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Research papers

Estimation of intensity-duration-frequency relationships according to the property of scale invariance and regionalization analysis in a Mediterranean coastal area

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ABSTRACT

Usually, networks of daily rainfall raingauges have a higher spatial cover than tippet bucket raingauges networks. Consequently, it would be of high interest to make use of daily rainfall information to asses IDF curves for unobserved locations. The present work proposes achieving this goal by using the assumption of simple scaling invariance. Indeed, series observed over sufficiently long periods for 10 tippet bucket raingauge, allowed us to test the hypothesis of simple scaling of annual maximum rainfall intensities in northern Tunisia. This assumption, combined with Gumbel model of maximum rainfall intensities allowed us to develop a methodology to estimate IDF curves from the daily rainfall totals. In fact, a regionalization formula which involves the percentile 90% of the annual maximum daily rainfall was developed and validated. This regionalization formula applied to daily data of 25 rainfall stations in the sub area of Tunis region, combined with the assumption of simple scaling has enabled us to develop Intensity Duration Area Frequency (IDAF) curves for Tunis area.

1. Introduction

The assessment of extreme precipitation is an important problem in hydrologic risk analysis and design. This is why the evaluation of rainfall extremes, as embodied in the intensity-duration-frequency (IDF) relationship, has been a major focus of both theoretical and applied hydrology. It has a link with sewage water systems, dams management and inundation risk mitigation. The IDF were initially established on the basis of frequency analysis of rainfall at a given station observed during a quite long period, using the annual maximum of the series (AMS) or a sufficiently high values exceeding threshold (POT). In such a case, the various reference time or resolutions are studied separately. Various forms of empirical IDF curves are found in the literature under the following form:

$$I_d^T = \frac{a}{(d^b + \theta)^m} \quad (1)$$

where a, θ, m and b are parameters depending on the meteorological conditions and the station location, I_d^T represents the rainfall intensity for the duration d and return period T. In (1), Talbot formula corresponds to $m = b = 1$ and Montana formula to $\theta = 0$ and $m = 1$.

Koutsoyiannis et al. (1998) considered that the dependency in d and the dependency in T can be modeled by two separate equations:

$$I_d^T = \frac{a(T)}{B(d)} \quad (2)$$

where the parameter $a(T)$ can take one of two forms:

$$a(T) = v + h \ln T \quad (3)$$

$$a(T) = KT^c \quad (4)$$

The second form is the oldest (Bernard, 1932). The American formula corresponds in (1) to $\Theta = 0$ and $m = 1$ with $a(T)$ as specified in (3). According to Koutsoyiannis et al. (1998), the function $a(T)$

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can be derived from the probability distribution function of the maximum rainfall intensity. Effectively, they proposed a general formula for IDF relationship whose forms were explicitly derived from several distributions such as Gumbel, Generalized extreme value (GEV), Gamma, Log Pearson III, Lognormal, Exponential, and Pareto. A general form of $a(T)$ reported in Koutsoyiannis et al. (1998) and Menabde et al. (1999) is:

$$a(T) = \mu + \sigma F^{-1}(1 - 1/T) \tag{5}$$

where μ and σ are respectively the scale and location parameters of the distribution function and F the cumulative distribution function.

Montana formula was adopted to model *IDF*-curves relationship in different regions of Tunisia (Thirriot et al., 1981; Saadaoui, 1986; Zitouni, 1997). In a recent study performed by DGRE-ST2i (2007), IDF curves using Montana, Talbot as well as the American formula designed for Northern Tunisia. The analysis was carried out using Hydraccess software from IRD (Hydraccess, 2000). Each series of annual maximum rainfall intensities was adjusted separately using the probability distribution functions: Gauss, Gumbel, Galton, Pearson III, Pearson V, Goodrich, Fréchet and WRC-USA. In the present work, data reported in DGRE-ST2i (2007) will be adopted as database for tipping bucket network.

Conversely to the previous IDF design framework, the various reference time or resolutions are not studied separately in case where the scale effect in rainfall series is considered. Indeed, Burlando and Rosso (1996) are the pioneers who sought to apply the assumptions of scale invariance to annual maximum series of rainfall depth (for durations ranging from 5 to 180 min). In their paper, the scaling and multiscaling properties of storm rainfall depth of different durations were analyzed and a lognormal probability distribution was used to model annual maximum rainfall depth. The key assumption is that the quantiles and moments of any order are scale invariant. Furthermore, Bendjoudi et al. (1997) provided a multifractal interpretation of the American formula based on the multifractal properties of scale invariance of rainfall series in relation to the critical order of moment divergence. The empirically observed scaling properties of annual maxima of mean rainfall intensity were noticed in Menabde et al. (1999) where the most important assumption is that the cumulative distribution function for any duration d has a standardized function form involving a function F independent of d. Based on Gumbel distribution model, different durations d were assumed to be related through a simple power law. Such an assumption was tested for two different sets of data from Australia and South Africa and they proved that annual maxima rainfall intensities are characterized by scale invariance for time scales ranging from about 30 min to 24 h (Menabde et al., 1999). Blanchet et al. (2016) extended this property for time scales ranging from 4 to 100 h. The modeling of maximum rainfall intensities by adopting the simple scale invariance property, as in Menabde et al. (1999), has been investigated and adopted later by Yu et al. (2004) as well as Bara et al. (2009, 2010). Thanks to this assumption IDF relationship for unobserved durations have been inferred from the daily resolution from which data series are always the most available in practice as stressed by Yu et al. (2004).

