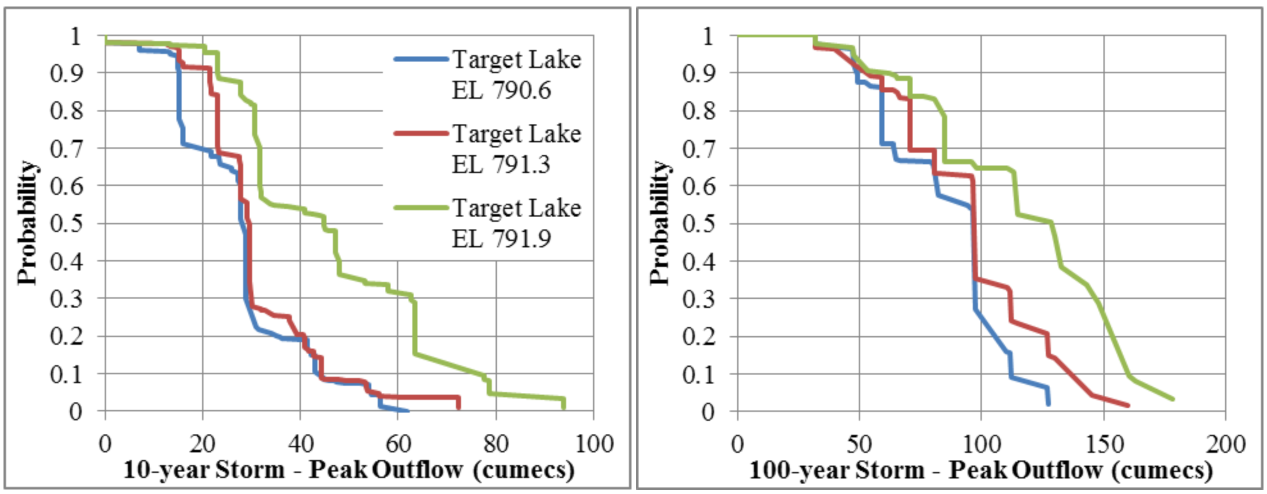

Figure 4. Probability distribution of peak outflows (10- and 100-year flood)

To develop a single probability distribution that considers the three different target reservoir elevations, the probability of a given target elevation for a given event is estimated. The target reservoir elevations vary by season, with the lowest target from November to January, the highest target from April to July, and the middle target for the remaining months. The probability of a given flood event occurring in a given month can be estimated using Seasonality Analysis, which is provided as part of the NOAA Precipitation Frequency Data Server (NOAA, 2016). Since each month corresponds to a given target reservoir elevation, the probability can be estimated for a given storm event. Using this data, the low, middle and high targets were estimated to have respective 7, 61, and 32 percent probabilities for the 10-year storm and respective 1, 80, and 19 percent probabilities for the 100-year storm. This data was used to combine the probability distributions shown in Figure 4 into a single distribution for each of the storm events, as presented in Figure 5.

In addition to estimating peak outflows, the event tree model can be used to estimate probability of a gate overtopping and dam failure for a given storm event. The probability of gate overtopping was estimated to be 19 and 27 percent for the 10- and 100-year floods, respectively. To estimate a dam failure, a simplified linear relationship between peak stage and dam failure probability was developed, with a failure probability (given an event) of 5×10^{-6} for peak stage EL 789.4 m (2590 ft) and 1×10^{-5} for peak stage EL 795.5 m (2610 ft). Using this relationship, the probability of failure given 10- and 100-year events were estimated to be 8.1×10^{-6} and 8.7×10^{-6}, respectively.

