ON THE CHALLENGES OF ASSESSING TRENDS IN TORRENTIAL FLOODING

« BACK TO CONTENT

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ABSTRACT

Climate change exerts an influence on the occurrence of many natural hazard events. It has done so in the past, and it will continue to do so in the future – with potentially severe effects on mountain communities. While there is clear scientific consensus about general cause-and-effect chains from a physical science point of view, supporting these relationships can be challenging for certain hazard processes from an empirical and data-driven perspective. Here we present some of these challenges taking the example of torrential flooding in the European Alps. We illustrate how these are related to the complexity of the underlying influencing effects, to limitations in terms of data availability and quality, as well as to the requirements imposed by strict statistical reasoning.

INTRODUCTION

Torrential flooding is a common natural hazard in mountain regions world-wide with considerable potential for loss, injuries and fatalities. As opposed to static river flooding, dynamic torrential flooding originates within small and steep mountain headwater catchments and is characterised by constantly or temporarily flowing watercourses with strongly changing perennial or ephemeral discharge and intermittent flow conditions (Schlögl et al., 2021). Torrential flooding thus summarizes various process types occurring in mountain catchments. In general, they are characterized by highly variable discharge and sediment transport volumes with bedload constituting a substantial part of the total load. However, the different process types such as fluvial sediment transport, debris floods and debris flows differ in terms of sediment concentration or peak discharge as well as time of onset, duration and recurrence interval.

With respect to climate change, knowledge about trends in the characteristics of torrential flooding events is needed for a proactive disaster risk reduction in mountain communities. The Sixth Assessment Report (AR6) of the IPCC (IPCC, 2021) focused on changes in intensity and magnitude, frequency, duration, timing as well as spatial extent of a wide range of climate hazards. It has been reported that the confidence about the extent and direction of expected future changes varies by climatic impact-driver and reference regions. Torrential flooding is not specifically investigated as a dedicated process type in AR6, only effects on periglacial debris flows are briefly mentioned in the context of permafrost thawing. Taking a broader view and acknowledging different wording in different hazard communities, low confidence in the direction of change is reported for landslides across a majority of reference regions, with only Asia being consistently characterized by an increase (medium confidence). The situation for river flooding is reported to be heterogeneous, with e.g. a high confidence for an increase in Western and Central Europe and a medium confidence in a decrease in Eastern Europe. Finally, changes in heavy precipitation are reported to increase (medium to high confidence) across a wide range of reference regions. Overall, findings of the IPCC indicate a lack of information on the expected future evolution of torrential flooding and hence imply further need for research.

In order to assess future trends, information about the underlying cause-effect relationships and drivers is fundamental. On the one hand, assessing natural hazard processes by means of numerical process modelling fosters understanding into the physical properties and behaviour of specific processes. On the other hand, statistical analyses of historic data often provide valuable insights into general patterns and interaction effects. In the following, we will focus on the latter and strive to explore the comprehensive list of climate change core characteristics as constituted by the IPCC: intensity and magnitude, frequency, duration, timing and spatial extent. Our analysis is mainly based on data on damage-inducing torrential flooding as collected by the Austrian Torrential and Avalanche Control Service (WLV). Following Heiser et al. (2019), we assume event completeness after 1945, which results in 11,253 torrential events being considered in the period between 1945 and 2022. In addition, we discuss several challenges and limitations associated with the statistical analysis of trends in torrential flooding.

TREND ANALYSES OF CORE CLIMATE CHANGE CHARACTERISTICS

Intensity and magnitude

We used the deposition volume of events as a proxy for event magnitude (Figure 1). A set of non-parametric trend tests (Mann-Kendall trend test, Wald-Wolfowitz runs test, Bartels test) consistently indicated a statistically significant decrease in the deposition volume over time. However, this trend may be attributed to an under-reporting of magnitude for smaller events in earlier years. Changes in the data recording procedure were implemented in 1972 and 2005. While the effect of the changes in 1972 is less pronounced, the percentage of events with a recorded magnitude abruptly almost quadrupled in 2005. Overall, the deposition volume is known for approximately 22 % of events. About 70 % of these events occurred in 2005 or later. Thus, the decreasing trend may very well be a consequence of the higher observation density

regarding information on magnitude since 2005, and thus just a reflection of a bias in the underlying data set.

