Letter

Snow-influenced floods are more strongly connected in space than purely rainfall-driven floods

Manuela I Brunner1,∗ and Svenja Fischer2
1 Institute of Earth and Environmental Sciences, University of Freiburg, Freiburg, Germany
2 Engineering Hydrology and Water Resources Management, Ruhr University Bochum, Bochum, Germany
∗ Author to whom any correspondence should be addressed.
E-mail: manuela.brunner@hydrology.uni-freiburg.de

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Abstract

Widespread floods that affect several catchments are associated with large damages and costs. To improve flood protection, a better understanding of the driving processes of such events is needed. Here, we assess how spatial flood connectedness varies with the flood generation process using a flood event classification scheme that distinguishes between rainfall-driven and snowmelt-influenced flood types. Our results show that the dominant flood generation processes in Europe vary by region, season, and event severity. Specifically, we show that severe floods are more often associated with snow-related processes than moderate events. In addition, we find that snow-influenced events show stronger spatial connections than rainfall-driven events. The spatial connectedness of rainfall-driven events depends on the rainfall duration, and the connectedness decreases with increasing duration. These findings have potential implications for flood risk in a warming climate, both locally and regionally. The projected decrease in the frequency of occurrence of snowmelt-influenced floods may translate into a decrease in the frequency of severe and widespread floods in catchments where snowmelt processes are important for flood generation.

1. Introduction

Widespread or regional floods affecting more than one catchment are associated with large damages and costs, as illustrated by the 2021 flood events in Germany (Kreienkamp et al 2021) or the lower Mississippi flood in 2019 (Pal et al 2020). Regional as opposed to local floods develop in regions where different catchments are likely to be jointly affected by flooding because of common flood generation mechanisms (Brunner et al 2020a). We need to better understand the mechanisms causing large-scale and spatially connected floods to improve the prediction of the magnitude of regional floods and to assess future changes in their likelihood.

Spatial flood extent and flood connectedness—a measure for the likelihood of flood co-occurrence at multiple locations—have been shown to vary both in space and time (Berghuijs et al 2019a, Kemter et al 2020, Brunner et al 2020b). Berghuijs et al (2019a) have demonstrated that the distance over which multiple catchments in Europe co-experience flooding is highly variable. Similarly, Brunner et al (2020b) have shown that spatial flood connectedness in the United States varies in space. Specifically, wetter regions such as the Pacific Northwest or the Appalachian region are more prone to regional flooding than drier regions such as the Great Plains. In addition, the strength of flood connectedness varies by season, with spring being the season with the strongest flood connectedness in the United States (Brunner et al 2020b).

The spatial connectedness of floods and their seasonal variations are insufficiently explained by the spatial connectedness of precipitation (Brunner et al 2020b). This observation suggests that other hydro-meteorological drivers than precipitation are important to determine the degree of flood connectedness. Such processes may include snowmelt, rain-on-snow effects, or soil moisture excess, which have been shown to influence the development of local floods (Stein et al 2019, Wasko and Nathan 2019, Berghuijs 2019).
et al 2019b). While previous studies have shown that the local magnitude of floods depends on the flood generation mechanism (Nied et al 2014, Smith et al 2018, Tarasova et al 2020a), it is yet much less clear how these mechanisms affect spatial flood connectedness. Few studies focusing on individual river basins or countries have investigated the relationship between spatial flood extent and flood generation mechanisms. They suggest that some seasons and flood generation processes are related to floods with larger spatial extents than others. For example, Uhlemann et al (2010) and Gvoždíková and Muller (2017) have shown that trans-basin flood events in some European river basins mainly occur in winter. In addition, Nied et al (2014) have shown that large-scale floods in the Elbe river basin are often related to snowmelt processes, while flash floods tend to have small spatial extents. Similarly, Krug et al (2020) have shown that past trans-basin flood events in Germany were associated with rainfall during widespread snowmelt. These previous studies provide some first evidence for a relationship between flood generation processes and flood extent at a regional scale. However, it remains to be systematically investigated how spatial flood connectedness is related to flood generation processes at larger spatial scales and in different hydro-climates.

