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A stochastic methodology to assess the impact of climate change on the Eugui hydrological dam safety (Spain)

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Abstract

Climate change is increasing the frequency and magnitude of extreme rainfall events, exacerbating flood risk in urban areas. Floods represent the main cause of dam overtopping. Therefore, a warmer climate can affect hydrological dam safety, leading to an increase of overtopping probability in the future. In this context, new methodologies are required to assess the impact of climate change on hydrological dam safety. This study provides a stochastic methodology that considers the impact of climate change on floods (inflow hydrographs in the reservoir) and on the probability of a given water level in the reservoir in the future. Moreover, an uncertainty chain analysis is done to consider all the sources of errors in the methodology. A fully distributed hydrological model, the Real-time Interactive Basin Simulator (RIBS) model, is used to assess the impact of climate on flood quantiles at a sub-daily scale. The continuous HBV hydrological model is combined with a reservoir operation model to assess the future initial reservoir water level frequency at a daily scale. An ensemble of 12 climate models provides the climate projections for two emission scenarios (RCP 4.5 and RCP 8.5) and three time windows (2011-2040, 2041-2070, 2071-2100). The results show an increase in the future of maxima reservoir water levels associated with the most extreme events, especially in the 2071-2100 time window and RCP 8.5. Overtopping probability also increases in this latter scenario, while no changes are expected for the RCP 4.5.

Keywords: Climate change; Hydrological dam safety; Floods

1. INTRODUCTION

In a warmer climate, extreme rainfall is expected to increase in magnitude and frequency (Donat et al. 2016). Therefore, floods risk is also expected to be exacerbated in the future under some Representative Concentration Pathways (RCP). For instance, Alfieri et al. (2015) found an increase of the 100-year flood on average in Europe in the RCP 8.5. Therefore, quantifying the expected changes on floods is important to plan adaptation strategies (IPCC, 2014). Floods are the main driver of dam overtopping (Costa, 1985), which caused almost 30% of all dam failures occurred over the last century worldwide (Jandora et al., 2008). For this reason, the intensification of extreme weather due to climate change can also impact hydrological dam safety.

Fluixà-Sanmartin et al. (2018a) state that most of the studies that analyze climate change and dam safety tend to focus only on the change assessment of inflow hydrographs in the future (Bahls and Holman, 2014; Chernet et al., 2014) neglecting other aspects, such as future variations in initial reservoir water levels.

This study presents a methodology based on a stochastic procedure that considers both the impact of climate change on floods and initial water levels in the reservoir, also quantifying the uncertainty in the procedure. Indeed, considering uncertainty in design rainfall estimation is crucial in dam safety analysis, as high return periods are involved in such analyses. Moreover, the proposed methodology also considers the uncertainty in the hydrological models, i.e. the residual model errors after their calibration. The Eugui Dam on the Arga River basin has been selected as case study.

2. Data and Case study

The case study is the Eugui Dam within the Arga River Basin in northern Spain. The river basin upstream to the dam is 69 km^2 and it is used for water supply and flood regulation of the downstream city of Pamplona (Figure 1). The data required for the methodology are divided into observed data, useful for the current scenario analysis, and climate projections, to assess the impact of climate change. The observed data are water level measurements at the reservoir, outflow discharges released by the dam, and rainfall and temperature time series. Observed data are used to calibrate the hydrological models (Section 3). Moreover, observations are also used to evaluate the hydrological dam safety of the current scenario.

