Hydrological classification of non-perennial Mediterranean rivers and streams: a new insight for their management within the WFD

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July 6, 2022

Abstract

Classification of natural flow regimes of non-perennial rivers and streams (NPRS) is an incipient field of research. NPRS represent approximately 70% of the total Mediterranean rivers and are expected to increase in the next decades as a result of climate change. Due to the ecological importance of NPRS and the need to improve national ecological assessment methods within the scope of the Water Framework Directive (WFD), this paper aims to classify the hydrological regime of 69 non-regulated streams, testing several hydrological indices related to the frequency, duration, timing, and rate of change in periods of flow cessation. Using daily flow records, a total of 315 indices were calculated and their relationships were examined with Principal Component Analysis (PCA) for different thresholds used to define zero-flow condition set at 0, 1, 2, and 5 l/s. Redundancy analysis identified five indices that better describe the patterns of hydrological variability in Mediterranean NPRS: number of days per year without flow, annual percentage of months without flow, mean daily of annual flows, coefficient of variation of Julian date of the annual start of zero flow and annual rise rate. Using these indices, a self-organizing map (SOM) was trained in order to categorize the NPRS into three groups with similar hydrological features. The results of this study provide a statistically-based hydrological classification of NPRS in Mediterranean environments. We expect that this classification will provide useful insights to water authorities to improve the assessments of the ecological status in this set of water bodies.

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Short title

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Funding information

Ministry for the Ecological Transition and the Demographic Challenge. Grant/Award Number: 21.834-060/0411

Acknowledgements

This research is based on project "Monitoring the effect of the ecological regime of flows established by the river basin management plans on the water bodies (21.834-060/0411)" provided by The Spanish Ministry for the Ecological Transition and the Demographic Challenge (MITECO) - DG Water. We also thank Rafael Muñoz-Mas for his help with the methodology and graphics.

Abstract

Classification of natural flow regimes of non-perennial rivers and streams (NPRS) is an incipient field of research. NPRS represent approximately 70% of the total Mediterranean rivers and are expected to increase in the next decades as a result of climate change. Due to the ecological importance of NPRS and the need to improve national ecological assessment methods within the scope of the Water Framework Directive (WFD), this paper aims to classify the hydrological regime of 69 non-regulated streams, testing several hydrological indices related to the frequency, duration, timing, and rate of change in periods of flow cessation. Using daily flow records, a total of 315 indices were calculated and their relationships were examined with Principal Component Analysis (PCA) for different thresholds used to define zero-flow condition set at 0, 1, 2, and 5 l/s. Redundancy analysis identified five indices that better describe the patterns of hydrological variability in Mediterranean NPRS: number of days per year without flow, annual percentage of months without flow, mean daily of annual flows, coefficient of variation of Julian date of the annual start of zero flow and annual rise rate. Using these indices, a self-organizing map (SOM) was trained in order to categorize the NPRS into three groups with similar hydrological features. The results of this study provide a statistically-based hydrological classification of NPRS in Mediterranean environments. We expect that this classification will provide useful insights to water authorities to improve the assessments of the ecological status in this set of water bodies.

Keywords

Non-perennial rivers and streams, intermittent rivers and ephemeral streams, IRES, hydrological classification, Mediterranean region, SOM.

Practitioner Points

- Natural flow regimes of non-perennial Mediterranean rivers and streams (NPRS) are classified using hydrological indices related to their frequency, duration, timing, and rate of change in periods of flow cessation
- Five indices describe the patterns of hydrological variability in Mediterranean NPRS: number of days per year without flow, annual percentage of months without flow, mean daily of annual flows, coefficient of variation of Julian date of the annual start of zero flow and annual rise rate
- Self-organizing map (SOM) categorize the NPRS into three groups with similar hydrological features. This classification is compared with others existing within the European Union. The similarities and differences are discussed to provide useful information for the development of specific assessment and management tools within the scope of the WFD

1. Introduction

Depending on the occurrence of flow or no flow periods of the natural flow regime, rivers could be classified into perennial or non-perennial. Although many terminologies have been used over time subject to research fields (e.g., arid, discontinuous, dry, ephemeral, episodic, intermittent, interrupted, irregular, non-permanent, seasonal, or temporary rivers), the term "non-perennial rivers and streams" (hereafter NPRS) refers to watercourses that cease to flow at the same point in time or space. Their defining characteristic is a temporary lack of surface flow, which leads to isolated pools or dry channels .

According to some estimates, these water bodies comprise at least 41% of the length of the global fluvial network . This percentage would increase in some regions of Africa, America, Australia, and Europe , depending on regional factors and local characteristics . Such is the case of the Mediterranean region, which includes temperate, semiarid or arid climates, where NPRS could represent 69% of the total length of the river network . This is because they are concentrated in the upper reaches of the basins with small drainage areas and steep slopes leading to a rapid delivery of water to the river channel, causing a lack of buffering from variations in precipitation . Considering that the future effects of global change (such as climatic and land use changes, impoundments, and increasing human water demands) are expected to be particularly severe in these freshwater ecosystems, the length and number of NPRS in the Mediterranean region is expected to increase over the next decades . As a consequence, non-perennial rivers have progressively received wider interest by water resource managers and the scientific community .

Recent studies in NPRS have advanced in characterizing geomorphological processes , biological communities , water quality , biogeochemical fluxes , status assessment and river management . All these studies highlight the importance of the different flow regime patterns (including the specific duration of the wet and dry phases) for biota and environmental processes in non-perennial freshwater systems. This is more evident in Mediterranean climate regions, as they are shaped by predictable seasonal events of flooding and drying over an annual cycle, with a strong inter- and intra-annual flow variation . The variability in the flow regime takes on a wide range of possibilities in terms of duration, frequency, and timing of the zero-flow periods, and rates of change between flowing and non-flowing conditions . The structure and functioning of each NPRS is historically adapted to the specific non-perennial flow patterns, which act as a major driver of their ecomorphological dynamics . The particular features of the components of non-perennial flow regimes also affect the human uses linked to the NPRS, enhancing a variety of socio-ecological non-perennial river systems, under distinctive biophysical contexts . Thus, ecological assessment methods of NPRS to evaluate the current status and historical trajectory of non-perennial freshwater systems require an advanced understanding of the flow-ecology responses . An improved understanding of the interaction among human uses, pressures, impacts, and responses of NPRS, could provide new insights into the most beneficial actions that should be selected to optimize management approaches to them . Indeed, developing knowledge about the dynamics that characterize this type of freshwater ecosystems could help change and improve the perception and attitudes of society towards NPRS . Both the ecological and the societal approaches to study different aspects of NPRS, require further interpretation of the hydrological gradients which characterize such systems. In this line, improving mechanisms to classify natural flow temporality would lead to better-informed management decisions about the NPRS.

The European water policy has been developed by the Water Framework Directive . The WFD states that, in order to evaluate the ecological status, the reference conditions for each type of water body have to be formerly defined. Subsequently, different biological quality elements (e.g. biological indices based on benthic macroinvertebrates assemblages, aquatic flora, and fish fauna) are compared with the reference conditions to establish the ecological status of the water body . However, there are limitations in the implementation of WFD in NPRS, as described by : (1) the establishment of a water body in the case of NPRS (a river stretch to be included in the river basin management plans) could be omitted due to their small catchment area or their limited annual discharge, and (2) the classification of river typologies considering the hydrological variability of NPRS is obviated due to the scarcity of hydrological data sets characterizing natural flow conditions. The aforementioned challenges have limited the capacity of EU member states to define both legally and technically non-perennial river typologies.

In the case of Italy or Spain, representative examples of Mediterranean climate conditions, despite the relative wide proportion of non-perennial rivers in their drainage network, there are no official studies aimed at classifying temporary flow patterns . In these countries, water authorities have used time thresholds (e.g., average number of days or months with no-flow), approved by legislation , to distinguish between temporary, intermittent, ephemeral and episodic river waterbodies. These thresholds were proposed based on initial assessments of flowing periods, on expert judgement or on external references instead of systematic analyses of continuous non-perennial flow gradients that could drive to statistically-based typologies (e.g., . Thus, the classification approach currently used by water managers faces several uncertainties. First, the best potential threshold to define the no-flow condition. Second, the suitability of defining specific non-perennial flow classes. Finally, the connection of types of non-perennial flows with ecological assessment methods for the optimization of restoration measures to mitigate the negative impacts derived from human activities.

In order to bridge the existing gaps in ecological assessment tools for NPRS, the ECOSTAT working group of the European Commission is currently working on a common standpoint to characterize, evaluate, manage, and monitor NPRS . With the purpose of developing a common method to analyse the ecological status of NPRS in the EU, research projects such as MIRAGE (https://cordis.europa.eu/project/id/211732), GLOBAQUIA (http://www.globaqua-project.eu/), LIFE+ TRivers (http://www.lifetrivers.eu/), and SMIRES (https://www.smires.eu/) have recently provided new insights into the functioning of this type of freshwater ecosystems. MIRAGE project started, for the first time, the study of temporal responses of rivers to hydrological, biogeochemical, and sediment transport events for the implementation of the WFD and specific management under the characteristics of flooding and drought of temporary streams. GLOBAQUA is an EU-funded project aiming to identify the prevalence and interaction between stressors under water scarcity, in order to improve water management practices and policies in rivers, including NPRS. The LIFE+ TRivers project provided the European river basin authorities a software (TREHS) to evaluate temporary river regimes as a first step for their ecological status assessment defined by the WFD in the NPRS. Finally, the SMIRES project was a COST Action that established a multidisciplinary network of scientists and experts from 32 countries, to consolidate and expand knowledge on NPRS and translate it into sustainable and science-based management of NPRS resources and biodiversity.

