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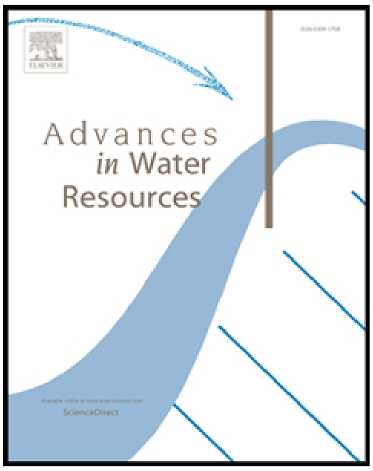

Hydrological change: Towards a consistent approach to assess changes on both floods and droughts

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Highlights

- We posit that consistent approaches are needed to assess changes on both hydrological extremes, i.e. floods and droughts
- We propose a method based on the theory of runs and threshold levels.
- We show an example application to the Po River, Italy

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Hydrological change: Towards a consistent approach to assess changes on both floods and droughts

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Abstract

Several studies have found that the frequency, magnitude and spatio-temporal distribution of droughts and floods have significantly increased in many regions of the world. Yet, most of the methods used in detecting trends in hydrological extremes 1) focus on either floods or droughts, and/or 2) base their assessment on characteristics that, even though useful for trend identification, cannot be directly used in decision making, e.g. integrated water resources management and disaster risk reduction. In this paper, we first discuss the need for a consistent approach to assess changes on both floods and droughts, and then propose a method based on the theory of runs and threshold levels. Flood and drought changes were assessed in terms of frequency, length and surplus/deficit volumes. This paper also presents an example application using streamflow data from two hydrometric stations along the Po River basin (Italy), Piacenza and Pontelagoscuro, and then discuss opportunities and challenges of the proposed method.

Keywords: Hydrological extremes, Human impact, Drought, Floods, Anthropocene

1. Introduction

The frequency, magnitude and spatio-temporal distribution of droughts and floods have increased in many regions around the world, and with this the related environmental, economic and social losses (Di Baldassarre et al., 2010; UN-ISDR, 2017; Winsemius et al., 2016). Studies examining trend detection on hydrological extremes usually: a) focus on either floods or droughts individually, while water management policies often account for both hydrological extremes, or b) are based on characteristics such as frequency, and/or absolute flow value (e.g. Mediero et al., 2014; Petrow and Merz, 2009), while other fundamental characteristics, such as duration and deficit/surplus volume, are not considered. In addition, in the case of flood trend detection, no method includes all previously described characteristics (Burn et al., 2016). These characteristics (duration and volume) do not only have a scientific application, but are also very useful in water management, where the (expected) duration and surplus volume of a flood can influence the type of mitigation measure that can be applied, and support the design of e.g. reservoirs for flood attenuation.

One example of a widely-used flood method is the Peak-Over-Threshold (POT; Alfieri et al; 2015; Bezak et al; 2014; Slater and Villarini, 2017). This method is defined based on the recurrence interval of the flood events (e.g. on average 1 event per year) and normally only quantifies the event peak flow. Another commonly used approach is the use of maximum and minimum annual flow data as proxies for the severity of floods and droughts, respectively (e.g.; Burn and Whitfield, 2016; Montanari, 2012; Slater and Villarini, 2017). While using annual maxima and minima is a consistent way to look at both extremes, volume and duration characteristics of floods and droughts are not captured. For drought assessment, other widely-used methods also include standardized indices (Huang et al., 2016; Joetzjer et al., 2013; Vicente-Serrano et al., 2014). But these indices are not able to quantify volume deficit characteristic, which make them less applicable in water management. Additionally, with standardized methods, data need to undergo a transformation to a theoretical distribution (e.g. gamma distribution), and the use of an inappropriate distribution could impart a bias in the resulting characteristics (Stagge et al., 2015).

In the Anthropocene, it is of especial importance to analyze floods and droughts conjunctively since humans continuously alter the characteristics of both hydrological extremes by changing land use, river morphology, water abstraction (Destouni et al., 2013; Hall et al., 2014; Van Loon et al., 2016). For instance, storage in dams and reservoirs can alleviate floods and alleviate or aggravate drought (López-Moreno et al., 2009; Rangecroft et al., 2016). Water abstraction for crop irrigation makes droughts more severe (Van Loon and Van Lanen, 2013). Flood protection measures, such as levees, can alter the frequency, magnitude and spatial distribution of flooding along the river (Blöschl et al., 2013; Di Baldassarre et al., 2009a, 2009b; Heine and Pinter, 2012).

