

Research papers

Regional process-based analysis of trends in flood peaks and volumes using hourly data

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ABSTRACT

Most studies on flood trends rely on daily discharge data at the station scale, limiting their ability to disentangle contrasting trends in different flood-generation mechanisms. This is particularly true for capturing short-duration processes such as flash floods. Here, we propose a process-based regional framework to investigate trends across different flood types using hourly data. We analyze 829 small to medium-sized catchments (<500 km²) across France using hourly discharge, radar rainfall, and reanalysis-based soil moisture data. Flood events are extracted using a peaks-over-threshold approach and classified into four categories based on response time (flash vs. slow) and antecedent soil moisture conditions (saturated vs. non-saturated). Catchments are grouped into four homogeneous hydro-climatic regions, and a spatio-temporal declustering procedure is applied to account for spatial and temporal dependence between concurrent events. Trends in flood peaks and direct runoff volumes are then assessed using regional quantile regression. Results reveal strong contrasts between regions and flood types. Only a few trends were detected for flood peaks, whereas flood volumes exhibit more frequent significant increasing trends. The strongest increases are found for flash flood volumes in mountainous and Mediterranean regions. For slow-onset floods, significant positive volume trends are observed in basins located in temperate regions, in line with increases in both rainfall totals and duration. Overall, flood volumes show a systematically higher sensitivity to change than peak flows. These findings demonstrate that flood trend detection critically depends on temporal resolution, flood type, and regional context, and that volume-based metrics provide complementary and often stronger signals than peak-based indicators for assessing evolving flood hazards.

1. Intro

Floods are among the most damaging natural hazards worldwide, and understanding how flood characteristics evolve under climate variability and change remains a central challenge in hydrology. Large-scale assessments across Europe have revealed heterogeneous and sometimes contradictory trends in flood magnitudes, reflecting the diversity of climatic drivers and catchment responses (Mudelsee et al., 2003; Blöschl et al., 2015; Kundzewicz et al., 2016; Blöschl et al., 2019; Bertola et al., 2021; Haslinger et al., 2025). However, most studies worldwide rely on daily discharge data (Villarini et al., 2009; Slater and Villarini, 2016; Wasko and Sharma, 2017; Sharma et al., 2018; Wasko and Nathan, 2019; Wasko et al., 2020a; Bertola et al., 2021; Slater et al., 2021; Kim et al., 2024; Fang et al., 2025), which limits the ability to detect changes in short-duration events and to disentangle trends in contrasting flood-generation processes.

Floods arise from a range of mechanisms, including infiltration-excess runoff during high-intensity rainfall, progressive soil saturation during prolonged precipitation, and rainfall-on-snow processes in mountainous environments (Tarasova et al., 2018, 2019; Blöschl, 2022; Tramblay et al., 2023; Tarasova et al., 2023; Tramblay et al., 2025). These mechanisms respond differently to climatic forcing. While flash floods are primarily driven by short-duration rainfall extremes (Gaume et al., 2009; Marchi et al., 2010; Tarolli et al., 2012; Amponsah et al., 2018; Noguera et al., 2021), slow-onset floods are more closely linked to cumulative rainfall and antecedent moisture conditions (Tramblay et al., 2010; Penna et al., 2011; Uber et al., 2018; Tramblay et al., 2019; Wasko et al., 2020b; Wasko and Nathan, 2019; Massari et al., 2023). As a result, changes in rainfall duration, intensity, and soil moisture may affect flood peaks and flood volumes in different ways.

Despite increasing recognition of process-based flood typologies (Merz and Blöschl, 2003; Berghuijs et al., 2016, 2019b; Tarasova et al.,

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2019; Sikorska-Senoner and Seibert, 2020; Stein et al., 2020; Zhang et al., 2022; Tarasova et al., 2023; Trambly et al., 2023), few studies have simultaneously combined hourly discharge data and a process-based flood classification to estimate flood trends for different flood-generating processes at the large scale. In particular, the potential divergence between trends in peak discharge and trends in cumulative flood volume remains largely unexplored, even though flood volume directly controls inundation extent and damage duration. This is perhaps largely because flood volumes are more difficult to estimate than peak discharge, requiring the separation of direct runoff from baseflow during the events (Mangini et al., 2018; Brunner et al., 2021; Dykman et al., 2023).

This study addresses this gap by developing a process-based regional framework to investigate contrasting trends in flood peaks and volumes across 829 small to medium-sized catchments in France. Using hourly discharge data, radar rainfall, and reanalysis-based soil moisture, flood events are extracted using a peaks-over-threshold approach and stratified by response time and antecedent soil moisture conditions. Catchments are grouped into homogeneous hydro-climatic regions, and a spatio-temporal declustering procedure is applied to account for event dependence. Regional quantile regression is then used to assess trends in both median and extreme flood metrics.

2. Data

We selected 829 French basins with hourly river discharge data comprising less than 20% missing hourly data between 1997 and 2024, with a minimum of 15 years of available data and a basin area of less than 500 km². The mean number of complete years is 26 years on average for all basins, with 86% of basins with more than 20 years of data.

For these basins, hourly precipitation data from the COMEPHORE reanalysis were used. The COMEPHORE precipitation product is a high-resolution observational dataset that combines radar measurements and rain-gauge observations within a unified processing framework to provide the best estimate of surface precipitation over metropolitan France (Fumière et al., 2019; Caillaud et al., 2021; Vigoureux et al., 2024). The dataset is available at hourly temporal resolution and 1 km spatial resolution, with continuous coverage over land.

Soil moisture for each basin was retrieved from the SAFRAN-ISBA-MODCOU (SIM) reanalysis covering the whole French territory at 8 km spatial resolution. This reanalysis dataset (Quintana-Seguí et al., 2008) is based on the ISBA land surface scheme, which simulates land surface processes over the full French territory at a daily time step, and provides among other variables the Soil Wetness Index (SWI).

3. Methods

This study presents a methodological framework for extracting and characterizing flood events in 829 small to medium-sized catchments in France using hourly discharge and precipitation data. The approach combines baseflow separation and a peaks-over-threshold event sampling strategy. The extracted flood events are subsequently characterized in terms of hydrological and meteorological descriptors relevant for process-based and statistical analyses.

