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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$10,000 km$^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).

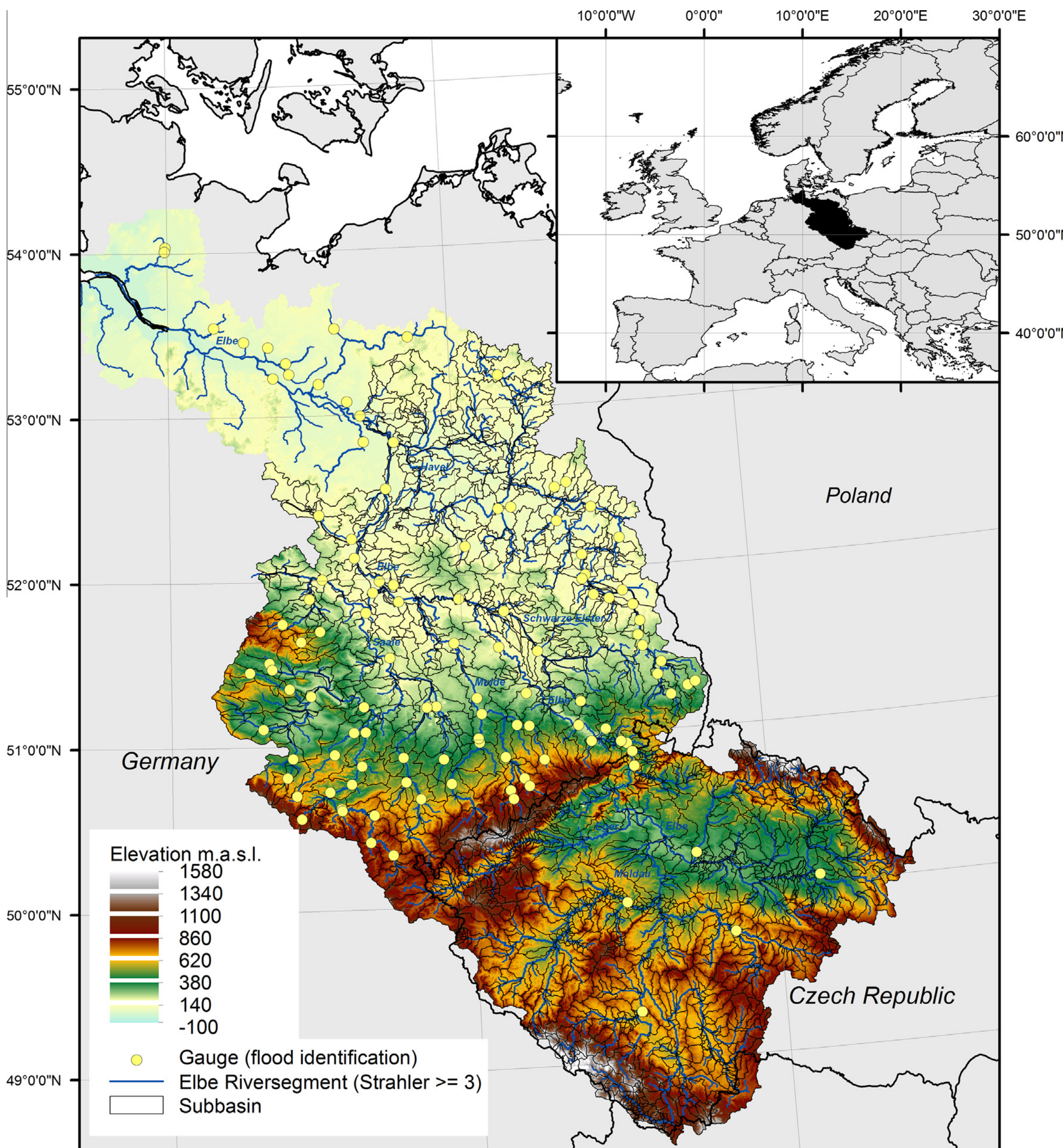


**Fig. 1.** Topographic map of the Elbe catchment. Yellow dots refer to the gauges applied in the flood event identification. Map of the regional setting of the Elbe catchment (upper right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$S = \sum_{i=1} \left( \lambda_i \frac{Q_i}{HQ2_i} \right) \Big| Q_i \geqslant HQ2_i \qquad (1)$$

$Q_i$ is the maximum daily discharge at gauge $i$ for the considered flood event. $Q_i$ is standardised by the 2-year flood $HQ2_i$. $\lambda_i$ is a weighting factor. It describes the fraction of the regionalized river network corresponding to gauge $i$ in relation to the overall regionalized river network i.e. $\sum \lambda_i$ equals unity. The regionalization scheme accounts for river length and river network topology and is based on the hierarchical ordering of river networks by Strahler (1964). In dependence of a gauges' Strahler-order, the total length of the upstream river stretches is estimated. In case of nested catchments, regionalization stretches from the downstream gauge to the upstream gauge. For details see Uhlemann et al. (2010). The severity estimation is restricted to gauges exceeding a 2-year flood. It is assumed that the 2-year flood corresponds to bankfull river flow below which no flood impact is expected.

The flood identification method is applied to daily average discharge time series of 114 gauges provided by various German water authorities and the Global Runoff Data Centre (GRDC). Catchment sizes vary from 104 km$^2$ to 131,950 km$^2$ and include a large number of nested catchments (Fig. 1, yellow dots). Half of the gauges have data that covered the entire analysis period. For each gauge, a hydrological year with more than 60 days of missing data was excluded. This resulted in between 68 (1957/1958) and 114 (1981) gauges in the analysis.

### 3.2. Classification

#### 3.2.1. Soil moisture patterns

As a representative of hydrological pre-conditions, daily patterns of soil saturation are used. Nied et al. (2013) classified daily soil moisture patterns for the Elbe catchment. The soil moisture

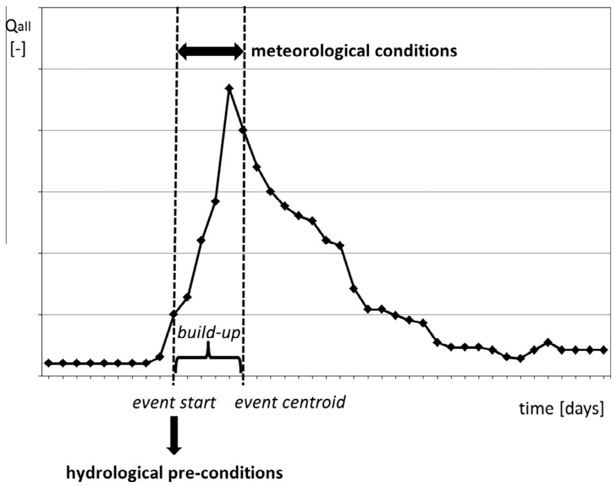


**Fig. 2.** Schematic flood event representation, denoting event start date, event centroid date, and build-up period.

pattern classification was carried out by simulating soil moisture with a rainfall-runoff model at 1945 subbasins (Fig. 1) for 38 parameter realizations. Days of similar soil moisture patterns were identified using a principal component analysis and subsequent cluster analysis on the principal components. The classification into 10 soil moisture pattern types (Fig. 3) was identified as most suitable. The soil moisture pattern types range from soil saturation in the entire catchment (pattern 9), soil saturation restricted to parts of the catchments, i.e. upstream (pattern 3) or mountainous areas (pattern 10), to dry soil moisture conditions (pattern 7). The frequency and seasonality of the soil moisture pattern types are displayed in Fig. 6a. The pattern types can be differentiated into summer (e.g. pattern 7), winter (e.g. pattern 9), and all-year patterns (e.g. pattern 5). Details on the classification approach are described in Nied et al. (2013).