To develop appropriate policies maintaining the benefits of hydrological variability (e.g. supporting ecosystem functions and biodiversity), while reducing the negative impacts of hydrological extremes (e.g. fatalities and losses), it is essential to capture how the characteristics of floods and droughts will plausibly change in the coming decades (Di Baldassarre et al., 2017). In this study, we aim at developing a consistent methodology that allows assessing changes in both hydrological extremes in terms of frequency, duration and volume. To better illustrate the method, we show an example application using the case of the Po River catchment (Italy), in which human influence has significantly increased over the past decades.

2. Method

Here we propose an alternative approach to consistently analyze changes in both floods and droughts. Our approach is based on the threshold level method, which comes from the theory of runs (Yevjevich, 1967; Rodríguez-Iturbe, 1969). It is a well-established method for scientific drought analysis (Fleig et al., 2006; Hisdal et al., 2006; Van Loon, 2015) and it is also being applied in water management, for example in the Po River basin (ARPA-CIMA, 2015). Some scholars have discussed the application of this method by computing deficit and surplus volumes or durations (Lee et al., 2015; Sen, 1980; Yevjevich, 1967), while Van Loon and Van Lanen (2013) and Rangecroft *et al.* (2016) used threshold levels to compare drought characteristics in naturalized and human-influenced conditions.

With the threshold method, floods and droughts are broadly defined as more/less water than "normal". This is done by defining high/low streamflow percentiles during the baseline period. These high/low percentiles are then used as threshold levels so that, a drought is defined when the flow is below the low-percentile threshold, and a flood when the flow is above the high-percentile threshold. The duration of the drought/flood event is defined as the consecutive number of days or months (depending on the accumulation time) that the flow is below/above the threshold. The deficit/surplus volume for each drought/flood event is calculated as the sum of the deviations from the threshold.

In our proposed methodology, we define droughts and floods using fixed (and symmetrical) thresholds, e.g. 99th (droughts) and 1st (floods) percentiles of the monthly time series.

This identification of consistent thresholds for both droughts and floods can result odd to some readers. Monthly streamflow might not be ideal to capture flood events, while a fixed 99th percentile threshold is not usual in drought analyses. Here we argue that common approaches to identify floods and droughts are influenced by the impact of these events: daily flood peaks can lead to levee breach and generate flooding, while less water than normal with respect to a monthly-variable threshold can have serious implication for agriculture. Thus, we also included an impact-focused analysis, which is also based on the threshold level method, but where droughts were defined using a monthly-varying threshold based on the 80th percentile of the monthly time series and floods were defined using a fixed threshold based on the 1st percentile of the daily time series. This second analysis is a less symmetrical version of the first method proposed, but keeps some elements of consistency, and reflects most common ways to study hydrological extremes.

3. Example application

The Po River basin is a well-studied area because of its relevance in Italy (it accounts for about 40% of the country's GDP) and the potential impact of increasing urbanization and exploitation of water resources (Montanari, 2012). As a result there are long-term and good-quality hydrological data available, which enables the application of our proposed methodology. We used streamflow data from two stations, Piacenza (upstream) and Pontelagoscuro (downstream), with contributing area of 42,000 km^2 and 71,000 km^2 respectively, for the period 1924–2009. This period was selected to assess the changes in extremes discussed by Kottegoda and Natale (1994), Zanchettin *et al.* (2008) and Di Baldassarre *et al.* (2009) as being linked to the fast industrial and agricultural expansion, as well as urbanization, that Italy experienced during the economic booming in the 1960s. For example, the increase of annual maximum flows peaks (Figure 1A, Montanari, 2012) was attributed to the building and heightening of levees over the past two centuries (Di Baldassarre et al., 2009a). The decrease in annual minimum flows in the lower part of the Po River (Figure 1B, Montanari, 2012) was attributed to water consumption by irrigated crops after the rapid expansion of irrigation that took place in second half of the 19th century shows (Kottegoda and Natale, 1994).

