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Review

Drought in the Po Valley: Identification, Impacts and Strategies to Manage the Events

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Abstract: The area surrounding the Po River, known as the Po Valley, provides a central contribution in the economy of Italy and is highly devoted to agriculture. Recently it has been hit by multiple droughts, among which the exceptional event of summer 2022 is considered the worst dry period of the past 200 years. In the near future, the frequency of such exceptional events is predicted to rise; thus, a deep knowledge of the past droughts that hit the area, the variables used to characterize the events, the impacts they caused and the mitigation strategies adopted to deal with dry periods is of the utmost importance for policy definitions and planning. This study maps the scientific literature published from 2000 to February 2024 on the topic of drought in the Po Valley using the Scopus and Web of Science databases. Overall, 44 articles have been identified and grouped in three main classes: event identification and characterization, impact analysis and management strategies. The main gaps found in the collected papers are the lack of evaluations of the impacts of drought events on human health, hydroelectric energy production and tourism. Furthermore, comprehensive drought management and planning in the area is never addressed in the considered articles. The mentioned aspects deserve more attention, especially the development of drought management plans and policies and the evaluation of their effectiveness.

Keywords: Po Valley; drought; drought impacts; drought management

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1. Introduction

The Po River, with its 652 km of length, is the major Italian watercourse. It originates at Pian del Re from Mount Monviso, flows eastward across Northern Italy touching cities such as Tourin, Piacenza and Cremona and ends with a delta entering into the Northern Adriatic Sea near the city of Venice (Figure 1). The river is located between the Alpine and the Apennines chains and its watershed has a surface of around 86,859 km^2, most of which (82,788 km^2) belongs to the Italian territory [1]. The vast valley around the river is known as the Po Valley (or Po plain); the area incorporates the part of the Po River basin belonging to the Italian territory. Almost all of the non-Italian basin is located in Switzerland, primarily in the Canton Ticino, which is crossed by the river Ticino, one among the most important tributaries of the Po. The small Diveria River, that flows through the Canton Valais (Switzerland) and the Verbania-Cusio-Ossola province (Italy), is a tributary of the Toce and therefore, through Lake Maggiore and River Ticino, of the Po. Thus, also a minor area of the Canton Valais belongs to the Po basin as well as minor areas located in France (Valle Etroite). The annual mean temperature ranges between 5 and 15 °C, with the lowest values in the Alpine areas and highest in the Apennines zones [2]. The valley has a humid, sub-tropical climate according to the Koppen classification with high values of relative humidity increasing from south to east due to the peculiar conformation of the valley [3]. The average annual precipitation is around 1200 mm, mainly distributed in the spring and autumn months. The valley exhibits low winds, which are especially weak in the winter season and show some of the lowest average speeds across the whole European continent [4].

The average Po River discharge at the station of Pontelagoscuro (located close to the city of Ferrara) in the period from 1970 to 2021 was 1509 m^3/s (data retrieved from https://doi.org/10.5281/zenodo.7225698, accessed on 10 February 2024). The river's highly complex hydrological regime is divided into three hydroclimatic regimes [5]: the Apennine rivers, which display a minimum in summer due to rainfall controlling their regimes; the snow-dominated Alpine reach, which typically peaks in flow between spring and summer; and the deltaic system, which is included in the UNESCO Man and Biosphere Program due to the region's high biodiversity and wide variety of habitats [6].

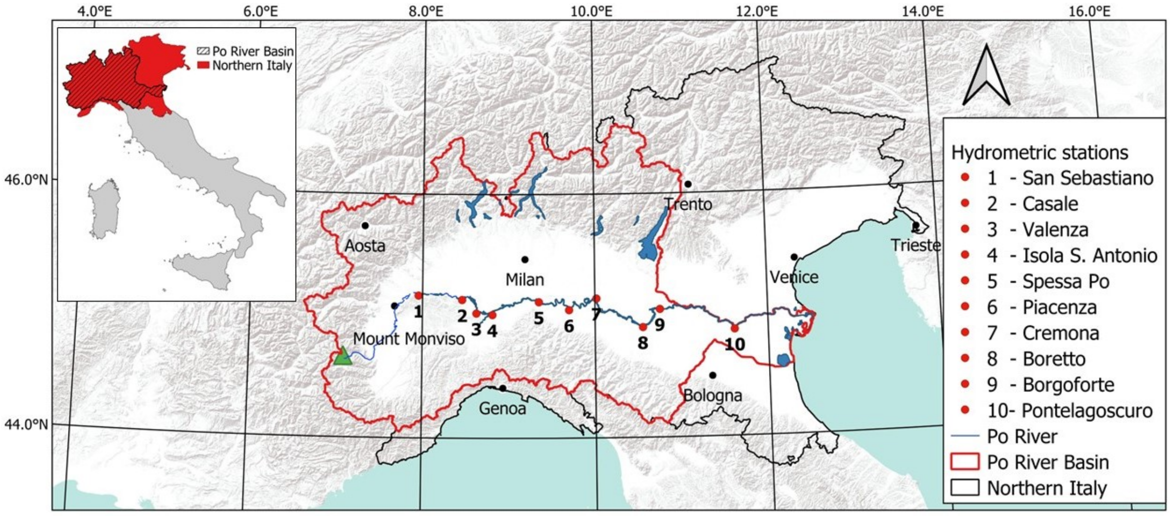

Figure 1. Location of the Po River, the Po Basin, the principal cities of the area and the hydrometric stations mentioned in the text.

The Po plain is home to about 23 million people, i.e., more than one-third of Italian citizens [7]. The region is among the most densely populated of Europe due to the abundance of cities with more than 100,000 inhabitants (Milan, Tourin, etc.) and a population density of about 355 people per km^2.

The Po valley is the most important economic area of Italy. It generates more than 34% of Italy's value added, and 29% of the country's industrial and service companies are based there [8]. The Po plain is a hub for industrial and agricultural activities, with a variety of industrial specializations, including food, clothing, textiles and mechanics. In addition, the Po Valley is one of the biggest agricultural regions in Europe and produces 35% of all crops farmed in Italy, with maize and rice being the principal crops planted there along with vegetables and orchards [9]. Furthermore, 55% of the Italian livestock production derives from only five provinces located in the Po plain [8].

The Po Valley is also the area with the highest number of hydroelectric plants in Italy. In 2016, 36% of the Italian hydroelectric plants were installed in Piedmont and Lombardy and generated 42% of the national hydroelectric power [10].

