Article

Stochastic assessment of the influence of reservoir operation in hydrological dam safety through risk indexes

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Abstract: Hydrological dam safety assessment methods traditionally assume that the reservoir is full while it receives the design flood. In practice, reservoir management strategy determines the probability distribution of reservoir levels at the beginning of flood episodes. In this study we present a method to economically assess the influence of reservoir management strategy on hydrological dam safety and downstream flood risk. The method was applied to a gated-spillway dam located in the Tagus river basin. A set of 100,000 inflow hydrographs was generated through a Monte Carlo procedure, reproducing the observed statistics of main hydrograph characteristics: peak flow, volume and duration. The set of 100,000 hydrographs was routed through the reservoir applying the Volumetric Operation Method as flood control strategy. Three different scenarios were studied: initial reservoir level equal to maximum normal level, equal to a maximum conservation level and following the probability distribution of initial reservoir levels. In order to evaluate economically the influence of initial variable reservoir level and compare the three scenarios, a global risk index was applied. The index combines the hydrological risk for the dam, linked to the maximum water level experienced in the reservoir while the flood is routed, and the flood risk in the downstream river reach, linked to the discharge releases from the dam. The results highlighted the importance of considering the fluctuation of initial reservoir level for assessing the risk related to hydrological dam safety. Within the case study, the global risk index reduced its value up to 93 % if variable initial reservoir level is accounted, from 1445.6 x10^3 to 93.0 x10^3 euros.

Keywords: hydrological dam safety; downstream safety; Volumetric Evaluation Method; Global Risk Index; initial reservoir level

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1. Introduction

Failure of Large Dams is a concern in many countries due to the high economic and social consequences associated to it. When designing a dam, engineers usually use techniques to assure that the risk associated to dam failure is low, being the standards applied different depending on the country in which the dam is located [1]. Even though the risk is low, the associated risk must be analyzed and updated, as the dam characteristics and climate conditions may vary along time [2].

The dam risk assessment field has evolved worldwide, with the appearance of different guides and procedures in several countries [3-5] to support dam stake-holders in the decision-making process related to dam safety.

Within this study, we proposed a methodology to analyze economically the influence of initial reservoir level in hydrological dam and downstream safety by the application of economic risk-indexes [6-7]. To do so, a stochastic procedure is proposed. First, we introduce the proposed methodology. Afterwards, we apply this methodology to a dam configuration based on a real case study. Finally, we analyze and discuss the results obtained, highlighting the main conclusions of this study.

2. Materials and Methods

A probabilistic approach was implemented within a Monte Carlo framework. The process was as follows:

- Generation of synthetic inflow hydrographs. An ensemble of synthetic inflow hydrographs representative of the observed historical annual maximum floods was generated.
- Stochastic initial reservoir level assignation. Depending on the scenario studied (a total of three, as will be explained in section 2.2), an initial reservoir level was assigned to each inflow hydrograph.
- Reservoir-Dam system routing. The ensemble of hydrographs was routed through the reservoir, obtaining a set of maximum reservoir levels and maximum outflows for each of the three scenarios studied.
- Risk-Index analysis. By using a global risk index analysis [6-7], we compared all the scenarios economically.

2.1. Generation of synthetic reservoir inflow hydrographs

In several countries, regulations require to consider return periods up to 10,000 years [1]. To assure that the results obtained were representative, a set of 100,000 hydrographs was generated [8-10], applying a methodology previously presented by Gabriel-Martin et al. [11]. This methodology permits to obtain stochastic inflow hydrographs representative of the peak-flow, volume and duration of the observed annual floods. The reader is referred to Gabriel-Martin et al. publication [11] for further details.

2.2. Initial reservoir level. Studied scenarios.

In order to assess the influence of initial reservoir levels, we studied three different scenarios:

- Scenario 1 (Sc.1): For all the 100,000 hydrographs, initial reservoir level was set equal to Maximum Normal Level (MNL).
- Scenario 2 (Sc.2): For all the 100,000 hydrographs, initial reservoir level was set equal to the Flood Control Level (FCL). We defined this level as the level that makes the maximum water reservoir level of return period 1,000 years equal to the Design Flood Level (DFL), fulfilling the regulation standards [12].
- Scenario 3 (Sc.3): For each one of the 100,000 hydrographs, a variable initial reservoir level was assigned. To do so, we analyzed daily reservoir levels measurements in the reservoir.

2.3. Reservoir-Dam system routing. Maximum Water Reservoir Level and Maximum Ouflow frequency curves

For each generated hydrograph (100,000 incoming floods) and scenario we simulated the operation of the dam gates applying the Volumetric Evaluation Method (VEM) [6, 13]. VEM is a real-time flood control method usually applied in Spanish dams. This method is based on four principles:

- Outflows are lower than or equal to the maximum antecedent inflows.
- Outflows increase when inflows increase.
- The higher the reservoir level, the higher the percentage of outflow increase.
- If the reservoir is at maximum capacity, outflows are equal to inflows while gates are partially opened.

