



Multivariate real-time assessment of droughts via copula-based multi-site Hazard Trajectories and Fans



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SUMMARY

Droughts, like floods, represent the most dangerous, and costly, water cycle expressions, with huge impacts on society and built environment. Droughts are events occurring over a certain region, lasting several weeks or months, and involving multiple variables: thus, a multivariate, multi-site, approach is most appropriate for their statistical characterization. In this methodological work, hydrological droughts are considered, and a multivariate approach is proposed, by regarding as relevant variables the duration and the average intensity. A multivariate, multi-site, frequency analysis is presented, based on the Theory of Copulas and the joint Survival Kendall's Return Periods, by investigating the historical drought episodes occurred at five main river sections of the Po river (Northern Italy), the most important Italian basin. The tool of Dynamic Return Period is used, and the new concepts of Hazard Trajectories and Fans are introduced, in order to provide useful indications for a valuable multi-site real-time assessment of droughts.

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1. Introduction

According to [Beran and Rodier \(1985\)](#), “Droughts are generally viewed as a sustained and regionally extensive occurrence of below average natural water availability, either in the form of precipitation, river runoff, or groundwater”. In literature, several works have pointed out as a main obstacle to the drought investigation the lack of a precise definition (see, among others, [Yevjevich, 1967](#); [Wilhite and Glantz, 1987](#); [Demuth and Külls, 1997](#)).

[Palmer \(1965\)](#) defined droughts as a meteorological phenomenon characterized by a prolonged and abnormal moisture deficiency. [Wilhite and Glantz \(1987\)](#) and [McKee et al. \(1993\)](#) summarized drought definitions as a natural phenomenon that originates from a deficit in precipitation, which results in water shortage for some activities or group. In a recent review, [Mishra and Singh \(2010\)](#) have defined droughts as a temporary phenomenon characterized by the reduction in the amount of precipitation received over an extended period of time, such as a season or a year.

[Dracup et al. \(1980a\)](#), reviewing several definitions of droughts, underlined that droughts are a wide concept covering different fields of study. Droughts have been categorized in four different

classes ([Dracup et al., 1980a](#); [Beran and Rodier, 1985](#); [Wilhite and Glantz, 1987](#)):

hydrological: relatively to below normal flow and depleted reservoir storage;
meteorological: relatively to below normal precipitation;
agricultural: if the soil moisture is not sufficient to support crop growth;
socio-economical: if the low water supply affects socio-economic activities.

These definitions describe only qualitatively a drought. Operational definitions, which consider main drought features like onset, termination, duration, severity, and intensity, are necessary to quantitatively address the problem ([Wilhite and Glantz, 1987](#)).

[Gumbel \(1963\)](#) defined the hydrologic drought as the smallest annual value of the mean daily discharge, and used the third asymptotic distribution of the smallest value (i.e., EV III type law) to derive the return period of droughts occurred in Muskegon (Michigan) and French-Broad (North Carolina) rivers. Similarly [Gannon \(1964\)](#) investigated the hydrologic droughts in Michigan, during the period May–October, defining these as the smallest value of the mean discharge over periods of 1, 7, 15, and 30 consecutive days, and used Extreme Value distributions. A criticism to these approaches is that hydrological droughts are described only

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through the maximum water deficit, without considering the length of the drought and the total water deficit.

Yevjevich (1967) proposed a threshold approach, also called *run method*, to identify hydrologic droughts. Thus, a drought (negative run) is characterized by a *duration*, the interval during which the discharge is below, or equal to, a fixed threshold, and a *severity*, defined as the cumulative volume deficit below the given threshold. The ratio between severity and duration is the *average intensity* of drought. Conversely, the period during which the discharge is above the fixed threshold is a positive run. The run method has been widely applied to yearly and daily data. Examples considering the former time scale include Sen (1977), Dracup et al. (1980b), Clausen and Pearson (1995), and also Clausen and Pearson (1998), where the threshold has been fixed equal to the long-term mean annual flow, or the 75% of it. Examples considering daily data include, among others, Zelenhasić and Salvai (1987), Tallaksen et al. (1997), Demuth and Külls (1997), Demuth and Heinrich (1997), Kjeldsen et al. (2000), Engeland et al. (2004), Byzedi and Saghaian (2009), and Byzedi (2010). However, the application of run method to sub-yearly time scales (e.g., daily ones) requires a particular attention to the possible presence of mutually “dependent” droughts, i.e. to the fact that a prolonged dry period may be interrupted by shorter ones where the flow exceeds the threshold level, and therefore a long drought turns out to be divided into a number of shorter ones.

Zelenhasić and Salvai (1987) studied the number, severity, duration, time of occurrence, largest duration, and largest severity of drought events of Sava river at Sr. Mitrovica, and Tisa river at Senta (both in ex-Yugoslavia), using the run method with daily data and, as thresholds, the 95-, 90-, 80-, 70-, and 60-percentile of the flow–duration curve. They found that the 95- and 90-percentiles are more statistically correct to identify droughts, since the events belong to the region of low extremes. The maximum annual duration and severity were modeled using an exponential distribution. Zelenhasić and Salvai (1987) have modified the run method to account for the temporal dependence of consecutive drought periods. They introduced two additional conditions: (i) two consecutive droughts, separated by a short interval (inter-event time) during which the flow is slightly above the threshold, have to be considered as just one drought, with duration and severity equal to the sum of the two events duration and severity, respectively and (ii) all droughts having a severity less than 0.5% of maximum value are discharged.

