Journal of Hydrology 559 (2018) 813–826

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Spatial coherence of flood-rich and flood-poor periods across Germany

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ARTICLE INFO

Article history:
Received 21 September 2017
Received in revised form 29 January 2018
Accepted 28 February 2018

This manuscript was handled by Marco Borga, Editor-in-Chief

Keywords:
Flood timing
Spatial coherence
Flood regimes
Climate variability
Catchment wetness

ABSTRACT

Despite its societal relevance, the question whether fluctuations in flood occurrence or magnitude are coherent in space has hardly been addressed in quantitative terms. We investigate this question for Germany by analysing fluctuations in annual maximum series (AMS) values at 68 discharge gauges for the common time period 1932–2005. We find remarkable spatial coherence across Germany given its different flood regimes. For example, there is a tendency that flood-rich/-poor years in sub-catchments of the Rhine basin, which are dominated by winter floods, coincide with flood-rich/-poor years in the southern sub-catchments of the Danube basin, which have their dominant flood season in summer. Our findings indicate that coherence is caused rather by persistence in catchment wetness than by persistent periods of higher/lower event precipitation. Further, we propose to differentiate between event-type and non-event-type coherence. There are quite a number of hydrological years with considerable non-event-type coherence, i.e. AMS values of the 68 gauges are spread out through the year but in the same magnitude range. Years with extreme flooding tend to be of event-type and non-coherent, i.e. there is at least one precipitation event that affects many catchments to various degree. Although spatial coherence is a remarkable phenomenon, and large-scale flooding across Germany can lead to severe situations, extreme magnitudes across the whole country within one event or within one year were not observed in the investigated period.

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1. Introduction

The typical frame in flood hydrology is the catchment view. However, the question whether flooding is coherent beyond catchment boundaries has recently received more attention. For example, Uhlemann et al. (2010) analysed trans-basin flood events that affect many sites in different river basins simultaneously. Such events are particularly relevant for disaster management and the (re-)insurance industry. Further, it has been observed that there are flood-rich and flood-poor periods, and that periods with higher or more frequent floods can be differentiated from periods with minor flood activity (for a compilation of European studies see Hall et al., 2014). It is an interesting and societally relevant question whether such fluctuations in flood activity are coherent in space.

Spatial coherence of flood activity, i.e. the synchronous occurrence of floods in the spatial domain, can be defined in terms of flood occurrence or in terms of flood magnitude. The first approach analyses the number of flood events, either based on POT (Peak-Over-Threshold) values or using proxies. For example, Llasat et al. (2005) reconstructed annual times series composed of three classes (no flooding recorded; at least one extraordinary flooding recorded; at least two extraordinary flooding recorded). Temporal changes in flood magnitude are typically investigated by using block maxima, as e.g. annual maximum values. Both approaches can be found in the literature, whereas studies using historical data typically use flood occurrence because magnitudes of floods prior to systematic measurements are very difficult to estimate.

Several studies stressed the large spatial heterogeneity in flood activity. Mudelsee et al. (2004) found notable differences and low correlation between flood occurrence rates of the neighbouring Central European rivers Oder and Elbe for the last 800 years. Similarly, Mudelsee et al. (2006) concluded that temporal variations in flood occurrence for the period 1500–2000 in the Werra catchment in central Germany contrasted with those in the nearby Elbe catchment. Böhm and Wetzel (2006) analysed the occurrence of floods and found that flood-rich and flood-poor periods since 1300 in the adjacent catchments Isar and Lech in south Germany only partly

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https://doi.org/10.1016/j.jhydrol.2018.02.082
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overlapped. Annual maximum floods of 15 tributaries of the Canadian St. Lawrence River were found to correlate with different climate indices, emphasizing significant spatial heterogeneity between sub-catchments (Assani et al., 2010). The analysis of flood-rich and flood-poor periods, described in terms of the frequency of events larger than the 10-year flood, since 1850 at 83 Swiss stations showed large regional differences, especially between north and south Switzerland (Schmocker-Fackel and Naef, 2010a). In contrast, other studies stressed the spatial coherence of flood activity, even across large distances (e.g. several 100 km). Llasat et al. (2005) found coherent periods of flood occurrence in three rivers in northeast Spain since the 14th century. They concluded that the coincidence of flood-rich periods with additional catchments in the west Mediterranean region suggested a large-scale response to climatic anomalies. Schmocker-Fackel and Naef (2010b) emphasized for 14 Swiss rivers, that flood-rich periods since 1500 were often in phase with flood-rich periods in the Czech Republic, Italy and Spain, but less often with those in Germany.

Hence, the literature on spatial coherence of flood-rich and flood-poor periods provides evidences for both spatial coherence across regions and for spatial heterogeneity. This is not surprising because the studies comprise different flood indicators, methods, temporal and spatial scales, and regions. For instance, the spatial scale is important because proximity tends to favour spatial coherence. Further, the degree of spatial coherence of flood activity should vary between regions whose flood generation is governed by different processes. Regions (e.g. Australia, see Kiem et al., 2003) whose flood activity is dominated by variations of the large-scale circulation (as represented by climate teleconnections) are expected to show stronger spatial coherence compared to regions characterized by a high-frequent atmospheric variability (e.g. westerly-dominated Central Europe, see Steirou et al., 2017). However, there seems to be consensus that the degree and causes of spatial coherence of flood activity need to be better understood (Hall et al., 2014).

