Changes in Mediterranean flood processes and seasonality

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Abstract

Floods are a major natural hazard in the Mediterranean region, causing deaths and extensive damages. Recent studies have shown that intense rainfall events are becoming more extreme in this region, but paradoxically without leading to an increase in the severity of floods. Consequently, it is important to understand how flood events are changing to explain this absence of trends in flood magnitude despite increased rainfall extremes. A database of 98 stations in Southern France with an average record of 50 years of daily river discharge data between ~~1958~~ 1959 and 2021 was considered, together with a high-resolution reanalysis product providing precipitation and simulated soil moisture. Flood events, corresponding to an average occurrence of one event per year (5317 events in total), were extracted and classified into excess rainfall, short rainfall and long rainfall event types. ~~Further, s~~Several flood events characteristics have been also analyzed~~computed~~: flood event durations, base flow contribution to floods~~the peak~~, runoff coefficient, total and maximum event rainfall and antecedent soil ~~The~~moisture. The evolution through time of the flood event characteristics and seasonality were analyzed. Results indicated that, in most basins, floods tend to occur earlier during the year, the mean flood date being on average advanced by one month between 1959-1990 and 1991-2021. This seasonal shift ~~can~~ could be attributed to the increased frequency of southern-circulation weather types during spring and summer. An increase in total and extreme event precipitation has been observed, associated with a decrease of antecedent soil moisture before rainfall events, linked to a smaller contribution of base flow during floods. The majority of flood events are associated with excess rainfall on saturated soils, but their relative proportion is decreasing over time notably in spring with a concurrent increased frequency of short rain floods. Therefore, this study shows that even in the absence of trends, flood properties may change over time and these changes need to be accounted for when analyzing the long-term evolution of flood hazards.

1. Introduction

There is a growing interest in understanding the evolution of floods occurring in different regions in the context of climate change. The recent sixth report of the Intergovernmental Panel on Climate Change (Ali et al., 2022), reported a mixture of observed trends in different Mediterranean countries, with both increasing and decreasing river floods and overall, a low confidence in their attribution to climate change. Several large-scale studies on changes in flood risk (Slater et al., 2021a; Blöschl et al., 2017, 2019) have indicated for the Mediterranean region a possible decrease over the last decades. This difficulty in detecting possible changes in flood hazard is doubtless linked to the fact that there are different types of floods (Tarasova et al., 2019; Berghuijs et al., 2019; Stein et al., 2020; Tramblay et al., 2022). Indeed, a distinction can be made between floods associated with soil saturation excess, soil infiltration excess or snowmelt-driven floods and the relative frequency of these different types of floods may change over time (Zhang et al., 2022). Furthermore, these changes can occur at local to regional scales, given complex combinations of climatic and physiographic triggers, making global generalization of changes in flood risk hazardous, if not irrelevant (Whitfield, 2012; Blöschl et al., 2015).

Only a few studies are focusing on changes in flood types over time, while it is important to understand the long-term changes in flood processes to evaluate how flood risk can evolve, in order notably to better adapt the flood mitigation strategies (Merz et al., 2014). The main limitation to perform such studies is the need for long time-series of river discharge, to have large samples of flood events to evaluate how their properties may change over time. For many regions of the world, the lack of observed river discharge data prevents this type of analysis. ~~Only a few~~Some studies attempted to analyze the changes in different types of floods for different regions (Berghuijs et al., 2019; Mao et al., 2019; Kemter et al., 2020; Bertola et al., 2021; Liu et al., 2022; Tramblay et al., 2022, Tarasova et al., 2023). Most of these studies rely on flood classification schemes, with various complexity depending on the type of data available, allowing a data-based separation of floods into their distinct generation mechanisms (Tarasova et al., 2019; Berghuijs et al., 2019; Tarasova et al., 2020; Stein et al., 2020, 2021; Tramblay et al., 2022). For basins under a Mediterranean climate, several studies reported complex interactions between precipitation increases and lower antecedent soil moisture, leading to thresholds effects (Brunner et al., 201) in the catchment response to changing hydro-climatic conditions (Wasko and Nathan, 2019; Cao et al., 2020; Bertola et al., 2021). Recent large-scale studies (Jiang et al., 2022, Tarasova et al., 2023) suggested a reduction of the frequency of floods driven by soil saturation in Europe, including basins in the Mediterranean area.

In French Mediterranean basins, several studies reported an increase in precipitation extremes (Tramblay et al., 2013; Blanchet and Creutin, 2022; Ribes et al., 2019) that did not translate into increased floods (Tramblay et al., 2019). It is hypothesized that, as many regions of the world, a decrease in soil moisture linked with a greater aridity can potentially offset the increase in precipitation extremes and thus not increase flood severity (Sharma et al., 2018; Tramblay et al., 2019; Wasko and Nathan, 2019; Wasko et al., 2021; Huang et al., 2022). Excess soil moisture was previously identified as an important flood driver notably in the Mediterranean (Kemter et al., 2020; Bertola et al., 2021), indicating that they can play an important role. Yet, beside ~~the~~ trend detection or changes in flood types, no study has provided an in-depth analysis of the joint long-term evolution of flood processes in Mediterranean basins~~these regions~~, in relation to their drivers such as precipitation, soil moisture and the evolution of synoptic weather patterns associated with floods. Therefore, the objective of the study is to evaluate how the characteristics of Mediterranean floods are evolving in time, not only in terms of flood event types, but also the seasonality of events, their duration, runoff coefficients, ~~and antecedent~~and antecedent soil moisture. A recent study (Tramblay et al., 2019) indicated no significant trends on flood hazards for a large ensemble of basins located in southern France. This database is used herein to further analyze the possible changes in flood generating processes and in the seasonality of flood events.

In section 2 are presented the different datasets used for this analysis, including river discharge, precipitation, soil moisture data and weather types classification. In section 3 the methods are presented, for event extraction, analysis of the seasonality and changes in the different flood drivers. Results are presented in section 4.

2. Data

We consider 98 catchments in southern France (Figure 1) where the time series of daily discharge exceeds 30 years of complete data between 1959 and 2021 (Tramblay et al., 2019). Among them, 48 basins have more than 50 years of data and the basins selected are not influenced by reservoir or dam regulation. The catchment sizes are ranging from 14 km² to 3195 km², with a mean size equal to 480 km² (see Table t1 in supplementary materials). Basins with a nival regime were removed, identified from the river discharge hydrographs and removing basins with more than 20% of precipitation falling as snow. In addition to river discharge data, the precipitation and soil moisture for each basin has been retrieved from the SAFRAN-ISBA-MODCOU (SIM) reanalysis covering the whole France territory at 8 km spatial resolution (Vidal et al., 2010~~Habets et al., 2008~~). Precipitation and soil moisture data have been extracted and averaged at the catchment scale. The soil moisture data extracted from SIM is a soil wetness index obtained from the normalization of the volumetric soil moisture content with the wilting point and field capacity, that ranges between 0 and 1. Land cover classes (forest, agricultural, urban) corresponding to 2018 have been extracted from the CORINE land cover inventory (Büttner, 2014). In addition, we used the weather type classification from *Electricité de France* (EDF), corresponding to a daily classification into 8 synoptic situations associated with rainfall events over France (Garavaglia et al., 2010). This classification is built on geopotential heights at 700 and 1000 hPa pressure levels associated with rainy days over France.

