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Repeating patterns in runoff time series: A basis for exploring hydrologic similarity of precipitation and catchment wetness conditions

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ABSTRACT

Runoff responses to precipitation at the catchment scale exhibit a high variability in space and time due to a complex interaction of numerous factors, e.g., topography, land use, soil properties, geology, and climatic conditions. To find similar patterns in the runoff response and examine the effects of these factors on runoff variability, previous studies have either compared and classified catchments in space or focused on grouping extreme events. Here, we analyzed runoff processes in three highly instrumented catchments in Germany and Austria individually and compared them to themselves in time. To this end, we used long-term time series of 10 to 13 years and classified runoff events as similar by performing a cluster analysis based on calculated goodness-of-fit criteria between each possible pair of runoff events. For each cluster, we examined the degree to which precipitation and catchment wetness conditions were similar to themselves at the respective times when similar runoff events occurred by calculating Spearman rank correlation coefficients (ρ) as well as their descriptive statistics. The similarities assessed varied among the three catchments, with the two catchments in western Germany with maritime climates showing a stronger correlation for soil moisture conditions ($\rho = 0.76$ and $\rho = 0.74$) for classified similar runoff events rather than precipitation ($\rho = 0.26$ and $\rho = 0.36$). The Austrian catchment with a predominantly continental climate showed an overall higher correlation for precipitation ($\rho = 0.57$) and a lower one for soil moisture ($\rho = 0.53$) for similar runoff events compared to the other two catchments. The proposed method assesses similarity of precipitation and wetness conditions under similar runoff responses, and gives an indication of possible influencing factors controlling runoff generation in the three catchments in relation to their respective wetness and precipitation patterns. The similarities investigated help identify similar catchment functioning and can be used, for instance, to develop enhanced catchment similarity indices.

1. Introduction

An enhanced hydrological process-understanding at the catchment scale is critical for a sustainable management of water resources, including quantity and quality of water systems (Johnes, 1996; Singh et al., 2017), groundwater bodies (Gleeson et al., 2012; Stumpp et al., 2016), and catchment-wide water resources interactions (Sophocleous, 2002; Winter, 2000). In this regard, the runoff response to precipitation is of high relevance since it integrates upstream flow paths of a catchment and thus reveals integrative information about runoff generation processes. The runoff response of a catchment is influenced by a complex interplay of spatiotemporally heterogeneous hydro-meteorological variables and physical catchment characteristics (Beven, 2000; Blöschl et al., 2013). Therefore, it still remains challenging to model the variability of runoff responses and to determine catchment-scale feedbacks between hydrological flux and state variables (Hrachowitz et al., 2013; Zehe et al., 2005). As a consequence, this variability hampers fundamental understanding and generalization of

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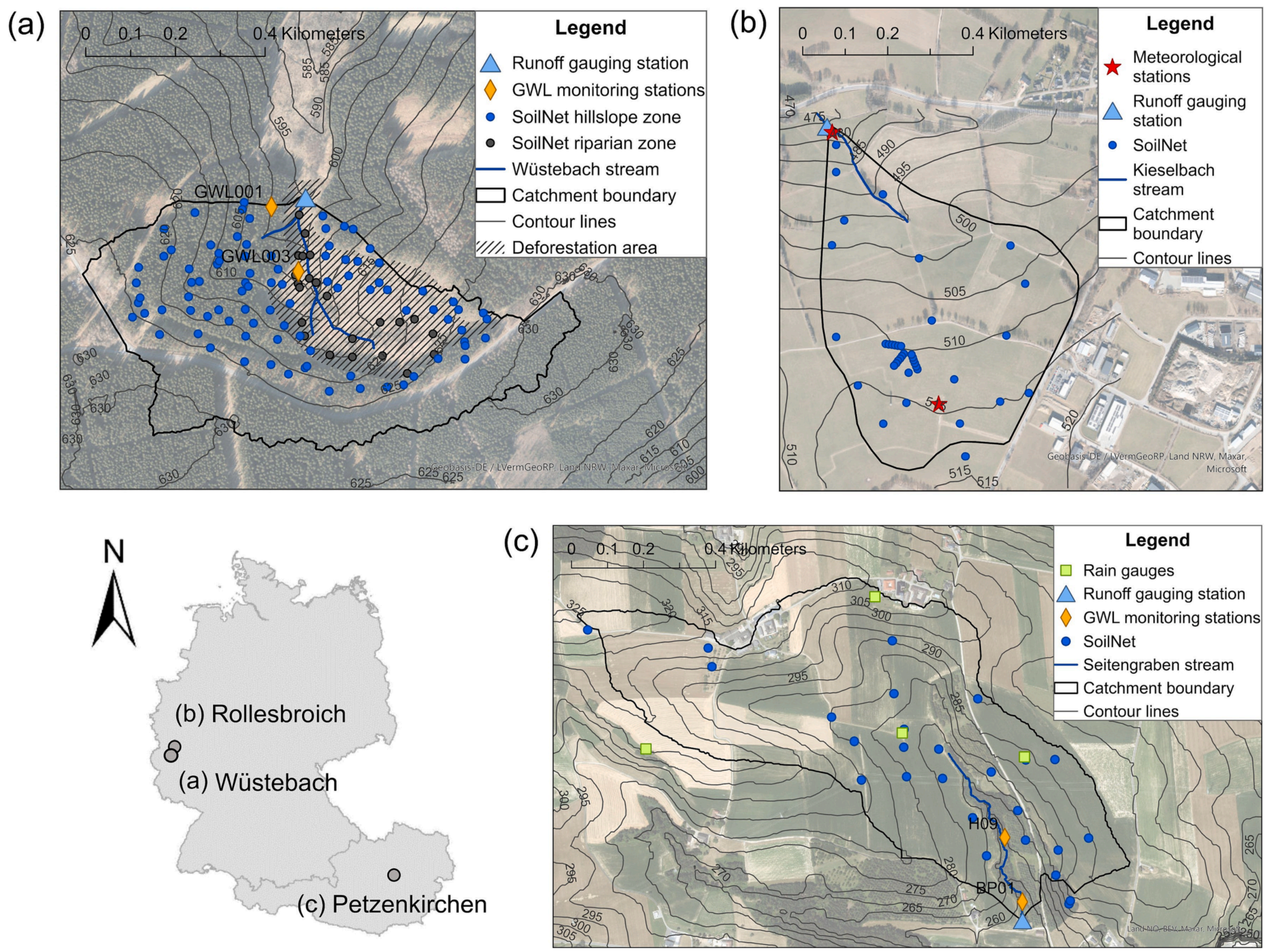

Fig. 1. Location and land use maps of the three study catchments in Germany and Austria indicating measurements sites with (a) Wüstebach (partly deforested in 2013), (b) Rollesbroich (extensively managed grassland), and (c) Petzenkirchen (agriculture).

catchment behavior (e.g., Hrachowitz et al., 2013; McDonnell et al., 2007). Nevertheless, a catchment's runoff response features organizational or repeating patterns in space and time, which could improve predicting a catchment's internal process dynamics (Merz et al., 2006; Sivapalan, 2005). Consequently, the search for similar spatial and temporal patterns of hydrologic flow and state variables contributes to a holistic understanding of runoff generation and catchment-internal processes affecting it (Blöschl, 2006).

Numerous studies have already examined spatial patterns of runoff as well as precipitation and soil water content. Spatial runoff patterns relied on the concept of "hydrologic similarity", emerging from comparative hydrology (Falkenmark & Chapman, 1989). This kind of similarity is based on the assumption that different catchments with similar climate and physical characteristics have a similar hydrologic response (Blöschl et al., 2013). Thus, assessing "hydrologic similarity" has primarily been centered around grouping catchments spatially to improve understanding of the interactions between catchment characteristics, climate, and runoff response. Catchments were spatially grouped based on (a) runoff regime characteristics (Hannah et al., 2005) including water transit times (Hrachowitz et al., 2009), (b) runoff either combined with climate (Coopersmith et al., 2012) or physical catchment features (Ley et al., 2011), and (c) a combination of climate and catchment characteristics (Merz et al., 2006; Merz & Blöschl, 2009; Sawicz et al., 2011, 2014). According to many of these studies, a first indicator of hydrologic similarity is spatial proximity (Merz & Blöschl, 2005; Oudin et al., 2008; Sawicz et al., 2011). More precisely, Sawicz et al. (2011) emphasized that this similarity resulting from spatial proximity may be due to equal climatic conditions controlling catchment hydrological processes. In fact, several studies identified the prevailing climate as the major driver for similar hydrological behavior (Berghuijs et al., 2014; Coopersmith et al., 2012; Kuentz et al., 2017). However, studies that focused on spatial comparisons between catchments are still subject to the uncertainty that arises from the geographical uniqueness of one place (Beven, 2000), meaning that no catchment can be a perfect copy of another. These uncertainties could be related to overlooking important factors influencing the characterization of similar runoff responses, precipitation events, or soil water and groundwater levels.

