Conference Proceeding

Rule operation model for dams with gate-controlled spillways

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Abstract: The study developed a rule operation model for gated spillways (named K-Method) which improved the performance of the volumetric evaluation method (VEM). VEM was proposed by Girón (1988) and is largely used in common practice in Spain. The K-Method was developed by modifying the VEM and by including a K factor which affects the released flows. A Monte Carlo simulation environment was designed to evaluate the method under a wide range of inflow conditions (100,000 hydrographs) and with return periods ranging from 1 to 10,000 years. The methodology was applied to the Talave reservoir, located in the south-east of Spain. Results showed that K-Values higher than one always reduced the maximum reservoir levels reached in the dam. For K-Values ranging from one to ten and for inflow hydrographs with return periods higher than 50 years, we found a decrease of the maximum levels and outflows compared with the VEM. Finally, by carrying out a dam risk analysis, a K-Value of 5.25 was the best reducing 8.4% VEM expected annual damage.

Keywords: Flood control operation, Gated spillway, Volumetric evaluation method; Rule operation.

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1. Introduction

Dam operations to manage the floods should guarantee the dam safety, minimize the risk of floods downstream the dam and maintain the reservoir at full operational capacity once the flood is over [1-5]. Dams with gated spillway represent around 30% of large dams around the world [6] and give more possibilities for water conservation and flood abatement than those with fixed-crest spillways [7]. They provide more flexibility of operation by incorporating different strategies for managing the floods [8]. On the other side, gate management during a flood event represents a challenge for the dam operator, who has to make decisions under pressure and in uncertain conditions. In addition, the time frame for decision making is usually extremely short, the information available is generally sparse, and the predictability of the meteorological situation is limited [9]. Real-time flood control operations in dams have historically been approached using predefined graphs obtained by simulation techniques [10]; or using simulation methods such as the volumetric method (VEM) [11], commonly used in Spain.

Simulation methods generally establish the total flow discharge at a time instant considering information about inflow, reservoir stage, stored volume and outflow discharged downstream available at the previous time [12]. Dams Master Plans include these methods, helping operators to manage floods in an efficient way [1]. These models are usually more flexible and easier to interpret for the dam operators comparing with others models like optimization models [13-18] or data-based learning models [19-24], among others.

The main objective is to develop a rule operation model for gated reservoirs with the aim of improving the VEM proposed by Girón [11] and by using a Monte Carlo approach. The proposed methodology allows to improve flood control operations, giving dam managers a tool to decide which is the best way of reducing flood risk associated to the dam and downstream safety.

2. Materials and Methods

A probabilistic approach was implemented combining a Monte Carlo framework and deterministic reservoir flood control rules. We proposed an operation rule named as K-Method, as an improvement of the wide used VEM [11]. A Monte Carlo environment was carried out to generate a set of storms and the corresponding hydrographs that were used as input to the reservoir. The abatement of the floods was implemented considering the proposed method. Additionally, its behavior was compared with the VEM and the Inflow-Outflow Method (I-O). I-O for gate operation exchange similar values of inflow to the reservoir by discharges, so no attenuation effect of the reservoir is considered while the gates are partially opened.

The methodology can be outlined with three main components:

1. Rainfall generation and hydrometeorological model.
2. Flood routing in the reservoir and dam operation applying the different operation simulation models: VEM, K-Method and I-O Method.
3. Result analysis.

In order to compare the behavior of the different operation rules through a large range of floods, the study considered return periods from one to 10,000 years. As recommended by other authors, for obtaining representative and robust results [25-28], we generated and analyzed 100,000 maximum annual reservoir inflow hydrographs. In order to generate the set of inflow hydrographs, the rainfall generation and the hydrometeorological model was based on the Monte Carlo simulation framework proposed by [28]. The reader may refer to [28] for a more detailed description of the processes involved.