Floods are shaped by the interplay of processes in the atmosphere, catchment and river network, and the spatial coherence of flooding is likely a consequence of the similarity in one or several of these processes. For example, Glaser et al. (2010) investigated the flood occurrence for 20 major rivers in Central Europe and the Mediterranean region and found that the number of floods was mainly triggered by regional climate forcing with typically minor influence on adjacent catchments. However, extreme, supra-regional climatic events, such as the cold winter 1784, triggered ice-jam floods across large parts of Europe. Hence, the strength of spatial coherence is expected to vary with the flood generation processes.

The most prominent cause for spatial coherence of flood activity is climate variability. Large-scale circulation modes, such as the El Nino Southern Oscillation, influence flood characteristics at the global scale (Ward et al., 2014). Northern hemispheric pressure anomalies, e.g. the North Atlantic Oscillation, have been shown to alter the flood activity over vast parts of Europe (Steirou et al., 2017). Mesoscale synoptic weather patterns have been identified as flood drivers at the regional scale, e.g. in Germany (Petrow et al., 2009). Climate variability may modulate flood activity by changes in event meteorology, such as increased flood event precipitation. In addition, climate variability might influence the catchment wetness, leading to systematic changes in initial conditions for flood events. Since catchment wetness is also influenced by the memory of catchments, climate mechanisms and catchment characteristics may work together in shaping flood-rich and flood-poor periods. In river basins, the river network may also contribute to spatial coherence of flooding, since downstream flood peaks may result from upstream floods. Hence, far-distance locations within river networks can be linked in their flood activity.

As an example for significant spatial coherence in flood magnitude, Fig. 1 shows (smoothed) time series of annual maximum flows for nine streamflow stations in Germany for which long systematic observations are available. The stations cover Alpine rivers at the southern border of Germany with catchment areas partly in Austria (Burghausen/Salzach) and Switzerland (Neuhausen/Rhine), the middle mountain range rivers in central Germany (Cochem/Mosel, Schweinfurt/Main) and in north Germany (Vlotho/Weser), and stations along the large rivers (Cologne/Rhein, Achleiten/Danube, Dresden/Elbe). Although the set of stations covers a broad spectrum of climate and landscape characteristics and samples different flood regimes, the synchronisation between the flood time series is remarkable. The ups and downs are often parallel and periods with major flood activity tend to occur at the same time at different gauges across different basins.

To better understand the degree and underlying mechanisms of synchronisation of flood-rich/-poor periods, we investigate the spatial coherence in the annual maximum streamflow (AMS) across Germany, representing an area of roughly 360,000 km^2. We consider years with high spatial coherence as those years which have AMS magnitudes of the different stations in the same range, for instance, high flood peaks throughout the hydrological year. Large heterogeneity in AMS values is considered as non-coherence. By using the timing of floods, we further distinguish two types of spatial coherence (or non-coherence). Event-type coherence is given when the AMS events within a hydrological year are caused by a few flood events that impact many catchments at the same time. Hence, AMS peaks at different gauges are clustered within a few events, whereas an event may last for a few days. On the other hand, non-event-type means that the AMS values are spread throughout the year, i.e. many flood events occur during one hydrological year.

The schematic representation in Fig. 2 illustrates our understanding of spatial coherence for an artificial data set. Each subgraph shows one hydrological year, whereas the AMS values of all gauges of this specific year are plotted versus their timing, i.e. occurrence in the year. To make the AMS values of different gauges comparable, they are standardized to zero mean and unit variance. A flood-rich and flood-poor year is given for each case. The upper left situation shows a non-event-type, coherent year. The timing of AMS values is spread throughout the year and AMS magnitudes are confined to a certain range. Non-event-type non-coherence is visualized in the upper right quadrant. AMS values occur throughout the year and AMS magnitudes vary widely, i.e. timing and magnitude vary randomly. Event-type coherence (lower left) is marked by a few events where many gauges show an AMS value at the same time, and AMS magnitudes are confined to a similar range. Event-type non-coherence (lower right) means that the AMS values are confined to a few events but AMS magnitudes vary widely.

Both types of spatial coherence are of importance. Event-type coherence is important for large-scale event response planning, such as provision of disaster management capacities for widespread floods. For the (re-)insurance industry that partly operates on an annual basis, non-event-type coherence is important as well because flood losses will cumulate throughout the year. Non-coherent years or periods are not interesting in the context of this paper. In such periods, AMS values occur randomly, and there is no signal that could be used for informing large-scale risk management or (re-)insurance.

There is little systematic work on spatial coherence of river flooding. Several studies have looked at spatial coherence of flood occurrence or magnitude (for an overview see Hall et al., 2014) but, to the authors' knowledge, no study has attempted to quantify the degree and type of coherence. Most studies have qualitatively compared flood activity for different catchments, for example, by averaging the number of flood events over a certain period, often

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