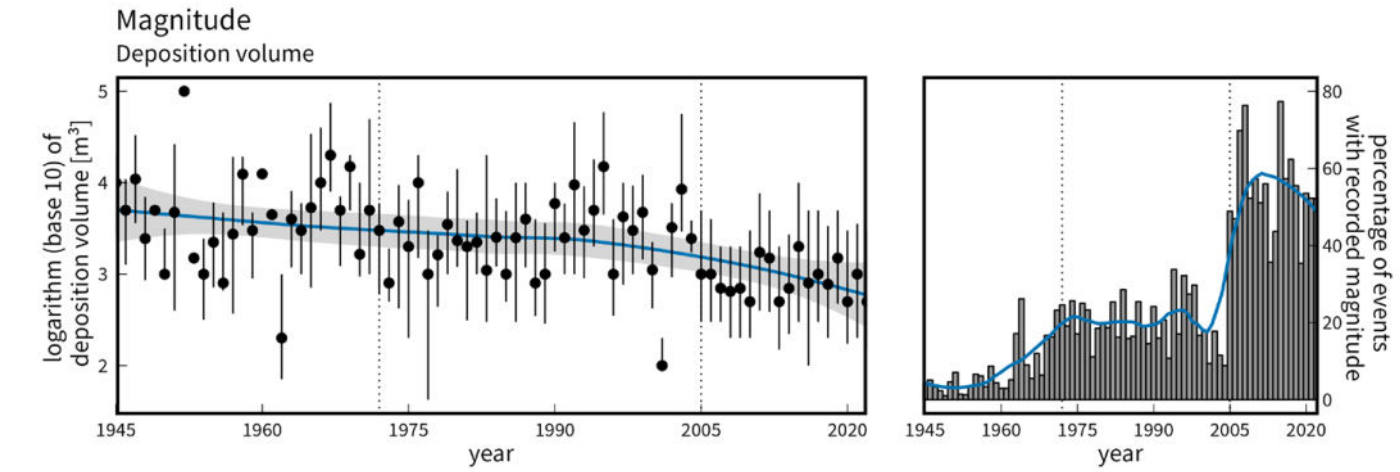

Figure 1: Illustration of event magnitude based on the recorded deposition volumes of torrential events for the period 1945-2022. Left: annual median (points) and corresponding interquartile range (error bars) of log-transformed deposition volumes. The blue line shows a local polynomial regression with a corresponding 95 % confidence interval. Right: Percentage of torrential events per year with observed magnitude. The dotted lines indicate changes in the modus operandi of the documentation procedure in 1972 and 2005.

Frequency

Event frequency (Figure 2) shows a significant positive trend according to the Mann-Kendall trend test, with a Theil-Sen slope of 0.97. However, the null hypothesis of randomness cannot be rejected by the two tests for randomness (Wald-Wolfowitz runs test, Bartels test). Breakpoints are clearly discernible in the cumulative number of events. Effects of changes in the documentation standard implemented in 2005 may have some influence on the number of recorded events in general. In addition, the event dataset is characterized by a high overdispersion (mean: 144 events per year; variance: 12,358), with the variance increasing notably after the year 2000. Compared to the apparent inter-annual variability, the estimated increase of about one additional event per year is rather low.

