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RESEARCH ARTICLE

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A multi-century meteo-hydrological analysis for the Adda river basin (Central Alps). Part II: Daily runoff (1845–2016) at different scales

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Abstract

A high-quality daily runoff time series of the Lake Como inflow and outflow, the longest for Italian Alps, was reconstructed for the 1845–2016 period in the Adda river basin. It was compared with contemporary monthly precipitation and temperature observations and estimated potential evapotranspiration losses. Trend analyses were conducted for daily flow maxima and 7-day duration minima of inflows into the lake showing a non-significant decrease and a significant increase, respectively. Although the annual precipitation time series exhibits a non-significant decrease, annual runoff volumes decrease with a rate of $-136\ \text{mm}\cdot\text{century}^{-1}$, with a significance level of 5%. Possible causes of variability of rainfall and runoff as North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation and Western Mediterranean Oscillation indexes and sunspot activity were also explored. Wavelet spectra analyses of monthly precipitation and runoff show some changes in the energy both at small and large scales and are effective in pointing out phenomena as droughts and the effects of dams' regulation. Conversely, wavelet coherence spectra indicate a weak correlation of NAO and sunspots with precipitation. In addition, the analysis of temperature and potential evapotranspiration tendencies suggests that the decrease of runoff has to be ascribed mostly to anthropogenic factors, including water abstraction for irrigation and increased evapotranspiration losses due to natural afforestation and, only in part, to climatic variability.

KEYWORDS

Adda basin, climate change, daily runoff, evapotranspiration, long-term trend

1 | INTRODUCTION

The scientific debate between researchers supporting the concept of the *ever changing* climate characters (Milly *et al*., 2008) or a pragmatic approach, assuming a stationary random component to explain the variability of hydrological data (Montanari and Koutsoyiannis, 2014), relies on the analysis of extended time series of variables but, also, under a clear picture of anthropogenic factors, which may have contributed to the variability of natural systems, such as watersheds. Climate change is a central topic in the agenda of scientists, politicians and the media because, for the first time in almost 5 billion years of the Earth's history, significant geophysical changes are also occurring due to anthropogenic causes. Humans, according to the large majority of Earth scientists, are inducing an acceleration of changes in the gas composition of the atmosphere and in some components such as the hydrosphere and the cryosphere, to levels which, perhaps, have passed the point of no return (IPCC, 2013, 2014).

The community of climatologists and meteorologists has been dedicated for decades in collecting, sharing and processing meteorological data on multi-secular horizons in large transnational geographical areas (e.g., Auer *et al.*, 2007; Brunetti *et al.*, 2009). The geographical fragmentation of river basins in various administrative areas often transnational or transregional, and the difficulties encountered in coordinating the hydrographic services responsible for this task have probably limited the creation of multi-century data sets of daily runoff series. For example, at the Global Runoff Data Center (https://www.bafg.de/GRDC/EN/Home/homepage_node.html) daily runoff data starting before 1850, at the end of the Little Ice Age, are available for only three gauging stations.

Multi-decadal analyses of variability and trends of runoff are available at regional and global scale. For instance, a regionally coherent picture of annual streamflow trends in Europe emerged, with negative trends in southern and eastern regions, and generally positive trends elsewhere, from the study of Stahl *et al.* (2010) for the 1962–2004 period, with fewer stations starting after 1932. Su *et al.* (2018) recently published the results of the trend analysis for the period 1948–2004 of the monthly and annual outflows of 916 rivers worldwide, flowing into the oceans, showing that for 120 of them the trends are positive, whereas for 51, they are negative with a statistical significance of 5%. Considering extremes, an important study on a European scale has made it possible to identify variations in the last 50 years, not so much in the intensity of the floods, as in their seasonal distribution (Blöschl *et al.*, 2017).

For the Italian basins, Zanchettin *et al.* (2008a; 2008b) have reconstructed a series of daily runoff for the Po River at Pontelagoscuro, dating back to the beginning of the nineteenth century. Beside a negative trend, they report a highly significant signal in the Fourier spectrum of their deseasonalized monthly runoff record at scale of 12.9 years, and they connect it to the solar activity. A number of other authors have searched for such a signature. The first, to the authors' knowledge, to question a possible linkage between sunspot numbers and hydrologic time series were Rodriguez-Iturbe and Yevjevich (1968) who conducted cross-correlation and Fourier spectra analysis and concluded that no significant correlation exists between rainfall or runoff and sunspots. Nevertheless, a wide number of studies examined the effect of sun forcing on variables like discharge, precipitation, sea level and various atmospheric indices (Grinsted *et al.*, 2004; Jevrejeva *et al.*, 2006; Moore *et al.*, 2006; Zanchettin *et al.*, 2008a, 2009) making especially use of wavelet analysis, as an alternative to Fourier transform.

Even though many authors have searched for a solar signature in meteorological and hydrological variables in many areas of the world, a clear consensus, based not only on statistical significance but also on strong physical reasoning, cannot be established. Moreover, correlations can be proven to be spurious when they are not accompanied by the appropriate significance levels or when there is a misuse of the available tools. In fact, Moore *et al.* (2006) have strongly criticized spectrum results with no significance testing or tested only against white-noise, when in reality the investigated climate index time series are lag-1 correlated autoregressive processes, and they suggest other plausible mechanisms, as the doubling of the 5.2–5.7 year cycle of the Atlantic Oscillation. Additionally, the use of a cross wavelet spectrum when investigating for cause–effect relations can lead to spurious cross-correlations; one should therefore opt for the wavelet coherence spectrum instead.

Apart from searching for the solar signature, wavelet transforms provide a powerful tool offering information in a multi-scale basis, ideal in cases of hydrological and geophysical time series that often exhibit transience. They have therefore been utilized extensively in hydrometeorological contexts focusing both on discharge and lake water level time series (e.g., Smith *et al.*, 1998; Coulibaly and Burn, 2004; Labat *et al.*, 2005; Küçük *et al.*, 2009; Rossi *et al.*, 2009; Zolezzi *et al.*, 2009; Carey *et al.*, 2013; Zhang *et al.*, 2014) and on rainfall data (Kumar and Foufoula-Georgiou, 1993; Marazzi *et al.*, 1996; Nakken, 1999; Markovic and Koch, 2005; Labat *et al.*, 2000). Wavelet analysis is also interesting to highlight the effect on runoff of hydropower operation as shown by Zolezzi *et al.* (2009), who focused their attention on the interpretation of the wavelet power spectrum of streamflow data explaining hydrological alterations – results of climate change or hydropower operations – in the Adige River. Similarly, Zhang *et al.* (2014) investigated the changes in periodicity for the East River, in China, where the construction of water reservoirs led to a disappearing annual cycle.

Other detailed analyses on the variability of the hydrological regime of Po River and some of its subbasins after 1920 are presented by Montanari (2012) who identified in the daily riverflow time series perturbations whose memory is maintained in the long term and whose long-term persistence increases with the catchment size. Also for the Adige River, in the Central Italian Alps, the analysis of the variability of the daily flow rates was focused on the period after 1923, when official runoff data were published (Zolezzi *et al.*, 2009).

Studies dating back to the mid-nineteenth century are however rare and, therefore, a contribution on a new high-quality 172-year-long daily runoff series, objective of the present work, is of important scientific value, especially because the analyses are run in parallel with those on the monthly catchment precipitation record, presented in the companion paper by Crespi *et al.* (2020).

With the objective of investigating and contributing to the knowledge of the variability of surface runoff of Italian rivers on a multi-secular horizon, at the University of Brescia long-term runoff series of rivers in the Italian central Alps, from Adige to Ticino River, are being collected and reconstructed. First results showed a more marked decrease in the annual runoff compared with that of rainfall (Ranzi *et al.*, 2017, 2018b).

In this study, we present a detailed reconstruction of the Lake Como daily levels at the hydrometer of the Adda River at Fortilizio in Lecco (Figure 1). From the flow measurements and the stage-discharge curve of Fortilizio, the daily outflows of Lake Como from January 1, 1845 to December 31, 2016 were obtained and, through the continuity equation of the lake, the daily inflows to the lake were also reconstructed. This is the longest time series of daily runoff for Italian Alps. In addition, this series has been compared with monthly precipitation averaged at the catchment scale (Crespi *et al.*, 2020).

The objective of the present article is twofold: (a) studying the role of climate change and variability, and natural forcing factors in general, on streamflow over a wide range of time scales; (b) highlighting how human operations altered the hydrological regimes. Specifically, we intend first to compare and cross-validate the tendency of precipitation at the catchment scale and corresponding runoff records over a multi-century monitoring period, as this is an analysis not frequently available in the scientific literature. Then, through wavelet coherence spectra, we are looking for possible links between natural forcings and climatic teleconnections with the observed hydrological patterns. Finally, for those signals which cannot be explained by natural phenomena only, we search for possible anthropic factors influencing the runoff variability.