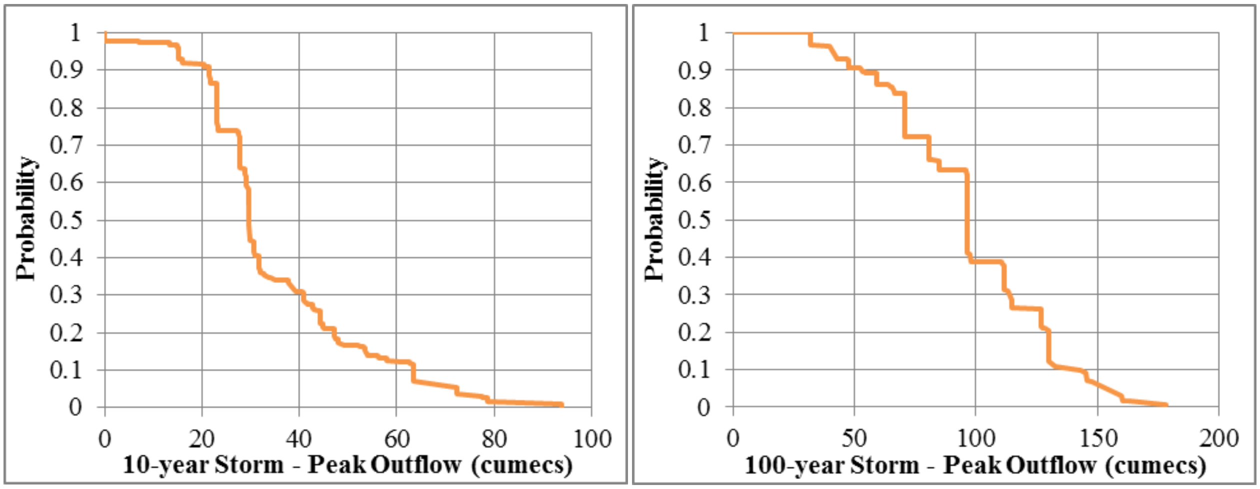

Figure 5. Combined probability distribution of peak reservoir stage (10- and 100-year flood)

2.2. Addressing Risks

As presented in Paxson et al. (2015), there are numerous approaches to reduce risks related to gated spillway operations, including:

- Regular inspection, maintenance, and testing of gates and operating systems to improve reliability.
- Development and implementation of an effective and easy to follow FOP, including operator training and FOP testing.
- Replacement of manually operated systems with automated systems.
- Replacement of some or all of the spillway gates with a fixed crest spillway, such as a labyrinth or piano key weir.

2.2.1. Case Histories

There have been several projects where gated spillway systems were replaced with more reliable spillways, often as part of a project to address other dam safety deficiencies. Several examples follow.

The original spillway at Sugar Hollow Dam in Virginia consisted of an ogee crest equipped with eight 1.5 m (5 ft) high vertical lift gates, which were operated manually using a hoisting system mounted on rails across a bridge over the spillway. In at least one instance, the operator had to open the gates while there was flow over the bridge, making operations very difficult. This gated system was replaced with a rubber bladder, which provided more efficient hydraulic performance and better debris passage than the original spillway. The new “gate” includes an automated system, which is operated based on water level control. This system has operated reliably for nearly 15 years. For additional information on the Sugar Hollow Dam and modeling and programming of the automated operation systems, refer to Paxson et al, 1999.

Tipping Fusegates are considered more reliable than manually operated gate systems. These “gates” typically only “operate” during extreme events (in excess of 500 or 1,000 year storms). At Canton Lake Dam in Oklahoma, the US Army Corps of Engineers selected Fusegates over more traditional Tainter gates (Hydroplus 2014a). Similarly, Fusegates were used at Jindabyne Dam in Australia (Hydroplus 2014b).

Examples of labyrinth spillways being used to replace gated structures include the Brazos Dam in Texas (Vasquez et al. 2009), the New London Dam in Minnesota (Minnesota DNR 2014), and the Lake Townsend and Linville Land Harbor Dams, both in North Carolina (Paxson et al. 2015). In all of these cases, the owner had difficulties related to maintenance and operations of the previous gated spillways.

At Malarce Dam in France, a piano key weir was constructed to provide spillway capacity in tandem with the existing large spillway gates. The piano key weir flows during floods prior to gate operations, providing twice as much time for the dam operator to travel to the dam to open gates, which was particularly important given the rapid watershed response time (Laugier et al. 2014).

2.2.2. Example Project – Gated Spillway Replacement

To address the risks related to the gated spillway in the example project, replacement of the gated spillway with a fixed crest weir is considered. As noted, the dam rehabilitation project will include construction of a large auxiliary spillway to provide hydraulic capacity to pass the PMF. The crest of this auxiliary spillway will be set at EL 795.5 m (2,610 ft), which corresponds to the estimated 200-year flood elevation if the gated primary spillway were replaced with a fixed crest weir, with a crest EL 792.9 m (2,601.5 ft). This is similar to the peak stage for the existing spillway if the gates were not operated and were overtopped. Replacing the gated spillway with a fixed crest weir will result in a larger auxiliary spillway depending on the assumption regarding gate operations during the PMF. If full opening of all gates is considered, the capacity of the existing primary spillway with the reservoir at top of dam is about 671 cumecs (23,700 cfs) compared to a capacity of 178 cumecs (6,300 cfs) for the fixed crest weir primary spillway. The computed PMF outflow is about 2,150 cumecs (76,000 cfs). Therefore, the additional capacity provided by the gates does not significantly impact the sizing of the auxiliary spillway. In addition, conservatism in design is typically recommended to provide redundancy in gates (i.e., provide more than the required capacity if all gates are operable).

If the gated primary spillway is replaced by a fixed crest weir in tandem with the new auxiliary spillway, operations during floods are simplified. Instead, the dam operator can focus on observing conditions (reservoir level, condition of dam and spillway, downstream flows, etc.) and coordinating with local emergency management agencies, as required with regard to either downstream flooding or a potential dam safety issue. In addition, the design can eliminate the need to set lowered monthly lake levels, increasing reservoir safe yield. When normal inflows are sufficient and exceed water supply withdrawals, the pool will be maintained at EL 792.9 m (2,601.5 ft).