In recent years, the area has been hit by multiple hydrological extremes, among which the severe drought of 2022 that forced the Italian Government to declare a state of emergency from July to December 2022 for those areas inside the Po and the Western Alps basins [11]. Given the persistency of dry conditions, at the end of 2022 the Italian Government decided to prolong the emergency for another twelve months[12]. The 2022 event is reported as the worst hydrological drought experienced in the area based on a 216-year river flow time series at the Po outlet (hydrometric station of Pontelagoscuro) [13]. Even if the sustained negative precipitation anomaly that characterized the 2022 event is unlikely to become a common feature of the future climate, it could significantly increase its frequency, particularly in a severe climate change state [14].

Climate forecasts for the Po plain predict fewer wet days and more intense precipitation during storms [15]. An increase in drought severity in Northern Italy, in terms of duration and percentage of drought-affected area, is also foreseen for the latter part of the century; the Alpine area will be significantly affected by higher positive temperature anomalies; recurring drought conditions will reduce the water availability for agriculture and power generation [16].

Given the relevance of the area of the Po Valley in economic terms and its high population density, the analysis of past droughts, the impacts they have caused and the management strategies that have been suggested or implemented to deal with the events is crucial to enhance the resilience of the basin to future extremes. This study thus aims at:

1. Identifying past droughts that have been reported in the area and review the indicators employed to characterize the events;
2. Analyzing the impacts of the identified extremes;
3. Revising the management strategies implemented or proposed to better deal with droughts;
4. Pointing out the literature gaps in both event identification, reported impacts and management strategies.

The article is structured as follows: Section 2 describes the methodology adopted to retrieve the studies analyzed while Section 3 discusses the results of the analysis and the literature gaps.

2. Materials and Methods

The initial step of this analysis is the identification of the pertinent scientific literature published from 2000 to February 2024 on the topic of drought in the Po Valley. The literature research was performed through the use of the online collections of Scopus (https://www.scopus.com/, accessed on 28 February 2024) and Web of Science (https://www.webofscience.com/, accessed on 28 February 2024). The two databases have been selected since they are the most renowned online databases for scientific literature investigation and are widely recognized for their reliability, completeness and multidisciplinary content.

The following criteria were applied to select the relevant literature:

1. The document must be published as a review or an article in a peer reviewed journal;
2. The document must be written in English;
3. The document must deal with the Po River and the valley surrounding the watercourse; therefore, the documents focused on the Poyang Lake (also known as Po Lake) located in China have been discarded, as well as those dealing with phosphates (PO) in rivers.

The keywords reported in Figure 2 have been used as the search criteria to identify the relevant literature. The papers were then further evaluated based on their relevance to the subject and split into three groups:

1. Articles dealing with drought events identification and characterization;
2. Articles describing the impacts of droughts;
3. Articles proposing drought management strategies or evaluating their effectiveness.

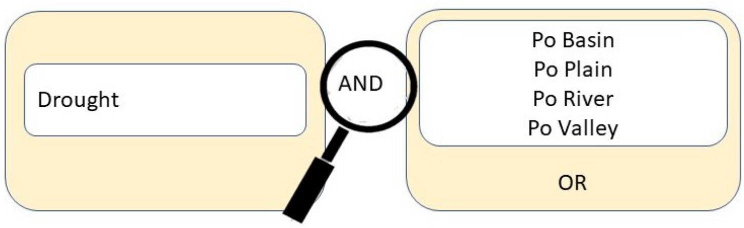

Figure 2. Search strategy: list of the keywords used to select the pertinent scientific literature.

3. Results and Discussion

Overall, 44 articles (reported in Table A1) were identified (Figure 3). No papers were published between 2000 and 2005; the number of articles dealing with droughts in the Po area dramatically increased in the most recent years (Figure 4). Six papers were published in 2020, and eleven in 2023, indicating the increase in attention on the topic that follows severe or extreme events such as those of 2017 and 2022.

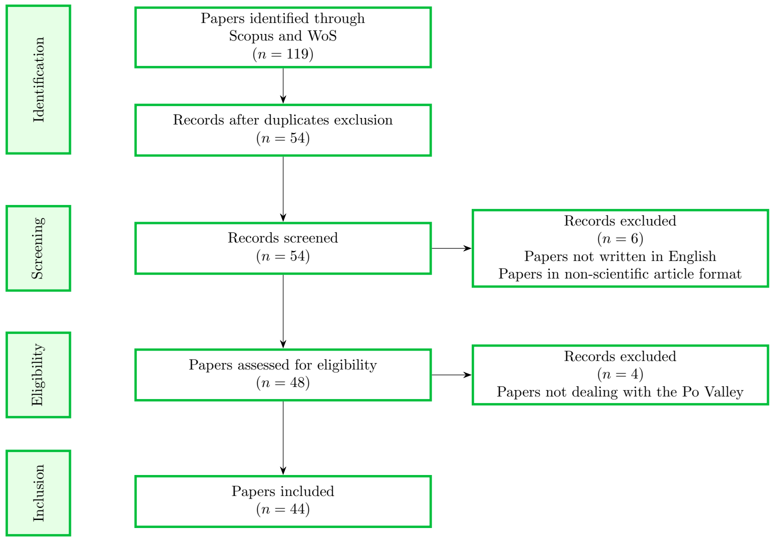

Figure 3. Flowchart showing the process and the criteria applied for searching and identifying the papers to be included in the review. The search period goes from 2000 to February 2024. WoS: Web of Science.

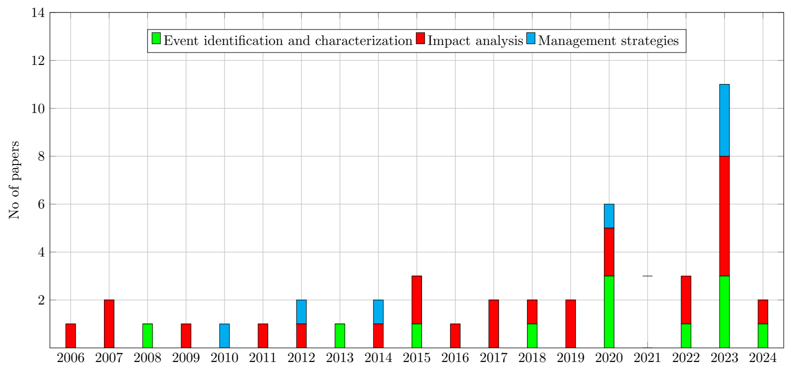

Figure 4. Number of papers published between 2000 and February 2024 on the topic of drought in the Po Valley and topics addressed by the literature.

The 44 papers have been divided into three groups according to their aim. The first group includes the papers focusing on event identification and characterization; the second covers articles describing the impacts of the drought events and the third those works dealing with drought management strategies. The major part of the analyzed papers evaluates the impacts of one or multiple drought events (twenty-five studies, representing 58% of the sampled papers), twelve papers deal with drought event identification and characterization, while only seven articles deepen drought management strategies (Figure 4). In the following sections, the three groups are investigated in detail.