In the following, after a brief description of the Adda river basin and of the data collection and quality check, the criteria for processing the data of the hydrometric lake levels and outflow from the lake outlet at Fortilizio and finally of the daily inflows are described in Section 2, where we also present the methods for the statistical analyses of the 172-year series. Results of the analyses are presented in Section 3. Finally, in Section 4, we discuss

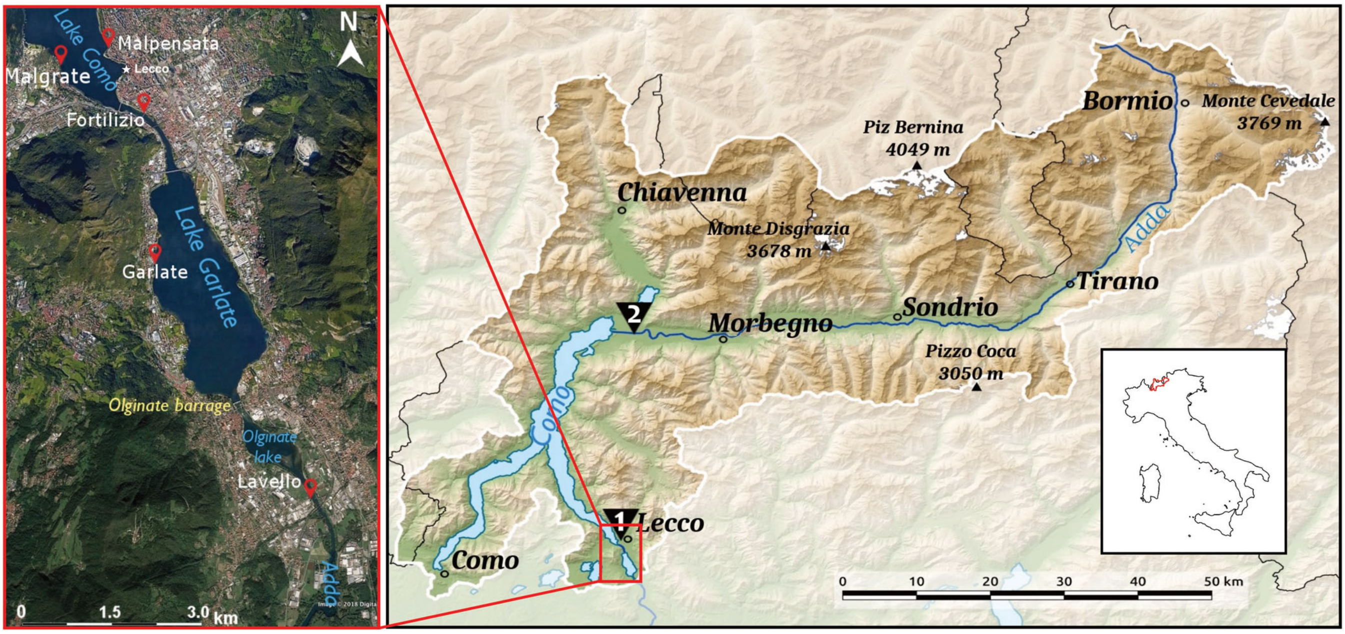

FIGURE 1 The Adda river basin with outlet at Lavello (right), and satellite imagery of the surroundings at the outlet (left). The figure shows also the position of the Fortilizio, close to Lecco, and Fuentes hydrometric stations, indicated by 1 and 2, respectively. *Source:* Google Earth. Lago di Como, Italia. 45°49′25″ N 9°23′31″E, Elevation 14.11 km. DigitalGlobe 2018, 24 July, 2018 [Colour figure can be viewed at wileyonlinelibrary.com]

the results and investigate the possible causes of runoff and runoff coefficient trends.

2 | MATERIAL AND METHODS

2.1 | Study area

The study area is located in the upper part of the Adda river catchment (Figure 1) in the Central Italian Alps. The Adda River is one of the main left-side tributaries of Po River and drains an area of about 8,000 km^2, 94% of which is in northern Italy and 6% in Switzerland. The upper part of the basin, gauged at the outlet of Lake Como in Lecco, covers an area of 4,508 km^2 and is mostly situated over the southern Alpine ridge in the region of Lombardy. This part extends from the sources of Adda River in the Rhaetian Alps and is characterized by a great orographic heterogeneity; its main valley, Valtellina, is oriented from East to West upstream othe Lake Como. Being located in a prevalently mountainous environment, this region is characterized by altitude gradients from about 200 m a.s.l. at Lake Como to more than 4,050 m a.s.l. at Piz Bernina. Land use is mainly covered by agricultural crops in the valleys, deciduous and coniferous forests, and bare rocks above 2,500 m a.s.l.

A number of Alpine glaciers, located in the groups of Bernina, Disgrazia and Ortles-Cevedale, are included in this study area, covering today an area of 65 km^2 (Salvatore *et al.*, 2015; Smiraglia and Diolaiuti, 2015). During the last decades, an intense reduction of glacier coverage and a strong volume loss have been observed (D'Agata *et al.*, 2018). The above loss corresponds to about $5.4{\cdot}10^7$ m^3 of water per year, contributing to the basin runoff with a specific depth of 12 mm·year^{-1}. Although this volume appears small (~1%) relative to the total annual precipitation, as it is mainly released during the summer months, it facilitates civil use, agriculture, industry and hydropower production, in periods of high water demand.

Due to the elevated water needs, a substantial number of artificial reservoirs has been built between 1920 and 1969 (De Marchi, 1970). The lakes of Cancano and S. Giacomo are two of the largest, with a total storage volume of about 188×10^6 m^3 of water, mainly used for hydropower generation. The artificial water volume storage complements the volume of the natural water reservoirs, the most important of which is Lake Como with a total surface of 145 km^2 and a potential storage volume of about 247×10^6 m^3, available after the construction of the Olginate barrage, completed in the year 1945. The barrage can control the outflow from the lake in the range of water levels between −0.50 and +1.20 m with respect to the null point of the Fortilizio staff gauge. The purpose of the regulation is to manage the water storage for irrigation and hydropower generation downstream and flood control in the lake.

2.2 | Data set

2.2.1 | Precipitation

The catchment precipitation time series was reconstructed at monthly resolution as described by Crespi *et al.* (2020) for the period 1845–2016. That paper presents also an annual catchment precipitation time series, corrected in order to take into account the systematic underestimation of solid precipitation of rain gauges.

2.2.2 | Runoff

Data from two hydrometric stations were used to permit the runoff reconstruction through the use of the continuity equation. The hydrometric station of Fortilizio is located at the lake outlet in Lecco, where a staff gauge was installed over the whole 1845–2016 monitoring period. Part of this time series was collected and quality checked by accessing to unpublished hydrometric data. Another hydrometric station was installed on the left lake shore at Malpensata (and after 1941 moved to the opposite shore of Lake Como, with the same hydrometric null point), just upstream of the outlet. Additionally, another hydrometric station with regular discharge measurements was installed, after 1940, a few kilometres downstream of the lake in Lavello (Figure 1).

For the pre-regulation period (1845–1945), some stage-discharge relationships for the outlet were available from the literature (Figure 2). A first one was proposed by Lombardini (1866), a distinguished hydraulic engineer who studied the runoff regimes of lakes and rivers worldwide, followed by a second one proposed by Fantoli (1921) until 1922 and a third one proposed by Citrini (1977) until 1945, based on energy and mass conservation equations. These curves are very consistent, and they are perfectly confirmed by discharge measurements conducted for the same river reach in the period 1923–1943 by the Italian Hydrographic Service and published on the Hydrological Yearbooks. The riverbed material at the lake outlet is composed by boulders, gravels and hard rock and can be considered stable, thus indicating that the stage-discharge curves by Fantoli can be applied to transform the daily water level record into a daily outflow record from the lake for the period prior to 1922. The daily inflows were, then, obtained by solving

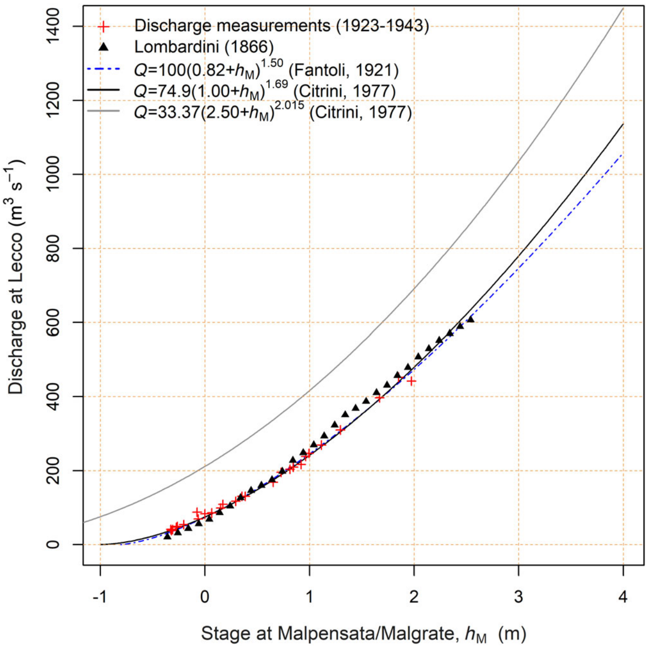

FIGURE 2 Pre- and post-regulation stage-discharge curves and comparison with discharge measurements. The grey upper curve is valid for the post-regulation (1946–2016) period [Colour figure can be viewed at wileyonlinelibrary.com]

the continuity equation and using the measured daily outflows and the water level at Malpensata/Malgrate hydrometric stations (Consorzio dell'Adda, 1958). For a short period between September 1944 and December 1945, when the preliminary dam operation started and the stage-discharge curves at Fortilizio in Lecco were not reliable to assess the regulated outflow, the runoff measurements at the Fuentes hydrometric station (Station 2 in Figure 1) were used to estimate the inflow and the lake continuity equation to assess the outflow. Further details on this issue can be found in Ranzi *et al.* (2018a).

For the post-regulation period (1946–2016), the stage-discharge relationship in free-flow conditions is substantially changed, as the flow capacity at the outlet increased after the outlet was widened allowing for greater outflows for the same water level (Figure 2).

The Lake Como daily water level series for the period 1845–2016 is shown in Figure 3, together with Lake Como inflow and outflow series.

For the analysis of the inflow series at Lake Como, we present in Section 3, two separate periods have been considered: from 1845 to 1919, before the construction of the major reservoirs in the upper Adda catchment started, and from 1967 to 2016 when all major reservoirs were completed. For the analysis of the outflow runoff series, the pre-regulation period which started in 1845 and ended in December 1945 has been separated from the post-regulation period starting from January 1946 when the Olginate barrage situated downstream of the city of Lecco (Figure 1) initiated to be operated.

2.2.3 | Sunspots, North Atlantic Oscillation and other indexes

As Zanchettin *et al.* (2008a) report a highly significant solar signature in the Po river runoff record, we considered in our analyses solar activity expressed as sunspot numbers.

Monthly averages of sunspot numbers date back to 1,749 and are available at http://solarscience.msfc.nasa.gov/SunspotCycle.shtml. For this study, only values for the period 1845–2016 were considered and when referring to yearly values were derived by averaging the monthly values within a year.

Besides sunspots, some indexes were also used to analyse the link of yearly runoff/precipitation with large scale atmospheric circulation variability.

Among them, we considered the North Atlantic Oscillation (NAO) index. NAO is a major climatic teleconnection that influences the European climate, particularly during winter (Osborn, 2011). The index expresses the amplitude of the pressure gradient over the North Atlantic Ocean, which is defined as normalized pressure difference between two extreme stations, located in Iceland and Azores or Gibraltar. Specifically, we used the NAO index monthly record dating back to 1823 developed by Jones *et al.* (1997), which is regularly updated and freely available at https://crudata.uea.ac.uk/cru/data/nao/.