Stemming from these efforts, this study aims at providing a statistically-based classification of non-perennial flow patterns in rivers and streams of the Western European Mediterranean region. This region offers an interesting test bed for this analysis for at least two reasons. First, due to the relative abundance of dryland areas and NPRS. Second, due to the lack of homogeneous criteria for their hydrological classification. Specifically, this study assesses natural flow patterns of unaltered non-perennial rivers focusing on hydrological metrics related to the frequency, duration, timing, and rate of change in periods of flow cessation. We hypothesized that non-perennial Mediterranean rivers and streams can be classified according to a few hydrological attributes since many of them are redundant in reflecting inter- and intra-annual flow variability . We also hypothesized that there is a similar relationship among different thresholds to define zero-flow conditions (0, 1, 2, and 5 l/s). Linked to previous efforts in the UE to characterize ecological conditions of NPRS, we expect that the hydrological classification obtained in this study will provide useful insights to water authorities to improve the assessment of the ecological status in this set of water bodies.

2. Material and methods

2.1. Study area

The study area includes 69 rivers from 15 basins located in southern France, Spain, and Portugal covering most of the western part of the European Mediterranean region (Fig. 1). Briefly, rivers of France are located on 4 temporary tributaries of the Rhone-Mediterranean basin district, very close to the Mediterranean Sea. In Spain, we studied 44 rivers, of which 16 are located in river basin districts that flow into the Mediterranean Sea (Catalonian, Ebro, Jucar, Segura and Andalusian Mediterranean basins) and 28 into the Atlantic Ocean (Tagus, Guadiana, Guadalquivir, Guadalete and Barbate basins). The 21 stations of Portugal drain into the Atlantic Ocean and belong to Guadiana, Algarve, Sado, Mira, Vouga, Mondego, Lis, Douro, Cavado, Ave and Leca river basin districts.

In natural conditions, all the rivers in these basins present a Mediterranean flow regime pattern, which implies two alternate periods: a high-flow period during the wet season (i.e. autumn to winter) and a low-flow period during the dry season (i.e. late spring and summer). However, the basins under study cover a large geographical area representing a wide gradient of climatic, topographic and geologic conditions which imply notable differences in hydrological regimes. The climate is mostly temperate although there are stations located in semi-arid regions of southern Spain. According to the Koppen-Geiger classification, the studied NPRS are matched with hot (Csa), warm (Csb), or cool (Csc) summer Mediterranean climate, and hot (BSh) or cold (BSk) semi-arid climate . Although the climate has a common pattern with mild and wet winters, and dry, hot, or cold summers, there are differences in the range of precipitation and temperature. The land use in the studied basins is dominated by agriculture, originated by the use of human society on the natural environment . The rivers and its stream tributaries are heavily regulated by the construction of dams and weirs, which have substantially altered the natural flow regime also reducing the number of unaltered gauging stations with flow data records .

(Here Fig. 1)

2.2. *Hydrologic data*

We used daily flow records from gauging stations in NPRS minimally impacted by human activities. Due to the lack unaltered stations with adequate data in Mediterranean NPRS , we assumed that most of them contained missing data (Table A1). The selection of NPRS in almost natural conditions implied avoiding hydrological alteration, deviation, or cessation of water due to transverse barriers (large dams or smaller weirs) located upstream. Data records were obtained from different sources. In Spain, they were obtained from the national database of public gauging stations of CEDEX (Centre for Hydrographic Studies; https://ceh.cedex.es/), or from the corresponding River Basin Authority. For this purpose, we first identified gauging stations without altered flow conditions using the national inventory of barriers on non-perennial rivers (available at https://sig.mapama.gob.es/geoportal). In France and Portugal, stations were obtained from SMIRES project database (https://www.smires.eu/). To identify those gauging stations in NPRS near to natural conditions, we used the AMBER barrier Atlas (https://amber.international/european) and hydrological pressures collected in the European WISE database (*www.eea.europa.eu/data-and-maps/data/wise-wfd-4*). The Supporting Information of Table A1 expands the information about the stations such as river basin where are located, country, coordinates, gauging station code, the length of the data period, the number of days of the data series and the number of days with missing data.

Gauging stations with more than 15 years of daily flow records were used, except one with 11 years in the Tagus basin in Portugal (Table A1). The median length of the data period was 36 years (IQR=26-43 years). All the series were validated for the calculation of zero-flow hydrological indices with *smires* package (https://github.com/mundl/smires). For each station we calculated a set of 315 hydrological indices that have been previously referred in other studies focused on perennial rivers (Eng et al., 2017; Olden and Poff, 2003), drought events in NPRS (Costigan et al., 2017; Delso et al., 2017) and low river flows (Henriksen et al., 2006; Kennard et al., 2010). Following Richter et al. (1996), the indices were classified into five groups characterizing hydrological conditions related to: (i) magnitude, (ii) frequency, (iii) duration, (iv) timing, and (v) rate of change of flow or drought events. A list of the calculated indices and their main characteristics is shown in Appendix B.

Finally, the hydrological indices were encoded for calculation with the*R* programming language . We used the *lfstat* package to calculate the number and duration of zero flow events. The*hydrostats* package was used for calculating the Colwell's index of predictability and seasonality , and the rate of change in the magnitude of the flow and the asymmetry (skewness) of the hydrological series. In order to calculate the indices, three conditions were adopted. First, all years of the series have been used, even those with incomplete records. Second, the hydrological year was set at the beginning of the Julian calendar year. Third, we defined different thresholds to define the days without daily flow at 0, 1, 2, and 5 l/s. This is due to false positives of null flows associated with the restrictions and uncertainties of the measurement of days without flow in gauging stations of NPRS .

2.3. *Hydrologic classification for non-perennial Mediterranean rivers and streams*

We used principal component analysis (PCA), an unsupervised learning statistical technique, to examine the relationships between the hydrological indices. Given the strong correlation between hydrological indices , we also utilized PCA to reduce the dimensionality by selecting prominent metrics for each attribute . Correlation matrices were used to equalize the contribution of the indices to the PCA regardless of the scale

. Following the PCA analysis, we selected indices with the highest loading coefficient (in absolute terms) associated to the five first components that accounted for approximately 70% of the total inertia for each of the zero-flow thresholds . Specifically, we reduce by more than half the hydrological indices with the loading coefficient, but it was not enough to choose the indices of each attribute that best define the hydrological pattern of NPRS and respond to the diversity of Mediterranean temporary flows. Thus, we decided to select one index for each attribute (magnitude, frequency, duration, timing, and rate of change) based on expert criteria and supported by statistical analysis. Here, we used both the repetition of the indices at each threshold with the highest loading coefficient associated (in absolute terms) to the first five PCA dimensions and hierarchical clusters based on the correlation distance for each group of selected indices with PCA of each attribute (Appendix C). PCAs and clusters were executed with the*FactoMineR* package .

Self-Organizing Maps (SOM) were used to classify temporal rivers into hydrological types according to similarities with the selected indices. SOM is an unsupervised machine learning technique that uses an artificial neural network to reduce multidimensional data into two-dimensional nodes heatmap. This is an interactive process that assigns a weight to each node on the map where the minimum similarity distance is chosen and the neighbourhood of the nodes is established. We followed the rule proposed by to determine the optimal dimension of the number of nodes in the map. The nodes must be close to 5[?]n where n is the number of samples analysed (in this study n=345). Consequently, our map should have approximately 93 nodes distributed by a layer of 9 rows x 10 columns. Additionally, we also evaluated the quality of the maps by means of quantization and topographic error of different layers (from 2 x 2 to 10 x 10). To identify clusters on the SOM output map and draw the boundaries, we applied a hierarchical cluster. The optimal number of clusters for a SOM output was determined using *NbClust* package in R , whereas SOM analysis and its graphical representation were generated with the *Kohonen* package .

2.4. *Comparing methods for Mediterranean non-perennial rivers and streams classification*

Finally, we compared the relationship of our results with three other hydrological classifications developed for Mediterranean rivers. Firstly, we used the classification of the Ministerial Order for Hydrological Planning of the Spanish legislation that classifies rivers into four categories depending on the number of days with presence of water throughout the year: (i) permanent river courses if water flows every day of the year, (ii) temporal river courses with presence of water during an average period of 300 days per year, (iii) intermittent with water flowing between 100 and 300 days per year, and (iv) ephemeral flowing less than 100 days per year. Secondly, we classified rivers following the Italian legislation depending on the number of months with presence of water in: (i) temporal river courses without presence of water for at least 2 of the last 5 years, (ii) intermittent with more than 8 months with water, (iii) ephemeral with less than 8 months with water, and (iv) episodic with water only after heavy precipitation events. Last, we applied the classification developed by LIFE+ TRivers project to evaluate the hydrological flow regime in NPRS according to the aquatic phase on biological communities . This classification is provided by TREHS free software tool and comprises four aquatic regime types or hydrotypes classification: permanent or perennial, intermittent-pools, intermittent-dry, and episodic or ephemeral. To carry out the comparison between the different classifications, we conducted an alluvial plot with *ggalluvial* and *circlize*package.