3.1. Events Identification and Characterization

Twelve of the reviewed papers deal with event identification and characterization. The main drought events over the 1900–2023 period retrieved from the selected articles are reported in Table 1. The recent 2022–2023 event is the most reported one; it is characterized in four papers, and by many documents released by the Po River Basin Authority (Autorità di Bacino Distrettuale del Fiume Po, ADBPO [17]). Additionally, seven studies describe the impacts associated to that event. It is followed by the 2003 event, characterized in five papers and analyzed through impact reporting in six other works. The 2006 event is instead reported in four articles and its impacts are explored in a further four studies.

The 2022–2023 drought is regarded as the most severe event that has affected the Po Valley. Actually, the mean Po River flow observed in summer 2022 was the lowest in the past two centuries [13]; the March 2022 Snow Water Equivalent (SWE) broke all negative records over the 1930–2023 period [18], and there has been a sequence of severely dry seasons (December–August and February–August) with no precedents with respect to the 1976–2005 period [14].

The 2003–2004 event lasted for 27 weeks and affected 58% of the basin area according to the Standardized Precipitation Evapotranspiration Index (SPEI) timeseries, making it the longest extreme event over the 1961–2017 period [19]. In the series of both the Standardized Precipitation Index (SPI) and the SPEI, 2003 was the driest year on records (during the 1951–2017 period); it was marked by a dry spell in summer with extreme temperature values combined with little precipitation [20]. The event severely impacted crop production, forcing farmers having to start irrigation earlier than usual, and dramatically reducing water availability in some zones of the Apennines [8]. Even if the drought started in summer 2003, it involved mainly the autumn and winter seasons, and thus it is not considered as one of the most severe ones in the Old World Drought Atlas [21], a product providing yearly maps until 2012 of dryness and wetness across Europe based on the reconstruction of the June–August Palmer Drought Severity Index (PDSI) through tree rings.

The 2006 event instead was characterised by lower-than-normal precipitation in May, June and July that, combined with limited snow melting, brought a low river discharge [22–24]. Thus, a meteorological drought resulted in a hydrological drought with various negative consequences, among which the most reported was a severe saltwater intrusion [25]. The event appears to be one of the most severe even in the Old World Drought Atlas. The dry periods in 1943–1952 and the 2005 and 2007 events are each reported by five papers, while the 2017 drought is reported by four articles (Table 1). Quite obviously, the most reported events coincide with the most extreme ones.

The index and indicators used to identify and characterize the drought events are highlighted in Table 1. The chosen indices are those traditionally employed to detect the various types of droughts. The already mentioned SPI and SPEI, applied for meteorological drought monitoring, are used in [19], and the AI (Aridity Index) is applied in [26] to assess the impacts of drought on crops. Agricultural drought indices such as the Normalized Difference Vegetation Index (NDVI) are used by [27], while indicators employed for the detection of hydrological drought, as the river discharge and the water level are used in many works (as for example [22,23]), together with the Standardized Annual Streamflow (SAS) reconstructed by [5]. The Snow Water Equivalent is applied by [18] to evaluate the anomaly in snow and thus detect the contribution given by the lack of snow to the drought conditions.

The bulletins released with a monthly frequency by the authority in charge of monitoring water use in the Po Basin district (Osservatorio Permanente sugli utilizzi idrici nel distretto idrografico del fiume Po of the ADBPO) show the trend of ten drought indices (as evidenced in Table 2) for the 2022–2023 drought event. The selected drought indices take into account meteorological (SPI, SPEI, Standardized Temperature Index, STI and SCDDI, Standardized Continuous Dry Days Index) and hydrological (SFI and Standardized Voulme Index, SVI) droughts, without considering agricultural drought. The analysis of indices' trend shows that the 2022–2023 was mainly a hydrological drought; severe and extreme values of SFI and SVI were reported during the entire 2022 and in some months of 2023 (February and March) in all the hydrometric stations of the Po River, while the meteorological drought hit only some areas of the valley. The assessment of lakes' water level is an added value of the documents, and an aspect never mentioned in the scientific literature.

It is interesting to note that combined drought indices, such as the Combined Drought Indicator (developed by [28] applied by the European Drought Observatory to issue drought alerts, are never used in the reviewed literature, as well as multivariate drought indices such as the Multivariate Standardized Drought Index (MSDI) proposed by [29]. However, the combination of multiple variables from different environmental compartments has proven to be more effective than the use of single variables or indices to detect and characterize drought conditions [30]. Moreover, drought characterization through soil moisture is never performed in the selected studies, although the variable is essential for agricultural drought monitoring and can now be retrieved from various products, such as ERA5, a reanalysis dataset available in near real time, and the Global Land Data Assimilation system [31], that combines remote-sensing and station-based data with land-surface models to produce soil parameters. Moreover, none of the cited studies applies the Palmer Drought Severity Index (PDSI) for drought detection or soil moisture balance estimation, even if many global datasets of the index are available today [32]. Soil moisture is positively correlated with crop-yield anomaly [33] and its use in agricultural drought monitoring could be interesting to identify conditions that can lead to crop failure.

Table 1. Summary of the events reported in the analyzed literature over the period 1900–2023. SAS: Standardized Annual Streamflow, SWE: snow water equivalent, NAO: North Atlantic Oscillation, NDVI: Normalized Difference Vegetation Index, SPI: Standardized Precipitation Index, SPEI: Standardized Precipitation Evapotranspiration Index, LST: Land Surface Temperature.

Event Date	Index/Indicator	Source (Event Identification)	Source (Impacts)
November 1920–December 1921	SAS	[5,34]	
March 1938	SPI, River discharge	[18,24]	
June–August 1943	SAS, River discharge, NAO, SWE	[5,18,22–24]	
November–December 1983	SPI, SPEI	[19]	
January–February 1989	SPI-SPEI	[19]	
May–June 1989	SPI-SPEI, River discharge	[19,23]	
July–November 1990	SPI-SPEI, River discharge	[19,23]	
November 1997–April 1998	SPI-SPEI	[19]	
June–September 1998	SPI-SPEI	[19]	
March–April 2002	SPI-SPEI	[19]	
August 2003–March 2004	SPI-SPEI, River discharge, NAO, NDVI, LST	[19,20,22,23,35]	[36–41]
May–August 2005	SPI-SPEI, NDVI, LST, River discharge, NAO	[23,24]	[27,37,39]
June–August 2006	River discharge	[22–24,42]	[25,36,43,44]
August–October 2007	SPI-SPEI, NDVI, LST	[19]	[27,36,37,40]
February–April 2012	SPI-SPEI, NDVI, LST	[19]	[27,41]
June–September 2012	SPI, SPEI, SWE	[18,19]	[43]
November 2015–February 2016			[36,37,43,45]
June–December 2017	SPI-SPEI, NDVI, LST	[19],	[27,46,47]
January–April 2019	SWE	[18]	
June–August 2020	SPI-SPEI, NDVI, LST		[27]
May 2022–April 2023	SWE, AI, River discharge	[13,14,18,48]	[9,26,49–52]

Table 2. Drought status over the 2022–2023 period according to the periodic bulletins released by the ADBPO [17]. SFI: Standardized Streamflow Index, SPI: Standardized Precipitation Index, SCDDI: Standardized Continuous Dry Days Index; STI: Standardized Temperature Index, SPEI: Standardized Precipitation Evapotranspiration Index, SVI: Standardized Volume Index.