3.1. Flood sampling

A flood sampling based on annual maximum series may fail to capture relevant flood variability, notably for dry years with low annual maxima values, motivating the use of alternative sampling strategies such as peaks-over-threshold (POT) methods (Lang et al., 1999) in the present study. Thresholds were selected for each catchment to yield an average of approximately 1.65 events per year, to minimize the sampling variance compared to that of annual maximum sampling (Cunnane, 1973). Only complete hydrological years with less than 20%

missing data were retained. Events including missing values were discarded. Once the flood events were extracted for each station, a two-step de-clustering procedure was applied to ensure event independence (Lang et al., 1999). Two flood peaks i and j were considered independent if they simultaneously satisfied the following conditions:

$$\Delta t_{\{ij\}} \geq \log(\text{area}) + 5d \quad (1)$$

$$Q_{\{\min, ij\}} \leq (2/3) \cdot \min(Q_{\{p, i\}}, Q_{\{p, j\}}) \quad (2)$$

where $\Delta t_{\{ij\}}$ is the time separation between consecutive peaks, $Q_{\{p, i\}}$ and $Q_{\{p, j\}}$ are the peak discharges, and $Q_{\{\min, ij\}}$ is the minimum discharge observed between the two peaks.

3.2. Calculation of flood characteristics

A crucial step to estimate direct runoff depths and flood event durations relies on separating direct runoff from baseflow from the total runoff time series, using the recursive digital filter proposed by Lyne and Hollick (Lyne and Hollick, 1979):

$$Q_{\text{base}}(t) = \alpha Q_d(t-1) + (1+\alpha)/2[Q(t) - Q(t-1)] \quad (3)$$

where Q_d is the direct runoff, Q is the total discharge, and α is a filter parameter. The Lyne and Hollick filter requires calibration of the parameter α (Nagy et al., 2024), which controls the relative contribution of baseflow and direct runoff. Physically, α represents the persistence of groundwater discharge and is closely related to the catchment recession behavior. The α parameter can be directly estimated from the slope of the discharge recession (Chapman, 1991; Tan et al., 2009; Ortenzi et al., 2025):

$$\alpha = e^{-kt} \quad (4)$$

For each recession segment, using observed river discharge, the recession constant k was estimated by fitting an exponential decay model (Tallaksen, 1995; Carlotto and Chaffe, 2019), and the median value across all valid recession segments was retained.

Following baseflow separation, flood events were identified as continuous periods of positive direct runoff. Event onset was defined as the initiation of direct runoff, and event termination as the time at which direct runoff ceased. For each flood event, several hydrological and meteorological descriptors were extracted, including direct runoff volume, flood duration, and peak discharge. The event rainfall was extracted. Initially, for each episode, rainfall is sought over a period corresponding to twice the response time of the basin (RT), estimated using the Giani et al. (2021) method for a first order estimate in order to detect flood events with no rain. If no rain was detected during this period, the flood event is discarded. In this study, purely snowmelt floods with zero precipitation during the episode are not considered, since the study focuses more on the fast runoff processes, while snowmelt floods usually last several days. However, there is already a large body of research indicating a sharp decline in the intensity of snowmelt floods in various European regions, including France (Wilhelm et al., 2022). For each identified flood episode, a search was conducted for all hours with non-zero precipitation before the event, and this search was stopped when a dry spell duration of 4 consecutive hours without rain were recorded. From this data, it is possible to calculate the total rainfall per event, the duration of the rainfall event, the maximum hourly rainfall, and the time lag (T_c) between the rainfall centroid and the flood peak, thus providing information on the response time for each event. In addition, the antecedent soil moisture from the SIM reanalysis was extracted the day before the start of the event.

Four categories of floods are considered, distinguishing between flash floods ($T_c < 6h$) and slow floods ($T_c > 6h$) (Marchi et al., 2010; Špitalar et al., 2014), as well as saturation excess floods, with saturated soils if the SWI > 0.75 (Kemter et al., 2023; Trambly et al., 2025).

3.3. Regionalization

To enable trends to be analyzed by flood type, grouping by homogeneous regions was carried out. This classification is based on a set of hydrological and climatic signatures that represent the behavior of basins during floods. The classification is based on an ascending hierarchical classification of variables that have been previously reduced via principal component analysis. The definition of the optimal number of groups is aided by the Silhouette Index (Rousseeuw, 1987), which assesses the consistency within clusters by comparing the similarity of a station to its own cluster versus others, and the Gap Statistic (Tibshirani et al., 2001), which compares the total intra-cluster variation to a null reference distribution to identify the underlying data structure.

The variables considered for each basin for the classification are:

1. Catchment altitude (ALT)
2. Flashiness Index (FI), that is the sum of absolute differences between consecutive hourly flows (Baker et al., 2004)
3. Mean annual rainfall (PTOT)
4. Mean annual snowfall (SNOW)
5. Mean annual potential evapotranspiration (PET)
6. Mean annual temperature (TEMP)
7. Response time of the catchment (RT), computed from rainfall and streamflow time series using the Detrending Moving-average Cross-correlation Analysis (Giani et al., 2021)
8. Catchment area (AREA)
9. The Simple Daily Precipitation Index (SDI), the average intensity of rainfall on wet days
10. The 99th percentile of hourly rainfall distribution (P99)
11. The infiltration excess (IE) importance, based on the coefficients in regression equations to predict event flow characteristics (McMillan, 2020)

The FI, RT and IE signatures have been computed with the TOSSH toolbox (Gnann et al., 2020), where the computation of these signatures are presented in details.

Once the regionalization procedure was completed, stations belonging to the same region were grouped together. Regional flood samples were then constructed by pooling the data from all stations within each region. Prior to pooling, flood magnitudes at each station were normalized by the station-specific mean flood, estimated from the corresponding flood sample.

3.4. Trend detection

Traditional approaches often analyze time series at individual stations independently, which may not capture the spatial coherence of extreme events or the dependency between nearby stations. To address these challenges, we create regional flood samples to detect trends. Flood events at multiple stations are often correlated in space and time, violating the independence assumption of standard statistical analyses, leading to an over-detection of significant trends (Douglas et al., 2000; Renard et al., 2008; Wilks, 2016). To mitigate this issue, we implemented a spatio-temporal declustering algorithm (Brunner et al., 2020).

To characterize the typical spatial extent of co-occurring flood events, we grouped individual events within the different regions into spatio-temporal clusters. Each cluster consists of events that occur within a 24-hour temporal window and with stations separated by no more than 250 km (Berghuijs et al., 2019a), ensuring that only geographically coherent events are grouped. This approach avoids artificially combining events that are simultaneous but widely separated across the region. Clustering was performed using the DBSCAN algorithm (Ester et al., 1996), which identifies groups of points in space–time that satisfy both temporal and spatial proximity criteria. For each identified cluster, we computed the pairwise distances among all stations within the cluster, thereby representing the overall spatial reach.

The mean distance, D , is computed from all clusters. This methodology allows a robust characterization of the spatial scales of flood events while accounting for both temporal simultaneity and geographic proximity. Thus, the spatial declustering is obtained by retaining only the maximum event within 24 h and within D (km) to reduce spatial redundancy before regional trend analysis.