*3.2.2. Weather patterns*

Daily patterns of meteorological conditions are classified using the objective classification algorithm SANDRA (Philipp et al., 2007). ERA 40 fields (Uppala et al., 2005) are evaluated on a 1.125° × 1.125° grid covering Europe (Fig. 1, small map). The parameters used are 500 hPa geopotential heights representing the steering circulation, temperature in 500 hPa indicating e.g. melting conditions, as well as the total column water vapour content indicating potential rainfall. In total, 40 weather pattern types are determined. The frequency and seasonality of the weather pattern types are displayed in Fig. 6b. Fig. 4 displays a selection of weather pattern types, which play a central role in this work. The complete set of weather pattern types is provided in Appendix.

*3.2.3. Flood types*

The flood types rain-on-snow flood, snowmelt flood, long-rain flood, short-rain flood, and flash flood by Merz and Blöschl (2003) are adapted to the scale of the Elbe River basin. The classification of the flood events into flood types is conducted manual and based on flood type indicators. Together, the flood type indicators describe specific characteristics and causative mechanisms of a flood event. For the classification of a flood event, the flood type indicators are displayed on diagnostic maps. Examples of diagnostic maps are e.g. Fig. 5 or Fig. 7 in Merz and Blöschl (2003). For clarity, only those flood type indicators of relevance for the particular flood event are displayed. The examination of flood type indicators is limited to those gauges and their corresponding catchments affected by at least a 2-year flood during the particular flood event (Fig. 5, red dots). Table 1 summarises how the indicators are used to define a certain flood type. It is assumed that each flood event can be assigned to one flood type. The following flood type indicators are applied:

- Spatial flood extent: the spatial flood extent addresses the number and spatial distribution of flood affected gauges. It can range from a single gauge to the entire river network. Floods of small spatial extent may be caused by convective storms, whereas large-scale flooding may be associated with frontal systems.
- Seasonality: as different flood types dominate in different seasons (Merz and Blöschl, 2003; Parajka et al., 2010; Petrow et al., 2007), the event start date is used as a flood type indicator.
- Snow cover: in wintertime, precipitation can fall as snow and is stored in the snowpack until melting starts. The amount and spatial distribution of snow water equivalent at the event start date and at the event centroid date are compared to shed light on snowmelt and/or accumulation.
- Air temperature: daily mean air temperature is examined in the event build-up period. It is assumed that on days with daily mean air temperature above 0 °C snowmelt occurs. Air temperature is used to separate precipitation into snowfall and rainfall. Below 0 °C precipitation is considered as snow. Above 2 °C, precipitation is considered as rainfall. In between, precipitation is considered as a mixture of rainfall and snow.
- Precipitation: the amount and spatial distribution of precipitation is examined for each day in the build-up period. For instance, short-rain floods are characterised by short duration, spatially limited, high rainfall amount, whereas long-rain floods are characterised by either basin wide stationary low rainfall or by spatially limited rainfall of high amount affecting several sites in the catchment progressively.
- Length of build-up period: the length of the build-up period is an indication of flood generation processes. For instance, the flood generating processes associated with flash floods are much faster than those associated with snowmelt. The reason in case of the latter is that the available energy (global radiation and turbulent heat exchange) controls the amount of melt (Merz and Blöschl, 2003) and causes snowmelt in different elevation zones and aspects progressively. Furthermore, the length of the build-up period is an indication of runoff processes in the river network. The length of the build-up period increases for large-scale flooding due to the downstream propagation of the flood wave.

For deriving the precipitation and air temperature indicators, daily meteorological data were provided by the German Weather Service (DWD) and the Czech Hydrometeorological Institute (CHMI). The station data were corrected for inconsistencies, data gaps and inhomogeneities (Österle et al., 2006, 2012). The Elbe catchment was subdivided into 1945 subbasins upstream of gauge Wittenberge (Fig. 1) and the meteorological data were interpolated on each subbasins centroid. As snow data were not available at the considered space–time scale, snow water equivalent was simulated for each subbasin with a semi-distributed rainfall-runoff model applying the degree-day method. The median simulated snow water equivalent out of 38 model realizations was used. For details see Nied et al. (2013).

*3.3. Quantification of the flood-prone behaviour of patterns*

The flood identification (Section 3.1) accounts for discharge peaks of various return periods and the spatio-temporal flood development in the entire Elbe catchment. For each regional flood, a certain date which separates the hydrological pre-conditions

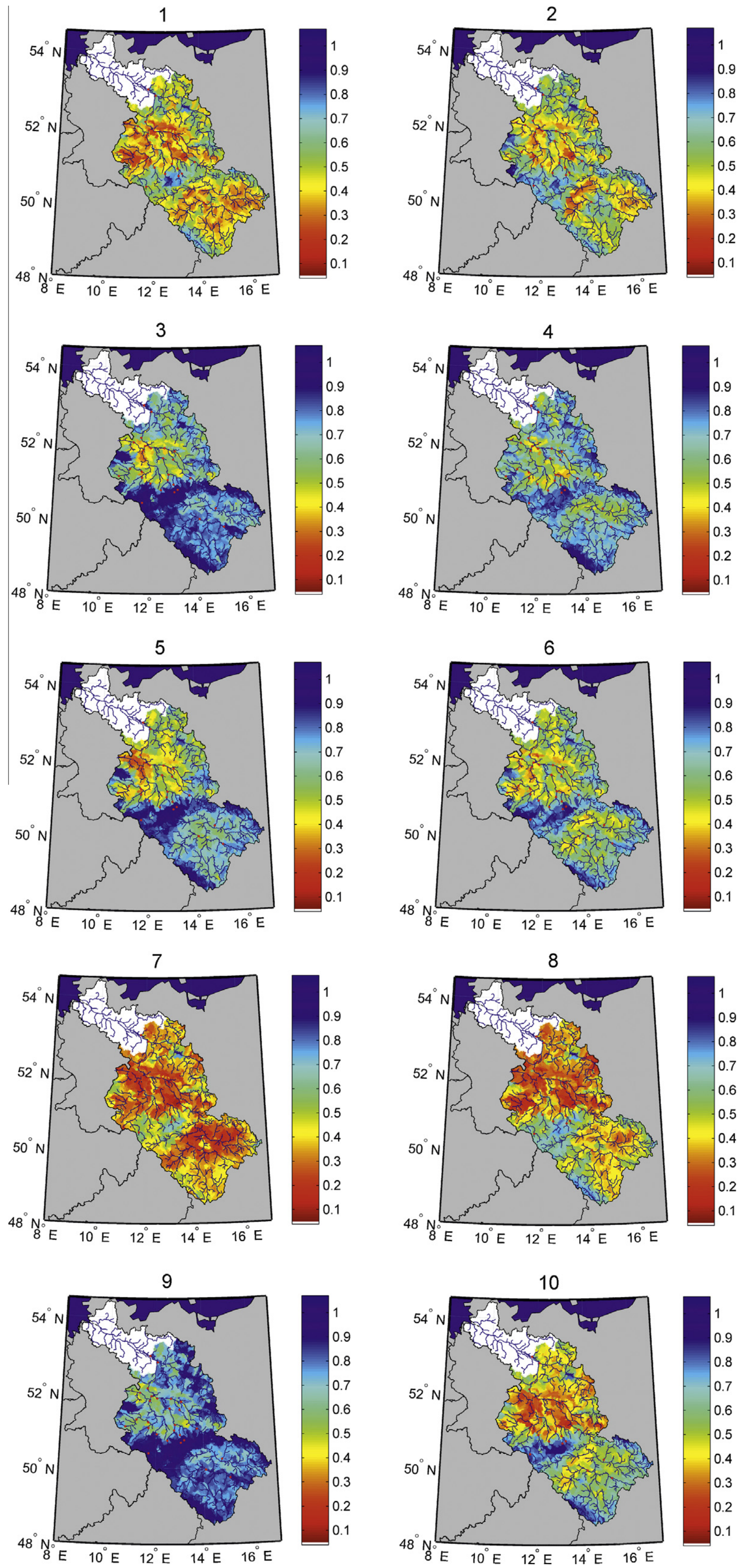


**Fig. 3.** Soil moisture pattern types as identified by Nied et al. (2013). Profile (layer-depth weighted average) soil moisture content is standardised by the field capacity of the respective soil type.

