POLITECNICO DI TORINO

Master's Degree in Environmental and Land Engineering

Master's Degree Thesis

A comparison analysis: the 2022 drought on the Rhone and the Po basins.

Supervisor

Alberto Viglione

Stefania Tamea

Candidate

Raphaëlle Corne

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Abstract

Global warming significantly affects the frequency and intensity of droughts worldwide. In Europe, the regions such as the Rhone basin in southeastern France and the Po basin in northern Italy has experienced several droughts in the last years and the future climate scenarios do show increasing drying in those areas. These two basins, separated by the Alps mountains, are unique due to their diverse sources of water flow (mountains, plains, Mediterranean areas). This report focuses on comparing the hydrological intensity of droughts in these two basins and aims to determine how they were affected by the 2022 drought event. To achieve this goal, hydrological data from French and Italian archives were compared using various indices.

A preliminary meteorological analysis was conducted using the Standardized Precipitation Index (SPI) calculated on gridded data. Over a span of 30 years, the data indicates a significant decrease in rainfall in the French basin, while the Italian side shows a slight increase in yearly SPI values. However, the SPI maps for 2022 highlight the extreme dryness in both basins, especially in the Po basin.

The hydrological conditions of the basins were studied using multiple indices to assess various drought parameters such as duration, frequency, and intensity. The primary analysis utilizes the QMNA (minimum annual monthly flow) to assess the exceptional low flow conditions. By examining the return period of QMNA and its evolution over 30 years, insights were gained into the impact of global warming and the response of water bodies to drought. Three distinct areas were studied: the northern plain of the Rhone basin in France, the downstream Italian area, and the Alpine region at the border of the two basins. Alarming low flow values were concentrated in the plain area, while the Alpine region showed a less dramatic variation, likely due to glacier and snow melt in summer.

Additionally, a daily threshold analysis of major river stations revealed divergent trends at the river mouths. The Po River experienced record minimum daily flows for 23% of the days for the years 2022 since 1968 at its downstream station, whereas the Rhone River recorded such conditions for 7% of the days. The 2022 drought set numerous hydrological and meteorological records in both basins. The Rhone basin has seen a progressive decrease in its water resource through the years, while the year 2022 has set unprecedented records for the Po basin. New policies has been established to reduce the consumption of water during this extremely dry period.

Table of Contents

List of Tables

List of Figures

Acronyms

QMNA
Annual minimum monthly flow

VCN3
Minimum annual mean flow calculated for 3 consecutive days

VCN10
Minimum annual mean flow calculated for 10 consecutive days

CNR
Compagnie Nationale du Rhône

ARPA
Agenzia Regionale per la Protezione Ambientale

RRSE
Reference network for monitoring low water levels

OSSEC
Outil de Suivi et de Surveillance des étiages en Coherence sur le Rhone

Chapter 1

Introduction

A drought is an event generated by extreme parameters and impacting the water cycle. This general assertion isn't the only definition of the drought, its perception is varying depending on multiple considerations: the area, the climate, the use of the resource. Many authors have tried to determine a global definition. One of the most accepted one is [1]: 'The chief characteristic of a drought is a decrease of water availability in a period and over a particular area. ' A more recent one could be: "a lack of water compared to the normal condition" from [2]. The reference to the normal, shows the consideration to the studied area but the value of the normal is still to be defined.

In Sought Europe, during the last two decades, the frequency and severity of drought has increased [3]. The climate change has an impact on the temperature, precipitation, and water flow regime. The futures scenarios doesn't show a change of trend and are even revealing a continuous increase in the drought frequency. The regions surrounding the Alps in France have a particular climate. Due to the proximity to the Alps, the Rhone Alpes region has a mountain climate when the Var is part of the Mediterranean one. The study of the streamflow in Rhone basin is a complex task that requires a deep understanding of these diverse climatic influences. The Po basin is presenting the same challenge with his localisation alongside the Rhone basin. The clear separation by the Alpes mountains gives a real distinction in the meteorological and hydrological trend observed in the two basins. This study aims to make the comparison of the hydrological 2022 drought intensity within the two basins using multiple indexes.
In order to calculate and visualise the results, the index and maps were modelized in R- studio.

Chapter 2

Material and Methods

A drought is part of a phenomenon where the lack of water observed. It is noticeable with multiple measurement method. In the literature we count 4 types of droughts: meteorological, hydrological, soil moisture and socio-economical drought. They are strongly correlated and impact on the overall water cycle. The human history has recorded numerous drought events of different intensity and duration. To characterise the intensity of a drought, we study the main parameters of its propagation on time and spatial scale. This thesis will focus on the analysis of the 2022 hydrological drought on the French Rhone River and the Po River.

2.1 Different types of droughts and their parameters

A drought is the decrease of water availability in the water cycle. Depending on the sector impacted Dracup and al. (1980)[4] and Wilhote et Glanz (1985) [5], have defined 4 types of droughts.

- Meteorological drought depends on atmospheric conditions covering a large area. It's defined as a precipitation deficiency during a long period of time.
- Hydrological drought is the deficit of surface flow in the water bodies. It has a longer duration and impact locally. This makes it more predictable than the meteorological drought [2]. Groundwater drought can also be part of the definition of hydrological drought.
- Soil moisture drought also called agricultural drought is relative to the reduced soil moisture impacting the vegetation water supply composition of the soil.
- Socio-economic drought is all the societal impact a deficiency in water supply will bring.

The connectivity between the different type of drought amplifies the impact of the phenomenon. Sheffield and Wood [6] established a connection between the factors initiating a hydrological drought (Figure 2.1). The depletion of water resources in various water bodies is a result of a more extensive phenomenon that can endure for extended periods, spanning months or even years.

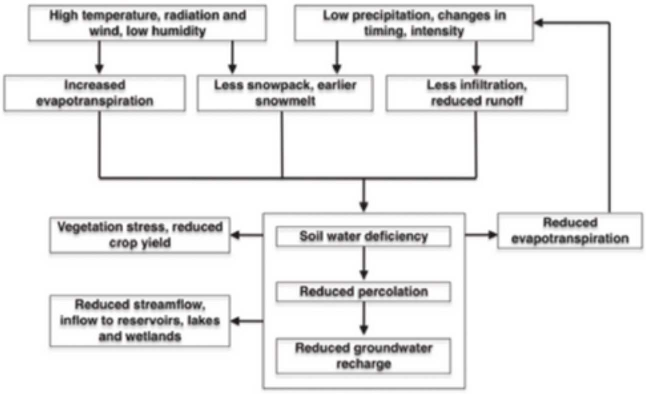


Figure 2.1: Propagation of drought through the hydrological system and the feed-backs to the atmosphere.[6]

As presented in the Figure 2.1, the hydrological drought is happening in the continuity of a meteorological drought. The absence of precipitation leads to an impossibility for the groundwater to recharge and for the soil to percolate. Reduced evapotranspiration has proportionally less impact on the catchment, it can only amplify the effect created by the meteorological or hydrological drought. The result of any drought is the depletion of water in the water body and a low quality of water for the environment. This type of drought has an impact on the largest range of categories: agriculture, ecosystem, energy and industry, navigation, drinking water, recreation [7].

The notions of time and spatial spreading are inner to the propagation of a drought. The deficit time isn't necessarily the same for each type of drought; It can have a delay between the two different types of droughts. A classification for hydrological drought based on the causing factors and with consideration of the spatial and time aspect has been proposed by Van Loon and Van Lanen: "classical rainfall deficit drought, rain-to-snow-season drought, wet-to-dry-season drought, cold snow season drought, warm snow season drought, snow-melt drought, glacier melt drought, and composite drought" [8]. This list considers the seasonal effect and the geographical localisation of the drought. For the determination of the general area of study a drought must not be misunderstood with an arid environment.

Aridity is long in time and can be permanent while drought is a shorter event occurring for a certain period of the year.

In term of analyse, a hydrological drought is defined through various parameters. The effect of the hydrological drought is revelled mostly during the period of low flow. In term of stream-flow, it is important to make the differentiation between the seasonal low flow events that are happening every year and the extreme low flow event that is a less common event, indicator of hydrological drought. The aim of this study is to emphasize the extreme aspect of the 2022 low flow. Depending on the country different reference are used to characterize the extreme low flow. In France the annual minimum monthly flow (QMNA) has been establish as a reference by the water law from 1992 while, the In US and Canada, the main index is the VCN7 [9]. These two indices reveal perfectly the anomaly in low flow.

2.2 Study area and time scale

The basins of the two longest rivers in Italy and France are separated by the Franco-Italian frontier and a morphological boundary: the Alps. The Po and the Rhone rivers measure respectively 652km and 812km (545 km in France) and discharging into the Mediterranean Sea.

2.2.1 The Po basin

Encompassing a vast drainage area of 71 000 km^2, the Po basin record daily river flow average of 1470 m^3/s . With his 141 main tributaries, the Po River Basin is connecting a network of 6750 km. the basin is exploited for the human activities: irrigation, hydro-power production, civil and industrial use. The Figure 2.2 present the annual hydrological flux determined by the Po River Basin Authority in 2006:

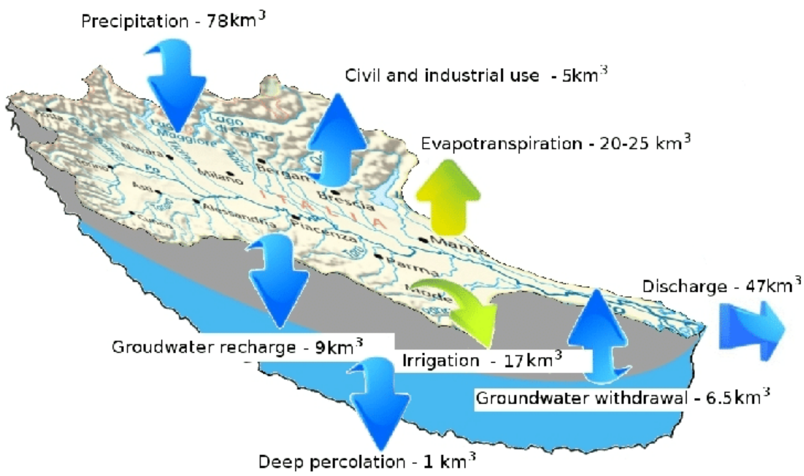


Figure 2.2: Mean annual main hydrological fluxes for the Po River basin (2006)

By compiling all the input output of the basin, the withdrawal from the aquifer is about 6.5 km^3, inducing an almost over exploitation of the groundwater resources [10]. The Po Valley is spread upon 8 different regions: Piedmont, Aosta Valley, Lombardy, Veneto, Liguria, Emilia-Romagna, Trentino-Alto Adige, and Friuli-Venezia Giulia. The basin is managed by the Autorità di bacino del fiume Po and its open-source data collection is handle by the Regional Agency for the Protection of the Environment (Agenzia Regionale per la Protezione Ambientale - ARPA) since the referendum of 1993 on the attribution of the environmental control tasks to regional agencies [11]. The hydrological data collected for this thesis have been downloaded from the Arpa Piemonte and the Arpa Emilia-Romagna. A few numbers of station in these regions are proposing a complete dataset of at least 30 years (Appendix A.2 and Appendix A.3). The low flow analysis is limited by the reduced number of years recorded in these stations.

2.2.2 The Rhone basin

The Rhone River holds great significance, as it ranks among the largest rivers in Western Europe and plays a crucial role as a watershed in the Mediterranean region, second in importance only to the Nile. Covering an expansive drainage area of 98,500 km^2, the Rhone basin is the third largest in France, highlighting its substantial hydrological impact. Its most downstream station (Beaucaire) records a mean annual flow of 1,720 m^3/s making the Rhone the largest freshwater input into the north-western Mediterranean Sea [12].

The hydrological gauging network is wildly implanted in France. The data of each hydrological station is available in open source on the national website Hydroportail. The data set used for this report is issue from the Reference network for monitoring low water levels (RRSE). Created in 2021, this selection only considers the station poorly influenced by human activities.