3. Methods

3.1 Extraction of flood events

We extracted a sample of flood events with a mean occurrence of 1 event per year using a peaks-over-threshold approach. This type of sampling is chosen since low annual maximum runoff could be observed during dry years (Farquharson et al., 1992). A de-clustering algorithm is applied to identify single events to avoid introducing autocorrelation in the analysis and ensuring that flood events are independent, using two rules (Lang et al., 1999):

first a minimum of n days between events, with $n = 5 + \log(\text{catchment area})$ and second, between two consecutive peaks, runoff must drop below ⅔ of the smallest peak. The maximum daily runoff of each event is kept. This means that for an event lasting several days, only the maximum daily discharge, and the corresponding date, are kept. Then, fFor each flood event, we computedextracted the total rainfall and maximum rainfall. The n-day previous precipitation is extracted. Total rainfall for each event is estimated by a cumulative sum of precipitation starting the day of the flood and before a flood and this aggregation stops if there are two consecutive days with precipitation close to zero (1 mm) to account for rainfall intermittency within events. The maximum daily precipitation is extracted from the same time interval used to compute total event precipitation. The soil moisture at the beginning of the events is extracted from the previous day of the start of the rainfall event. A base flow filter has been used to separate direct runoff and base flow for each eventtime series, using the Lyne Hollick Filter (Lyne and Hollick, 1979), with its default parameters. For each flood event, the base flow corresponding to the peak has been extracted to estimate the direct runoff, corresponding to the event rainfall contribution, in addition to base flow. Different metrics characterizing each flood event have been computed: total rainfall (mm), event maximum rainfall (mm), duration of the rainfall event (days), duration of the flood event (days), antecedent soil moisture (0-1) and runoff coefficient (0-1). The runoff coefficient was computed for each event as the ratio of direct runoff depth and total event precipitation

3.2 Analysis of the mean date of occurrence

Circular statistics (Burn, 1997; Berens, 2009) are used to analyze flood timing. The dates are first converted into an angular value, then from this sample of angular values, the mean date of occurrence (θ) can be computed, together with the concentration index (r) which measures the variability of the flood occurrences around the mean date. Using the dates of flood events, considering hydrological years starting September 1, θ and r are computed from the sample of dates. The first step in the analysis of seasonality is to test against circular uniformity. Circular uniformity refers to the case in which all angular values of flood dates around the circle are equally likely, indicative of the absence of flood seasonality. In that case, the computation of the mean date would have little relevance. The Rayleigh (Fisher, 1993) and the Hermans-Rasson (Landler et al., 2019) tests are used to test against uniformity for unimodal distributions, to verify the presence of flood seasonality (ie. meaning that floods do not occur randomly throughout the year). To associate flood events and weather types, for each rainy day corresponding to flood events, the weather type has been extracted from the weather type's classification.

3.3 Classification of flood generating processes

A classification is applied to the flood events, adapted from a previously implemented classification at the global scale (Stein et al., 2020), in the United States (Stein et al., 2021) and Africa (Tramblay et al., 2022). This approach relates the occurrence of rainfall amounts above various thresholds to the occurrence of floods. Flood events in each catchment are classified according to three hydrometeorological generating processes, namely, the excess rainfall, short rainfall, long rainfall using a decision tree. Excess rainfall is defined as a flood event triggered by rainfall higher than average occurring over wet soils (i.e. soil moisture above than 50% saturation), short rainfall as a single daily rainfall event above high thresholds (the 95th percentile computed over the whole time series of rainfall) and long

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rainfall as several consecutive days (> 2 days) with rainfall above the 95th percentile of rainfall summed over 7 days. The classification first evaluates if a larger than average multi-day rainfall fell on wet soil to determine if the flood event was an excess rainfall type of flood. If that was not the case, it evaluates whether the thresholds for long rainfall and then short rainfall are exceeded. If no process could be identified, the class “other” is assigned.

3.4 Changes in flood characteristics

To assess the changes over time in flood dates and generating mechanisms, we split the records of each station into two periods of equal length. Given that most stations have records starting after the 1960s, on average the first period is ranging from 1959 to 1990 and the second one from 1991 to 2021, with a pivot year within +/- 5 years around 1991, allowing the comparison of the two time slices across the different stations. To assess the relative changes in the flood drivers, the frequency of each driver for each time period has been computed, and then we computed for each station the relative change (%) in each driver contribution (Berghuijs et al., 2019). In addition, to detect trends on the long-term frequency of event types per year pooled at the regional scale, we used the Mann-Kendall test for trends, modified to account for autocorrelation in the time series (Hamed and Ramachandra Rao, 1998).

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We use the same approach to estimate changes in the different flood events characteristics, and we applied the two-tailed Wilcoxon test to check the difference in medians. In addition, to assess the regional significance of the trends, we also computed the Mann-Kendall test on flood events characteristics pooled at the regional scale. For flood dates, we computed the mean dates of occurrence for the two time periods and assessed the significance of the difference using the Watson and Williams test, which is a circular analogue to the two sample t-test (Watson and Williams, 1956). Finally, to estimate potential relationships between different flood characteristics, the Spearman correlation coefficient (ρ) is computed.

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4. Results and discussion

4.1 Change in flood event characteristics

There are several changes in flood event characteristics as seen in Figure 2 between the two sub-periods, ~~1958~~1959-1990 and 1991-2021. On average, total event precipitation is increasing in 65 basins (66% of basins), maximum event rainfall is increasing in 76 basins, consistent with previous studies in this area (Ribes et al., 2019; Tramblay et al., 2019; Blanchet and Creutin, 2022), while on the opposite antecedent soil moisture is decreasing in 71 basins, baseflow contribution is decreasing in 75 basins and runoff coefficient is decreasing in 68 basins. These changes in soil moisture, base flow and runoff coefficients are consistent with an overall increase of aridity in southern Europe mostly driven by higher evapotranspiration (Tramblay et al., 2020) and have been also observed in other regions with a similar climate (Ho et al., 2022). The ~~number of local statistically significant changes for each flood event characteristic are~~number of local statistically significant changes for each flood event characteristic is given in Table 1. These numbers remain small but it should be reminded that sample sizes are quite short for a robust statistical assessment in a context of high interannual variability. To overcome this issue, we also assessed the regional

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significance of these changes in flood event characteristics. We performed a regional pooling of the events and applied the Mann-Kendall test to detect trends in the regional series of event characteristics. As shown in table 1, all the detected changes are regionally significant except the decrease in base flow contribution to peak discharge during floods. Overall, an increase in total event rainfall can be observed, mostly caused by the increase of maximum rainfall during the events (the changes in the two variables are correlated, with $\rho = 0.52$), while the flood event durations are on average decreasing, consistent with studies at the global scale (Wasko et al., 2021).

