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Extreme flood abatement in large dams with gate-controlled spillways

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SUMMARY

In this study the flood abatement effect at dams with gated spillways under a wide range of extreme floods is analysed (100 < return period <10,000 years). A group of integrated models (rainfall generator, hydrological model and dam operation model) interacting within a Monte Carlo simulation framework is used for producing numerous hydrologic events at 21 sites across mainland Spain, and the hydrologic response applied to 81 configurations of dams and reservoirs. Common behavioural patterns are identified and dimensionless coefficients classified, based on the hydrologic variables and the dam and reservoir characteristics. The relationships between these coefficients are analysed, with a significant degree of correlation both among the cases and the varying magnitude of floods being obtained. Finally, models that enable evaluation of the abatement capacity of a dam with a gated spillway in the event of a flood with *Tr* between 500 and 10,000 years are offered. In addition, they allow the frequency curve of such a maximum flow to be obtained, something which could serve of use not only during the design phase but also in the evaluation of the hydrologic safety of dams.

1. Introduction

The advent of new regulations and standards aimed at increasing the safety of large dams has influenced design and, in many cases, fomented the need for evaluation of current safety levels and modification of complementary drainage structures. The abatement capacity of a dam will depend on the hydrologic load, the dam and reservoir characteristics, the existing operational rules, the volume to abate floods and other foreseen uses. Dams with gated spillway (GS), which make up 30% of large dams around the world (ICOLD, 2003a), have greater levels of water conservation and flood abatement than those with a fixed-crest (FC) spillway. Such an advantage is due to their manoeuvrability, though they are more susceptible to operational failure (Kleivan and Torbla, 1988; ICOLD, 1998). In Fig. 1 the distinguishing levels and flows of GS dams are shown (ICOLD, 1994).

Abatement capacity can be expressed as the ratio between the maximum outflow discharged by the dam (Q_o) and the maximum inflow at the reservoir entrance (Q_i). For the GS dams, two behavioural patterns may be distinguished, one for frequent flooding (i.e., $10 < Tr < 20$ years for dams and reservoirs with a single purpose as is the case of most hydropower dams, irrigation or water supply, and $50 < Tr < 100$ years for multipurpose dams where flood abatement is important but is combined with others uses) and another for design and extreme floods ($Tr > 500$ years) (ICOLD, 2006; EWG, 2010). In the case of frequent floods the magnitude of abatement is influenced by various factors, such as the initial reservoir water level of the reservoir, the respective operational restrictions and rules, and the existence of flood forecast and warning systems, amongst others. In the case of design and extreme floods, the manoeuvrable capacity of the GS reaches its limit, given that the opening of the gates is at 100% and abatement depends essentially on the relationship among the characteristics of the reservoir, dam and spillway, as well as the hydrologic load on the dam.

Different approaches are used to study the evaluation of hydrologic safety of dams. The event based hydrological methods considering the probable maximum precipitation (e.g.: WMO, 1973; USGS, 1986; FEMA, 2004a,b) or a storm design with a *Tr* associated (e.g.: SPANCOLD, 1992, 1997; DEFRA, 2002) are extensive. With some limitations due to high computational demands, continuous simulation hydrological methods are also used (e.g.: Cameron et al., 2000; Boughton and Droop, 2003; Blazkova and Beven, 2004, 2009). Other possible approaches involve flood frequency data analysis (e.g.: USGS, 1982; Rossi et al., 1984; NERC, 1975; Burn, 1990; CEH, 1999), use of paleoflood techniques (e.g.: Benito et al., 1998; Baker et al., 2002; Benito and Thorndycraft, 2004)

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Nomenclature

ARMA	autoregressive moving average
FC	fixed-crest spillway
FNTWL	outflow at normal top water level (m^3/s)
FS	flood storage (hm^3). The part of the active storage (the volume available for use for power generation, irrigation, flood control or other purposes) especially in flood control (ICOLD, 1994)
FSCH	flood surcharge (hm^3). The volume between the NTWL and the MWL (ICOLD, 1994)
GS	gated spillway
ICOLD	International Commission on Large Dams
IL	initial level (meters). Level in the reservoir at the beginning of the flood event
LWG	frequent flood events with a low-to-moderate return period
MWL	maximum water level (meters). The maximum water level, including flood surcharge, which the dam has been designed to withstand (ICOLD, 1994)
NTWL	normal top water level (meters). Maximum level at the dam to which water may rise under normal operating conditions (ICOLD, 1994)
OTF	optimum threshold flow. The value of the threshold flow that reaches the best linear fit to the UPG and LWG (m^3/s)
OTF_y	value of Q_o corresponding to the OTF (m^3/s)
PFC	peak flow coefficient
Q_i	maximum inflow at a reservoir (m^3/s)
Q_o	maximum flow discharged by a dam (m^3/s)
SPANCOLD	Spanish National Committee on Large Dams
TF	threshold flow. Values of Q_i that determine different LWG and UPG (m^3/s)
TFC	threshold flow coefficient
TFC_y	threshold flow coefficient but using OTF_y
Tr	return period (in years)
UPG	group of flood events with a high return period ($500 < Tr < 10{,}000$ years)
USC	upper slope coefficient. The slope of the line of fit of the UPG for TF = OTF. Represents the mean efficiency of the peak flow abatement for higher floods (UPG)
VC	volume coefficient
VEM	volumetric evaluation method (Girón, 1988)
V_i	volume of the inflow hydrograph (hm^3)

