

Abstract

Flood frequency analysis is a cornerstone of hydrological design and flood risk management, yet it remains challenged by pronounced spatial heterogeneity and increasing temporal non-stationarity, mainly driven by climate and land use change. Traditional approaches commonly assume that observations are independent, identically distributed, and stationary over time. These assumptions may prove inadequate to represent evolving flood-generating processes and to support robust decision-making under future hydroclimatic conditions. This doctoral thesis addresses these challenges by making advances towards the development of a spatio-temporal framework for flood frequency estimation, explicitly accounting for uncertainty, also applicable to ungauged or poorly gauged basins.

First, from a spatial perspective, the thesis advances regional flood frequency analysis by introducing a multi-model framework that integrates flood quantile estimates and associated uncertainties from three distinct regional models calibrated on a shared, harmonized dataset. Applied to the Po River basin, this approach yields more robust and stable design flood estimates than the individual regional models. These results provide the basis for a systematic revision of design floods across the Po River basin, supporting an update of flood hazard assessments for hydraulic planning and risk management.

Second, from a temporal perspective, the thesis develops an operational methodology to incorporate precipitation extremes variation into flood frequency analysis. Intensity–Duration–Frequency (IDF) curves and Flood Frequency Curves (FFC) are related through quantile-quantile relationships, whose slopes represent the elasticity of floods to precipitation extremes. Assuming that the percentage variations of precipitation and flood quantiles are linked by the quantile-quantile relationship, modified FFCs accounting for the projected changes in precipitation extremes are obtained. Extensive sensitivity analyses and numerical experiments are conducted to delineate the domain of applicability of the approach. Results show that the method performs robustly for large return periods and in catchments where flood changes are primarily controlled by precipitation extremes, while its reliability decreases where runoff generation processes play a dominant role. Applications to more than 200 catchments in the Po River basin, using CMIP5-CORDEX projections under the RCP8.5 scenario (2071–2100), reveal strong spatial heterogeneity in flood response and a nonlinear amplification of rare flood extremes.

Third, the thesis introduces a Bayesian event-based flood frequency model that explicitly represents storm characteristics, antecedent soil moisture conditions, and temperature-driven processes. This framework enables consistent propagation of uncertainty from climate forcing to flood quantiles and allows attribution of projected flood changes to individual physical mechanisms. Applications to Austrian catchments show that changes in precipitation intensity are the dominant driver of projected flood increases, while also representing the largest source of uncertainty due to climate model spread. Processes related to temperature and soil moisture exert a secondary but more systematic influence, modulating flood response across seasons and return periods with comparatively lower uncertainty. By disentangling the contributions of uncertainty sources, the analysis demonstrates that flood quantile projection uncertainty is driven mainly by (i) parameter-response uncertainty, arising from model parameter uncertainties propagation under future climate conditions, and (ii) climate-forcing uncertainty, reflecting differences among ensemble members of the climate model projections.

Taken together, these results demonstrate that flood frequency curves should be interpreted as dynamic representations of evolving hydrological systems. The thesis highlights the complementarity of the proposed approaches—the combination of different regional models, the method of elasticity for incorporating precipitation change into flood frequency analysis, and the derived distribution approach for the attribution of flood changes to different mechanisms—and provides a flexible toolbox for flood estimation under climate

change. The proposed frameworks contribute to a more transferable and robust assessment of flood hazards, supporting adaptation strategies and hydraulic design in a changing climate.