Month	SFI1	SFI3	SPI1	SPI3	SCDDI	STI1	STI3	SPEI1	SPEI3	SVI1
January 2022			Near normal	Near normal	Near normal	Near normal	Near normal	Near normal		Como lake: moderate drought
February 2022	Piacenza:extreme drought; elsewhere moderate	Near normal	Moderate drought	Moderate drought	Moderate drought	Near normal	Near normal	Western area: moderate drought; elsewhere: near normal		Lake Maggiore: severe drought; Lake Iseo: severe drought; Lake Como: near normal; Lake Garda: near normal
March 2022	Piacenza: extreme drought (SFI < -2.5); elsewhere: extreme drought (SFI $= -2$)		Northern area: moderate drought; elsewhere: near normal	North wesr: from moderate to severe drought (SPI3 < -1 SPI3 < -2); elsewhere: near normal	North west: from moderate to severe drought	Near normal	Western area: moderate drought; elsewhere: near normal	Northen area: moderate drought; elsewhere: near normal		Lake Maggiore: extreme drought; Lake Como: moderate drought; Lake Iseo: moderate drought; Lake Garda: near normal

Table 2. *Cont.*

Month	SFI1	SFI3	SPI1	SPI3	SCDDI	STI1	STI3	SPEI1	SPEI3	SVI1
April 2022	Extreme drought		Piedmont and Lombardy: from moderate to severe drought; elsewhere: near normal	Piedmont and Lombardy: from moderate to severe drought; elsewhere: near normal	Near normal	Near normal	Western area: moderate drought; elsewhere: near normal	Southern part of Piedmont and Lombardy: moderate drought; elsewhere: near normal	Southern part of Piedmont and Lombardy: severe drought; elsewhere: moderate drought	Lake Maggiore: extreme drought; Lake Como: moderate drought; Lake Iseo: extreme drought; Lake Garda: near normal
May 2022	Piacenza: extreme drought; elsewhere: moderate drought	Extreme drought	Northern area: moderate drought; elsewhere: near normal	Emilia Romagna: near normal; elsewhere: from moderate to extreme drought	Near normal	Western area: extreme drought; elsewhere: near normal	Western area: moderate drought; elsewhere: near normal			Lake Maggiore: severe drought; Lake Como: near normal; Lake Iseo: moderate drought; Lake Garda: moderate drought
June 2022	Extreme drought	Extreme drought	Western area: from moderate to severe drought; elsewhere: near normal	Moderate drought	Near normal	Southern Piedmont: extreme drought; Western area: moderate drought: elsewhere: severe drought	From moderate to extreme drought	Severe drought	Lombardy and Emilia-Romagna: extreme drought; elsewhere: severe drought	Lake Maggiore: severe drought; Lake Como: severe drought; Lake Iseo: severe drought; Lake Garda: moderate drought

Table 2. *Cont.*

Month	SFI1	SFI3	SPI1	SPI3	SCDDI	STI1	STI3	SPEI1	SPEI3	SVI1
July 2022	Extreme drought	Extreme drought	Eastern area: from moderate to severe drought; Valle d'Aosta: extreme drought; elsewhere: near normal	Moderate drought	Near normal	Piedmont and Lombardy: extreme drought; elsewhere: severe drought	Extreme drought	Severe drought	Severe drought	Severe drought
August 2022	Extreme drought	Extreme drought	Northern area: from moderate to severe drought; elsewhere: near normal	From moderate to severe drought	Near normal	Western area: moderate drought; elsewhere: near normal	North west: severe drought; elsewhere: moderate drought	Near normal	North west: from severe to extreme drought; elsewhere: near normal	Lake Maggiore: severe drought; Lake Como: extreme drought; Lake Iseo: severe drought; Lake Garda: severe drought
September 2022	Extreme drought	Extreme drought	Near normal	North west: from moderate to severe drought; elsewhere: near normal	Near normal	Southern area: moderate drought; elsewhere: near normal	Western area: severe drought; elsewhere: near normal	Near normal	North west: from severe to extreme drought; elsewhere: near normal	Lake Maggiore: severe drought; Lake Como: near normal; Lake Iseo: severe drought; Lake Garda: severe drought

Table 2. *Cont.*

Month	SFI1	SFI3	SPI1	SPI3	SCDDI	STI1	STI3	SPEI1	SPEI3	SVI1
October 2022	Extreme drought	Extreme drought	Near normal	Central area: moderate drought; elsewhere: near normal	Near normal	Extreme drought	Westren area: from moderate to severe drought; elsewhere: near normal	Eastern area: extreme drought; elsewhere: near normal	Near normal	Lake Maggiore: moderate drought; Lake Como: near normal; Lake Iseo: moderate drought; Lake Garda: moderate drought
November 2022										
December 2022										
January 2023	Piacenza, Cremona and Pontelagoscuro: moderate drought: Boretto and Borgoforte: near normal	Moderate drought	South west: moderate drought; Emilia Romagna: from moderate to severe wet; elsewhere: near normal	South west: moderate drought; eastern area: moderate wet; elsewhere: near normal	Lombardy and Valle d'Aosta: from moderate to extreme drought; elsewhere: near normal	Northern area: severe drought; elsewhere: moderate drought	Moderate drought	Emilia-Romagna: moderate wet; elsewhere: near normal	Emilia-Romagna: moderate wet; elsewhere: near normal	Lake Maggiore: moderate drought; Lake Como: near normal; Lake Iseo: moderate drought; Lake Garda: severe drought