2.2.3. Example Project - Risk Model for Proposed Modifications

For the project that is the subject of this paper, replacing the gated primary spillway system with a fixed crest weir eliminates a number of steps/actions in the FOP; the need to predict rainfall and inflows, operator onsite, and gate operations. As a result, the scenarios to model flooding for the fixed crest weir are simplified significantly. Only the starting reservoir elevation impacts the outflows and peak stage for an inflow flood event. To estimate probabilities for the fixed crest weir, an exceedance plot of reservoir elevation was developed based on historical reservoir levels prior to implementation of the FOP reservoir targets.

To illustrate the reduction in risk related to outflows, the probability distributions of peak outflow for the existing gated primary spillway and the proposed replacement fixed-crest weir are plotted in Figure 6.

Figure 6 shows that there is potential for increased peak outflow with the fixed crest weir for the 10-year flood. This is likely due to the application of the target reservoir elevations in the FOP. Even if the reservoir isn't at the target elevation at the start of the storm, implementing the target elevation into the FOP results in a release at the start of the storm, providing a drawdown of the reservoir which results in additional flood attenuation. If this potential for increased flooding is a concern for the dam owner, the new spillway could include some form of gates to accommodate an initial drawdown or release at the start of the storm. For the 100-year flood, the impact of attenuation is less, resulting in lower computed peak outflows for the fixed crest weir than the gated spillway.

The computed peak stage for the fixed crest weir is typically higher than for the existing gated spillway, and this increased hydrologic loading (reservoir levels) could result in an increased risk of dam failure. The probability of failure is estimated using the same simplified procedures as for the gated spillway, resulting in a failure probability of 8.2×10^{-6} and 9.0×10^{-6} for the 10- and 100-year floods, respectively. This represents a relatively small increase in risk.

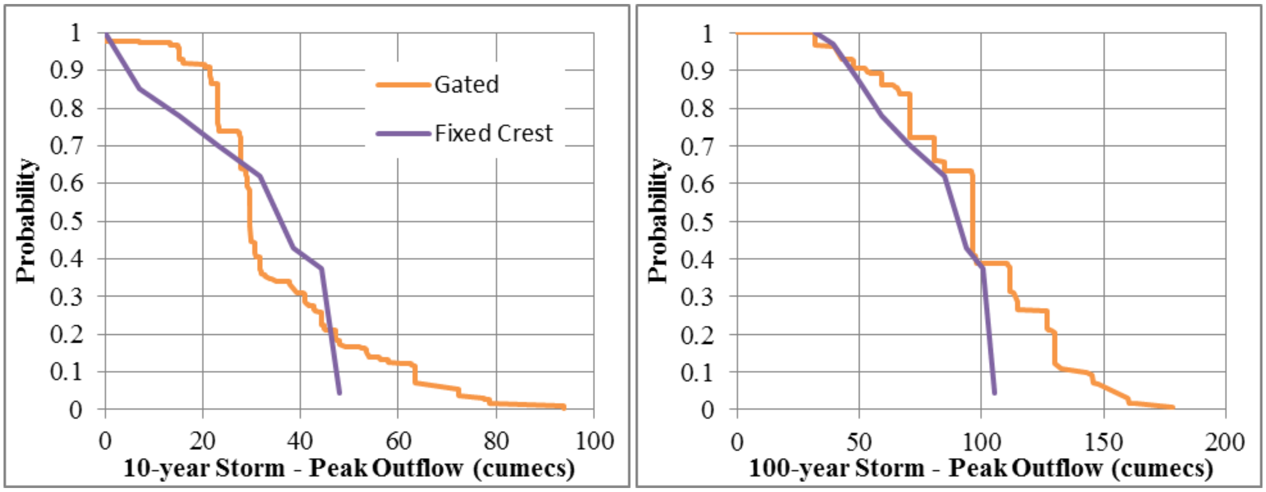

Figure 6. Probability distributions of peak outflow for gated and fixed crest spillways

3. CONCLUSIONS

Gated spillway systems are often necessary to meet specific project requirements. However, these systems present challenges with regard to reliability of operations and the potential for operations (mechanical, electrical, and human) to result in adverse consequences. While reduced operability or inoperability of gates increases risks related to passage of very large floods, potentially resulting in a dam failure, operations during more "routine" flood events could result in higher risks related to downstream flooding (i.e., while the consequences may be less, the probability of damage could be significant higher than a dam failure scenario).

The development of a framework to evaluate the risks of a gated spillway system should consider all aspects of the operations, including flood prediction, operator availability, reliability of the gated system, and operator error. An event tree can be used to model this framework and develop probability distributions for outflow. These distributions can be used to evaluate options for replacement of the system.

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