To estimate trends in extreme events, we apply quantile regression (Koenker and Bassett, 1978) to the time series obtained after declustering. Quantile regression can estimate the conditional quantiles of a response variable as a function of explanatory variables, here time, providing a robust alternative to mean-based regression. For a given quantile level $\tau \in (0,1)$, the conditional quantile of the response variable y at time x (in years) is modeled as a linear function:

$$Q\tau(y|x) = \beta_0 + \beta_1 x \quad (5)$$

Quantile regression estimates coefficients by minimizing an asymmetric loss function, which weights positive and negative residuals differently. Formulated as a linear programming problem, this approach enables the analysis of temporal trends in specific quantiles while remaining robust to outliers and non-Gaussian error distributions (Ouali et al., 2016). Uncertainty in the quantile regression trend estimates was assessed using a cluster bootstrap approach (Field and Welsh, 2007). Instead of resampling individual observations, entire gauging stations were resampled with replacement, and all declustered flood events associated with each selected station were retained. This strategy preserves the temporal dependence within stations and accounts for the hierarchical regional structure of the dataset. The 95% confidence intervals were estimated using the BCa (Bias-Corrected and Accelerated) method (Efron and Tibshirani, 1994). This method corrects for both bias and skewness in the bootstrap distribution, which is particularly important in quantile regression, where estimators are generally not symmetric.

4. Results

4.1. Local trends

In this initial approach, we apply a trend test with a standard quantile regression station by station, with a bootstrap to estimate the significance of the trend, as is commonly done in most studies on flood trends. Here, we only look at the change in the median; given the size of the samples, it would not be robust to perform trend detection for higher quantiles. For peak trends, we observe a moderate downward signal at several stations (Fig. 1). But overall, there is a small number of significant trends at the national level. Conversely, trends in volume are more pronounced towards an increase, yet with a similar proportion of significant trends (around 100, out of 829). Nevertheless, it should be noted that, when it comes to trends in flood volumes, they are mostly positive—where the trends are significant. Areas with significant increase in flood volume are concentrated on the tip of Brittany in western France, in central France, and in the northeast and southwest. These regions are broadly reflected in the trends observed over the flood duration, which are even more pronounced than the trends in volume (Fig. 1). Overall, there has been an increase in rainfall totals during episodes, with a majority of increasing trends. In certain regions, there has also been an increase in the maximum intensity of hourly precipitation, especially in the northwestern central region. The largest number of trends is found for rainfall duration, which is increasing in several regions, whose spatial distribution is very similar to the trends observed in both flood volumes and duration. It is interesting to examine these maps to assess the spatial distribution of trends not only in flood peaks and volumes, but also in flood duration, and to compare them with trends in maximum rainfall intensity and rainfall-event duration. These maps reveal a strong spatial correspondence between areas exhibiting significant upward trends in flood volume and those showing increases in flood duration. The latter largely overlap with areas where significant

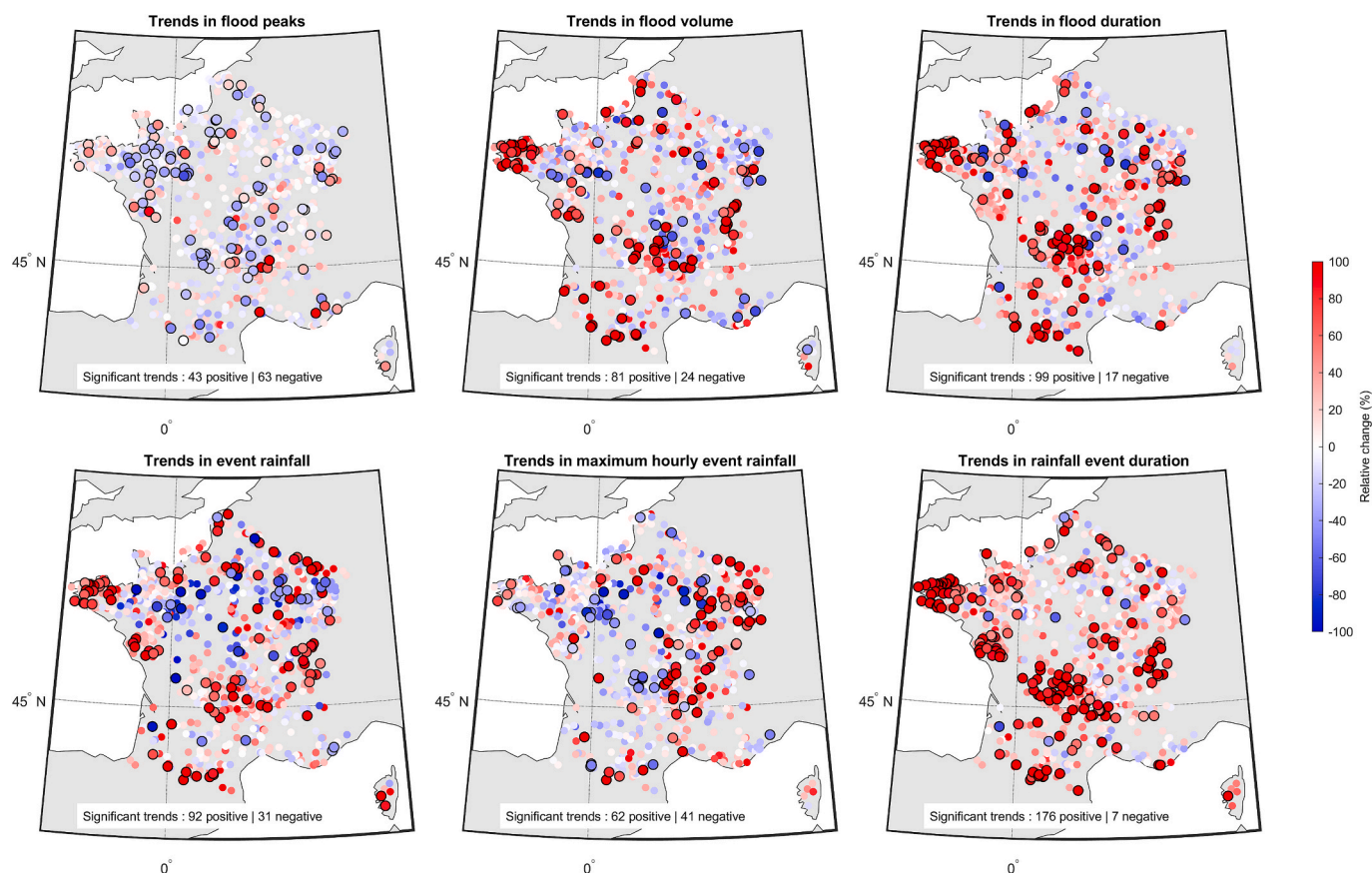


Fig. 1. Map of trends obtained by quantile regression analysis on the median of various indicators: hourly peak flow during the events, direct runoff volume during flood events, duration of the direct runoff, event total rainfall, event maximum hourly rainfall rate and rainfall event duration associated to flood events. The significance of the trends was obtained using a bootstrap to compute the 95% confidence interval for the trend. Stations with significant trends are indicated with a more prominent bold symbol. The relative change corresponds to the total percentage change over the full study period.

trends in rainfall-event duration are observed. We can therefore conclude that, at the national scale in France, the observed increases in flood volume are primarily driven by longer flood durations in some regions, which in turn appear to be linked to increases in the duration of rainfall events, rather than to increases in rainfall amounts during those events. Conversely, trends in flood peaks do not exhibit a consistent spatial correspondence with increases in the maximum intensity of rainfall events. This indicates that changes in rainfall intensity alone may not constitute a reliable indicator for explaining or assessing changes in flood peak magnitudes.