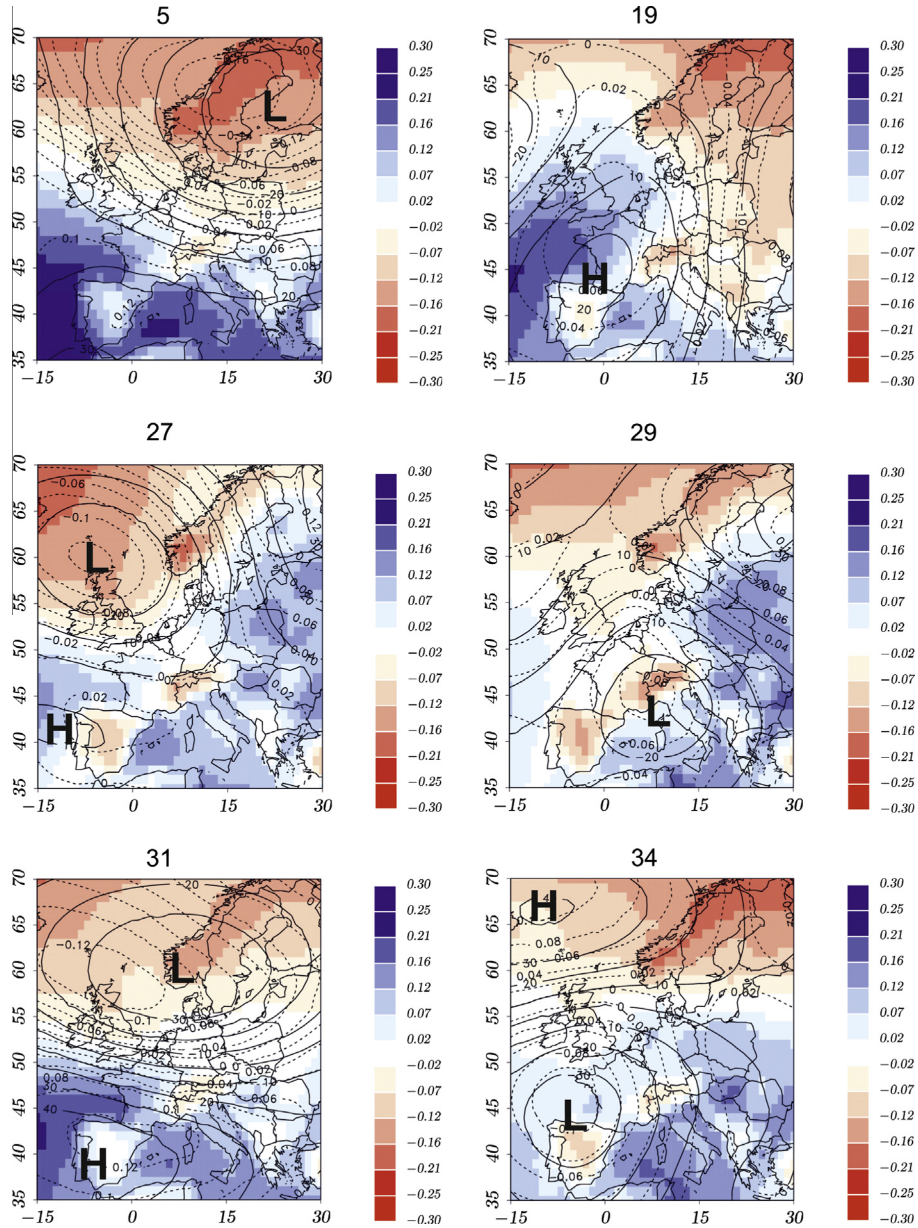


**Fig. 4.** Weather pattern types. Meteorological cluster centroids. Shaded contours show mean cluster anomalies in the vertically integrated moisture content [kg/m$^2$], solid isolines show mean anomalies in the 500 hPa geopotential [m], and dashed isolines are mean anomalies in 500 hPa air temperature [°C].

from the event meteorology can be identified. The pre-conditions are defined as the catchment state i.e. soil moisture patterns, at the event start date, and the meteorological conditions i.e. weather patterns, are considered during the flood event build-up period (Fig. 2). This enables a clear separation between the influence of hydrological pre-conditions and meteorological conditions on flood occurrence as well as on flood type.

To quantify the flood-prone behaviour of patterns, the efficiency *eff* is calculated. *eff* is defined as the frequency of floods related to pattern *i* divided by the overall frequency of flood occurrence.

$$eff_i = \frac{n_{i|flood}}{N_i} \times \left(\frac{n_{flood}}{N}\right)^{-1} \quad (2)$$

where $n_{flood}$ is the number of floods, $N$ the number of days in the analysis period, $n_{i|flood}$ the number of floods related to pattern $i$ and $N_i$ the number of days related to pattern $i$. The efficiency is independent of the group size of the individual patterns and analogous to the performance index PI of Duckstein et al. (1993). In case $eff_i > 1$, pattern $i$ favours the occurrence of floods and is entitled a flood-prone pattern. For instance, if $eff_i = 2$, the relative frequency of flood occurrence under pattern $i$ is two times as high as one would expect under all groups together.

Each weather pattern is weighted in accordance with the number of days it occurs in the build-up period. The weighting coefficient is the reciprocal of the length of build-up period. Thus, each flood event receives the same weight and the efficiency is independent of the length of the build-up period. To quantify the flood-prone behaviour of pattern combinations, *eff* is calculated for all combinations of soil moisture and weather patterns. The soil moisture pattern at the event start date is combined with each weather pattern in the respective build-up period. Again, it is ensured that each flood event receives the same weight independent of the length of the build-up period by weighting in accordance with the length of the build-up period. In the end, soil moisture as well as weather patterns favouring a certain flood type are identified by calculating *eff* for each pattern-flood type combination.