These changes in precipitation are associated with a decrease of antecedent soil moisture, before the beginning of the rainfall events. This decrease is also related to a smaller contribution of base flow during floods in some basins. There is indeed a significant correlation between the relative changes in the base flow contribution to peak runoff and soil moisture ($\rho = 0.56$), indicating that the soil moisture decrease is likely the main driver of these changes. There is also for most basins a significant nonlinear relationship (exponential type) between the flood events antecedent soil moisture and runoff coefficients, as reported in many studies (Penna et al., 2011; Rogger et al., 2013; Raynaud et al., 2015; Tarasova et al., 2020). Indeed, for the first time period, 1959-1990 the median Spearman correlation between antecedent soil moisture and flood runoff coefficients (see supplementary figure S1) is equal to 0.43 and is significant at the 5% level in 56 basins (67 basins at the 10% significance level). For the second time period, 1991-2021, the median correlation is increasing to 0.45 and is significant in 64 basins at the 5% significance level (68 at the 10% significance level). These results show, contrary to popular belief, that at the catchment scale drier soils produce less runoff, and this characteristic is even slightly accentuating over time. Indeed, increased runoff coefficients induced either by hydrophobic soil conditions following droughts (Burch et al., 1989), soil crusting and sealing (Bissonnais and Singer, 1993) or compaction (Alaoui et al., 2018), are well documented processes that mostly occur at the local plot scale that do not produce discernible effects at the catchment scale. This observation is reinforced by the fact that no negative correlation between runoff coefficients and initial soil moisture was detected. About the explanatory factors of the association between soil moisture and runoff coefficients, we found stronger correlations (significant at the 5% level) between these two variables in catchments with higher percentage of urban or agricultural areas, and on the opposite weaker correlations along with increased percentage of forests or mean catchment altitude. There is only a very small increase of the correlations for larger basins (no significant correlation with basin sizes), indicating that this relationship between soil moisture and runoff coefficient remains valid for all basins scales considered in the present study. This relationship between runoff coefficients and antecedent soil moisture remained stable between 1959-1990 and 1991-2021 (Figure 3).

4.2 Changes in flood dates

Floods in southern France tend to occur mainly during November or December for basins close to the Mediterranean, East of the Cévennes mountainous range, while for basins located on the western part of the region, they tend to occur later during winter months, centered in January or February (Figure 4). Both the Rayleigh and Hermans-Rasson tests reject the null hypothesis of uniformity at the 5% level, indicating that floods do not occur randomly throughout the year. In most cases, the seasonal distribution is unimodal, except for a few cases; in about 15 stations the maximum occurrence of floods is observed in late autumn or winter and a secondary minor peak of occurrence is observed, usually centered around the month of March or April. These floods are associated with rainfall events rather than snowmelt, since for only 3 basins the snowfall contribution reaches 19% of total precipitation whereas the snowfall contribution is much lower for the remaining 12 basins (less than 5%).

For 79 basins, floods tend to occur earlier during the year, on average by -22 days between ~~1958~~1959-1990 and 1991-2021 (Figure 5, left panel). On the opposite, for 19 basins the mean flood date occurs later in the second period with an average of +12 days. These changes in the mean date are significant in 26 basins at the 0.1 level according to the Watson and Williams test (18 basins at the 0.05 significance level). There are two differentiated spatial patterns: all basins where floods tend to occur earlier are located widespread in the center of the Mediterranean region, and basins where floods tend to occur later are found only in the northwestern margin of the domain. In these basins, the mean floods occur in late winter, until February and March. The same spatial patterns of changes in mean flood dates have been observed by Blöschl et al. (2017), but without providing the possible causes of these seasonal shifts. For the concentration index (i.e., the variability around the mean date) similarly two different patterns are found: for basins where floods tend to occur earlier, the concentration index is increasing, meaning more floods are clustered around the mean date, while for western basins where floods tend to occur later, the concentration index is decreasing, meaning a larger variability in flood dates (Figure 5, right panel).

To assess the regional changes in flood dates, we first separated in two regional samples the stations where floods ~~tend to~~ occur earlier (sample 1) or later (sample 2). Then we used the Watson-William test, previously used to assess changes in flood dates in each station, to compare these two regional samples. The test results indicate that for the 19 stations where floods tend to occur later, the change in flood dates are not significant at the 5% level (p value = 0.0821), on the opposite, for the 79 stations where floods are occurring earlier, the change is significant (p value = 5.34.10^-8).

4.3 Associations between flood occurrence and weather patterns

The seasonal patterns observed for the floods are closely related to the occurrence of different weather types in different sub-regions. As shown in figure 6, most basins located east of the Cévennes mountainous range have floods associated with WT4, Southern Circulation, and western basins with WT2, ~~Atlantic circulation~~Steady Oceanic. The most frequent pattern associated with 37% of floods, WT4, is known to be triggering intense rainfall events in this region (Ducrocq et al., 2008; Tramblay et al., 2013). Interestingly, the WT6, Eastern circulation, and WT7, Southwestern circulation, are both associated to a lesser extent with floods across the whole region, but without notable spatial differences in the relative frequency of floods associated with these weather types. Change in flood ~~seasonality could~~seasonality could~~an~~ be ascribed to changes in the seasonal occurrence of the weather types (Figure 7): WT4 tends to occur more frequently from March to August during 1991-2021 compared to 1959-1990, and these changes are statistically significant (see supplementary figure S2). When looking at the actual count of WT4 days, this change represents an increase of 69 events during that 6-month period for 1991-2021, so an average of +2.2 days per year. Associated with a warmer Mediterranean Sea over the last

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decades notably during summer (Pastor et al., 2020), the combination of these two factors could explain the earlier occurrence of floods east of the Cévennes mountainous range. Similarly, there is an ~~notable~~ increased frequency of WT2 in January, February and March between 1991-2021 and 1959-1990, that is also significant (supplementary figure S2)~~,~~ that could be possibly related to the later occurrence of floods west of the Cévennes range. Although this change in weather types seasonality leading to heavy rainfalls is a plausible cause of the observed changes in the flood seasonality, more research is needed to better understand these relationships and attribute changes in flood seasonality. Notably, to analyze in more detail the moisture supply from the Mediterranean or Atlantic seas, the interaction with the atmospheric thermodynamics, the duration, localization and the spatial dependence of the rainfall episodes inducing floods.

