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On the relationship between hydro-meteorological patterns and flood types

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SUMMARY

Flood generation is triggered by the interaction of the hydrological pre-conditions and the meteorological conditions at different space–time scales. This interaction results in floods of diverse characteristics, e.g. spatial flood extent and temporal flood progression. While previous studies have either linked flood occurrence to weather patterns neglecting the hydrological pre-conditions or categorised floods according to their generating mechanisms into flood types, this study combines both approaches. Exemplary for the Elbe River basin, the influence of pre-event soil moisture as an indicator of hydrological pre-conditions, on the link between weather patterns and flood occurrence is investigated. Flood favouring soil moisture and weather patterns as well as their combined influence on flood occurrence are examined. Flood types are identified and linked to soil moisture and weather patterns. The results show that the flood favouring hydro-meteorological patterns vary between seasons and can be linked to flood types. The highest flood potential for long-rain floods is associated with a weather pattern that is often identified in the presence of so called 'Vb' cyclones. Rain-on-snow and snowmelt floods are associated with westerly and north-westerly wind directions. In the analysis period, 18% of weather patterns only caused flooding in case of preceding soil saturation. The presented concept is part of a paradigm shift from pure flood frequency analysis to a frequency analysis that bases itself on process understanding by describing flood occurrence and characteristics in dependence of hydro-meteorological patterns.

1. Introduction

Floods are generated by the interaction of various physical processes. These include hydrological pre-conditions (e.g. soil saturation, snow cover), meteorological conditions (e.g. amount, intensity and spatial distribution of precipitation), runoff generation processes (e.g. infiltration and lateral runoff on hillslopes), as well as river routing (e.g. superposition of flood waves). The combination of these physical controls may be important, especially at the regional scale ($\geqslant 10{,}000\ \mathrm{km}^2$), where flooding can affect many sites simultaneously, whereas other sites remain unaffected (Merz and Blöschl, 2008a).

Three main approaches exist to describe regional flood events in terms of their spatio-temporal physical causes. They can be categorised into (1) flood event description, (2) classification into flood types and (3) linkage of flood occurrence to atmospheric circulation patterns. Following (1), detailed descriptions on e.g. soil moisture conditions, snowmelt and spatio-temporal distribution of rainfall are provided by scientific case studies. Examples in Central Europe are studies on the Elbe flood in August 2002 (Ulbrich et al., 2003a,b), the Rhine flood in January 1995 (Chbab, 1995; Engel, 1997) or the Danube flood in June 2013 (Blöschl et al., 2013). Furthermore, numerous reports and documentations about specific floods are compiled by governmental authorities and non-governmental bodies and are published as grey literature (Uhlemann et al., 2013). These descriptions are either qualitative or quantitative and in general limited to the case of severe flooding. In approach (2), the findings about individual flood events of diverse magnitude and extent are generalised by classifying them into different categories. For instance, Merz and Blöschl (2003) separated

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floods in accordance with their generating processes into long-rain floods, short-rain floods, flash floods, rain-on-snow floods, and snowmelt floods. Alila and Mtiraoui (2002) classified flood events based on storm type, El Niño-Southern Oscillation conditions and decadal-scale climatic variability. Hirschboeck (1987) conducted a flood classification based on precipitation, synoptic weather patterns and snowmelt. In approach (3), a probabilistic link between flood occurrence and daily atmospheric circulation patterns is sought (e.g. Bárdossy and Filiz, 2005; Duckstein et al., 1993; Petrow et al., 2009; Prudhomme and Genevier, 2011). Circulation patterns characterise the main modes of variability of atmospheric state by classifying individual weather situations. However, due to the small sample size of flood events compared to the overall number of days, Prudhomme and Genevier (2011) raised the question "if any link [between flood occurrence and circulation patterns] found is not a consequence of specific samples of events but truly is representative of physical processes". To date, this question, if and to which extent large-scale circulation patterns and flood generating processes are related, has not been explicitly addressed.

In this paper, we therefore propose to combine the process-based flood type classification approach (2) with an analysis of the link between flood occurrence and atmospheric circulation patterns (3). As different flood types have different characteristics, e.g. spatial extent and temporal flood progression, it is important to understand the conditions under which they occur. For example, climate change might alter the relative importance of the flood generating mechanisms. This might require to adapt flood management strategies (Van Loon and Van Lanen, 2012).