To apply our method, we split the streamflow data of the Po River at Piacenza and Pontelagoscuro in two periods: 1924–1953 (*baseline*) and 1980–2009 (*human influenced*). The splitting is based on the implicit assumption that changes in hydrological extremes can be explained by the significant increase in human activities that took place in 1960s, since no major climatic change has been reported after the precipitation shift that occurred in 1920 (Zanchettin et al., 2008). However, during the baseline period the hydrology of the Po was already altered by water abstraction, reservoirs and levees, but these human alterations of the hydrological regime were further enhanced during the human influenced period (Kottegoda and Natale, 1994; Zanchettin et al., 2008). Distinguishing between human and climate influences on hydrological extremes remains a key challenge to address and it is out of the scope of this paper.

Flood and drought thresholds were obtained at each station for the baseline period, and then applied to both the baseline and human influenced periods. Hence, we obtained a set of characteristics for the extreme events occurring at each station and at each period, allowing us to assess changes in time and space. The set of characteristics included number of events, and the average length and deficit/surplus volume of the events occurring at the period in question.

4. Results and discussion

Table 1 and Figure 2 show the results obtained with the consistent approach using symmetrical thresholds, while Table 2 shows the outcomes of the analysis using different thresholds for floods and droughts. Overall, the results from the two analyses showed that during the human influenced period there was an exacerbation of both hydrological extremes, in terms of duration and magnitude, i.e. surplus/deficit volume (Tables 1 and 2, and Figure 2B and C). This overall outcome is consistent with previous studies (Di Baldassarre et al., 2009a; Kottegoda and Natale, 1994). However, this result was shown differently by the two analyses. In the consistent approach using symmetrical thresholds we found that flood and drought events were less frequent and had higher magnitude at both upstream and downstream stations during the human influenced period, with the downstream station showing a much larger difference in surplus/deficit volume (Table 1). In the analysis using different thresholds we found that drought events were more frequent and had higher magnitude at both stations during the human influenced period, while this was only shown for floods at the downstream station (Table 2). The difference in flood trends between the two stations can be partly attributed to the completion of the levee system between Piacenza and Pontelagoscuro that took place after the 1951 flood event (Di Baldassarre et al., 2009a). In terms of drought trends, the differences between Piacenza and Pontelagoscuro were limited (Table 2).

With the use of the threshold level method on the two approaches, it was possible to obtain the same set of (important) characteristics for both extremes. In the consistent analysis, the thresholds were based on the same accumulation timescales, and were symmetrically defined. This allows describing the changing patterns of floods and droughts in the same terms, therefore making it possible to compare the results of both extremes. The comparability of the results is also true for the impact-focused approach that, even though it defines each threshold differently, it is based on the same methodology.

The threshold level method has been mostly used for drought applications, but our results showed the usefulness of this method for flood applications as well. With the threshold method we were able to capture the most important flood events in the Po River, as reported by Zanchettin et al. (2008) and Montanari (2012). This method is therefore a good candidate for the consistent methodology because it reflects flood and drought definitions (i.e. more/less water than normal), it is easy to apply, it helps increase scientific understanding of processes, and it gives useful information for the management and modeling of both extremes.

In this example application, epistemic rating errors such as changes in the cross section of the channel - to which low flows can be especially sensitive - are considered to be small due to the yearly update of the rating curves at the Po River since the 1920s (Kottegoda and Natale, 1994). The latter is especially true for our drought analysis, which has been done with monthly accumulated streamflow values. In the case of the high flows, errors due to rating-curve uncertainty in the Po River can be significant (Di Baldassarre and Montanari, 2009). Yet, these errors were found to be similar for flood conditions (Di Baldassarre and Claps, 2011), and therefore their effect on trends was considered to be limited. Moreover, the challenge of separating out human and climatic influences was partly addressed here by limiting the example application only to the period after a major shift in precipitation that occurred in 1920 (Zanchettin et al., 2008). Yet, distinguishing between human and climate influences on hydrological extremes remains a key challenge to address.

4. Conclusions

In this study, we discussed the need for improving the available methods to assess changes in droughts and floods. Decision making within e.g. water and disaster management can be greatly benefited by assessments made with a consistent approach that, in addition to trend detection, include other characteristics such as duration and deficit/surplus volume. We therefore proposed a methodology based on the threshold level method or theory of runs.