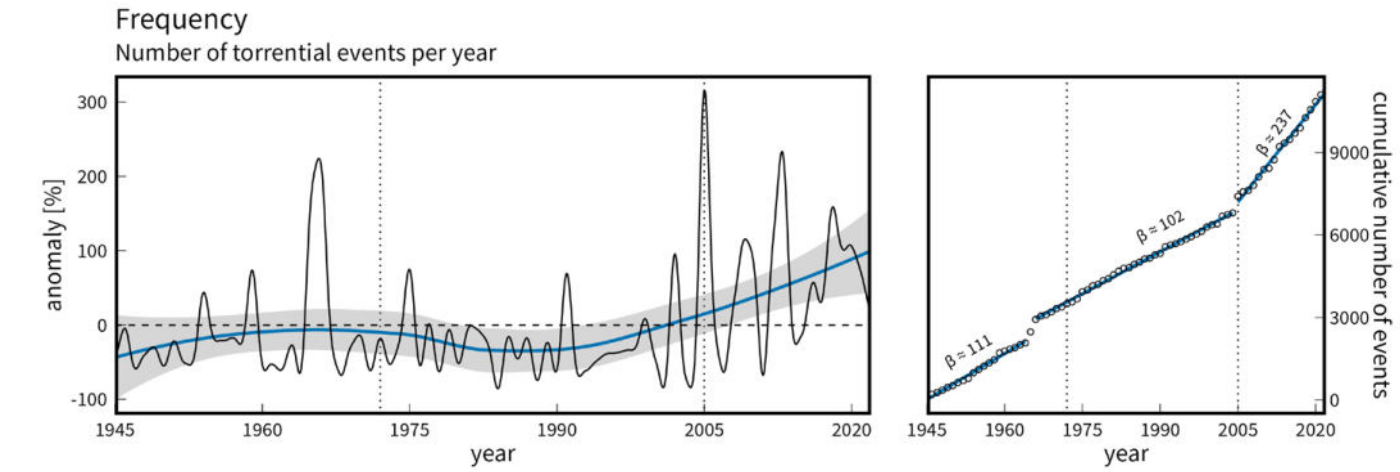

Figure 2: Illustration of event frequency based on the number of damage-inducing torrential events per year for the period 1945-2022. The dotted lines indicate changes in the modus operandi of the documentation procedure in 1972 and 2005. Left: Number of events per year. The blue line shows a local polynomial regression with a corresponding 95 % confidence interval. The right panel shows the cumulative number of torrential events from 1945 to 2022. The breakpoints indicate changes in the rate of annual increase (β). The second change in 2005 is particularly pronounced, and the average annual event rate more than doubles from approx. 102 events to 237 events per year.

Duration

Changes in event duration cannot be reliably assessed due to lack of data on precise event onset and end.

Timing: seasonality

Date information is available for 71 % of all torrential events recorded between 1945 and 2022. There is an obvious peak in event occurrence during summer, with most torrential flooding events occurring in July and August (Figure 3). The median event day is around 23 July (day 204). While some studies have reported shifts in seasonality towards spring due to changes in timing of maximum discharge, earlier onset of snowmelt or permafrost degradation, we cannot confirm the presence of any significant seasonal shifts for torrential flooding in Austria so far.

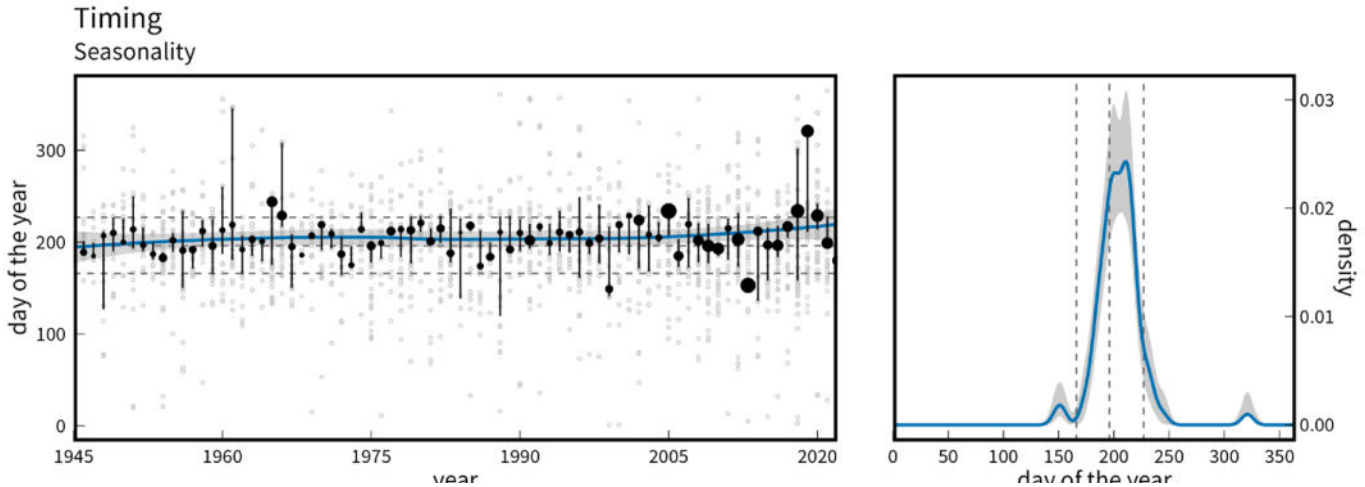

Figure 3: Illustration of event seasonality based on the day of the year of event occurrence in the period 1945-2022. Left: Day of the year at which the individual events occurred (grey open circles) as well as annual median event day (black points) and corresponding interquartile range (error bars). The blue line shows a local polynomial regression with a corresponding 95 % confidence interval. Right: Median distribution and its 95 % confidence interval based on 5,000 bootstrap samples (shaded area). In both subplots, the grey dashed lines equal the midpoints of the months June, July and August, respectively.

Spatial extent

The deposition area of events was used as a proxy for the spatial extent of events (Figure 4). This information is only available from 2012 onwards. Thus, the time series is too short to perform reliable trend analysis. Arguably, this characteristic is of lesser relevance for torrential flooding, as the occurrence of torrential processes is bound to steep headwater catchments by definition. Changes in event magnitude would be of more relevance.