This analysis clearly illustrates the limitations of a station-by-station analysis with limited time periods. The relatively short observational record, combined with substantial temporal variability, limits our ability to detect statistically significant trends robustly. Furthermore, detecting rare events is complex for the same underlying reasons. Finally, it is not possible to distinguish trends for different types of flood events, notably flash floods, as this would further reduce the sample size. This is shown in Fig. 2, with both the proportion of flash flood events per basin and the proportion of floods on antecedent saturated soils. Regarding flash floods, it is interesting to note that there is no real preferential spatial distribution. There is a correlation with the size of the basins, but it is very weak ($\rho = 0.1$), even though it is statistically significant at the 5% level. We can also observe that the sample size for flash floods is very small, with a mode of around 5 to 10 episodes per basin, which does not allow for a robust trend analysis. Regarding floods linked to initial soil saturation conditions, there is a very different distribution between northern France, where this type of flood is very common, and the basins of southern France, where it is rare. The sample sizes in the case of floods associated with saturated soils are larger, with

between 15 and 25 years of data available, depending on the basins given the relatively higher proportion of these episodes, notably in the North.

4.2. Regionalization

The choice of the number of regions in clustering is guided by the analysis of various statistics. The gap statistic shows a marked increase between 4 and 5 clusters, followed by a plateau for higher cluster values, indicating marginal gains beyond four groups (supplementary figure S1). The silhouette index reaches a clear maximum for three clusters, reflecting optimal separation between groups and good internal cohesion. Based on these results, a partition into four clusters was chosen in order to better capture the hydro-climatic and physiographic diversity of the basins studied, while maintaining robust physical interpretability. Indeed, by placing stations in the PCA space (supplementary figure S2), we can clearly see that groups (3) and (4) are well differentiated, while there is some overlap between stations in groups (1) and (2), yet these two groups have distinct characteristics in terms of runoff response, notably expressed by different catchment areas (Fig. 3).

The regionalization process identified four distinct clusters, each representing a specific hydrological regime driven by a combination of physiographic and climatic drivers (Figs. 3 and 4):

- **Region 1 (Temperate Large):** This region is characterized by low-elevation large catchments (ALT) with the longest response times (RT). Floods occur predominantly during winter (Jan–Feb). The negative IE and low SDI and P99 suggest that flood generation is primarily controlled by progressive soil saturation.

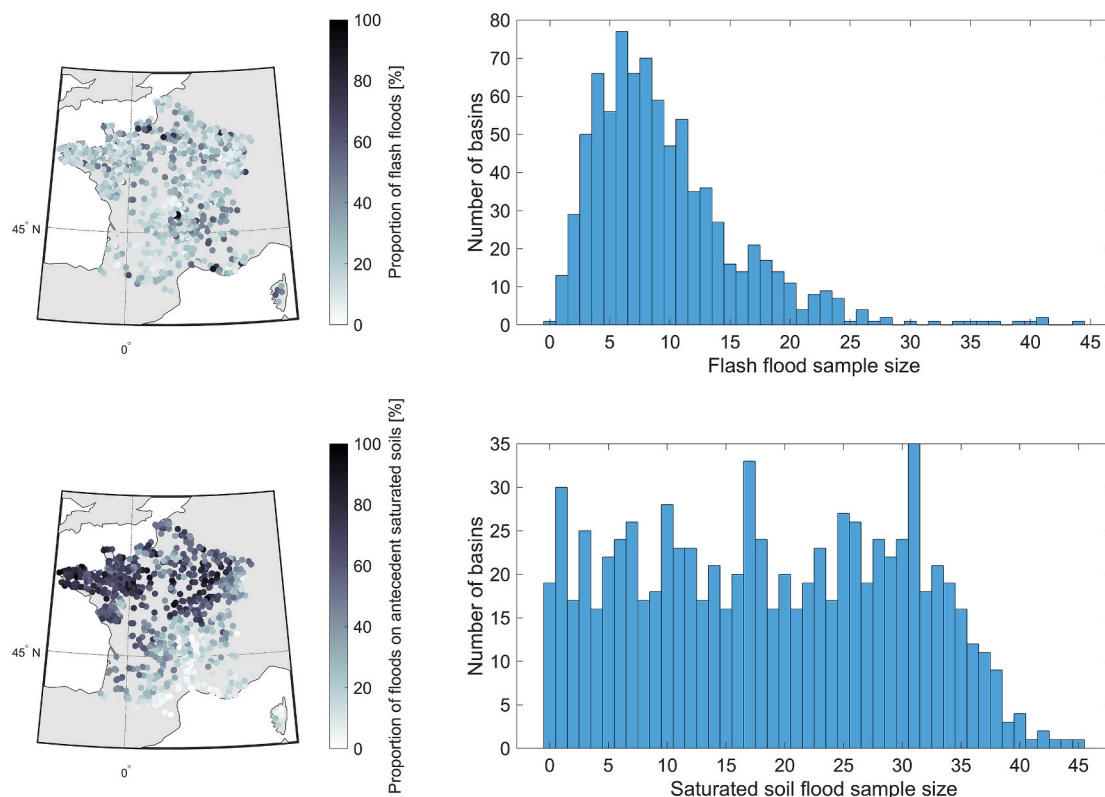


Fig. 2. Map of proportion of floods for each basin corresponding either to flash floods or floods on antecedent saturated soil (left), and histograms showing sample sizes corresponding to flash floods or episodes on saturated soil (right).

- **Region 2 (Temperate Small):** Catchments in this group show moderate altitudes and a higher Flashiness Index (FI) compared to region 1. While still winter-dominant but with a more scattered seasonality, this region exhibits a flashier response, with higher FI, IE and shorter RT than region 1, likely due to smaller basins. These basins are indeed on average smaller than those in region 1.
- **Region 3 (Mediterranean):** This region stands out as the most extreme. It displays the highest precipitation intensity (SDI, P99), evapotranspiration (PET), and temperature (TEMP). Floods are concentrated in autumn (Nov) and are characterized by very short response times and high flashiness. The strongly positive IE confirms that these events are often driven by high-intensity rainfall exceeding infiltration capacity.
- **Region 4 (Mountainous):** Defined by the highest altitudes and significant snowfall (SNOW), this region experiences its mean peak flood activity in winter. Although it receives the highest total annual precipitation (PTOT), it also has the second higher IE effect and short RT.