3. Results

3.1. Redundancy index analysis

A total of 315 hydrological indices of magnitude, frequency, duration, timing, and rate of change have been calculated which characterize the hydrological series in NPRS for different periods of the year (Table A3). The PCA showed an inertia ranging between 36.2 and 38.0% for the first axis and between 16.3 and 16.9% for the second (Fig. 2), reaching approximately 70% when grouping the first five components for the thresholds of 0, 1, 2, and 5 l/s. Results revealed multiple linear correlations between indices. It is also noted that the indices of frequency and duration of zero flow had a positive correlation with the first axis, while flow magnitude had a positive correlation association with the second (Fig. 2).

(Here Fig. 2)

Additionally, the first indices with the highest loading coefficient associated with the first, second and third dimensions were frequently the same, only changing for the fourth and fifth dimensions for the different thresholds (Table C1). Consequently, only 171 indices were selected for the redundancy index analysis based on clusters with correlation distance between hydrological indices within the same attribute (magnitude, frequency, duration, timing and rate of change) in different thresholds (Table C1 and Fig. C2 to Fig. C7). As a result of the dimensionality reduction and the redundancy analysis, five hydrologic indices were selected: number of days per year without flow (DU035), annual percentage of months without flow (FE052), mean daily annual flows (MA001), CV of Julian date of the annual start of zero flow (TI002) and annual rise rate (RC001) (Table 1).

(Here Table 1)

3.2. Hydrologic classification for non-perennial Mediterranean rivers and streams

The optimized SOM with minor quantization and topographic errors included a grid of 3 x 8 nodes. Fig. 3 shows maps gradually distributed according to the five selected hydrological indices, thus the gauging stations with similar characteristics are located into the same node and remain close to other neighbourhood nodes in a two-dimensional heatmap. As a consequence of applying the cluster classification, the maps show two boundaries that divide the maps into three zones, grouping the stations into three clusters (I, II and III). For example, gauging stations with high values of number of days per year without flow are shown in yellow and located in the lower part of the map, while low values are represented in blue in the upper part of the map. The same occurs with the annual percentage of months without flow and coefficient of variation of Julian date of annual start of zero flow. In contrast, gauging station with low values of the mean daily annual flow are located in the upper area of the map.

(Here Fig. 3)

With regard to cluster classification, Fig. 4 represents the groups obtained by training a SOM with the five selected variables whereas table 2 shows the main characteristics of each cluster. Cluster I is composed of gauging stations with high values of number of days per year without flow (231.45 +- 97.07 days/year, see Fig. 4 and Table 2), annual percentage of months without flow (76.87 +- 23.52%), CV of Julian date of annual start of zero flow (2.23 +- 0.92), and annual rise rate (3.69 +- 6.19 l/day). It also included rivers with low values of mean daily annual flow (0.53 +- 0.70 l/day). Cluster II is an intermediate group between the other two clusters. It displayed mean values between 144.14 +- 54.40 days/year for the number of days per year without flow and 47.32 +- 15.23% for the annual percentage of months without flow. It also exhibited values of 0.72 +- 0.65 l/day for mean daily annual flow, 0.63 +- 0.27 for CV of Julian date of the annual start of zero flow, and 2.00 +- 1.98 l/day to annual rise rate. In contrast, cluster III included rivers with low values of number of days per year without flow (24.57 +- 25.68 days/year), annual percentage of months without flow (11.25 +- 10.09%), Julian date of annual zero flow (0.25 +- 0.17), and annual rise rate (1.35 +- 1.72 l/day), but with high values of mean daily annual flow (2.06 +- 3.80 l/day).

(Here Table 2)

(Here Fig. 4)

3.3. Comparison of classifications for Mediterranean non-perennial rivers and streams

The alluvial diagram for Mediterranean NPRS reveals differences between MATTM, IPH and LIFE+ TRivers hydrotypes classifications and the three clusters obtained in this study (Fig. 5). Cluster I is represented by 9% of the stations, compared to 41% in cluster II and 51% in cluster III regarding our SOM classification. Using the MATTM classification, most stations are intermittent rivers (87%), followed by ephemeral (10%) and episodic (3%). Using the IPH classification, most are temporal (62%), followed by intermittent (35%) and ephemeral (3%). Applying the hydrotypes of the LIFE+ TRivers project, 19% of the stations are of episodic type, 1% of intermittent-dry, 61% of intermittent-pools, and 19% of perennial.

(Here Fig. 5)

Additionally, figure 6 shows the relationships between the categories of the different classifications. Cluster I is composed of equal parts (33%) of ephemeral, episodic and intermittent rivers, cluster II by ephemeral (18%) and intermittent (82%) and cluster III only by intermittent (100%) in MATTM classification. Similarly, cluster I is represented by ephemeral (33%), intermittent (50%), and temporal (17%); cluster II by intermittent (75%), and temporal (25%) and cluster III only by temporal (100%) rivers in the IPH classification. Besides, cluster I is mainly represented by episodic hydrotypes (33%), intermittent-dry (17%), and intermittent-pools (50%), cluster II by episodic (25%), intermittent-pools (71%), and perennial (4%), and cluster III by episodic, intermittent-pools, and perennial (11, 54, and 34%, respectively). Also, 100% of episodic and ephemeral rivers on MATTM are ephemeral and intermittent rivers on IPH, respectively. In contrast intermittent rivers of the MATTM are intermittent (29%) or temporal (71%) in IPH classification. Moreover, 100% of the episodic type of MATTM are also episodic of hydrotype classification, but varies for the rest of the types due to the ephemeral rivers on MATTM may be episodic (29%), intermittent-dry (14%) or intermittent-pools (57%) and intermittent rivers on MATTM may be episodic (15%), intermittent-pools (63%) or perennial rivers (22%). Finally, 100% of the ephemeral type of IPH is also episodic of hydrotypes TRivers classification. However, intermittent types are 25% episodic-type, 4% intermittent-dry, 70% intermittent-pools versus temporal types that are 12% episodic-type, 58% intermittent-pools, and 30% perennial.

(Here Fig. 6)

4. Discussion

Hydrological classification is a fundamental tool for the ecological status assessment of WFD by water managers. The main objective of this study was to develop a classification with relevant hydrological indices in order to categorize non-perennial rivers and streams (NPRS) of the western Mediterranean region. Using unaltered streamflow data, our analysis suggest that the natural flow regimes of NPRS can be characterized through the selection of a few indices from a wide set of attributes of duration, frequency, magnitude, seasonality, and rate of change of periods of flow cessation . The results highlighted the strong correlation between variables for the different thresholds used to define zero-flow condition set at 0, 1, 2, and 5 l/s. This means that some variables of a few attributes could envelope the inertia of NPRS flow diversity and be used to classify them. Our analysis of hierarchical clusters (based on the correlation distance matrix of the same attribute) and the repetition of indices at each principal component (for the different thresholds) allowed us to select 5 relevant metrics of different hydrological attributes, such as number of days per year without flow (duration), annual percentage of months without flow (frequency), mean daily annual flows (magnitude), coefficient of variation of Julian date of the annual start of zero flow (timing) and annual rise rate (rate of change). Our SOM classification, developed from a set of 69 gauging stations and the selected 5 hydrological indices, showed three groups associated with the temporality of the flow cessation. However, beyond this hydrological characterization of temporality patterns, there is incomplete development of river typology in the context of WFD to evaluate the relationship between hydrology of NPRS and ecology of biological communities, and there is a need to improve tools to evaluate their ecological status, and integrate the establishment of measures into national legislation. Below, we briefly summarize the methodological considerations of the classification and its relevance to the NPRS management. We also compare it with other existing classifications to analyse further research needs.

4.1. Methodological considerations

As hypothesized, we observed high correlations among the 315 calculated indices. This was particularly evident between metrics that describe duration and frequency and those related to magnitude (Fig.2). This result is not surprising considering the high redundancy and multicollinearity among hydrological variables . As a consequence, statistical techniques for selecting a reduced set of non-redundant indices are necessary to represent the hydrological gradients . In our study, we first selected 171 indices with the highest loading coefficient associated with the first dimension of the PCA (Table C1), and many of them were also correlated (Figs.AC1-AC7). Similar processes to reduce the number of indices have been reported in previous studies for hydrological classifications (e.g., . Considering that PCA analyses provided many indexes for each attribute, we refined the selection using cluster analysis and repetition of metrics in the first 5 dimensions of PCA. However, these results need to be interpreted with caution, since we prioritized the selection of annual indices, such as number of days or percentage of months without flow per year, mean daily of annual flows, coefficient of variation of Julian date of the annual start of zero flow and annual rise rate.

As also hypothesized, our results indicate that the PCA and the correlations between the indices are analogous for all thresholds 0, 1, 2, and 5 l/s to define zero-flow conditions. Similar results were obtained by , who found no significant change in zero-flow indices for thresholds of 1, 2 and 5 l/s. However, they found that upper thresholds (i.e. 10 l/s) were not suitable for characterizing periods of low flow. They applied different thresholds considering that river gauge stations may have different measuring tools and some thresholds may not be ecologically relevant. In fact, described the causes of zero-flow stream gauge measures and their consequences (e.g., ecological status, statistical classification, or hydrological modelling) for understanding hydrology, biochemical, and ecological processes in NPRS.

