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Temporal clustering of floods in Germany: Do flood-rich and flood-poor periods exist?

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ABSTRACT

The repeated occurrence of exceptional floods within a few years, such as the Rhine floods in 1993 and 1995 and the Elbe and Danube floods in 2002 and 2013, suggests that floods in Central Europe may be organized in flood-rich and flood-poor periods. This hypothesis is studied by testing the significance of temporal clustering in flood occurrence (peak-over-threshold) time series for 68 catchments across Germany for the period 1932–2005. To assess the robustness of the results, different methods are used: Firstly, the index of dispersion, which quantifies the departure from a homogeneous Poisson process, is investigated. Further, the time-variation of the flood occurrence rate is derived by non-parametric kernel implementation and the significance of clustering is evaluated via parametric and non-parametric tests. Although the methods give consistent overall results, the specific results differ considerably. Hence, we recommend applying different methods when investigating flood clustering. For flood estimation and risk management, it is of relevance to understand whether clustering changes with flood severity and time scale. To this end, clustering is assessed for different thresholds and time scales. It is found that the majority of catchments show temporal clustering at the 5% significance level for low thresholds and time scales of one to a few years. However, clustering decreases substantially with increasing threshold and time scale. We hypothesize that flood clustering in Germany is mainly caused by catchment memory effects along with intra- to inter-annual climate variability, and that decadal climate variability plays a minor role.

1. Introduction

Only eleven years after the disastrous flood in August 2002 in the Elbe and Danube catchments in Central Europe (the most expensive natural disaster for Germany so far), the same catchments were hit by another exceptional flood. The June 2013 flood was even more severe in hydrological terms although damages were significantly lower (Merz et al., 2014b; Schröter et al., 2015). Another example for exceptional flooding occurring within rather short time periods is the Rhine flood in December 1993, which was followed by a hydro-meteorologically very similar event in January 1995. Such reoccurrences give rise to the hypothesis that floods in Central Europe are temporally organized in flood-rich and flood-poor periods.

Temporal clustering of floods may have considerable consequences for flood estimation, flood design and risk management (Merz et al., 2014a), and clustering of catastrophic events is an important issue for the insurance industry when modelling the pricing of insurance contracts (Khare et al., 2015). Flood design is typically based on the T-year flood, i.e. the flood discharge that has a 1/T probability of being reached or exceeded in a given year. Based on the usual iid (independent, identically distributed) assumption of flood frequency analysis, the T-year flood quantile is assumed constant in time. However, temporal clustering may introduce serial correlation in the flood time series and invalidate the independence assumption. Serial correlation may reduce the information content of the sample and increase the uncertainty for flood quantile estimation (Koutsoyiannis, 2005). Further, temporal variations in the frequency and magnitude of flooding may bias flood design. The relevance of this effect depends on the ratio of oscillation period and observation length. If the oscillation period is significantly smaller than the observation length that is used for flood estimation, the effects of clustering may be negligible for design purposes (Jain and Lall, 2001). On the other hand, decadal-scale fluctuations may significantly bias estimates that are based on 30 or 40 years of record (Hirschboeck, 1988). Hence, it is of

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utmost importance to understand not only if clustering exists but how clustering changes with the time scale.

Flood clustering is typically explained by linkages between flood frequency or magnitude and climate. There are well-organized modes of inter-annual, inter-decadal and lower-frequency climate variability (Barnston and Livezey, 1987). This variability may have a significant impact on the occurrence and magnitude of floods by changed atmospheric moisture uptake, transport and deposition (Hirschboeck, 1988). For example, ENSO (El Niño Southern Oscillation), with inter-annual variations in the range of two to seven years, has been linked to floods in Peru (Waylen and Caviedes, 1986), in the United States (Cayan et al., 1999; Jain and Lall, 2000, 2001; Sankarasubramanian and Lall, 2003), China (Lin et al., 2005; Zhang et al., 2007), Australia (Kiem et al., 2003). Ward et al. (2010, 2014) presented a global analysis of flood discharge sensitivities to ENSO based on observed and modelled river flows, respectively, suggesting complex sensitivity patterns, but significant correlation for catchments covering more than a third of the global land surface. Other climate modes, such as the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), or the Pacific/North American Index (PNA) have been shown to lead to flood episodes of varying intensity as well (e.g., Pizaro and Lall, 2002; Bouwer et al., 2006; Kingston et al., 2006; Petrow et al., 2009; Delgado et al., 2012; Villarini et al., 2013).