Table 2. *Cont.*

Month	SFI1	SFI3	SPI1	SPI3	SCDDI	STI1	STI3	SPEI1	SPEI3	SVI1
February 2023	Piacenza, Cremona and Pontelagoscuro: moderate drought: Boretto and Borgoforte: severe drought	Piacenza: extreme drought; Cremona and Ponte-lagoscuro: moderate drought; elsewhere: extreme drought	Northern area: extreme drought; elsewhere: near normal with wide areas in moderate drought conditions	South west: moderate drought; elsewhere: near normal	Near normal	Eastern area: from severe to extreme drought; elsewhere: near normal	Moderate drought	Near normal	Near normal	Lake Maggiore: moderate drought; Lake Como: near normal; Lake Iseo: moderate drought; Lake Garda: severe drought
March 2023	Piacenza, Cremona and Pontelagoscuro: extreme drought: Boretto and Borgoforte: severe drought	Piacenza, Cremona and Ponte-lagoscuro: extreme drought: Boretto and Borgoforte: severe drought	Near normal	Near normal	Near normal	Near normal	From moderate to extreme drought	Near normal	North west: moderate drought; elsewhere: near normal	Lake Maggiore: moderate drought; Lake Como: near normal; Lake Iseo: near normal; Lake Garda: extreme drought
April 2023	Extreme drought	Extreme drought	South east: from moderate to extreme drought; elsewhere: near normal	Moderate drought	Near normal	Piedmont: mderate drought; elsewhere: near normal	From moderate to extreme drought	Near normal	Souther area: severe drought; elsewhere: moderate drought	Lake Maggiore: moderate drought; Lake Como: near normal; Lake Iseo: near normal; Lake Garda: extreme drought

Table 2. *Cont.*

Month	SFI1	SFI3	SPI1	SPI3	SCDDI	STI1	STI3	SPEI1	SPEI3	SVI1
May 2023	Near normal		Emilia Romagna and Piedmont: extreme wet; elsewhere: moderate wet			Near normal		Near normal		Near normal
June 2023	Near normal	Piacenza and Pontelagoscuro: severe drought; Cremona, Boretto and Borgoforte: moderate drought	Near normal	Emilia Romagna and Piedmont: extreme wet; Alps: moderate drought; elsewhere: moderate wet	Near normal	Piedmont and Lombardy: moderate drought; elsewhere: near normal	Near normal	Near normal	Emilia Romagna and Piedmont: extreme wet; elsewhere: near normal	Near normal
July 2023	Near normal									Near normal
August 2023	Piacenza, Cremona and Pontelagoscuro: severe drought: Boretto: moderate drought; Borgoforte: near normal									Near normal
September 2023	Near normal									Near normal
October 2023	Near normal									Near normal
February 2023	Near normal									Near normal

A further consideration concerns the start and end periods of the reported drought events. The beginning and conclusion of a drought are not always coherent among the various documents that report the same event. This clearly depends on the indices used for event detection that can identify meteorological droughts, due to a lack of precipitation, in advance with respect to hydrological droughts that are linked with a reduced river streamflow. The discrepancy in the reported events among the articles published in the literature should again be related with the use of different indices for event characterization. Nonetheless, the 2022–2023 event was identified independently from the index used. The bulletins of the ADBPO reported reduced streamflow, low precipitation (in terms of both rainfall and snow) and high temperatures and are coherent with the cited literature, that underlines the exceptionally low river discharge [13], the extremely negative SWE [18] and the negative values of AI [26]. The 2003 event was again detected by the major part of the considered indices: SPI, SPEI, NDVI and river discharge. The situation appears to be different for the 2006 drought. In the cited literature the event is detected only through reduced river discharge; however, the 2005 dry period, identified through SPI and SPEI, could probably be considered the meteorological drought that has driven the hydrological drought of 2006.

3.2. Impact Analysis

Fifty-seven percent of the reviewed documents, corresponding to 25 articles, deal with drought impact analysis. The considered impacts range from crop losses due to water scarcity to changes in the ecosystem compositions of the river and increase in nitrate pollution concentrations in water due to the decrease in the river streamflow.

The impacts described in the reviewed papers have been divided into the following classes:

1. Impacts on agriculture (agricultural): reduction in crop yield, increase in water used for irrigation, etc.
2. Impacts on the economy (economic): increase in commodities prices, changes in goods production practices, etc.
3. Impacts on river hydrology (hydrological): interactions between the main river and the groundwater, changes in the water cycle, etc.
4. Impacts on river ecology (ecological): change in nutrient concentration or in species density or behaviour, etc.
5. Impacts on water pollution (pollution): increase in pollutant concentration in water, etc.
6. Impacts on multiple sectors (multiple): more than one of the previously described impacts is reported.

Thirty-six percent of the papers reporting drought impacts are focused on the ecological effects of dry conditions (Figure 5).

According to [53], the drought spell length has a significant impact on macroinvertebrate assemblages in the Po River. The recent increase in drought frequency is expected to impoverish benthic communities in prealpine rivers. Ref. [25] analyzed phytoplankton composition and its abundance along the Adriatic coast from January to September 2006. The study discovered that during the 2006 drought (January to June), the small cell size diatoms belonging to the *Cyclotella* and *Thalassiosira* genus, which can grow in oligotrophic conditions, were present. Ref. [54] found that the amount of phytoplankton in the Po River exhibits peaks and low values, primarily linked with floods and droughts.

The presence of coleopters of the species *Agabus paludosus* in the interstitial zone of the Po River streambed during droughts was documented by [55]. It was hypothesized that these coleopters, which are commonly found in the steam banks of the Po River, enter the substratum to escape unfavorable hydrological conditions and stay confined to the interstitial zone until water returns. According to [46], the hyporheic zone, a sedimentary area where surface water and shallow groundwater mix, is a crucial part of the suite of refuges for invertebrate communities in the event of water scarcity. It helps the local fauna adapt to disturbance events like droughts. The study also found that the hyporheic zone could be a potential source of recolonization after flow resumption, or stresses caused by strong withdrawal of surface water. Ref. [27] evaluated the vegetation response to drought and discovered that in the Po area the vegetation types with the stronger response to droughts are those that are highly perturbed by agriculture, while herbaceous communities and woods are less sensitive and recovered rapidly after a drought. Ref. [56] assessed the role of riparian vegetation in mitigating drought risk founding that riparian areas are effective in regulating hydrological extremes such as floods and droughts. Finally, two articles concentrated their attention on saltwater intrusion: ref. [38] stated that, even during a particularly dry year like 2012, continuous measurements of total dissolved solids and piezometric heads near a Po river canal showed that freshening was taking place in the unconfined aquifer's shallow section while the bottom part was marked by high relic salinity; ref. [44] investigated the dramatic saltwater intrusion of 2006 and found a negative correlation between salinity and NDVI, indicating that vegetation in the study area was heavily affected by saltwater intrusion.