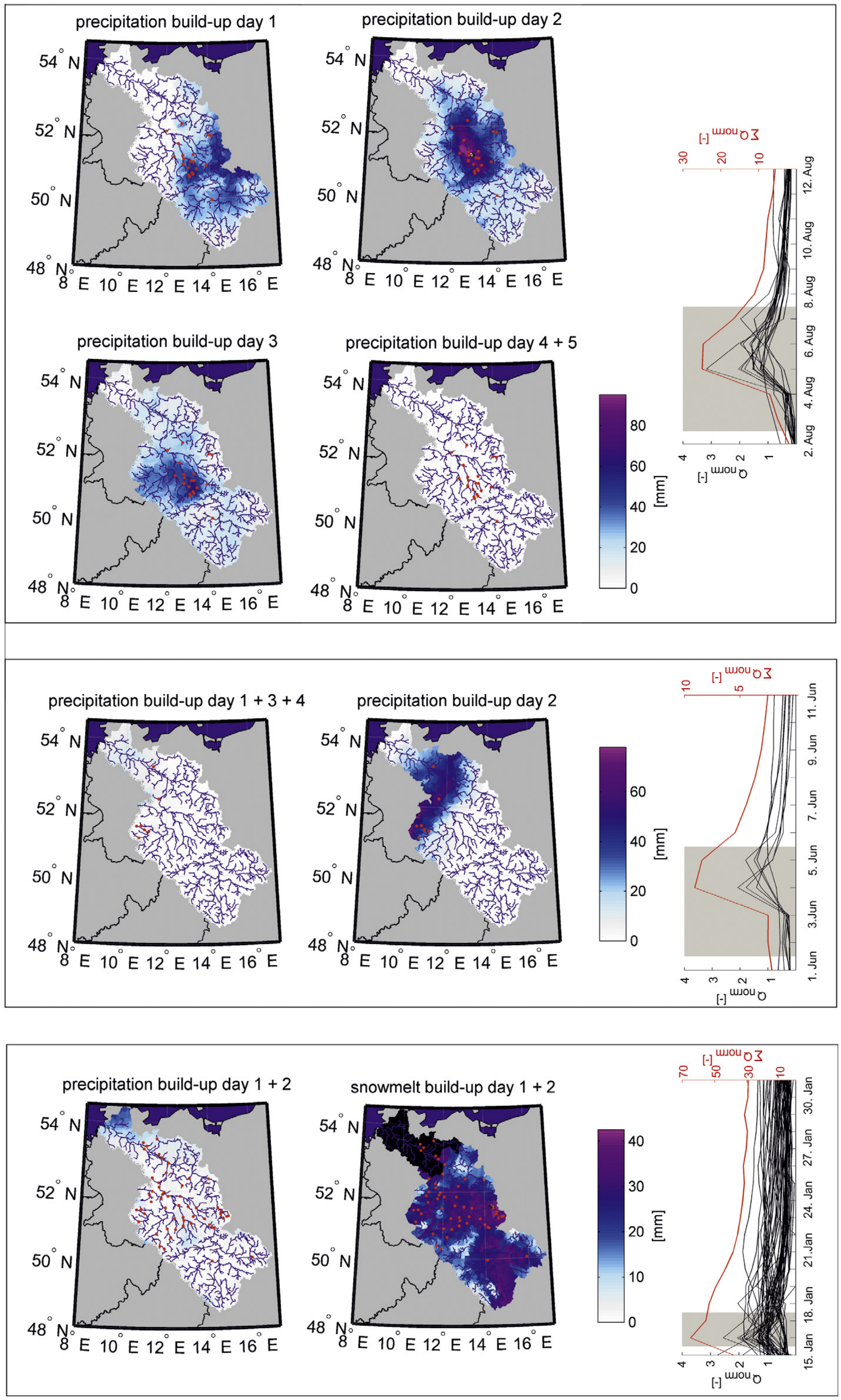


**Fig. 5.** Diagnostic maps, exemplified for three flood events. Red dots mark gauges affected by at least a 2-year flood. Top: Precipitation in the build-up period [mm]. Long-rain flood 2–13 August 1983. Length of the build-up period is 5 days. Severity 22. Middle: Precipitation in the build-up period [mm]. Short-rain flood 1–11 June 1981. Length of the build-up period is 4 days. Severity 9. Bottom: Precipitation and snowmelt in the build-up period [mm]. In the black coloured area simulated snowmelt values are not available. Snowmelt flood 15–31 January 1968. Length of the build-up period is 2 days. Severity 81. Discharge (black) and discharge sum (red) of flood affected gauges normalised by their 2-year flood. Grey rectangle marks the build-up period of the respective flood event. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To test whether the determined *eff* value of a specific pattern (pattern combination) is significantly flood-prone, a bootstrap analysis is performed. The flood periods are randomly redistributed in time and *eff* is calculated for each pattern (pattern combination) as before (Eq. (2)). The procedure is repeated 20,000 times resulting in 20,000 *eff* values for each pattern (pattern combination). From the distribution of the 20,000 random *eff* values, the 95th percentile is derived for each pattern (pattern combination). The *eff* value of a specific pattern (pattern combination) determined from the observed (undistributed) flood periods, is

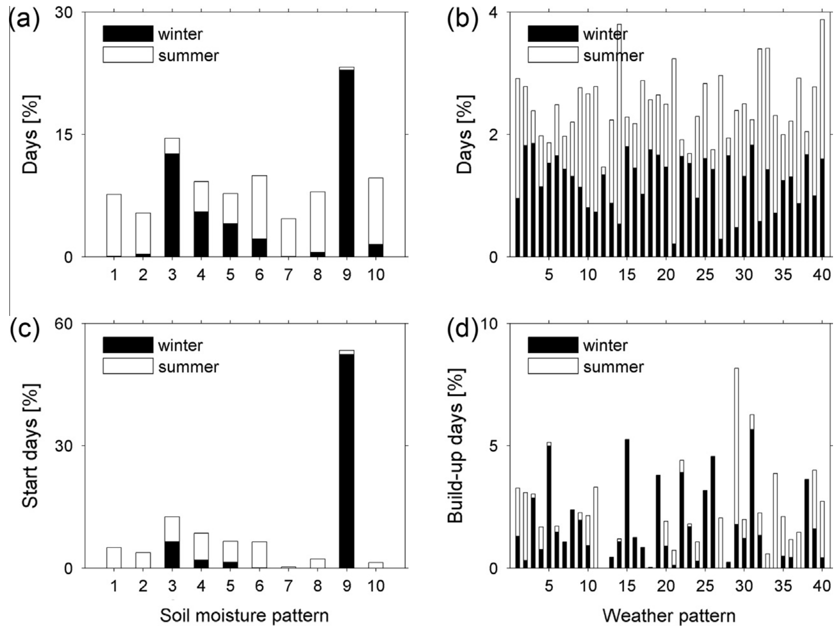


**Fig. 6.** (a) Frequency and seasonality of the soil moisture pattern types in general. (b) Frequency and seasonality of the weather pattern types in general. (c) Frequency and seasonality of the soil moisture pattern types at the event start date. (d) Frequency and seasonality of the weather pattern types during the event build-up period.

**Table 1**
Flood types.

| Flood type indicator | Flood type | | | | |
|---|---|---|---|---|---|
| | Rain-on-snow flood | Snowmelt flood | Long-rain flood | Short-rain flood | Flash flood |
| Spatial flood extent | Snow covered areas and optionally others | Snow covered areas and optionally their downstream regions | Regional to basin wide | Local to regional | Local |
| Seasonality | Winter/spring | Winter/spring | No seasonality | No seasonality | Summer |
| Snow cover | Yes | Yes | Possible | Possible | No |
| Air temperature | Above 0 °C in the snow covered areas | Above 0 °C in the snow covered areas | Above 0 °C, in the snow covered areas below 0 °C | Above 0 °C, in the snow covered areas below 0 °C | |
| Precipitation | Snow covered areas receiving rainfall, additionally snow free areas may receive rainfall | No | Either basin wide stationary low intensity rainfall or spatially limited high intensity rainfall affecting several sites in the catchment progressively within the build-up period (>1 day) | Spatially limited high rainfall of short duration (~1 day) | Local |
| Length of build-up period | Medium | Long (>4 days) | Long (>4 days) | Medium | Short (~1 day) |

significantly flood-prone, if it exceeds the 95th percentile of the randomly obtained *eff* distribution. The bootstrap analysis is conducted for each flood type, too. Here, the flood periods associated with a particular flood type are redistributed in time.