To identify the most discriminating variables between hydrological regions, a univariate analysis of variance (one-way ANOVA) was performed for each explanatory variable, considering regional affiliation as a classification factor (supplementary figure S3). For each variable, the null hypothesis of equality of means between clusters was tested. Statistical significance was assessed using p-values associated with Fisher's statistic (F). High F values combined with low p-values indicate a strong discriminating capacity of the variable in question. The results show that precipitation intensity variables (notably SDI) and catchment characteristics (area and altitude) have the highest F values and very low p-values, highlighting their dominant role in the structuring of hydrological regions. Conversely, certain physiographic variables such as integrative variables like FI show more moderate contrasts between regions, possibly because their effect is already embedded in other

variables (ALT/SDI for FI for instance).

4.3. Regional trend detection

Flood peak trends were analyzed using quantile regression for the median ($\tau = 0.5$) and extreme ($\tau = 0.90$) quantiles, for the four different flood categories (Fig. 5) and after the spatio-temporal declustering. The analysis of flood peaks highlights no clear contrasts between flood types, regions, and τ thresholds regarding statistical significance and trend magnitude. For flash floods, statistically significant trends in flood peaks are rare. On saturated soils, in most cases, no region exhibits confidence intervals that exclude zero due to high uncertainty. On non-saturated soils, the patterns are similar, with significant increasing trends only for the 90th percentile of slow-onset floods in Region 2. Increasing trends are found for floods on saturated soils for mountainous and Mediterranean regions, with a larger magnitude than in other regions, albeit these trends are not significant. Regarding flood volumes (Fig. 6), the results show more frequent statistically significant signals and larger changes compared to peak-based indicators. Among the significant trends, the most notable is a marked increase in the extreme ($\tau = 0.90$) flash-floods and slow floods, associated with saturated soils, in mountainous regions, with increases of nearly 50%. This trend is also observed, with a greater magnitude, in Mediterranean regions, although the increase is not statistically significant. The other significant trends concern regions 1 and 2 for slow-onset floods associated with unsaturated soil conditions and flash floods on non-saturated soils in region 1 (for $\tau = 0.5$). A systematic comparison between peak-based and volume-based indicators reveals that volumes exhibit larger amplitudes and more frequent statistical significance. For rare events ($\tau = 0.90$), volume changes are more strongly expressed than peak changes, particularly for flash floods in Regions 3 and 4. Similarly, for slow floods, volume metrics capture significant changes on non-saturated soils that are not as much reflected in peak-flow data. At the $\tau = 0.5$ threshold, while peak

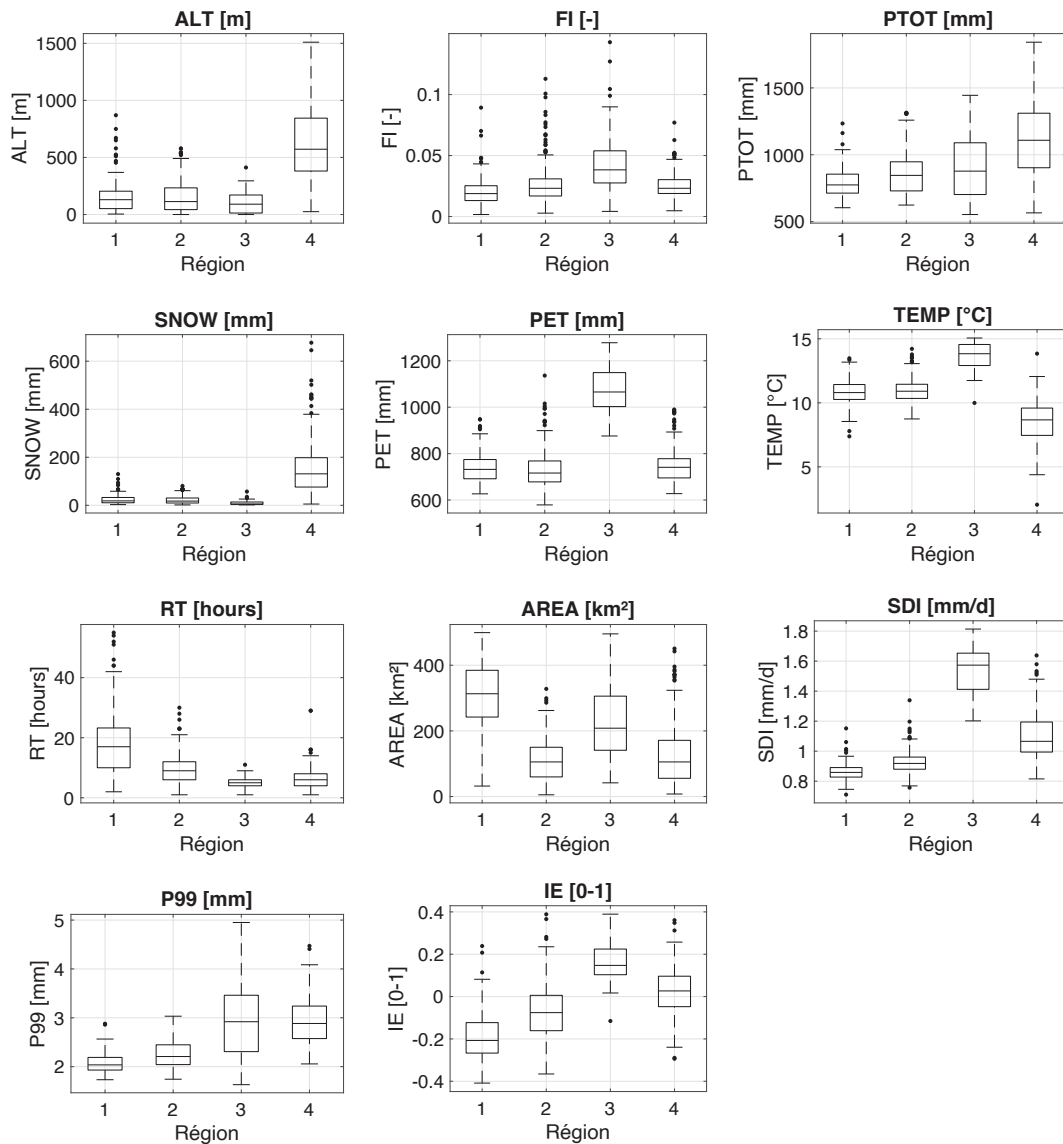


Fig. 3. Box plots showing the distribution of physiographic characteristics of the catchments across the four regions.

trends are uniformly weak, volume trends show more significant positive signals. Across both thresholds, volumes consistently demonstrate stronger sensitivity to climate and regional changes than peaks.