Thus, in addition to spatial classification approaches, temporal patterns in hydrologic flow and state variables were also sought, typically in the context of extreme runoff events, i.e., floods. Floods were mainly classified by previous studies based on their cause, i.e., rainfall- or snowmelt-induced floods (Tarasova et al., 2019). They were either derived from thresholds for shares of snowmelt and rainfall volume (Collins et al., 2014), precipitation thresholds combined with soil moisture (Merz & Blöschl, 2003; Nied et al., 2014; Sikorska et al., 2015), runoff (Fischer et al., 2016; Gaál et al., 2012, 2015), or by integrating other measures e.g., temperature (Turkington et al., 2016). In particular, similarity of runoff response types was assessed by calculating the ratio of volume to peak (Gaál et al., 2012) or combined with the Spearman rank correlation between the two parameters (Fischer et al., 2016; Gaál et al., 2015).

Apart from a catchment's runoff response, other studies focused on identifying similar patterns in precipitation events either based on spatial distribution of storms (Romero et al., 1999; Seibert et al., 2007), temporal patterns in precipitation intensities (Barbosa et al., 2018; Llasat, 2001), or a combination of spatial distribution and temporal pattern of the precipitation event (Crétat et al., 2012; Rigo & Llasat, 2004). Besides precipitation, attempts have been made to identify spatiotemporal patterns in soil moisture at the catchment (Brocca et al., 2012; Korres et al., 2015; Mälicke et al., 2020) or hillslope scale (Martini et al., 2015). For instance, Mälicke et al. (2020) applied a cluster analysis to soil moisture observations in one catchment and showed that spatial information contained in the observation data was redundant in time, reflecting a somewhat organized catchment soil moisture distribution.

Despite these advancements, so far only extreme runoff events have

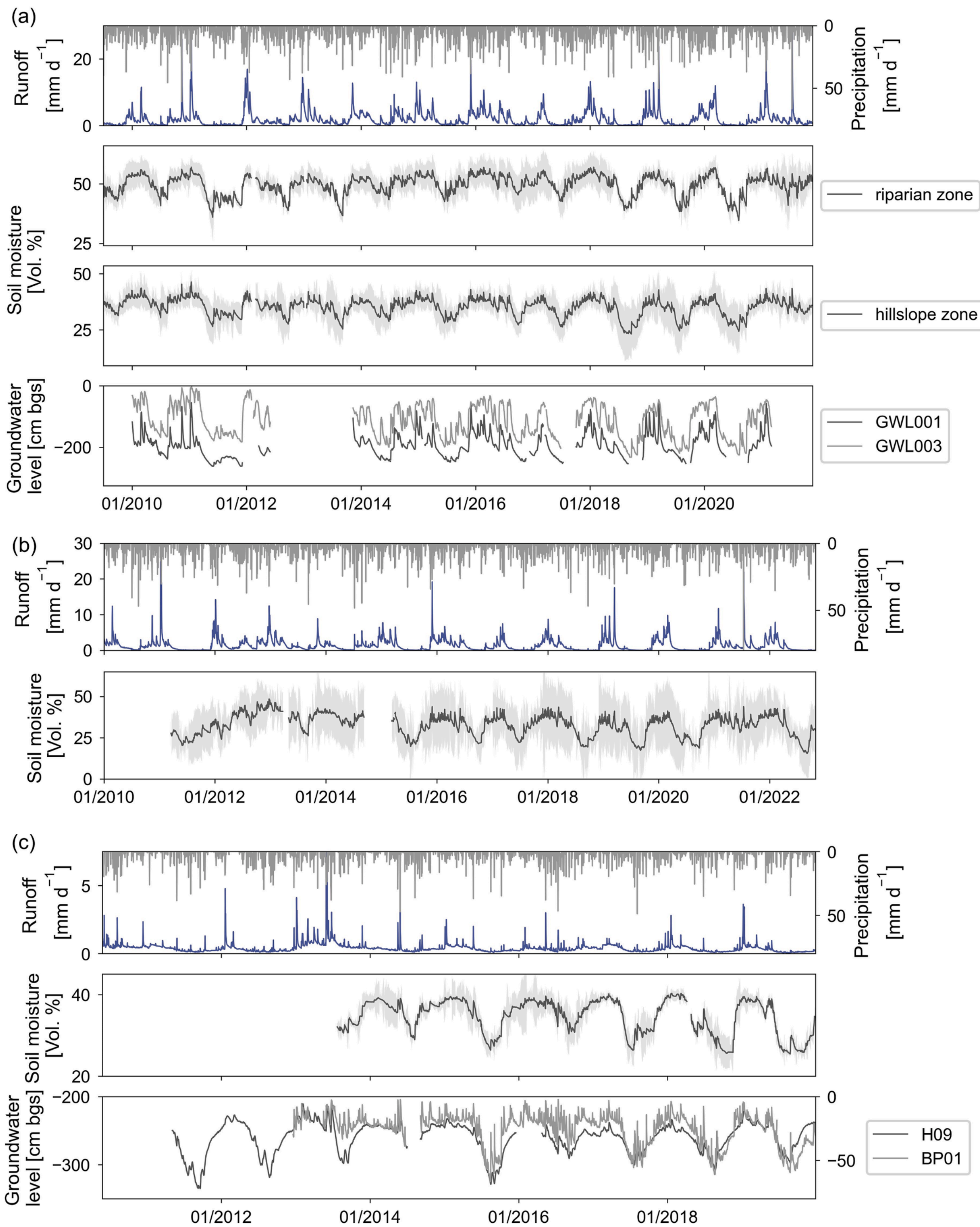

Fig. 2. Time series of observed daily precipitation (grey bars from top), runoff at the catchment's outlet (blue), aggregated soil moisture (dark grey), and groundwater level (dark and light grey), if available, in (a) Wüstebach, with soil moisture in the riparian and hillslope zones and groundwater level at station GWL001 (dark grey) and GWL003 (light grey), (b) Rollesbroich, and (c) Petzenkirchen, with groundwater level at station H09 (left axis, dark grey) and BP01 (right axis, light grey). Grey bands for soil moisture data indicate upper and lower boundary of the depth-weighted mean ± the Coefficient of Variation (CV), respectively.

been considered in the search for recurring patterns in precipitation and soil moisture at the catchment scale, i.e., maximum annual flood peaks (Gaál et al., 2015; Merz & Blöschl, 2003). In addition, when characterizing similar catchment hydrological processes, catchment-scale observation data including e.g., soil moisture, were either not taken into account or were acquired from conceptual models (Berghuijs et al., 2016; Merz & Blöschl, 2003; Nied et al., 2014; Stein et al., 2020). However, we anticipate that incorporating combined precipitation and *in-situ* measured catchment wetness data into a similarity framework could provide additional insight into how runoff responses evolve at the catchment scale.

In this study, we developed a novel method to investigate similarity of precipitation and catchment wetness conditions (soil moisture and groundwater level) based on recurring patterns in runoff, thus making use of the integrative information contained in the runoff time series. In this regard, analyzing corresponding patterns of precipitation and wetness conditions over time may be useful in evaluating the driving factors of a similar runoff response. Therefore, instead of comparing different catchments spatially, we compared the runoff responses of individual catchments at different points in time, and evaluated the similarity of respective precipitation and catchment wetness conditions if they resulted in a similar runoff response. For this purpose, we used about 10 years of spatiotemporal high-resolution data of precipitation, runoff, soil moisture, and groundwater level of three small-scale catchments with different land uses (forest, agriculture, and grassland). In our study, we used daily mean values of the temporally highly resolved measurement data for all variables investigated. In addition, dense spatial networks of soil moisture observations are available for all investigated catchments, which were spatially averaged for this work (see section 3 "Data and methods" for more details).

Therefore, the objectives of the present study are to (1) develop a robust method for identifying similar runoff responses in a catchment to evaluate the similarity of respective precipitation and wetness conditions (2) determine similarities and differences of hydrologically similar precipitation and wetness conditions between the three study catchments, and (3) investigate the usefulness of the applied approach in evaluating the drivers of the runoff response in relation to precipitation and wetness conditions in each catchment.

2. Study area

We chose three catchments with different characteristics, located in Germany and Austria, having long-term, spatially and temporally high resolution records of hydro-meteorological data. The characteristics in terms of size, location, and land use are illustrated in Fig. 1.

The Wüstebach headwater catchment has a size of 38.5 ha and is located in the low mountain ranges of the Eifel National park in Western Germany. It belongs to the Lower Rhine/Eifel Observatory of the Terrestrial Environmental Observatories network (TERENO; Bogena et al., 2018). The prevailing climate is characterized as temperate and humid, with a mean annual precipitation of about 1200 mm yr^{-1}, a mean annual discharge of about 700 mm yr^{-1}, and a mean annual air temperature of 7 °C (Zacharias et al., 2011). The fraction of precipitation falling as snow is generally below 10 % of annual precipitation, with snow cover extending to a maximum period of 3–4 weeks per year (Hrachowitz et al., 2021). Elevation ranges from 595 to 628 m above sea level (a.s.l.) with catchment-wide mean slopes of 3.6 % up to a maximum of 10.4 % (Graf et al., 2014). The flatter riparian zone covers about 10 % of the catchment. Soil depths are shallow, ranging from less than 1 m to a maximum of 2 m (Graf et al., 2014) with soil types of cambisol and planosol dominating at the hillslope, while gleysols and histosols prevail in the riparian zone (Bogena et al., 2018). The underlying bedrock is largely made of Devonian shales and sandstone (Richter, 2008) overlain by periglacial layers (Borchardt, 2012). Land cover in the Wüstebach catchment mainly consists of forest plantation with Norway spruce *(Picea abies)* and Sitka spruce *(Picea sitchensis)*. To commence regeneration of a near-natural beech *(Fagus sylvatica L.)* forest, about 8 ha or 21 % of the catchment's area was deforested in September 2013 resulting in a clear-cut completely covering the riparian zone (see Fig. 1) (Bogena et al., 2018; Wiekenkamp et al., 2016).