Among the 453 hydrological stations including 306 stations still in activity proposed by Hydroportail on the Rhone basin, only 105 stations with more than 30 years of stream-flow record and included in the RRSE has been analysed. A recent article has presented the OSSEC (Outil de Suivi et de Surveillance des étiages en Coherence sur le Rhone), a tool made to monitor the low flow on the Rhone basin [13]. This tool is based on the classification of the low flow depending on their dominant hydrological regime (Appendix A.1) where we can notice on the map that each tributary is part of a sub-basin. For more precision in the analysis, we will use the classification at the origin of this map: developed by E. Sauquet and al. [14]. Figure 2.3 depicts the reference associated with each river, established through a hierarchical cluster analysis of observed normalized monthly runoff time series. The results is the formation of 12 distinct flow regime groups. The use of this larger number of groups was necessary to differentiate between pluvial regimes and snow-melt-fed regimes, as well as to distinguish between pluvial oceanic patterns and pluvial Mediterranean patterns.

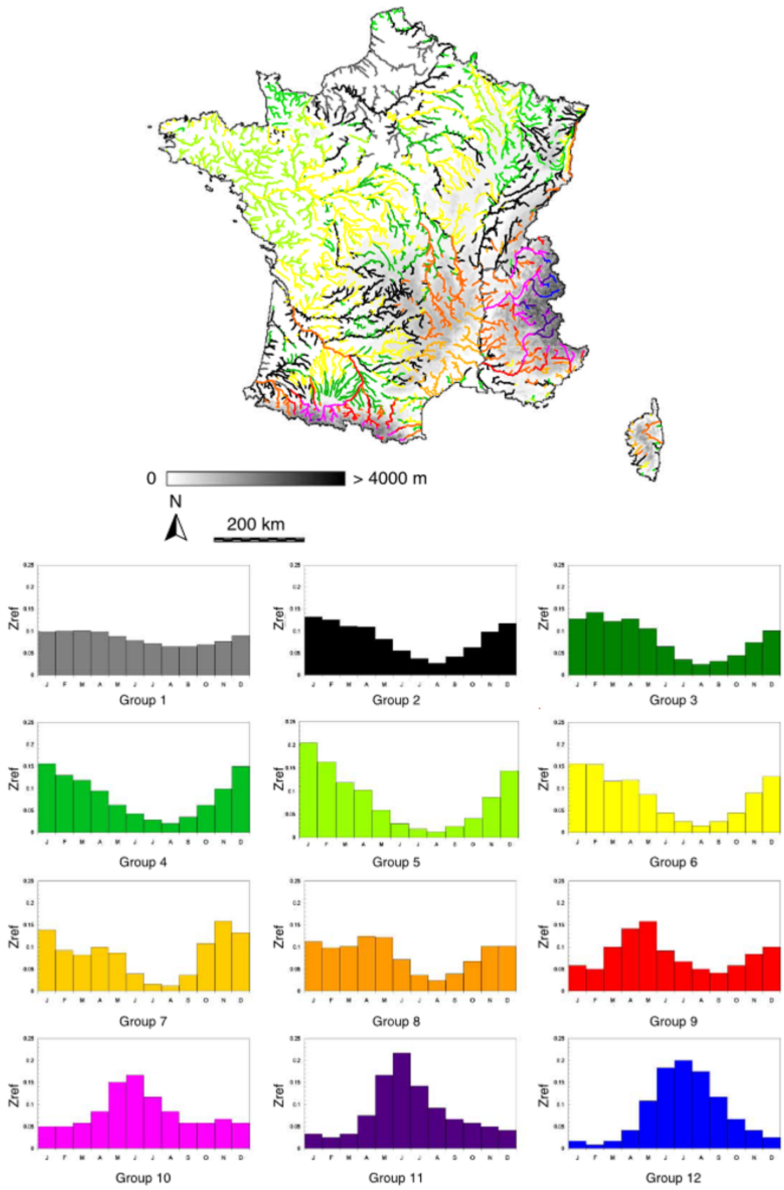


Figure 2.3: Map of river flow regime based on the twelve reference hydrographs for France [14]; 1 to 6: pluvial river flow regimes; 7 : Mediterranean river flow regimes; 8 and 9 : transition regime; 10, 11, 12: snow-melt-fed regime

Our study is taking interest in the area of the Rhone basin, where hydrological references are a mixture of pluviometric, snow-melt, Mediterranean, and transitional influences. We can assume a similar repartition for the Po basin. In his paper, Montanari[10] mentions the existence of a similar map and provides references associated with some stations on the Po.

Location	Period	Area (km^2)	Fluvial regime
Po at Pontelagoscuro	1920–2009	71 000	Pluvial regime with two peak periods
Po at Piacenza	1924–2009	42 030	Pluvial regime with two peak periods
Po at Moncalieri	1942–1984	4885	Pluvial regime with two peak periods
Tanaro at Farigliano	1944–1973	1522	Pluvial regime with two peak periods
Stura di Lanzo at Lanzo	1946–1981	582	Mixed alpine and pluvial regime; autumn discharge is low
Dora Baltea at Tavagnasco	1951–1989	3314	Alpine regime with only one peak during summer

Table 2.1: Stations details of the Po basin

2.2.3 A basin comparison

To verify the presence of a trend between the historical data and the recent one, the data sets needed to be large enough to see the climate change effect. To be able to compare the catchment response of the two basins, we calculate our threshold value and other index over a 30-year period.

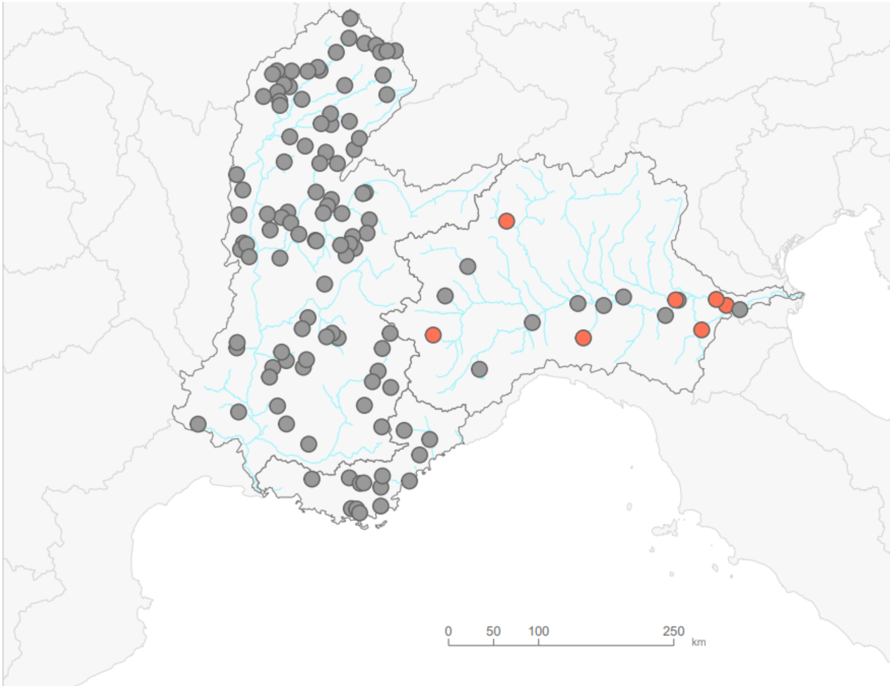


Figure 2.4: Rhône basin and Po basin map with their hydrological stations (grey points: stations with more than 30 years of data, red points: stations with more than 20 years of data)

The Figure 2.4 present the stations used for the analysis. The availability of data in Italy is limited by the lack of continuity in most of the data-set. 105 stations included in the RRSE have been analysed for the Rhone basin while only 17 stations issue of the Arpas archives were recorded. Among them, the analysis includes 10 stations with more than 20 years recorded data.

The main difficulty of this analysis lies in the equivalency of data. The two countries do not centralize their data in the same manner. Furthermore, the monthly evolution report shared by Eau de France and the Autorità di bacino del fiume Po do not present the same index comparisons. Depending on their climate and databases, the two countries have favoured different indices to characterize drought.

2.3 The hydrological indices

The intensity of a drought is difficult to quantify due to the number of available indices [2]. Each index is related to a specific indicator of the water cycle. The distinction between indicator and index can be defined with the following definition: "Indicators are variables or parameters used to describe drought conditions while indices are typically computed numerical representations of drought severity, assessed using climatic or hydro meteorological inputs" [15]. The list of the main existing indices is available in the Handbook of drought Indicators and indices. They are adapted to meteorological data, hydrological data but also for the soil moisture, the remote sensing data, and model analysis. Their multiplicity allows to cover the entire dimension of the environmental analysis but can also complexify the approach to define the drought. A choice in the identification methods is necessary. To identify the 2022 drought and understand its specificity, the analysis is considering the following parameters: Timing, Intensity, Duration, Spatial extent. To determine the significance of trends, the non-parametric Mann-Kendall statistic test that measures the degree to which a trend is monotonically increasing or decreasing is applied on the dataset of every station [16].

In hydrological analysis, a key factor is the value of extreme low flow. To determine what qualifies as low flow, a threshold is employed.

2.3.1 Threshold level method

The threshold level method as defined by Yevjevich [17], establish a parameter constraint to determine the classification of a drought by the defining the limit value of a low flow. The limit can either be a constant or a variable (Section 2.3.4). The threshold typically aligns between the 70th and 95th percentiles of the flow rate curve. Variable threshold gives the opportunities to analyse seasonality anomaly [8] while fixed threshold enlights the extremes values recorded and hence, gives an indication on the exceptionality of the event. Since our study aims to shows extreme magnitude of the 2022 drought and compare its footprint over two basins, a fixed threshold will be defined for the analysis.

One aspect that need to be considered with this approach is the phenomena of pooling in the studied hygrograms. The threshold separate sequences of consecutive droughts with lower intensity coefficients that are part of a larger interconnected event. To mitigate this issue the implementation of a minimum time interval gives the possibility to group the little events.

2.3.2 The annual minimum monthly flow (QMNA)

The QMNA is a based index giving the minimum annual stream-flow value among all the months. The mean of every months is calculated and the lowest value is taken as reference. QMNA-5 which is the return period associated to the QMNA is a wildly use index in France to show the severity of the low flows. The return period is calculated on the basis of a 30-year record and a log-normal distribution.

The analyse made from the QMNA in this report will measure the intensity of the observed drought based on the return period associated to the QMNA value of each station for 2022.

2.3.3 Consecutive minimal volume for 3 and 10 days (VCN3 and VCN10)

The VCNs indices give an intensity value of the drought based on the duration of the most extreme low flow value in the year on 3 days (and 10 days) moving average. The VCN3 characterise a low flow situation for a very short period and is useful to reveal extreme event. VCN10, on the other side, is determined on a much larger period and can give an indication on the duration of the event. The moving-average filter is applied to reduce short-term disturbances of the discharge record[18].

C. Lang [9] established a statistical method that demonstrate the very probable status of the VCN10 (biennial frequency). The probability to have more than 10 consecutive days without precipitation decrease then fast. Moreover, a 10-day duration for calculating VCN could ensure more stable flow rates in most cases, which is not as guaranteed with longer duration or QMNA. On the other side, a duration shorter than 10 days might give much importance to frequently disrupted low flow rates or low flow with errors rate. The VCN10 is also very close from the VCN7 (regular indexe for numerous other country).

These VCNs are pointing the most extreme value recorded during the years. It brings information on the possible outpacing record or visible trend during the years. However, it doesn't show the seasonality factor. This can be a problem for the evaluation of the winter hydrological impact. To resolve this issue, the calculation of these indices can can be done on seasonal period from May to September and from October to April.