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4.4 Changes in flood generating processes

When first applying the classification of flood-generating processes on all floods, we find a predominance of excess rainfall events (Figure 8), followed by long rain and short rains, that is consistent with the known flood-generating processes in this region (Mediterranean episodes) and, in particular, the strong influence of saturated soils on runoff generation with floods mostly occurring during the autumn (Tramblay et al., 2010, 2019). The category 'other' regroups only 0.97% of ~~floods,~~floods and it represents mostly events with very low precipitation amounts, likely due to an underestimation of rainfall in the SAFRAN database for some events. It is worth noticing that despite the large sample of basins considered, the patterns are remarkably consistent and homogeneous across different basin sizes and locations. There is a significant, yet low, correlation (ρ = 0.26, p-value = 0.008) between the ratio of excess rain floods and catchment size, with a larger proportion of excess rain in larger basins, while on the opposite there is an even weaker and negative correlation (ρ = -0.16, p-value =0.09) between the ratio of short rain and basin size. It should be noted that floods driven by short rain episodes are potentially affecting smaller regions than floods driven by excess floods (Brunner and Dougherty, 2022). For 30 basins (not necessarily the largest ones), the proportion of excess rain exceeds 80% of the total number of flood events (see supplementary figure S~~2~~3). For short rain and long rain, the maximum contributions observed much lower, ~~are~~ 36% and 32%, respectively, but these maximum values are only found in small basins. Indeed, basins when short rain or long rain exceed 30% of episodes are only found in basins smaller than 100 km².

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The mean date of occurrence is significantly different between the three flood types~~drivers~~, according to the Watson and Williams test. As shown on figure 9, the highest proportion of floods induced by short rain is observed during September to November, while the floods induced by long rain are mostly occurring during October to December, and excess rain floods are observed in late autumn and winter, with a peak in ~~January~~February. This is consistent with the annual soil moisture cycle in this region: at the end of the summer the soils are dry and it takes several months to replenish the soil moisture level, which is at highest during winter. If examining the long-term changes in this ~~seasonal~~ monthly repartition of flood types ~~drivers~~ (see supplementary figure S~~3~~4), the frequency of excess rain is decreasing from February to ~~October~~ April, and also in October, while increasing during winter months. This implies that the season during which excess rain floods are occurring is reducing in length and concentrated during wet winter months. On the opposite the frequency of short or long rain floods is increasing in June and September, months that are getting drier over time in this region..

The noticeable changes in flood processes over time are a reduction of Excess rainfall in 71 basins and an increased frequency of short rains in 53 basins and Long rains in 63 basins (Figure 10), while short rain and long rain floods are decreasing for 19 and 22 basins, respectively. For excess rain, there are only 16 basins where their relative proportion is increasing;, they are mostly located on the margins of the Alps and Pyrenees mountains. For more frequent events (ie. if considering an average of 3 episodes per year instead of one), the number of basins with a change is larger, with a reduction of Excess rainfall in 82 basins out of 98 (results not shown). This indicates that the soil moisture depletion has more impacts on small to moderate flood events, as previously observed by Bertola et al. (2021). There is no relationship between the rate of change in the different flood generating processes and catchment sizes indicating a clear regional pattern. The average magnitude across all basins of these changes remains low, on average -4.1% for excess rain, +1.2% for short rain and + 2.1% long rain. Yet, the magnitude of these changes is ranging from +15% to -21% for excess rain, +11% to -20% for short rain and +12% to -11% for long rain, depending on the catchment, indicating that local catchment characteristics could strongly modulate the regional signal. In addition, the average values over the whole domain are hiding some local changes: for instance, short rainfall floods are increasing in the southeastern part of the Cévennes while decreasing for the northwestern part as seen in Figure 10.

4.5 Regional changes

To assess whether the changes in the relative influence of the three different flood types are significant at the regional scale, we computed for each year the relative frequency of the different flood types, all basins together. It is indeed not possible to do this analysis for each station independently, due to the small size of the samples over the two periods. These changes in the occurrence of flood types are significant at the regional scale according to the Mann-Kendall test (Figure 11), for the frequency of excess rain floods and short rain floods, at the 5% significance level, but not for the long rain floods. All events pooled regionally, the decrease in excess rain floods is equal to -13% between 1959-1990 and 1991-2021, and the increase of short rain floods is equal to +36%. In addition, to assess whether these results are robust to the thresholds used in the classification of flood events, a Monte Carlo experiment has been also conducted. Results show (see supplementary figure S5) that regional changes in excess rain and short rain floods are not dependent on classification thresholds, while it is not the case for long rain floods. In terms of flood severity for the different flood types, the median flood computed for each basin is strongly correlated to basin size (ρ = 0.78) for floods caused by excess rain, short rain (ρ = 0.80) and long rain (ρ = 0.75); and very similar results are found for the maximum flood. On the contrary, the specific discharge of flood peaks is non linearly related to basin sizes, with a clear threshold effect for basins smaller than 500 km² that have a much larger specific discharge than larger basins.

Given that there are different flood sample sizes in the different basins corresponding to different flood-generating processes, we pooled regionally the flood events. To do so, we computed the specific discharge for each event (i.e. the flood magnitude divided by catchment area) to analyze the distributions of specific discharge for all the events associated with excess rain, long rain or short rain. Specific discharge is used herein since it is a good indicator of flash floods severity, notably in this Mediterranean region (Delrieu et al., 2005, Ruin et al., 2008). Figure 12 shows that the short rain floods are more severe, in terms of specific discharge, than excess rain or long rain floods at the regional level (as shown also by Tarasova et al., 2023). The regional distributions for the different event types are different according to the Kolmogorov-Smirnov test. It must be noted that for a given basin the magnitude of the different types of floods may not be very different, showing the strong variability from one event to another that is not solely linked to the flood trigger. When comparing the different flood distributions between the time periods 1959-1990 and 1991-2021, the differences in flood magnitudes between excess rain, long and short rain are reduced. This is mainly due to a slight decrease in the specific discharge of short rain floods, notably for flood events with a return level higher than 10 years, while the excess rain floods show very little changes in intensity over time.