Regarding to the reservoir routing and gated-controlled rule operation we applied three methods: The volumetric evaluation method (VEM), the I-O and the K-Method. VEM was proposed by Girón [11] and it is a simulation model that allows to calculate in real time the outflow during a flood event in reservoirs with controlled outflows. VEM is based on three principles:

1. Outflows are lower or equal than inflows while the inflow hydrograph is increasing.
2. Outflows increase when inflows increase.
3. The higher the reservoir level, the higher the percentage of outflow increases.

VEM manages the available flood control storage progressively, increasing the outflows as the flood control storage decreases.

Figure 2 shows the general scheme of the method implementation. First, the reservoir volume was obtained (S_i). The proposed outflow (Q_P) was chosen in function of the reference zone (1,2,3 or 4) and whether the reservoir volume increase or decrease ($\Delta S_i > 0$ or $\Delta S_i < 0$). Once Q_P is obtained, it is compared to the discharge at the current reservoir level ($O_{disch}(S_i)$) and the maximum of the previous inflows (I_1, I_2, … ,I_i), being the minimum of the three values the selected flow for being released through the gates (O_i).

The K-method is a modification of the VEM. A factor (K) is applied to the expression of Q_1 proposed by the Girón method:

$$\text{If } S_i^F \le \Delta S_i : Q_1 = \frac{\Delta S_i}{\Delta t}; \text{ else } Q_1 = \mathbf{K} \cdot \frac{\Delta S_i{}^2}{S_i^F \cdot \Delta t}, \quad (1)$$

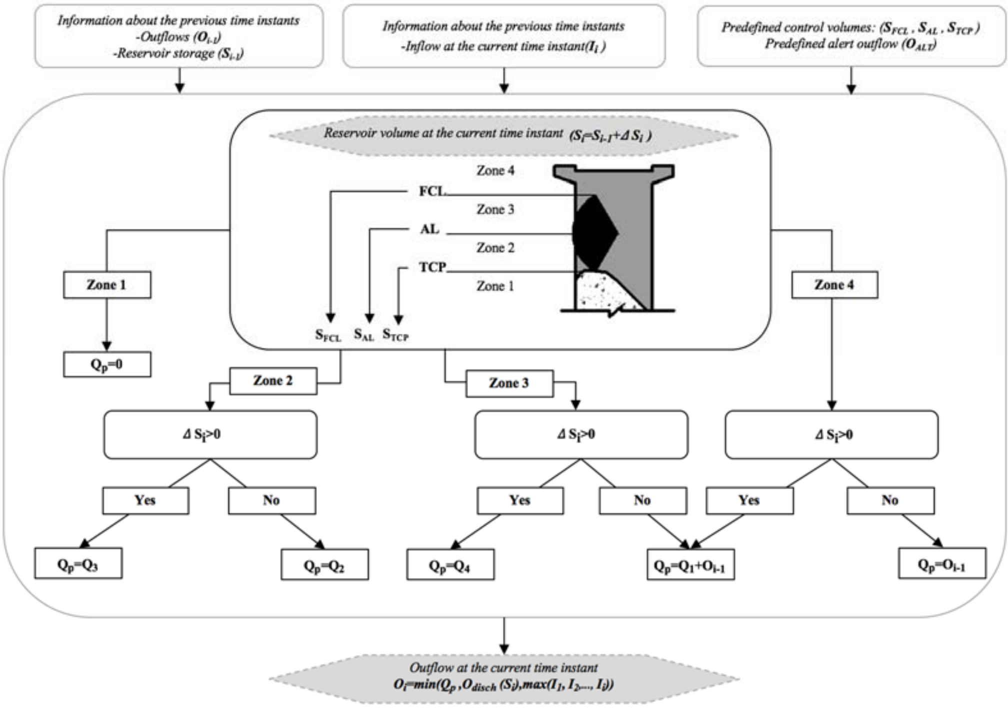

Figure 2. Volumetric evaluation method scheme (developed from [11]). Four different zones with their corresponding proposed discharge formulas were defined (Q_1, Q_2, Q_3 and Q_4, not shown). S_{TCP} represents the volume at the top control pool, S_{AL} is the volume at activation level, S_{FCL} is the volume at the flood control level, S_i is the volume in the reservoir at the time i, S_{i-1} represents the volume in the reservoir at the previous time i-1, O_{i-1} is the discharged at the previous time instant and the alert outflow is O_{ATL} (which represents the threshold of outflow from which it is expected to have damage downstream).