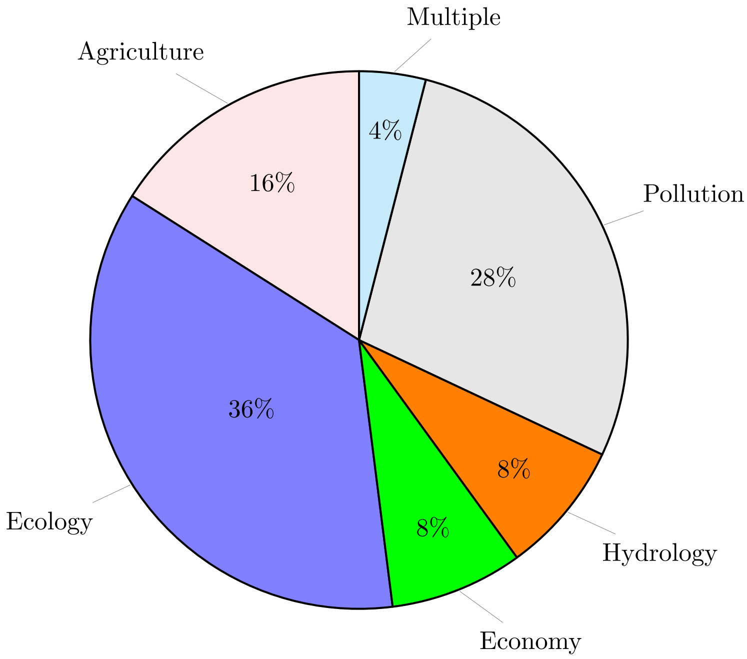

Figure 5. Drought impacts reported in the considered articles.

Twenty-eight percent of the reviewed articles deal with pollution propagation in the Po river during droughts. Ref. [49] investigated the consequences of saltwater intrusion on nitrogen dynamics during the 2022 summer drought; the high concentration of nitrogen in the Po River water, combined with saltwater intrusion, could be a relevant driver for eutrophication of both the river and the Adriatic Sea. Ref. [43] emphasized that the severe drought that occurred in 2012 lead to soil fracturing, which allowed quickly contaminated water to seep into the ground during the first fall rainfall events, resulting in nitrate peaks of several grams per liter. Ref. [39] reported that periods of reduces Po River streamflow affect the biogeochemistry of the North Adriatic; the decrease in phosphorous during droughts might enhance oligotrophy. Ref. [40] underlines that changes in nutrient dynamics in the Northern Adriatic Sea suggest that human activity and river water discharges have significantly influenced the sea's productivity over the past 40 years. Future changes are therefore expected, especially in the event of severe droughts and a further decline in anthropogenic phosphorus loads.

Ref. [57] came to the conclusion that the isotopic variance throughout different hydrological periods (droughts and floods) is limited, plausibly because the different contributions pertaining to surface runoff and groundwater recharge have homogenized. Ref. [47] report that the isotopic anomaly detected during the 2017 drought is larger at the watercourse's terminal section, where the river's flow gradually slows down and experiences significant evaporation in the meanders of the deltaic branches. Finally [45] found that high concentrations of nutrients and conservative ionic species were present in the water samples taken in Po River in the summer of 2015 that were, therefore, characterized by a high electrical conductivity.

Four papers, corresponding to the 16% of the 25 studies describing the impacts of droughts, deal with agriculture. Ref. [26] evidenced that rice fields in the Po basin area are at high risk of becoming unsuitable for rice production because 76% of their surface might turn to aridity in the future; refs. [9,58] reported wheat and maize yield reduction during droughts in the Po valley, while [59] concluded that deeper-rooted crops planted in the Po valley are more likely to withstand prolonged periods of drought.

Two papers evaluated the impacts of drought on the water cycle. Ref. [60] modeled a confined/unconfined alluvial aquifer system to assess surface water/groundwater interactions and concluded that the predicted fluctuations in groundwater and Po river fluxes are significant; ref. [52] used monthly seasonal and permanent water body levels (retrieved from satellite images) for drought mapping and showed that in 2022, the total coverage of water bodies was observed to be less than 11 km^2, primarily comprising permanent water bodies from past years, indicating the loss of permanent water bodies compared to previous July periods.

Two studies reported economic impacts linked with droughts in the basin: ref. [37] reported that droughts have different effects on farmers and consumers. While some farmers experienced severe yield losses, agriculture as a whole found the drought beneficial in economic terms, while the majority of the burden was shifted onto final prices, i.e., consumers. According to [36] instead, irrigation constraints result in increasing incremental losses in agricultural areas of the lower Po River basin, which are further exacerbated by negative inter-sectoral feedbacks at the regional level.

Finally, [41] used the $EDII_{ALPS}$ database to analyze the distribution patterns of documented drought damages from 2000 to 2020 and evidenced that, in the dataset, there are 119 records available for the Po basin distributed over six years. The years 2003 and 2017 stand out, with more than 50 and more than 25 entries, respectively.

Drought impacts are commonly classified as economic, environmental and social [61]. The 25 reviewed articles basically deal with economic and environmental impacts of drought, while they are completely ignoring the effects of droughts on people's health, although it is widely acknowledged that droughts negatively impact on human health by exacerbating the risk of respiratory diseases and asthma due to poor air quality [62], and increasing the hospitalization and the mortality rates for cardiovascular diseases, mainly among elderly people [63]. The Po plain is already characterized by a poor air quality with particulate matter concentrations that exceeds both the European limit values and the guidelines of the World Health Organization (WHO) [64]. Furthermore, the region is situated between two mountain chains, the Alps and the Apennines, has low winds and is often subjected to persistent atmospheric blocking and high-pressure systems, which are connected with the escalation of excessive temperatures and deterioration of air quality. Therefore, the assessment of the effects of drought on public health could be interesting to evaluate the implementation of measures to limit the negative impacts of drought on a population that is becoming increasingly older.

Moreover, drought has also been linked with mental illnesses even in developed countries. Drought events seem to have more significant negative effects on rural communities and farmers; particularly, Australian farmers reported drought as one of their major sources of stress because of low crop production, inadequate conditions for livestock and challenging workloads [65]. Since, in the Po plain, agriculture (both crop production and livestock) is one of the principal economic activities, deepening the relationship between drought and farmers' mental health could be interesting to understand if the results of the cited Australian study hold in the case of the Po basin too.

The spreading of vector-borne diseases, such as the West Nile fever, in case of droughts is also reported in the literature [66]. The West Nile virus and other arboviruses are already present in some areas of the Po valley, as witnessed by the 116 confirmed West Nile cases reported by the Lombardy region over the period from July to December 2023 [67]. Research on the spreading of vector-borne diseases in the area could be beneficial to increase the knowledge on virus propagation since it is well acknowledged that climate change is already influencing the spread of a variety of vector-borne diseases in Europe and will continue to do so in the next decades [68].