and the analytical probabilistic approach (e.g.: Eagleson, 1972; Rodriguez-Iturbe and Valdés, 1979; Quader and Guo, 2006), among others. In Spain, it is common the use of a design storm with a *Tr* associated and a hydrometeorological model to obtain a design flood with the same *Tr*, a hypothesis which, according to Adams and Howard (1986), Alfieri et al. (2008) and Viglione and Blöschl (2009), is not necessarily true (SPANCOLD, 1992; 1997; Minor, 1998; ICOLD, 2003b). Such an approach is essentially a deterministic one using a single probabilistic concept, which associates a *Tr* with a design storm. Other processes involved in dam safety analysis are defined in accordance with project criteria and included in a deterministic manner (e.g.: storm durations, initial soil moisture conditions, parameters characterising the runoff generation, initial reservoir level). Recently, probabilistic methods have emerged which allow clear representation of the stochastic nature of not only hydrologic variables but also those associated with abatement in the reservoir (Arnaud and Lavabre, 2002; Aronica and Candela, 2007; Blazkova and Beven, 2009; Burton et al., 2010).

Study of the abatement effect at reservoirs has been carried out in prior studies by making simplifications. Marone (1964) for instance, presented (for fixed-crest spillways (FC) and specific shapes of inflow hydrographs) the linear relationship $Q_o/Q_i = 1 - (FCSH/V_i)$, being FCSH the flood surcharge (volume between the normal top water level and the maximum water level; ICOLD, 1994; Fig. 1) and V_i the inflow hydrograph volume. This linear relationship showed similar results to those offered by Sordo-Ward et al. (2012). Marone (1971) extended his previous results to the analysis of the flood abatement of gated spillways with different open positions, although without applying any gate operation during the flood event. Sordo-Ward et al. (2012) emphasised the general behaviour of the abatement effect and considered a wide range of basin area sizes, hydrologic loads, and reservoir and FC spillway configurations. Hager et al. (1984), Hager and Sinniger (1985) and Horn (1987) obtained results in graph form in which they estimated lamination by considering parameters dependent on the form of the hydrograph (Q_i), the period prior to the peak of the hydrograph (tp), the dimensions and shape of the reservoir and spillway. For instance, Hager and Sinniger (1985) adopted a single peak inflow hydrograph at the entrance of the reservoir shaped with the Maxwellian distribution and applied it to FC spillways. Horn (1987) used the dimensionless unit hydrograph from the United States Soil Conservation Service adjusted by the Pearson type III density distribution function and applied it to reservoirs with FCs and orifice spillways. In a further study, Akan (1989) considered multiple *Tr* floods and included dimensionless coefficients in common flow equations at a reservoir and, using finite difference models, showed in graphic form lamination by taking into account the coefficients defined. For the entrance to the reservoir, the analysis used a dimensionless unit hydrograph from the aforementioned United States Soil Conservation Service and applied it to FC spillways. Hong (2008, 2010) estimated the lamination at an orifice and FC reservoir from a numeric model based on the hydrologic continuity Equation and the Runge–Kutta numerical method and considering trapezoidal and triangular inflow hydrographs. Additionally, the analytical probabilistic method has also been applied to the study of the abatement effect of detention ponds at urban catchment areas. A continuous rainfall series is divided into discrete rainfall events and exponential probability distributions are used to approximate the observed frequency distributions of rainfall event volume, duration and interevent time (Eagleson,

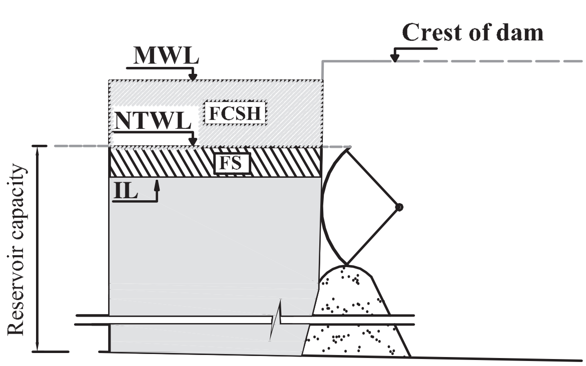

Fig. 1. Terms used in the study. Flood storage (FS), flood surcharge (FSCH), normal top water level (NTWL), maximum water level (MWL), initial level (IL). Each term is explained in the list of acronyms and other terms section.