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Flood routing studies in risk analysis

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ABSTRACT: While developing a Risk Model, the flood routing analysis' objective is to provide the system loading (peak reservoir levels, overtopping durations, discharges …). In order to accomplish this, the needed data are: incoming hydrographs, starting pool levels, spillway and outlet works properties (including functionality), reservoir physical properties and flood routing procedures. This leads to a parametric flood routing analysis, considering all the possible permutations of input variables. All this is done from a probabilistic point of view.

The present article proposes a framework to carry out these analyses and to include them in Quantitative Risk Models. This framework is valid both for individual dams and systems of dams. Results for several case studies are presented.

1 INTRODUCTION

Flood routing is one of the main functions of dams and arguably the one that most affects the safety of downstream towns. Compared to the flood's potential damage, the dam reduces downstream damages, delaying the start and flattening the hydrograph's peak. Besides, if the reservoir level is below its full capacity, the volume of the outflow hydrograph will be smaller than the one entering the reservoir.

In Risk Analysis, flood routing studies are focused in obtaining the response of the dam-reservoir system to the hydrological loads, through the calculation of the outflow hydrographs and the evolution of reservoir levels, providing the data needed to:

- Calculate the downstream consequences of outflow discharges.
- Estimate the probability of reaching certain loads (peak reservoir level, possible overtopping and its duration, etc), which shall be used to quantify the probability of dam failure.

2 INPUTS NEEDED IN FLOOD ROUTING ANALYSIS

Flood routing analysis requires several data inputs, in order to correctly define the operation of the dam and the conditions to which it is being subjected.

2.1 *Inflow hydrographs*

The inputs related to the reservoir inflow are obtained from hydrological studies of the catchment area, which are usually available for existing dams. For these studies to be useful to the risk analysis they should estimate a series of inflow hydrographs for different return periods, (usually at least to 10,000 years, but sometimes higher return periods are needed). In case the available data do not cover the desired range of return periods, they may be extrapolated using a variety of methods; the range of applicability of extrapolations depends on the type of data used for flood frequency analysis (Swain et al., 1998).

2.2 *Previous level*

A previous pool level in the reservoir when the flood begins shall be provided as a starting point for the flood routing analysis. It will also determine its initially stored volume.

A non-exceedance probability distribution for the previous level can be obtained through the analysis of the reservoir's historical data, or synthetic level series. While using historical data, some postprocessing might be needed, to ensure that the conditions represent the reservoir level *before* the flood starts.

2.3 *Characteristic curve of the reservoir*

The characteristic curve provides the water volume stored in the reservoir for any pool level. These data are usually available in the dam's safety file.

2.4 *Discharge-elevation curves of spillways and outlet works*

Discharge-elevation curves of spillways and outlet works provide the dam-reservoir system's response to hydraulic loads. Knowing the characteristics of the spillways and outlet works in the dam, these curves will give the outflow discharge as a function of the reservoir water level and the opening of the regulation gates. These curves are usually available in the dam's safety file, although they can be calculated from standard formulas (Sentürk 1994, SPANCOLD 1997, USBR 1987).

2.5 *Gate operation procedures*

When any of the spillways or outlet works has regulated gates, an operation procedure must be defined as an input to the flood routing analysis, in order to determine the desired outflow discharge at any given moment. These procedures will usually be defined depending on a variety of factors, such as the reservoir's water level and its evolution, the inflow discharge, time, etc. They are sometimes detailed in the dam's operating rules (although it should be checked if they are updated and currently in use) or might be provided by the dam's personnel.

2.6 *Gate functionality*

In flood routing studies, the possibility of gates failing to open should be taken into account. Since usually a dam has several gates (or several outlet works) used for flood routing, all the different combinations of gate functionalities have to be considered. Thus, each gate functionality combination will generate a different dam response, leading to different loads on the system.

Functionality probabilities are not directly included in flood routing analysis, but they are considered afterwards in the risk model.

3 FLOOD ROUTING CALCULATION

3.1 *Individual dam analysis*

In a hydrological system, the inflow $I(t)$, outflow $O(t)$ and storage $S(t)$ variables are related by the continuity equation (Chow et al., 1997):

$$\frac{dS}{dT} = I(t) - O(t) \tag{1}$$

There are several ways in which this expression can be solved using a temporary discretization. In a general way, the implementation of the flood routing follows the natural processes that are taking place in these events, integrating the input data described in previous sections.