5. Conclusions

The aim of this study was to document the evolution of the characteristics of Mediterranean floods, using a large database of long river discharge records in southern France. In most basins, floods tend to occur earlier during the year, the mean flood date being on average advanced by one month. This seasonal shift can be attributed to the increased frequency of southern-circulation weather types during spring and summer, thatsummer that are strongly associated with the occurrence of floods in this region. Over time, floods also tend to be more clustered in time over the different basins, as reflected by a decreasing variability in flood occurrence throughout the year. On the contrary, for the westernmost basins influenced by Atlantic circulation patterns, floods tend to occur later during the year, also due to a seasonal shift of the flood-generating circulation patterns that are occurring more frequently in late winter. During floods, an increase in total and extreme event precipitation has been observed, associated with a decrease of antecedent soil moisture before rainfall events, linked to a smaller contribution of base flow during floods. It can be concluded that it is the depletion of soil water content, due to increased aridity in south France notably related to higher evapotranspiration rates (Tramblay et al., 2020), that is the likely cause of the absence of flood trends despite the increase in extreme rainfall. It should be also noted that over all basins, dryer soils are associated with lower runoff coefficients, and this relationship remains valid over time. The majority of flood events are associated with excess rainfall on saturated soils, but that proportion is decreasing over time with a concurrent increased frequency of short rain, potentially leading to more severe floods. At the regional scale, floods induced by short rains are indeed of higher magnitude, but due to a lower runoff coefficient induced by drier antecedent soil moisture, the specific discharge associated with short rain flood is decreasing over time. These results are consistent with those obtained in other regions, showing that floods do not necessarily increase with the increase in extreme precipitation, and that soil moisture seems to play a key role in explaining these changes and the lack of trends ultimately on flood hazard (Wasko and Nathan, 2019; Bertola et al., 2021; Wasko et al., 2021). The results of the present study are rather homogeneous given the different catchment sizes and land use types, indicating that changes in flood types are mainly resulting from regional climate change and not only local changes, such as land cover or agricultural practice changes, nor the increase of urban and peri-urban areas.

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Nonetheless, if the observed trend in increased short rain floods is persisting in the upcoming decades, the severity of floods, particularly the most important ones, could increase along with the rise in rainfall extremes particularly in areas where the soil infiltration potential is low, such as in mountainous or urbanized areas, that have expanded a lot in recent years. This aspect could be further investigated using climate scenarios.

One of the main perspectives of this work would be to perform a similar analysis at sub-daily time steps, that would be more adapted to analyze changes in flash floods characteristics, notably in terms of the flashiness response of the catchments (Baker et al., 2004; Li et al., 2022). Indeed, the daily time step prevents a thorough analysis of changes in rainfall patterns, notably at shorter time steps. Yet, there is no gridded dataset of hourly precipitation before the 2000s in Southern France, that does not allow to repeat such a similar study over 62 years. However, given the availability of radar rainfall over France, it would be possible to analyze, at least for the recent years after 2000, the evolution of several characteristics, such as the evolution of storm hydrographs, concentration time and the flashiness response of the basins. Another relevant prospective work would be to analyze the spatial extent of floods. Given the future evolution of weather types associated with floods in combination with more local to regional characteristics, such as soil moisture state, these types of events may impact simultaneously wider, or smaller, parts of the region considered, and this could have serious implications on risk management (Brunner et al., 2021; Brunner and Dougherty, 2022). Therefore, the joint analysis of flood occurrence in nearby basins would be highly relevant. Finally, there is also a need for new approaches to incorporate these changes in flood generating process into engineering practice (Slater et al., 2021b), notably to estimate the return levels for different types of infrastructure design.

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Data availability

The computed catchment-based indicators are available upon request to the corresponding author.

Author contributions

Y.T.: Conceptualization, investigation, data curation, formal analysis, writing—original draft preparation. YT designed the experiments, performed the analyses, and wrote the paper. PA, GA, ML, EP, LN and ES Conceptualization, data curation, writing—reviewing and editing.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1: Number of local significant changes in the median of flood events characteristics detected by the Wilcoxon test and results of the regional Mann-Kendall test on flood event characteristics

Indicator	**Number of significant local changes (Wilcoxon, 10%)**	**pvalue of the regional MK test**	**Regional changes between 1959 and 2022 (%)**
Flood event duration	17	**0.0046178**	-0.40%
Base flow contribution to peak	15	**0.5687962**	-8.62%
Runoff coefficient	19	**0.0000002**	-14.62%
Total event rainfall	16	**0.0011851**	9.01%
Maximum event rainfall	27	**0.0000000**	13.47%
Antecedent soil moisture	12	**0.0000008**	-9.80%

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Supplementary materials

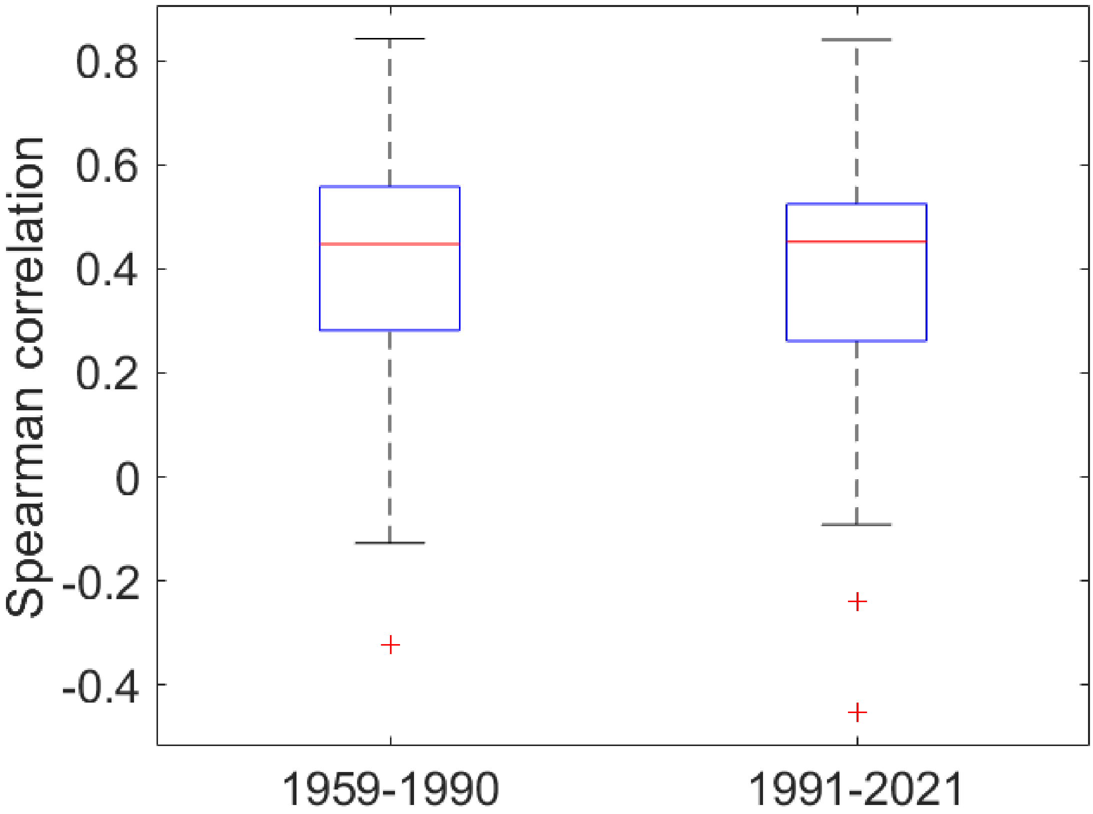

Figure S1: Spearman correlation coefficients between runoff coefficients and antecedent soil moisture. For each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the 99% of the data and the 1% outliers are plotted with the '+' marker symbol.