As can be seen in Figure 2 the K factor affects the calculation of discharges in zones 2, 3 and 4. A wide range of K-Values were analyzed (varying from K = 0.1 to K = 500 with intervals of 0.05) in order to improve the reservoir management rules. Finally, we implemented the I-O method. This method consists on applying, for all zones, the expressions corresponding to zone 4, this is, the outflows equal the inflows when the hydrograph is increasing (until the maximum discharge capacity in which it begins to work as a fixed-crest spillway).

2.1. Case study

The proposed methodology was applied to Talave reservoir. It is located in the province of Albacete, in the south-east of Spain. It belongs to the Mundo river basin, being Talave watershed area 766.5 km^2. The climate of the region is mediterranean (mean annual precipitation of 557 mm). The main characteristics of the dam-reservoir system configuration are shown in Table 1. The principal uses of the reservoir are flood regulation, hydropower generation and water supply for the Region of Murcia.

Table 1. Characteristic reservoir levels and outflows of the dam configuration.

Reservoir levels (m.a.s.l)		**Maximum outflow capacity at design flood level (DFL) (m^3/s)**		**Characteristic outflows (m^3/s)**	
Top of control pool (TCP)	508.9	Gated-spillway	284.9	Alert outflow (O_{ALT})	100
Activation level (AL)	509.3	Fixed-crest spillway	41	Warning outflow (O_{WARN})	150
Flood control level (FCL)	509.9	Bottom outlet	99.5		
Design flood level (DFL)	511.3	Lower water intakes	18	Emergency outflow (O_{EMER})	300
Crest of dam (COD)	512.4	Medium water intakes	123		

3. Results and discussion

First, we compared the K-Method and I-O to the VEM applying a comparative scheme based on quadrants analysis (Figure 2). The points located in the upper right quadrant (Q_{I}) represent events where the maximum level reached in the reservoir and the maximum outflow were higher than by applying VEM. The points located in the upper left quadrant (Q_{II}) show an intermediate situation with lower maximum levels but higher outflows. Lower left quadrant (Q_{III}) represent cases for which both maximum level and maximum outflow are lower than by applying VEM (the best situation). Lower right quadrant (Q_{IV}) represent intermediate situations with higher maximum levels and lower maximum outflows. We also associated the return periods of the inflow hydrographs. Results for some analyzed K-Values and I-O are reported in Figure 2.