## 4. Results

### 4.1. Flood events

Eighty-two flood events are identified in the analysed time period 1957–2002. 38% of the events are summer (May–October) events. Ten times, the flood start date and the event centroid date are not consecutive i.e. they fall on the same day. This is especially the case for events of low severity *S* (*S* ranges between 1 and 7). In wintertime, extreme long build-up periods of more than 20 days are found. The median build-up period is 4 days.

Long-rain floods are the dominant flood type in the analysis period (Table 2). 22% of flood events are classified as long-rain floods, followed by 20% of flood events, where rain-on-snow is the dominant flood generating process. 18% of events are short-rain floods, 17% of events snowmelt floods. Flash floods are the smallest group containing 10% of flood events. In accordance with the process-based flood types, rain-on-snow floods and snowmelt floods are restricted to wintertime, whereas flash floods are restricted to summertime. Short-rain and long-rain floods occur in summer as well as in wintertime, although the majority of long-rain floods are summer events. The length of the build-up period, a flood type indicator, is in the median highest for long-rain floods and snowmelt floods.

The median flood severity *S*, a combined measure of event magnitude and spatial extent, is highest for rain-on-snow floods, followed by long-rain floods and snowmelt floods. As the gauging network is dense, the severity can be considered as a measure of event impact at the basin scale. In case of rain-on-snow floods, a high rainfall amount is possible beside snowmelt, resulting in a large spatial flood extent of miscellaneous magnitudes. The median percentage of the regionalized river network affected by rain-on-snow floods is 61%. 52% of gauges are affected by at least a

2-year flood and 7% by at least a 10-year flood. Snowmelt floods have the second largest flood extent. In the median, 33% of the regionalized river network is flood-affected. The observed flood peaks are of minor magnitude and variability. Considering the median values, 34% of gauges are affected by at least a 2-year flood and only 2% by at least a 10-year flood. Long-rain floods have in the median a similar flood extent as snowmelt flood (32%), although the flood peaks are of higher magnitude. This is expressed in the higher severity and the higher percentage of gauges affected by at least a 10-year flood in case of long-rain flooding. Short-rain floods have a small spatial flood extent (13%) of miscellaneous magnitudes. The median percentages of gauges affected by at least a 2-year flood and a 10-year flood are 14% and 2%, respectively. Flash floods, although they can be of high magnitude, affect only a limited part of the catchment (2%) and have therefore a low median flood severity. 13% of flood events are unclassified due to their not well defined flood generating processes. There is neither precipitation nor snowmelt in the build-up period.

Diagnostic maps of precipitation and snowmelt, exemplified for three flood events, are presented in Fig. 5. The red dots mark gauges affected by at least a 2-year flood and thus the spatial flood extent. The first flood event (Fig. 5, top), which lasted from 2 to 13 August 1983, is classified as a long-rain flood. In the first 3 days of the build-up period, a high amount of precipitation occurred, affecting progressively several sites in the Elbe catchment. For comparison, the second flood event (Fig. 5, middle), 1–11 June 1981, is classified as a short rain flood. High, spatially limited precipitation is restricted to a single day of the build-up period. The third example (Fig. 5, bottom) shows a snowmelt flood (15–31 January 1968). Within the build-up period, a high amount of snowmelt occurred due to positive air temperature (not shown) under the absence of precipitation.

Furthermore, Fig. 5 presents the discharge and discharge sum of the flood affected gauges normalised by their 2-year flood. The grey rectangle marks the build-up period of the respective flood event. Note that the definition of the build-up period (Section 3.1) incorporates all discharge gauges and is not limited to the flood affected gauges as shown here. In case of the long-rain flood (Fig. 5, top), the discharge peaks occur at three consecutive days. Few gauges show a discharge peak greater than a 2-year flood. In case of the short-rain flood (Fig. 5, middle), the flood-affected gauges have approximately the same magnitude and occur on two consecutive days. The snowmelt flood (Fig. 5, bottom) is characterised by almost constant discharge. Peak discharges are not necessarily restricted to the build-up period.

### 4.2. Hydro-meteorological patterns related to flood occurrence

First, the hydrological pre-conditions, i.e. soil moisture patterns, and the meteorological event conditions, i.e. weather patterns, are separately linked to the flood events. The frequency and seasonality of the flood start dates separated by soil moisture pattern type

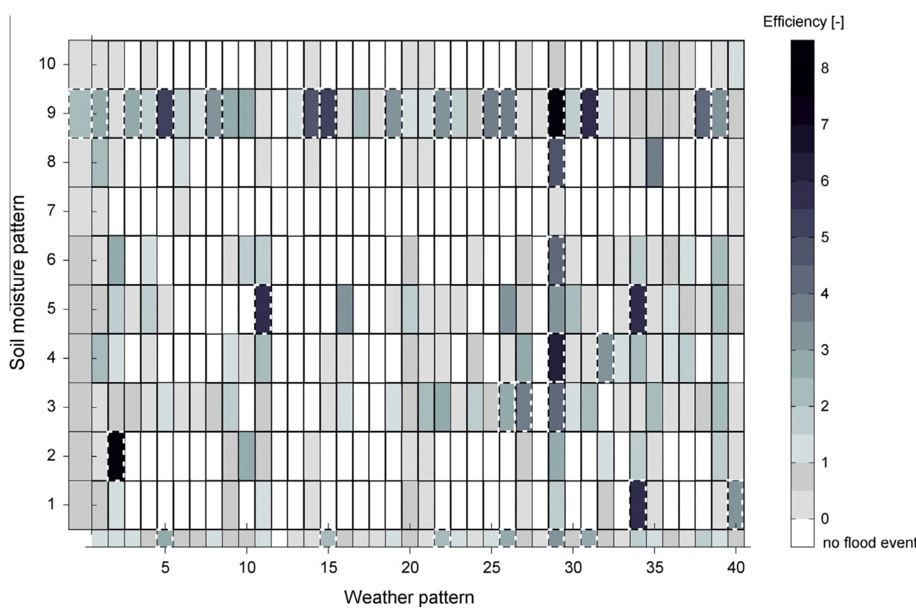


**Fig. 7.** Efficiencies of soil moisture and weather patterns respectively (margins) as well as efficiencies of soil moisture-weather pattern combinations (matrix). Soil moisture patterns are considered at the event start date. The weather patterns are considered in the event build-up period. Dashed framed panels show a significant flood-prone relationship.

**Table 2**
Flood types and their characteristics.

| Flood type | Events (%) | Winter events (%) | Summer events (%) | Build-up period (days) median | Flood severity $S$ (–) median | Gauges $\geqslant HQ_2$ (%) median | Gauges $\geqslant HQ_{10}$ (%) median | Regionalized river net $\geqslant HQ_2$ (%) median |
|---|---|---|---|---|---|---|---|---|
| Rain-on-snow flood | 20 | 20 | 0 | 5 | 77 | 52 | 7 | 61 |
| Snowmelt flood | 17 | 17 | 0 | 6 | 42 | 34 | 2 | 33 |
| Long-rain flood | 22 | 4 | 18 | 9 | 51 | 29 | 4 | 32 |
| Short-rain flood | 18 | 8 | 10 | 3 | 15 | 14 | 2 | 13 |
| Flash flood | 10 | 0 | 10 | 2 | 3 | 6 | 1 | 2 |
| Unclassified | 13 | 13 | 0 | 0 | 6 | 3 | 1 | 5 |
| $\sum$ | 100 | 62 | 38 | – | – | – | – | – |

are displayed in Fig. 6c. The frequency and seasonality of the flood build-up dates separated by weather pattern type are displayed in Fig. 6d. Floods are unequally distributed among the patterns. For instance, 53% of flood start dates are linked to soil moisture pattern 9, whereas weather pattern 12 was never linked to past flood occurrence. For some patterns, flood occurrence is restricted to the summer or winter season. Other patterns cause flooding year-round. For all patterns, the seasonality of the flood start dates (Fig. 6c) deviates from pattern seasonality (Fig. 6a). Same is true for the flood build-up dates (Fig. 6b and d). For instance, weather pattern 15 is only related to flood occurrence in winter. However, the pattern occurs in summer too.