Steirou *et al.* (2017) have carried out an extensive review regarding the possible correlations between NAO and, among else, precipitation showing the variability of Pearson's correlation coefficient within Europe. In particular, the zero correlation line crosses Central Europe and in the Italian Alps a negative correlation of the above variables is observed. Additionally, Wrzesiński and Paluszkiewicz (2011) detected negative links between NAO and mean flow for the majority of the Alpine area, in agreement with the findings of other studies (López-Moreno *et al.*, 2011; Shorthouse and Arnell, 1999; Zanchettin et al., 2008a, 2008b). These results are confirmed by the Adda basin precipitation records which highlight a negative correlation between the two variables at the monthly scale (significant at 5% level for all months, excluding June and September), with correlation coefficient, ρ, ranging from −0.317 to −0.138, and a significant negative correlation for the winter months (December to March), with $\rho = -0.204$ (Supporting Information Figure S1).

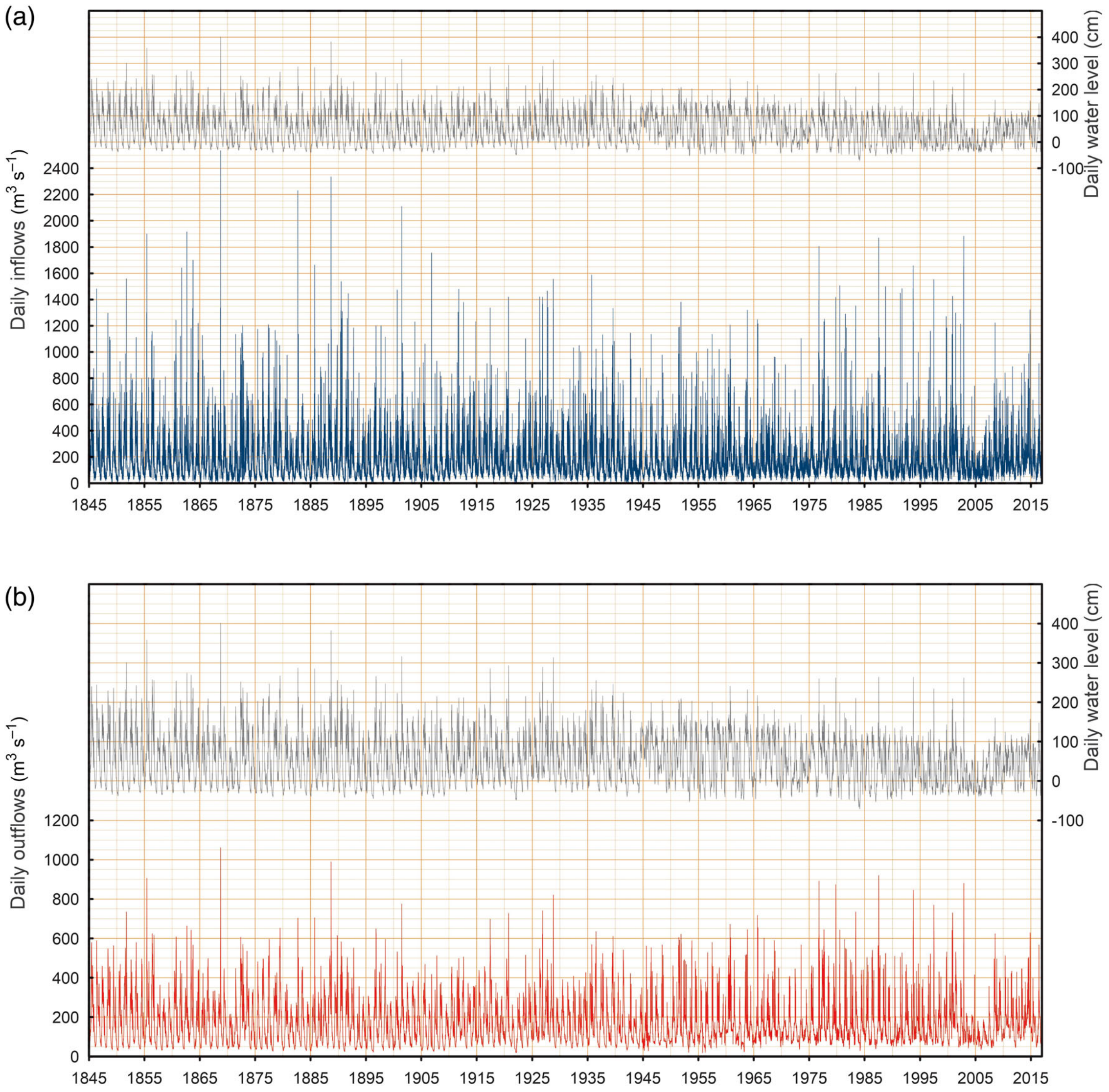

FIGURE 3 The daily Lake Como water level (grey) for the period 1845–2016, together with (a) inflow and (b) outflow series [Colour figure can be viewed at wileyonlinelibrary.com]

We also considered the Western Mediterranean Oscillation index, defined by means of Padua (45°24′N–11°52′E) and San Fernando (Cádiz) (36°28′N–6°12′W) monthly sea-level pressure values (Martin-Vide and Lopez-Bustins, 2006, data available at: http://www.ub.edu/gc/en/wemo/). Also this index highlights significant correlation with the Adda basin precipitation and runoff records. Specifically, significant positive correlations between WeMO index and precipitation were found both at the monthly scale, with ρ values ranging from 0.165 to 0.441, and for the winter months ($\rho = 0.379$). Finally, we considered the Atlantic Multidecadal Oscillation (AMO) index, which refers to North Atlantic detrended sea surface temperature. Specifically, we used the record available at NOAA ESRL (https://www.esrl.noaa.gov/psd/data/timeseries/AMO/). Some recent papers (see e.g., Zampieri *et al.*, 2017; Brugnara and Maugeri, 2019) seem to indicate a relevant influence of this index on alpine precipitation. However, in our data, we found a significant positive correlation of AMO with precipitation only for the month of July ($\rho = 0.155$).

2.3 | Methods

In order to detect possible trends and their significance in the runoff data, the non-parametric Mann–Kendall (MK) test was employed (Sneyers, 1992), accompanied with Theil–Sen slope estimator (Sen, 1968). The runoff data were also subjected to a running trend analysis, allowing to investigate the trend of each sub-interval of at least 21 years.

Besides performing trend analysis, we attempted to decode the signal of the Lake Como inflow and outflow time series of the Adda River, detecting possible changes and variations at different time scales, linked to physical processes or to human interaction. These linkages were sought mainly within processes that have a potentially logical and physically explained cause–effect relationship, namely between the solar forcing, climate indexes and precipitation/runoff. Moreover, a possible influence of the regulation of the reservoirs was considered. Specifically, we applied wavelet analysis to the Adda river catchment runoff and precipitation records and we considered the wavelet coherence-spectra between them and the records of solar sunspots and climate indexes. A practical insight on wavelet theory can be found, among else, in Torrence and Compo (1998) and is briefly presented in the Supporting Information. Moreover, we investigated the Lake Como outflow record inspected by means of the wavelet analysis to point out changes resulting from the lake regulation.

3 | RESULTS

3.1 | Climatology of Lake Como inflows and outflows

The average Lake Como inflow in the period 1845–2016 was 165.3 $m^3 \cdot s^{-1}$, corresponding to 1,157 $mm \cdot year^{-1}$, with maximum mean daily inflow of 2,535 $m^3 \cdot s^{-1}$, corresponding to 48.6 mm of daily precipitation over the entire investigated catchment, in the most severe flood

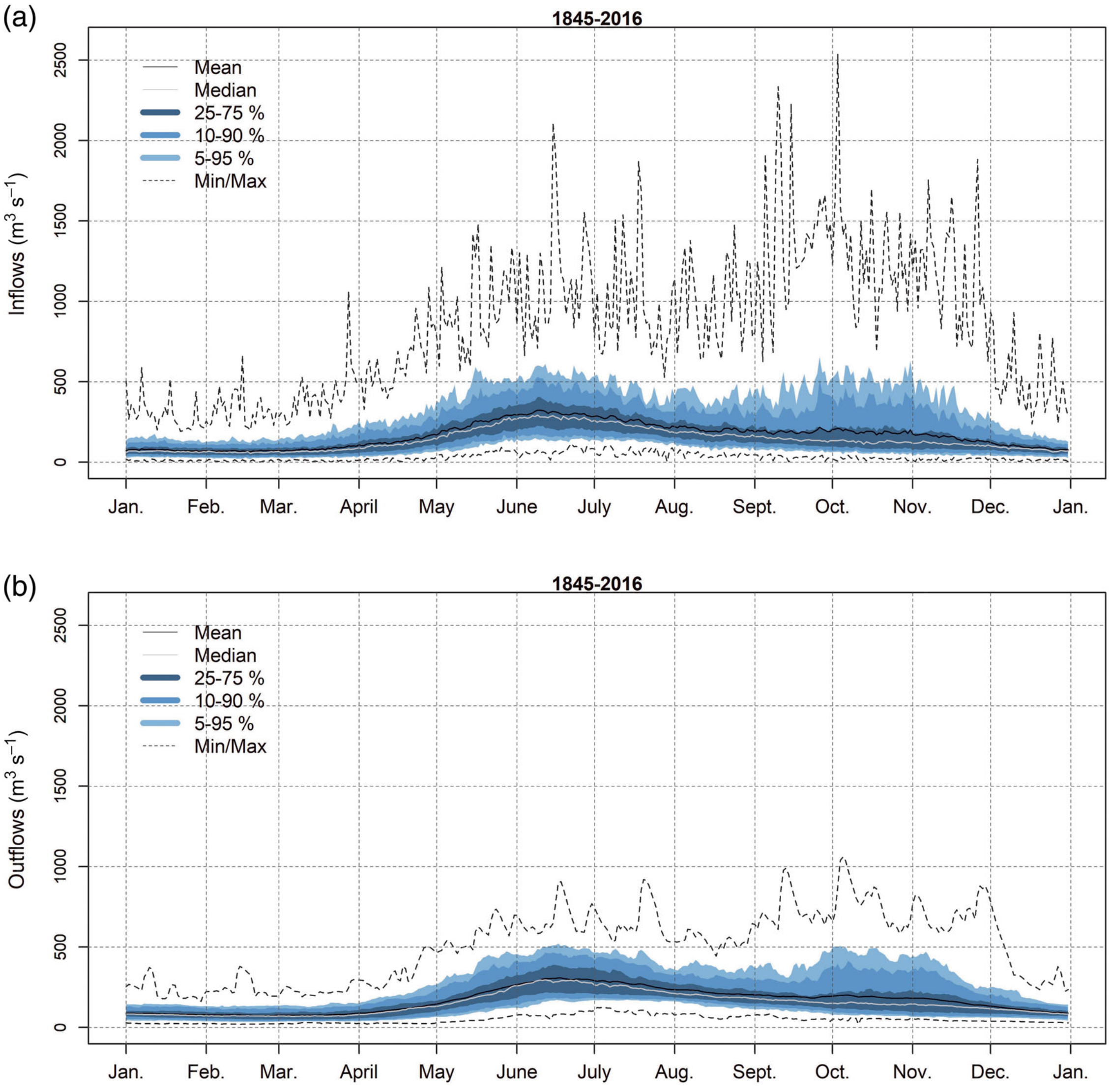

FIGURE 4 (a) Seasonal mean, median, maxima, minima, and 5, 10 and 25% upper and lower quantiles of Lake Como inflows in the 1845–2016 period. (b) Same as (a) but for Lake Como outflows [Colour figure can be viewed at wileyonlinelibrary.com]