Here, we assess whether and how spatial flood connectedness varies with the flood generation process in Europe by focusing on differences between rainfall- and snow-influenced floods. We hypothesize that snowmelt-influenced flood types show stronger spatial dependencies than rainfall-driven flood types because of the more pronounced seasonality of snowmelt compared to precipitation. That is, snowmelt tends to occur synchronously in space because of simultaneously increasing temperatures in a large region. To study the relationship between flood types and spatial flood connectedness, we apply a flood classification scheme to a large sample of flood events extracted from 863 nearly natural catchments in Europe. We then quantify spatial flood connectedness for these different flood types using complex networks (Luke 2015, Kolaczyk and Csardi 2020). This combination of flood classification with complex network analysis allows us to explicitly assess the effect of different flood generation processes on spatial flood connectedness.

2. Methods and materials

2.1. Dataset

To analyze the relationship between flood types and the strength of spatial flood connectedness, we compile a data set of 863 catchments in Europe. The catchments are part of the Global Runoff Data Centre database (GRDC 2019) and fulfill the following three criteria. First, they have daily streamflow data for the period 1981–2012 representing current climate conditions. We chose this period because of its good spatio-temporal coverage (France is no longer included from 2013, i.e. no updates have been done). Second, they are included in the Global Streamflow Indices and Metadata Archive (GSIM) database (Do et al 2018). This database provides catchment boundaries to compute areal averages of climatic data and information on human influences (number of dams) to identify ‘nearly’ natural catchments. Third, they are nearly natural, i.e. uninfluenced by dams according to the GSIM database.

For each of these catchments, we derive a set of hydro-climatic time series using gridded ERA5-Land reanalysis data (ECMWF 2019, Muñoz-Sabater et al 2021) downloaded from the Copernicus data store and catchment boundaries extracted from the GSIM. ERA5-Land provides hourly time series for a number of variables describing the water and energy cycles over land at a spatial resolution of 9 km for the period 1981–2020. We compute areal sums of precipitation and snowmelt for the period 1981–2012, i.e. the period overlapping with the period for which streamflow data are available for all catchments.

2.2. Flood identification and classification

For each catchment, we identify flood events using a variance-based separation algorithm on the daily discharge time series (Fischer et al 2021). This algorithm defines the beginning of flood events as the point where the mean 3 d moving window variance plus \( \theta \) times the standard deviation of the 3 d moving window variance is exceeded. This threshold is similar to the 2-\( \sigma \)-rule for detecting outliers. Instead of \( \theta = 2 \), we here used \( \theta = 0.25 \) because Fischer et al (2021) have shown that this is the best choice for flood event separation in most catchments. Each of these threshold exceedances defines a flood event. The variance was used as a threshold to allow for the detection of abrupt discharge increases even in periods with low baseflow, which is hardly possible when using a classical quantile-based threshold. Then, the end of the flood events is defined as the point where the flow falls again below the level of discharge at the beginning of the flood event. The flood peak is defined as the maximum discharge of the flood event, the volume as the discharge sum from the beginning to the end of the event, and the duration as the number of days elapsing between the beginning and end of the event. We work with direct peak discharge...
and flood volume. That is, we subtract baseflow from discharge before computing these flood characteristics. The baseflow is separated using a straight-line method, that defines baseflow as the flow below a line drawn between the flow at the beginning of the event and the flow at the end of the flood event. To evaluate the variance-based event identification procedure, we checked if all large floods were included in the flood sample identified. For this purpose, we identified a second flood sample using a classical fixed threshold at the 98%-quantile of all daily discharge values. We then determined how many of the local maxima above this threshold were included in the flood sample identified using the variance-based threshold. About 85% of the flood events identified using the classical flood threshold were included in the sample identified using the variance-based threshold. This comparison demonstrates that the variance-based threshold identifies most flood events that are considered severe based on a classical quantile-based threshold.