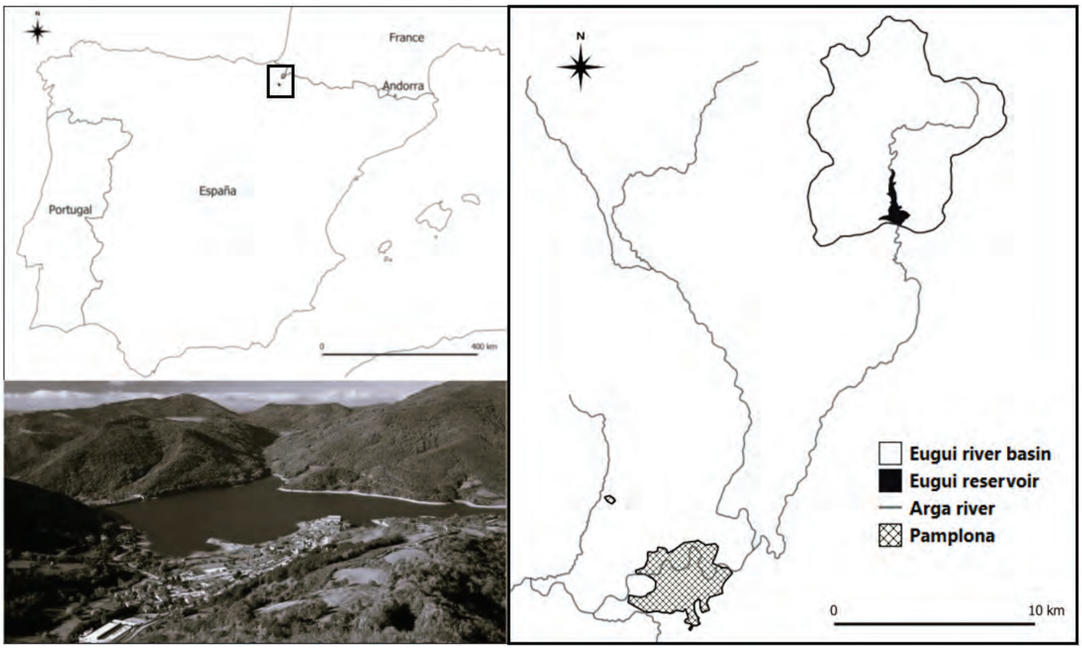

Figure 1. Eugui reservoir on the Arga River in Northern Spain

Climate projections are supplied by 12 climate models (Table 1) for two emission scenarios, RCP 4.5 and RCP 8.5, and three time windows in the future (2011-2040, 2041-2070 and 2071-2100).

Table 1. Ensemble of climate model used in the study

ACRONYM	**GCM**	**RCM**
ICH-CCL	ICHEC-EC-EARTH	CCLM4-8-17
MPI-CCL	MPI-ESM-LR	CCLM4-8-17
MOH-RAC	MOHC-HadGEM2-ES	RACMO22E
CNR-CCL	CNRM-CM5	CCLM4-8-17
ICH-RAC	ICHEC-EC-EARTH	RACMO22E
MOH-CCL	MOHC-HadGEM2-ES	CCLM4-8-17
IPS-WRF	IPSL-CM5A-MR	WRF331F
IPS-RCA	IPSL-CM5A-MR	RCA4
MOH-RCA	MOHC-HadGEM2-ES	RCA4
ICH-RCA	ICHEC-EC-EARTH	RCA4
CNR-RCA	CNRM-CM5	RCA4
MPI-RCA	MPI-ESM-LR	RCA4

3. Methodology

The methodology is divided into three main phases, which are further characterized in several steps (Figure 2): assessment of the impact of climate change on floods (i-iv); evaluation of expected water level frequency curve in the future (v-viii); hydrological dam safety analysis (ix-xi). The quantification of the expected changes in flood quantiles is done with the fully distributed Real-time Interactive Basin Simulator (RIBS) model (Garrote and Bras, 1995 a and b). This analysis has been done to assess the future fluvial flood hazards in the city of Pamplona with an ensemble of climate models in Lompi et al. (2021). Nevertheless, expected changes in flood quantiles are also available for the Eugui reservoir, as RIBS provides the results in each cell of the domain. The calibration of the RIBS model (i) has been done using the most extreme flood events occurred in Pamplona, identified by using a peak-over-threshold analysis with the data recorded at a hydrometer located in the city. The RIBS model parameters have been randomized with Monte-Carlo simulations, minimizing the model error calculated with a set of objective functions. After the calibration of the model, a Generalized Extreme Value (GEV) distribution is fitted to the maximum daily rainfalls to evaluate design events for seven return periods: 2, 5, 10, 50, 100, 500 and 1000 years. Design rainfalls are spatially distributed with the Thiessen Polygons technique to determine the design floods in the current scenario (ii). Delta changes of rainfall are extracted from Garijo and Mediero (2019), where the authors evaluated the future design rainfalls in the Iberian Peninsula. The spatial distribution of delta changes and design rainfall of the current scenario is combined to determine the future design rainfall fields, which is the input of the RIBS model (iii). By comparing the peak flood quantiles in the current and in the future periods, the quantification of the expected changes in inflow hydrographs in the reservoir is achieved (iv). While the RIBS model is used to assess just the extreme events at the Eugui Dam, the assessment of the changes in reservoir water level frequency is assessed with the combination of a continuous rainfall runoff model (HBV) (Bergstrom, 1976; Bergstrom, 1992), and a reservoir operation model. HBV needs just three climatic inputs: rainfall, temperature, and potential evapotranspiration, which is determined externally with the Hargreaves equation (Hargreaves, 1981; Hargreaves, 1985) in both the current and future scenario. First, HBV is used to determine future inflow discharges in the reservoir with a daily time step, after its calibration (v). Then, a reservoir operation model is developed to simulate daily outflow discharges in the future, considering environmental flows, water supply demands for the city of Pamplona and flood routing of the most extreme daily inflow discharges obtained with the HBV model (vi). Variations in reservoir storage volumes (and reservoir water levels) are assessed by using a mass balance that considers inflow and outflow discharges, obtaining the time series of simulated daily reservoir water levels for both the current scenario (vii) and the future scenario (viii). A stochastic procedure is used to generate random inflow hydrographs associated with random initial water levels in the reservoir (ix). Two independent probability vectors of 10 000 values, extrapolated from a uniform distribution, are generated, as there is no evidence of a potential correlation between observed flood peaks and initial reservoir water levels. The relationship between probability and inflow peak is obtained with GEV distributions that are fitted to the outputs of the RIBS model. The random initial reservoir water levels are generated associating the reservoir water level frequency curve of the current and future scenarios with the random probabilities. Therefore, for each scenario, given by 12 climate models, three time windows and two RCPs, 10 000 flood events are modelled in the reservoir with the Volumetric Evaluation Method (VEM), which is a routing flood process (xi) developed for dams with gated spillway (Girón, 1988). The outputs of the VEM are 10 000 maxima reservoir water levels, one for each flood event.