We found that number of days per year without flow and annual percentage of months without flow (identified in the first dimension of the PCA) contain the greatest degree of variation for all the thresholds used to define zero flow conditions (Table 1). These metrics, related to duration and frequency attributes, express stream drying events and are common to describe the flow temporality . They indicate the unavailability of water during the dry phase and act as an environmental bottleneck for species of these ecosystems . Furthermore, indices of magnitude were found mainly in the second dimension of the PCA. Mean daily annual flows is repeated in all the zero-flow thresholds and has been reported as a major variable for hydrological characterization in perennial rivers . Surprisingly, we found that timing and rate of change attributes were identified in subsequent PCA dimensions; CV of Julian date of the annual start of zero flow in the third dimension and annual rise rate only in the fifth, both described by . Taken together, these results suggest that duration, frequency and magnitude indices (mostly selected in the first and second components) are more important than timing and rate of change indices (selected from the third component). These findings indicate that these attributes were best at predicting the temporal variability on the flows; duration and frequency in the dry phase and magnitude in the wet, reinforcing the importance of these two phases for the structure and composition of the aquatic fauna . However, in this study we have retained at least one metric for each of the five attributes for a better characterization of the variability of the NPRS, both in dry and wet periods, and to facilitate comparison with other available classifications.

4.2. Typology for Mediterranean non-perennial rivers and streams.

In this study, we considered only hydrological indices to categorize Mediterranean NPRS based on statistical criteria. The patterns described by the SOM classification suggest the existence of three groups (clusters I, II, and III) that reflect the interaction between ranges of the five attributes values (Fig.3 and 4, Table2). As expected, cluster I encompasses rivers almost dry during the year with many days and months without flow (usually with an onset of the dry phase in the first months of the year), with low daily flows and high annual rise rate. The cluster II lies between dry rivers (cluster I) and rivers with flows occasionally interrupted by drought (cluster III) with fewer days and months with zero-flow and with combinations of high flows. Our results indicate that the number of days and the percentage of months per year without flow are the most valuable attributes for Mediterranean NPRS classification, since they form well-defined groups. Similarly, CV of Julian date of annual start of zero flow has three compact and differentiated groups, due to that in rivers with no flow during most of the year, the dry periods tend to occur earlier . Conversely, the metrics of mean daily annual flows and annual rise rate (Fig.4) showed less variability, suggesting a lower discrimination capacity, a relationship that has also been shown in other studies .

Similarly to other studies , we included the number of zero-flow days to categorize NPRS. suggests a clear relationship between the duration and frequency of cessation periods for different ecotypes of the Guadiana basin, and other authors classified the NPRS according to the number of days of the dry riverbed as intermittent, ephemeral or episodic. The work by defines intermittent rivers cease seasonally or occasionally the flow (usually for weeks to months), ephemeral streams flow only in response to precipitation or snowmelt events (days to weeks) and episodic streams maintain surface water only during very short periods (hours to days), primarily after heavy rainfall events. In this line, our results are similar to the national legislation of Italy and , where days or months per year without flow are employed to distinguish between permanent, temporal, intermittent, and ephemeral water bodies. For example, in Italy , NPRS are classified according to the number of dry months as intermittent (less than 8 months per year), ephemeral (more than 8 months per year) and episodic (only water circulation after intense precipitation events). In Spain , temporary rivers are defined as those flowing for more than 300 days per year and possible dry periods; intermittent rivers are those flowing between 100 and 300 days per year; and ephemeral rivers are those flowing during less than 100 days per year. Similarly to national legislation, our results indicate three groups (Fig.3 and 4) which we would define as ephemeral rivers (cluster I), intermittent (cluster II), and temporal (cluster III), but we acknowledge notable differences in the range of days and months without flow ranges (Table 2). Apparently, the ranges of our classification are not closed but cluster I (ephemeral) would have more than 181 days or 7 months (59.6%) with zero-flows, while cluster II (intermittent) between 100 and 187 days or between 4 (35.8%) and 7 (56.3%) months without flow, and cluster III (temporal) with less than 46 days and 2 (20.0%) months with zero-flows. As far as we know, this is the first classification in which undisturbed gauging stations to obtain ranges based on statistical analysis of real data were used, providing new insights that improve the understanding of the hydrological dynamics in these water bodies. Their integration into national legislation, which currently classifies NPRS based on expert judgement criteria (e.g., Spain and Italy), would undoubtedly lead to better management strategies aimed at achieving the objectives set by the WFD.

Nevertheless, the applicability of these results might be affected by the limited number of NRPS water bodies controlled by gauging stations . For example, 39% of France's rivers were NPRS applying a regional predictive model, but only 20% of the total gauging stations in France had zero flow episodes . In addition, some caution is needed when interpreting the results of this study. Our classification is based on data from 69 gauge stations, which represent a small proportion of the total NPRS located in the Mediterranean region. The use of a more extensive dataset would undoubtedly contribute to a wider and more robust classification. For example, we noticed a notable lack of episodic rivers, defined by as rivers with flowing water only during a few hours or days, depending on the rainfall event and its intensity. Since our study has used flow data on a daily scale, it was not possible to detect short-time-scale hydrological changes and none of the gauge sites used in this study was classified as episodic. Given the importance of NPRS in terms of the number of these freshwater ecosystems and considering the limited gauge sites used to measure them, more hydrological data would provide a more robust hydrological classification. For this reason, alternative data acquisition of periods of flow cessation would be necessary. The use of sensor loggers , remote sensing techniques with unmanned aerial vehicles , empirical observation, statistical approaches, process-based hydrological modelling , and multi-temporal satellite data , may solve this problem though notably increasing the costs .

4.3. Ecological status and typologies of non-perennial rivers and streams.

The Water Framework Directive requires biomonitoring quality elements to assess the ecological status of rivers. For this purpose, it is first necessary to define the limits of the water bodies to be included in the river basin management plans. However, NPRS water bodies are frequently excluded because many of them have small drainage areas or hydrological datasets are not available . In addition, NPRS are often omitted from ecological status assessments because of inadequate knowledge about their biological and hydrological characteristics (Mazor et al., 2014; Stubbington et al., 2017). The methodologies in place focused on aquatic organisms present during the wet phase, whereas dry-phase communities remain poorly characterized and the metrics used to establish ecological status in perennial rivers can only be applied in non-perennial rivers when flow is present . Consequently, the European Commission recognized the need to include ”temporary rivers” in national intercalibrations of the status of their water bodies . However, the inclusion of NPRS in a single type of water body (temporary rivers) may be imprecise for the evaluation and transferability of ecological status in Mediterranean rivers described by WFD, due to the high spatio-temporal variability of their flows . Therefore, well-defined hydrological typologies that bring together quality assessment, typologies and hydrology with zero-flow of NPRS are needed .

Here, we have categorized Mediterranean rivers into three groups based on the study of the variability of metrics related to their main attributes of duration, frequency, magnitude, timing, and rate of change. As expected, the comparison with the other three typologies (Fig.5 and 6) used to classify NPRS reveals that our groups differ slightly from the types reported by Spanish and Italian legislation and the TREHS software . Moreover, our classification is strongly associated with the temporal change gradient from ephemeral to temporary-types. It is important to note that the denomination of the typology varies between classifications, although many of the typologies coincide with each other (Fig.5). For example, 100% of the stations grouped in cluster III are intermittent in MATTM classification or temporary in IPH classification, 100% of the episodic or intermittent rivers of MATTM are ephemeral or temporary in IPH, respectively, and 100% of the episodic rivers in MATTM or ephemeral in IPH are episodic in hydrotypes TRivers classification. The use of a single variable without statistical basis (number of days per year of zero flow) to classify NPRS makes the Spanish regulation biased and does not adequately reflect the hydrological diversity of these ecosystems.

Furthermore, described the difficulties of only using the hydrological regime to classify non-perennial rivers: i) the main hydrological features relevant to biological communities in temporary rivers are not quantitative (i.e. discharges), but qualitative (i.e. the presence of flowing water, stagnant pools or the lack of surface water); ii) flow records do not report the permanence of isolated pools in periods of zero-flow; iii) many NPRS are ungauged, and their natural flow regime must be evaluated by alternative methods (e.g. remote sensing or rainfall-runoff models); and iv) the complexity of sampling these ecosystems due to the difficulty for recognizing the wet and dry phases. In this context, they developed a novel approach to evaluate the ecological status of NPRS. It defines four aquatic phases for NPRS, such as perennial, intermittent-pool, intermittent-dry, and ephemeral. In this way, used aquatic phases to propose NPRS classification that allows evaluating their ecological status. Our study has also highlighted some of these limitations, establishing a non-visual typology based on the numerical data of the flow series to improve the ecological assessment using quality elements connected with the hydrological patterns and pressure gradients. It would also provide a starting point to improve the management strategies guided to the achievement of the good ecological status, based on measures related to improve hydrological alteration and ecological connectivity .