The Rollesbroich catchment is situated in the Eifel region of Western Germany and part of the TERENO network. It has an area of about 40 ha, with a mean annual precipitation of 1033 mm yr^{-1}, discharge of 520 mm yr^{-1}, and air temperature of 7.7 °C. Altitudes range from 474 to 518 m.a.s.l. with slopes of 0 to 10 % (Gebler et al., 2019) and an average slope of 1.6 % (Bogena et al., 2018). A heavily weathered top layer (saprolite) with a thickness of ~ 0.1 to 0.5 m covers the underlying bedrock, which consists of sandstone and siltstone. Cambisols (gleyic) dominate in the south, while stagnosols occur in the north with a soil depth of 0.5 to 1.5 m (Gebler et al., 2019; Korres et al., 2010). As an extensively managed grassland site, the catchment is mainly covered by perennial rhygrass *(Lolium perenne L.)* and smooth meadow grass *(Poa pratensis L.)* (Bogena et al., 2018). A drainage system was installed in the source area about 80 years ago to prevent waterlogging, which has affected the fast runoff response of the catchment (Gebler et al., 2019).

Situated in the western part of Lower Austria, the Hydrological Open Air Laboratory (HOAL) Petzenkirchen catchment covers an area of 66 ha with an altitude between 268 and 323 m.a.s.l. and an average slope of 8 %. The prevalent climate is continental, with a mean annual precipitation, discharge, and temperature of 823 mm yr^{-1}, 195 mm yr^{-1}, and 9.5 °C, respectively. Tertiary sediments of the Molasse zone and fractured siltstone dominate the underlying bedrock. While gleysols can be found close to the stream, main prevailing soil types include cambisols and planosols, which are characterized by shallow depths and moderate to poor infiltration capacity. As an agriculturally used catchment, the largest share of land cover is arable land with 87 %, including winter wheat and maize, followed by 6 % forest, 5 % pasture, and 2 % paved surfaces. In the 1940s, in about 15 % of the total catchment area tile drains were installed, located mainly in the south-western and north-eastern part to avoid waterlogging. In addition, the upper part of the stream, about 25 % of its length, was piped in the course of the drainage measures as well. Close to the stream in the south-east, a saturated, small wetland area is located which typically responds quickly to rainfall (Blöschl et al., 2016).

3. Data and methods

3.1. Data preparation

3.1.1. Precipitation and runoff

Daily runoff and precipitation data were available from 07/2009 to 12/2021 (~12 years) for the Wüstebach catchment, from 01/2010 to 10/2022 (~13 years) for the Rollesbroich study site, and from 05/2010 to 12/2019 (~10 years) for the Petzenkirchen catchment (Fig. 2). In Wüstebach and Rollesbroich, runoff was measured at the catchment's outlet with a V-notch weir for low flows and a Parshall flume for medium to high flows (Bogena et al., 2015; Qu et al., 2016). At the catchment's outlet in Petzenkirchen, runoff data were obtained with an H-flume (Blöschl et al., 2016). We acquired daily precipitation measurements for Wüstebach from the meteorological station at Monschau-Kalterherberg (German Weather Service DWD, station number 3339), situated about 9 km north-west of the study site. We used data from the distant station to obtain a continuous time series of precipitation data for the Wüstebach catchment. It would have been even better to use data from a station within the catchment to avoid uncertainties related to small-scale convective rainfall events. However, since rainfall data in the Wüstebach was not available before the deforestation, we used the same meteorological station to maintain data consistency over the entire study period. Precipitation records of Wüstebach were corrected for evaporation and wind drift as proposed in Richter (1995). In Rollesbroich, we obtained precipitation records from a weight-based gauge (OTT Pluvio), located in the central part of the catchment and installed in July 2013. For the preceding time period from 01/2010 – 07/2013, we acquired precipitation data from the standard Hellmann-type tipping bucket at the outlet of the catchment. We obtained daily precipitation data for Petzenkirchen by calculating the arithmetic mean of four rain gauges (weighing OTT Pluvio), three of which were situated directly in the catchment and the fourth close to its boundary, since spatial variability between the four stations is low (Vreugdenhil et al., 2022).

3.1.2. Soil moisture

Soil moisture data were available from 07/2009 to 12/2021 for Wüstebach, from 03/2011 to 10/2022 for Rollesbroich, and from 07/2013 to 12/2019 for Petzenkirchen on a daily basis (Fig. 2). In Wüstebach, installation of the wireless sensor network SoilNet started in the beginning of 2009, measuring soil moisture in three depths (5, 20, and 50 cm) at 150 locations (Bogena et al., 2010). Based on a previous quality control of soil moisture measurements conducted by Wiekenkamp et al. (2016), we selected 108 sensor locations providing sufficient data quality and eventually used them in the analysis. Since the Wüstebach catchment can be clearly divided into riparian and hillslope zones, we assigned each sensor to one of these two zones, resulting in 22 and 86 sensor locations in the riparian and hillslope zone, respectively. In the Rollesbroich study site, soil moisture measurements began in 2011 at 87 SoilNet locations in 5, 20, and 50 cm depth and continued until May 2015. Starting from end of 2014, additional sensors at 41 locations were gradually installed of which we selected 33 to have a continuous time series. Soil moisture data measured in the first period from 2011 to 2015 were acquired from the dataset published by Qu et al. (2016), while for the second period sensor data was obtained from the TERENO data portal (TERENO, 2022). The wireless sensor network with 32 sensor locations in Petzenkirchen was in service since mid of 2013 and stopped operation towards the end of 2021, measuring soil moisture in four depths (5, 10, 20, and 50 cm). After checking the sensors in Petzenkirchen for continuity and outliers, we selected 29 sensor locations to receive a continuous time series. In Rollesbroich and Petzenkirchen, we spatially averaged soil moisture measurements in each depth over the entire catchment area while in Wüstebach, we calculated spatial averages for the riparian and hillslope zone separately. Subsequently, we determined a depth-weighted mean, considering a soil depth of 1 m and assigning weights of 0.1, 0.2, and 0.7 for the 5, 20, and 50 cm depth, respectively, in Wüstebach and Rollesbroich. Due to additional measurements being available for the 10 cm depth in Petzenkirchen, we assigned according weights of 0.05, 0.05, 0.2, 0.7 for the 5, 10, 20, and 50 cm depth, respectively.

3.1.3. Groundwater level

Groundwater level in the Wüstebach catchment was measured at four locations, all of which were situated in the riparian zone. Out of these four, two (GWL001 and GWL003) provided fairly continuous data for the period from 01/2010 to 03/2021 and thus, we selected them for further analysis to draw comparisons between the two sites. GWL001 is located further downstream within the forested area, while GWL003 is found further upstream closer to the stream in the deforested zone (Fig. 1). In Petzenkirchen, station H09 provided data from 05/2011 to 12/2019. It is situated in the riparian zone in the mid-section of the stream on a lower slope serving as an indicator for groundwater levels in the transition between riparian and hillslope zone (Pavlin et al., 2021; Vreugdenhil et al., 2022), so that we used it in the analysis. Furthermore, Haught & van Meerveld (2011) found that the distance of wells from the stream is an important factor in the relationship between groundwater and streamflow, so we additionally selected piezometer BP01 (12/2012 – 12/2019) which only had few data gaps and is located closer to the stream. Overall, BP01 showed a different dynamic compared to H09 when correlated to each other (Pearson's $r = 0.69$) (Fig. 2). Since the other wells in Petzenkirchen showed similar behavior to either station H09 or BP01, we considered the two wells selected to be representative for the catchment. In Rollesbroich, there were no groundwater level observations available as groundwater is restricted to deeper fissured rocks.

3.2. Similarity of runoff events

To compare the runoff response of a catchment at different points in time, runoff events were first separated. Runoff event separation is still an ongoing matter of debate in hydrological sciences with studies either developing their own methodology (e.g., Mei & Anagnostou, 2015; Merz et al., 2006; Tarasova et al., 2018b) or separating manually and subjectively through visual inspection (Dupas et al., 2016; von Freyberg et al., 2018). In order to reduce degrees of freedom and increase objectivity, we used an algorithm developed by Tang & Carey (2017) to identify runoff events. First, base flow was separated by applying the recursive digital filter technique by Nathan & McMahon (1990). Second, we identified and extracted runoff events using a local minima method (runoff events that fall below a specified threshold are eliminated). Here, we conducted a sensitivity analysis to assess the influence of the peak threshold parameter on the number of separated events. We used the mean runoff after base flow separation in each catchment as a reference and varied it by ± 10 % increments to assess how the total number of separated events evolved. The number of separated events decreased exponentially with increasing peak threshold and the mean runoff approximately coincided with the point at which the slope became almost linear, so that number of separated events did not change considerably after that point. Therefore, we set the threshold to the mean runoff after base flow separation for all three catchments, with values of 1.32 mm d^{-1}, 0.84 mm d^{-1}, and 0.16 mm d^{-1} for the Wüstebach, Rollesbroich, and Petzenkirchen catchment, respectively.