After the event identification, we classify the flood events into different flood types. Flood classification is a powerful tool to understand the spatio-temporal variability of flood generation processes. Different classification schemes have been proposed to group flood events according to their flood-generating mechanisms (Merz and Blöschl 2003, Sikorska et al 2015, Brunner et al 2017, Fischer et al 2019, Stein et al 2019, Tarasova et al 2019). Most classification schemes rely on variables describing the meteorological forcing and catchment state to distinguish between different flood types such as short rain floods, long rain floods, excess rainfall floods, rain-on-snow floods, or snowmelt floods (Merz and Blöschl 2003, Sikorska et al 2015, Stein et al 2019).

Here, we use the classification scheme proposed by Fischer et al (2019) to separate three rainfall-driven flood types with distinct hydrograph shapes from two snow-influenced flood types using the concept of time scale, i.e. the relation between flood volume and flood peak (Gaal et al 2012). This classification scheme has the advantage that it is easily applicable to large data sets and does only require daily discharge, precipitation and snowmelt time series. In a first step, it separates rainfall-driven from snow-influenced floods. To do so, it compares the proportion of snowmelt with the total amount of flood-generating water. A threshold of 20% snowmelt is applied to separate rainfall-driven from snow-influenced events. Events with more than 20% of snowmelt are classified as snow-influenced and those with less than 20% as rainfall-driven (Kampf and Lefsky 2016, Fischer et al 2019). In a second step, the rainfall-driven floods are further classified according to their flood timescale by optimizing the linear relationship between direct flood peak and volume. For this purpose, the peak-volume pairs are sorted by their flood timescale and divided into three groups. These three groups are defined by maximizing the sum of the coefficients of determination of the three linear regressions between peak and volume. The classification scheme directly takes into account the hydrograph shape as flashy hydrographs result in a short timescale while long-duration floods with large volumes result in long timescales. In a third step, the snowmelt-influenced floods are further classified using k-means clustering (James et al 2013) on three variables, i.e. precipitation sum, snowmelt sum, and runoff coefficient. The flood classification procedure results in five flood types, which are clearly distinct in terms of their rainfall and snow characteristics (Fischer et al 2019, Fischer and Schumann 2021) (figure 1):
• R1: flood events with a high flood peak and a small volume, associated with heavy rainfall of high intensity
• R2: flood events with a moderate peak and volume, associated with medium-duration rainfall of uniform intensity
• R3: flood events with a large volume, associated with long, successive rainfall events
• S1: rain-on-snow floods, where rainfall falls on a snow cover; these events are associated with high amounts of rainfall and less snowmelt compared to snowmelt floods
• S2: snowmelt floods induced by considerable snowmelt and potentially modulated by precipitation; these events are associated with substantial snowmelt contributions and no or only small amounts of rainfall.

The classification of flood types resulted in 48 006 events of type R1, 33 461 events of flood type R2, 21 578 events of flood type R3, 14 929 events of flood type S1, and 6857 events of flood type S2 for all catchments under consideration. On average, catchments experienced 65 R1-floods, 45 R2-floods, 29 R3-floods, 20 S1-floods and 10 S2-floods. That is, rainfall-driven floods are more common than snowmelt-influenced floods. These numbers vary considerably across catchments and depend on catchment conditions and the location of the catchment. Please note that R1-floods associated with heavy rainfall can have a duration of several days and hence should not be considered as flash floods, which typically have a duration of a few hours. Instead, R1-floods can be caused by rainfall of high intensity with varying duration. An example of such an R1-flood is the 2002 flood event in Central Europe.