2.3.4 The low flow index LFI

The LFI is an index that classify drought per type with consideration of a daily threshold and the duration of each event[19]. It is a powerful index to estimate the dryness of the period in consideration of the seasonality effect. However, in the case of this study, it will net be used. The determination of the threshold is based on a moving window (here on 31 days). Each day's t gets a threshold corresponding to the X^{th} (usually 80^{th}, 90^{th} or 95^{th} ; here we will use 95^{th}) percentile of the flow duration curve created with the 31-days window centred in t. It can be written as:

$$Q_{95,t} = \inf\left\{S_t : F_{(S_t)} \geq 0.95\right\} \quad \text{avec} \quad S_t = \bigcup_{y=1}^{n} \bigcup_{j=t-15}^{t+15} Q_{y,j} \tag{2.1}$$

Where $Q_{y,j}$ is the streamflow on the j^{th} day of the y^{th} year and St the partial daily flow duration curve. Each station (or cell for a grid map) gets 365_{xn} daily value of threshold (n the number of years). The second step is the calculation of the duration of an event defined as a period of consecutive days where $Q_t < Q_{95,t}$: $d_t = t_{e,i} - t_{s,i} + 1$. Its deficit is calculated as follow:

$$D_i = \sum_{t_{s,i}}^{t_{e,i}} (Q_{95,t} - Q_t) \tag{2.2}$$

Where $t_{s,i}$ and $t_{e,i}$ are the initial and final time steps of the run, respectively. The drought duration can be altered by the phenomena of pooling: one day get a value above the threshold and numerous droughts are calculated as separated event (Figure 2.5).

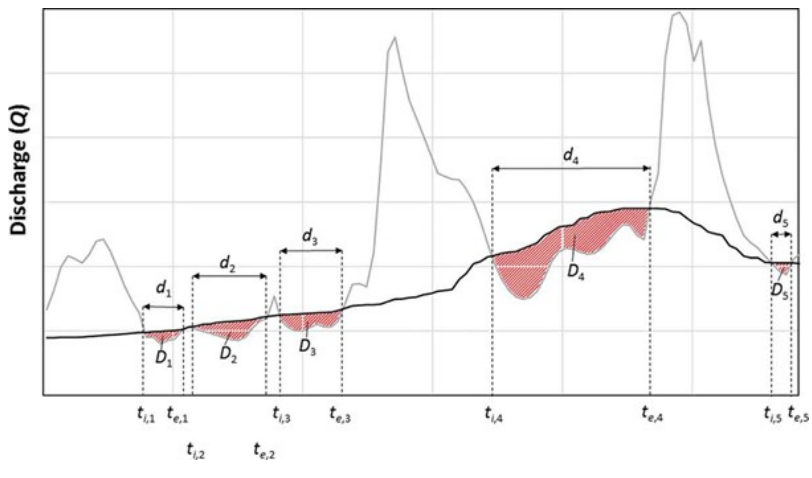


Figure 2.5: Schematic representation of a sequence of runs with examples of total deficit, duration, mutually dependent events and minor events. Discharge (Q) is shown as a grey line and the low-flow threshold (Q95) as a black line [19].

To remediate to this division, Zelenhasićand Salvai (1987) introduced an inter-event time method which define a minimum gap period, t_c under which two small events are considered as one. The Figure 2.6 explain with precision the step where the LFI undergo. The step one is to determine the first event, then to measure its duration.

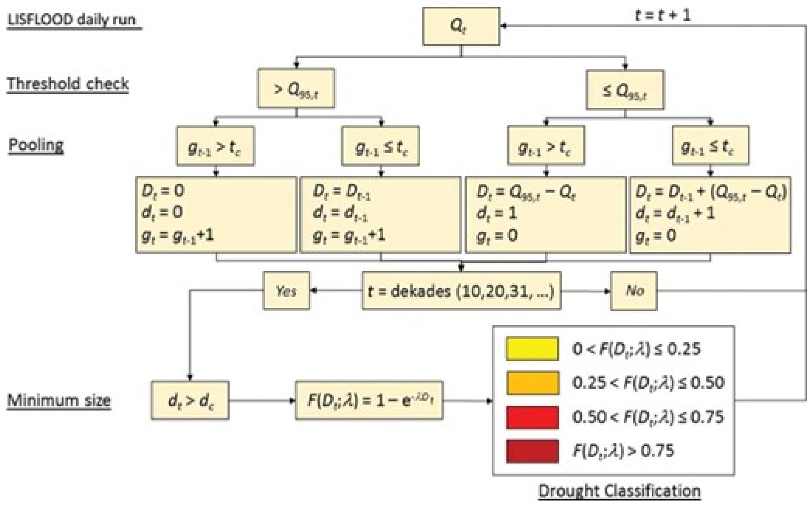


Figure 2.6: Flowchart describing the computational scheme for the implementation of the proposed low-flow index into an operational monitoring system. The variables $Q_{95,t}$ and λ are derived from the historical baseline dataset as described in the text, and the initial conditions are defined as $D_0 = d_0 = 0$ and $g_0 = \infty$. For operational convenience, the decadal FD values obtained are classified into four drought classes based on commonly used quantiles: mild drought: $0 < \text{FD} \leq 0.25$; moderate drought:$0.25 < \text{FD} \leq 0.50$: severe drought, $0.50 < \text{FD} \leq 0.75$; and extreme drought: $\text{FD} > 0.75$

The data analysed are issue from the Interactive Map viewer of the European Drought Observatory (EDO). The LFI has been originally implemented with on discharge data simulated by the LISFLOOD model over Europe for the period between 1995-2015. The use of this modelized data give the possibility to verify obtain with the previous indices and to have an overall visualisation of the 2022 drought.

The calculation of the LFI is the same as the steps explain above in this section. The EDO interactive Map is using a t_c =10 days. It means that every event that has a time gap under 10 days is considered as one only event and their duration is merged. This index however is not sufficient to have precise result, it only gives an overall estimation of the drought.

2.3.5 Testing the data

To verify the trend between the years of the QMNA, the results have been tested by the Man-Kendall method. The variation in year of the QMNA is visible through the calculation of the Sen slope. The Mann-Kendall statistical test [20][21] is a non-parametric statistical test used for trend detection. This test is quite robust because it does not make any assumptions about the distribution of the data. The only assumption made is the independence of the data.

We test the null hypothesis H0: "the series is stationary" against the alternative hypothesis H1: "the series exhibits a trend" at a significance level α. The parameter α is the Type I error rate: it represents the risk of rejecting the null hypothesis H0 when it is true.

The Mann-Kendall test suggests the presence or absence of a systematic trend but does not quantify the intensity of the changes. An order of magnitude for the change is provided by the Sen's slope estimator. By definition, Sen's slope estimator for a set of pairs of points (Xi, Yi), i = 1, ..., n is the median of the slopes (Xi Xj) / (Yi Yj) calculated for all pairs of points. In the context of a trend analysis, Sen's slope is the median of the slopes (Xi Xj) / (ti tj), where (ti) i = 1, ..., n represent the dates associated with (Xi) i = 1, ..., n.

The slope A is used to plot the visible linear trends on summary graphs with the estimated y-intercept as follows: B = γX Aγt where µ represents the respective mean of the two variables [22].

2.4 The meteorological Indexes

The Standardized Precipitation Index (SPI) The diversity of the parameters and precipitation index adapted to specified climate, makes difficult the geographical comparison. The World Meteorological organisation as determine in 2009 the SPI as referent drought criteria. This index has been created to quantify the precipitation deficit for different time scale. Its calculation is based on the probability of precipitation during a certain time laps. The SPI method has been described by Mckee and al. (1993 [23], 1995 [24]) and Edwards (1997) [25]. It is considered a very flexible index, describing wet period as well as dry ones and adaptable to the studied parameter [26]:

- Meteorological anomaly (SPI calculated with a moving average of 1-2 months)
- Agricultural effect (SPI calculated over 3-5 months)

- Hydrological anomaly (SPI calculated over 6-24 months)

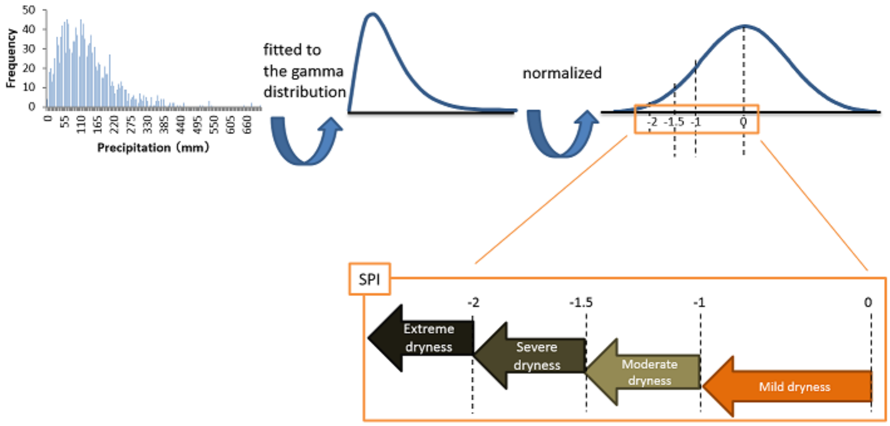


Figure 2.7: Schematic representation of SPI calculation [27]

The calculation of SPI (Figure 2.7 is made based on a long precipitation data-set (at least 20 years) that is fitted to a probabilistic distribution and transformed afterward into a normal distribution for the mean SPI to be equal to 0 (Edwards and MacKee 1997 [25]). The SPI values correspond to the standard deviation of the monthly precipitation value with the median. For the SPI calculated over 1 month the average value of precipitation in this month A is compared with all the average value of the month A of every year. For the SPI with a longer time scale (n months) the average value of the last n month is calculated and compared to the average value of the same time laps of every year of the data set. The resulting dataset is cut from the n-1 first monthly values for which we can't calculate the mean of the n first values. The average of each day is then compared to a distribution fitted to the original's values. The result obtained is the SPI. The negative values indicate a lack of precipitation while the positive values are an increase of precipitation comparing to the median.

In this study the precipitation data are issue from the ERA5-Land, a reanalysis dataset. This reanalysis has been develop by combining model data and observations data from all around the globe. Its grouped monthly mean data for a spatial resolution of 9 Km on a reduce Gaussian grid [28].

The SPI is calculated with R studio trough the package Precintcon Version: 2.3.0 [29]. This package contains multiple functions creating index helpful to analyse the precipitation intensity, concentration, and anomaly. The SPI function is performed using the gamma distribution. Angelidis and al.[30] Presented in 2012 the different possible distributions suitable for the SPI calculation. The gamma distribution went out as the most accurate.

As saw in the presentation of the type of drought, the hydrological drought and meteorological drought are separated by a shift in time. To fully understand the impact of the meteorological drought on the 2022 hydrological drought, the SPIs were calculated on a seasonal period. It gives a better understanding of when the lack of water due to precipitation had an impact on the hydrological water body.

The SPI results in Table 2.2 give an idea of the state of the environment:

SPI values	**Interpretation**
2.0+	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

Table 2.2: SPI values

Chapter 3

Results

3.1 The 2022 drought

In 2022, both the Rhone basin and the Po basin experienced a series of remarkable records. The overall year was characterised by a strongly reduced amount of precipitation and intense temperature.

From October 2021 to March 2022, an unusual weather pattern settled over northwestern and southeastern Europe, resulting in lower rainfall and temperature anomalies of up to 3.5°C in northern Italy. This led to reduced snowfall, causing a decrease in the Po streamflow. From April to August, the negative precipitation pattern persisted due to a North African anticyclone, which contributed to extreme conditions during the summer drought [31]. Even though the end of summer hinted at milder temperatures, the river discharge and water storage recorded by the Autorità di Bacino Distrettuale del Fiume Po in October remained below the seasonal average.

In the Rhone basin, the anticyclone situation led to dry spring conditions resembling summer and a drop in groundwater levels.