5. Conclusions

In summary, we classified the natural hydrological regimes of NPRS located in the western Mediterranean region using daily flow data sets from 69 unaltered gauging stations. Using hydrological series of at least 11 years of duration, a total of 315 hydrological indices were calculated using different thresholds to define no-flow conditions (i.e. 0, 1, 2, and 5 l/s). We did not find notable statistical differences between the different thresholds and after redundancy analysis. A neural network model was calibrated with the 5 hydrological metrics that better describe the attributes of flow magnitude, duration, frequency, and timing of the zero-flow periods, and rate of change between flowing and non-flowing conditions. The 5 hydrological metrics describe annual attributes as number of days or percentage of months per year without flow mean annual flows, coefficient of variation of Julian date of the annual start of zero flow and annual rise rate. The analysis concluded that three different categories of NPRS can be defined, namely: ephemeral, intermittent, and temporal rivers. Ephemeral rivers are dry for most of the year and would have a low flow during the wet phase with water in their riverbed. Intermittent rivers have a dry phase not as long as ephemeral rivers, and, as a rule, more water runs through their bed. Temporal rivers are more briefly interrupted by a period of drought. Additionally, our classification revealed ranges that are not closed and different from the national legislation classifications of Spain and Italy. Ephemeral rivers could be dry for more than 181 days or 7 months, intermittent rivers between 100 and 187 days or between 4 and 7 months, and temporal rivers less than 46 days and 2 months. Therefore, our results could serve for the conservation and management of these rivers, establishing a necessary typology in future studies of ecological status of WFD, with well-defined groups based on statistical analysis. The lack of studies addressing the hydrological diversity of these freshwater ecosystems makes our study a basis for future efforts aimed at improving management strategies of this type of river courses. Additionally, future analyses guided to a better characterization of biological communities associated with different types of NPRS will allow a better understanding of the ecological implications of temporality on the biota and will advance in better ecological status classification and management of these ecosystems. Finally, due to the relative low number of NPRS analysed, the resulting classification should be considered as a first approximation and should be tested and calibrated with other gauging stations not included in the study.

References

Tables

Table 1. Hydrological indices selected from the first five components of the PCA and the correlation analysis for threshold defined as zero flow below 0, 1, 2 and 5 l/s.

Dim.	Code	Hydrological indices	Units	Thresholds (l/s)
1	DU035	Number of days without flow (annual)	days/year	0, 1, 2, 5
1	FE052	Percentage of months without flow (annual)	%	0, 1, 2, 5
2	MA001	Mean daily flows (annual)	l/day	0, 1, 2, 5
3	TI002	CV of Julian date of annual start of zero flow	Dimensionless	0, 1, 2, 5
5	RC001	Rise rate (annual)	l/day	1, 5

Table 2. Summary of the cluster groups obtained by training self-organizing maps (SOM) using the hydrological indices selected for the non-permanent Mediterranean rivers. The mean, standard deviation, coefficient of variation and interquartile range are included of number of days per year without flow (DU035, in days/year), annual percentage of months without flow (FE052, in %), mean daily annual flows (MA001, in l/day), CV of Julian date of the annual start of zero flow (TI002) and annual rise rate (RC001, in l/day).

Cluster	Hydrological indices	Mean	Standard deviation	Coefficient of variation	Interquartile range
I	DU035	231.45	97.07	0.42	181.61 - 307.98
	FE052	76.87	23.52	0.31	59.65 - 96.29
	MA001	0.53	0.70	1.31	0.06 - 0.67
	TI002	2.23	0.92	0.41	1.53 - 2.96
	RC001	3.69	6.19	1.67	0.53 - 2.34
II	DU035	144.14	54.40	0.38	100.41 - 187.11
	FE052	47.32	15.23	0.32	35.83 - 56.31
	MA001	0.72	0.65	0.90	0.24 - 0.99
	TI002	0.63	0.27	0.44	0.44 - 0.79
	RC001	2.00	1.98	0.99	0.51 - 2.72
III	DU035	24.57	25.68	1.04	2.65 - 46.19
	FE052	11.25	10.09	0.90	2.16 - 20.07
	MA001	2.06	3.80	1.84	0.25 - 1.95
	TI002	0.25	0.17	0.70	0.12 - 0.37
	RC001	1.35	1.72	1.28	0.27 - 1.57

Figures

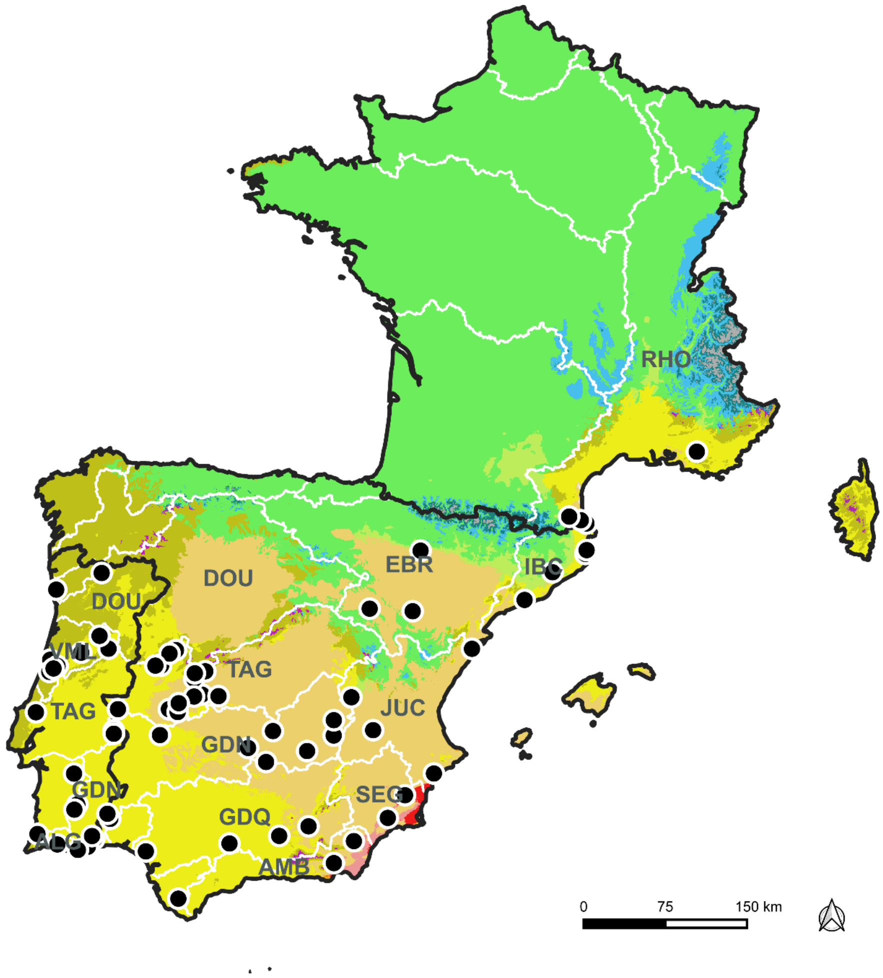


Figure 1. Map of the 69 gauging stations used to develop the hydrologic classification of non-perennial rivers in France, Spain, and Portugal. Abbreviation of each studied river basin district (see Table A1) and Köppen-Geiger classification has been added (see legend on .

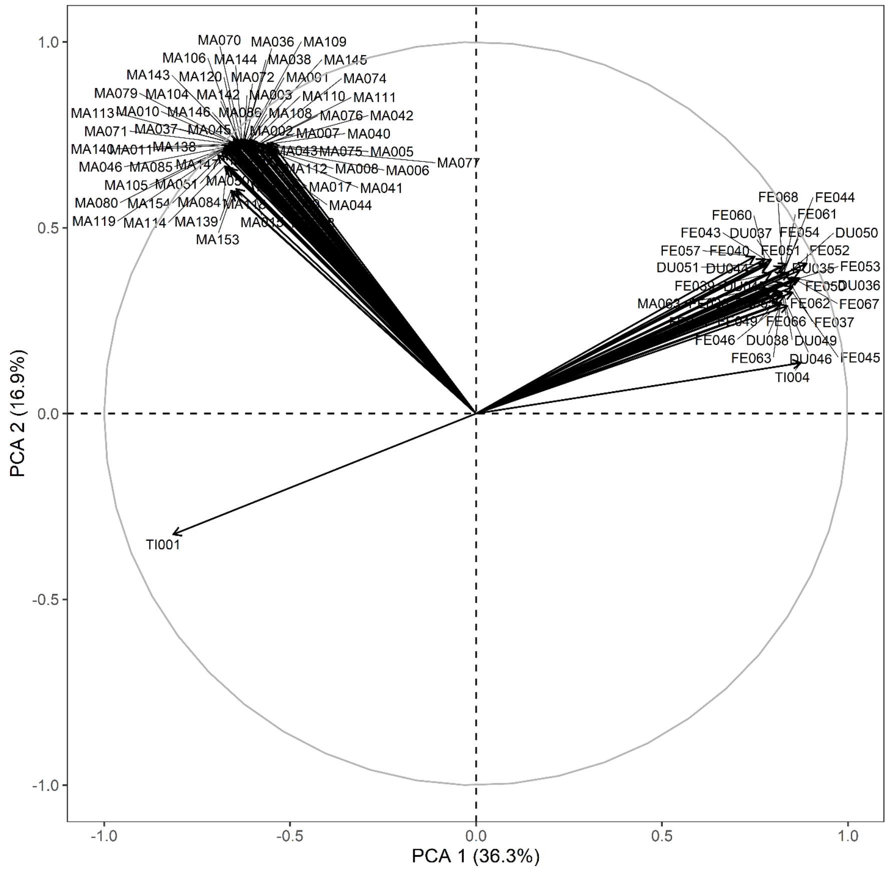


Figure 2. Principal component analysis of 315 hydrological indices that describe ecologically relevant flow regime characteristics such as magnitude (MA), frequency (FE), duration (DU), timing (TI), and rate of change (RC). The percentage of explained variation (%) of the first two dimensions for a threshold of 0 l/s. Only the first 100 variables that contribute most to the dimensions are represented.