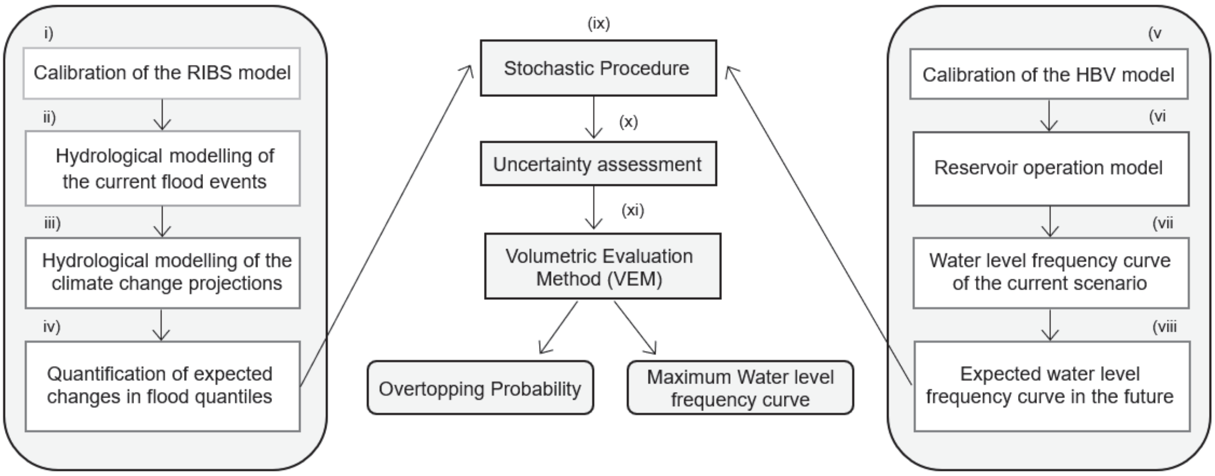

Figure 2. Flowchart of the methodology.

Moreover, uncertainty is assessed to identify the main sources of error in the methodology. First, while uncertainty in the estimation of rainfall quantiles is obtained by generating 10 000 rainfall series for each scenario, the RIBS and HBV models uncertainties are considered by generating 10 000 model errors from a normal distribution. In these latter cases, the normal distribution are fitted to the observed model errors, i.e. the residual error evaluated as the difference between observed and modelled discharges after the calibration of the two models. After the incorporation of the uncertainty, seven percentiles are extracted from the 10 000 simulations for each scenario: 5%, 10%, 32%, 50%, 68%, 90% and 95%. The results of this study are expressed as delta changes of maxima reservoir water levels, i.e. the difference between the future and current maxima reservoir water levels associated with a given return period. Moreover, the overtopping probability is calculated in each scenario as the exceedance probability of the overtopping threshold that is obtained considering the elevation of the dam crest and the effect of potential wind waves.

4. RESULT AND DISCUSSION

The results are shown by using the maximum reservoir water level frequency for the ICH-RCA climate model in the RCP 8.5 and 2071-2100 time window, as an example. The thickest black line represents the median value of the results after the incorporation of the uncertainty, while the grey lines show the other percentiles. The black solid circles are the results obtained for the same model and scenario using the methodology without the uncertainty analysis. The grey dashed line is the overtopping threshold, i.e. the maximum reservoir water level before overtopping can occur.