A balance in any time step is established in the reservoir between the previous volume, the inflow discharge (given by the inflow hydrographs) and the outflow discharge (through the spillways and outlet works). For example the following steps can be followed:

1. Initial reservoir conditions are defined: previous pool level PPL and storage S_0.
2. Calculation of the inflow discharge to the reservoir $I(t)$ resulting of the inflow hydrographs.
3. Calculation of the outflow discharge Q_{OR} (determined by the dam's Operating Rules).
4. Calculation of the maximum outflow discharge $Q_{\max}$ (determined by the maximum capacity of the spillways and outlet works), and the overtopping discharge $Q_{overtop}$.
5. Calculation of the storage increase ΔS in the reservoir as a balance between inflow and outflow.
6. Calculation of the storage S and pool level H resulting from the storage increase ΔS in the previous step.
7. Restart of the process from Step 1 until the end of the inflow hydrograph.

The general diagram for obtaining the flood routing is presented in Figure 1, including the necessary data in each step.

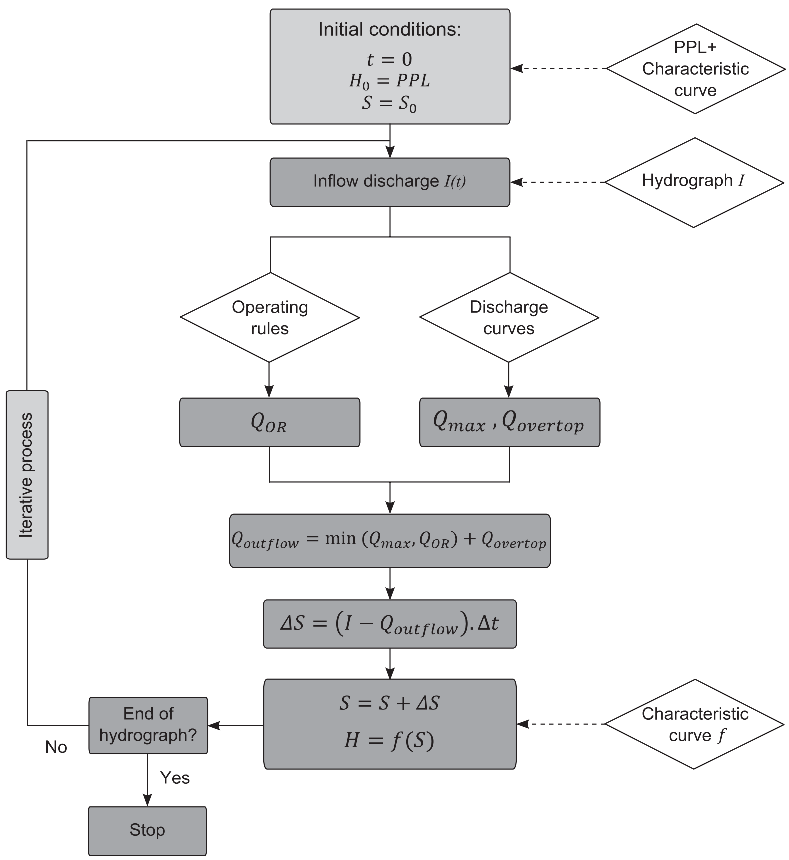

Figure 1. Flood routing flow chart.

3.2 *Dam system analysis*

Considering a system of n dams, called 1, 2, 3 … (where dam i is upstream of dam $I + 1$, and downstream of dam $I - 1$) the hydraulic loads on each dam depend on the natural inflow hydrology of its catchment area, as well as on the upstream dam outflows.

If rainfall events are happening on the catchment area between dam i and dam $i - 1$, rainfall can be in the same order of magnitude in the catchment areas of dams $i - 1$, $i - 2$ …, and produce other inflow discharges which shall determine outflows in these dams. So, when calculating the flood routing analysis of dam i, the possible outflows of upstream dams can be considered, since they determine an additional hydraulic load. These inflow discharges will be added to the flows coming from the intermediate catchment areas.

Also, when considering the transmission of an outflow discharge into a downstream reservoir, the natural attenuation of the hydrograph due to transit along the intermediate river bed should be considered. In the case of dams separated by relatively large distances, the assumption of the upstream discharge entering the downstream reservoir—instantly or with a time delay- could lead to overestimated peaks in the inflow. Several methods ranging from complex hydraulic models to simplified equations like the Muskingum one (Chow 1998) can be used to route the hydrograph between two reservoirs.

When analyzing a system of two dams, considering the possible failure of the upstream dam will double the number of scenarios to study. This consideration increase the complexity of the studies, so, before implementing them, their importance, with the relative size of the separate reservoirs and catchment areas, should be analyzed.

In a risk analysis of an individual dam, where the dam is part of a multiple dam system, it may be sufficient to consider that the previous pool levels of the rest of the dams are fixed at their Maximum Legal Levels, and that their spillways and outlet works are always working properly. However, if a detailed analysis is intended, the complete studies of previous levels, gate functionality, etc should be integrated in the model.