The main rivers

Figure 3.1 illustrates the position of the 2022 stream-flow of the main rivers in comparison to the mean and minimum values of each day of the year. In Italy, downstream stations of the river (Boretto and Pontelagoscuro) indicated that the daily streamflow values in 2022 were consistently below average, with over 23% of days reaching their lowest values since 1968. Valence and Beaucaire stations showed fewer extreme values: while over 88% of days were below the average, only 7% of years recorded minimum values at these stations.

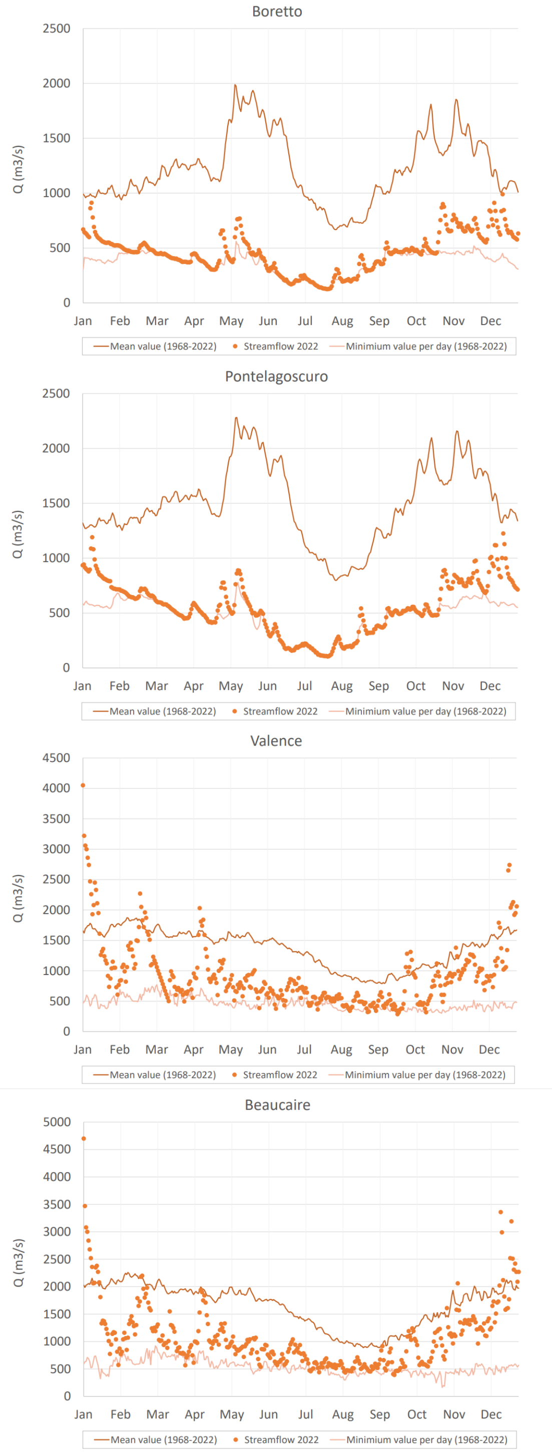


Figure 3.1: Streamflow comparison between the 2022 year and the avreage over 54 years. Boretto and Pontelagoscuroare situated downstream the Po river. Valence and Beaucaire are located on the main Rhone river.

The following table is giving a summary per month of the situation of 2022.

	Boretto	**Pontelagoscuro**	**Valence**	**Beaucaire**
Days of 2022 with streamflow value under the minimum recorded	83	95	34	25
Days of 2022 with streamflow value under the mean value	365	365	322	333
Maximum consecutive days of minimum recorded	8	6	5	5

Table 3.1: Stations details of the Po basin

The situation of the streamflow at the mouth of the river is not independent of the human activities. At the middle of the 20th century, the Rhone River has been heavily modified to develop the hydroelectricity. Between the Leman lack and the Mediterranean Sea, we can count 19 dams with 17 diverting channels [32], while on the Po river, between Turin and Polesella, the streamflow is modify thought 6 dams. Numerous reservoirs are also positioned on the affluent of the rivers, reducing or injecting water in the rivers. The Rhone is the most modified river of Europe, and the effect of these constructions is visible on the mean streamflow over the year. The Figure 3.1 shows a relative constant line for the mean streamflow for valence and Beaucaire while for the Italian stations (Boretto and Pontelagoscuro) the seasonal effect is fully represented with an increase of the average flow before the summer (during the melting season) and during winter. Due to human activities, these stations are not representative of the climate change and evolution of low flow. However, they give an indication on the state of the main canal and the effect of the constructions on the low flow of the drought.

3.2 The meteorological analysis

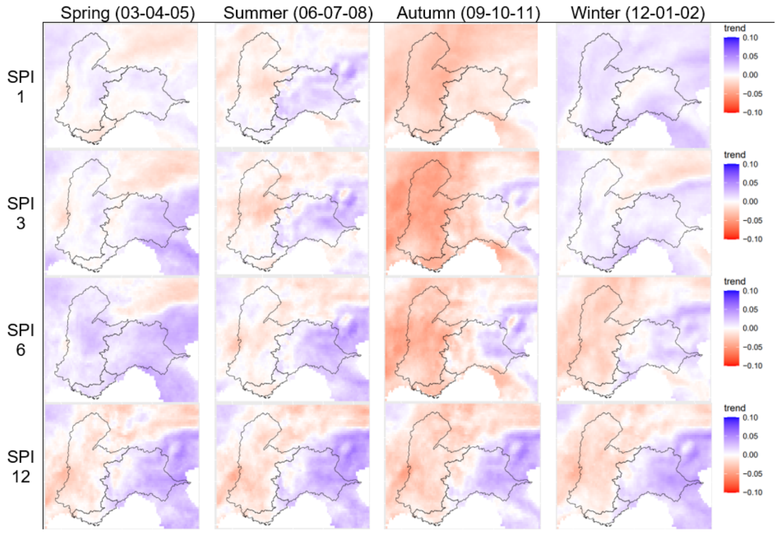


Figure 3.2: Seasonal trend evolution of the SPI from 1990 to 2022

The Figure 3.2 present the evolution of the SPIs trend oven a period of 32 years. The time scale considered for the calculation of the SPI give to the representation of the SPI an impact on different environmental parameters: 3 to 6-month time scales are used in the quantification of the superficial water, while 12 and more months are suitable for the subsoil moisture. The SPI 1 of this figure show the evolution pluviometry of the seasons with a calculus on each month. This index depicts only a small change: the pluviometry within the months wasn't modify. However, a tendency is visible for the months of Autumn.
On the Rhone basin this decrease trend of precipitation in Autumn is even validated by the SPI 3 and SPI 6 meaning the deficit of water is highly impacting the water-body. The Po basin, also witnessed a decrease in its rain amount in the last 32 years but the cumulative calculation assessed by the SPI 3 and SPI 6 shows that the downstream area of the basin has a positive trend. The increasing trend of precipitation occurring in the summer and most probably during the winter are frequent enough to compensate and reverse the negative trend in the Autumn. Spring and Winter are characterised an overall increase of precipitation (SPI 1) However, the negative trend in Autumn have an influence on the winter SPI 6. The cumulative calculation of the precipitation over 6 months shows that the deficit of precipitation in the Rhone basin is still having effect on the winter. The SPI 12 calculated on a full year are presenting the same geographical trend. The natural frontier of the Alps surrounding the Po basin is extremely visible: the trend on the area above

the mountains is negative while the trend on the area under the chain is positive. It implies that the two basins are submitted to different meteorological pattern.

This result can make us wonder how the 2022 year could have been a such critical year, seeing that the Po basin has a yearly increase in his precipitation level.

To acknowledge it we selected only the SPIs calculated on the 2022 year:

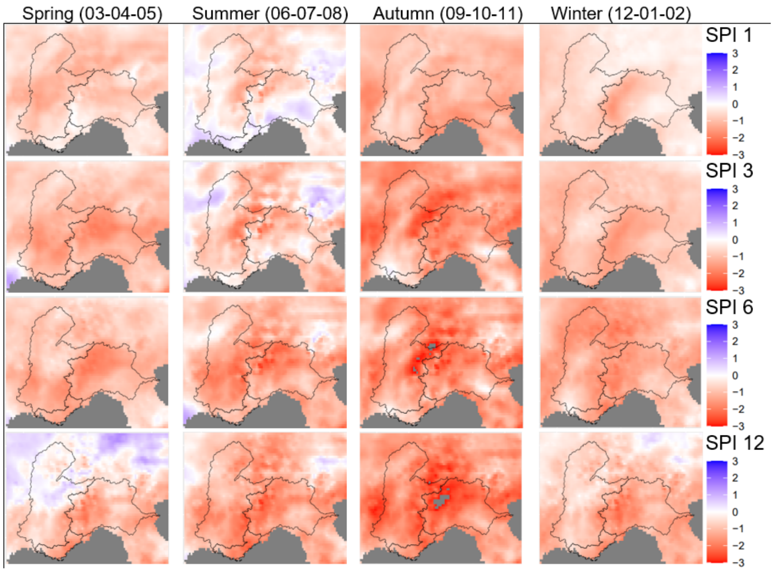


Figure 3.3: Seasonal maps of the SPI (1 – 3 – 6 – 12) of the Rhone and Po basin of the 2022 year

The Figure 3.3 displays maps characterised by extremes negative values of SPI indicating the evolution of an extremely dry year in both basins. As the trend analysis foreshadowed it, the most impacted period of the year is the autumn. Two area seems to be heavily touched by the scarcity: the north Rhone basin on the border with the Alps and the western Po basin near Turin. For the first one, the lack of water is particularly noted in autumn in the SPI 1 to 6. However, during the other seasons, the area is considered a dry land exception made of the spring. The SPI 12 even shows positive values. The second area on the Po basin seems the most impacted by the lack of rain with value of SPI12 even superior to 3. This area positioned just under the mountain chain receive a amount of precipitation way below the normal for the entire year (SPI 1 to 6).

The overall situation confirmed the event of a dry years for both basin and a lack of precipitation during the entire year compared to an average year.

In addition to the trend analysis, the Figure 3.3 contribute to define the year 2022 as a year of record on the two basins. The precipitation trend illustrated the relative change of precipitation of the two basins while the 2022 values of the SPI show the extreme variability of the climate. The next step in this analysis is to compare this result to the hydrological results.

3.3 The Hydrological analysis

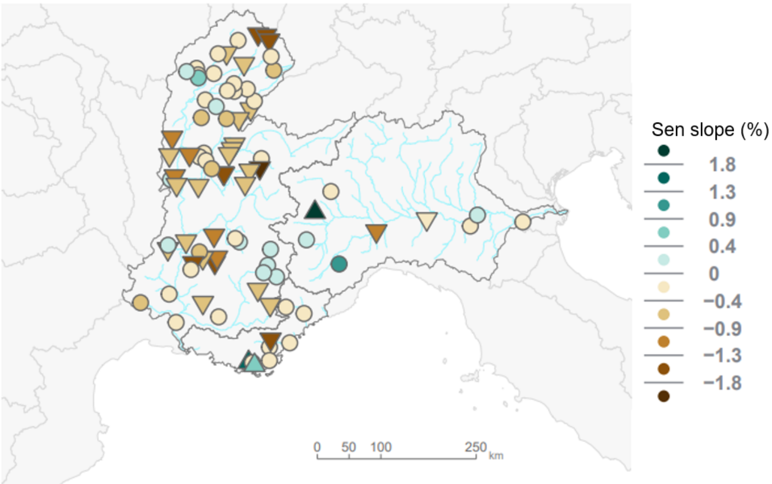


Figure 3.4: Sen slope apply on the QMNA from 1968-2022; triangles points represent the stations for which the trend is validated by the Man-Kendall test.