There are a number of studies on temporal fluctuations in flood occurrence for Germany and neighbouring regions in the scientific literature on paleo and historical floods. (For a compilation of studies on flood changes for other European regions see Kundzewicz (2012) and Hall et al. (2014).) Swierczynski et al. (2013) reconstructed a 7100-year long flood record from varved lake sediments in Lake Mondsee in Austria. This record contains striking fluctuations in flood occurrence showing 18 flood-rich periods with durations between 30 and 50 years. Mudelsee et al. (2003) analysed historical flood data since CE 1500 for the Central European rivers Elbe and Oder. Significant variations in the occurrence rate of heavy floods during the past centuries were detected. For the same period, Sturm et al. (2001), Jacobeit et al. (2003) and Glaser et al. (2010) reconstructed flood occurrence from documentary evidence for several Central European rivers and found significant flood-rich and flood-poor periods. Phases of maximum flood activity in Bohemian rivers (Elbe River and others) since 1501 were concentrated in the latter part of the 16th century and in the 19th century (Brázdil et al., 2005). Flood-rich periods have been reported for rivers in France, for example for the Loire at Orléans and the Seine River at Paris (Brázdil et al., 2012). Schmocker-Fackel and Naef (2010a) identified four flood-rich periods (1560–1590, 1740–1790, 1820–1940, since 1970) for 14 Swiss catchments. At the river Rhine at the Swiss-German border, the highest number of summer floods since 1268 occurred in the period 1651–1750, with no severe winter floods since the late 19th century (Wetter et al., 2011). It can be summarised that the studies reconstructing historical floods for Germany and neighbouring regions typically conclude that flood-rich and flood-poor periods at the scale of several decades to centuries are a widespread and important phenomenon. It should be noted that most of these studies classified historical floods based on documentary evidence. In some instances, this classification builds on societal impacts which depend both on the magnitude of the flood and the exposure and vulnerability of the affected regions. Hence, the reconstruction of historical flood occurrences is not only associated with higher uncertainties compared to systematically recorded data, the derived flood frequencies might also depend on societal aspects.

Studies on temporal clustering of floods in Germany or neighbouring regions based on systematic data are rare. Based on 102 long-term records since 1900 from gauges across Europe, Mediero et al. (2015) found significant clustering of floods occurring in Atlantic and Continental regions covering northern and central Germany. Schmocker-Fackel and Naef (2010b) analysed a data set of 83 gauges in Switzerland, augmented with data on historical floods since 1850, and concluded that flood-rich periods alternated with flood-poor periods. Robson et al. (1998) and Robson (2002) analysed annual maxima data and peak-over-threshold flood data for a large number of catchments in UK and for different time periods and found fluctuations in flood occurrence and magnitude. In their review paper on flood regime changes in Europe, Hall et al. (2014, p. 2745) concluded that "… future flood change analyses of systematic data should actually focus on identifying flood-poor and flood-rich periods instead of only detecting whether trends exist….". We address this call by investigating temporal clustering of flood occurrence based on systematic data from 68 streamflow gauges across Germany.

A question, which has not received much attention in the flood clustering literature, is how to determine flood-rich and flood-poor periods. The majority of studies that investigate flood clustering, in particular studies analysing historical data, apply simple and subjective methods to decide whether flood-rich and flood-poor periods exist. Most often, a time series showing the number of flood occurrence within prefixed time windows, e.g. 10 or 30 years, is generated. Flood-rich periods are then identified visually or by simple rules, such as a period is considered as flood-rich if the number of floods is larger than the mean number plus one standard deviation. (An overview of methods used in studies on European floods in the period 1560–1810 is given in Schmocker-Fackel and Naef, 2010a.) To determine clustering objectively, we deploy objective measures and test the statistical significance of clustering.

A simple measure for clustering is the dispersion index which has been used in analysing clustering of storms (e.g., Mailier et al., 2006; Vitolo et al., 2009) and floods (e.g., Eastoe and Tawn, 2010; Mediero et al., 2015). It investigates the number of event counts in a time window and relates the variability of counts to the expected value. The dispersion index identifies times series where events do not occur randomly but are clustered in time. Another approach for quantifying clustering is the kernel occurrence rate estimation. It estimates the time variation of event counts as smooth function of time. It has been applied to analyse flood occurrence in Central Europe (Mudelsee et al., 2003, 2004) and Portugal (Silva et al., 2012). For both approaches, Monte Carlo simulation allows determining whether variations in flood occurrence deviate for a given significance level from the null hypothesis of time-constant occurrence rate.

In this paper, we address the following questions: (1) Is there significant temporal clustering in flooding in Germany? (2) Does the significance of clustering change with flood severity and time scale? (3) How can the significance of clustering be determined objectively? To answer these questions, we select flood times series from 68 gauges across Germany. To understand if clustering changes with flood severity, different peak-over-threshold (POT) time series are analysed by applying the dispersion index method and two variants of the kernel occurrence rate estimation. The three methods are deployed for different time scales to understand if the significance of clustering changes with time scale.

2. Study area and data

We study temporal clustering in flood occurrence at 68 streamflow gauges distributed across Germany with mean daily discharge observations (Fig. 1). The selection of the streamflow gauges was based on the following criteria: (1) complete coverage of Germany, (2) large number of gauges for a common time period, (3) medium- and large-scale catchments, (4) time series as long as possible, (5)