For what concerns the economic impacts of drought, it is interesting to note that no documents addressing the issues related to the lack of water for hydroelectric power generation or cooling of industrial sites have been published, even though in the 2022–2023 event, the interruption in electricity production from hydroelectricity due to the low Po River streamflow has been reported by newspapers [69]. It is in fact commonly acknowledged that hydroelectric power generation is extremely sensitive to streamflow fluctuations, and recent studies have demonstrated the decreasing in hydroelectric generation during droughts in Brazil [70] and China [71].

Additionally, impacts on tourism were also reported by newspapers, highlighting multiple negative effects of the drought on this industry: the absence of snow on the Alps caused a decrease in skiers staying in mountainous locations, the hot summers induced tourists to avoid visiting cities such as Milan and Venice and the reduced water availability forced hotel keepers to decrease the number of visitors [72]. The impacts of droughts on tourism have been explored further in a few studies: a water crisis due to a persistent drought damaged the image of Benidorm (located on the south-east coast of Spain) as a holiday destination; the city's revenues from tourism were reduced and the site became unattractive for richer and more demanding visitors [73]. More recently, [74] evidenced that a drought lead to a decrease in hotel occupancy and visitors spending time in the Western Cape province (South Africa), together with to a decline in tourist arrivals at major attractions. However, even if drought heavily affects tourism, no articles have deeply analyzed the topic, although tourism is a relevant source of income for Italy.

The two mentioned aspects are particularly critical for the Po area and for sure deserve more investigation, since the frequency and severity of droughts are expected to increase in the near future.

Finally, the environmental impacts of drought are the ones most exlpored in the selected articles. However, the impacts on local flora and fauna have been reported only in a couple of articles ([53,55]). Studies assessing the impacts of droughts on tree species distribution or on other species of both vertebrates and invertebrates could contribute to enhance the knowledge of ecosystem dynamics in dry periods.

3.3. Drought Management Strategies

Seven articles analyzed management strategies to deal with drought events in the Po area. A cost–benefit analysis of a proposal to reuse part of the final effluent from the Ferrara wastewater treatment plant for irrigation and to utilize the site for recreational purposes too is discussed in [75]. The reuse of wastewater for agricultural purposes is mandatory since the Italian Ministry for the Environment has declared that the area surrounding the city of Ferrara is at risk of environmental crisis due to drought and the eutrophication of the Po River. The study concluded that the project is financially feasible and can therefore contribute to increase the water availability for agriculture, thus contributing to effective water management.

Water management for irrigation purposes is the focus of [76] too. The authors evaluated, through various field experiments, the application of deficit irrigation to potatoes and fresh and processed tomatoes and concluded that the proposed irrigation schedule could serve as a framework for developing water-saving deficit irrigation in various local soil and meteorological conditions.

A real-time drought forecasting system for irrigation management is proposed in [77]. The system has been developed for the optimization of the water use for irrigation by combining medium-range meteorological ensemble forecasts with hydrological simulations of water balance to forecast soil water content. The system has been tested in 2012 on maize fields in the Po valley area and the forecasts have been demonstrated to be highly reliable at least for 7–10 days ahead of time. Ref. [78] assessed the costs of transitioning drought management institutions in Italy toward informal, participatory and consensus-based approaches during several recent drought events. The work analyzed the allocation of water abstraction licences in the Po basin and concluded that there is an over-allocation of such licences.

Refs. [50,51] also deal with management strategies to preserve water for irrigation. The first work underlines that, in a climate change context, groundwater will be used more frequently than surface water for irrigation purposes. Since groundwater-fed irrigation promotes higher NO_3 levels due to groundwater recirculation, the authors propose managed aquifer recharge actions to counteract the increase in groundwater NO_3 concentration. The second work evidences that abundant fertilization in the Po plain and the use of groundwater irrigation leads to high nitrogen concentration in the river groundwater, and thus to the violation of the Nitrate and Water Framework Directives of the European Union during dry periods. They therefore suggest the development of precision agriculture systems through the installation of humidity sensors, the exploitation of satellite-derived information on photosynthetic performances of crops along the vegetative period and the concurrent shift of crops. All the actions could be viewed as important adaptation strategies to deal with future droughts.

The last paper on management strategies instead proposes afforestation and reforestation as effective actions to combat drought and climate change [79]. The best-performing trees to be used in the Po plain context because of their high drought tolerance are oak species, pines and ash trees.

Six of the papers proposing drought management strategies are focused on actions to reduce or optimize water use in agriculture, indicating the importance of the sector in the economy of the Po valley and how a decrease in water use for irrigation or resources optimization could benefit water availability during droughts in future contexts.

The ADBPO bulletins report the watercourses on which the ADBPO issued exceptions to the European Directives on the minimum river flow (MRF). The same documents suggest measures to be implemented in correspondence of the most critical drought episodes. For example, in July 2022, the following actions are recommended: a 20% decrease in water withdrawal from the Po River and its tributaries, the interruption of the exceptions on MRF for water withdrawal for irrigation purposes, lake water volume monitoring and the monitoring of the water content of the Alpine reservoir for hydroelectric production. The suggested actions should be undertaken by the responsible authorities, such as regions, cities or other agencies, and the evaluation of the effectiveness of the described measures belong to the same authorities.

A major limitation of both the reviewed literature and the ADBPO bulletins concerns the fact that they do not address the three pillars of drought management (monitoring and early warning, vulnerability and impact assessment and mitigation, preparedness and response [61]) but concentrate their attention on some aspects of the chain. Example of drought management policies or their implementation to the case study of the Po valley are lacking. The ADBPO has developed its own drought management plan [80]; however, the document describes three past drought events (2003, 2005 and 2007), reviews the indicators used in the literature to evaluate drought conditions and proposes a short description of the observed drought impacts. The implementation of effective drought management strategies involving not only the agricultural sector but also citizens and industrial stakeholders is of huge importance given the increasing frequency of drought events.

4. Conclusions

The Po Valley is crucial to Italy's economy and is heavily reliant on agriculture. Several droughts have affected the territory in recent years, with the 2022–2023 episode being regarded as the worst in the last 200 years.

By analyzing the scientific literature published from 2000 to February 2024 available through Scopus and Web of Science, this study aims at gathering insights from past events to plan for future mitigation strategies. The reviewed literature focused on three main areas: drought impacts, event identification and management strategies. Overall, 44 relevant articles were identified.

Studies on drought impacts primarily addressed the environmental consequences of dry periods (effects on ecosystems, vegetation, agriculture, water pollution, etc.). Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and river discharge emerged as the main indicators for drought event characterization while existing management strategies primarily target agricultural water use optimization through techniques like precision irrigation and wastewater reuse.