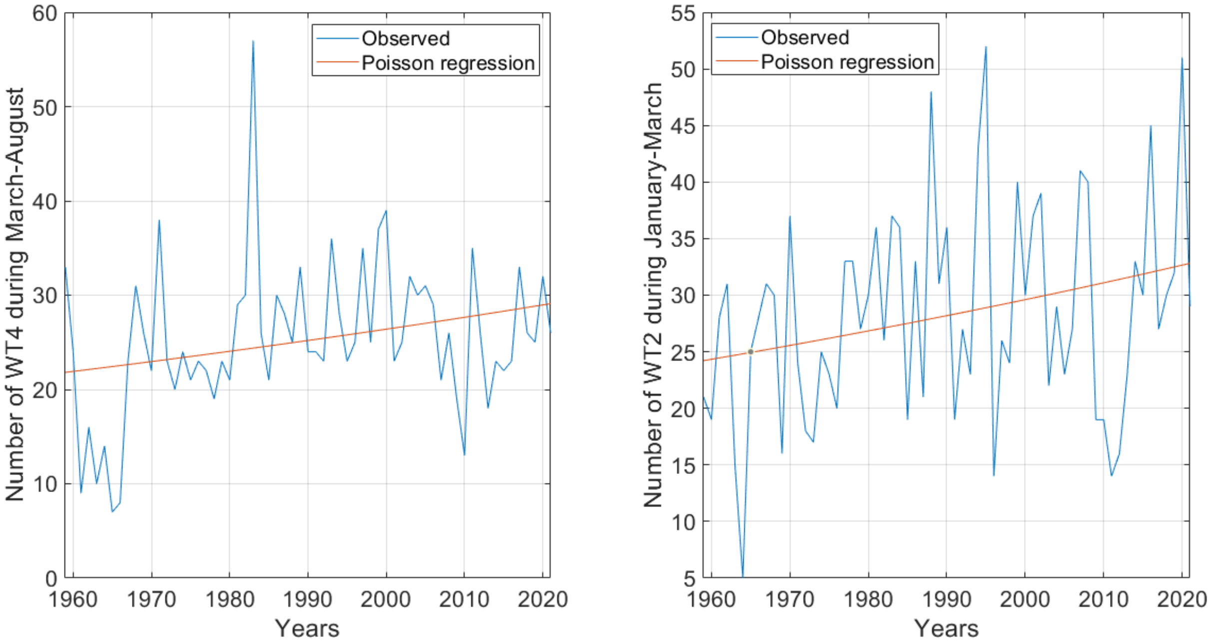

Figure S2: Annual number of weather type 4 (WT4), describing a Southern circulation, in the left panel, and annual number of weather type 2 (WT2), describing a Steady Oceanic circulation, right panel, between 1959 and 2021. The annual counts have been modelled with a Poisson regression, a Generalized Linear Model form of regression that assumes that the response variable has a Poisson distribution. A bootstrap resampling has been applied to compute the 95% confidence interval for the Poisson regression coefficients, verifying that it does not include zero. In addition, the Deviance test that determines whether the model fits significantly better than a constant model has been applied, resulting in pvalues = 7.4791e-04 for the WT4 March-August model and 1.7074e-04 for the WT2 January-March model.

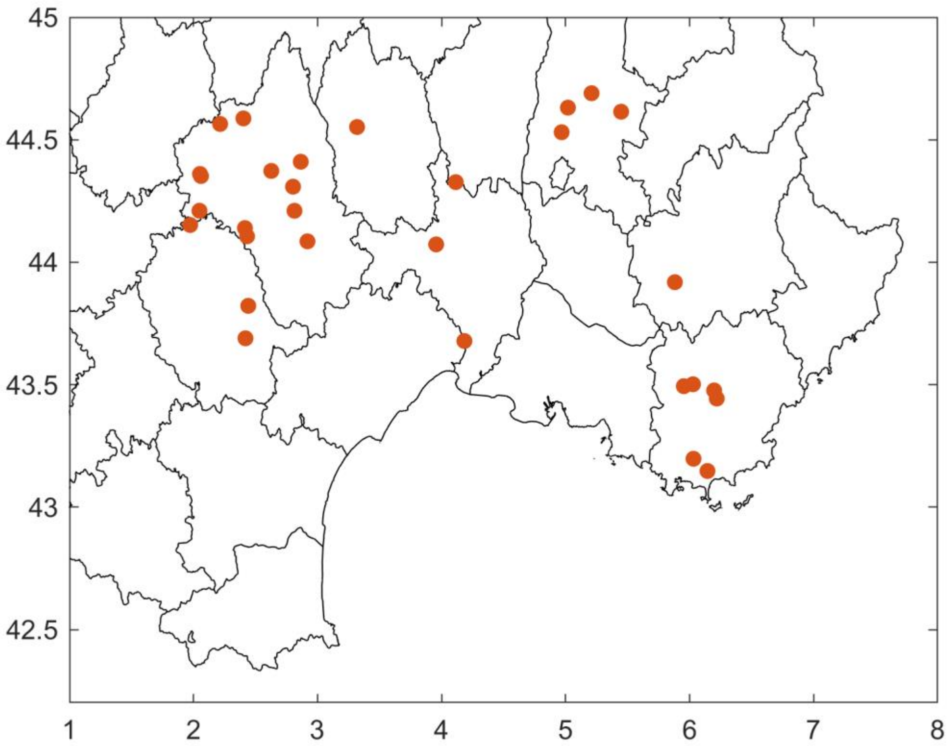

Figure S3: Locations of basins where the relative frequency of excess rain floods is above 80% (30 basins)