The efficiency of soil moisture as well as weather patterns is displayed at the margins of Fig. 7. In case of soil moisture only one pattern, pattern 9, the predominant soil moisture pattern in wintertime, exceeds an efficiency of 1 (efficiency 2.3, significant). 18 weather patterns exceed an efficiency of 1. Significant flood-prone patterns are 5 (efficiency 2.9), 15 (efficiency 2.3), 22 (efficiency 2.3), 26 (efficiency 2.6), 29 (efficiency 3.4), and 31 (efficiency 2.8). Altogether, they make up 34% of flood event build-up days.

In the next step, soil moisture patterns and weather patterns are combined to examine their joint influence on flood generation. The matrix of Fig. 7 displays the efficiencies of all pattern combinations. In the analysis period, a limited number of hydro-meteorological pattern combinations have led to flood occurrence. A high efficiency is either observed if few flood events are associated with a rare pattern combination. For instance, soil moisture pattern 9 and weather pattern 29 coincided 34 times in the analysis period. 1.4 times (decimal number due to the applied weighting in the build-up period) the coincidence resulted in flood occurrence. Or if both, the absolute number of flood events and the relative frequency of the pattern combination are high. For instance, soil moisture pattern 9 coincided with weather patterns 5, 15 and 31, in total 462 times. The coincidence resulted 12.4 times in flood occurrence (15% of flood events). Almost irrespective of the simultaneous weather pattern, soil moisture pattern 9 has a significant flood-prone efficiency. Same is true for weather pattern 29 which shows a significant flood-prone efficiency almost irrespective of the simultaneous soil moisture pattern. These findings emphasise the great flood potential of soil moisture pattern 9 and weather pattern 29. Their combination results in the highest observed efficiency (8.3, significant) which illustrates that a flood-prone soil moisture pattern together with a flood-prone weather pattern can increase the efficiency. Furthermore, a soil moisture pattern that does not favour flooding can reduce the efficiency of a flood-prone weather pattern, e.g. soil moisture pattern 1 and weather pattern 29, and vice versa, e.g. weather pattern 21 and soil moisture pattern 9. It is also observed that the combination of two flood-prone patterns can result in an efficiency decrease, e.g. soil moisture pattern 9 (significantly flood-prone) and weather pattern 34 (insignificantly flood-prone). Another interesting finding is that in certain cases, the flood favouring-conditions of a weather pattern are limited to one specific soil moisture pattern. For instance, in case of weather pattern 15, flood-prone combinations are limited to the combination with soil moisture pattern 9.

### 4.3. Hydro-meteorological patterns related to flood types

For the interpretation of the pattern-flood link (Fig. 7) in terms of flood generating processes, the flood types are stratified according to their soil moisture patterns (Fig. 8, top) as well as weather patterns (Fig. 8, middle, bottom). As neither the soil moisture patterns nor the weather patterns were included in the flood typology (Sections 3.2.3 and 4.1), the patterns can be regarded as independent from the flood typology.

In both cases, patterns favouring a particular flood type (*eff* > 1) exist. In case of soil moisture, high efficiencies are related to soil moisture pattern 9. Highest efficiencies are found for rain-on-snow

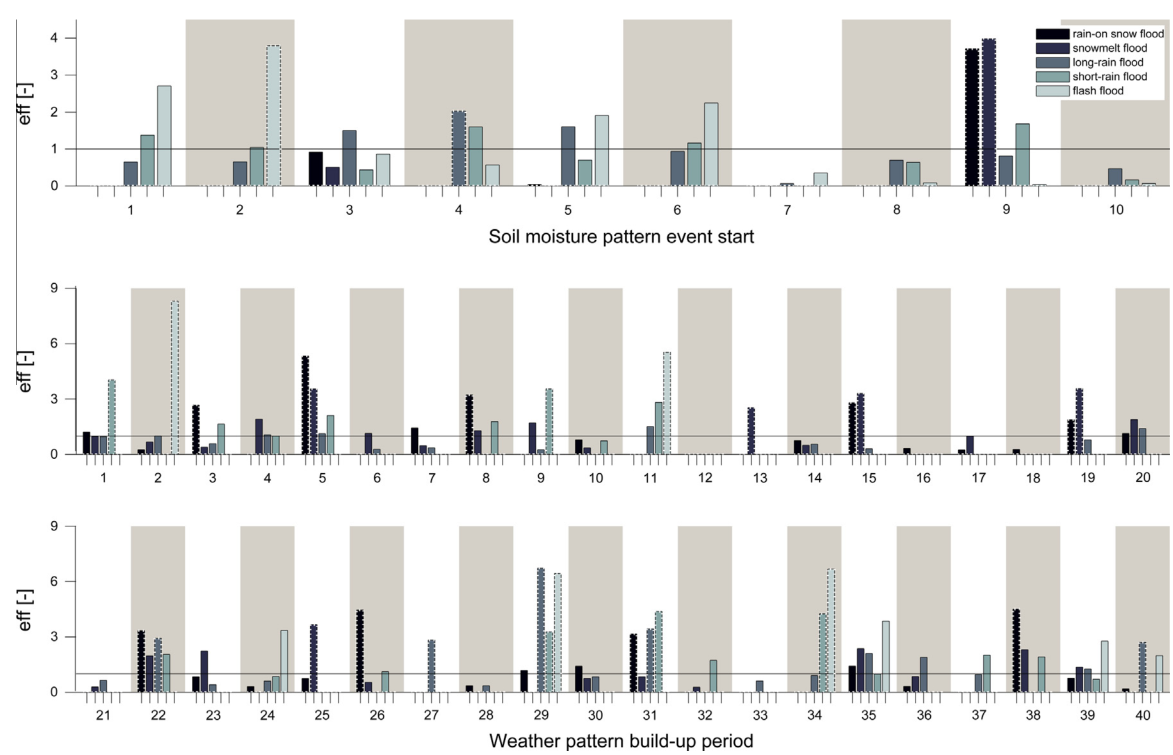


**Fig. 8.** Flood types and their associated soil moisture and weather patterns excluding unclassified flood events. Each bar represents the pattern efficiency stratified by flood type. Soil moisture patterns are considered at the event start date. The weather patterns are considered in the event build-up period. Dashed framed bars show a significant flood-prone relationship.

floods (efficiency 3.7, significant) and snowmelt floods (efficiency 4.0, significant). Short-rain floods have a higher efficiency (efficiency 1.7, insignificant) compared to long-rain floods (efficiency 0.8, insignificant). The efficiency of flash floods related to soil moisture pattern 9 is marginal. Flash floods show the highest efficiencies related to soil moisture patterns 1, 2, 5 and 6 (efficiency 1.9–3.8). In case of soil moisture pattern 2, the relationship is significant. Long-rain floods show high efficiencies with respect to soil moisture patterns 3, 4 and 5 (efficiency 1.5–2.0). The relationship is significant only in case of soil moisture pattern 4. Short-rain floods are linked to a variety of soil moisture patterns. Efficiencies greater than 1 are found in case of soil moisture patterns 1, 2, 4, 6 and 9. However, none of these are significant.

