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# Stage-wise optimizing operating rules for flood control in a multi-purpose reservoir

Frederick N.-F. Chou, Chia-Wen Wu *

*Department of Hydraulic and Ocean Engineering, National Cheng-Kung University, 1 University Rd., Tainan, Taiwan*

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SUMMARY

This paper presents a generic framework of release rules for reservoir flood control operation during three stages. In the stage prior to flood arrival, the rules indicate the timing and release discharge of pre-releasing reservoir storage to the initial level of flood control operation. In the stage preceding the flood peak, the rules prescribe the portion of inflow to be detained to mitigate downstream flooding, without allowing the water surface level of reservoir to exceed the acceptable safety level of surcharge. After the flood peak, the rules suggest the timing for stepwise reduction of the release flows and closing the gates of spillways and other outlets to achieve the normal level of conservation use. A simulation model is developed and linked with BOBYQA, an efficient optimization algorithm, to determine the optimal rule parameters in a stage-wise manner. The release rules of Shihmen Reservoir of Taiwan are established using inflow records of 59 historical typhoons and the probable maximum flood. The deviations from target levels at the end of different stages of all calibration events are minimized by the proposed method to improve the reliability of flood control operation. The optimized rules satisfy operational objectives including dam safety, flood mitigation, achieving sufficient end-of-operation storage for conservation purposes and smooth operation.



## 1. Introduction

Flood operations of gate-controlled reservoirs are generally carried out in three stages: (1) prior to flood arrival; (2) preceding flood peak; and (3) post peak. Each stage has its specific objective and operating characteristics. Prior to the onset of flooding, operators have the option of pre-releasing reservoir storage to the initial level of flood control operation (IL). The aim is to prepare sufficient detention capacity. During the stage preceding the peak, operators seek to alleviate downstream flooding by detaining the inflow in the available detention zone, without allowing the water surface level (WSL) of reservoir to exceed the acceptable safety level of surcharge (SL). After the peak has passed, spillway gates must be closed to reach the end-of-operation normal pool level of conservation use (NL); this level is capable of accommodating subsequent demands for water. There may be multiple sub-stages within each stage, repeated transitions between stages during a multi-peak flood, or different ways to define the span of each stage. Nonetheless, the operations of these three stages should remain the basic and major components due to the very nature of a multi-purpose reservoir in reaction to a flood: to prepare, mitigate and store. This generic concept of stage-wise flood moderating has been adopted by many reservoirs with flood control purpose around the world (Pitman and Basson, 1980; Kojiri et al., 1989; Faber, 2001; Government of India Central Water Commission, 2005; Chang, 2008; Wei and Hsu, 2009; Huang and Hsieh, 2010; Li et al., 2010a, 2010b; SEQwater, 2011; Chou and Wu, 2013).

Among the above operating objectives, the prevention of dam overtopping takes precedence, followed by the objectives of flood mitigation and achieving the desired level of end-of-operation storage. In order to ensure the safety of dam, the IL is usually designed during the planning of reservoir to safely accommodate the probable maximum flood (PMF). For reservoirs with limited capacities and significant perennial water supply demands, the conservation zone usually overlaps with the flood control zone. This overlap yields an NL that is higher than the IL, thus prompting the necessary pre-release prior to the actual beginning of a flood. Pre-releasing the storage of reservoir to attain this requisite IL in the first operating stage not only satisfies the safety requirement, but also promotes flood attenuation as it generates more detention capacity. On the other hand, it may elevate the risk of water shortage if the subsequent floodwater fails to recover the pre-released storage. Decision makers may select a different pre-release target

* Corresponding author. Tel.: +886 (6) 275 7575x63250 18; fax: +886 (6) 274 1463.
E-mail addresses: hyd4691@mail.ncku.edu.tw (F.N.-F. Chou), chiawenwu1977@gmail.com (C.-W. Wu).

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during real-time operation in response to the forecasted inflow volume and time of year, based on the tradeoff between flood control and water usage (Faber, 2001; Li et al., 2010a, 2010b; Chou and Wu, 2013). With the target pre-release level assigned, the balance between flood mitigation and water conservation prior to a flood's arrival is determined, and the operating goal is simply to achieve the target pre-release level by the end of the first stage.

During the stage preceding peak, the primary task is to detain flood and the WSL of reservoir will be raised consequently. A perfect mitigating strategy with comprehensive knowledge of inflow process would fully utilize the available detention volume to mitigate flooding and thus elevate the WSL of a reservoir to a maximum approaching the designed flood level (DL), which represents the maximum surcharge level of a reservoir. Nonetheless, the uncertainty about future inflows prevents the adoption of such a high risk strategy, since an underestimation of flood volume will directly lead to overtopping of a dam. In reality, a SL is usually assigned well below the DL in order to accommodate unexpected extreme inflow, while the zone below SL can still be used for flood detention. The value of SL is usually determined subjectively based on decision makers' experience and risk tolerance with respect to flood mitigation and protecting dam safety. Regulating the WSL of a reservoir to reach the SL at end of the stage preceding the peak will maximize the prescribed detention function without compromising dam safety. The capacity above the SL can be regarded as backup space for storms that exceed forecasted levels, e.g. the occurrence of a PMF. Thus, a feasible mitigation strategy corresponding to a specific SL should also safely accommodate the PMF volume within the space between IL and DL.