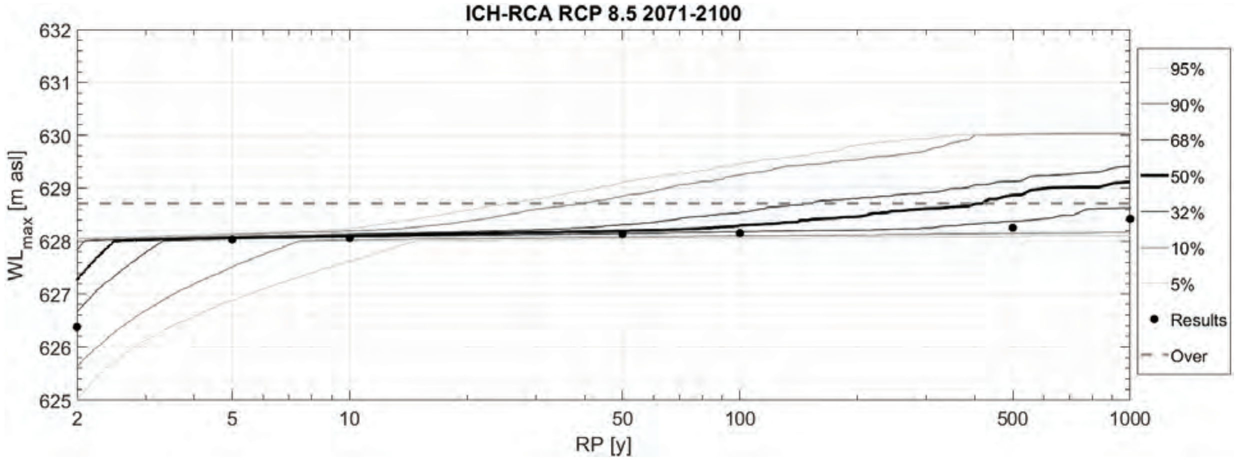

Figure 3. Results of maxima reservoir water levels for the ICH-RCA climate model in the 2071-2100 time window and RCP 8.5. Black solid circles represent the results obtained for the seven return periods without considering uncertainty; lines show the results after the incorporation of the uncertainty; the grey dashed line is the overtopping threshold.

The results show that the maximum reservoir water level for all the return periods between five and 50 years is 628 m a.s.l. Indeed, this is the reservoir water level at which the gated spillways open in flood events. Such a level is constant because dam operations with the gated spillway can release an outflow discharge that can be greater than the inflow discharge. In this scenario, overtopping will occur for a flood event with a return period of almost 500 years, as the median values of the results after the incorporation of uncertainty is concerned. Looking at the black solid circles, overtopping will not occur for events up to the 1000-year return period. Indeed, the evaluation of uncertainty does not give just a confidence level to the results, but highlights how the hydrological dam safety analysis without the consideration of uncertainty can tend to underestimates in the results. Nevertheless, a complete overview of the results can be obtained only with the ensemble of all the climate models.

