CUMULATIVE DISSERTATION

When extreme floods are not as rare as they seem: controls of heavy-tailed flood peak distributions

by Elena Macdonald

Submitted to the
Faculty of Science at the University of Potsdam, Germany

Prepared at the
Section Hydrology at the GFZ German Research Centre for Geosciences, Potsdam, Germany

Scientific Summary

Many observed time series of streamflow and precipitation exhibit heavy-tailed distributions. This means that the upper tail of a distribution decreases slower than exponentially, leading to a higher occurrence probability of extremes. If we underestimate the tail heaviness of a distribution, we might get caught by surprise when an extreme event happens, which in turn can result in malign and devastating consequences. A recent example of a surprising flood with severe consequences is the flood in the Ahr Valley in the west of Germany in 2021. The distribution which was used to derive flood hazard maps and which was based on systematically recorded flows was nearly light-tailed. In contrast, considering historical floods suggests the distribution to be extremely heavy-tailed. Understanding the controls of heavy-tailed flood peak distributions can make tail estimations more robust and reduce surprises.

Although previous studies have analysed potential causes of heavy tail behaviour of flood peak distributions, partly contradictory results exist and the knowledge is still dispersed and limited. The aim of this thesis is therefore to enhance the understanding of the factors and processes which govern the upper tail of flood peak distributions. The upper tail is here quantified using the shape parameter of the Generalized Extreme Value (GEV) distribution. A positive shape parameter characterises a heavy-tailed distribution. A wide range of potential heavy tail controls is assessed to find their relative importance, and the identified dominant processes are analysed in detail.

Through a literature review, a thorough overview of the current knowledge on flood peak heavy tails is presented, and 9 hypotheses on potential heavy tail controls are formulated. This lays the foundation for a multivariate analysis of potential controls: for 480 German and Austrian catchments, event and catchment characteristics are derived based on the reviewed literature, and their effects on the tail behaviour analysed. This allows the identification of the most important drivers of tail heaviness, and provides insights on the interaction between these drivers. The dominant controls are subsequently analysed in detail through model simulations. A model chain consisting of a weather generator and a hydrological model is set up, first, with spatially homogeneous conditions, and second, with spatially variable conditions.

Runoff generation and rainfall characteristics have been identified as the dominant controls of flood peak tail behaviour. For both, distinct differences between small and large events have been linked with heavy-tailed flood peak distributions. With regards to the runoff generation, process shifts, such as the activation of an additional and faster runoff component, tend to lead to heavy tails. Rainfall distributions have been found to asymptotically control flood peak distributions beyond a catchment-specific threshold return period. In addition, increasing spatial variability of rainfall results in flood peak distributions with lighter tails, especially for large catchments. In general, large catchments tend to have distributions with lighter tails than small catchments.

The findings from this thesis are valuable for the robust estimation of flood peak tails in hydrological practice. They can help to adjust estimations from pure statistical methods through the causal expansion of information. Robust tail estimations are required, for example, for adequate flood design values and hazard maps. The advancements presented in this thesis with regards to heavy tail controls are valuable to reduce underestimation or overestimation of extreme floods.