If we look at the number of episodes for each region and type of flood, we see quite significant differences (supplementary figure S4). Given the number of stations, there are a large number of floods in the regions 1 and 2. Nevertheless, we see that in several cases, particularly for slow floods, there is a high degree of redundancy between episodes, which means that the same episode affects a large number of stations simultaneously, explaining the sharp decrease in the number of stations between the raw sample and the sample after spatio-temporal clustering. It should also be noted that for regions 3 and 4, the number of episodes is much lower, particularly for Mediterranean regions. This implies that statistical inference for calculating trends is based on a smaller number of points and this why the confidence intervals are large. Caution is needed in particular to interpret the trends in Region 3, in the Mediterranean, in the case of saturated soil conditions, since the number of events is very low. The computed episode spatial extents are comparable with previous work, such as Berghuijs et al. (2019b). For Atlantic and continental stations in regions 1 and 2, the distances measured are between 100 and 150 km, while for Mediterranean and mountainous regions in regions 3 or 4, the distances are between 50 and 70 km (Fig. 7).

It is interesting to note that the spatial extent of episodes is influenced more by the region in which the floods occur than by the types of floods themselves.

5. Discussion

Our study provides several novel insights that were not accessible in previous large-scale analyses. Indeed, most existing studies rely on daily streamflow data and do not focus on individual flood types. In contrast, our analysis is based on hourly observations and explicitly distinguishes multiple flood types. To our knowledge, this represents one of the first large-scale assessments of flood changes across different flood-generating processes at such fine temporal resolutions. This approach reveals substantial heterogeneity in flood responses that cannot be captured using daily data alone, particularly for flash-flood events. Compared with the study of Bertola et al. (2020), our findings reveal a more nuanced picture of flood changes. Bertola et al. (2020) reported a general decrease in flood magnitudes in southern Europe. In contrast, by distinguishing floods according to their generating processes, we show that this decrease is not uniform across flood types. Some flood categories exhibit markedly different trends, highlighting that aggregated analyses of all flood events may conceal important process-specific

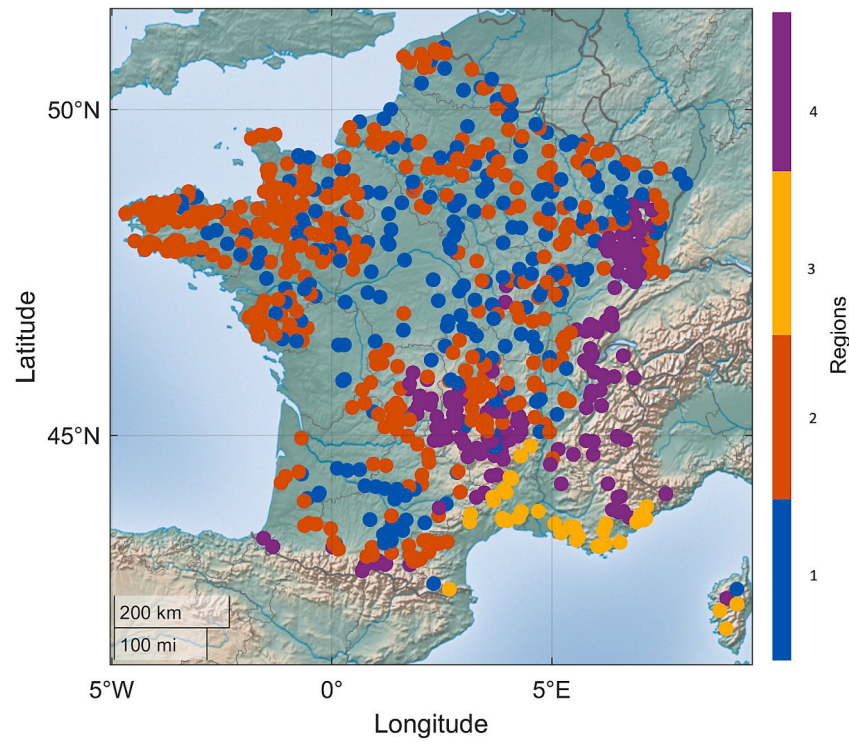


Fig. 4. Map of the four regions identified.