To get spatial IDF relationship and to infer IDF from observed sites to non-observed sites, regionalization tools were proposed (Marand and Zumstein, 1990; Neppel, 2005). Regionalization means the transfer of data from one catchment to another (Bloschl and Sivapalan, 1995). Here instead of watersheds, gauged sites are observed locations and ungauged sites are unobserved locations. According to Hingray et al. (2009), there are two types of regionalization in IDF studies. The first one allows setting locale parameters constant by region. In this case the IDF are assumed invariant within a given region. The second type consists in establishing regional estimation models that estimate, at a given site, the parameters of an IDF model. In this case, IDF parameters vary within the region. Zahar (1997) studied the spatial variability of the parameter b in Montana formula for Central Tunisia. He linked the parameter b of Montana formula to the ratio of fall season Gradex to annual Gradex of 24 h (the Gradex is the scale parameter of Gumbel distribution). Then he proposed the estimation of extreme hourly rainfall statistics at a given location from the daily rainfall statistics.

Moreover, it is important to integrate the IDF curves on surfaces which give rise to Intensity-Duration-Area-Frequency (IDAF) curves. The IDAF curves are obtained by separately considering IDF (i.e. time scale) and areal reduction factor (ARF) (i.e. space scale) components of the extreme rainfall distribution. Their computation requires inferring areal rainfall distributions over the range of space scales and timescales that are the most relevant for catchment scale analysis. The IDAF curves are very useful since they account the amount of rainfall in relation to a given surface and a given return period. Such estimations are determined for design storms and design hydraulic structures as well as for characterizing the severity of storms. Ramos et al. (2005) quantified the risk related to Mediterranean storms observed over the city of Marseille. This approach has been adopted by Norbiato et al. (2007) and Ceresetti et al. (2011) to quantify the severity of flash floods occurred respectively east of the Italian Alps and Mediterranean mountainous region of southern France.

De Michele et al. (2001) argued that ARF is largely influenced by the return period especially for large values of return period. According to Langousis (2005) and Svensson and Jones (2010), ARF is affected by the shape of the watershed geometry, seasonal climatic characteristics and topography. Several authors (Veneziano and Langousis, 2005; Langousis, 2005) agreed that the empirical curves ARF are often characterized by a scale invariance behavior in space and time under specific limits. Several studies were interested in the scaling invariance of ARF/IDAF curves and their relationship with multifractal formalism (De Michele et al., 2001, 2002, 2011).

So, the aims of this study are firstly to develop the scaling behavior of tipping bucket rainfall data northern Tunisia. Secondly, it is proposed to take advantage of such approach to derive regional IDF and IDAF curves. In Section 2 databases are presented. Methodology is developed in Section 3. Section 4 presents main results and discussion and then the conclusion is drawn.

2. Rainfall data analysis

The study area is reported in Figs. 1 and 2. It is located Northern Tunisia and is limited by the Mediterranean Sea northern and eastern. Two types of data series are investigated for the study: tipping bucket raingauges and daily rainfall totals raingauges. Two spatial scales are also considered. The first one is northern Tunisia which covers 23,573 km^2 (Fig. 1). The second one is Tunis area with an extent of 2697 km^2 (Fig. 2).It is a sub area of northern Tunisia. The former is assumed as a regional scale and Tunis area as local scale for this study. Note that the large scale area is only 10 times greater meaning a scale ratio of roughly 3, which is quite small and may justify the information transfer operated in the regionalization procedure. Raingauge locations of Northern Tunisia are reported in Fig. 1 and those belonging to Tunis area in Fig. 2. In Tunis area, daily rainfall totals are collected from a network of 41 raingauges. So, the spatial density of this daily rainfall network is 66 km^2/station. Among the 41 stations, 6 are outside the study area. They are adopted for interpolation purposes using kriging. One single tipping bucket raingauge series in Tunis Manoubia station is considered in Tunis area. To get an idea of the magnitude of the maximum rain in the Tunis area, we also introduced the map