At each time step (hourly), the released outflow was the minimum among: a) the outflows proposed by VEM, b) the maximum discharge capacity at the current reservoir level and c) the maximum of the antecedent inflows. Once the gates were completely opened, the spillway structure behaves as a fixed-crest spillway. The initial reservoir level depended on the scenario studied. After applying the VEM to all scenarios, for each scenario we obtained a set of 100,000 reservoir level and

100,000 outflow flood control time series, from which we derived the Maximum Water Reservoir Levels (MWRL) and Maximum Outflows (MO) frequency curves.

2.4. Risk Index analysis.

To carry on an economic assessment of the obtained result, we implemented the global risk index (I_R) analysis proposed by Bianucci et al. [7]. This method accounts for a single indicator of the global risk associated for the MWRL and MO applying the concept of expected annual damage by applying [14] using damage cost curves.

2.5. Limitations of the Methodology

The methodology applied had some limitations that should be noted:

1. Regarding to the inflow hydrographs, the limitations of the methodology are those exposed in [11].
2. Regarding to the flood control operation method (VEM), it has the advantage of its simplicity. However, it is a fixed method that cannot be adapted to the specific conditions of the dam, other than the flood control volume. Other flood control management models could have been tested, for instance K-Method [6].
3. The methodology was applied to one dam with a determined configuration. This could limit the generalization of the results obtained. For instance, results related to initial reservoir level could variate if there are modifications in the regular operation of the reservoir.

2.6. Case Study

The proposed methodology was applied in a case study based on a gated-spillway gravity dam located in the Tagus river basin. The dam is located in the province of Caceres, in the east of Spain. The dam basin has an area of 1,850 km^2. The climate of the region is Continental (mean annual precipitation of 1,000 mm and a mean annual runoff value of 1,020 hm^3). The main purpose of the reservoir is irrigation, having also hydropower generation as a secondary purpose.

The characteristics of the basin and dam-reservoir system configuration are shown in Table 1. The dam spillway consists of 5 gates, each one being ten meters wide by 5.75 meters high, that compose the main spillway. The other operative discharge structure considered is a bottom outlet in the dam body.

To carry on the study, we used a gauge station located at the reservoir location with data of daily flows and reservoir volumes from 1958/59 to 2012/13 (hydrological years, from October 1st to September 30th). With these data, we were able to generate the synthetic inflow hydrographs and generate the initial reservoir levels for Sc.3.

Table 1. Characteristic reservoir levels and spillway of the dam configuration studied.

Reservoir Levels (m.a.s.l)		**Maximum Outflow Capacity at Maximum Normal Level (MNL) (m^3/s)**	
Maximum Normal Level (MNL)	386	Gated-spillway	2200
Design flood level (DFL)	387		
Crest of dam (COD)	388	Bottom outlet	57

3. Results and Discussion

3.1. Generation of synthetic reservoir inflow hydrographs

We generated 100,000 reservoir inflow hydrographs stochastically using the available 55 years of daily reservoir inflow data (1958/59–2012/13). Figure 1 shows the peak-flow volume relationship between the observed and generated sample, showing how the synthetic events represent correctly the main hydrograph characteristics.

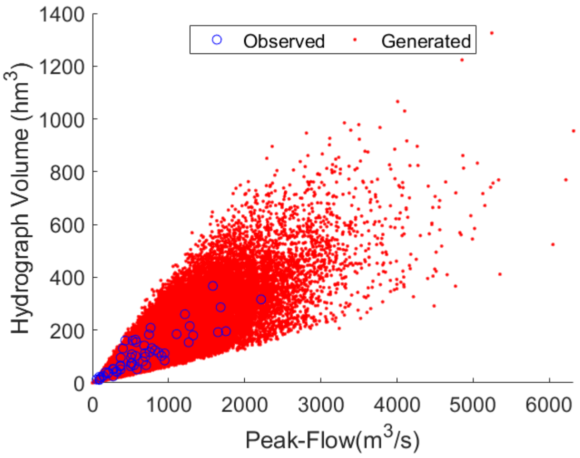


Figure 1. Synthetic inflow hydrograph generation. Sample of 100,000 simulated floods (red dots) and its comparison to the observed floods (blue-edged circles). Horizontal axis shows values of peak-flow, whereas the vertical axis represents the hydrograph volume.

3.2. Initial Reservoir Level Assesment

In order to assess initial reservoir level, we carried out an analysis of observed data:

1. First, we analyzed in which months annual maximum observed flood occurred (1958/59 to 2012/13) and obtained the probability distribution of monthly annual floods.
2. Afterwards, we analyzed the daily reservoir volumes in the reservoir to obtain the initial reservoir volume frequency distribution. To do so, we discarded reservoir data from 1958/99 to 1965/1966, as those years did not represent normal operation years as the reservoir was filling-up [5]. Therefore, we obtained the cumulative frequency distribution of exceedance of the monthly daily reservoir levels using the reservoir level time series from 1966/67 to 2012/13 (Figure 2).