In the end of the flood, the reservoir should store sufficient water to support normal operation for all purposes over a long period. This target level NL specifies the upper limit of storage for conservation use. Its value may vary in accordance with monthly patterns of reservoir inflow and perennial water usage. Since the NL is usually lower than the SL, detention of flood waters preceding peak does not conflict with the goal of reaching desired storage at the end of the flood. Thus achieving the respective target values for IL, SL and NL at the end of each stage will inherently satisfy the assigned multiple objectives of the entire flood control operation. This characteristic allows stage-wise evaluations of operating strategies, thereby simplifying real-time flood control operation *in situ*.

Under the framework of stage-wise operation, the transition of stages is determined simply based on the real-time measured inflow of the reservoir, which is sufficient to judge whether the flood is arriving, rising or receding. The operation can then adapt to the associated requirements and objectives of the current stage. In order to achieve multiple objectives, many studies have applied optimization methods to identify real-time operating policies for reservoirs. The employed approaches include linear programming (Windsor, 1973), goal programming (Can and Houck, 1984), network flow programming (Braga and Barbosa, 2001), nonlinear programming (Unver and Mays, 1990), dynamic programming (Shim et al., 2002), mixed integer programming (Needham et al., 2000; Hsu and Wei, 2007; Chou and Wu, 2011), optimal control theory (Wasimi and Kitanidis, 1983; Karbowski et al., 2005; Kearney et al., 2011; Delgoda et al., 2012), genetic algorithm (Chang, 2008) and other heuristic algorithms (Li et al., 2010a, 2010b; Qin et al., 2010; Valeriano et al., 2010), or combinations of these (Niewiadomska-Szynkiewicz et al., 1996). These methods regard reservoir releases as decision variables to be optimized and require future inflow to be forecasted. However, forecasts of rainfall and runoff processes are always uncertain during real-time operations. These uncertainties limit the optimized policy to be only effective for the current period or a few following periods (Cheng and Chau, 2001). The processes of rainfall–runoff forecasting and dynamic optimization of future operations must be sequentially performed throughout the operating horizon to guide reservoir release in each period (Pitman and Basson, 1980; Shim et al., 2002). Forecasting methods that incorporate probability may serve to manage hydrological uncertainty in real-time. Additional works will be required to forecast the distribution of future inflows and evaluate operating responses to more generated realizations (Mediero et al., 2007; Kearney et al., 2011; Delgoda et al., 2012). Inevitably, when great uncertainty is introduced, the performances of all these approaches will degenerate due to their reliance on the reliability of real-time forecasts.

The above assertion is supported by the operating experiences of Tsengwen Reservoir, the largest reservoir in Taiwan, during Typhoo Morakot in 2009, which is a worldwide well-known event and damaged the watershed of Tsengwen Reservoir severely. Prior to the invasion of this typhoon, the Central Weather Bureau (CWB) of Taiwan forecasted a total rainfall depth of 650 mm. However, the unexpected slow movement of Morakot brought record-breaking rainfall for southern Taiwan. The torrential storm caused malfunction of most of the telemetric rain gauges in the watershed of Tsengwen Reservoir, which originally recorded a 3-day rainfall depth of 1711 mm and led to an unreasonable runoff coefficient of 1.47 according to the inflow measured at the dam site. It was modified to 2485 mm in the post-flood review by Chou and Wu (2010b). The reservoir inflow peaked at 11,729 $m^3/s$, which is very close to 12,430 $m^3/s$ as the PMF of Tsengwen Reservoir. Without accurate data during this severe typhoon emergency, operators were forced to rely on documented procedures and their own experiences, rather than the forecast-optimization systems of Tsengwen Reservoir. After the flood, several projects were carried out in order to evaluate and adapt the operating strategies and rules of the reservoir for severe conditions.

In contrast to the optimization approach, which relies upon accurate forecasts, a well-established operating rule can properly guide reservoir release based simply on real-time measurements available from the dam site. No matter how good the forecast-optimization models are, having another effective alternative available is always a gain, especially since rule-based operation is much simpler, more computationally efficient, more reliable when the forecast is highly uncertain, and also valuable as evidence to sufficiently support the decision maker in court when the operation invokes public controversy (Valdes and Marco, 1995).

This study presents a method to develop the optimal release rules for reservoir flood control operation. In the following section, a comprehensive framework of rules covering all three stages of flood operation is proposed. These user-friendly rules are devised from operating insights and simple hydrologic concepts. A simulation model based on these rules is constructed to analyze flood control operations with respect to the PMF as well as historical flood events. The Bounded Optimization BY Quadratic Approximation (BOBYQA) algorithm of Powell (2009) is used to calibrate the optimal rule parameters complying with the characteristics and objectives of different stages of flood operation. The target values of the IL, SL and NL levels are assumed to be given conditions when applying the proposed method. These levels are usually specified by the decision maker based on relative prioritization of dam safety, flood mitigation and water conservation objectives. With these conditions specified, the proposed method strives to achieve a target WSL at the end of each stage, thus achieving the assigned objectives. Case study results validate the effectiveness of the proposed method.