2.3. Spatial dependence
We assess the strength of spatial flood connectedness using complex network theory, which enables visualizing and describing structures and connections of large data sets (Luke 2015, Kolaczyk and Csardi 2020). We first compile a data set consisting of the dates of flood occurrences across all catchments, following the procedures proposed by Brunner et al (2020b) and Brunner and Gilleland (2021). Then, we convert this set into a binary matrix, which highlights the flood events the different catchments were affected by. Next, we use the binary matrix of overall flood occurrences to map networks of flood co-occurrences and to quantify the flood connectedness of a station with other stations. Here, flood connectedness is defined as the number of catchments with which certain catchments co-experience flood events. For each pair of catchments, we compute the number of flood co-occurrences, i.e. flood occurrence on the same day, to compile a co-occurrence matrix. We compute an overall co-occurrence matrix by considering all events and one co-occurrence matrix per flood type by only counting co-occurrences where both catchments experienced the same flood type. We use these co-occurrence matrices as an input for the network analysis. A pair of catchments is assumed to be connected if they co-experienced a certain number of flood events of the same flood type. The threshold for this connectedness definition is set to 25% of the median number of floods with a certain flood type across catchments. That is, we call a pair of catchments connected if they co-experienced at least 25% of the median number of floods of a certain flood type in the past. This information on (non-)connectedness is stored in an adjacency matrix $A$, which is used to build the complex network graph $G = (V, E)$, where $V$ represents vertices, i.e. network nodes (in our case catchments), and $E$ represents edges, i.e. links connecting the nodes (in our case connecting pairs of catchments co-experiencing flood events). $A$ is defined so that

$$A_{ij} = \begin{cases} 1, & \text{if } \{i,j\} \in E \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

To compare the network properties of the flood-type specific networks, we compute a measure of connectedness and a measure of connectedness length for each of the catchments. Connectedness is described by the network degree (also called centrality degree), which defines the number of edges incident on a certain node, i.e. how many catchments a certain catchment is connected with. Connectedness length is defined for each existing edge as the Euclidean distance between catchment outlets of flood-dependent but not necessarily physically connected catchments (Martinez and Chavez 2019). We compare the overall network degree and connectedness length for the different flood types by comparing the distributions of degree and connectedness length across catchments for the different flood types.

3. Results

3.1. Flood type variability
The dominant flood type, i.e. the flood type that is most frequently observed in a catchment, varies over Europe (figure 2(a)). Overall, the flood type dominating most often is that of floods associated with high-intensity rainfall (R1) followed by floods associated with rainfall of uniform intensity (R2). Only in very few catchments, the dominant flood type is associated with snow-related processes. Exceptions are a few catchments in Scandinavia and in Central and Western Europe, which most frequently experience snowmelt floods (S2) and rain-on-snow floods (S1), respectively. While rainfall-driven floods dominate the overall picture, most catchments show a large variability in the flood types they experience (figure A2) and floods influenced by snowmelt become more important as event severity increases. When considering only those floods with the 10%
largest flood peaks, snow-related floods become the most dominant flood type in wide parts of Central Europe and the southern UK and remain important in Scandinavia (figure 2(b)). In other regions such as the northern UK, the Alps, and parts of Scandinavia, rainfall remains the main flood driver for severe events. However, these severe floods are hardly ever dominated by short rainfall (R1 floods). Instead, rainfall of longer duration becomes the dominant process associated with severe floods.

The most dominant flood type also varies considerably by season (figure A1 in the appendix). In spring, snowmelt floods (S2) are the most frequent floods in most catchments in Europe, particularly in western Europe and Scandinavia, where the rising temperatures in spring lead to a melting of the snow cover and thus increased snowmelt. Exceptions are the UK and Austria, where medium-duration or long-duration rainfall floods occur most often. In summer, heavy rainfall floods are most frequent because of thunderstorms, except in the Alps, where medium-duration rainfall flood events are most common. In autumn, floods are most often caused by rainfall with some regions being dominated by short rainfall floods and others by floods associated with longer precipitation events. In winter, when many catchments show a snow cover, rain-on-snow floods cause flood events most frequently. Hence, the consideration of flood types might explain the seasonal variations in flood connectedness observed in previous studies.