As a first step of determining similarity of runoff events, we calculated a goodness-of-fit (GOF) criterion between every possible combination of event pairs. The Nash-Sutcliffe-Efficiency (NSE, Eq. (1)) (Nash & Sutcliffe, 1970) and a volume error (VE, Eq. (2)) were combined to the Nash-Volume Error (NVE, Eq. (3)) (Lindström, 1997):

$$NSE = 1 - \frac{\sum (Q_1 - Q_2)^2}{\sum (\overline{Q}_2 - Q_2)^2} \tag{1}$$

$$VE = \frac{\sum |Q_1 - Q_2|}{\sum Q_2} \tag{2}$$

$$NVE = NSE - \chi |VE| \tag{3}$$

Q_1 and Q_2 are the respective runoff events obtained from event separation with $\overline{Q}$ representing the mean over the entire event length, and parameter χ is a weight for the volume error set to 0.1 as proposed by Lindström (1997) and used in e.g., Razavi & Coulibaly (2017) or Samuel et al. (2011). Using a combined GOF criterion instead of multiple individual ones allowed to additionally use it as input in the form of a similarity matrix in the subsequent cluster analysis.

If the NVE between runoff event pairs exceeded a threshold of 0.65, we assumed the runoff events to be similar. We adopted 0.65 as the threshold because several studies that used NSE as the objective function considered this to be a "satisfactory" or "good" fit between runoff time series (e.g., Moriasi et al., 2007; Saleh et al., 2000; Singh et al., 2005). Since we additionally penalized the NSE with a volume error leading to a decrease in the overall objective function, we anticipated that the threshold also holds valid for the calculated NVE. To determine whether similar runoff events could further be grouped into coherent clusters including more than two events, we subsequently conducted a cluster analysis. Based on the similarity matrix of the GOF criterion, a hierarchical, agglomerative cluster algorithm using single linkage was applied to group runoff events according to their similarity. In single linkage hierarchical clustering, two clusters with the minimum distance between members of the two clusters are merged (e.g., Gower & Ross, 1969). Since determining the number of resulting clusters can be

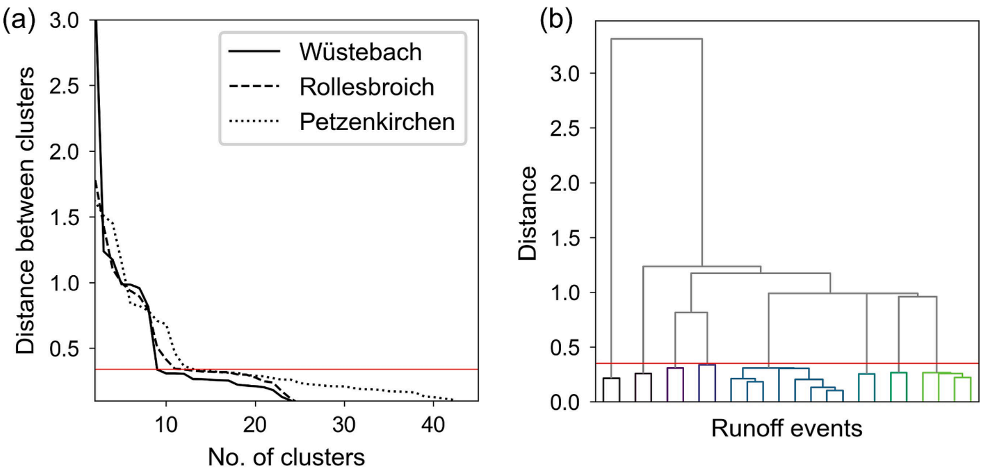

Fig. 3. (a) Scree plot showing the distance between clusters as a function of the number of clusters in all three catchments with the red line indicating a distance of 0.35 and (b) example of a dendrogram with formed clusters at the respective cutoff distance.

subjective, we used the calculated dendrograms displaying a similarity tree of runoff events in each catchment in combination with a scree plot to assess how the number of clusters changed with a varying cutoff distance on the y-axis (Fig. 3). The scree plot shows the distance between clusters as a function of the number of total clusters. The point at which the scree plot changes from a steep downward slope to a more uniform slope is an indication of the optimal number of clusters, which is then used as cutoff distance in the dendrogram. In each study catchment, we found the changing point at a distance between clusters of approximately 0.35.

3.3. Statistical analysis of precipitation and wetness conditions

After forming clusters of similar runoff events for each catchment, we extracted the respective precipitation and wetness conditions based on daily observation data, i.e., soil moisture and groundwater level (if available), for the corresponding time periods in the clusters. In a second step, we calculated Spearman rank correlation coefficients (ρ) between all event pairs occurring within each cluster to evaluate whether precipitation and wetness conditions showed similar temporal variabilities for the different times when similar runoff events took place. The significance of pairwise correlations was evaluated at a 95 % confidence level ($p < 0.05$). In addition, we determined the mean correlation over each cluster for observed precipitation, soil moisture, and groundwater level. For soil moisture, we used both the observations at distinct depths of 5 cm, 10 cm, 20 cm, and 50 cm as well as the depth-weighted mean in the analysis. Furthermore, we calculated descriptive statistics of precipitation and wetness conditions for each event, including the arithmetic mean, standard deviation, minimum, maximum, 25 %-, 50 %-, and 75 %-percentiles. For precipitation, the total amount that fell during the respective period was calculated additionally. To assess whether seasonality had an effect on the clustering of runoff events, as well as on the strength of correlation between precipitation or wetness conditions for similar events, we assigned a meteorological season to each event based on the day of its occurrence: March-May (spring), June-August (summer), September-November (autumn), December-February (winter). Since the division of events into seasons based on calendar days might, for some events, not reflect the expected, regional climatic conditions of a given season (e.g., unnaturally warm temperatures in December), we additionally calculated the mean temperature over three days prior to the runoff events as well as over the entire event lengths. There were no major outliers in mean temperatures for the runoff events that would lead to substantial alterations in the results, and we proceeded using the division based on the day of occurrence for further analysis.

4. Results

4.1. Similarity of runoff events

Runoff event separation and calculation of the goodness-of-fit criterion resulted in 24, 25, and 46 runoff events which were classified into eight, ten, and twelve clusters of similar events for the Wüstebach, Rollesbroich, and Petzenkirchen catchment, respectively (Fig. 4). The majority of clusters consisted of only two runoff events, i.e., pairs in all three catchments. However, in Wüstebach and Petzenkirchen larger clusters of eight and seven runoff events, respectively, were formed as well. Clusters in Petzenkirchen generally involved a higher number of

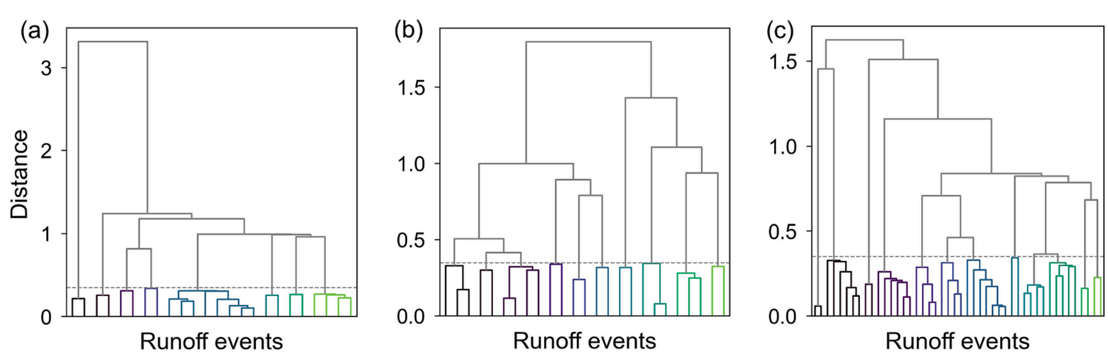

Fig. 4. Dendrograms of clustered runoff events showing number of events inside respective clusters (color-coded) with a respective cutoff distance of 0.35 for (a) Wüstebach, (b) Rollesbroich, and (c) Petzenkirchen.

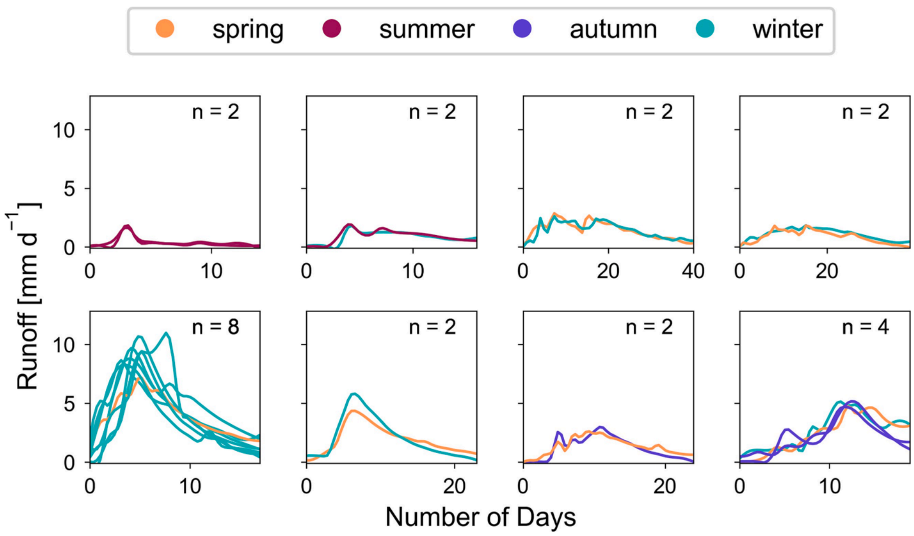

Fig. 5. Formed clusters of runoff events in the Wüstebach catchment showing meteorological seasons of spring (orange), summer (pink), autumn (purple), and winter (cyan).