This map (Figure 3.4) provides the Sen slope for the period between 1968 and 2022. Most of the points show a negative trend. The upper Rhone is particularly affected, while the stations situated in the mountains have increasing values. Both the Rhone River and the Po River display a negative trend at their downstream stations. This implies that if some sources of the tributaries do not experience a decrease in water flow, the basin is still affected by the decreasing water flow of other tributaries. The Figure 2.3 presents the dominant source of streamflow for the Rhone basin, aiding in the understanding of the results. The upper part of the Rhone basin is influenced by a pluvial regime. The SPI 12 index shows a decrease in precipitation during the last three decades. This index corroborates the results depicted on this map since the water deficiency is caused by changes in meteorological conditions. The stations positioned in the middle and downstream of the Po River also indicate a negative trend, however, their trend isn't strong

and some of them aren't validate by the Man-Kendall test. Some value near to the Alps are even showing positive trend, witness of the correlation between the SPI 12 of the Figure 3.2 and the trend observed in Figure 3.4 in the Alpine area.
Considering the geographical position of the basin (bordered by the Alps mountains to the East and North), we can hypothesize that the stations along the main river are influenced both by tributaries with a dominant snow melt factor and stations with a dominant pluviometry factor. This helps explain the slightly negative trend. However, there is a dominant positive trend: the stations at higher altitudes in the Alps mountains, both in France and Italy. These are the stations influenced by Mediterranean snow melt and Mediterranean circulation for those located on the coast.

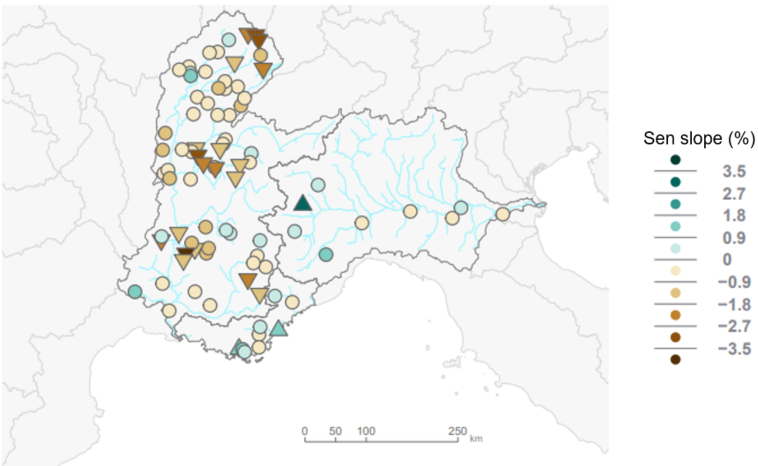


Figure 3.5: Sen slope apply on the QMNA from 1990-2022; triangles points represent the stations for which the trend is validated by the Man-Kendall test.

Figure 3.5 present the same result than the Figure 8 but with the time analysis shorter. The geographical analysis of the tendencies is still valid for this map. The differences are located in the intensity of the trend: The evolution on the last 30 years is stronger, witnessing the overall change at a bigger scale than hydrological change only.

In association with the QMNA study, the VCNs bring an additional information, it allows to exclude short time extreme and show the minimum average on multiple days.

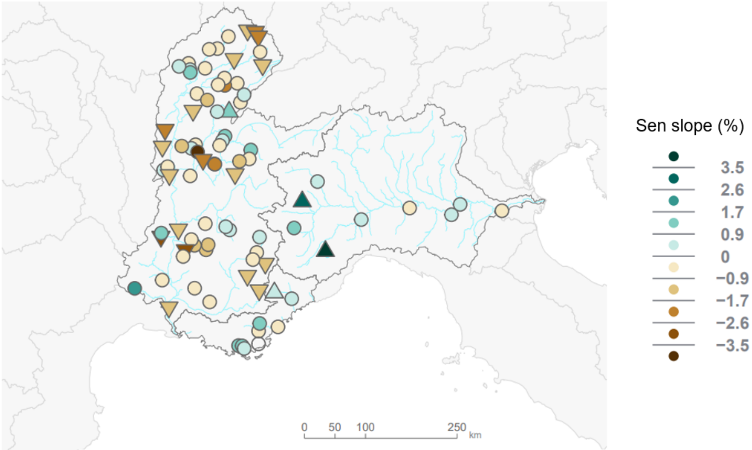


Figure 3.6: Sen slope apply on the VCN3 from 1990-2022; triangles points represent the stations for which the trend is validated by the Man-Kendall test.

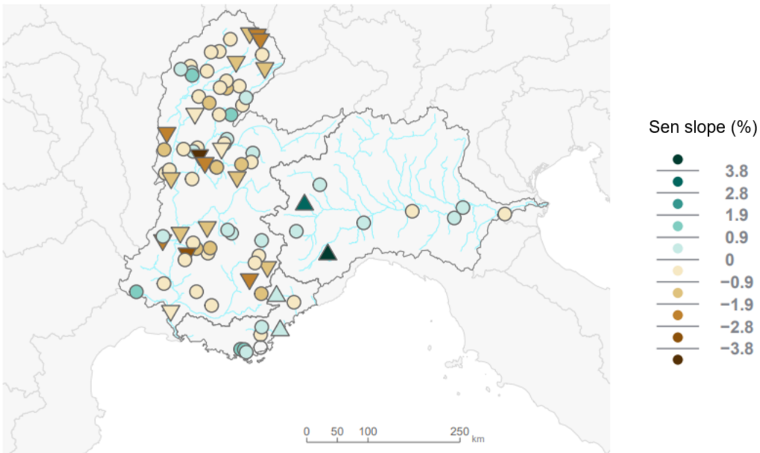


Figure 3.7: Sen slope apply on the VCN10 from 1990-2022; triangles points represent the stations for which the trend is validated by the Man-Kendall test.

The results observed with the VCN 3 and VCN 10 map continue to show similar information. The study of the correlation of QMNA and VCNs can only confirm the trend proposed for each station.

One problem is present : some of the station don't have record of the 2022 year. However, for the station with record, the following graph shows the similitude between the 2022 QMNA and VCNs:

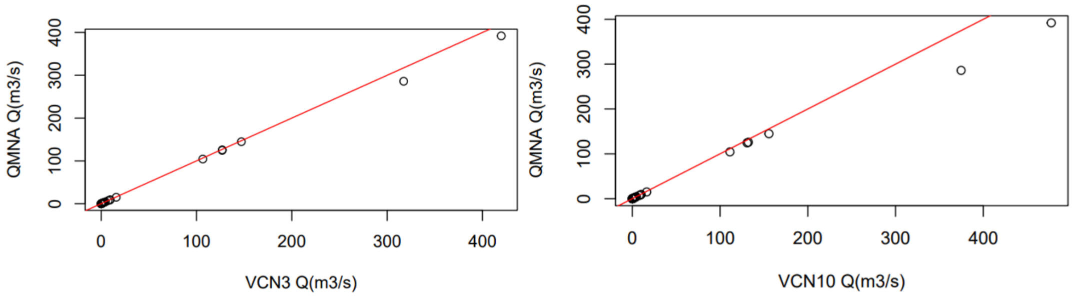


Figure 3.8: Correlation between QMNA and VCNs of 2022

Most of the stations with recorded data from 2022 show a QMNA value similar to VCN3 (Figure3.8). For the Valence and Beaucaire stations, characterized by very high stream-flow values, the VCN10 value differs significantly from the QMNA value. The minimum mean value over a 10-day period exceeds the QMNA for this year. A low mean over a longer period signifies that the scarcity last long in time and wasn't due to a fast drainage. Higher value of QMNA than VCNs would have signify a human activity impact.

However, to assess how exceptional this year is compared to others, the return period for the year 2022 has been calculated for each station.

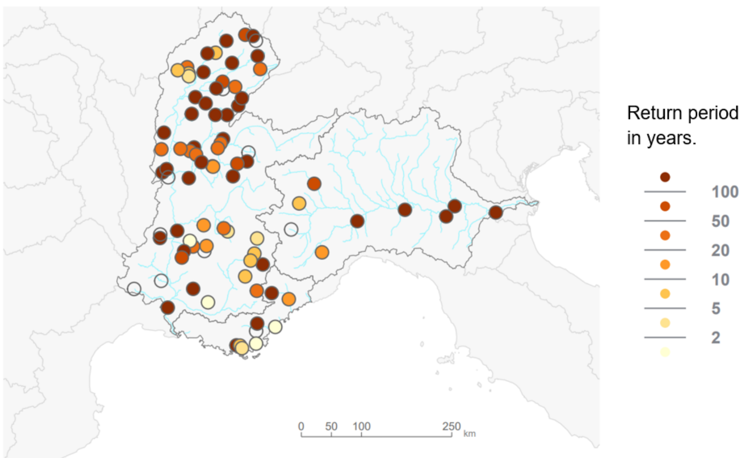


Figure 3.9: Return period associated to the 2022 QMNA. (Repartition of the value in Appendix A.5 and A.4)

Based on the application of lognormal law on the 30 years data set (1990-2022), more than 46% of the station have the value of their QMNA inferiors to a return period of 90 years (Figure 3.9). In France, the multiplicity of the station gives the opportunity to identify the area where the event is has the highest degree of exceptionality. The upper Rhone basin is still the most impacted by the drought, showing low flows with a probability of a 100-year event. Same Situation goes for the man river: the station of Valence and Beaucaire indicate the minimum value of QMNA on the 30 years period. In Italy, the stations on the main river are also witnessing an extreme event.

As for the Figure 3.9, the stations in altitude even though showing a result under the average value, doesn't represent any extreme event.

These indexes are reliable to have an overview of the spatial severity of the drought but the flow evolution during the years isn't visible. This index needs to be completed by a daily analysis.

3.4 The Minimum flow analysis by threshold value

Station Name	Number of days under Q80	Maximum continuous duration under Q80	Period
Le Breuchin à la Proiselière-et-Langle	96	71	07 - 09
La Lanterne à Fleurey-lès-Faverney	129	90	07 - 09
La Saône à Ray-sur-Saône	85	67	07 - 09
Le Salon à Denèvre	128	77	07 - 09
L'Ognon à Servance [Fourguenons]	127	79	07 - 09
Le Rahin à Plancher-Bas	NA	NA	NA
L'Ognon à Beaumotte-Aubertans	144	92	07 - 09
L'Ognon à Pesmes	137	91	07 - 09
La Tille à Arceau [Arcelot]	142	96	07 - 10
La Tille à Cessey-sur-Tille	125	95	07 - 10
La Norges à Genlis	66	27	07 - 08
L'Ouche à Plombières-lès-Dijon	120	86	07 - 10
Le Doubs à Labergement-Sainte-Marie	109	53	07 - 08
Le Doubs à la Cluse-et-Mijoux [Pontarlier amont]	126	124	05 - 09
Le Dessoubre à Saint-Hippolyte	105	43	07 - 08
Le Rupt à Dung	132	91	07 - 09
La Loue à Vuillafans	102	51	07 - 08
Le Lison à Myon - RG technolog puis sonde	NA	NA	NA
La Loue à Chenecey-Buillon	109	51	07 - 08
La Loue à Champagne-sur-Loue	117	52	07 - 08
Le Doubs à Neublans-Abergement	130	68	07 - 09
La Grosne à Jalogny [Cluny]	159	82	07 - 09

La Brenne à Sellières [les forges Baudin]	166	79	07 - 09
La Seille à Saint-Usuge	95	74	07 - 09
La Reyssouze à Montagnat	177	48	07 - 08
La Veyle à Lent	195	85	07 - 09
Le Renon à Neuville-les-Dames	166	88	07 - 09
L'Ardière à Beaujeu	157	82	07 - 09
La Brévenne à Sain-Bel	174	85	07 - 09
L'Azergues à Lozanne	133	65	07 - 09
Le Bronze à Bonneville - Thuet	NA	NA	NA
Le Borne à Saint-Jean-de-Sixt	107	64	07 - 09
La Valserine à Lélex [Niaizet]	117	69	07 - 09
La Valserine à Chézery-Forens [Chézery]	108	69	07 - 09
La Semine à Châtillon-en-Michaille [Coz]	122	50	07 - 08
Le Fier à Dingy-Saint-Clair	103	63	07 - 09
Le Chéran à Allèves [La Charniaz]	135	56	07 - 08
Le Séran à Belmont-Luthézieu [Bavosière]	146	94	07 - 09
Le Groin à Artemare [Cerveyrieu]	146	73	07 - 09
La Bourbre à Tignieu-Jameyzieu	164	75	07 - 09
La Saine à Foncine-le-Bas	96	52	07 - 08
Le Hérisson à Doucier	122	72	07 - 09
Le Suran à Pont-d'Ain	153	95	07 - 09
L'Albarine à Saint-Rambert-en-Bugey	141	87	07 - 09
L'Yzeron à Craponne	NA	NA	NA
La Glueyre à Gluiras [Tisonèche]	111	43	07 - 08
L'Eyrieux à Beauvène [Pont de Chervil]	NA	NA	NA
La Drôme à Luc-en-Diois	NA	NA	NA
Le Bès à Châtillon-en-Diois	121	53	07 - 08