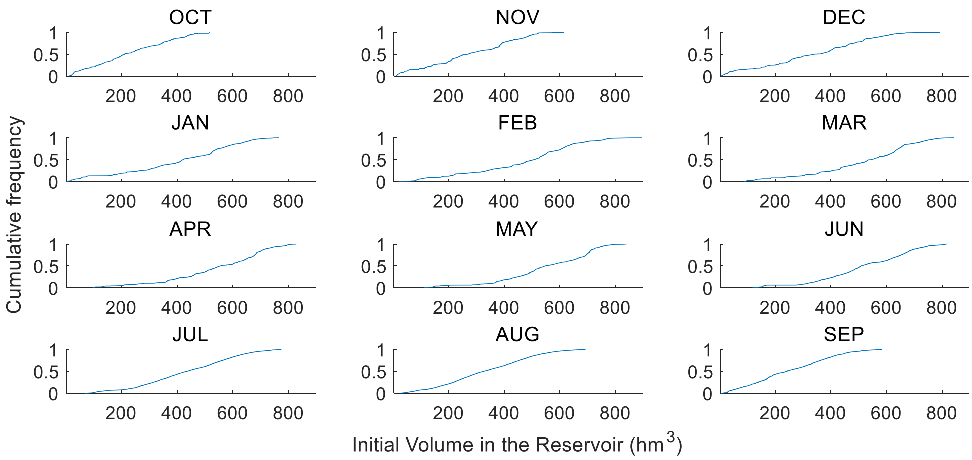


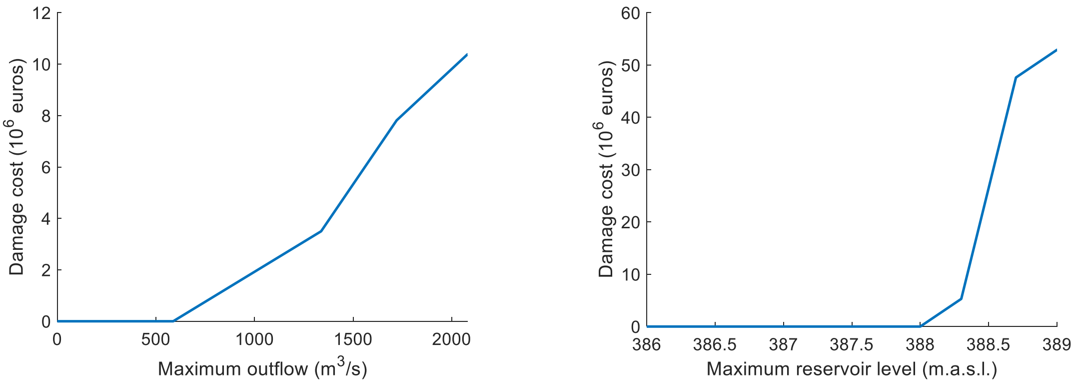
Figure 2. Initial Reservoir Level Assessment. Empirical reservoir level distributions associated to each month of the year.

3.3. Maximum Water Reservoir Level and Maximum Ouflow frequency curves

As exposed in the methodology we obtained 100,000 MWRLs and 100,000 MOs for each one of the three scenarios. These frequency curves were necessary to proceed with the global risk index analysis of section 3.4.

3.4. Risk Index Analysis

We quantified the influence of initial reservoir variability applying the global index procedure [7]. To do so, we obtained damage cost curves associate to the maximum outflows (Figure 3a) and maximum reservoir levels (Figure 3b). We obtained the global risk index for each one of the three scenarios as shown in Table 2.



(**a**) (**b**)

Figure 3. Damage Cost Curves. (**a**) Damage cost curves associated with maximum outflows (**b**) Damage cost curves associated with maximum reservoir levels.

Table 2. Global risk index for the different scenarios.

Scenario 1 I_R **(10^3 euros)**	**Scenario 2** I_R **(10^3 euros)**	**Scenario 3** I_R **(10^3 euros)**
1445.6	980.5	93.0

4. Conclusions

The proposed methodology permits to asses through a stochastic procedure the influence of initial reservoir level and its influence in economic risk indexes. The results obtained showed:

- For the case study, considering the fluctuation of initial reservoir level provided a more realistic assessment of hydrological dam and downstream safety.
- The global risk index reduced its value up to 93 % if variable initial reservoir level is accounted, from 1445.6 x10^3 to a value of 93.0 x10^3 euros in the case study.

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Author Contributions: Ivan Gabriel-Martin proposed the methodology, conducted the numerical experiments and participated in paper writing; Alvaro Sordo-Ward and Luis Garrote participated in the analysis and discussion of results, contributing to the general idea of the research; and Isabel Granados helped in the general idea of the research and wrote the English edition of the manuscript.

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