Our methodology was found to be an effective and simple way to consistently assess changes on both hydrological extremes, and to obtain important characteristics such as frequency, duration and deficit/surplus volume. Additionally, we discussed the potential use of our methodology in understanding how human activities influence both hydrological extremes. A consistent treatment of drought and flood changes opens up new opportunities to schematize their interactions and feedbacks with social dynamics, e.g. socio-hydrological modeling, which is one the main objectives of *Panta Rhei - Everything flows*, the current decade of the International Association of Hydrological Sciences (Montanari et al., 2013; McMillan et al., 2106).

Acknowledgements

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Figures

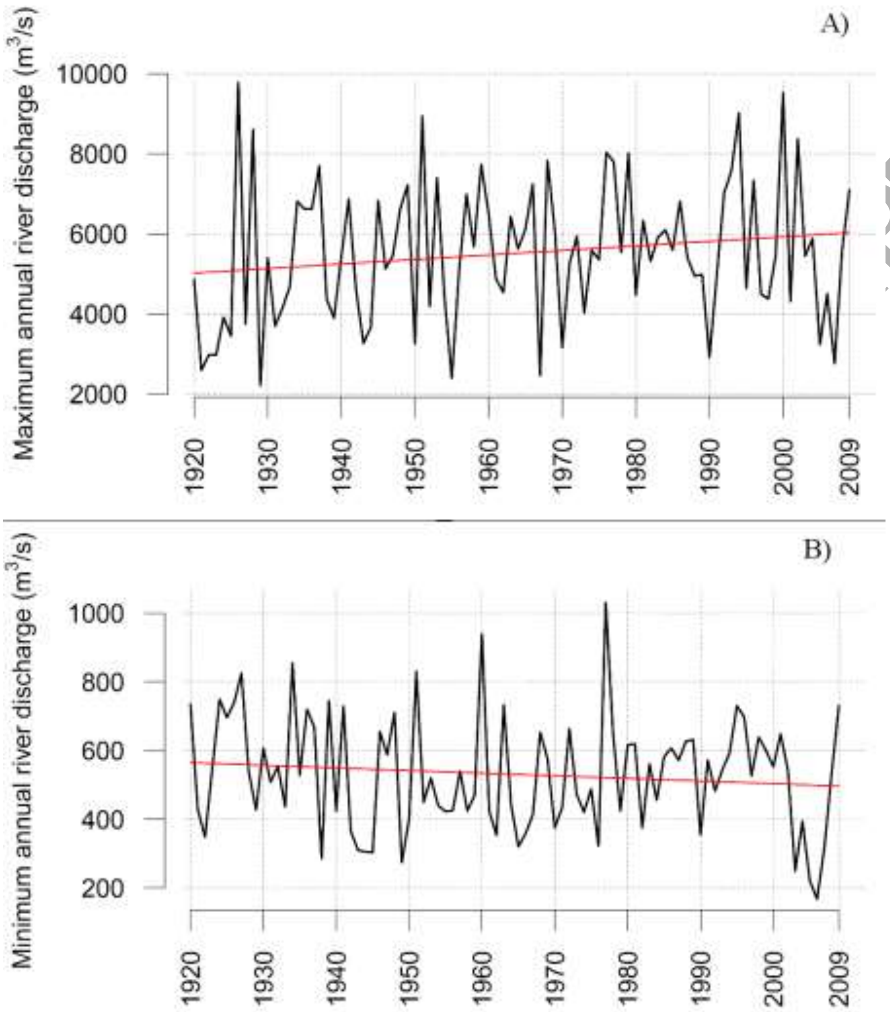

Figure 1. Hydrological extremes in the period 1920-2009 on the Po River at Pontelagoscuro, Italy (Source: Montanari, 2012): A) Annual maximum daily discharge series and linear regression; B) Annual minimum daily discharge series and linear regression (Source: Montanari, 2012).