In a system with several dams in series or in parallel the hydrograph entering the downstream reservoir depends not only on the flood entering the system but also on whether the upstream dams fail or not.

4 INSERTION IN THE RISK MODEL

The influence diagram (Serrano-Lombillo et al., 2009) of a generic risk model is represented in Figure 2. Each one of the nodes represents a variable. Flood routing analysis is used to obtain the information for nodes "Maximum Pool Level" and "Dam Outflow Hydrograph" in the risk model. Depending on the studied failure modes, some other outputs, such as the duration of an overtopping, may be needed.

In order to integrate the results into the risk model, it is necessary to repeat the flood routing process for each possible combination of:

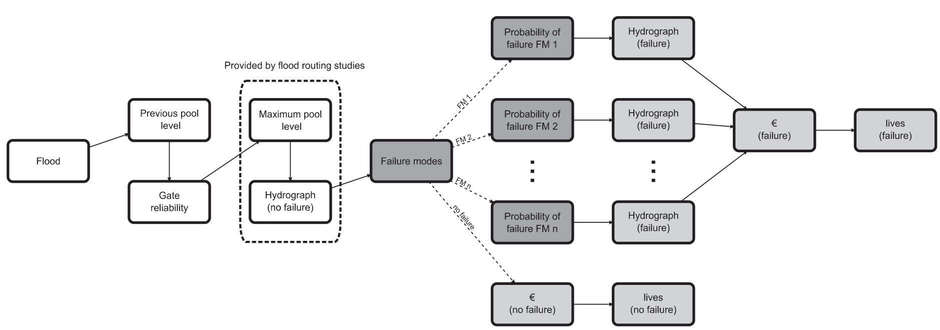

Figure 2. Integration of flood routing analysis in risk models.

– Previous Pool Level.
– Incoming flood.
– Functionality of the spillways and outlet-works.
– Any other variable contributing to the flood routing.

The amount of generated data is important, to a larger or lesser degree, depending on the number of combinations. They should be studied by extracting a selection of the results considered most relevant, such as peak pool levels, peak outflow discharge, height and duration of overtopping, speed of level decrease, etc. The study of these results through different charts can help to understand how the system reacts to the loads it may be subjected.

Once all flood routings are calculated the results must be integrated into the risk model through a relation between different variables. For each combination of flood, previous pool level and gate functionality, the peak reservoir level, downstream hydrograph and characteristics of the overtopping (if any) are determined (other variables could be obtained, if needed).

When all these combinations are mixed in the risk model with their corresponding probabilities, the results are the exceedance probability curves of the output variables (peak reservoir level, depth of overtopping, etc.), which define the loading part of the risk equation.

5 CASE STUDY

The presented methodology has been successfully applied to a portfolio of 27 dams (numbered from 1 to 27). The purpose of this study was to obtain the data needed for a full Quantitative Risk Analysis, however, only the results of depth of overtopping and overtopping probability are discussed next.

Overtopping depths (maximum pool level minus dam crest level) are shown in Figure 3 with each dam subjected to its 10,000 years return period flood and considering all spillways and outlets as fully operative. The annual probability of overtopping appears in greyscale (black: higher probability, grey: intermediate probability, white: smaller probability) (see also Figure 4).

Analysis of this portfolio also included an evaluation of the overtopping probability of each dam. In Figure 4, each probability of overtopping as a result of flood analysis is shown, using the same greyscale as Figure 3.

A synthesis of the hydraulic/hydrological characteristics of the dams is represented in Figure 5, with Freeboard storage/Total flood volume ratio on the horizontal axis and Spillway

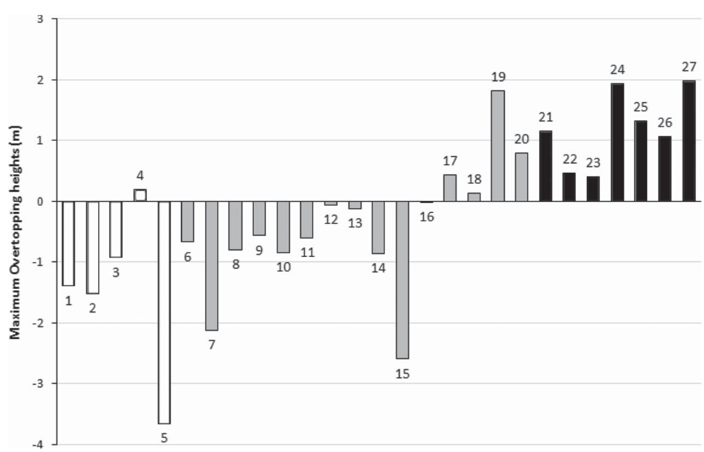

Figure 3. Maximum overtopping heights in a portfolio of 27 dams, with each subjected to its 10,000 years return period flood.