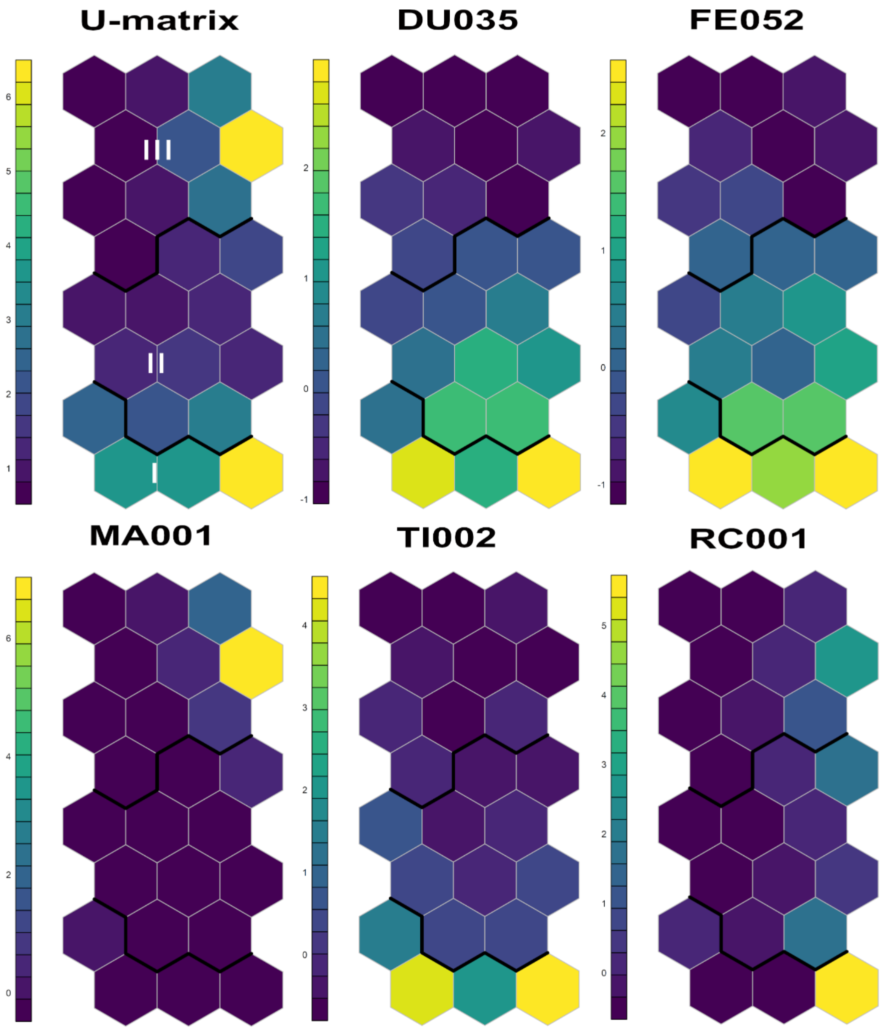


Figure 3. Self-organizing map (SOM) for the variables: number of days per year without flow (DU035), annual percentage of months without flow (FE052), mean daily annual flows (MA001), CV of Julian date of the annual start of zero flow (TI002) and annual rise rate (RC001). Warm colours (yellow) indicate high values while cool colours (blue) represent low values for each variable. The U-matrix (unified distance matrix) and cluster classification applied to the boundaries of the map is added.

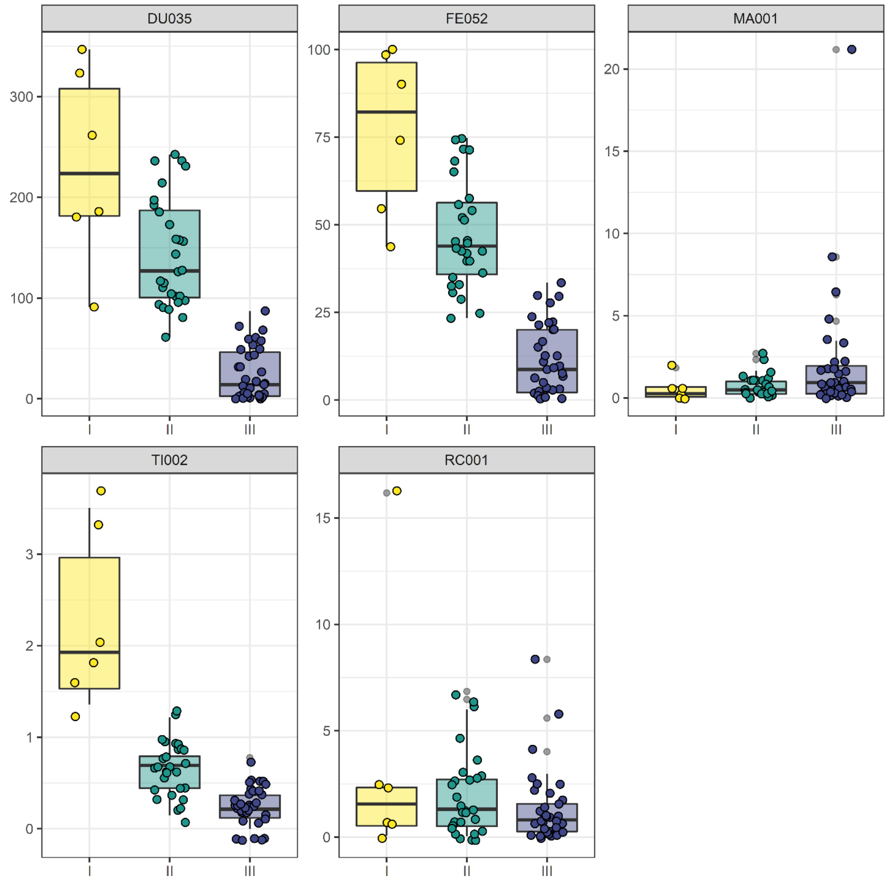


Figure 4. Box-plots illustrate cluster groups obtained by training a self-organized map (SOM) with the selected indices; number of days per year without flow (DU035, in days/year), annual percentage of months without flow (FE052, in %), mean daily annual flows (MA001, in l/day), CV of Julian date of the annual start of zero flow (TI002) and annual rise rate (RC001, in l/day).

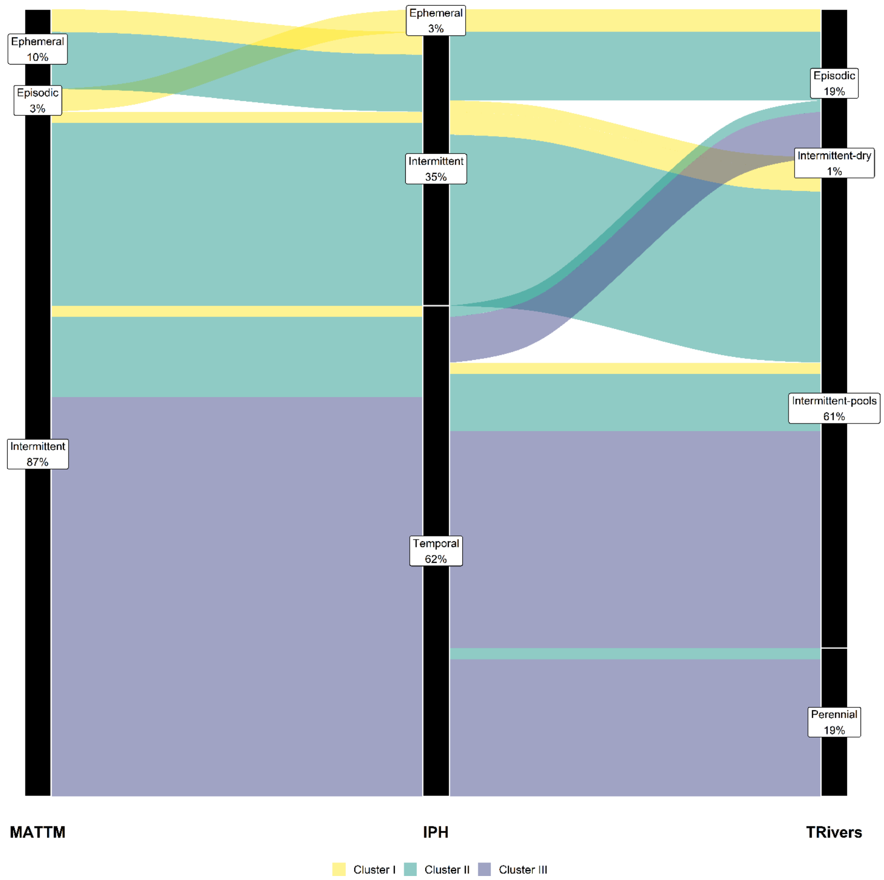


Figure 5. Alluvial diagram relating sampling stations of non-perennial Mediterranean rivers, Italian (MATTM), Spanish (IPH) and hydrotypes classification (aquatic phases of biological communities) of LIFE+ TRivers project with the three clusters obtained on SOM. The width of the connection is based on the frequency of occurrence of the different combinations of the categories of each characteristic.