Another question which has not been addressed to date is how the link between circulation patterns and flood occurrence is modified by other processes amplifying or hindering flood generation. For instance, the impact of soil saturation on flood generation is widely acknowledged (e.g. Marchi et al., 2010; Merz et al., 2006; Norbiato et al., 2009; Parajka et al., 2010; Sivapalan et al., 1990) and plays a central role in flood forecasting (e.g. Fundel and Zappa, 2011). Nevertheless, it is commonly disregarded when establishing the link between circulation patterns and flood occurrence. The limitations of looking only at circulation patterns to describe flood events is further illustrated in catchments where snow processes are important resulting in a weak link between precipitation and discharge events (Parajka et al., 2010; Petrow et al., 2007).

In this paper, we identify flood types at the regional scale of the Elbe catchment, based on an adaptation of the flood typology of Merz and Blöschl (2003) and analyse their relationship to circulation patterns. The combination enables to relate large-scale atmospheric conditions to earth's surface flood processes. The objective is, on the one hand, to examine whether a particular circulation pattern favours a particular flood type. On the other hand, we study the influence of the pre-event soil moisture conditions in modifying the link between circulation patterns and flood occurrence. Complementary to the classification of atmospheric circulation patterns, we utilise a soil moisture pattern classification. We develop the approach exemplarily for the Elbe catchment.

The remainder of this paper is organised as follows: First the study area is described. The data and methods section introduces the applied techniques to identify flood events and to classify them into flood types. Distinct daily soil moisture and weather pattern types are introduced and the method linking them to flood occurrence is explained. The results, i.e. the stratification of the identified flood events into flood types and their related hydro-meteorological patterns, are presented and discussed in Sections 4 and 5. The last section concludes our findings.

2. Study area

The study region is the 148,268 km^2 large Elbe/Labe River basin (Fig. 1). The Elbe originates in the Czech Republic and crosses north-eastern Germany before flowing into the North Sea. The climate ranges between continental in the upper and middle Elbe to temperate in the lower Elbe (IKSE, 2005). Average annual precipitation is strongly modified by the relief and varies from 450 mm in the middle Elbe to above 1000 mm in the mountainous areas. In winter, precipitation falls as snow. In dependence of elevation and snow depth, snow melts predominantly in March, although it can persist until May (IKSE, 2005). The main land use types are cropland (51%), forest (30%) and grassland (10%) (CORINE European Environment Agency, 2000). In the northern lowlands, sandy soils, glacial sediments and, restricted to the valleys, loamy soils are found. In the southern highlands, thin cambisols are the main soil type. In the Saale and Mulde tributaries, chernozems and luvisols dominate (Hattermann et al., 2005). The Elbe River basin has been affected by severe flood events, e.g. December 1974/January 1975 (Schirpke et al., 1978), August 2002 (Engel, 2004; Ulbrich et al., 2003a,b) and June 2013 (Conradt et al., 2013; Merz et al., 2014).

3. Data and methods

Regional flood events are derived from observed discharge time series and categorised into process-based flood types. Afterwards, flood events and the identified flood types are linked to distinct patterns of hydrological pre-conditions and meteorological conditions. The analysis period is September 1957 to August 2002.

3.1. Flood definition and identification

Investigating the combined influence of the hydrological pre-conditions and the meteorological conditions on flood occurrence and flood type in the Elbe catchment requires a basin wide view. The flood definition has to take into account regional-scale flood generation i.e. simultaneous or time shifted flooding at several gauges. A flood identification scheme proposed by Uhlemann et al. (2010) is applied. The method consists of a systematic spatio-temporal peak flow search around each 10-year flood recorded in the river basin. Every flood event is characterised by time and location. The event start date is the date, up to 3 days in advance of a 10-year flood, at which at least one gauge in the river basin has a significant peak. At the event end date, up to 10 days after the last occurrence of a 10-year flood, the final significant peak is detected. Peak significance is ascertained by calculating the 90th percentile v of the residuals between daily observed discharge and its moving average $P(t)$ (13 days moving window). If a peak in the observed time series exceeds $P(t) + v$, it is considered significant. Two regional flood events are independent, if at least 4 days are between the event start date and the event end date of the previous flood. Daily overall discharge Q_{all} is defined as the discharge sum of all gauges in the basin standardised by their respective 2-year flood. The event centroid is the date after the occurrence of the largest increase in Q_{all} compared to the preceding day. The time period after the event start date including the event centroid date is called event build-up period. The length of the build-up period depends on flood type and spatial extent and accounts for the catchment reaction time as well as flood routing. A schematic representation of a flood event's temporal progression and overall discharge Q_{all} is presented in Fig. 2.

Additionally, each flood event is characterised by a measure of the overall event severity S which combines spatial flood extent and flood magnitude (Uhlemann et al., 2010).