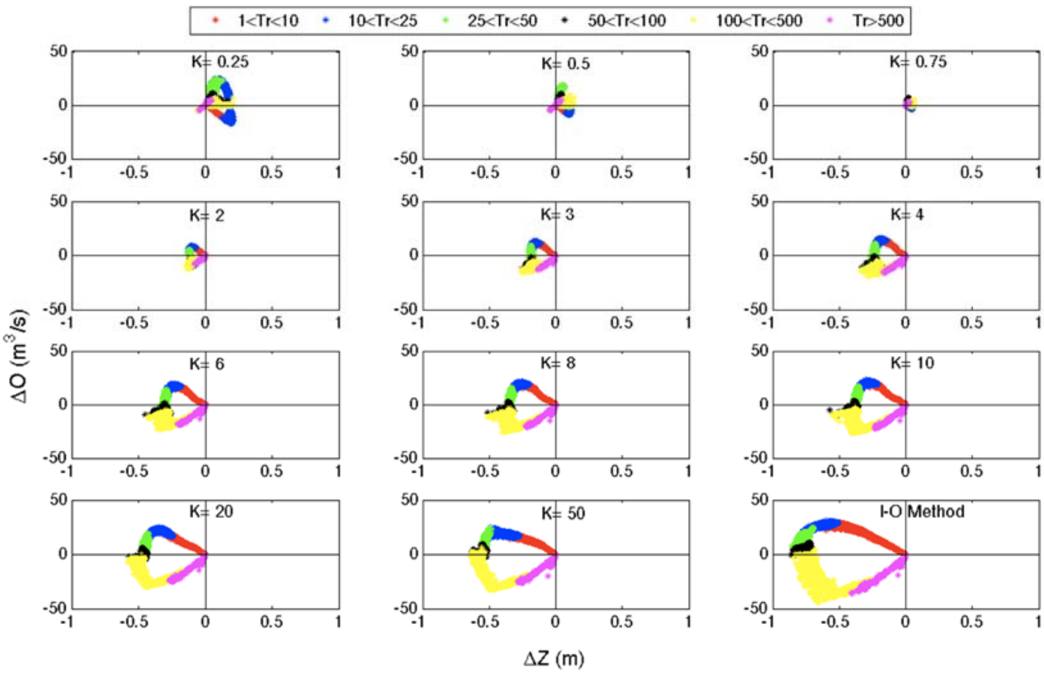

Figure 2. Comparison of K-Method (for different K-Values) and I-O respect to MEV. Horizontal axis shows the increments of maximum reservoir level in meters (ΔZ) by applying the K-Method and I-O compared to MEV. Vertical axis shows the increments of maximum outflow in cubic meters per second (ΔO) of each method compared with MEV. Red points correspond to events with Tr ranging from 1 to 10 years, blue points ranging from 10 to 25, green points from 25 to 50, black points from 50 to 100, yellow points from 100 to 500 and magenta points from 500 to 10.000 years.

It can be seen that if K-Values were lower than one, there was no improvement respect to the VEM: most of the points were in Q_{I} or Q_{IV}. Therefore, we focused the following analysis in K-Values higher than one, in which the entire set of events were placed in the Q_{II} or Q_{III}. Moreover, when analyzing the percentage of cases in Q_{III} and their corresponding Trs (Table 2), all the events with Tr lower than 25 years were located in Q_{II} (regardless the analized K-Value), improving the maximum levels but worsening the outflows by comparing with VEM. Nevertheless, the maximum outflows for K-Values higher than one and lower than ten, for inflows with Tr lower than 25 years, did not jeopardize downstream safety as O_{ALT} was not exceeded. For Tr ranging from 25 to 500 years, the percentage of cases included in Q_{III} (quadrant with the best situation) decreased as K-Value increased. For incoming inflows with Tr higher than 500 years, all points were located in Q_{III}, regardless of K-Value.

We also analyzed the improvement in absolute terms of ΔZ and ΔO. When analyzing ΔZ, the higher K-Value was, the higher improvement regardless the range of Trs studied. However, when analyzing ΔO there were different behaviors depending on the Trs studied. The improvement of ΔO decreased as K-Value increased for Trs lower than 50 years. Within the range from 50 to 100 years, ΔO decreased or increased depending on the K-Values studied, being the improvement close to zero. For Trs higher than 100 years, the improvement of ΔO increased as K-Value increased. Therefore, the choice of a K-Value will depend on whether the dam manager decide to prioritize the number of events improved or the entity of improvement. Since the maximum reservoir levels decreased for all cases, the hydrologic dam safety is improved but may imply a decrease in downstream safety (increase of maximum outflows). However, as it was stated, for K-Values from one to ten, the outflows obtained did not exceed O_{ALT}, causing no damages downstream the dam for inflows of return periods lower than 25 years.