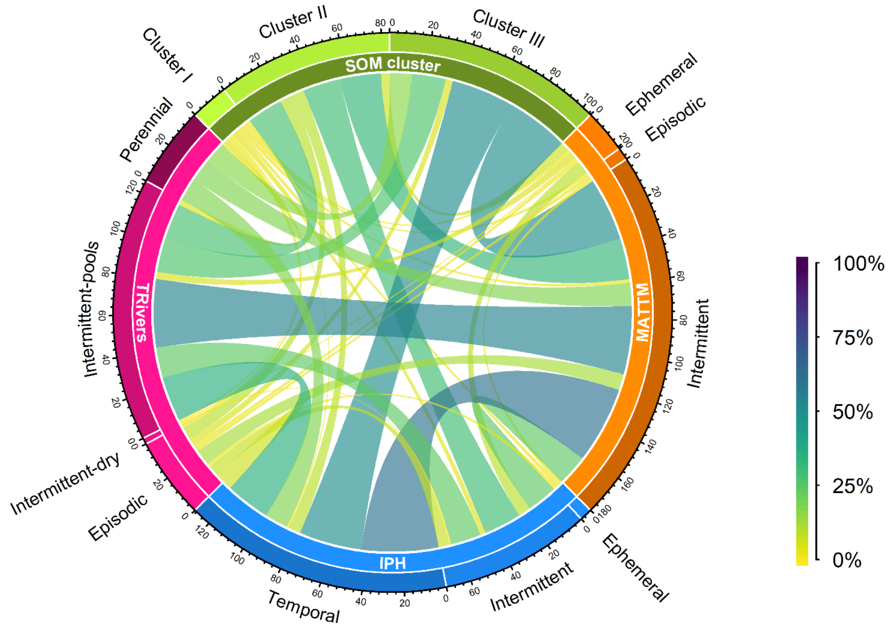
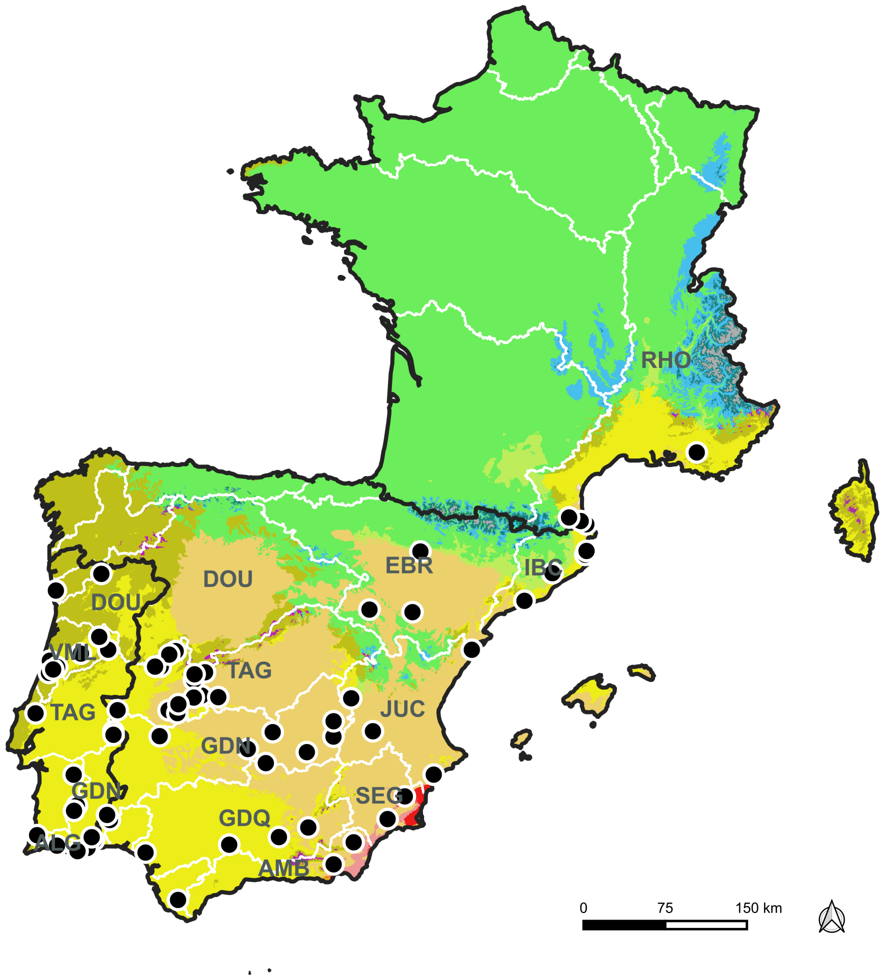
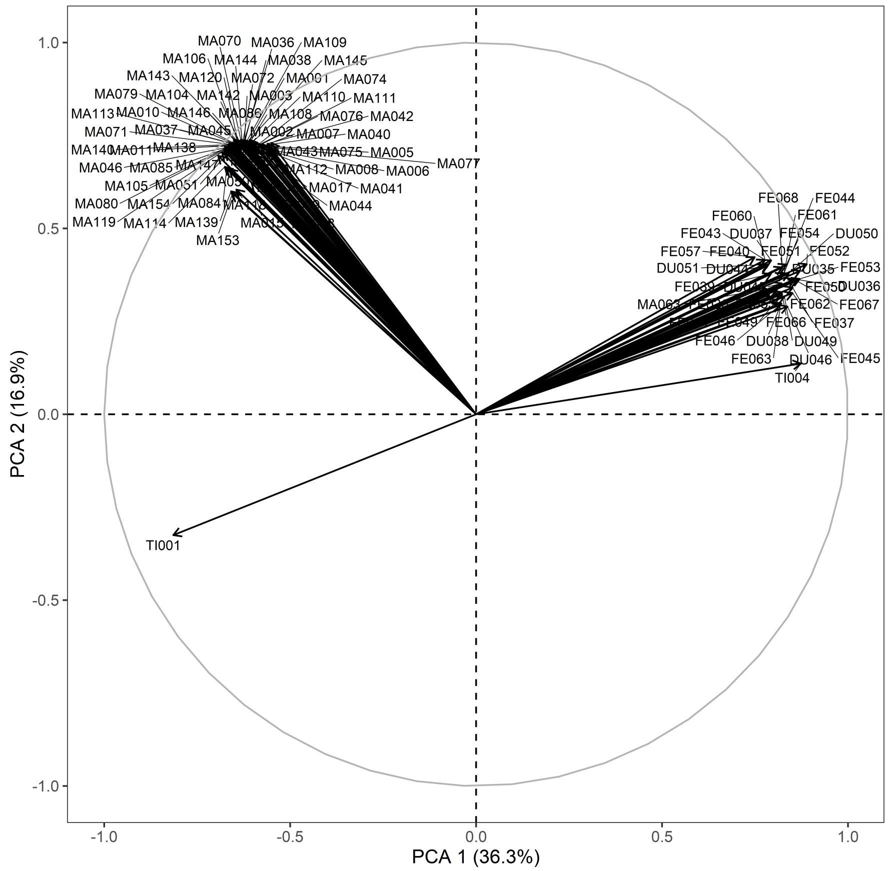


Figure 6. Chord diagram relating sampling stations of non-perennial Mediterranean rivers between different types of SOM (cluster I, II and III), MATTM (ephemeral, episodic, intermittent and ephemeral), IPH (ephemeral, intermittent and temporal) and TRivers (episodic, intermittent-dry, intermittent-pools and perennial) classification. The width of the connection is based in the percentage of occurrence between of the categories of each classification.