La Drôme à Saillans	109	52	07 - 08
La Gervanne à Beaufort-sur-Gervanne	95	43	06 - 07
Le Roubion à Soyans	125	70	29 - 06
Le Jabron à Souspierre	118	52	26 - 06
La Cèze à la Roque-sur-Cèze	NA	NA	NA
L'Auzon à Mormoiron	158	87	12 - 06
Le Gardon de Saint-Jean à Corbès [Roc Courbe]	90	23	07 - 01
La Bonne à Entraigues [Pont Battant]	102	38	08 - 09
La Roizonne à la Valette [La Rochette]	86	40	08 - 09
L'Adouin à Saint-Martin-en-Vercors [Tourtre]	107	63	06 - 08
La Durance à l'Argentière-la-Bessée	68	53	01 - 03
La Durance à Embrun [La Clapière] - DREAL PACA	154	97	01 - 04
L'Ubaye à Barcelonnette [Abattoir]	193	102	01 - 04
L'Ubaye au Lauzet-Ubaye [Roche-Rousse] - DREAL PACA	240	98	01 - 04
Le Bès à la Javie [Esclangon-Péroure]	251	61	09 - 10
L'Issole à Saint-André-les-Alpes [Mourefrey] - DREAL PACA	238	55	02 - 04
Le Coulon à Saint-Martin-de-Castillon [Coste Raste]	247	167	05 - 11
Le Gapeau à Solliès-Pont	151	113	04 - 08
Le Réal Martin à la Crau [Decapris]	171	53	09 - 10
Le Gapeau à Hyères [Sainte-Eulalie]	68	43	07 - 08
L'Aille à Vidauban [Le Baou]	NA	NA	NA

La Nartuby à Trans-en-Provence [CD 555] - Décathlon	365	365	01 - 12
La Môle au Lavandou [Destel]	172	152	06 - 11
L'Agay [Le Grenouiller] à Saint-Raphaël	8	6	10 - 01
Le Var à Entrevaux [Pont-levis]	300	109	01 - 04
L'Esteron au Broc [La Clave]	252	209	05 - 12
Chisone a San Martino	NA	NA	NA
Dora Baltea a Tavagnasco	120	40	03 - 04
Stura di Lanzo a Lanzo	185	107	01 - 04
Tanaro a Farigliano	277	106	09 - 12
Tanaro a Montecastello	249	172	06 - 11
Boretto	293	164	05 - 10
Borgoforte	295	166	05 - 10
Piacenza	347	120	01 - 05
Pontelagoscuro	322	169	05 - 10
Beaucaire	163	36	08 - 09
Valence	170	89	07 - 09

Table 3.2: Duration of the low flow under Q80 per stations.

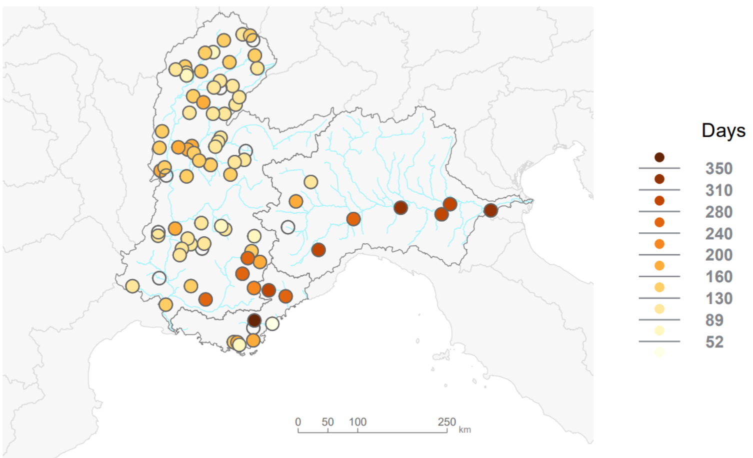
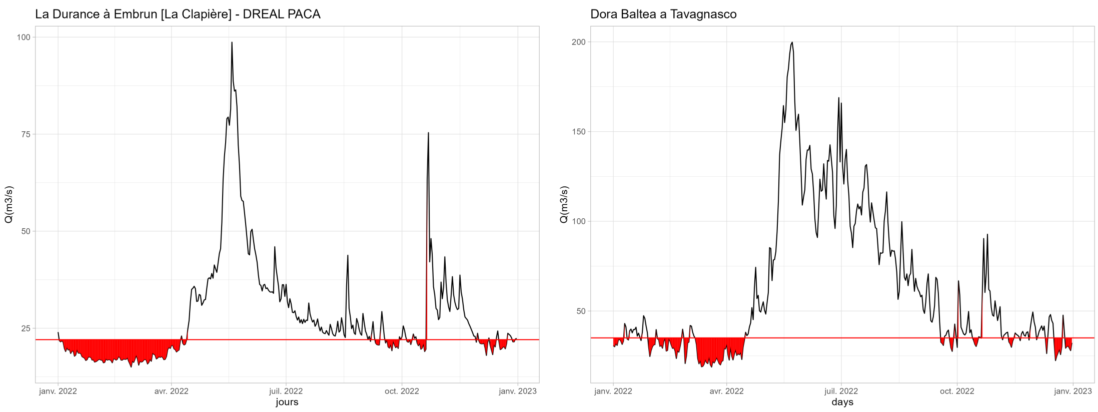


Figure 3.10: Number of days Q2022<Q80 calculated over a period of 30 years.

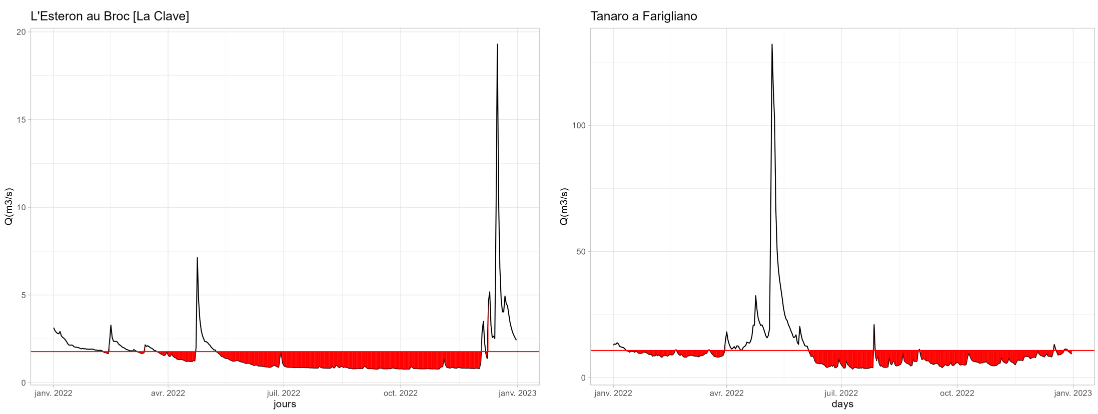
The evaluation of the number of days under the annual threshold flow with an 80% probability of exceeding shows another aspect of the 2022 drought on the basins. Even though the value of the return period of the QMNA was less pronounced for the mountainous area, the duration of the scarcity are higher for this region. The Italian basin shows less points of record for 2022, however every flows regimes was represented by at least one station. These stations are influenced by human activities as are the Beaucaire station and the Station of Valence. However, the two French stations recorded less than 170 days below the threshold while, all the Italian station are in situation of scarcity for more than 290 days.

As presented in Figure 2.3, the hydrographs have different aspect depending on their water supplies. The following Figure illustrate examples of such differences:

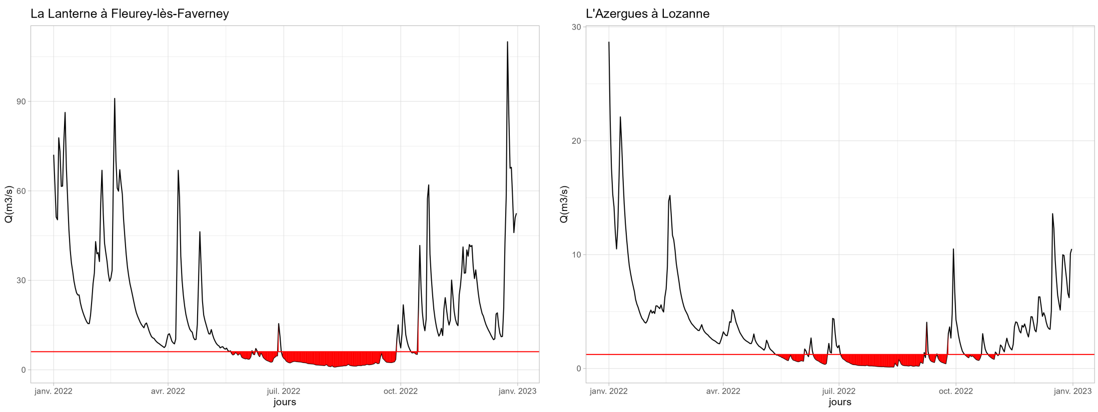
Alpine stations



Alpo-Mediterranean station



North Rhone basin area



Italian stations on or closed to the main river

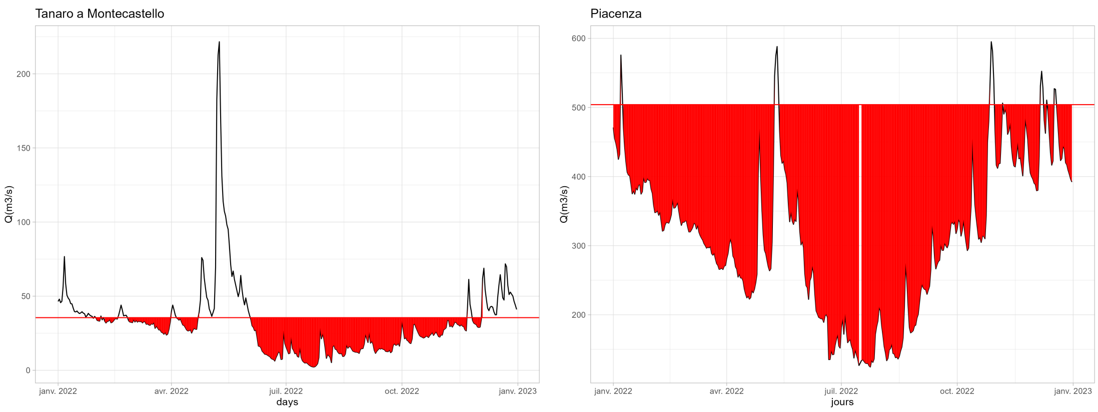


Figure 3.11: Hydrographs of the 2022 years with the annual threshold flow with an 80% probability of exceeding are various localisation on the map

The difference between the 4 specified localisation is revealing of the evolution of the drought in the area. The alpines stations (Figure 3.11) are led by the snow melting season between April and May for the Italian as for the French ones. Following this time, the stream-flow finds a normal level of flow, above the threshold. The Alpo-Mediterranean station seems to be the most touched station in France, with almost the full year streamflow under the threshold. A pic of streamflow is visible in May, result of the snow-melt, but this pic isn't high (in countrary of the rain season, where the pic recorded is higher) and the period end fast. The summer and Autumn hit the most with almost all of the value under the Q80 threshold. Same situation is observed at Farigliano where the majority of the recording are under the threshold but where the snow-melt period has a more important effect

If the QMNA analysis show that record has reach in the north of the Rhone basin, the duration of the scarcity in the river is not as alarming than for the other stations. The stream-flow recorded in this area is driven by the meteorological condition. Even though the winter was dry, the rain event was enough to keep the flow above the threshold. The low QMNA values come from the long duration and extreme low flow recorded during this period.
This is not the case of the Italian station on the main river. As seen before in the main river analysis, the 2022 years was probably the hardest recorded for these stations. Neither the rain, the snow-melt coming from the affluent could preserve the streamflow to be at almost 80% of the time under the threshold of Q80%.