3.2. Flood types and spatial dependence
Similar to the dominant flood type, the strength of spatial flood connectedness shows strong regional variations (figure 3(a)). Spatial connections over all flood events are pronounced in the United Kingdom and in Central Europe, particularly in mountain regions such as the Alps, the Massif Central or the Pyrenees. In contrast, Scandinavia and Eastern Europe show only weak spatial connectedness. These spatial connectedness patterns vary by flood type (figures 3(b)–(f)) with spatial connections being stronger for the snow-influenced (S1 and S2) than for the rainfall-driven flood types (R1, R2, and R3). Snowmelt floods (S2) show the strongest spatial connections because regions in Central Europe, the UK and Scandinavia experience snowmelt flooding in the same season (winter, figure A1(d)). Rain-on-snow floods (S1) are a bit less but still clearly spatially connected, particularly in Central European mountain regions and the UK. The rainfall-related flood types (R1–R3) show similar but less pronounced connectedness patterns than snow-related flood types. Floods are spatially connected within the UK, within the Alps, and within the Massif Central, while other regions such as Scandinavia and Eastern Europe show only weak spatial connectedness. This spatial connectedness pattern is similar for all three rainfall-related flood types, but its strength decreases as rainfall duration increases from R1 to R3 floods.

The visual impression that snowmelt-influenced floods are more strongly connected than rainfall-driven floods is confirmed by the distribution of node degrees (i.e. the number of catchments a certain catchment is connected with) across catchments for the different flood types (figure 4(a)). In the case of rain-on-snow and snowmelt-related floods, catchments are on average co-experiencing flooding with 8 and 18 catchments, respectively. In the case of short, medium, and longer rainfall events, connections exist
Figure 3. Spatial flood connectedness patterns for different flood types: (a) all types combined, (b) S1: rain-on-snow, (c) S2: snowmelt, (d) R1: intense precipitation, (e) R2: moderate precipitation, and (f) R3: long precipitation. Lines connect pairs of catchments that have co-experienced a certain number of floods of the particular flood type in the past (threshold: 25% of the median number of floods of a certain type across catchments). The dot size indicates the node degree, i.e. the number of catchments a certain catchment is connected with.

Figure 4. Comparison of complex network properties across flood types: (a) connectedness strength (node degree) and (b) connectedness length (Euclidean distance in degrees) across catchments.

Discussion

We proposed a methodology to assess the effect of flood generation processes on spatial flood connectedness, which combines flood type classification with complex network analysis. This methodology allowed us to quantify the effect of different flood generation processes on flood connectedness, which is only possible because different