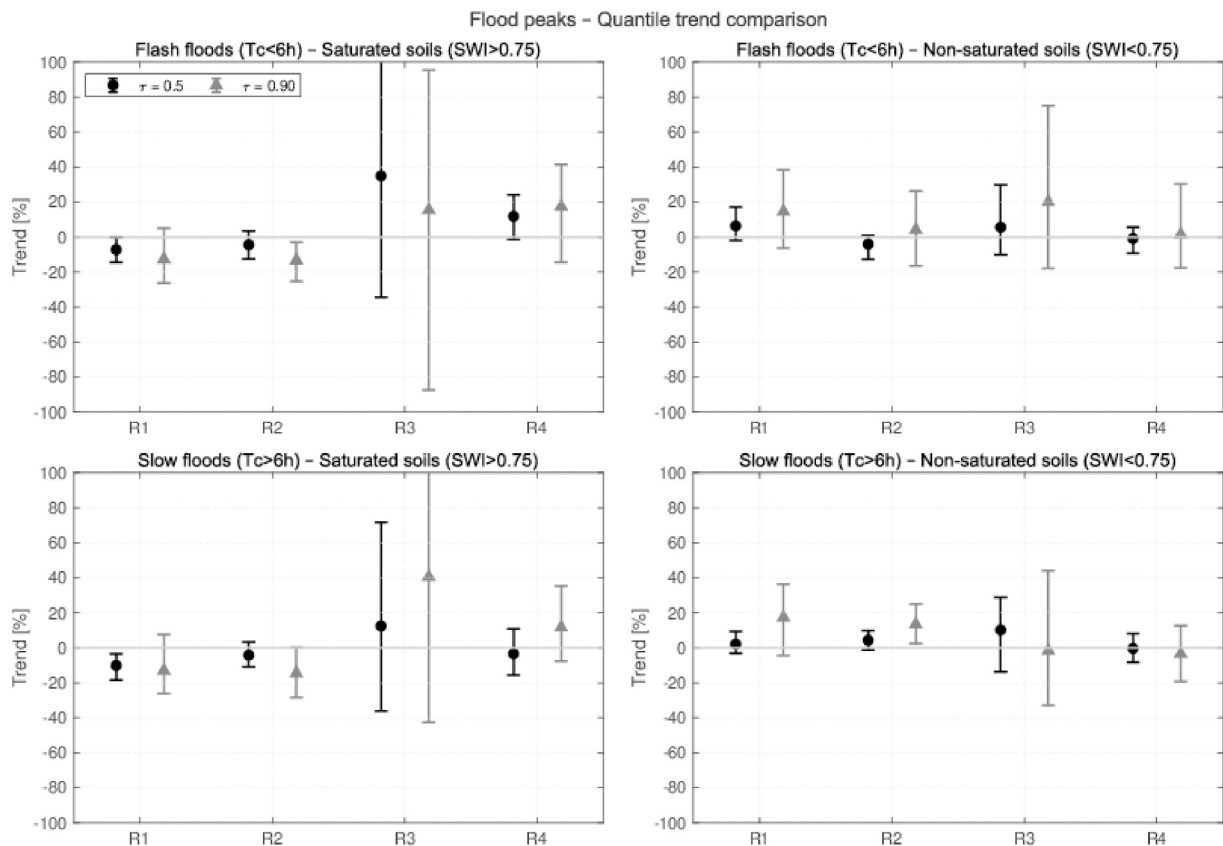


Fig. 5. Results of flood peak trend analysis for different types of floods and for the four regions. The bars represent the 95% confidence interval around the trends obtained by quantile regression.

changes. This conclusion is not limited to Mediterranean regions but is also observed across other parts of our study domain, demonstrating the

clear advantage of analyzing flood trends separately for different flood-generating mechanisms rather than considering all events jointly. A

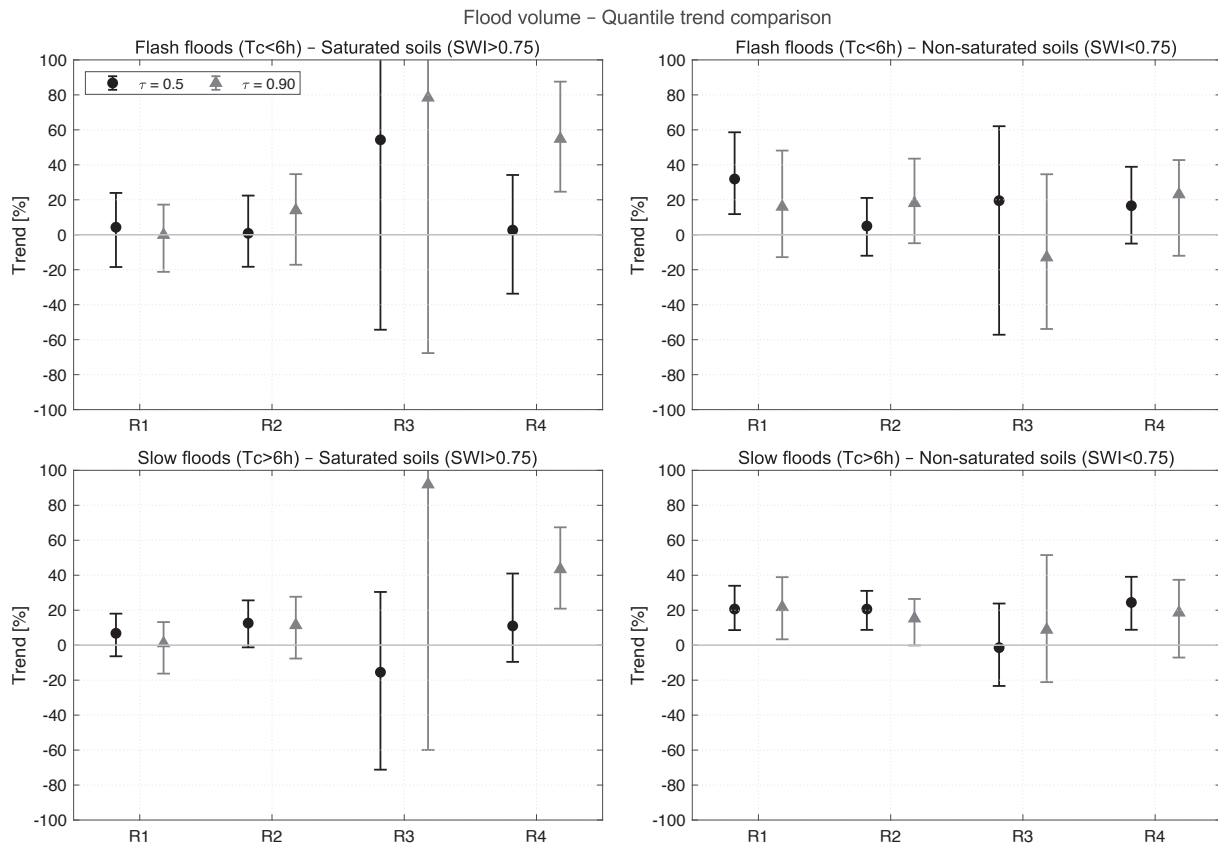


Fig. 6. Results of flood volume trend analysis for different types of floods and for the four regions. The bars represent the 95% confidence interval around the trends obtained by quantile regression.

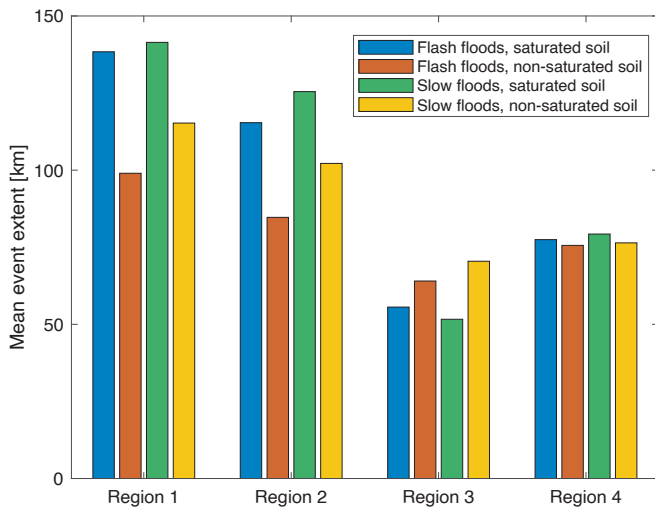


Fig. 7. Average spatial extent of flood events for different regions and different types of floods.

result that is consistent with Bertola et al. (2020) is that the most extreme floods often exhibit stronger increases in intensity than more frequent events. This suggests that the risk associated with major flooding may be increasing in many regions, even where changes in frequent flood characteristics remain limited. A similar study in Austria by Haslinger et al. (2025) reported a marked increase in flood intensities across most catchments. Such widespread increases are not observed in the majority of the basins analyzed herein, despite several regions sharing broadly comparable climatic conditions with Austria. This

suggests that the results obtained for Austria cannot be readily generalized to other European regions, even where climatic conditions appear similar.