Table 1
Spearman rank correlation coefficients (ρ) for precipitation (P), soil moisture (SM), and groundwater level (GWL), averaged over clusters with more than two events. Soil moisture is divided into riparian and hillslope zones for Wüstebach. Groundwater level is displayed individually for stations GWL001 and GWL003 in Wüstebach and stations H09 and BP01 in Petzenkirchen. Values in bold indicate correlation coefficients with $p < 0.05$ for all event pairs inside the cluster.

	Wüstebach						Rollesbroich			Petzenkirchen				
Cluster	# Events	P	SM riparian	SM hillslope	GWL001	GWL003	# Events	P	SM	# Events	P	SM	GWL H09	GWL BP01
1	2	−0.03	**0.74**	**0.98**	–	**0.93**	3	0.41	**0.99**	2	**0.79**	**0.87**	**0.97**	**0.96**
2	2	−0.12	**0.70**	**0.91**	–	–	2	0.04	–	6	0.52	**0.81**	**0.83**	**0.87**
3	2	0.30	**0.44**	**0.61**	**0.70**	–	4	0.47	0.41	2	**0.88**	–	0.71	–
4	2	**0.52**	**0.94**	**0.97**	–	–	2	**0.65**	**0.95**	6	0.73	0.64	**0.85**	**0.89**
5	8	0.41	**0.82**	**0.75**	**0.84**	–	2	**0.52**	**0.59**	4	0.22	0.46	0.60	**0.91**
6	2	0.34	**0.88**	**0.60**	–	−0.41	2	0.24	**0.73**	4	0.52	0.50	0.38	–
7	2	**0.55**	**0.86**	**0.81**	–	**0.67**	2	0.33	**0.96**	7	0.53	0.47	0.53	0.63
8	4	0.08	**0.69**	0.43	**0.89**	−0.27	3	0.45	0.71	2	0.48	**0.71**	−0.50	0.57
9							3	0.19	–	4	0.38	–	**0.82**	–
10							2	0.34	0.58	5	0.49	0.10	−0.15	0.75
11										2	**0.86**	0.25	–	**0.88**
12										2	0.47	–	**0.86**	–
Mean		0.26	0.76	0.76	0.81	0.23		0.36	0.74		0.57	0.53	0.54	0.81
Median		0.32	0.78	0.78	0.84	0.20		0.38	0.72		0.52	0.50	0.71	0.88
Standard deviation		0.23	0.15	0.19	0.08	0.58		0.17	0.20		0.19	0.24	0.44	0.13

runoff events with approx. 60 % of clusters containing more than two events, compared to Wüstebach (25 %) and Rollesbroich (40 %).

Clustered runoff events including their respective meteorological season are displayed in Fig. 5 for Wüstebach and in Figs. A.1 and A.2 for Rollesbroich and Petzenkirchen in the supplementary material, respectively. In all three catchments, grouping of events according to distinct meteorological seasons was not evident for the majority of clusters. Still, we observed that clusters predominantly emerged between runoff events in spring and winter season both in Wüstebach and Rollesbroich. For instance, the cluster in Wüstebach which contained the highest number of events consisted of seven winter events, i.e., during periods when soil moisture was high (Fig. 1), and one event in spring. In contrast, clusters in Petzenkirchen included an increased number of runoff events which took place in autumn and summer compared to Wüstebach and Rollesbroich. Particularly, the largest cluster in Petzenkirchen with seven runoff events contained three events in summer and four in autumn.

4.2. Statistical analysis of precipitation and wetness conditions

The calculated mean Spearman rank correlation coefficients for variables of precipitation, soil moisture, and groundwater level data across events in the clusters are shown in Table 1. Present gaps resulted from discontinuity in the time series data for the two groundwater level stations in Wüstebach, and in Petzenkirchen for piezometer BP01 as well as soil moisture observations before 2013.

4.2.1. Precipitation

Mean Spearman rank correlation coefficients between precipitation events over all clusters reached 0.26 ± 0.23, 0.36 ± 0.17, and 0.57 ± 0.19 in Wüstebach, Rollesbroich, and Petzenkirchen, respectively. With regard to seasonality, we did not identify a distinct pattern between significance of correlations or descriptive statistics and meteorological seasons in Wüstebach and Rollesbroich (data not shown). This was particularly evident for the largest clusters in Wüstebach, which incorporated eight events (seven of which in winter), since correlation coefficients within the cluster varied strongly with a mean ρ of

Table 2
Mean Spearman rank correlation coefficients of soil moisture over all clusters for similar runoff events in distinct measurement depths for the three catchments, with values displayed separately for riparian and hillslope zone in the Wüstebach catchment.

Catchment	Soil moisture (depths) 5 cm	10 cm	20 cm	50 cm
Wüstebach (riparian zone)	0.75	–	0.68	0.71
Wüstebach (hillslope zone)	0.63	–	0.74	0.77
Rollesbroich	0.69	–	0.71	0.73
Petzenkirchen	0.53	0.56	0.55	0.45

0.41 and a respective standard deviation of 0.27. In contrast, higher correlations of precipitation events and similar statistics in Petzenkirchen were evident mainly for similar meteorological seasons. In particular, the precipitation for similar runoff events in Petzenkirchen was significantly correlated for three clusters which comprised two similar runoff events each (clusters 1, 3, and 11 in Table 1). In only one of these clusters, which contained two spring events with a correlation of 0.79, were both mean precipitation intensity (5 mm d^{-1} for each) and precipitation totals similar (68 and 67 mm). Likewise, only one other cluster, comprising two winter events, had precipitation with equal mean intensities (2 mm d^{-1}) and similar total sums (21 and 19 mm). In Wüstebach and Rollesbroich, two clusters each showed significant, moderately strong correlations between precipitation events (Table 1). Furthermore, descriptive statistics revealed equal maximum precipitation intensities in Wüstebach for precipitation events in two clusters (28 mm d^{-1} and 19 mm d^{-1}) with insignificant correlation. Likewise, two clusters in Rollesbroich (7 and 9 in Table 1) had similar maximum intensities of the two (14 and 15 mm d^{-1}) and three events (9, 6, and 8 mm d^{-1}) inside respective clusters.

4.2.2. Soil moisture

Depth-weighted mean of soil moisture was significantly correlated for the majority of similar runoff events in Wüstebach, with significant correlations of soil moisture in the riparian zone for all clusters and for seven out of eight clusters in the hillslope zone. In Rollesbroich, we found significant correlations for half of the 10 clusters, while in Petzenkirchen soil moisture was significantly correlated for only 25 % of the clusters (Table 1). Mean correlation coefficients over all clusters for the depth-weighted soil moisture mean amounted to 0.76 for both the riparian and hillslope zone in Wüstebach, and to 0.74 and 0.53 in Rollesbroich and Petzenkirchen, respectively. Thus, soil moisture patterns generally displayed a stronger agreement for similar runoff events in Wüstebach and Rollesbroich in comparison to Petzenkirchen. In addition, mean correlation coefficients for distinct depths in the three catchments are shown in Table 2. Since variability between depths was low, we focused on the depth-weighted mean soil moisture in the following analysis and discussion.

In all three catchments, we observed significant correlations of soil moisture for all similar event pairs which occurred during spring. In Wüstebach, correlation between two soil moisture events in spring reached 0.94 and 0.97 in the riparian and hillslope zone, respectively, while in Rollesbroich we observed a correlation of 0.96 between two spring events. In addition, we detected the strongest correlation of soil moisture in Petzenkirchen between two events in spring with $\rho = 0.87$ ($p < 0.0001$). Similarly, soil moisture in Wüstebach and Rollesbroich was significantly correlated for almost 90 % of similar runoff event in the winter season, i.e., when the catchment was in a wet state. The largest cluster in Wüstebach with a majority of events in the winter season showed significant correlations of soil moisture in both riparian and hillslope zone with correlation coefficients of 0.82 and 0.75, respectively. In summer, i.e., during the dry state, the number of significant correlations of soil moisture was lower with significant correlations in about 30 % of all summer event pairs in all three catchments.