ever observed which occurred on October 3, 1868. Concerning low flow indexes, the minimum inflow with duration of 7 days was 11.8 $m^3 \cdot s^{-1}$, observed in the year 1922. The month with the highest inflow of 378 mm was October 1993, whereas the year with the highest inflow of 1822 mm was 1872. Comprehensive statistics of inflow and outflow data can be found in Ranzi *et al*. (2018a).

The Lake Como inflow record has a marked seasonality. Focussing on the medians of the values recorded for each day of the year in the 1845–2016 period, the highest values occur at end of May to the beginning of June. Then the values decrease in summer and in the first part of autumn, remain almost constant from mid-October to mid-November, decrease again until January, remain almost constant until mid-March and finally increase until the end spring maximum (Figure 4). Moving from the median to higher percentiles, also a second maximum in autumn becomes progressively evident and the highest values generally occur in this season (Figure 4), because it has the strongest skewness of the distributions of the daily inflow values. This strong skewness is also evident from the much higher mean values of the daily inflows with respect to the corresponding median values (Figure 4).

In order to investigate the long-term evolution of the yearly cycle of Como Lake inflows and outflows, we

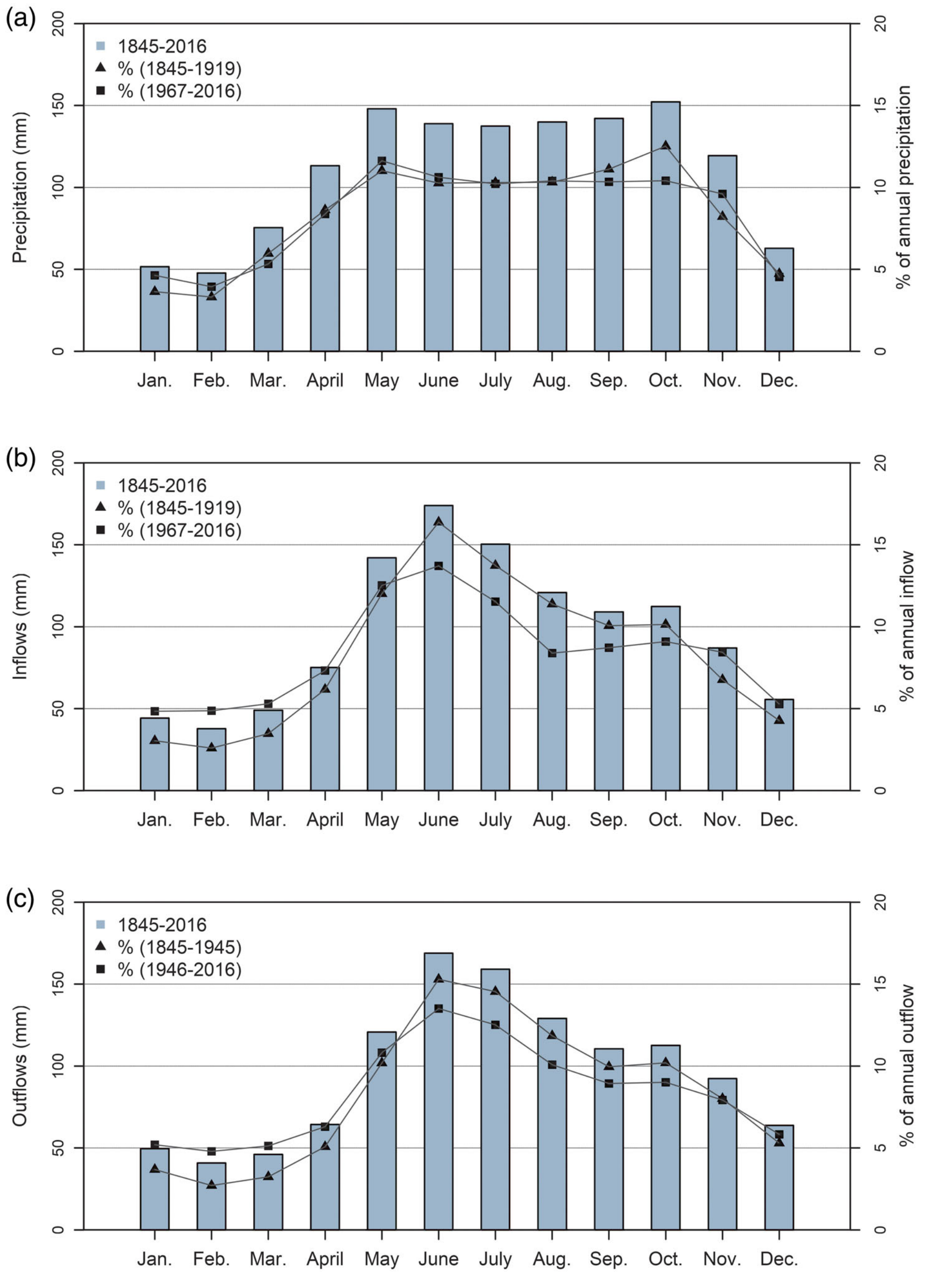

FIGURE 5 (a) Yearly cycles of precipitation, (b) Lake Como inflows and (c) Lake Como outflows in the 1845–2016 period, and relative contributions of each month to the corresponding (a) yearly precipitation, (b) Lake Como inflows and (c) Lake Como outflows. For precipitation and Lake Como inflows, the relative contributions are reported for the two periods 1845–1919 and 1967–2016, whereas for Lake Como outflows, they are reported for the two periods 1845–1945 and 1946–2016 for the reasons described in the article [Colour figure can be viewed at wileyonlinelibrary.com]

considered the records of monthly precipitation, inflow and outflow together with the relative contributions of each month to the corresponding yearly mean values. We compared the yearly cycle of these relative contributions in the period 1845–1919 with the corresponding yearly cycle in the period 1967–2016 to better highlight the effect of reservoirs in the second period, as described in Section 2.2.2. This comparison is shown in Figure 5. It highlights a decrease of precipitation in October and an almost unchanged distribution of monthly precipitation throughout the year, when considering the two periods, but also a marked decrease of the seasonality of the Lake Como inflows moving from the first to the second subperiod (Figure 5b). This marked decrease of seasonality, which is not present in the catchment precipitation record (Figure 5a), is due to the reservoirs used for hydropower generation plants, requiring the storage of relevant water volumes during summer and autumn and its release in the cold months of January–April and November–December when the value of energy is higher. Specifically, from June to October, 10% of the mean annual runoff was stored in the post-reservoir construction period (1967–2016) in excess to the natural condition period (1845–1919). We recall also that after 1963 a volume corresponding to 20 mm of runoff was diverted to the Adda River in the first months of the year from the Spoel watershed, a tributary of the Inn River flowing North of the Alpine ridge.

Focussing on Lake Como outflows, the most relevant change in the seasonality occurs when the barrage situated just downstream of the city of Lecco began to operate in 1946. By comparing panels b and c in Figure 5, it can be observed that during the lake regulation period the outflow in the months of July and August increases to meet the irrigation demand in the downstream agricultural areas. Runoff increases also in November and December to meet the hydropower generation demand in the downstream reach of the Adda River. The corresponding volumes are stored in the Lake Como mainly during the months of April and May as a result of spring precipitation and snowmelt.

3.2 | Long-term trends of annual runoff

The yearly average runoff series at Lake Como gives evidence of a marked decrease in the 1845–2016 period (Figure 6 and Table 1). The trend of annual inflow, which is basically the same of outflow as the lake storage is compensated over the years, is significant at the 5% level. Its Theil-Sen slope turns out to be $-136\ \text{mm}\cdot\text{century}^{-1}$, corresponding to a reduction of $11.8 \pm 3.2\%\ \text{century}^{-1}$, which causes a runoff decrease of 233 ± 63 mm over the entire investigated period considering standard error estimates. As discussed more in detail by Crespi *et al*. (2020), also the yearly record of average catchment precipitation has negative slope. The catchment precipitation decrease is however much lower (see Figure 6), and it is not statistically significant. Therefore, the investigated catchment highlights a strong decrease in the runoff coefficient series ($-6.4 \pm 1.0\%\ \text{century}^{-1}$) (Table 1).

This decrease can potentially be explained as an effect of the increased evapotranspiration losses, caused by the increase in temperature and by the expansion of the forested areas, as noted for the adjacent Adige basin (Ranzi *et al*., 2017). Other possible reasons could be the withdrawal of water for irrigation and anti-frost purposes of almost 2,200 ha, cultivated primarily with fruit, vines and corn, upstream of Lake Como, as well as for drinking water purposes (mounting to about 1 $\text{m}^3\cdot\text{s}^{-1}$ in the last decades).