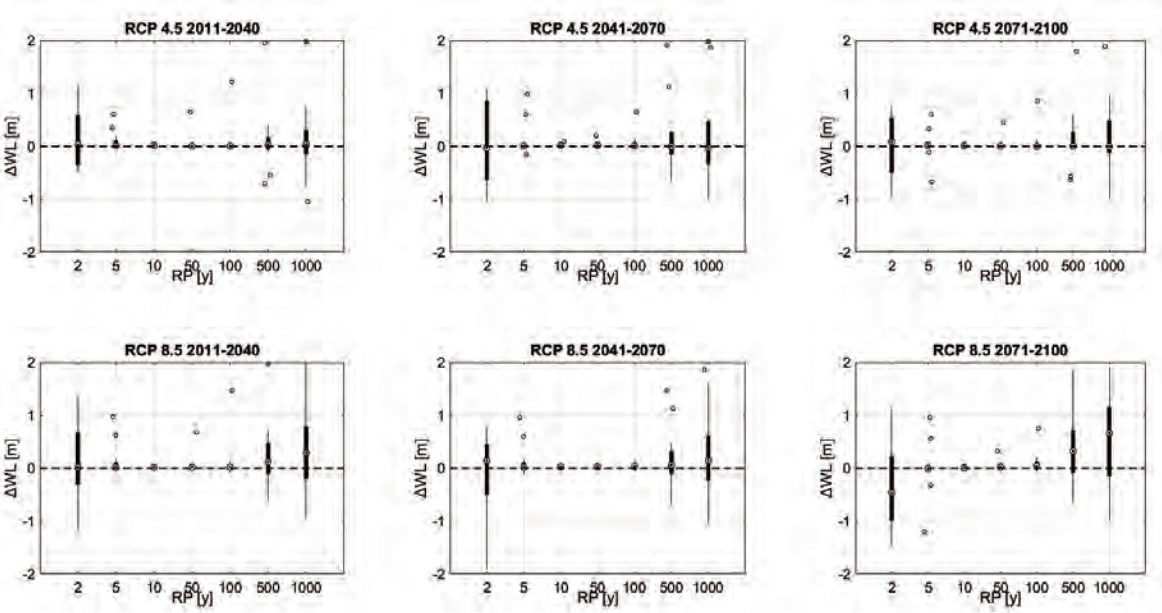

Figure 4. Boxplots of delta changes of maxima reservoir water levels in the two emission scenarios and three time windows, obtained with the ensemble of the 12 climate models after the incorporation of the uncertainty.

Figure 4 shows the delta changes in maxima reservoir water levels achieved in flood events for the three time windows and for the two emission scenarios obtained with the median values of the results. Empty black circles represent outliers, the marked circles are the median values of the boxplot, the thickest black line is the interquartile range. Delta changes of maxima reservoir water levels associates with return periods between five and 100 years are zero in all the scenarios, because, as in Figure 3, almost all the climate models have a maxima reservoir water level equal to 628 m a.s.l. both in the future and current scenario. A higher variability is evident in the maxima reservoir water levels with return periods of two, 500 and 1000 years. Nevertheless, the median values of the boxplots are positive, pointing to an increase in flood risks at the Eugui dam, only for the most extreme events in the RCP 8.5, especially in the 2071-2100 time window. The increase of maxima reservoir water levels will also lead to an increase in the overtopping probability for the same scenario.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Alfieri, L.; Burek, P.; Feyen, L.; Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci*. 19, 2247–2260.

Bahls, V. and Holman, K.(2014). Climate Change in Hydrologic Hazard Analyses: Friant Dam Pilot Study - Part I: Hydrometeorological Model Inputs, Tech. rep., U.S. Department of the Interior, Bureau of Reclamation.

Bergstrom, S. (1976). Development and application of a conceptual runoff model for Scandinavian catchments. SMHI Norrköping, Report RH07.

Bergström, S. (1992). The HBV-Model — Its Structure and Applications. SMHI Reports RH No. 4, Norrköping.

Chernet, H.H., Alfredsen, K., and Midttømme, G.H. (2014). Safety of Hydropower Dams in a Changing Climate, *J. Hydrol. Eng.*, 19, 569–582

Costa, J.E. (1985). Floods from dam failures. Rep. No. 85-560. Denver: US Geological Survey

Donat, M.G., Lowry, A.L., Alexander, L. V., O'Gorman, P.A., Maher, N. (2016). More extreme precipitation in the world's dry and wet regions. *Nat. Clim. Chang*. 2016, 6, 508–513

Fluixá-Sanmartín, J., Altarejos-García, L., Morales-Torres, A., and Escuder-Bueno, I. (2018). Review article: Climate change impacts on dam safety, *Nat. Hazards Earth Syst. Sci*., 18, 2471–2488.

Garijo, C., Mediero, L. (2019). Assessment of changes in annual maximum precipitations in the Iberian Peninsula under climate change. *Water*, 11, 2375

Garrote, L., Bras, R.L. (1995). A distributed model for real time forecasting using digital elevation models. *J. Hydrol.* 7, 279–306

Garrote, L.; Bras, R.L. (1995). An integrated software environment for real-time use of a distributed hydrologic model. *J. Hydrol.* 167, 307–326.

Girón, F. (1988). The evacuation of Floods during the Operation of Reservoirs. In *Transactions Sixteenth International Congress on Large Dams*; Report 75; International Commission on Large Dams (ICOLD): San Francisco, CA, USA, Volume 4, pp. 1261–1283

Hargreaves, G.H. (1981). Responding to tropical climates. The 1980-81 Food and Climate Review, The Food and Climate Forum, Aspen Institute for Humanistic Studies, Boulder, Colo., 29–32.

Hargreaves, G.H., and Samani, Z.A. (1985). Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.*, 1-2, 96–99

IPCC: Climate Change (2014): Impacts, Adaptation, and Vulnerability, Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, Cambridge, UK, New York, NY, USA, 20

Jandora, J., J. Říha, and Vysoké učení technické v Brně. (2008). The failure of embankment dams due to overtopping. Brno, Czechia: VUTIUM

Lompi, M., Mediero, L., Caporali, E. (2021). Future Flood Hazard Assessment for the City of Pamplona (Spain) Using an Ensemble of Climate Change Projections. *Water*, 13, 792