The research identified several topics that deserve to be explored more deeply. The human health consequences of droughts, including the potential spreading of vector-borne diseases, remain unexplored. Similarly, the impact of droughts on tourism and hydropower generation, crucial sectors for the Po Valley's economy, requires further study. A more comprehensive understanding of droughts' influence on the Po Valley's ecosystems by assessing the impacts of droughts on tree species distribution and on more species of both vertebrates and invertebrates could contribute to a better knowledge of ecosystem dynamics in dry periods.

Additionally, drought characterization is rarely performed through the use of combined indicators or soil moisture; the use of such indicators, especially in early-warning systems and drought monitoring, could enhance the performance of the systems and provide useful indications for drought planning.

Strategies to reduce water consumption in agriculture (precision irrigation and reuse of wastewater) and afforestation and reforestation are proposed as effective actions to increase drought resilience. Exploring and implementing more comprehensive drought management strategies extending beyond the optimization of water use for irrigation is essential.

By delving into these unexplored areas and building upon existing knowledge, future research can significantly improve the Po Valley's preparedness for future droughts and could bring to a better understanding of the effectiveness of management strategies in increasing drought resilience.

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Appendix A. Summary of the Reviewed Articles

Table A1 summarizes the 44 reviewed articles.

Table A1. Summary of the reviewed studies.

Reference	Data Used	Reported Events	Group	Reported Impacts	Type of Impact
[27]	NDVI-EVI-LST from MODIS, SCIA database for precipitation and temperature	Events from 2000 to 2020	Impact analysis	Impacts on vegetation	Ecological
[48]	Precipitation ERA5, snowmelt IT-SNOW, River discharge Pontelagoscuro	2022	Event identification		
[26]	Aridity Index, precipitation (CHIRPS), VHI, ARPA Veneto	Summer 2022	Impact analysis	Saltwater intrusion, yield decrease	Agriculture
[49]	Water temperature and daily discharge at Pontelagoscuro (ARPA Emilia)	May–July 2022	Impact analysis	Saltwater intrusion	Pollution
[50]		Summer 2022	Management strategies		
[51]		Summer 2022	Management strategies		
[9]	EOBS	2003, 2007, 2022	Impact analysis	Yield decrease	Agriculture
[44]	River discharge at Pontelagoscuro, NDVI (Landsat 5)	June–September 2006	Impact analysis	Impacts on vegetation due to saltwater intrusion	Ecological
[14]	Precipitation and temperature (ERA5), River discharge at Pontelagoscuro (ARPAE)	2022	Event identification		
[79]		Management strategies			
[18]	Snow depth (stations), Precipitation and temperature (ERA5), River discharge (ARPAE)	1949, 2012, 2019, 2022, 2023	Impact analysis	Reduced groundwater recharge from snow	Hydrological
[52]	Surface water (Landsat, Sentinel 1/2)	July 2022	Impact analysis	Loss of permanent water bodies	Hydrological
[13]	River discharge at Pontelagoscuro, Precipitation and temperature (ERA5)	1943, 1945, 1950, 1976, 2003, 2005, 2006, 2007, 2012, 2022	Event identification		
[58]	Precipitation and temperature (EOBS)	2003, 2005, 2007	Impact analysis	Yield reduction	Agriculture
[5]	Streamflow (stations, global run-off data center)	1921, 1943–1952	Event identification		
[41]	Precipitation and temperature (ERA5)	2003, 2012	Impact analysis	119 reported drought impactsin the $EDII_{ALPS}$ database	Multiple
[19]	Precipitation and temperature (SCIA database)	Events from 1965 to 2017	Event identification		
[78]		2003, 2006, 2007, 2017	Management strategies		
[35]	Precipitation (EOBS), River discharge at Pontelagoscuro (ARPAE)	Event identification			
[46]		July 2017–January 2018	Impact analysis	Drought was the overwhelming driver of the observed faunistic patterns	Ecological

Table A1. *Cont.*

Reference	Data Used	Reported Events	Group	Reported Impacts	Type of Impact
[40]	River discharge at Pontelagoscuro (ARPAE)	2003–2007	Impact analysis	Drought causes a time-lag between the delivery of the pollutants from catchments and their accumulation	Pollution
[20]	Precipitation and temperature (ARPAL, ARPAV, ARPAE, ARPAP)	2003	Event identification		
[56]	GI (Copernicus Land Monitoring Services, Sentinel 2, Natura 2000)		Impact analysis		Ecological
[47]		2017	Impact analysis	Oxygen and hydrogen stable isotopes displayed a relation significantly different from that recorded in the previous investigation	Pollution
[36]		2003, 2006, 2007, 2015	Impact analysis	High transaction costs	Economic
[42]	River streamflow	Events from 1920 to 2010	Event identification		
[37]		2003, 2005–2007, 2012, 2015	Impact analysis	Crop price increase for customers	Economic
[45]	River discharge at Pontelagoscuro	2015	Impact analysis	High electrical conductivity of water due to high concentrations of conservative ionic species	Ecological
[43]		2003, 2006, Summer–Autumns 2012, 2015	Impact analysis	Salt crusts rich in nitrates	Pollution
[23]	River discharge	1943, 1945, 1965, 1989–1990, 2003, 2005, 2006	Event identification		
[38]		2012	Impact analysis	Saltwater intrusion	Ecological
[57]			Impact analysis	Limited isotopic variation in distinct hydrological periods (peak discharge in April, drought in August)	Pollution
[60]			Impact analysis	Impacts on groundwater and aquifers	Hydrological
[77]	Probabilistic forecast (REPS)		Management strategies		
[22]	River discharge at Pontelagoscuro	1943, 2003, 2006	Event identification		
[75]			Management strategies		

Table A1. *Cont.*

Reference	Data Used	Reported Events	Group	Reported Impacts	Type of Impact
[54]			Impact analysis	Alteration in peaks of phytoplankton abundance	Ecological
[39]		2003, 2005, 2007	Impact analysis	Reduced nutrient supply in the basin	Pollution
[76]			Management strategies		
[59]			Impact analysis	Deeper-rooted crops more tolerant to drought	Agriculture
[24]	River discharge (ARPAE), NAO, rainfall (ISAC-CNR), LST	1938, 1949, 2003, 2005, 2006	Event identification		
[25]		January–June 2006	Impact analysis	Absence of the spring development of phytoplankton	Ecological
[53]	Number of days without flow		Impact analysis	Impoverishment of the benthic coenoses, disappearance of many taxa	Ecological
[55]			Impact analysis	Presence of coleopters of the species *Agabus paludosus* within the interstitial zone of the streambed	Ecological

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