In order to better investigate the temporal trends, a running-trend analysis was performed on the 1845–2016 annual discharge seasonal record. The Theil–Sen slopes

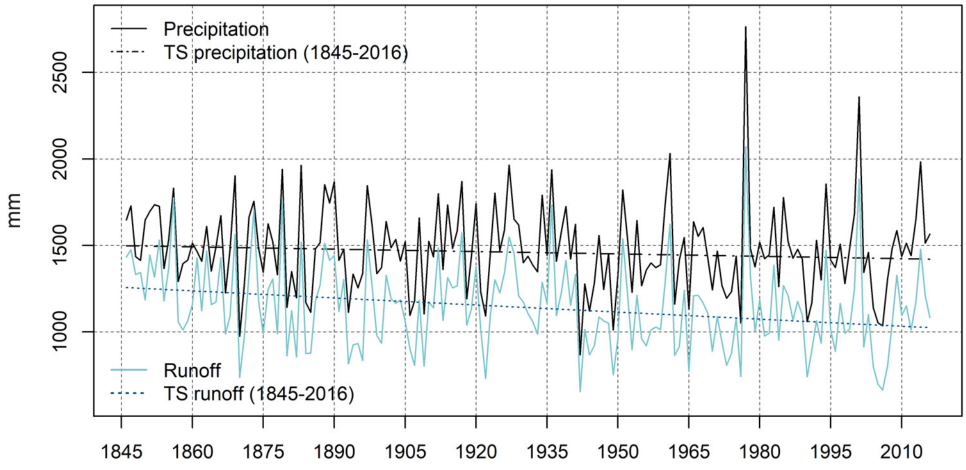

FIGURE 6 Theil–Sen trend of annual precipitation and annual runoff of the Adda river basin in the hydrological years starting with September 1845 until August 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Mann–Kendall Z statistic and Theil–Sen slope, along with *p* values (significance in bold) and 95% confidence interval of the Theil–Sen slope for the annual runoff and runoff coefficient of the entire period (hydrological year)

Series	Period	Z_{MK}	Theil–Sen	*p* value	95% confidence interval
Inflow	1846–2016	−3.53	−136 mm·century^{-1}	.00	[−210, −62] mm·century^{-1}
Runoff coefficient	1846–2016	−6.21	−0.06 century^{-1}	.00	[−0.08, −0.04] century^{-1}

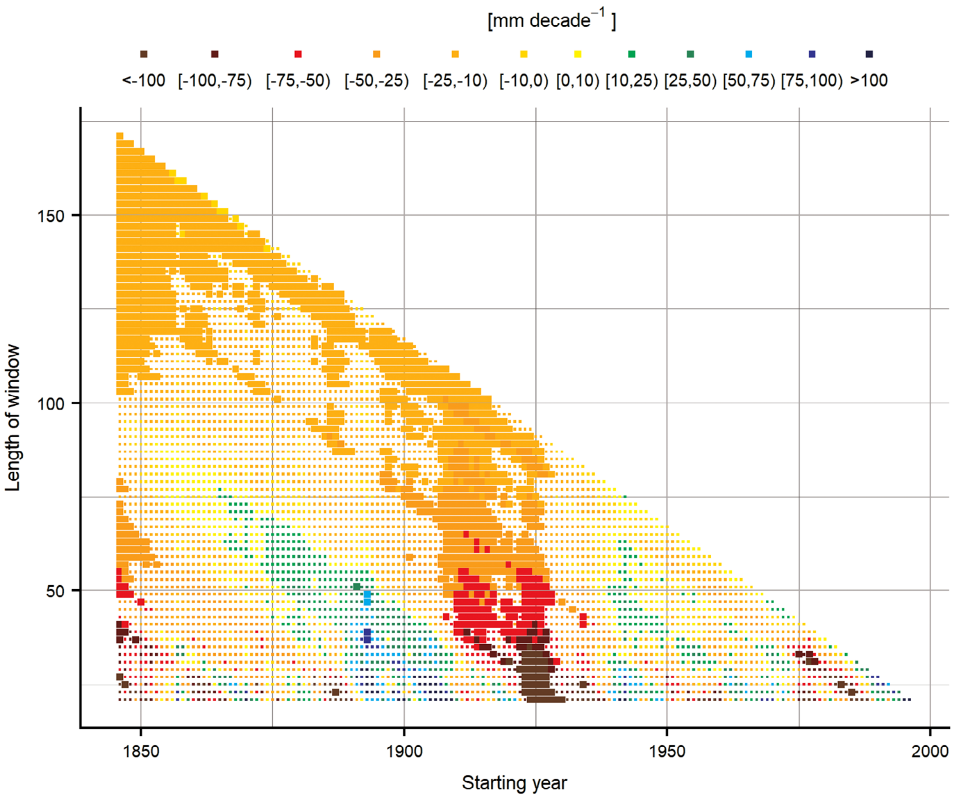

FIGURE 7 Running trend of annual inflow runoff. Trend values are expressed by colours, whereas the significance of trend is represented by the pixel size (larger pixels for Mann-Kendall *p* values <.05)

and MK significances were computed on windows of increasing width from 20 years up to the entire period spanned by the series and running from the beginning to the end of the record. The results (Figure 7) highlight that all the windows longer than 150 years have 5%-significant negative trend. Moving to shorter periods, the fraction of time windows with high-significance trend becomes lower. However, almost all significant trends are the negative ones, with some of them very relevant, up to −100 mm·decade^{-1} for periods ending with the severe droughts of the 1940s and the early 2000s. The strongest negative trends concern windows starting in the 1910s and 1920s. They are due to a relative maximum in the runoff yearly record in the first part of the 20th century, followed by a strong runoff reduction in the 1940s. It is worth noticing that also some of the windows of the most recent years have negative runoff trends. They are due to the first decade of the 21st century that was very dry.

The pattern of the runoff running trends is reflected by a similar pattern of the precipitation running trends observed in Crespi *et al.* (2020, figure 9). It is worth noticing that also the runoff coefficient follows this pattern, as shown in Crespi *et al.* (2020, figure 10), as a result of the non-linearity of the runoff response to precipitation forcing, as the transformation of precipitation into runoff is more efficient when precipitation increases.

3.3 | Long-term trends of inflow maxima and minima

Also the record of the annual maxima of the daily mean inflow values has negative slope in the period 1845–2016, with a decrease of −110 ± 56 m^3·s^{-1}·century^{-1} (Table 2; Figure 8). However, this trend is not significant at the 5% level.

TABLE 2 Mann–Kendall *Z* statistic and Theil–Sen slope, along with *p* values ($p < .05$ in bold) and 95% confidence interval of the Theil–Sen slope for the daily annual maximum and annual 7-day minimum inflow

Series	Period	Z_{MK}	Theil–Sen ($m^3 \cdot s^{-1} \cdot century^{-1}$)	*p* value	95% confidence interval ($m^3 \cdot s^{-1} \cdot century^{-1}$)
Maxima	1846–2016	−1.86	−110	.06	[−221, 6]
Minima	1846–2016	**−7.70**	**16.0**	**.00**	**[13, 19]**

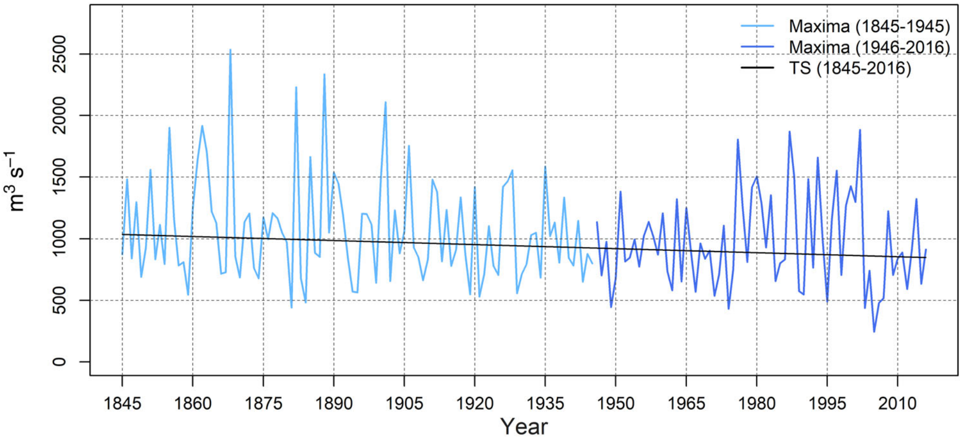

FIGURE 8 Theil–Sen trend of annual maxima daily inflow to Lake Como (Adda river basin) [Colour figure can be viewed at wileyonlinelibrary.com]

The long-term trend in the annual maxima of daily flow is also evident comparing the annual cycle for the sub-periods 1845–1919 and 1967–2016 (Figure 9). In fact, the comparison between these two periods gives evidence of the decrease of peaks in the second period where no daily maxima exceed 2,000 $m^3 \cdot s^{-1}$, whereas 4 days with such high floods did occur in the first period. In addition, less skewed statistics of inflow for each day of the year are observed.

The decrease of annual maxima is due both to the general decrease of runoff and to the attenuation effect of the alpine reservoirs upstream of the lake, even though the latter effect seems to be much more important than the former one (Malusardi and Moisello, 2003; Moisello and Vullo, 2009).

This anthropic effect is more evident on low flows than on high flows, since, due to the upstream regulation operated by dams, water is stored during periods of abundance and released during periods of high demand or water scarcity. In fact, the annual minima of mean daily runoff of 7 days – index of the low flow regime – has a significantly increasing trend of 16 ± 1.5 $m^3 \cdot s^{-1} \cdot century^{-1}$ in the investigated period (Figure 10 and Table 2).