RHO
EBR
IBC
DOU
DOU
VML
TAG
TAG
JUC
GDN
GDN
SEG
GDQ
ALG
AMB
0
75
150 km


PCA 2 (16.9%)
PCA 1 (36.3%)
1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0
MA070
MA036
MA109
MA106
MA144
MA038
MA145
MA143
MA120
MA072
MA001
MA074
MA079
MA104
MA142
MA003
MA110
MA111
MA113
MA010
MA146
MA086
MA108
MA076
MA042
MA071
MA037
MA045
MA002
MA007
MA040
MA140
MA011
MA138
MA043
MA075
MA005
MA077
MA046
MA085
MA147
MA112
MA008
MA006
MA105
MA051
MA017
MA041
MA080
MA154
MA084
MA044
MA119
MA114
MA139
MA015
MA153
TI001
FE068
FE044
FE061
FE060
FE043
DU037
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DU050
FE057
FE040
FE051
FE052
DU051
DU035
FE053
FE039
FE050
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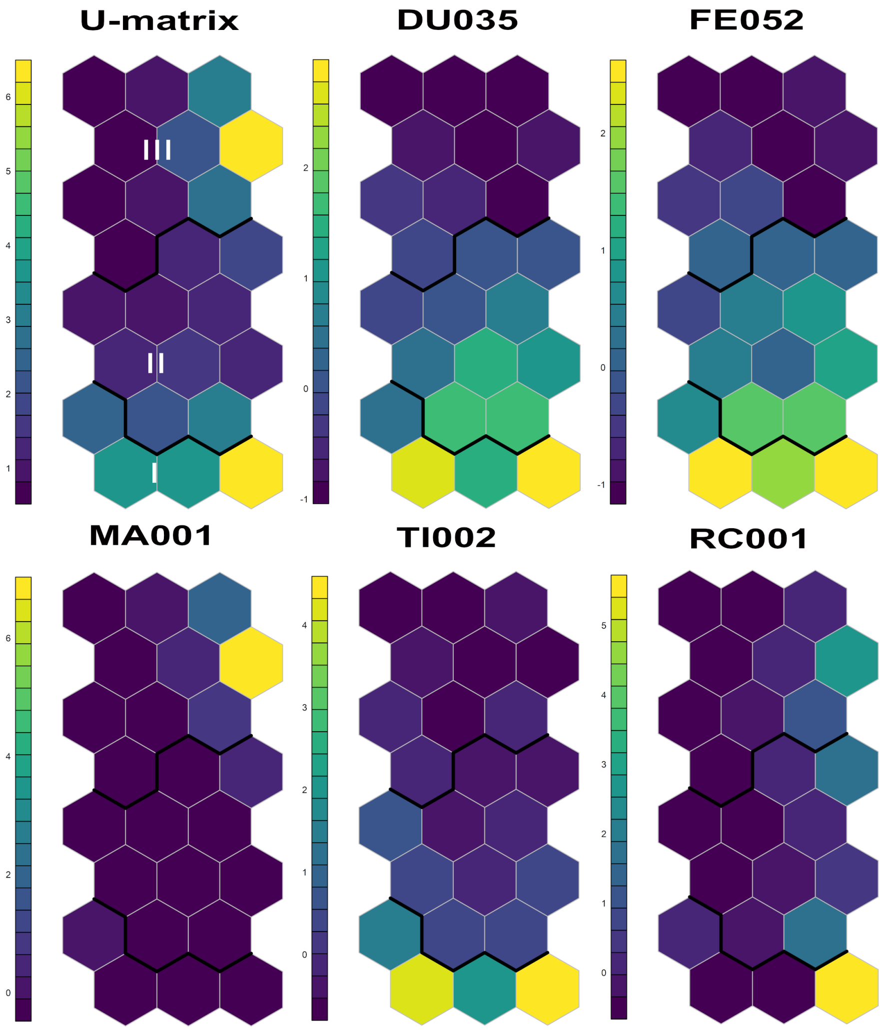
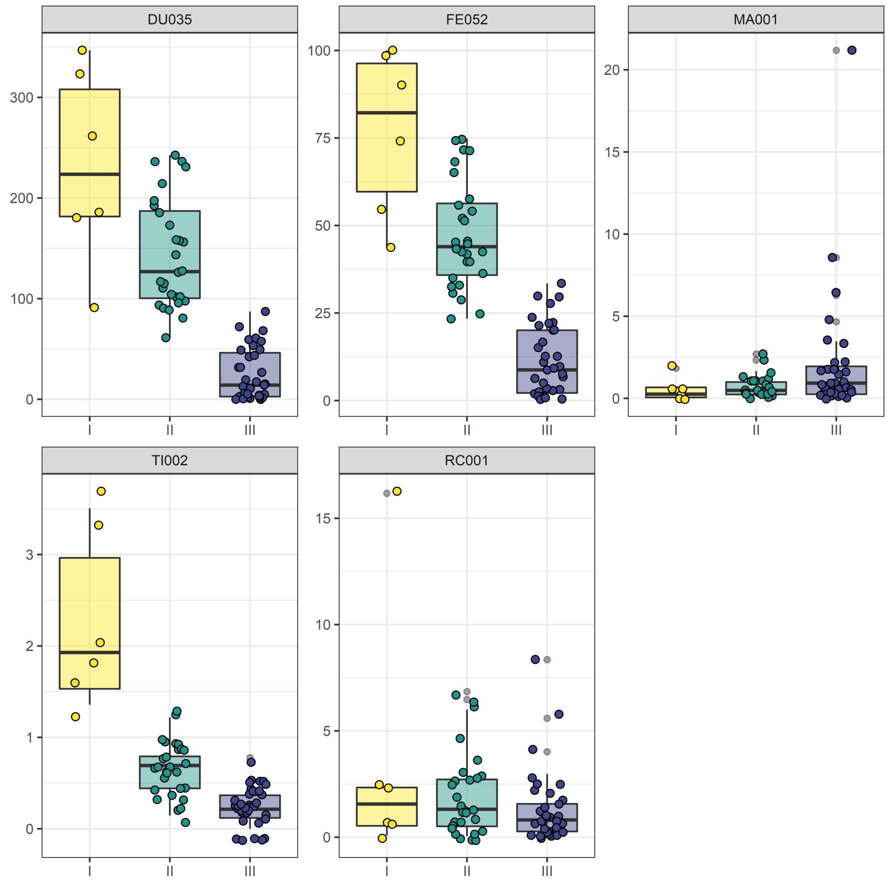
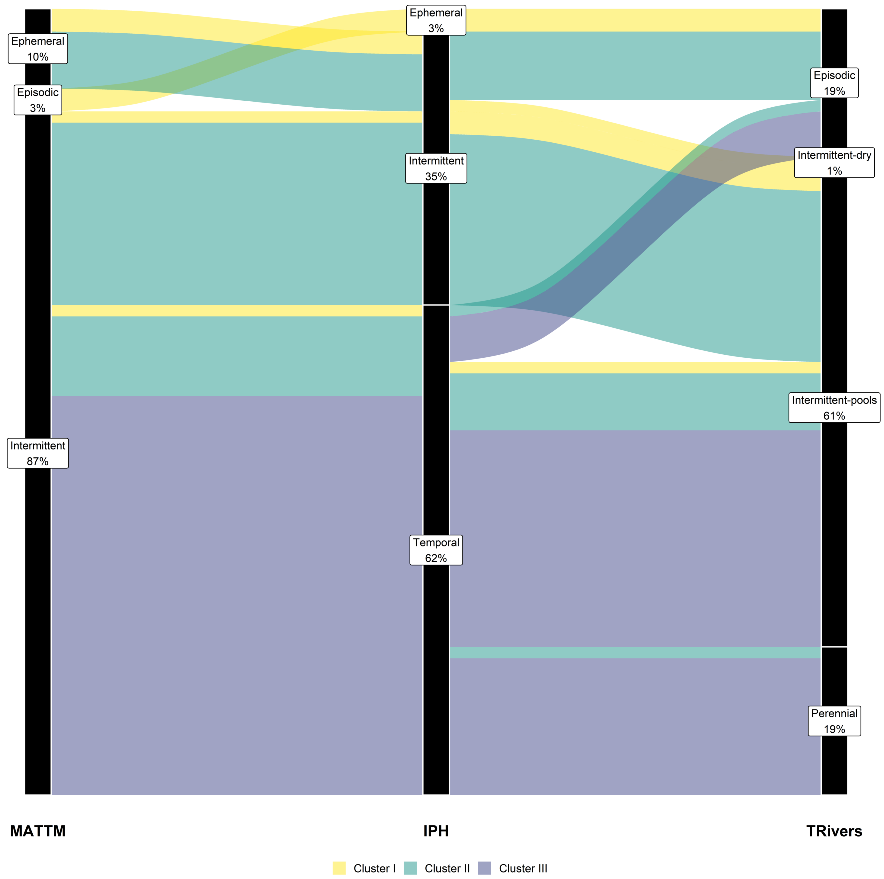
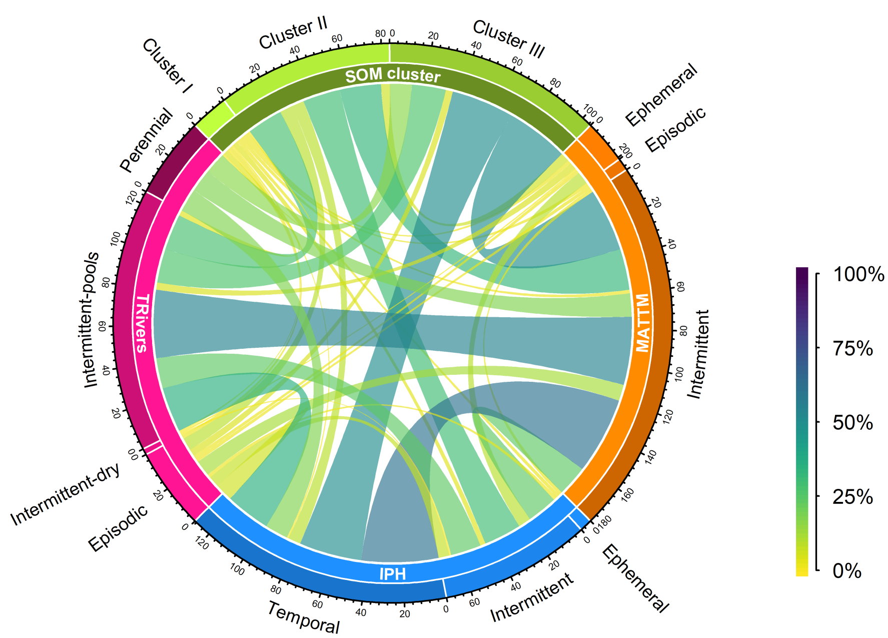
FE045
TI004



U-matrix
DU035
FE052
MA001
TI002
RC001
III
II
I


DU035
FE052
MA001
TI002
RC001
0
100
200
300
25
50
75
5
10
15
20
1
2
3
I
II
III


Ephemeral
10%
Episodic
3%
Intermittent
87%
Ephemeral
3%
Intermittent
35%
Temporal
62%
Episodic
19%
Intermittent-dry
1%
Intermittent-pools
61%
Perennial
19%
MATTM
IPH
TRivers
Cluster I
Cluster II
Cluster III


SOM cluster
Cluster I
Cluster II
Cluster III
Ephemeral
Episodic
MATTM
Intermittent
IPH
Ephemeral
Intermittent
Temporal
TRivers
Episodic
Intermittent-dry
Intermittent-pools
Perennial
100%
75%
50%
25%
0%