Compared to soil moisture patterns, several weather patterns show considerably higher efficiencies with respect to certain flood types. For instance, weather patterns 2, 11, 29 and 34 show high efficiencies ($\geqslant 5$) with respect to flash flooding. Patterns 15, 19 and 25 are predominantly linked to snowmelt floods, whereas patterns 5, 26 and 38 favour rain-on-snow events. Especially, pattern 29 is linked to long-rain flooding. Patterns 1, 9, 29, 31 and 34 are linked to short-rain flood occurrence.

For the flood events examined in detail (Fig. 5), the long-rain flood has a dry soil moisture pattern at the event start date (pattern 8) and 60% of the build-up days are associated with weather pattern 29, often associated with long-rain flooding. The short-rain flood is generated on a dry soil moisture pattern (pattern 1), too. 75% of the build-up days are linked to weather pattern 34, favouring this flood type. In case of the snowmelt flood, 50% of the build-up days are associated with the weather pattern 19 and the remaining 50% with the weather pattern 25, both favouring this flood type.

## 5. Discussion

### 5.1. Flood events

Adopting a catchment view, the flood identification integrates peak discharge at numerous gauges in space and time into one 'observed' flood event. Therefore, a flood event according to the definition provided in Section 3.1 incorporates a multiplicity of information compared to a peak discharge at a single gauge. For instance, the 82 flood events include 2370 gauges having at least a 2-year peak discharge.

The classification of the observed events into flood types shows that diverse flood generating mechanisms exist in the Elbe River catchment. The flood types along with their probability of occurrence vary seasonally. In dependence of the flood type, spatial flood extent, temporal flood progression, and flood magnitude change. Due to these different characteristics, the flood types require dissimilar flood risk management.

The classification incorporates independent information from different data sources (simulated snowmelt, observed precipitation and air temperature, as well as observed discharge), mutually affirming flood occurrence. As the relationship between these indicators is complex, a manual classification was applied. The manual classification with the help of diagnostic maps has an advantage over quantitative rules, since essential details and hydrological expert knowledge can be incorporated. For the majority of events, the assumption that one flood is the result of the same process, i.e. each flood is assigned to one flood type, is revealed by the diagnostic maps. However, similar to many natural phenomena, the boundaries between the process types are not sharp (Merz and Blöschl, 2003). For instance, snowmelt accompanied by rainfall in the high altitudes, whereas in the lowlands merely rainfall contributes to flood generation. A second example is local rainfall embedded in large scale synoptic systems as was the case in the Elbe flood in August 2002. In these cases, the prevailing process in the entire flood-affected catchment is identified with the help of the diagnostic maps and the flood event is assigned to the respective flood type. For instance, the flood in August 2002 is classified as a long-rain flood, although spatially limited high intensity rainfall (Tarolli et al., 2013) affected several sites in the catchment progressively within the build-up period.

The identified flood event set may be biased towards floods in the German part of the Elbe catchment, as only a limited number of gauges were available in the Czech part of the catchment. In particular, flood events restricted to Czech tributaries may be missing in the flood event set. However, flood events of similar characteristics may have been identified in the German tributaries.

The low percentage of detected flash floods may be attributable to their small extent and short duration behaviour. Hence, a large number of flash floods may not be represented in the precipitation and gauge data at hand. To identify a larger fraction of flash floods, discharge and precipitation data of higher spatio-temporal resolution may be necessary. Eleven flood events are unclassified due to ambiguous flood generating processes. Neither precipitation nor snowmelt is observed in the build-up period. The unclassified flood events are restricted to wintertime. They are of very short duration and low severity. In general, they are of limited spatial extent affecting several gauges along one river reach. Therefore, discharge measurement errors are unlikely. It is hypothesised that these flood events are related to either dam drawdown or ice jams. High-intense rainfall of low spatio-temporal resolution or erroneous snowmelt simulation could also be an explanation.

### 5.2. Hydro-meteorological patterns related to flood occurrence

While the large-scale meteorological conditions have been frequently classified and linked to flood occurrence, the pre-event catchment conditions are commonly neglected. The combined linkage between hydro-meteorological patterns and flood occurrence (Section 4.2) revealed that floods are the result of a complex interaction between meteorological event characteristics and pre-event catchment conditions. The seasonal cluster distribution (Fig. 6a and b) and the deviating seasonality of the flood start days (build-up dates; Fig. 6c and d) inside the cluster exemplifies this complex interaction. In case of soil moisture pattern 9 and weather pattern 29, flood occurrence is widely independent of the coinciding weather/soil moisture pattern. Soil moisture pattern 9 (Fig. 3) is characterised by catchment wide soil saturation. A small amount of rainfall can result in flood generation. Besides soil moisture pattern 9, soil moisture pattern 3 is characterised by catchment wide soil saturation (excluding part of the western Elbe, Fig. 3). For 18% of weather patterns, past flood occurrence is restricted to the coincidence with these two soil moisture patterns, i.e. they have only led to flood occurrence in case of preceding soil saturation. Soil moisture pattern 3 and 9 occur typically in winter (Fig. 6a), and during associated floods snowmelt might additionally contribute to flood generation.

Weather pattern 29 (Fig. 4) is a low pressure system over South Europe transporting warm and moist air masses towards Central/Eastern Europe. So called 'Vb' cyclones which have been identified as flood-favouring in numerous studies (Jacobeit et al., 2006; Petrow et al., 2007; Ulbrich et al., 2003b) are mostly assigned to this weather pattern. This weather pattern is a summer pattern. However, in 20% of cases it occurs in the winter season (Fig. 6b). When the weather pattern 29 coincides with soil moisture pattern 9, a winter pattern, the efficiency is highest, as this rare pattern combination has a high relative frequency of flood occurrence. Thus, besides the frequency of occurrence, seasonality is of importance when combining hydro-meteorological patterns. This is further illustrated when estimating seasonal efficiencies. For instance, the all-season efficiency of soil moisture pattern 4 in combination with weather pattern 29 is 6.1 (Fig. 7). Restricting the efficiency estimation to the summer season, the efficiency rises to a value of 12.3, whereas the winter efficiency is 0.9.

Due to the diverse pattern seasonality, flood occurrence as well as pattern frequency of a particular soil moisture/weather pattern is non-uniformly distributed over its subgroups of pattern combinations (Fig. 7). As a consequence, the efficiency increases in some subgroups, whereas it decreases in others.

In the approach developed in this study, the weather patterns are considered in the event build-up period and weighted according to their relative occurrence. Thus, the linkage between weather patterns and flood occurrence is independent of the length of the build-up period as each flood event receives the same weight. The pattern persistence and succession within the build-up period are not addressed. Second, the linkage is independent of the spatial flood extent. Flood events of large spatial extent, affecting many sites in the catchment, receive the same weight as more local flood events. Thus, patterns favouring large-scale flooding are not overrepresented.

The applied linkage ensures a clear separation between hydrological pre-conditions and meteorological conditions. In addition, it takes into account the temporal flood development of the different flood events/types by an event specific build-up period (Fig. 2, Fig. 5). Similar to our approach, Duckstein et al. (1993) applied seasonal build-up periods according to seasonally varying flood generation. Other studies used a fixed time lag for all flood events. For instance, Parajka et al. (2010) estimated the relative frequency of atmospheric circulation patterns from the day and the two preceding days of the maximum annual floods, and Petrow et al. (2009) applied a time lag of one to three days in dependence of the catchment size.