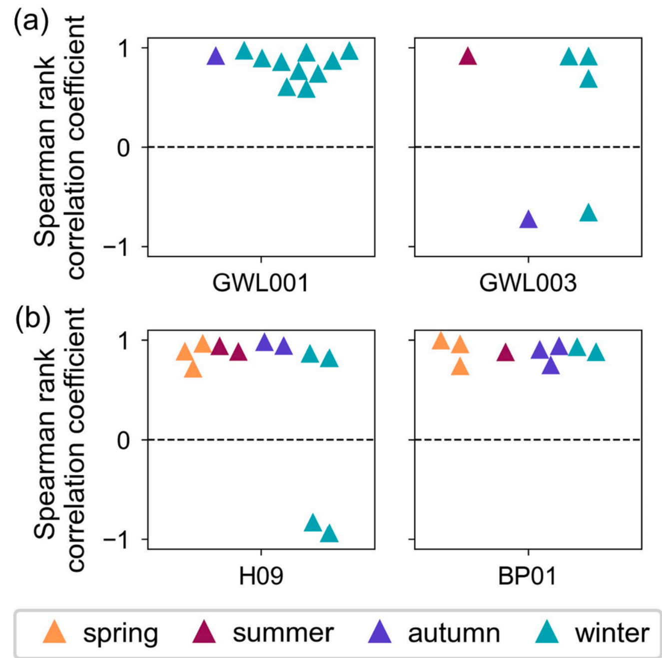

Fig. 6. Spearman rank correlation coefficients of groundwater level observations for similar runoff events in respective meteorological seasons in (a) Wüstebach and (b) Petzenkirchen.

4.2.3. Groundwater level

In the Wüstebach catchment, groundwater level at stations GWL001 and GWL003 was significantly correlated for similar runoff events in all and half of the clusters, respectively (where data was available). In Petzenkirchen, we found significant correlations of groundwater level in almost half of clusters and in around 60 % of clusters with available data at station H09 and BP01, respectively. Fig. 6 shows Spearman rank correlation coefficients of groundwater level observations ($p < 0.05$) for similar event pairs which occurred in the same meteorological season in Wüstebach and Petzenkirchen. During winter, all available event pairs at station GWL001 in Wüstebach were significantly correlated with a mean correlation coefficient of 0.83, while at GWL003, 67 % of all winter event pairs showed a significant positive correlation. In Petzenkirchen, event pairs in winter showed significant positive correlations in 50 % of pairs at station H09 and in 67 % of pairs at station BP01 (non-significant correlation coefficients not shown in Fig. 6). For similar events in spring, i.e., drying season, we determined significant correlations in Petzenkirchen for all available event pairs at station H09 as well as BP01 with mean correlation coefficients of 0.86 and 0.90, respectively. In contrast, during summer, the number of significant positive correlations was lowest with 40 % and 33 % of available summer event pairs at stations H09 and BP01, respectively.

In both catchments, groundwater levels were additionally significantly correlated in clusters with events in different meteorological seasons. For instance, we observed the strongest correlation of groundwater level in Wüstebach at GWL001 in one cluster which included four similar events in winter, spring, and autumn ($\rho = 0.89$). Similarly, although observation data was unavailable for one event in a cluster consisting of six events, groundwater level in Petzenkirchen showed high mean correlations for the remaining five events independent of the season with cluster averages of 0.83 and 0.87 for station H09 and BP01, respectively. In addition, we determined significant correlations of groundwater levels in one cluster with six events, none of which occurred in summer. Correlation in this cluster was similar for the two stations H09 ($\rho = 0.85$) and BP01 ($\rho = 0.89$), accompanied by a low standard deviation of correlation coefficients of 0.09 and 0.08, respectively.

Table 3
Summary of Spearman rank correlation coefficients for each variable and catchment, with the first row including the entire range of calculated correlations and the second including only significant correlations per catchment ($p < 0.05$).

Catchment	Precipitation	Soil moisture		Groundwater level	
		riparian	hillslope	GWL001	GWL003
Wüstebach	0.26	0.76	0.76	0.81	0.23
	0.53	**0.76**	**0.81**	**0.81**	**0.80**
Rollesbroich	0.36	0.74		–	
	0.58	**0.84**		–	
				H09	BP01
Petzenkirchen	0.57	0.53		0.54	0.81
	0.84	**0.80**		**0.87**	**0.90**

5. Discussion

5.1. A method for investigating hydrologic similarity

In this study, the first objective was to develop a robust method for evaluating the similarity of precipitation and wetness conditions in a catchment based on identified similar patterns in the runoff time series. We showed that similar runoff events could be identified in all three catchments, some of which were triggered by similar precipitation or wetness conditions as indicated by Spearman rank correlations (Table 3) and descriptive statistics based on catchment-wide observation data. Comparing significant and the mean of correlation coefficients (Table 3), the strength of correlation increases when only significant correlations are considered in all three catchments. This is due to the fact that, especially for precipitation, only a limited percentage of clusters had significant correlations for all events pairs within a cluster. The inclusion of all correlation coefficients in the mean, however, provides a summary measure of the overall strength of the relationship between variables themselves and is therefore used in the further discussion.

The proposed approach is comparable to previous studies that determined hydrograph-based parameters such as the ratio of volume and peak flow (Gaál et al., 2012) or the Spearman rank correlation between the two characteristics (Fischer et al., 2016; Gaál et al., 2015) as a basis for classifying flood generating processes, including precipitation. However, we relied on the established consensus in hydrological modeling as to when observed and model-simulated runoff should be considered as similar (expressed in terms of the objective function), while comparing two observed runoff events in our method. The advantage over previous similarity studies is that the decision for a similarity criterion is shifted to a well-established, literature-based objective function in combination with subsequent cluster analysis. However, still the objective function value and the subsequent algorithm for cluster analysis have to be chosen, and thus our approach remains partly subjective. Although preliminary tests of the influence of the objective function value on results in our study did not show major changes (data not shown), we recommend that future studies test the sensitivity of the proposed method to not only the objective function value, but the objective function itself.

In contrast to our approach, the majority of previous studies investigated runoff similarity by comparing the runoff of multiple catchments altogether. An exception to this approach is the study of Gaál et al. (2015), who grouped maximum annual runoff peaks into different flood types of multiple catchments, but also analyzed them for individual catchments. They suggested, however, to apply the grouping not only to maximum annual floods but to extend it to all or peak-over-threshold runoff events within a catchment. This is in line with our proposed method, where we not only focused on runoff extremes but investigated the entire range of occurring runoff events above a pre-defined threshold within one catchment at different points in time. Similar to our approach that considers the entire flow regime of one catchment, Knighton & Nanson (2001) grouped runoff responses into single, multiple, and compound events and found the magnitude, duration, and time-to-peak to gradually increase from single to compound events. Yet, they only took into account the runoff response and therefore did not aim to analyze similarity of patterns in precipitation or moisture conditions in the catchment.

To investigate one and the same catchment at different points in time is particularly beneficial with respect to stationary boundary conditions. Yet, catchments change over time, e.g., due to vegetation growth or climate change. We argue, however, that these changes progress relatively slowly (with the exception of direct anthropogenic interventions), and the difference of a catchment to itself between two points in time will still be less than the difference between two distinct catchments. In other words, in the decadal time-scale of our study, temporal catchment differences are negligible compared to spatial ones, with the notable exception of deforestation in the Wüstebach catchment. According to Wiekenkamp et al. (2016), a reduction of evapotranspiration and thus increase in soil moisture storage was observed in the Wüstebach catchment immediately after deforestation. However, actual evapotranspiration rates increased again in the second year after deforestation, suggesting some resilience of the catchment to this anthropogenic change (Ney et al., 2019; Wiekenkamp et al., 2016). Thus, we conclude that our proposed method is based on nearly stationary physical properties of the investigated catchments. In turn, the method could enable monitoring of (anthropogenic) changes over longer time scales, as it objectively determines similar runoff responses and corresponding precipitation and soil moisture conditions. In this way, process-based changes in temporal patterns of runoff could be detected and attributed to catchment alterations.

Limitations of our method are, besides the already discussed subjective choice of an objective function threshold, that the calculated correlations of precipitation and catchment wetness were based on daily measurements that were spatially integrated. Since most analyzed runoff events of this study were several days long, we assume that a higher temporal resolution, e.g., hourly, would not change our results drastically. Nevertheless, similar sub-daily runoff events should be tested in further studies. Furthermore, we averaged soil moisture over the entire catchment based on spatially distributed observation data, but the runoff at the outlet is also a result of the averaging process of the catchment. Therefore, spatiotemporal variations of soil moisture would need to be considered to test whether certain sub-areas mainly control the runoff response. For this, spatial dispersion functions of soil moisture observations could additionally be investigated as was done by Mälicke et al. (2020). With regard to the method itself, applying a cluster analysis generally introduces uncertainty in terms of the chosen distance metric, the cluster algorithm itself, and the chosen number of resultant clusters. It was not the aim of the present study to investigate the influence of different cluster analysis methods on the results, but we recommend that this should be investigated in future studies.