3.4 | Precipitation and runoff wavelet spectra

In Figure 11, the Morlet6-wavelet spectrum of the monthly precipitation series deseasonalized by subtracting from each monthly data the monthly mean and dividing by the monthly standard deviation is represented (the corresponding spectrum for the non-deseasonalized record is reported in Supporting Information Figure S2), thus obtaining a zero-mean, unit-standard deviation time series, which smooths the effect of the annual cycle. Instead, a 12-year-scale energy peak appears in the wavelet spectrum thus suggesting a possible link with the solar activity as previously discussed for the Po River by Zanchettin *et al.* (2008b); Zanchettin *et al.* (2008a; 2008b) and more generally argued by some authors as Dong *et al.* (2018), with others, as Tsiropoula (2003), being more sceptical towards the existence of a physical mechanism which might result in meaningful linkages. For the monthly inflow data into the Lake Como, a 12-year energy peak is still present, together with the annual periodicity (Figure 12). In this case, we normalized the series by subtracting the long-term mean and dividing by the standard deviation, and so we did not remove the annual cycle, whereas the spectrum we obtain for both normalized and deseasonalized records of daily inflows is reported in Supporting Information Figure S3. It is worth noticing that the wavelet spectrum at annual scale exhibits an evident energy loss around 2005 when a severe drought occurred (see also Figure 6) but not in correspondence of the drought in the 1940s. In order to investigate further the wavelet spectrum of both inflow and outflow from the Lake Como, trendlines of the wavelet power spectrum at different scales were plotted for the two periods, before and after 1946 (Figure 13), when the lake regulation started with the Olginate barrage.

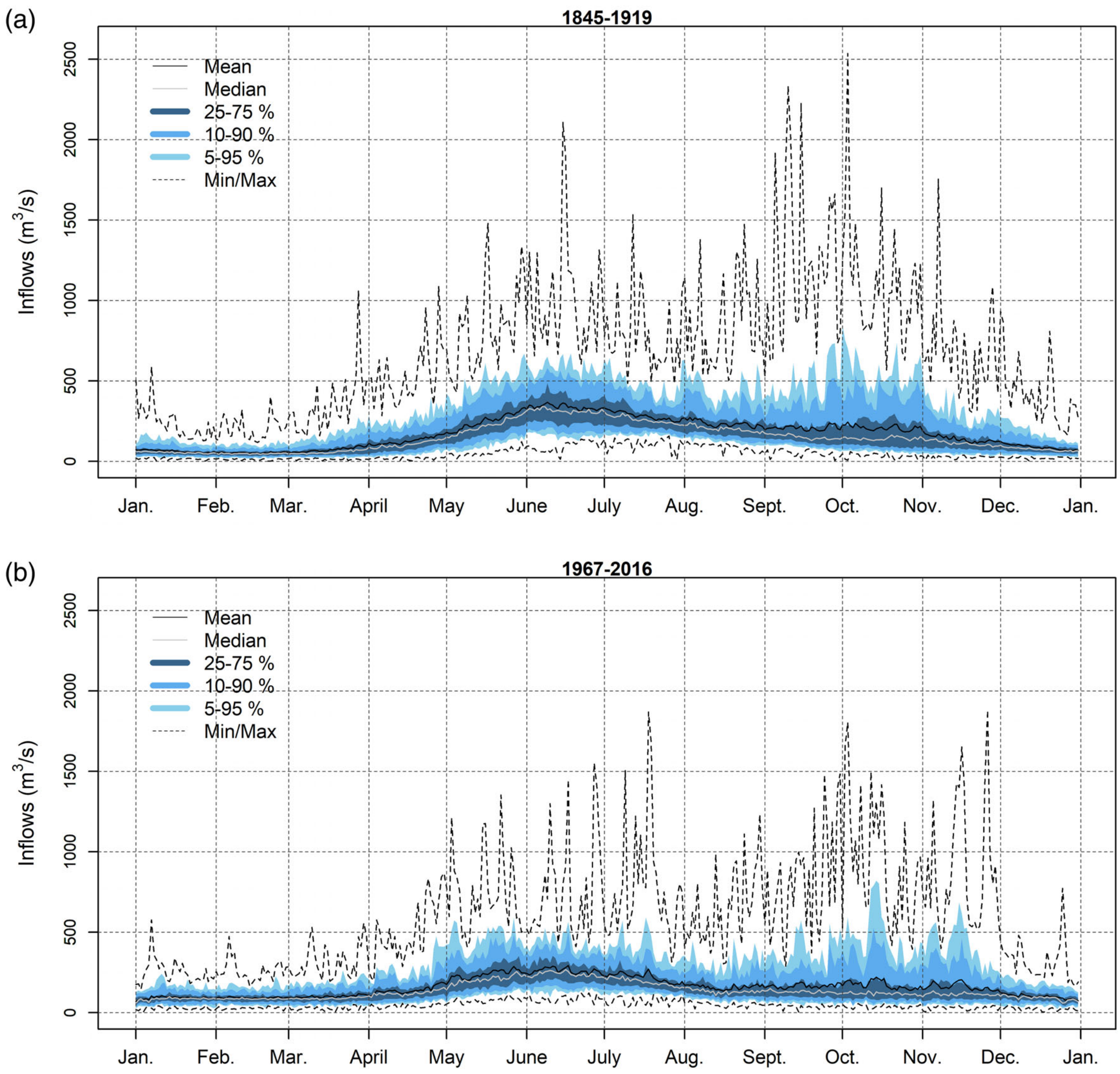

FIGURE 9 Seasonal mean, median, maxima, minima, and 5, 10 and 25% upper and lower quantiles of Lake Como inflows in the (a) 1845–1919 and (b) 1967–2016 periods [Colour figure can be viewed at wileyonlinelibrary.com]

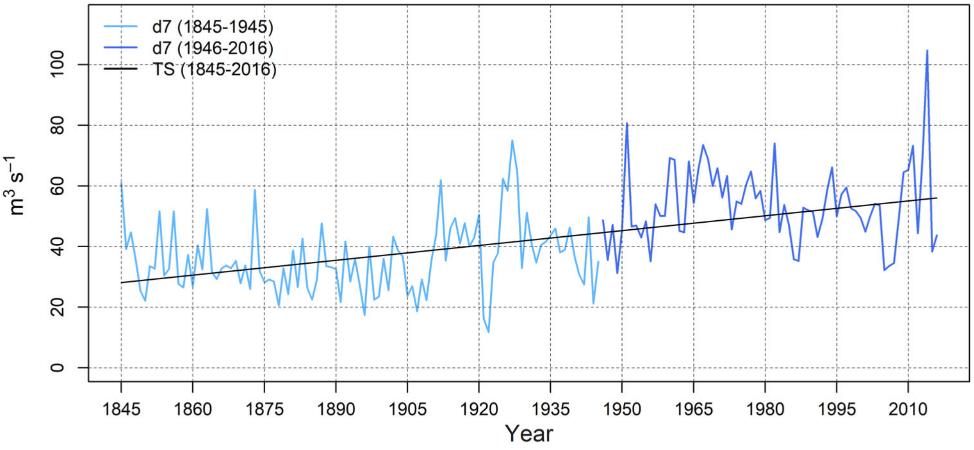

FIGURE 10 Theil–Sen trend of annual 7-day minimum inflow to Lake Como (Adda river basin) [Colour figure can be viewed at wileyonlinelibrary.com]

We can observe that the long-term annual scale trends are declining, a confirmation using the wavelet tool that the annual runoff is decreasing, as discussed previously. More interesting is the increasing trend of the 7-day scale fluctuations of inflow, indicating that the progress of the completion of the reservoirs upstream Lake Como after

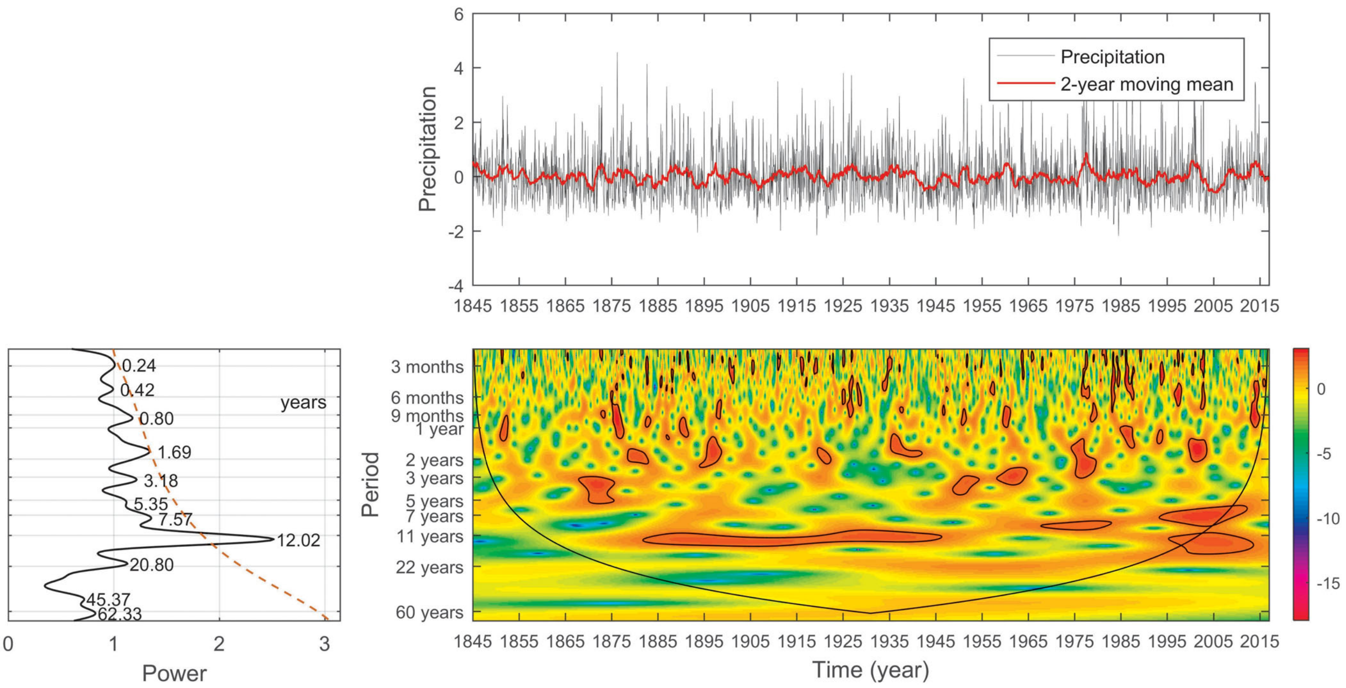

FIGURE 11 Time series, dimensionless wavelet spectrum (bottom right) and global wavelet spectrum (bottom left) of monthly precipitation (deseasonalized); 5% significance levels are marked with black contour lines in wavelet spectrum and COI-cone of influence; in global wavelet spectrum, 5% significance levels are marked with the dashed red line