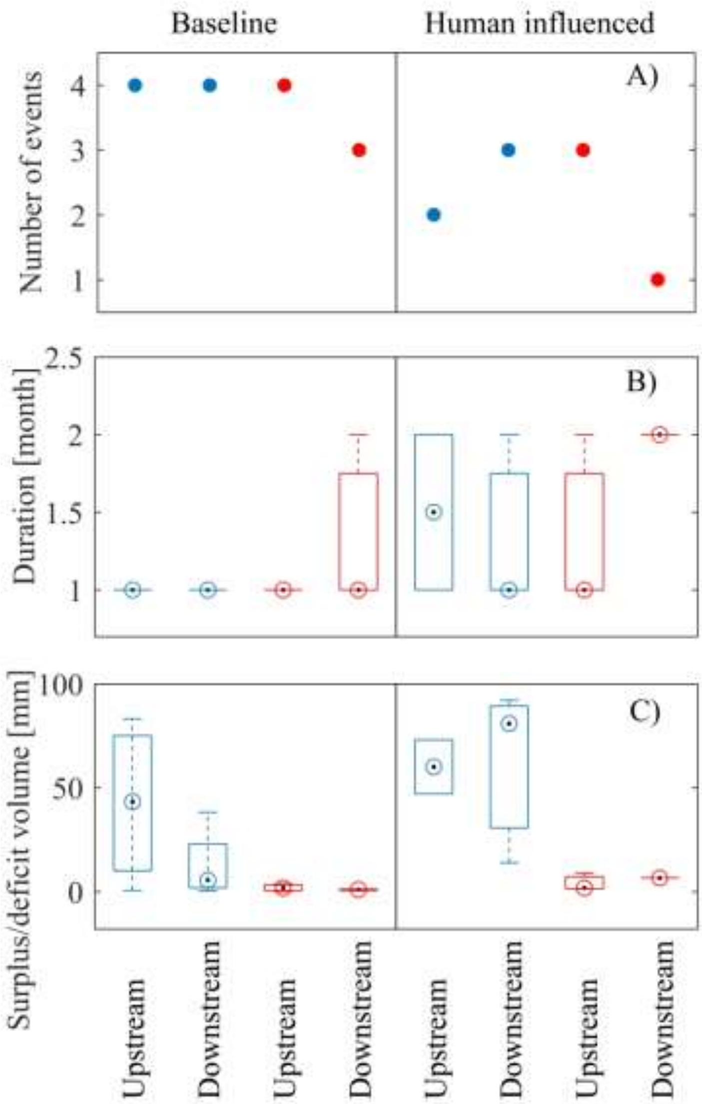

Figure 2. Boxplots showing the 100% distribution of the characteristics values for floods (blue) and droughts (red) obtained using the consistent approach in the example application. Droughts (floods) were defined on a monthly timescale based on the 99th (1st) percentile of the total time series. The boxplots cover the interquartile range (25th–75th percentile) and the median is shown by the marker.

Tables

Table 1. *General statistics of the consistent approach example application. Droughts (floods) were defined on a monthly timescale based on the 99th (1st) exceedance percentile of the total time series. For each characteristic, the relative change with respect to the baseline period is included in parenthesis.*

	Piacenza 1924–1953	Piacenza 1980–2009 (% change)	Pontelagoscuro 1924–1953	Pontelagoscuro 1980–2009 (% change)
Flood events (number)	4	2 (-50%)	4	3 (-25%)
Flood duration (average) [months]	1	1.5 (50%)	1	1.3 (33.3%)
Flood volume (average) [mm]	42.5	60 (41.1%)	12.3	62.3 (404%)
Drought events (number)	4	3 (-25%)	3	1 (-66.7%)
Drought duration (average) [months]	1	2 (100%)	2	2 (0%)
Drought volume (average) [mm]	1.8	4 (118%)	0.9	6.6 (464%)

Table 2. *General statistics of the impact-focused approach application example. Floods were defined on a daily timescale with a fixed threshold based on the 1st percentile. Droughts were defined based on a monthly varying threshold based on the 80th percentile. For each characteristic, the relative change with respect to the baseline period is included in parenthesis.*

	Piacenza 1924–1953	Piacenza 1980–2009 (% change)	Pontelagoscuro 1924–1953	Pontelagoscuro 1980–2009 (% change)
Flood events (number)	39	45 (15.4%)	28	32 (14.3%)
Flood duration (average) [days]	2.8	2.6 (-5.3%)	3.9	4.9 (26.8%)
Flood volume (average) [mm]	7	5 (-27.3%)	4.6	6.9 (49.8%)
Drought events (number)	36	38 (5.6%)	38	40 (5.3%)
Drought duration (average) [months]	2.0	2.3 (14.5%)	1.9	2.3 (21.4%)
Drought volume (average) [mm]	14.1	19.9 (41%)	14.8	17.7 (20%)