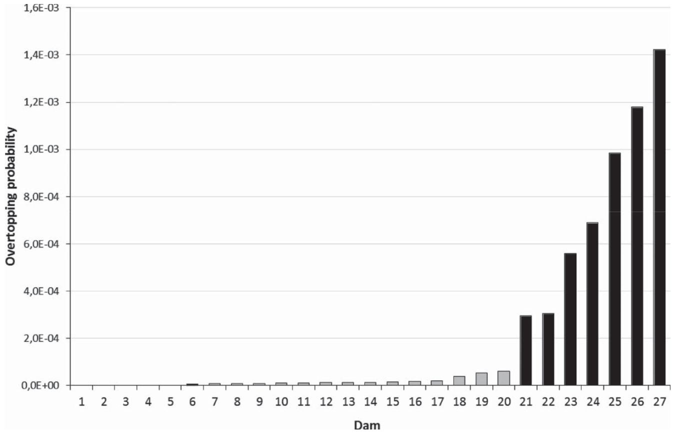

Figure 4. Individual probabilities of overtopping in the portfolio of 27 dams, calculated in the risk model.

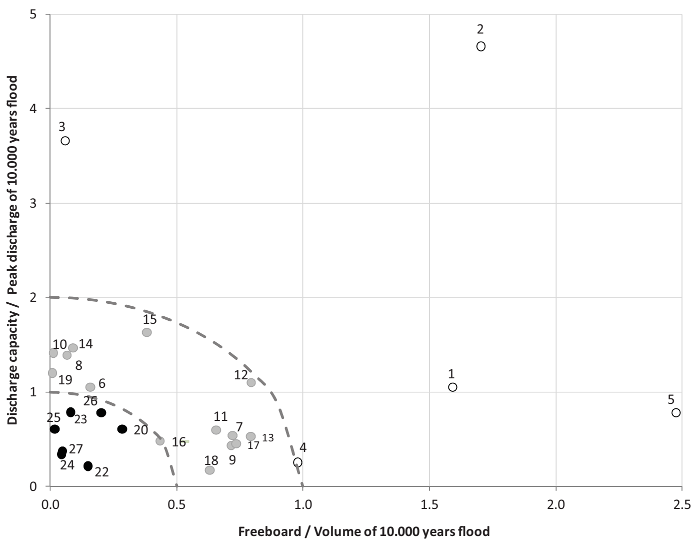

Figure 5. Spillway capacity/Peak discharge ratio vs. Freeboard storage/Total flood volume ratio on the portfolio of 27 dams with each dam subjected to its 10,000 years return period flood, with overtopping probabilities on greyscale (black: higher probability, grey: average probability, white: zero probability).

capacity/Peak discharge ratio on the vertical axis (10,000 years return period floods were considered). In these results there is a clear correlation between the probability of overtopping (in the same greyscale as Figures 3 and 4) and the dam characteristics' stress in flood routing. Three areas can be defined: the first one (black points), near to the origin, includes dams with a high probability of overtopping; the second one (grey points) includes dams with an intermediate probability of overtopping; and finally the third one (white points) represents dams with zero or very low overtopping probability.

This leads to understand how the hydraulic safety depends strongly on two components:

– Hydraulic characteristics of the dams: discharge capacity and volume of storage/freeboard.
– Hydrological loads of the system: peak discharge and volume of flood.

Thus, by defining and representing these data properly, it is possible to have an overview of the dam's safety and to draw a qualitative diagnosis from a hydrological point of view, starting from more or less reliable information about the dams.

6 CONCLUSIONS

Flood routing analysis is a useful method to estimate the response of dams (single or as a connected system) to hydrological events, involving a wide range of flood return periods, as well as separate configurations of starting pool levels and spillways/outlets functionality.

The information required is usually available in the dam's safety file, although its accuracy and validity should be checked through a comprehensive review and site inspection. The analysis shall reproduce the characteristics of the dam and the way it is operated during a flood. Calculations are performed through storage balance in time steps, resulting in data series describing the evolution in time of each output variable during the flood event.

Technical documents usually include basic flood routing studies, although they are often restricted to a few limited cases and conditions. Their integration in a risk model demands a more comprehensive approach, extended to a wider range of hydrological return periods, previous pool levels and dam conditions.

Flood routing analysis is a fundamental step in building a dam risk model, providing the loads of the system, which are included in the corresponding nodes.

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