

Summary

Conceptual rainfall–runoff models are widely used in hydrology and represent a primary tool for generating predictions, particularly in data-scarce contexts. However, in many practical applications, these models are still employed in a deterministic framework, without adequately accounting for the multiple sources of uncertainty affecting their outputs. This thesis provides a comprehensive investigation of uncertainty in conceptual rainfall–runoff modelling, with the dual objective of clarifying its main sources and developing practical tools for its quantification in operational settings.

Chapter 2 begins with the development of a large-scale regional rainfall–runoff model over the Greater Alpine Region, with a focus on reconstructing flood events. This application serves as an example to highlight key modelling limitations, showing how uncertainties increase significantly near extreme events and when models are applied to ungauged catchments. These findings demonstrate that neglecting uncertainty can lead to misleading results, particularly in operational contexts.

Building on this evidence, Chapter 3 investigates the statistical properties of rainfall–runoff model residuals through a large multi-catchment, multi-model study across the continental United States. The analysis focuses on key features such as marginal distributions, dependence structures, and temporal correlations. Both general patterns and catchment-specific behaviors are identified and related to climatic and morphological characteristics. In addition, the impact of residual transformations aimed at stabilizing statistical properties is assessed, highlighting which features can be effectively controlled and which remain inherently difficult to model within standard error modelling frameworks.

Based on these insights, Chapter 4 then explores practical post-processing approaches for aggregated uncertainty estimation. The focus is placed on parametric methods, due to their potential improvements in out-of-sample

applications and regionalization. A first approach consists of a copula-based method (C-method) designed to stochastically generate residual and discharge time series. Its performance is evaluated against established non-parametric resampling techniques, showing comparable performance but also revealing limitations that would require increased model complexity, potentially hindering regional applicability.

To address this issue, in Chapter 5, a second approach is developed, focusing on the direct estimation of confidence intervals without generating full time series. This method, formulated as a parametric copula-based reinterpretation of the BLUECAT (Koutsoyiannis and Montanari, 2022) framework, is implemented in two versions targeting different flow regimes. The introduction of parametric tail modeling allows extrapolation beyond observed extremes. Results indicate performance comparable to non-parametric methods, with improved estimation of uncertainty for high-flow conditions, as confirmed by peak-over-threshold analyses.

Chapter 6 of the thesis addresses uncertainty estimation for predictions in ungauged catchments through a regionalization of the previously proposed parametric BLUECAT framework. Model components, including deterministic predictions, copula dependence structures, and discharge distributions, are transferred to ungauged sites to estimate confidence intervals. The results are again comparable to those obtained with non-parametric approaches, while highlighting areas for methodological refinement.

Overall, the findings do not support, within the tested conditions, the hypothesis that parametric post-processing methods systematically outperform simpler non-parametric alternatives. At the same time, the results identify clear directions for future research, suggesting that further methodological developments may enable parametric approaches to achieve improved performance, especially in ungauged catchments, in uncertainty estimation for rainfall–runoff modelling.