The flood event set provides a range of hydro-meteorological pattern scenarios observed in the analysis period. Extending the analysis period and incorporating additional gauges, as well as a modification in the flood definition e.g. change of POT, might reveal additional flood-prone combinations and may strengthen or weaken the existing ones. Same is true for the bootstrap analysis which estimates the confidence of the calculated efficiencies under the assumption that the small (flood) sample at hand is representative of the analysed phenomena. In the present set of observed flood events, the number of some hydro-meteorological pattern combinations is rather small, although their impact on flood occurrence seems to be considerable. The sample size of flood-related hydro-meteorological pattern combinations could be extended by a modelling framework, e.g. the simulation of flood events by combining soil moisture patterns and weather patterns. This would not only strengthen the results of our approach on the link between hydro-meteorological patterns and flood occurrence, but would enable to expand the presented pattern approach to flood severities (Eq. (1)) combining the findings of Petrow et al. (2009) and Sivapalan et al. (2005). Petrow et al. (2009) identified a relationship between flood magnitude and the frequency of flood-prone circulation patterns neglecting the influence of the antecedent conditions. Sivapalan et al. (2005) demonstrated that the flood frequency curve increases dramatically if the seasonality of rainfall and antecedent soil moisture are in phase.

### 5.3. Hydro-meteorological patterns related to flood types

As the flood types have different characteristics (Section 4.1), e.g. spatial extent, magnitude and temporal progression, it is important to understand the conditions under which they occur. A dependency between flood types and soil moisture patterns as an indicator of hydrological pre-conditions is detected (Fig. 8). This relationship is attributable to their seasonal characteristics. Long-rain floods and flash floods predominantly occur in the summer season and are therefore linked to summer soil moisture patterns (e.g. pattern 5), whereas rain-on-snow floods and snowmelt floods are linked to pattern 9, the predominant winter soil moisture pattern. Short-rain floods are observed year-round. They appear together with summer as well as winter soil moisture patterns. In rare cases, a typical winter soil moisture pattern, e.g. pattern 3, occurs in summer (Fig. 6a). Therefore, the pattern is observed in conjunction with summer flood types, too. However, the relationship is not flood-prone (*eff* < 1).

Compared to soil moisture patterns, several weather patterns show considerably higher efficiencies with respect to certain flood types (Fig. 8). Flash flood related patterns (pattern 2, 11, 29 and 34) are all associated with the transport of moist air from the Mediterranean towards the Elbe catchment. The large efficiencies with respect to flash floods are a consequence of the small flood type sample size (10% of events). If only one flash flood event is related to a weather pattern of mean group size, the pattern efficiency increases to a value of 4.9.

The wind direction of rain-on-snow and snowmelt floods associated patterns (pattern 5, 15, 26 and 38) is predominantly westerly or north-westerly confirming non-evaluated observations by Beurton and Thieken (2009) and Petrow et al. (2007). These patterns occur predominantly in winter/spring and lead to mild weather and thawing conditions, as they show positive anomalies in air temperature as well as precipitation, suggesting a combination of snowmelt and rainfall. The pattern predominantly linked to snowmelt floods (pattern 19) shows positive anomalies with respect to air temperature and negative anomalies with respect to precipitation suggesting melting conditions. During this pattern subtropical air masses are transported to Central Europe. Less explicit, this is also the case for pattern 25. The previous weather patterns (5, 15, 19, 25, 26 and 38) have only led to flood occurrence in winter. This seasonal flood relevance is confirmed by their attribution to winter flood types as rain-on snow and snowmelt floods and explains why their flood-prone behaviour is restricted to soil moisture pattern 9 (Fig. 7). Soil moisture pattern 9 is the predominant winter soil moisture pattern when rain-on snow and snowmelt floods occur. However, the presence of snow is required for the generation of these flood types. A separation into snow-free and snow days may reveal the frequency of snow within these combinations and its influence on flood generation.

Especially important for long-rain flooding are patterns 27 and 29. Both patterns are summer patterns associated with the transport of moist Mediterranean air into the catchment. In the case of pattern 27, the cyclone is located north of the British Isles and the transport is less effective than for pattern 29, which is often identified in the presence of a "Vb" cyclone passing over the Mediterranean region. The efficiency of pattern 27 rises when the soil moisture pattern gets wetter (Fig. 3, Fig. 7). This provides a further indication, how soil moisture conditions can influence flood generation. In winter, long-rain floods are associated with pattern 31, which is an intense low pressure over Northern Europe that leads to a moist and mild air transport from the Atlantic towards Central Europe. The pattern is also associated with short-rain flood occurrence in winter. Especially, patterns 1, 11, 29 and 34 are linked to short-rain floods between April and August. All of them transport Mediterranean air masses towards the Elbe catchment.

Pattern 12 is associated with the transport of dry continental air masses and was never linked to past flood occurrence in the study period.

## 6. Conclusions

Our presented approach is a step in the direction of the concept of 'flood frequency hydrology' introduced by Merz and

Blöschl (2008a,b). This concept signifies a paradigm shift from pure flood frequency analysis to a frequency analysis that bases itself on process understanding of flood generation. We have demonstrated a flood identification method that enables to separate hydrological pre-conditions and meteorological conditions, and their respective influence on flood generation at the regional scale. As a result, flood occurrence is estimated with respect to hydro-meteorological patterns and pattern combinations. 18% of weather patterns only caused flooding in case of preceding soil saturation. Irrespective of the coincident weather/soil moisture pattern, catchment wide soil saturation (pattern 9) and a weather pattern assigned to 'Vb' cyclones (pattern 29) have the highest flood potential.

The classification of flood events into flood types reveals seasonal flood generating mechanisms with diverse spatio-temporal flood extent as well as flood severity in the Elbe River catchment. In winter, rain-on-snow and snowmelt events have been observed, whereas the summer flood types are long-rain floods and flash floods. Short-rain floods occurred in both seasons.

The flood types are linked to soil moisture and weather patterns. The flood type is primarily determined by the season, by the presence of snow, and by the atmospheric conditions in the build-up period. The large-scale atmospheric conditions, i.e. weather patterns contributing to floods in the Elbe River basin, change between seasons. For different seasons and flood types, either diverse pressure systems transporting moist air masses towards the Elbe River basin or inflowing warm air masses leading to snowmelt or rain-on snow events have been identified. The dependency between flood types and soil moisture patterns is attributable to their seasonal characteristics.

While the results exemplify the influence of hydrological pre-conditions, i.e. soil moisture on the link between weather patterns and flood occurrence, and the influence of meteorological conditions on the flood type, the flood sample size is limited due to the rare nature of flood events. Therefore, future work will extend the pattern classification by a modelling framework, not only to increase the sample size but also to estimate flood risk in dependence of hydro-meteorological pattern combinations and to relate hydro-meteorological pattern combinations not only to flood occurrence but also to flood type. However, model simulations cannot replace the value of observations. It is of particular importance to maintain existing (dense) gauging station networks, as flood events recorded in high spatio-temporal resolution can further improve our understanding of flood generation which is exemplified in this study.

An advantage of the developed classification approach is its suitability to deal with inhomogeneities. As the patterns can be attributed to flood types of diverse characteristics, the flood sample can be subdivided and analysed according to the flood generating patterns. Furthermore, the developed classification approach is suitable to deal with instationarities. For instance, climate as well as land use change might alter the relative frequency of soil moisture patterns. Changes in the atmospheric conditions might alter the relative frequency of weather patterns and thus flood types. Thus, if the present weather pattern-flood (type) link is known and adequately reproduced in Global Circulation Models, their future changes could be assessed. As a result, the timing and relative frequency of the flood generating mechanisms may shift with implications for present and future flood risk management.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2014.09.089.

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