The duration of the scarcity in the two-basin variate depending on the localisation of the stations. The stations the more affected are the snow-melt related station and the Italian stations. These latter ones, however, are affected by human activities. The management of the drain and water release in the river is specific to certain management policies and so, are different.

Chapter 4

Discussion and Conclusions

4.1 A global analysis

This analysis has shown the similarities and differences of the two basins. The meteorological analysis predicted a more intense lack of water for the area of the Alps on the frontier, with particularly extreme values around the city of Turin. However, the daily and QMNA analysis revealed that the Alpine stations from France and Italy are the least affected by the hydrological scarcity of the period. A more in-depth analysis with the snow-melt result and the temperature result could help understand the evolution of the high altitude stations records. Moreover, the ephemeral rivers are not represented, and only a few studies mention them. Their recording could provide additional information on the state of the soil even in the mountainous area.

The plain land of the Rhone and Po River is both particularly affected by hydrological scarcity but for different reasons. The North Rhone basin has shown a drop in pluviometry that has affected the tributaries of the Rhone, while the mouth of the Po basin had a reduced streamflow due to the additional lack of water in its tributaries and human actions. The stations at its mouth have recorded the worst year in 30 years. The Rhone basin doesn't have this fate due to heavy modifications made on the main river that have removed the seasonality effect from its hydrographs.

Globally, apart from the Alpine station, autumn was the most critical season for the rivers. The SPI analysis also pointed to this conclusion for the entirety of the two basins.

Aside from climate change and meteorological analysis, the evolution of the hydrological data records depends on the policies taken by the authorities during dry periods and especially drought periods.

To complete this analysis, the Rhone-Alps region policies and Po basin policies policies have been compared.

4.2 The policies

4.2.1 A European discussion on the drought theme:

The European Geoscience Union (EGU) [33] has published a study on the management of the 2018 and 2019 drought in Europe. This discussion between countries assesses the perceptions and results of the monitoring strategies of each country. Multiple indices were considered. The result of this study enlightens the benefit of having national and international drought risk management. A drought is not contained on a national scale but can impact and have various results throughout the continent. The conclusion also proposes some possible guidelines and strategies for the countries: the establishment of a clear and global definition of drought in the Water Framework Directive, the development of specific guidance on drought indices, and "the formation of an inter- and trans-disciplinary collaborative EU working group focusing on drought risk management and estimation of the potential benefits and downsides of a European Drought Directive."

4.2.2 The Rhone basin policy

In France, the 2022 drought was managed through the application of the July 23, 2021 decree on water restrictions. This decree aims to ensure the organization of crisis management and the principles of implementing measures to limit water withdrawals by different users. It has been defined with four levels of severity: vigilance, alert, reinforced alert, and crisis. In 2022, the state of crisis was reached in coastal departments and some others, and the state of reinforced alert was declared in almost all the Rhone basins (Figure 4.1) In the case of the 4^{th} level of severity, water resources are dedicated only to uses classified as a priority (Table 4.1)[34].

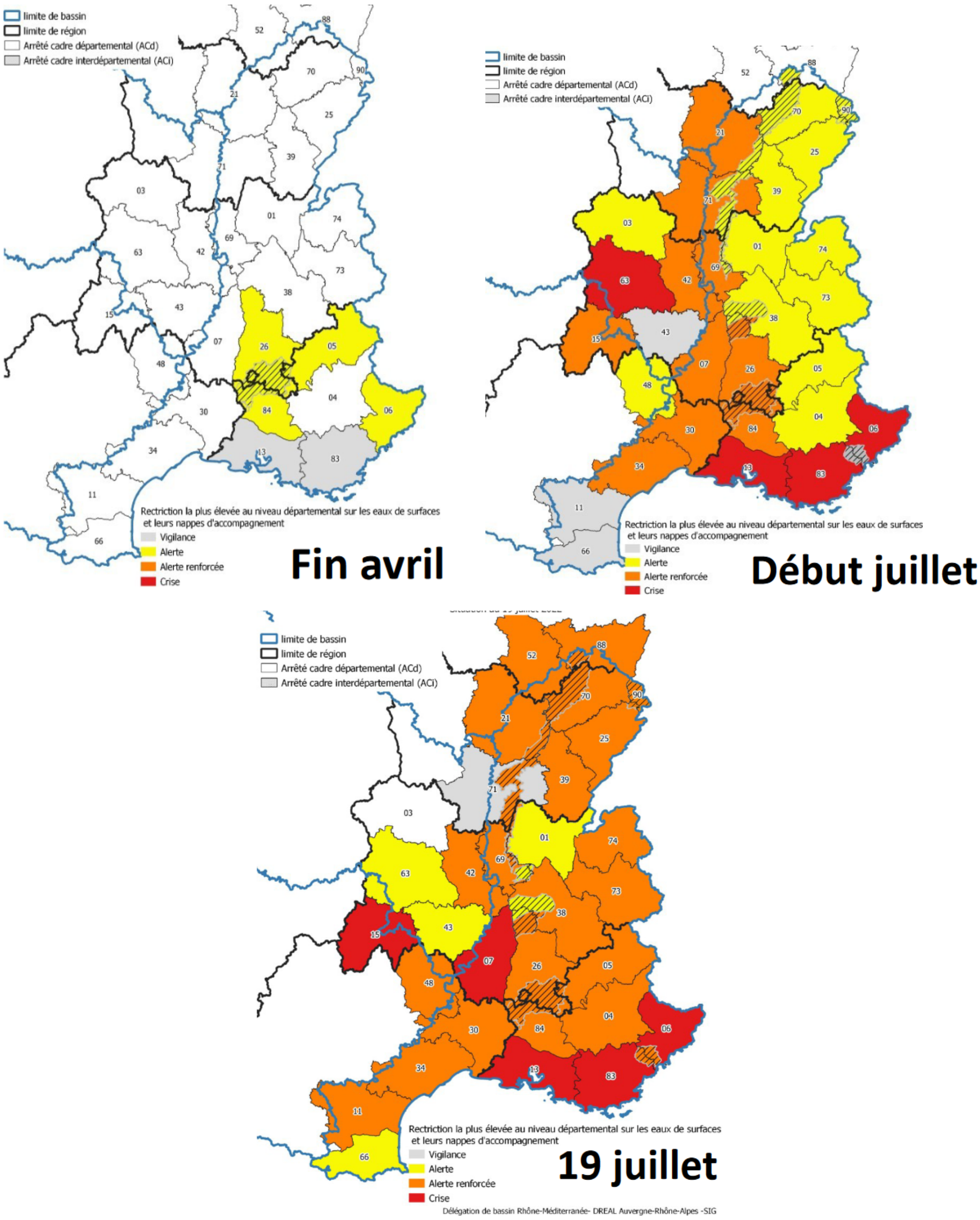


Figure 4.1: Evolution of the gravity map in the Rhone basin [34]

Category	**Essential**	**Exemption / Adaptation**	**Limitation during Crisis**
Domestic: Drinking water	YES	Restriction of consumed volumes depending on situation	
Domestic: watering, washing, swimming pool	NO	Prohibition	Health or safety imperative
Communities: watering, washing, fountain	NO	Prohibition	Health or safety imperative (except problem of drinking water)
Economical: watering, washing	NO	Prohibition	Health imperative, green of golf courses (except drinking water)
Industry	NO	Very significant reduction in pumping	If provided for in ICPE order or health and safety issues
Nuclear energy production or hydraulic	YES	Limitation of draining and rejections	Case by case if security issues, environment or securing national electric production
Agriculture: individual irrigation or collective	NO	Prohibition of irrigation, reduction of pumping in canals	Non-conforming crops on max 10% of the irrigated UAA + hydraulic safety of canals
Agriculture: watering, fish farming	YES		
Leisure: swimming, water sports	NO	Draining/filling prohibition of water bodies, use restrictions.	Commercial use upon Police de l'eau

Table 4.1: Water consumption policies during a crisis event.[34]

The actions taken during these extremely dry events aim to sensitize the population to induce a reduction in potable water consumption and to prevent forest fires by linking the drought risk to the risk of forest fires. More controls are organized to verify the application of the legislation.

Following this drought episode, a preparation plan for an extreme drought situation was created: the plan ORSEC eau potable. This policy is based on four pillars:

- Warn the population,
- Secure the network,
- Pumping the water from secondary source (from authorized and if necessary unauthorized resources),
- Rationalization and prioritization of the water use with as a last resort, the injection of non-potable water in the domestic network.

To stay informed about the decrees regarding drought management, the website VigiEau [35] is a regularly updated national tool.

4.2.3 The Po basin policy

On the Italian basin, the restrictions are also reinforced. The monthly reports made by the Autorità di Bacino del fiume Po define the severity level for the year 2022:

January	**February**	**March**	**April**	**May**	**June**
	Low without precipitation	Low without precipitation	Medium with precipitation	Medium with precipitation	Medium with precipitation
July	**August**	**September**	**October**	**November**	**December**
High	High	High	Medium with precipitation	Medium with precipitation	

Table 4.2: Severity of the hydrological volume

The report of August also provides guidelines for the authority to establish water restriction policies and raises questions about the management of water bodies [36].

The anterior measures defined in the previous report were followed to preserve the use of potable water while maintaining good quality in the surface waterbody and groundwater.

The August report present a new plan to address the condition of extreme dryness in the basin. Two axes of work were defined: legislation related to pumping and legislation related to the discharge into the environment:

- A reduction of the daily drainage exceeding 20% of the average for 3 consecutive Mondays.
- Interruption of the exemption for the use of irrigation (except for permanent crops or crops, but only after an evaluation of their needs).
- Evaluation of the volume of water in the Alpins lakes and reservoirs in order to authorize a possible increase in discharge in compatibility with the water level and the optimized use of the hydropower stations.

The Autorità di Bacino Distrettuale del Fiume Po has defined the terms of a new project financed by the EU: the Life Climax Po, which discusses the implementation of adaptation strategies to face climate change [37]. This involves:

- Improving the governance of climate adaptation in the Po River basin and incorporating it into the governance model by developing guidelines, tools, and methodologies
- Informing and educating the public on the subject
- Developing water security by improving water retention structures and enhancing nature-based solutions.

The Polytechnic of Turin actively contributes to this project, providing a scientific environment for the development of management operations for the extensive Alpine lakes and artificial reservoirs. The university is also engaged in evaluating water needs for agriculture uses and river management in the event of floods. In pursuit of one of the project's objectives, Polito is working on popularizing and establishing an adapted culture to address current environmental challenges[38].

4.3 Conclusion

The 2022 drought set numerous records in Europe, with SPI values sometimes even lower than -3, indicating an extremely dry year. The Rhone and Po basins recorded alarmingly low flows in their stations. Depending on their location and associated flow regimes, the duration of the scarcity and the value of the extreme varied.

While the alpine stations had the least alarming QMNA results in 2022, they remained below seasonal norms throughout the entire year. The North Rhone basin, under a pluvial regime, exhibited extremely alarming results due to the lack of precipitation in 2022. However, the most dramatic results were recorded at the mouth of the Po basin, where 23% of the days were registered as minimum in the last 30 years. In comparison, the stations at the mouth of the Rhone recorded only 7% of the days as minimum.