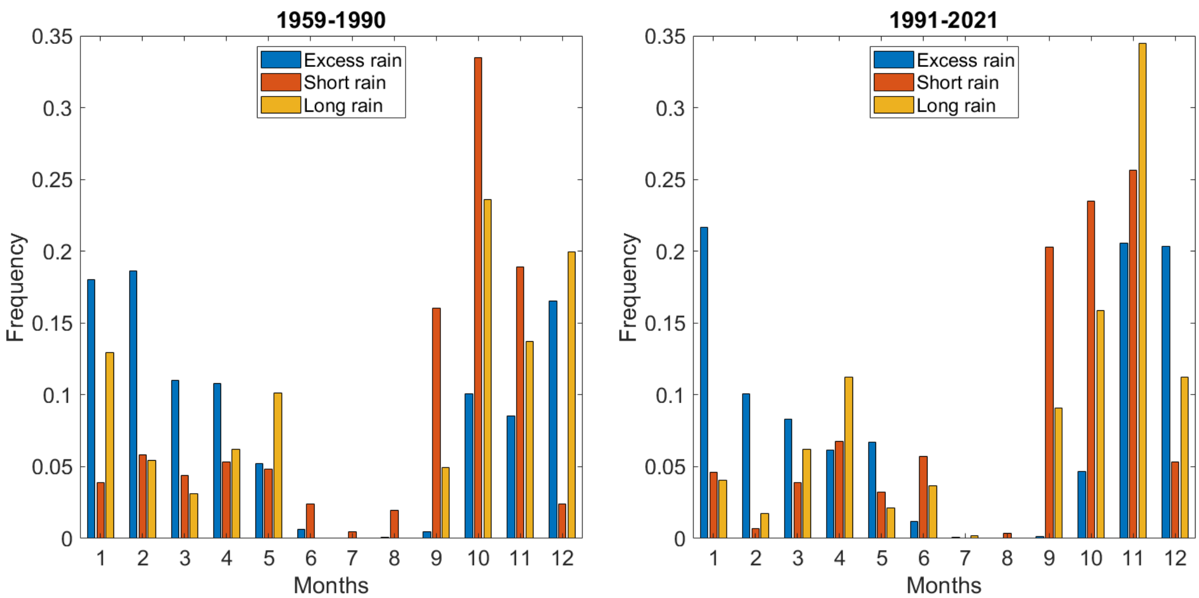

Figure S4: Monthly frequency of flood types between 1958-1990 and 1991-2021

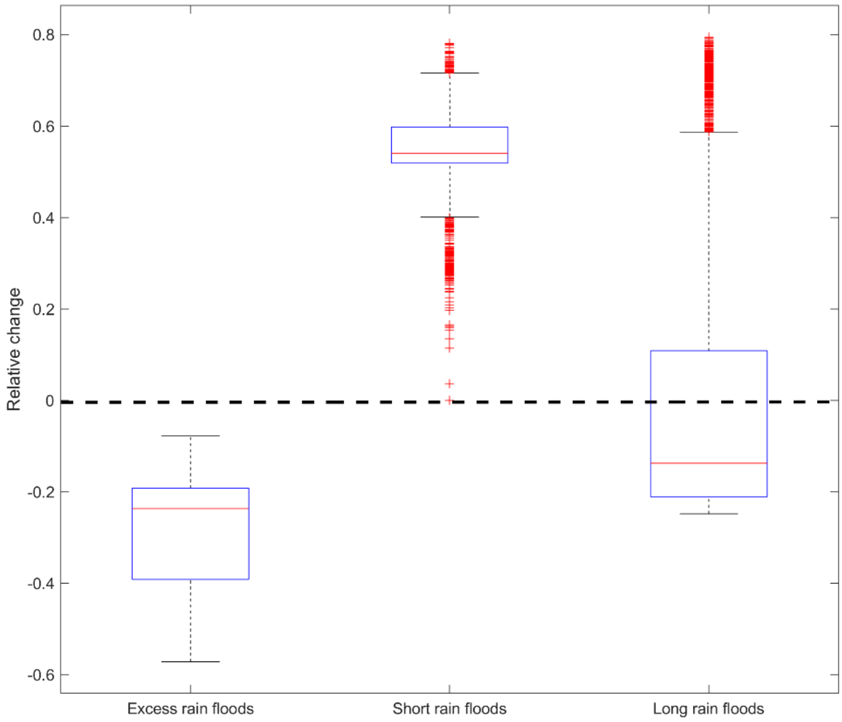

Figure S5: Relative changes in the regional frequency of excess rain floods, short rain floods and long rain floods, given a range of classification thresholds analyzed via a Monte Carlo experiment (using 5000 experiments with these threshold ranges: Extreme rainfall [0.7 1], Soil Wetness Index [0.4 1]). For each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the 99% of the data and the 1% outliers are plotted with the '+' marker symbol.

Table T1: List of selected catchments

Name	Station code	Longitude (wgs84)	Latitude (wgs84)	Catchment area (km²)
LArdeche à Pont-de-Labeaume	V5004010'	4.30	44.66	424.529
LArdeche à Vogué	'V5014010'	4.41	44.56	891.224
LAltier à Altier [La Goulette]	'V5046610'	3.89	44.46	152.605
LARDECHE à SAINT-MARTIN-DARDECHE [SAUZE-ST-MARTIN]	'V5064010'	4.54	44.32	3195.527
Le Toulourenc à Malaucene [Veaux]	'V6035010'	5.21	44.21	249.189
Le Lauzon à Villeneuve	'X1335010'	5.88	43.92	218.244
LAsse à Beynes [Chabrieres]	'X1424010'	6.25	44.02	520.52
La Têt [partielle] à Perpignan	'Y0474030'	2.89	42.71	1864.007
LAgly à Estagel [Mas de Jau]	'Y0664040'	2.72	42.78	1245.183
Le Fresquel à Villepinte	'Y1314010'	2.08	43.28	323.193
LORB à VIEUSSAN	Y2554010'	2.98	43.54	1313.918
Le Vidourle à Marsillargues	'Y3464010'	4.18	43.68	1127.742
LArgens à Carces [aval]	'Y5112010'	6.20	43.48	1599.405
La Siagne à Pégomas	'Y5534030'	6.93	43.59	598.008
Le Langouyrou à Langogne	'K2064010'	3.86	44.73	99.061
La Clamouse à Chastanier	'K2134010'	3.77	44.73	62.547
Le Blau à Chalabre	'O1464010'	2.02	42.98	92.565
La Goudech à Saint-Maurice-de-Ventalon [La Cépede]	'O3006710'	3.79	44.34	14.136
Le Tarn au Pont-de-Montvert [Fontchalettes]	'O3011010'	3.76	44.36	82.782
Le Rieumalet au Pont-de-Montvert	'O3015520'	3.75	44.37	116.304
Le Tarn à Bédoues [Cocures]	'O3031010'	3.62	44.35	300.528
Le Brianaon aux Bondons [Cocures]	'O3035210'	3.61	44.36	36.848
Le Tarnon à Florac	'O3064010'	3.60	44.31	189.175
La Mimente à Florac	'O3084320'	3.61	44.32	157.23
Le Tarn à Montbrun [Pont de Montbrun]	'O3121010'	3.49	44.34	865.888
Le Tarn à Mostuéjouls [La Muse]	'O3141010'	3.23	44.22	1404.289
La Breze à Meyrueis	'O3165010'	3.44	44.18	42.316
La Jonte à Meyrueis [aval]	'O3194010'	3.43	44.18	136.271
La Dourbie à Dourbies [Le Mazet-récent]	'O3314010'	3.46	44.07	61.705
La Dourbie à Nant [Pont de Gardies]	'O3364010'	3.29	44.08	629.914
Le Tarn à Millau [2]	O3401010'	3.07	44.09	3170.058
La Muze à Montjaux [Saint-Hippolyte]	'O3454310'	2.92	44.09	159.495
LAgout à Fraisse-sur-Agout	O4102510'	2.81	43.62	29.801
Le Gijou à Vabre [Rocalé]	'O4194310'	2.42	43.69	289.605
Le Dadou à Paulinet [Saint-Jean-de-Jeanne]	'O4704030'	2.44	43.82	49.003
Le Serre à Coussergues [Resuenhe]	'O5055010'	2.86	44.41	36.123
LAveyron à Onet-le-Chateau [Rodez]	'O5092520'	2.63	44.37	709.266
LAveyron à Villefranche-de-Rouergue [Recoules]	'O5192520'	2.06	44.35	1372.823
LAlzou à Villefranche-de-Rouergue [barrage Cabal]	'O5224010'	2.05	44.36	292.046
La Serene à Saint-André-de-Najac [Canabral]	'O5284310'	2.05	44.21	148.873
LAveyron à Laguépie [1]	'O5292510'	1.97	44.15	2165.787
Le Viaur à Arques	'O5312910'	2.80	44.31	180.512
Le Vioulou à Salles-Curan [Trébons-Bas]	'O5344010'	2.81	44.21	80.503