Our findings are consistent with the broader European analysis of Fang et al. (2025), using daily data, which demonstrated strong regional variability in flood changes across Europe. In particular, we also observe increasing flood volumes in several regions, a pattern that has been reported at the global scale by Najibi and Devineni (2018) and is likely related to changes in precipitation regimes. Furthermore, our results indicate substantial shifts in flood-generating processes in mountainous regions. The observed evolution of floods, especially the strongest events in mountain environments, is consistent with previous studies such as Sikorska-Senoner and Seibert (2020). These regions are characterized by pronounced transitions from snowmelt-dominated and mixed flood regimes toward increasingly rainfall-driven regimes, particularly at lower elevations. Such process shifts have profound implications for future flood hazards and water-resource management. For flash floods, relatively few studies are available because trend analyses at hourly or sub-daily temporal resolutions remain rare. Nevertheless, some recent studies have highlighted increasing flash-flood risk in several regions, in agreement with our findings (Llasat et al., 2025; Honzířková et al., 2026). The overwhelming majority of previous flood trend studies have been restricted to daily observations, which are inherently unable to fully characterize changes in flash floods. Our results therefore provide new evidence on the evolution of these events and demonstrate the added value of high-frequency hydrological observations for understanding changing flood hazards.

The proposed methodological framework relies on several methodological assumptions that should be considered when interpreting the results. First, the baseflow separation approach assumes that streamflow recession can be described by a linear and time-invariant exponential decay, characterized by a single recession constant α for each catchment.

While this assumption is widely adopted in hydrological studies, real catchments may exhibit non-linear recession behavior or temporal variability in groundwater contributions that are not captured by this simplification. Second, the identification of recession segments used to estimate α assumes that rainfall influence is absent during these periods. Undetected precipitation or spatial variability in rainfall not captured may bias the estimation of the recession constant, particularly in small or fast-responding catchments. These model formulations may therefore affect the delineation of episodes and thus the calculation of their duration. Nevertheless, it should be noted that a much more local approach, with data tailored to each basin, is complex to implement on a national scale, as in the present study with more than 800 basins.

The declustering procedure effectively accounts for spatial and temporal dependence among concurrent events, preventing over-estimation of trend significance, in the case of a single event affecting several basins simultaneously. Without this step, events affecting multiple stations would bias the regional trend analysis, particularly in regions with dense gauging networks and produce many false positive trends (Renard et al., 2008; Wilks, 2016). The spatial extents of clustered events estimated in the present study are fully consistent with previous studies in Europe (Berghuijs et al., 2019a), and this reinforces the robustness of the results obtained using different methods. Nevertheless, it should be noted that the dependency structure may change from one episode to another, probably related to the combination of the rainfall triggering event properties and the physiographic characteristics of the basins impacted. The approach used herein could be greatly improved by using explicit modeling of inter-site dependency (Blanchet et al., 2018; Serinaldi, 2024) and the evolution of these properties over time. This work could be the subject of future studies, analyzing the links between the rainfall and flood spatial co-occurrences. It should be also noted that flood sampling and declustering were here performed prior to flood-type classification. Future work could investigate whether conducting the sampling and declustering separately for each flood-generating process in the different regions could influence the resulting trend estimates and their interpretation. Investigating such process-specific sampling approaches could provide additional insight into the evolution of flood-generating mechanisms under climate variability and change. However, it would also require redefining the criteria used to identify flood events, as flood thresholds would need to be consistent at the regional scale while accounting for differences among flood-generating processes.

Hydrological frequency analyses generally focus on flood peak discharges, which are used to design structures such as culverts, bridges, and river training works (Mediero et al., 2010; Gaál et al., 2015; Ionno et al., 2024). Numerous studies have addressed the estimation of flood peak frequency curves, whereas flood volumes have received considerably less attention, despite their importance for the design of certain hydraulic structures, particularly dams, where the entire flood hydrograph must be considered. In spillway design, relying solely on the peak discharge is insufficient. As shown in the results, across regions and flood types, volume-based indicators display a greater sensitivity to change than peaks. Several mechanisms may explain this pattern, notably a possible increase of rainfall duration rather than instantaneous intensity, or non-linear storage effects within catchments, limiting peak amplification. This highlights the importance of including volumes in hazard assessment, as relying solely on peak discharge may underestimate evolving risks. Our results suggest that changing design standards based solely on peak flows may not capture the actual changes in flood volume, particularly for slow floods and catchments sensitive to cumulative rainfall. Volume-based trends indicate a need for updating infrastructure and management strategies, as flood hazard may increase beyond what peak-based assessments suggest.

6. Conclusions

This study provides new insights into the contrasting trends of flood

peaks and volumes across different flood types and hydro-climatic regions in France, based on one of the largest hourly flood datasets analyzed at a national scale. Our results demonstrate that flood trends cannot be generalized across all types of events, as the response of flood regimes strongly depends on the underlying generation mechanisms and regional characteristics. Flood events show limited or non-significant trends in peak discharges, yet their volumes exhibit more substantial increases in different regions. This discrepancy highlights the limitation of relying solely on peak-based metrics to assess evolving flood hazards.

The most pronounced increases concern extreme flash flood volumes in mountainous and Mediterranean regions, while in temperate regions that are predominant across France, flood volumes increase by about +25% under non-saturated conditions. For slow-onset floods, trends in volumes are stronger and significant, compared with trends in peak discharge, in temperate climates. The results highlight marked spatial contrasts: mountainous and Mediterranean basins exhibit the strongest positive trends in extreme flash flood volumes; temperate regions show more moderate but spatially widespread increases, mainly for slow floods. For mountainous areas, the significant trends are likely driven by shifts in rainfall seasonality and changing rainfall-on-snow processes combined with declining snowpack.

Finally, our findings emphasize the necessity of high-resolution, process-based analyses for accurate flood trend detection. Hourly discharge data, combined with process-based classification, regionalization, and spatio-temporal declustering, enable the identification of subtle but important signals that are otherwise obscured by daily or annual maximum approaches. By revealing the limitations of peak-based assessments and the complementary role of volume-based indicators, this work provides a robust foundation for improving flood hazard assessment, infrastructure design, and water resources management in a changing climate. These results strongly advocate for moving beyond traditional daily peak analyses and highlight the importance of integrating high-frequency data and mechanistic understanding in future flood risk studies.

CRediT authorship contribution statement

Yves Tramblay: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Patrick Arnaud:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Pierre Javelle:** Writing – review & editing, Methodology, Data curation, Conceptualization.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2026.135949>.

Data availability

All the datasets used in the study are in the public domain and open access.

The instantaneous discharge data can be accessed from: <https://hydro.eaufrance.fr/>.

The radar rainfall reanalysis COMEPHORE can be accessed from: <https://www.data.gouv.fr/datasets/reanalyses-comephore>.

The SIM reanalysis can be accessed from: <https://www.data.gouv.fr/datasets/donnees-changement-climatique-sim-quotidienne>.

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