5.2. Comparison of the three catchments

Our results show that the degree of similarity of precipitation and wetness conditions in runoff clusters varied across the three catchments. In detail, mean correlations of precipitation and wetness conditions showed similar magnitudes in Petzenkirchen, indicating minor differences between precipitation, soil moisture, and groundwater level. The two catchments in close proximity to one another, Wüstebach and Rollesbroich, had comparable results in terms of correlation of precipitation ($\rho = 0.26$ and $\rho = 0.36$) and soil moisture patterns ($\rho = 0.76$ and $\rho = 0.74$). Although the two study sites differ in their land use (forest, grassland), but only to some extent in their soil types (cambisol/planosol, cambisol/stagnosol), the correlation of soil moisture patterns was similar for identified similar runoff events in the two catchments. This is consistent with findings of previous studies, suggesting that spatial proximity may be a more accurate predictor of hydrologically similar runoff regimes compared to physical catchment attributes (e.g.,

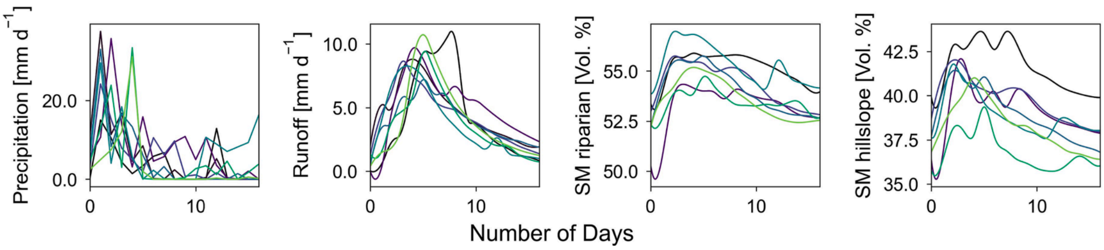

Fig. 7. Precipitation, runoff, and soil moisture (SM) in the riparian and hillslope zone for the largest cluster of similar events in Wüstebach containing seven winter events and one spring event. Colors indicate the distinct events within the cluster.

Jehn et al., 2020; Merz et al., 2006; Sawicz et al., 2011, 2014). In most cases, spatial proximity is associated with similar prevalent climate or bedrock characteristics. For instance, Berghuijs et al. (2014) developed a similarity framework of seasonal water balances for 321 catchments in the continental U.S. They found that climate indices, including seasonality and timing of precipitation, snow fraction, and aridity index, dominated the classification of catchments into coherent clusters, which included catchments lying in close proximity to one another. At the same time, clusters overlapped with maps of regional soil and vegetation classes, indicating co-dependency of landscape and climate. Further studies identified climate as the major driving factor for similar catchment runoff regimes as well (e.g., Coopersmith et al., 2012; Kuentz et al., 2017). Our results support these findings, since Wüstebach and Rollesbroich feature a similar, maritime climate with an approx. ratio of potential evapotranspiration to precipitation $\frac{PET}{P}$ of 0.5 and 0.6, mean annual runoff of 700 and 500 mm, and a temperature of 7 °C and 7.7 °C, respectively. Thus, similar climate conditions both in Wüstebach and Rollesbroich could have led to a similar development soil moisture conditions, which in turn resulted in similar runoff events. In contrast, Petzenkirchen has a $\frac{PET}{P}$ ratio of approx. 0.8 with a mean annual runoff of 195 mm, and air temperature of 8.5 °C, highlighting the predominantly continental climate. This long-term influence of climate, including precipitation and evapotranspiration patterns that affect soil moisture, on landscape features such as soil types may thus be decisive in generating similar runoff responses. Zheng et al. (2023) also showed that climate attributes such as aridity index and catchment geological features had high predictive power on event-based runoff coefficients, supporting the hypothesis of a co-evolving landscape and climate influencing the runoff response. In our study, this relation may explain calculated low correlation of event-based precipitation patterns in Wüstebach and Rollesbroich. That is why, in future applications of the proposed method, further hydro-climatic variables such as evapotranspiration should be explicitly included. As additionally underlined by Merz & Blöschl (2009), event runoff coefficients in medium- to large-sized Austrian catchments were also mainly controlled by climate and antecedent soil moisture conditions. However, we only investigated three catchments, and our approach should be expanded to further sites to get a clearer picture on how and under which conditions similar precipitation and wetness conditions may occur.

5.3. Precipitation and wetness conditions for similar runoff responses

The correlation of precipitation, soil moisture, and groundwater level during similar runoff events can potentially provide insight into the extent to which these variables influence the catchments' runoff responses. Correlation coefficients of precipitation in Wüstebach and Rollesbroich were generally weak and did not follow a seasonal pattern. Whether the low correlation of precipitation events in the Wüstebach catchment ($\rho = 0.26$) was affected by the distance (9 km) of the meteorological station cannot be answered. However, similar results in the Rollesbroich catchment ($\rho = 0.36$) with a comparable climate to the Wüstebach indicated that temporal patterns in precipitation were not well correlated for similar runoff responses in the two catchments. Although precipitation temporal patterns often lacked significant correlation, descriptive statistics revealed that particularly similar maximum intensities were apparent in both Wüstebach and Rollesbroich, related (and possibly leading) to similar runoff events. Other studies support these findings, suggesting that besides precipitation volumes (Penna et al., 2011), maximum precipitation intensity plays a major role in runoff generation (Blume et al., 2007). In contrast, precipitation patterns in Petzenkirchen had higher correlations and were mainly significant for events which took place in the same season in two out of three cases, with event pairs occurring in spring and winter. Matulla et al. (2003) investigated seasonal precipitation patterns in Austria and identified geographical regions of similar patterns dependent on the main airflows during cold periods, thus leading to recurring precipitation patterns in winter.

In both Wüstebach and Rollesbroich, we observed strong correlations of soil moisture conditions for similar runoff events, indicating a higher influence of soil moisture on the runoff response rather than the precipitation's temporal pattern. Tarasova et al. (2018a) suggested that for catchments with higher water storage capacity, soil moisture may have a higher influence on runoff generation compared to precipitation, so that storage capacity may be larger in Wüstebach and Rollesbroich compared to Petzenkirchen (see also Fig. 2). Particularly in the Wüstebach, soil moisture revealed a similar temporal pattern for almost all runoff clusters. Nevertheless, calculated high correlation coefficients of soil moisture were cluster-specific and were related to the similar runoff events within the respective clusters only. During winter months, when the catchment is in a wet state, both soil moisture in the riparian and hillslope zone were significantly correlated. This indicates a similar response of the two zones during the wet state as displayed in Fig. 7.

In line with our observation, other studies suggested that above a certain soil moisture value, the hillslope zone may additionally contribute to runoff (Detty & McGuire, 2010; Penna et al., 2011; Stockinger et al., 2014). In the Wüstebach catchment, Stockinger et al. (2014) found a soil moisture threshold of 35 vol% for the contribution of the hillslope zone to runoff. This is consistent with our observation, as 86 % of clusters had strong soil moisture correlations on the hillslope when mean soil moisture values exceeded 35 vol% for respective events within each cluster. On average, soil moisture in the riparian and hillslope zones showed a similar correlation in the wet state with correlation coefficients of 0.82 and 0.75, respectively.

Furthermore, groundwater levels in Wüstebach were significantly correlated at both stations during the wet season for the majority of similar event pairs. Yet, the station located further downstream (GWL001), which has not been directly influenced by the deforestation, generally revealed stronger correlations for similar runoff responses. Previous studies suggest that deforestation can impact the groundwater system by increasing percolation to the aquifer or subsurface runoff in the wet season (Nepstad et al., 1994) and reduce vegetation-accessible water storage capacity (Hrachowitz et al., 2021). However, to assess how the deforestation affected groundwater dynamics and the runoff response in the Wüstebach catchment was beyond the scope of this study and was done in other studies (Wiekenkamp et al., 2016, 2020).

Regarding wetness conditions for similar runoff events in

Petzenkirchen, soil moisture showed overall weaker correlations than in Wüstebach and Rollesbroich. This suggests that water storage capacity in the Petzenkirchen catchment may be limited, which is underlined by its rather flashy runoff response (Fig. 2) and moderate to poor infiltration capacity of soils (Vreugdenhil et al., 2022). In addition, the shallow groundwater level observed close to the stream in the riparian zone (BP01) showed overall strong correlations for similar runoff events, i.e., was a better indicator of similar runoff responses than the deeper aquifer at the lower slope (H09). Pavlin et al. (2021) implied that the relation between seasonal stream patterns and the deeper aquifer is more pronounced compared to event-based patterns in the stream, so that it may mainly contribute to base flow. This may be a reason why in our study the deeper groundwater level was not strongly correlated, as we investigated event-based patterns. Furthermore, the strong correlation of groundwater level in BP01 is also reflected in the results of Pavlin et al. (2021), who found a continuous connectivity of the riparian zone to the stream in Petzenkirchen, whereas the lower slope with the deeper groundwater has a much lower connectivity. Stations in closer proximity to the stream, such as BP01, may also be more impacted by streamflow than vice versa. In this context, Haught & van Meerveld (2011) suggested that the distance to the stream may be a dominant factor in the relation between streamflow and groundwater table dynamics. This hypothesis is in line with our findings regarding groundwater level observations in Petzenkirchen, whereas in Wüstebach, the more distant station to the stream not directly affected by deforestation showed stronger correlations for similar runoff events.