with 5, 2, and 2 catchments, respectively. The connectedness of rainfall-driven floods depends on rainfall duration and events caused by shorter lasting precipitation events are slightly more connected. While there are pronounced differences in the strength of connectedness between flood types, differences in the connectedness length (i.e. the distance across which catchments co-experience flooding) are much weaker (figure 4(b)).
flood types are considered separately. The approach involved different threshold choices. For example, we used a variance-based threshold to identify flood events. Alternatively, one could work with a classical quantile-based threshold, which focuses on absolute threshold exceedances only. A second threshold choice is made in the flood classification, where we used a 20% threshold to separate snowmelt from non-snowmelt influenced flood events. This value is based on previous studies (Kampf and Lefsky 2016, Fischer et al 2019) and could be adjusted in other regions and for other applications if desired. Last, we set a threshold to define spatial flood connectedness (25% of the median number of floods of a certain flood type across catchments). Our sensitivity analysis demonstrates that a decrease/increase in the threshold leads to an increase/decrease in the connectedness (figure A3 in appendix). However, the main result of our connectedness analysis, i.e. that snow-influenced floods are more strongly connected than rainfall-influenced floods, remains hardly affected by the threshold choice. Only for very low thresholds (10%), some rainfall-driven floods (R1) show similar connectedness as the snow-influenced flood types (S1 and S2). At higher threshold choices (from 20% on), snowmelt-influenced floods are more strongly connected than rainfall-driven floods. Another methodological choice we had to make was how to define co-occurrences. Here, we defined them as co-occurrences of peak flow at a pair of stations on the same day. Alternatively, one could use the whole flood period to identify co-occurrences. Because such an alternative approach would attribute more weight to those flood types with longer flood durations (i.e. the connectedness increases with event duration), we decided to focus on the peak flow dates only. Instead of using co-occurrence counts to define spatial flood connectedness, one could use some sort of correlation measure between flood event magnitudes at pairs of catchments (see e.g. Sivakumar and Wolde meskel 2014, Han et al 2018, Brunner and Gilleland 2021). Such a definition would require the definition of joint threshold exceedances in order to be able to compute pairwise correlation metrics. Our approach of studying flood connectedness variations with the flood type could also be used with alternative flood type classification schemes (e.g. Merz and Blöschl 2003, Sikorska et al 2015, Stein et al 2019, Tarasova et al 2020b). Furthermore, it could be used in other regions with different hydro-climates and potentially other dominant flood generation processes. Such processes could e.g. include coastal flooding or compound flooding, such as joint riverine and coastal flooding or joint pluvial and coastal flooding (Bevacqua et al 2019, Hendry et al 2019).

We demonstrate that in most European catchments, flood generation is dominated by rainfall rather than snow characteristics (figure 2(a)). This finding corroborates results of earlier studies showing that floods in Europe are mainly caused by different types of rainfall mechanisms, while snow-influenced floods occur less frequently (Merz and Blöschl 2003, Sikorska et al 2015, Stein et al 2019, Tarasova et al 2020b). However, our results also show that snow-influences are crucial for the formation of severe events, particularly in the Alps and in Scandinavia (figure 2(b)). This is in line with results by Tarasova et al (2020a) who have shown that the dominance of processes related to snowmelt consistently increases from moderate to severe flood events in German regions where floods occur predominantly in winter. In addition, we also highlight variations in the relevance of flood types by season. Snow-influenced events are most frequent in spring and winter, while rainfall-influenced floods dominate in summer and autumn in most parts of Europe (figure A1 in the appendix). These seasonal patterns are linked to the seasons of snow availability and snowmelt-occurrence.

We also show that the strength of spatial flood connectedness varies considerably in space. For example, regions in Central Europe are more strongly connected than regions in Scandinavia or Western Europe. These large spatial variations agree with findings by Berghuijs et al (2019a) who have shown that the distance over which multiple river basins in Europe flood synchronously varies substantially. Here, we demonstrate that the strength of spatial flood connectedness is importantly shaped by the flood generation process. That is, certain flood types, particularly those related to snowmelt processes, lead to strongly connected events, while others lead to more localized events (figure 3). This finding that snowmelt processes are important for flood connectedness corroborates results by Brunner et al (2020b) who have shown that precipitation connectedness alone is insufficient to explain spatial flood connectedness. It also supports findings by Nied et al (2014) who have demonstrated that snowmelt floods in the Elbe catchment are associated with large spatial extents. Because of the important influence of snowmelt on the spatial properties of floods, mountain regions such as the Alps, the Pyrenees or the Massif Central stick out as regions with particularly pronounced flood connectedness (figure 2(a)). This importance of mountain regions with respect to flood connectedness has also been indicated for the Rocky Mountains in the United States (Brunner et al 2020b).