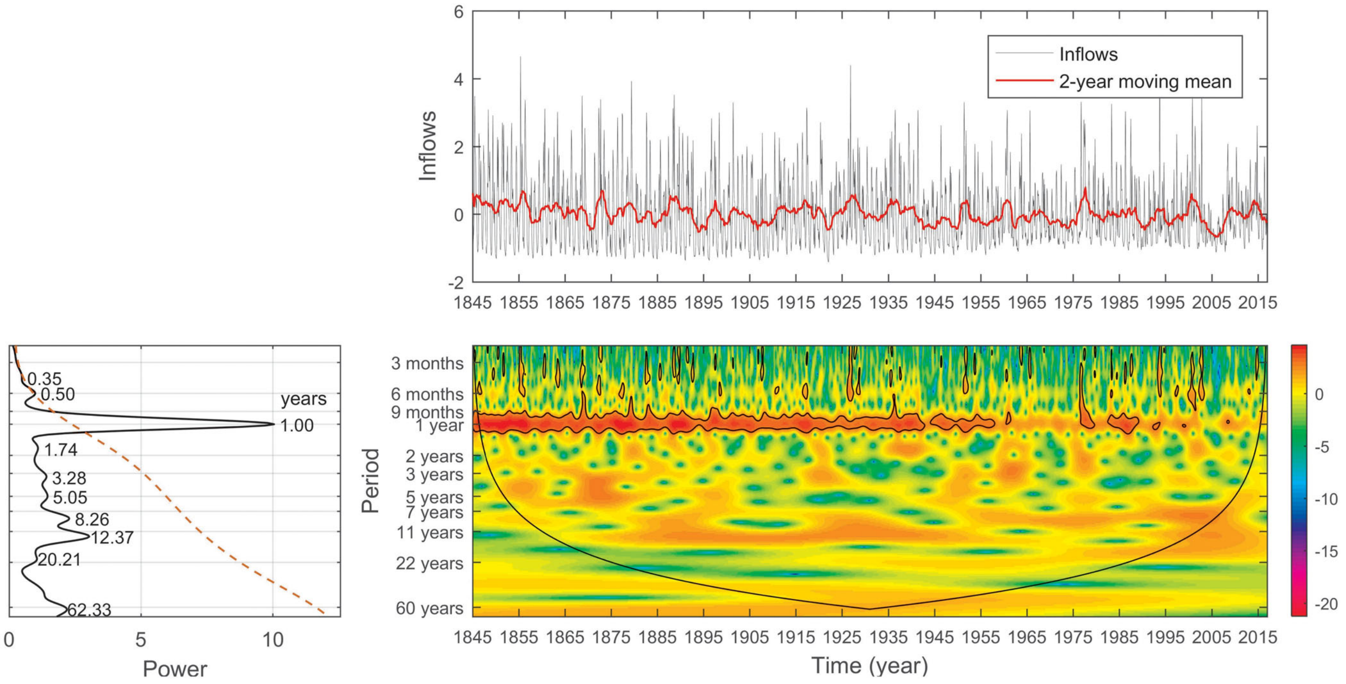

FIGURE 12 Time series, dimensionless wavelet spectrum (bottom right) and global wavelet spectrum (bottom left) of Lake Como monthly normalized inflow; 5% significance levels are marked with black contour lines in wavelet spectrum and COI; in global wavelet spectrum, 5% significance levels marked with the dashed red line

the 1940s introduced an artificial weekly component in the runoff regime, as already observed by Zolezzi *et al.* (2009) for the Adige River. Even more remarkable is the sudden increase, after 1946, of the 2- to 7-day scale fluctuations in the outflows from the lake, indicating that the Olginate barrage operations significantly changed the outflow regime.

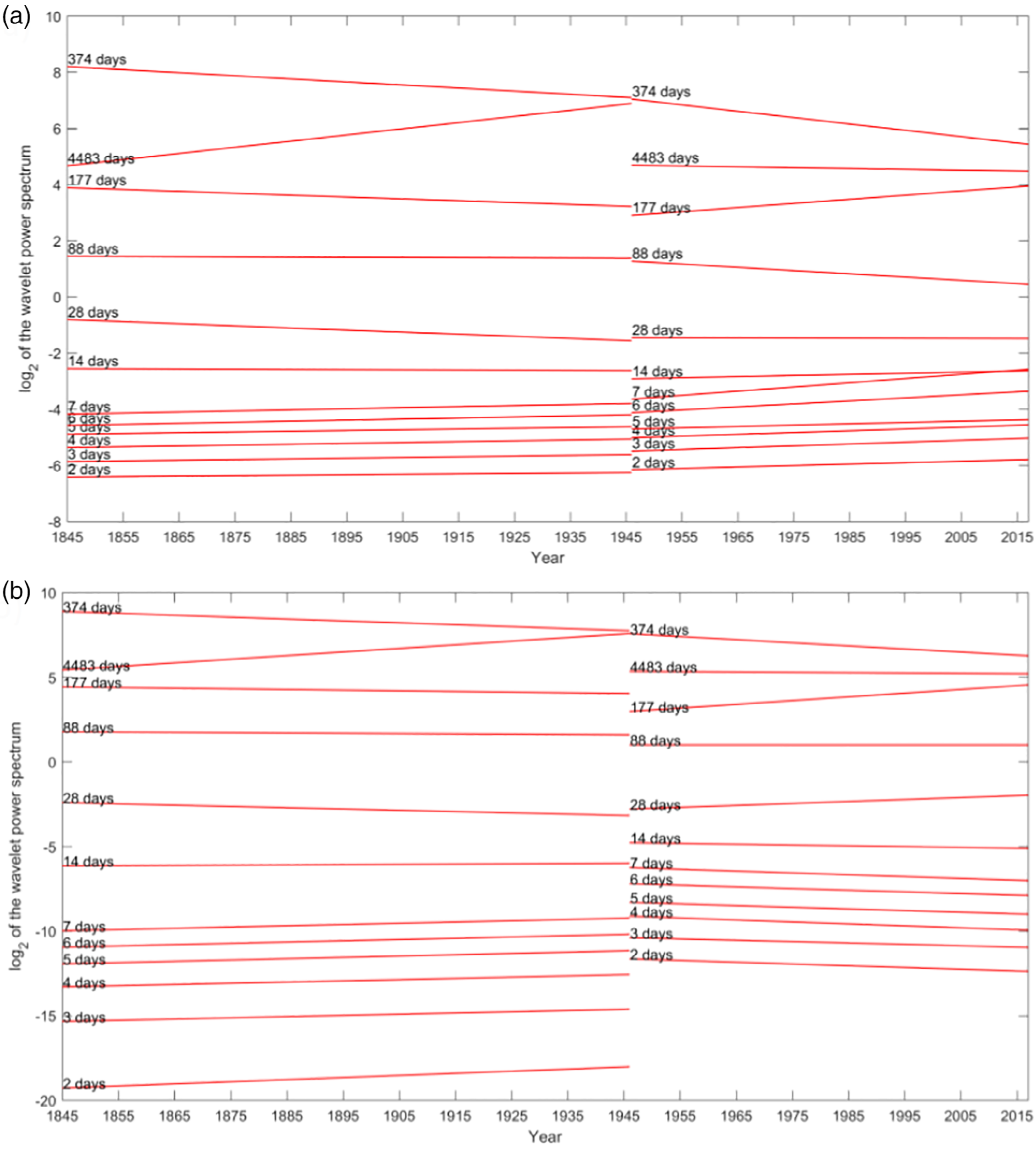

FIGURE 13 Linear regression trends of the wavelet energy spectrum of the (a) inflows and (b) outflows of Lake Como (Adda basin) for various characteristic scales [Colour figure can be viewed at wileyonlinelibrary.com]

3.5 | Wavelet coherence spectra

Because of the observed energy at about 12-year scale, we subjected the Adda River precipitation and runoff time series to a wavelet coherence analysis considering them together to the sunspot and the climate index records.

The wavelet coherence between the monthly sunspots and precipitation results in a very unclear picture (Figure 14). As it is seen, no consistent significant wavelet coherence areas are depicted inside the cone of influence (COI). The same results are supported by the wavelet coherence spectrum of sunspots and precipitation after deseasonalization (depicted in Supporting Information Figure S4) where only few and scattered areas of significant coherence are present. Also the deseasonalized runoff-sunspots coherence spectra (depicted in Supporting Information Figure S5) do not indicate any highly clear coherence and neither the correlation between precipitation and sunspots is significantly different from zero. Therefore, the common energy peak observed around the 11–12 year scale in the precipitation and runoff records and sunspots may be coincidental and no clear evidence is present of a direct cause–effect relationship.

Also the wavelet coherence spectra of precipitation and runoff (deseasonalized and not deseasonalized) and

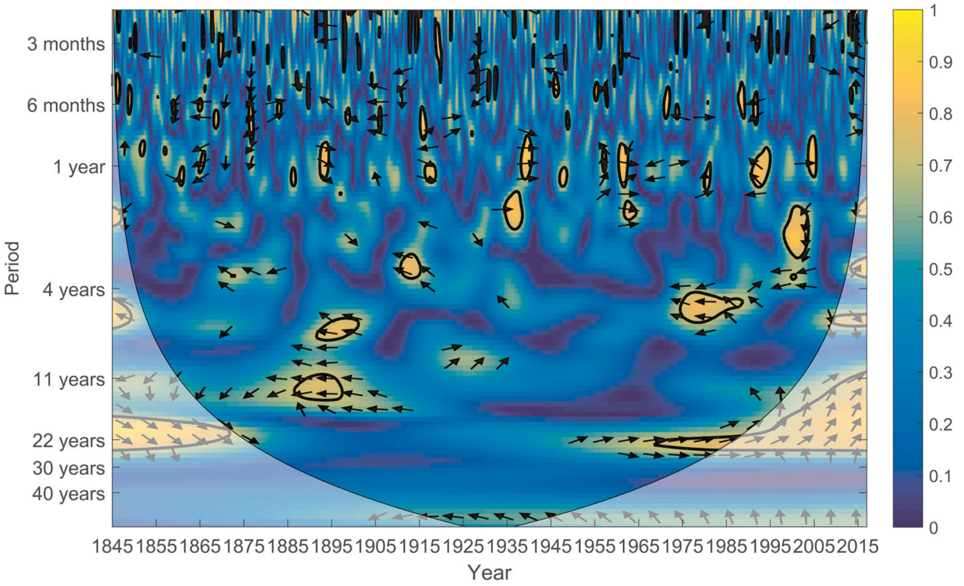

FIGURE 14 Wavelet coherence spectrum of monthly sunspots and monthly precipitation, 5% significance levels marked with black contour lines and COI; arrows pointing to the right indicate in-phase between the two variables, arrows pointing down indicate that the first variable anticipates the second by T/4, with T being the wavelet scale, and left-pointing arrows indicate anti-phase