Le Céor à Centres [Lestrebaldie]	'O5424010'	2.41	44.14	234.279
Le Giffou à Saint-Just-sur-Viaur [La Fabreguerie]	'O5464310'	2.43	44.11	222.379
Le Bramont à Saint-Bauzile [Les Fonts]	'O7035010'	3.48	44.47	131.761
Le Lot à Balsieges [Bramonas]	'O7041510'	3.42	44.49	678.166
Le Coulagnet à Marvejols	'O7085010'	3.32	44.55	114.106
Le Lot à Banassac [La Mothe]	'O7101510'	3.20	44.44	1659.843
Le Dourdou à Conques	'O7874010'	2.40	44.59	818.424
Le Rieu-Mort à Viviez [2]	'O7944020'	2.21	44.56	271.221
La Drôme à Luc-en-Diois	'V4214010'	5.45	44.61	278.286
La Drôme à Saillans	'V4264010'	5.21	44.69	1633.187
Le Roubion à Soyans	'V4414010'	5.02	44.63	294.712
Le Jabron à Souspierre	'V4455010'	4.97	44.53	191.256
Le Borne à Saint-Laurent-les-Bains [Pont de Nicoulaud]	'V5045810'	3.96	44.58	85.973
La Gagniere à Gagnieres [Bannes]	'V5425210'	4.11	44.33	71.836
La Ceze à la Roque-sur-Ceze	'V5474010'	4.52	44.21	1473.942
LOuveze à Vaison-la-Romaine	'V6052010'	5.07	44.24	852.264
LAuzon à Mormoiron	'V6125010'	5.19	44.06	145.033
Le Gardon de Sainte-Croix à Gabriac [Pont Ravagers]	'V7115010'	3.72	44.19	68.229
Le Gardon de Mialet à Générargues [Roucan]	'V7124010'	3.96	44.08	353.838
Le Gardon de Saint-Jean à Corbes [Roc Courbe]	'V7135010'	3.96	44.07	362.303
LAsse à Beynes [Chabrieres]	'X1424010'	6.25	44.02	520.52
Le Coulon à Saint-Martin-de-Castillon [Coste Raste]	'X3434010'	5.52	43.85	483.142
La Baillaury à Banyuls-sur-Mer	'Y0105210'	3.11	42.47	35.046
La Massane à Argeles-sur-Mer [Mas den Tourens]	'Y0115410'	2.99	42.53	17.363
Le Mondony à Amélie-les-Bains-Palalda	'Y0245210'	2.67	42.47	39.454
LAmple à Reynes [Le Vila]	'Y0255020'	2.70	42.50	63.686
La Canterrane à Terrats [Moulin den Canterrane]	'Y0325010'	2.74	42.60	46.208
LAgly à Saint-Paul-de-Fenouillet [Clue de la Fou]	'Y0624020'	2.51	42.81	238.068
Le Verdouble à Tautavel	'Y0655010'	2.74	42.81	476.468
La Berre à Villeseque-des-Corbieres [Ripaud]	'Y0824010'	2.84	43.04	251.709
Le Treboul à Villepinte	'Y1325010'	2.07	43.28	231.692
La Clamoux à Malves-en-Minervois	'Y1416210'	2.44	43.26	96.078
LArgent Double à la Redorte [Les Salices]	'Y1435410'	2.62	43.27	198.79
LOrbieu à Luc-sur-Orbieu	Y1564010'	2.78	43.18	825.161
LArre au Vigan [La Terrisse]	'Y2015010'	3.66	44.00	218.422
La Vis à Saint-Laurent-le-Minier	'Y2035010'	3.68	43.94	712.973
LHérault à Laroque	'Y2102010'	3.70	43.92	1295.549
La Lergue à Lodeve	'Y2214010'	3.32	43.73	245.37
La Mare au Pradal	'Y2525010'	3.11	43.63	163.555
Le Lez à Montferrier-sur-Lez [Lavalette]	Y3204010'	3.87	43.65	178.515
LArc à Pourrieres	'Y4002010'	5.73	43.49	68.023
LArc à Meyreuil [Pont de Bayeux]	'Y4022010'	5.52	43.50	425.522
Le Gapeau à Sollies-Pont	'Y4604020'	6.03	43.20	275.32
Le Réal Martin à la Crau [Decapris]	'Y4615020'	6.11	43.19	379.106
Le Gapeau à Hyeres [Sainte-Eulalie]	'Y4624010'	6.14	43.15	480.707
Le Cauron à Bras [Pont de lAvocade]	'Y5005210'	5.95	43.49	198.59

LArgens à Chateauvert	'Y5032010'	6.03	43.50	714.003
Le Caramy à Vins-sur-Caramy [Les Marcounious]	'Y5105010'	6.17	43.44	284.139
LIssole à Cabasse [Pont des Fées]	'Y5106610'	6.22	43.44	337.121
LAille à Vidauban [Le Baou]	'Y5215020'	6.43	43.40	243.538
La Nartuby à Trans-en-Provence	'Y5235010'	6.48	43.51	261.951
La Môle au Lavandou [Destel]	'Y5435010'	6.44	43.20	60.051
Le Grenouiller à Saint-RaphaÔö£?¢l [Agay]	'Y5505410'	6.85	43.44	62.658
Le Loup à Tourrettes-sur-Loup [Les Vallettes]	'Y5615010'	7.01	43.70	274.138
Le Loup à Gourdon [Loup amont]	'Y5615020'	6.98	43.71	38.889