5.4. Possible developments of the proposed method

As shown for the three catchments in this study, the approach of comparing a catchment to itself in time is useful to investigate possible driving factors for similar temporal patterns in runoff time series. The proposed method provides a more objective classification of runoff responses compared to previous studies since it uses well-established goodness-of-fit criteria combined with a hierarchical clustering algorithm. We clearly found similar patterns in the investigated small-scale headwater catchments and it would be interesting to test the method also at a larger spatial scale in a next step. Additionally, the method could be extended to catchments with a wider range of climatic conditions and physical characteristics to investigate if climate (rather than distance) might be an important factor in explaining similar temporal runoff patterns. Since high-resolution soil moisture data is not available in most catchments, alternative approaches such as conceptual or spatially-distributed, physically-based modeling or remote sensing technologies could be used to derive soil moisture. After comparing multiple catchments to themselves in time, calculated temporal similarities of rainfall and wetness conditions leading to similar runoff patterns could be clustered in space to link them to the prevailing regional climate. Catchments that are similar in terms of climatic and physical characteristics may also exhibit comparable influencing factors on runoff patterns, as was shown by this study for the Wüstebach and Rollesbroich catchments. At a larger spatial scale, the extended approach could lead to an enhanced classification of catchments into clusters with similar driving factors for the runoff response, i.e., representing process similarity of catchments. This could improve catchment similarity indices, which are used in similarity-based regionalization methods to predict runoff in ungauged catchments (e.g., Guo et al., 2021; Parajka et al., 2005). Therefore, an improved classification including process-based indices would also be beneficial for runoff prediction in ungauged catchments, because it would allow to increase the accuracy of regionalization methods applied to ungauged catchments with similar climatic and physical characteristics.

6. Summary and conclusions

In this study, we developed a robust method to determine similar runoff responses at different points in time and then investigated the degree of similarity of respective precipitation and wetness conditions. We used runoff as an integrative measure of catchment-wide water flow, performed cluster analysis, and calculated Spearman rank correlations of clusters for precipitation and catchment wetness using long-term high resolution data of three small-scale hydrological observatories. The proposed approach of comparing a catchment to itself in time rather than searching for similar behavior in different catchments has the major advantage of analyzing the runoff response under constant physical boundary conditions, i.e., catchment characteristics. In addition, we examined precipitation and wetness conditions from *in-situ* observation data rather than from alternative model-based approaches. Obtained results differed between Wüstebach, Rollesbroich, and Petzenkirchen, indicating that precipitation and wetness conditions influenced the runoff response to different degrees in the three catchments. While soil moisture was strongly correlated over time during similar runoff events in the Wüstebach and Rollesbroich catchments, temporal patterns of precipitation were not, considering the overall mean of correlation coefficients. In contrast, with the Petzenkirchen catchment being exposed to a different climate and thus a different landscape evolution, influencing factors on the runoff response shifted towards event-based precipitation patterns rather than soil moisture dynamics. Therefore, in our similarity approach, it became evident that the two catchment with similar climate, soil type and bedrock characteristics also had similar factors influencing the runoff response. These results support the hypothesis of the long-term climatic influence on soil moisture storage and thus runoff (co-evolution of landscape and climate), not only in medium- to large-sized catchments but also in the small-scale catchments studied. The applied method helped to identify possible drivers of the runoff response in terms of precipitation, soil moisture, and groundwater level in the three catchments, however, other variables such as for instance evapotranspiration were not explicitly considered, but should be in future applications. Furthermore, applying a hydrological model in addition to the purely data-driven approach could provide additional insights into flux and state variables at the catchment scale. The results of this study could in turn be incorporated into a modeling approach to reduce uncertainty of model predictions. In addition, the evaluated similarities in precipitation and wetness conditions could be used to develop improved catchment similarity indices in combination with established indices based on physical catchment and runoff regime characteristics.

Finally, our findings complement the search for a general hydrological similarity framework by showing that temporal patterns of wetness conditions in different catchments exhibit a greater similarity for those sites that are in close proximity to each other. We propose to expand this approach to other catchments with long-term data globally in the future. In this way, the suggested time-based approach would contribute not only to improving the understanding of the rainfall-runoff process in general, but also to comparing catchments that are spatially distributed and have different physical and climatic characteristics.

CRediT authorship contribution statement

Adriane Hövel: Conceptualization, Data curation, Methodology, Formal analysis, Visualization, Writing – original draft. **Christine Stumpp:** Conceptualization, Writing – review & editing, Supervision. **Heye Bogena:** Methodology, Resources, Data curation, Writing – review & editing. **Andreas Lücke:** Methodology, Resources, Data curation, Writing – review & editing. **Peter Strauss:** Resources, Data curation, Writing – review & editing. **Günter Blöschl:** Resources, Data curation, Writing – review & editing. **Michael Stockinger:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

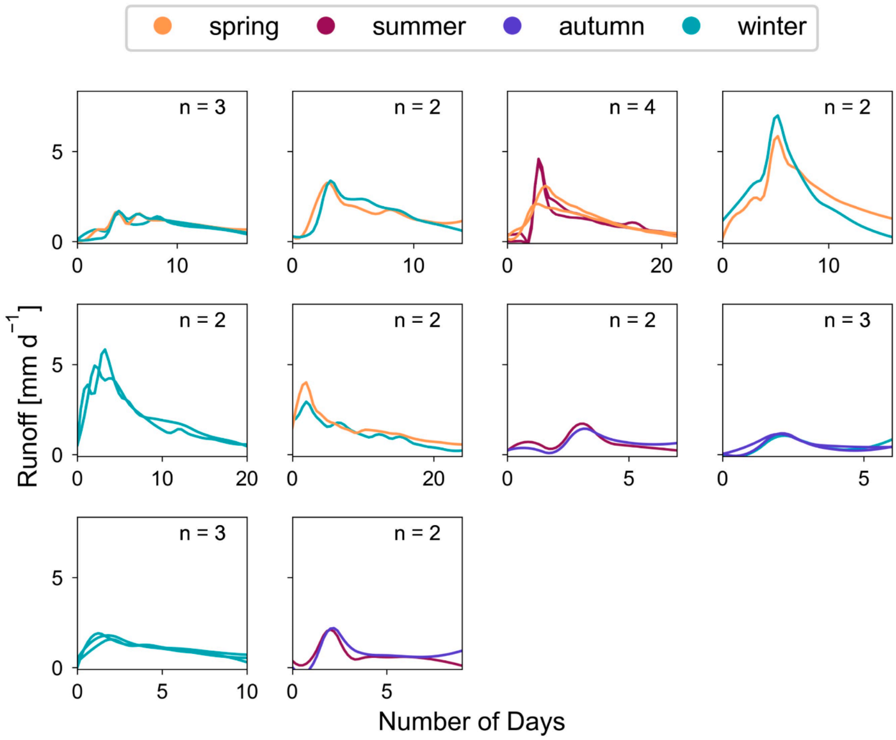

Fig. A1. Formed clusters of runoff events in the Rollesbroich catchment showing meteorological seasons of spring (orange), summer (pink), autumn (purple), and winter (cyan).

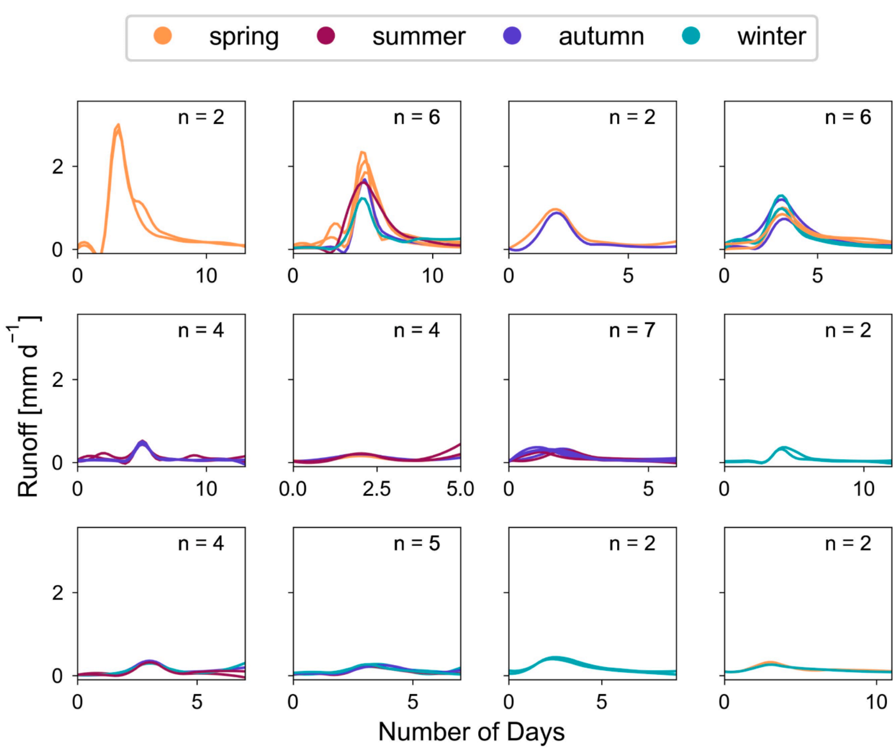

Fig. A2. Formed clusters of runoff events in the Petzenkirchen catchment showing meteorological seasons of spring (orange), summer (pink), autumn (purple), and winter (cyan).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Clusters of runoff events for Rollesbroich and Petzenkirchen. Cluster numbering (Table 1 in the manuscript) follows the numbering from top left to bottom right (row by row) in Figs. A1 and A2.

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