This difference is due to different factors. The lack of rain was more important in the Po basin for the years 2022 (especially in the area around the city of Turin) while the infrastructures on the mains rivers and the legislation in place in the two basins differ. However, the trend of the SPI 12 over 32 years shows a increasing dryness over the Rhone basin while in contrary, the Po basin is receiving more rain. These two analysis are enlightening the effect of the Alps mountains on the meteorological regime of this regions.

Appendix A

Appendix

A.1 Dominant factor affecting the streamflow signature

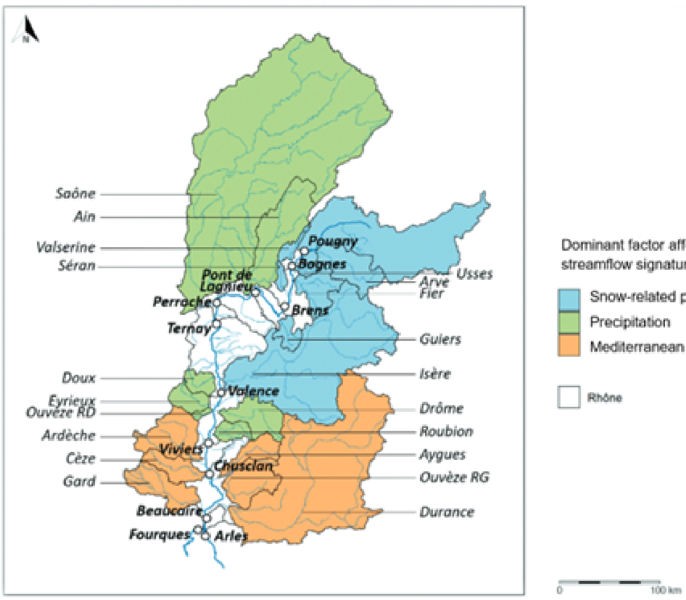


Figure A.1: Rhône basin with their dominant factor affecting the streamflow signature[13]

A.2 Italian data

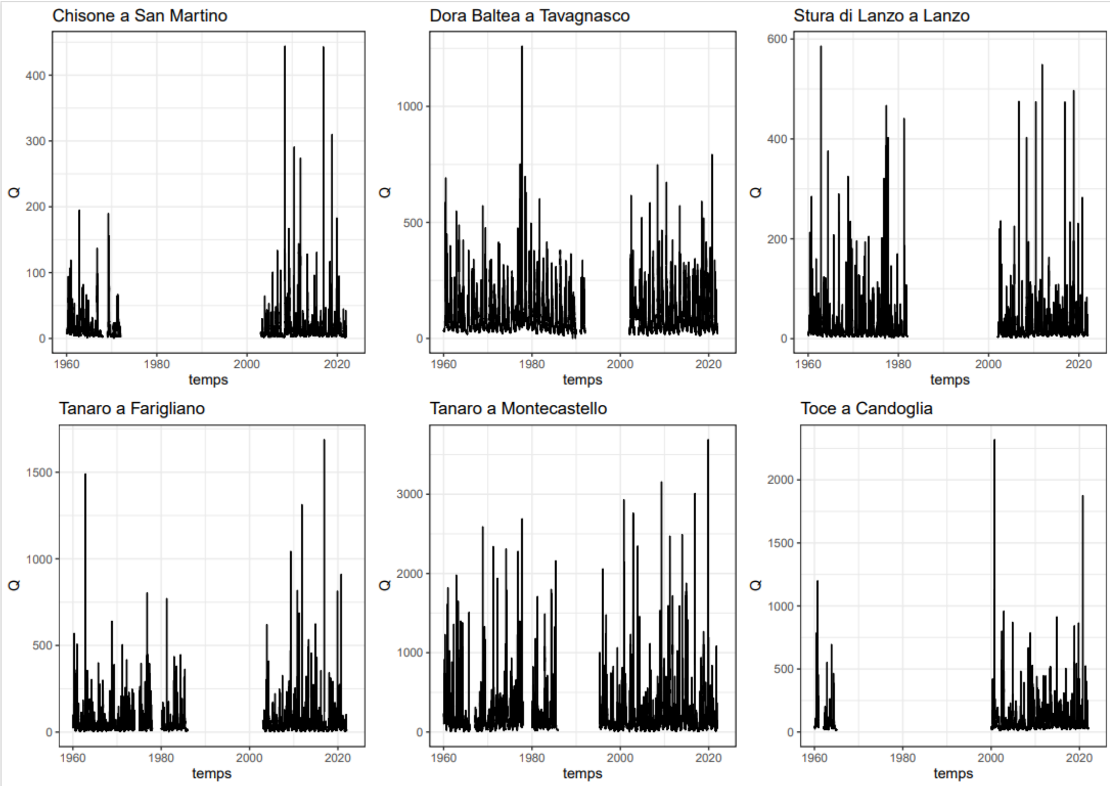


Figure A.2: Piedmont stations

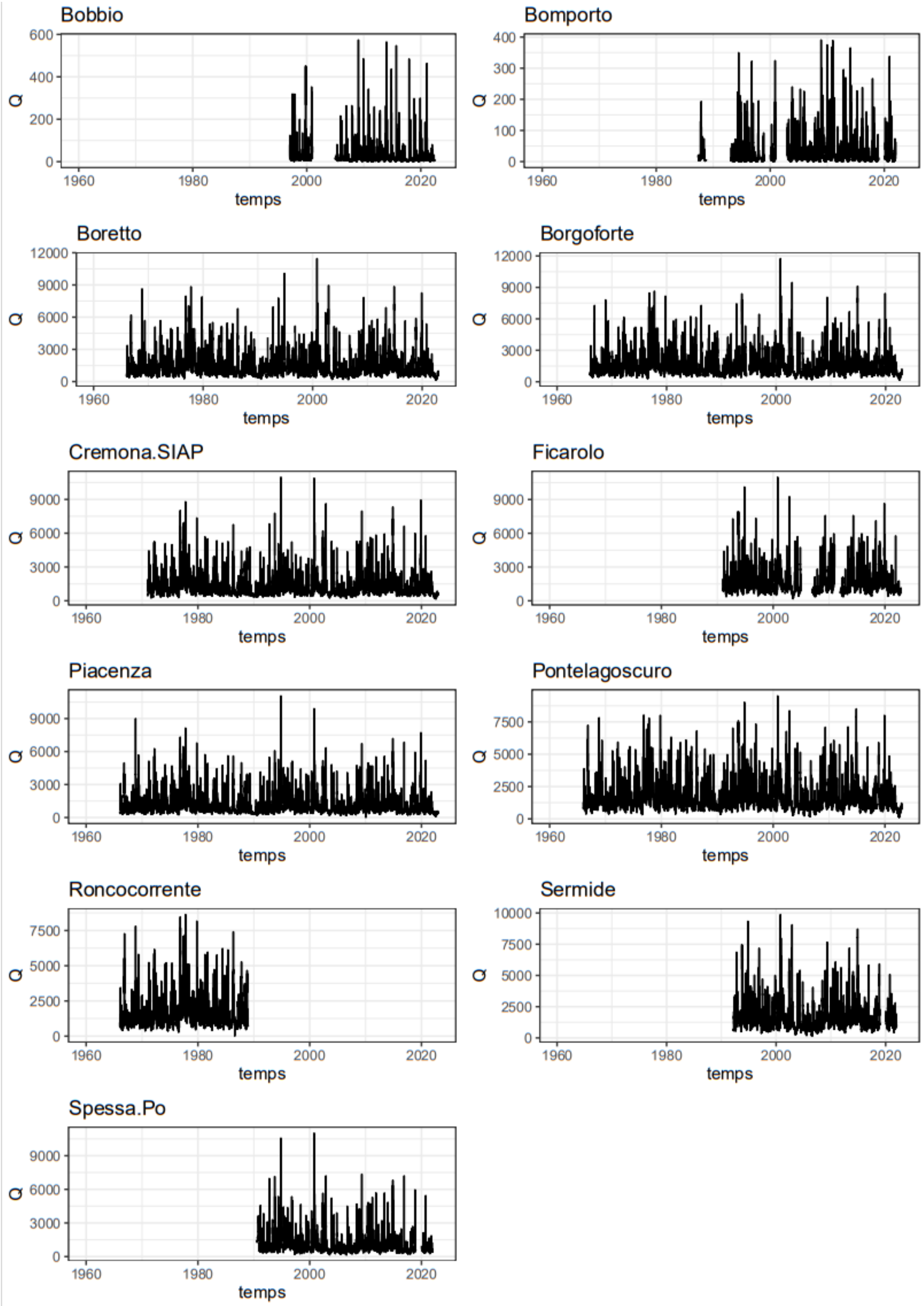


Figure A.3: Po basin stations

A.3 QMNA precision

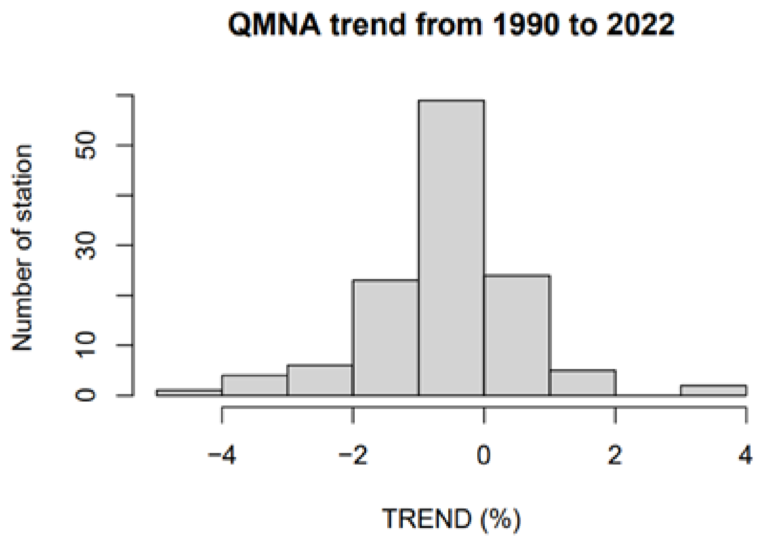


Figure A.4: Sen slope per stations from 1990 to 2022

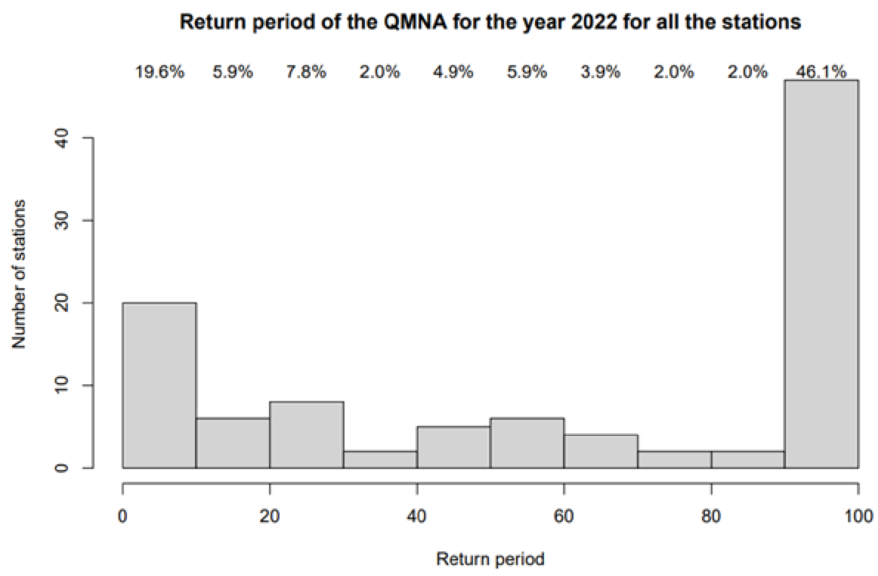


Figure A.5: Repartition return period of the QMNA for the year 2022

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