Tallaksen et al. (1997) applied the run method to daily data of two catchments in Denmark, using as thresholds the 50-, 70- and 90- percentile of the flow–duration curve. Three different procedures were considered to pool together mutually dependent droughts: (i) an inter-event time and volume criterion, (ii) a moving average procedure, and (iii) a method based on the sequent peak algorithm. The first criterion, similar to the one proposed by Zelenhasić and Salvai (1987), states that if the inter-event time between two successive droughts is less than, or equal to, a critical duration, and the ratio between the inter-event excess volume and the preceding deficit volume is less than a critical value, then the two droughts have to be pooled into a single drought, with duration equal to the sum of the durations of the two events and the inter-event time, while the volume is given by the sum of the two events volumes minus the inter-event excess volume. The moving average procedure has to be applied directly to the flow time series to smooth it and remove the minor peaks; then, the run method can be applied to the smoothed time series. The sequent peak algorithm, used for the design purposes of reservoirs, states that a drought is identified as a continuous period of storage depletion; thus, two droughts are dependent if at the beginning of the second one the reservoir has not yet recovered from the first one. The drought volume is the maximum storage depletion within

the event, and the duration is given by the difference in time between the maximum depletion instant and the starting time of the drought. The same methodologies have been applied by Fleig et al. (2006) to sixteen daily flow series collected at different sites of the world, with thresholds equal to 70- and 90-percentiles of the flow–duration curve.

Demuth and Külls (1997) used the run method for analyzing daily data of 27 stations in the south of Germany, using as a threshold the 90-percentile of the flow–duration curve. To avoid dependence problem of successive droughts, a termination criterion at 10% was used: a positive volume of a maximum 10% of the foregoing drought volume is allowed before terminating an event. Demuth and Külls (1997) extracted the maximum annual duration and severity, and for each of these estimated the parameters of LogNormal, Generalized Extreme Value, Pearson III, and Generalized Pareto distribution using L-moments and Partial Probability Weighted Moments. Demuth and Heinrich (1997) investigated the drought duration in 111 stations located in south Germany, using as a threshold the 90-percentile of the flow–duration curve, and a termination criterion at 10%.

Kjeldsen et al. (2000) studied droughts occurrences in ten Zimbabwian rivers (some ephemeral and others perennial) using daily data. In this case, the threshold was chosen to vary monthly, due to the strong seasonality of the region climate, and defined as the 75-percentile of the monthly flow–duration curve. Note that, for ephemeral rivers, the expected flow during the dry season is zero, which corresponds to a truncation level equal to zero. In the case of a drought starting in the rainy season, the begin of the dry season involves an increase in the duration, but not in the severity. The drought can also go over the dry season and foregoing in the next rainy season until the daily stream flow is below the threshold. Perennial rivers yield no problem regarding the drought definition, being the thresholds different from zero in all the months. Possible mutually dependent droughts were identified using the sequent peak algorithm methodology (Tallaksen et al., 1997). To estimate the return period of drought severity and duration, a two-component exponential distribution was used for both variables.

Engeland et al. (2004) applied the run method to daily Norwegian data, using as a threshold the 70-percentile of the flow–duration curve, and a 10-days moving average procedure to cope with dependent droughts. A Generalized Extreme Value and a Generalized Pareto distribution were fitted to the maximum annual severity.

Recently, Byzedi and Saghaian (2009) and Byzedi (2010) used the run method, with a truncation level at the 70% of the daily discharge, and the inter-event time criterion to pool together dependent droughts, to investigate forty-four hydrometric stations in South-Western Iran. A frequency analysis of the annual maximum drought severity and duration was performed.

In literature, until 2000, the drought frequency analysis has been addressed principally under a univariate framework: viz., by calculating the probability distribution of drought duration and drought severity, and considering these variables as independent. However, droughts are multi-dimensional random phenomena characterized by duration, severity and intensity variables, each dependent on one another. Thus, a multivariate probabilistic framework is advisable for a proper description of droughts.

The introduction of *Copulas* in hydrology (De Michele and Salvadori, 2003) has greatly facilitated the multivariate modeling of droughts: see, among others, Shiau (2006), Serinaldi et al. (2009), Shiau and Modarres (2009), Kao and Govindaraju (2010), Wong et al. (2010), Song and Singh (2010, 2011), Mirabbasi et al. (2012), Ganguli and Reddy (2012), Reddy and Ganguli (2012), Chen et al. (2013), De Michele et al. (2013), Ganguli and Reddy (2014), and also Mishra and Singh (2011) for a review. In the above mentioned works, with the exceptions of Kao and Govindaraju

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