Table 2. Percentage of cases located in the third quadrant (Q_{III}) for the different range of return periods (Tr) studied depending on the K-Value (K) adopted. First value is associated to the lowest limit of the interval of K-Value studied

K-Value	Range of % of Cases in Q_{III}					
	Tr<10	10<Tr<25	25<Tr<50	50<Tr<100	100<Tr<500	Tr>500
1<K<5	0-0	0-0	72-23	100	100-100	100-100
5<K<10	0-0	0-0	23-4	100-92	100-100	100-100
K>10	0-0	0-0	4-0	92-0	100-93	100-100

In order to quantify the influence of K-Value, we approached the problem applying a risk-based methodology based on [18]. We implemented the overall risk index (I_R) analysis applying the concept of expected annual damage [29], being I_R expressed in euros. We obtained the partial risk indexes associated to the maximum reservoir level (I_Z) and the maximum released outflows (I_O). By adding I_O and I_Z we estimated the overall risk index (I_R). For Talave, the value of K that optimized I_R is 5.25, with a reduction of 8.4% compared with the I_R associated to VEM (Figure 5). Even though it may seem a small reduction, there should be taking into account that applying K-Method has no costs associated and the improvement would be applied during the whole dam life.

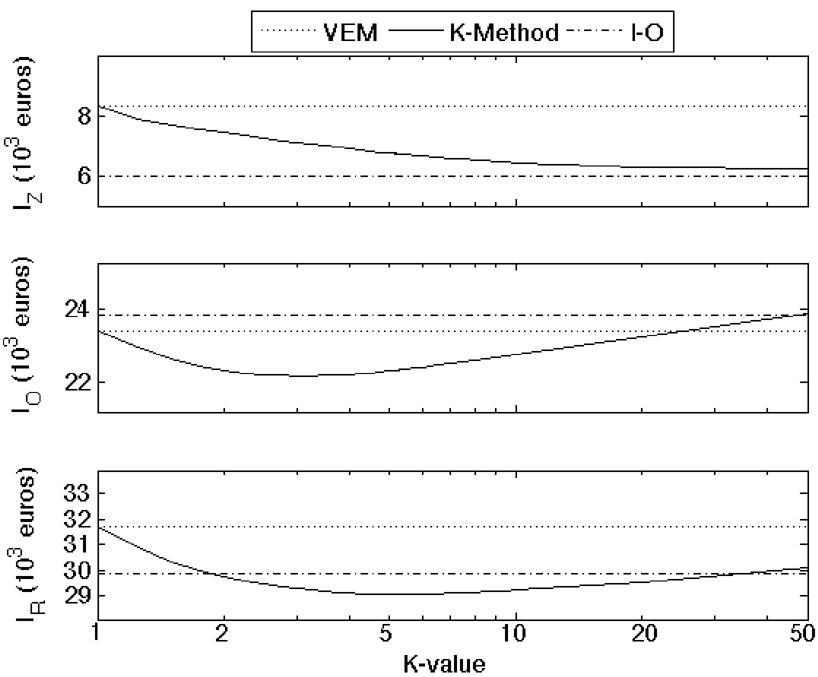

Figure 3. Risk indexes for MEV, I-O method and different values of K-Method. Upper subplot vertical axis shows I_Z, which is the storage risk index. Middle subplot vertical axis shows I_O, which is the released flow risk index. Lower subplot vertical axis shows I_R, which is the global risk index. Horizontal axis shows the different values of K. The optimum K for I_R is 5.25.

5. Conclusions

The proposed K-Method developed in this work improved the Volumetric Evaluation Method (VEM), which is largely used for operation of gated spillways in Spain. It was shown that the best K-Value depends on the dam manager interests:

- Any K-Value adopted (higher than one) reduces the maximum reservoir levels reached in the dam. Therefore, the adoption of K-Method allows the dam manager to reduce the flood control volume increasing the useful water volume in the reservoir.
- For K-Values ranging from one to ten, for the study case, there was an improvement of the VEM for inflows of return periods higher than 50 years.
- For return periods of inflows lower than 25 years, K-Method reduces maximum reservoir levels but increases maximum outflows respect to VEM. Although, the increase of outflows did not endanger downstream safety.
- By carrying out a dam risk analysis, a K-Value of 5.25 was the best reducing 8.4% VEM expected annual damage.

The proposed procedure should be applied to other reservoirs and dams in order to recognize common trends and behaviors.

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Conflicts of Interest: The authors declare no conflict of interest.

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