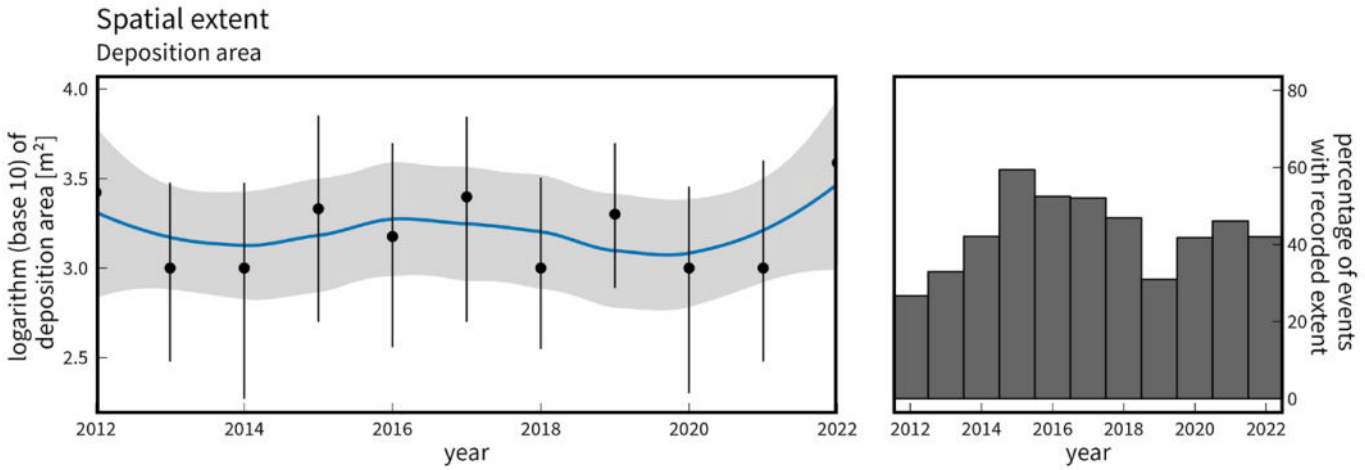

Figure 4: Illustration of the spatial extent based on the recorded deposition area of torrential events for the period 2012-2022. Left: annual median (points) and corresponding interquartile range (error bars) of log-transformed deposition volumes. The blue line shows a local polynomial regression with a corresponding 95 % confidence interval. Right: Percentage of torrential events per year with observed deposition area.

CONCLUSION

Summarizing, reliably detecting generalizable trends in the underlying characteristics of interest from data sets of historic torrential event occurrence is challenging due to a number of reasons (Table 1).

Challenge	Type	Description	Solution
Incomplete inventory	Inventory bias	Underreporting of events (frequency), specifically for smaller events (magnitude) in earlier years	Check inventory for completeness (Heiser et al., 2019)
Impact-based inventory	Inventory bias	Only damage-inducing events are reported	Clearly document the relevant target variable, control for relevant drivers (Schlögl et al., 2021)
Complexity of drivers	Inventory bias	Complex processes and forcings may govern event occurrence	Account for relevant drivers, e.g., climate, exposure, mitigation or land use changes (Schlögl et al., 2021, Heiser et al., 2023)
Short time series	Statistical analysis	Time series may be too short to derive robust trends	Clearly state limitations and uncertainties when reporting results
Small effect sizes	Statistical analysis	Effect sizes might be too small (due to lack of data) to be statistically significant	Report statistical power or clearly discuss the meaning or negative results to avoid the misinterpretation of underpowered studies
Faulty generalization	Statistical analysis	Exploratory analysis is mistaken as inferential analysis	Careful use of statistical tools (Heiser et al., 2023)

Table 1: Overview of challenges when assessing trends in torrential flooding.

Most of the challenges listed are directly related to the documentation technique (completeness, data quality, missing data, data series too short, etc.) and can therefore be considered in future or ongoing data collection campaigns. However, dynamically changing drivers pose a particular challenge when assessing trends in torrential flooding. These drivers include, inter alia (c.f.: Fuchs et al., 2015; Sebald et al., 2019; Galia et al., 2021; Kaitna et al., 2023):

- climate change (e.g., seasonal shifts, shifts in intensity-duration relationships),
- mitigation activities (e.g., torrent control structures with special focus on their design lifetimes, awareness raising)
- exposure dynamics (e.g., number and type of exposed buildings and structures, spatial planning), and
- land use changes (e.g., soil sealing, management of protective forests).

These drivers directly influence event occurrence through cause-effect relationships that are characterized by complex interactions and non-linear effects. Therefore, controlling for these effects is of core importance when assessing trends in torrential flooding in a changing climate.

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