In addition to the different natural flood generation processes, spatial flood connectedness is also influenced by human flow regulation (Brunner 2021), which is not considered in our analysis because of our focus on natural catchments. For example in the United States, regulation effects reduce spatial flood connectedness in winter suggesting that reservoir regulation may reduce the risk of regional flooding during this season (Brunner 2021).

The snowmelt-related floods, which we found to be strongly connected in space, are often also the most
severe floods in terms of magnitude (figure 2(b)). This behavior is in line with findings by Kemter et al (2020) who pointed out positive correlations between flood magnitudes and extents for the majority of catchments in Europe. In addition, it has potential implications for flood magnitudes in a warming climate. Climate change leads to a shift in the snowmelt period towards earlier in the year (Coopersmith et al 2014, Brunner et al 2019, Muelchi et al 2021) and to a decrease in snowmelt contributions because of a shift in the snowline (Marty 2008, Hu et al 2020). These changes have potential impacts on the seasonality and magnitude of local floods (Saraulsiene et al 2015, Bööschl et al 2017, 2019) and on the relative importance of different flood generation processes (Li et al 2019). Our results suggest that this effect is not limited to local flood characteristics but extends to spatial characteristics. That is, the probability of regional floods with strong spatial connections might change. Specifically, we expect fewer large-scale events in snow-influenced regions if snowmelt contributions become less important for flood generation (Chegwidden et al 2020, Sikorska-Senoner and Seibert 2020). For example, in the Columbia River basin, there are first indications that a decrease in snowmelt contributions may lead to a decreasing synchronicity between high flows in snowmelt-dominated basins (Rupp et al 2021). Such changes in the spatial dependence have important implications for regional flood hazard and risk, which are modulated by the strength of spatial flood dependencies (Thieken et al 2015, Brunner et al 2020a). The exact direction and magnitude of change in spatial flood connectedness and associated hazard have to be assessed using targeted modeling experiments, e.g. by coupling climate simulations with a hydrological model (Clark et al 2016, Hakala et al 2019).

5. Conclusions

We analyzed how spatial flood connectedness varies by flood generation process using a flood event classification scheme distinguishing between three rainfall-driven and two snowmelt-influenced flood types. Our results show that the most frequent flood type of catchments in Europe varies spatially, by season, and by event severity, with severe events being more often influenced by snow (mainly in winter and spring) than moderate events. In addition to being locally severe, these snow-influenced floods are also spatially more strongly connected than rainfall-driven floods. These findings have potential implications for future flood risk in regions where snowmelt-influenced floods are relevant. Changes in the snowline and the seasonality of snow accumulation have been shown to lead to changes in the frequency of occurrence of snowmelt-influenced floods. Our results suggest that these changes also influence the regional characteristics of flood events, which may become less connected as snowmelt contributions become less important for flood generation.

Data availability statement

The data on which this article is based are available through the GRDC database (GRDC 2019) and the Copernicus data store.

The data that support the findings of this study are openly available at the following URL/DOI: www.hydroshare.org/resource/da1c282a2b464a02841672077056b5cf7.

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Author contributions

MIB and SF jointly designed and developed the method for this analysis. They both contributed to the data analyses and the drafting and editing of the manuscript.

Conflict of interest

The authors declare no competing interests.
Appendix

Figure A1. Most frequent flood type per catchment and season: (a) spring (March–May), (b) summer (June–August), (c) autumn (September–November) (d) winter (December–February). Dot size represents the relative importance of a flood type in a catchment. That is, the larger the dot is, the more frequent is the dominant flood type in that catchment.

Figure A2. Frequency of each flood type in 10 randomly selected catchments.
**Figure A3.** Sensitivity analysis towards the choice of the connectedness threshold: Connectedness (i.e. node degree) across catchments for different flood types and connectedness thresholds (0.1, 0.2, 0.25, and 0.3).

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**ORCID iD**

Manuela I Brunner [https://orcid.org/0000-0001-8824-877X](https://orcid.org/0000-0001-8824-877X)

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