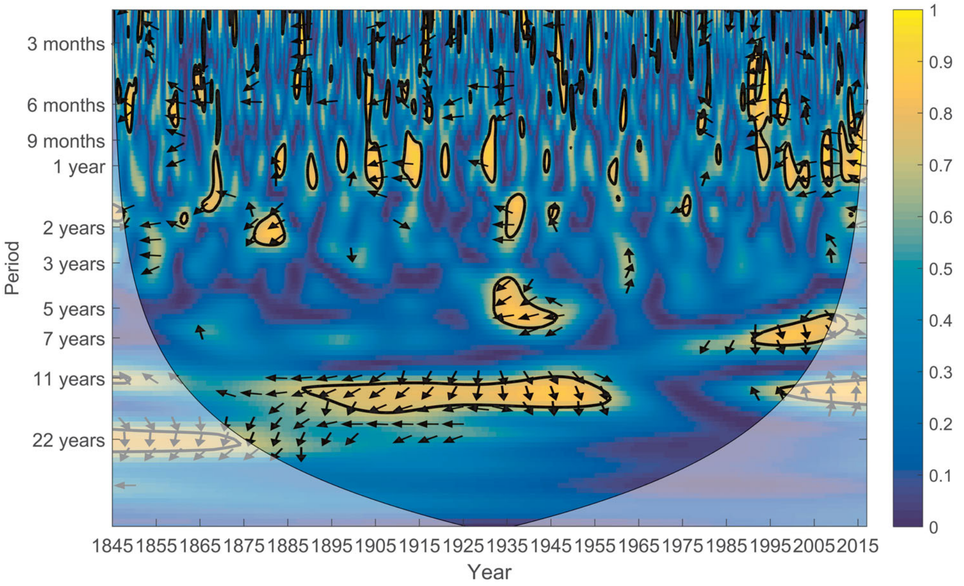

FIGURE 15 Wavelet coherence spectrum of NAO monthly index and monthly precipitation, 5% significance levels marked with black contour lines and COI; arrows pointing to the right indicate in-phase between the two variables, arrows pointing down indicate that the first variable anticipates the second by T/4, with T being the wavelet scale, and left-pointing arrows indicate anti-phase

the climate indexes considered in this paper, generally, do not highlight clear results. The main findings seem to be:

- An area of significant coherence between precipitation and the NAO index at the 11–17 year band during the period 1880–1955 (Figure 15). The downwards pointing arrows suggest however a possible lead of one half of the respective time scale of 11 years, that is, about 5.5 years, of one against the other, which is somewhat difficult to explain physically;
- An area of significant coherence between precipitation and the AMO index at the 15–30-year scale band during the period 1920–1985 (Supporting Information Figure S6).

Moreover, some other sparse significant phase coherences at various scales are observed, but as they are not consistent, they may be considered spurious.

4 | DISCUSSION AND CONCLUSIONS

We intend to discuss here the possible reasons of the observed significant negative trend of runoff and of the runoff coefficient, pointed out in the statistics of Table 1, in Figures 6 and 7 and shown also in Figure 10 of the companion paper by Crespi *et al.* (2020).

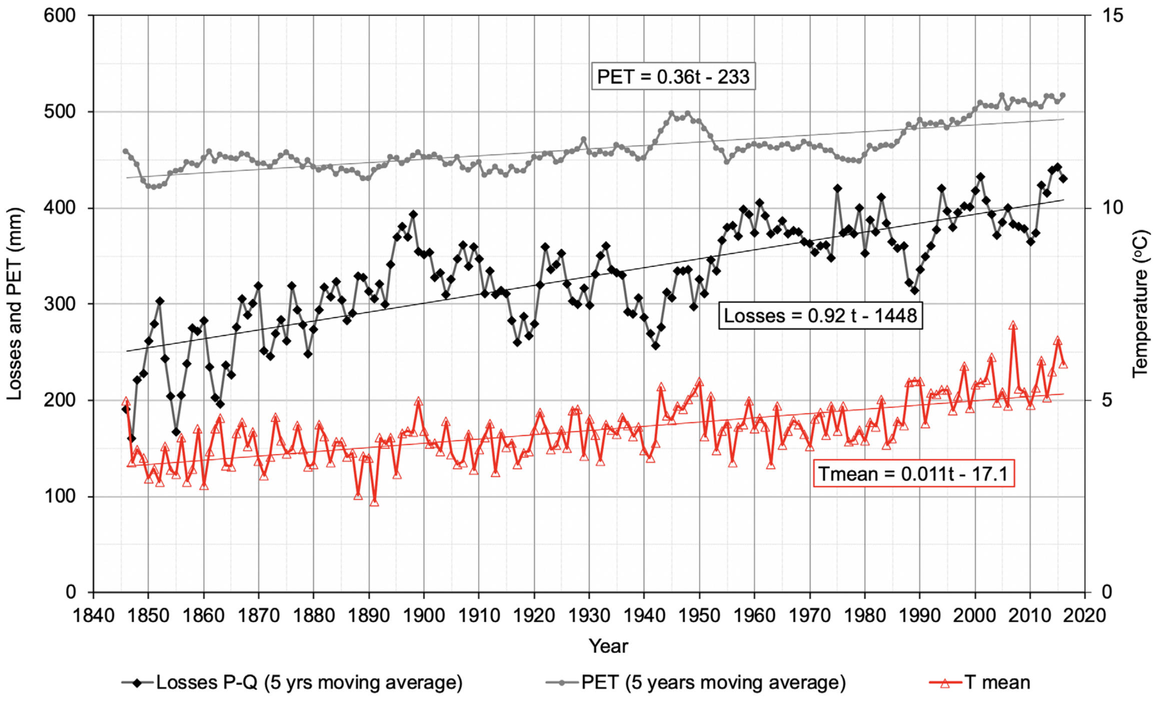

FIGURE 16 Annual losses, PET and mean temperature for the hydrological years 1846–2016. PET, potential evapotranspiration [Colour figure can be viewed at wileyonlinelibrary.com]

A possible explanation can be derived from Figure 16 showing the mean annual temperature estimated as areal average over the basin and derived from a 30-arc sec gridded dataset of monthly temperature covering the study domain (Brunetti *et al.*, 2006, 2009, 2014). The linear regression line has a slope of +1.1°C·century^{-1}, a value which is consistent with the temperature trends in the Alpine region reported by several authors as Böhm *et al.* (2001), Auer *et al.* (2007) and Brunetti *et al.* (2009). The same figure shows the mean areal potential evapotranspiration (PET) estimated with the Thornthwaite method computed on the same grid and then spatially averaged. It can be compared with annual water losses estimated as the difference of corrected precipitation and runoff, thus neglecting the effect of water storage in artificial reservoirs, lakes, groundwater, snow and glaciers. The corrected precipitation record we use here (see Crespi *et al.*, 2020) takes into account the underestimation of solid precipitation which is known to be relevant in mountain areas (Sevruk et al., 2009) and specifically in the investigated area (Eccel *et al.*, 2012; Grossi *et al.*, 2017). The assumption that water storage is not relevant for this estimation is reasonable as the change of these storage volumes at annual scale can be neglected with the exception of glaciers which experienced a significant retreat that in the last three decades accelerated with a volume loss of 12 mm·year^{-1}, as already discussed in Crespi *et al.* (2020), providing an additional contribution to runoff.

Part of the discrepancy between PET and the estimated annual losses is due to the fact that actual evapotranspiration is less than the potential one. However, it is worth noticing that observed losses increase in time, with a rate of 92 mm·century^{-1}, much more rapidly than PET estimates which show an increasing trend of 36 mm·century^{-1}. The higher trend of observed losses could be partly explained by the increased water exploitation for irrigation, civil water supply and services. However, it is also a result of the enhanced evapotranspiration losses from forested areas which in Europe and the Alps expanded their extent because of natural afforestation (FAO, 2018) as observed by Ranzi *et al.* (2017) in the nearby Adige basin. This conjecture could be supported by further investigations including the analysis of long-term land use changes and simulation of actual evapotranspiration losses.

In summary, the time series of the Lake Como daily inflow and outflow runoff reconstructed for the 1845–2016 period, compared with contemporary monthly precipitation and temperature observations and estimated PET losses, provides new data for a better insight into the driving factors of the hydrological cycle in mountain areas over long-time scales. A 5% significant decreasing trend of −136 mm·century^{-1} was observed for annual runoff, to be compared to the much lower non-significant trend −41 mm·century^{-1} of annual uncorrected precipitation (Crespi *et al.*, 2020). The changes in runoff regime cannot be explained by climatic changes alone and other factors influence several aspects of the observed variability.

Annual daily runoff maxima exhibit a decreasing trend, although not statistically significant, with lower values after the mid-20th century when the hydropower reservoirs were close to be completed. This could be partly explained by the fact that extreme flood volumes could be stored in the reservoirs thus reducing the peak intensity.

The observed significant increase of annual 7-day runoff minima is likely a result of the upstream reservoirs management practices that increase the hydropower generation in winter, when the natural runoff regime exhibits its minima. The impact of water management practice on the runoff record is also highlighted by the multi-scale spectral analysis conducted by the wavelet transform. It indicates, in fact, an increasing trend of high-frequency energy in both the daily inflow and outflow time series, observed especially after the completion of the upstream hydropower reservoirs and the start of the Olginate barrage regulation at the Lake Como outlet.

At larger time scales, the wavelet analysis allows to point out the drought period of both precipitation and runoff observed in the first decade of the 2000s and the long-term decrease of runoff. However, this analysis does not support a solar signature in the precipitation and runoff records. Our results, therefore, do not confirm the conclusions of Zanchettin *et al.* (2008a) who suggest the influence of the solar activity on runoff records for the Po River. Also, the phase coherence of Adda catchment precipitation and runoff with the climate indexes considered in the article turns out to be rather low, and it does not highlight clear cause–effect relationships.

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SUPPORTING INFORMATION

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