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Empirical study of extreme rainfall intensity in a semi-arid environment at different time scales

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A B S T R A C T

Mediterranean environments are typical of semi-arid regions, dominated by episodes of torrential rain in which the critical variable is not the total rainfall, but the intensity. This paper studies the maximum rainfall intensities at different observation time scales, from 5 min to 24 h, over eastern Spain from 1994 to 2007. The statistical rainfall characteristics for each time scale are analysed and the effects of specific geographical factors – altitude, aspect and distance to the sea – for each observation interval are tested.

The results show that extreme intensities are heavily dependent on the time scale. There are two important turning points in this trend, at 1 h and 6 h. With regard to the influence of geographical factors, distance from the sea is particularly important as it is significant for almost all observation time scales. Altitude is only significant between time scales of 30 min and 6 h. Aspect is not significant. Two intensity patterns are also observed: the first includes the highest intensities, at altitudes from 200 to 400 m and at locations 20–30 km from the sea, while the second is related to lower intensities, higher altitudes (900–1000 m) and longer distances to the sea (90–100 km).

1. Introduction

The intensity of precipitation is a crucial variable for environmental and hydrological studies, and is of particular importance in semi-arid environments (Bracken et al., 2008; Bull et al., 1999; Hugues, 2005; Yair and Raz-Yassif, 2004). However, the rainfall characteristics are very dependent on the scale factor, which is completely different in humid and arid areas (Yair and Raz-Yassif, 2004). Therefore, an important issue for applied research in semi-arid environments is to define which rainfall indicator is the most representative and what is the best time scale for carrying out the analysis. As Klemes (1983) mentioned, we cannot impose a scale but instead have to search those which exist and try to understand how they work.

Semi-arid climates are dominated by high energy, low frequency rainfall events. These episodes show high intensity, short duration and an extremely variable spatial–temporal distribution (Armengot, 2002; Beguería et al., 2009; Llasat, 2001; Peñarrocha et al., 2002; Romero et al., 1999). An example of this is the Mediterranean side of the Iberian Peninsula, where despite the average annual rainfall being in the range from 500 to 700 mm, a single event can double, and even triple, this total (Gil Olcina, 1989). Records of over 800 mm of precipitation have been registered in one day (as happened in the town of Gandia, in November 1987). In general, it is very common to reach intensities over 100 mm/h at the height of a storm.

Consequently, the critical parameter of these events is the rainfall intensity rather than the rainfall total. Magnitudes such as those described above are critical for soil erosion (Coppus and Imeson, 2002; Larson et al., 1997; Martinez-Mena et al., 2001; Poesen and Bunte, 1996) for triggering mass-movements (Bacchini and Zannoni, 2003; Cannon, 1988; Chien-Yuan et al., 2005; Wilson and Wieczorek, 1995) and above all for rainfall-runoff conversion processes (Bull et al., 1999; Greenbaum et al., 1998; Yair and Raz-Yassif, 2004). In this sense, for the particular case of "ramblas" and ephemeral streams, it has been demonstrated that high rainfall intensities can reduce significantly the initial infiltration soil capacity. Thus, runoff thresholds are overcome because of these high intensities, and runoff starts even though soils are not yet saturated (Bull et al., 1999; Cammeraat, 2004; Lange et al., 2003; Yair and Lavee, 1985). As a result flash-floods of ephemeral streams are highly dependent on rainfall intensity (Bracken et al., 2008; Camarasa and Tilford, 2002; Cudennec et al., 2007; Kokkonen et al., 2004).

Despite the importance of intensity, it is not easy to identify reference thresholds (Montesarchio et al., 2009) because the characteristics of rainfall differ according to the time scale used for

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observation (Berne et al., 2009; Dunkerley, 2008; Jebari et al., 2007; Valdés et al., 1985; Waymire and Gupta, 1981). Nonetheless, it is by no means clear what the most appropriate time interval for measuring rainfall intensity is. The study of convective cells advises working with intensity thresholds of around 48–50 mm/h and a period of approximately 1 h between one event and the next (Llasat, 2001). Studies of debris-flow use the rainfall accumulated during the 14 days preceding the event and the time intensity of the 5 days before the onset of mass movement (Chien-Yuan et al., 2005). For soil erosion, Martinez-Mena et al. (2001) consider that an intensity of 15 mm/h lasting 30 min can be considered as "erosive rainfall". For runoff production in ephemeral streams, the rain thresholds used are around 30–60 mm accumulated over several hours (Camarasa and Segura, 2001; Cammeraat, 2004). In short, in terms of natural processes and resource and risk management, it is imperative to find an observation scale that is appropriate for both types of phenomenon being dealt with and also for the specific objectives concerned.

Interest in assessing the characteristics of precipitation intensity at different observation scales is increasing in the international literature. Authors including Bengtsson and Milloti (2010) have emphasized the importance of short-term rainfall information for applied issues such as the design of storm water drainage systems. However, in general there is a lack of short-term rainfall data, and even when this information is present, the data quality is often poor. This problem is very serious in most semi-arid countries, where rainfall data are normally recorded daily. This is why many papers use mathematical models to estimate the intensity for shorter time scales (hour, minute), based on reprocessing daily data (Bacchini and Zannoni, 2003; Egozcue et al., 2006; Rusjan et al., 2009; Salson-Casado and García-Bartual, 1998). However, recent studies show that many of the estimated intensity values are unrealistic (Bengtsson and Milloti, 2010). It is therefore essential to study the characteristics of precipitation intensity at different scales, to determine which scales are the most representative, to identify how the maximum values of each time scale are spatially distributed, and to assess which are the main geographical influences.

To address these issues, this paper analyses the behaviour of maximum rainfall intensity over observation periods ranging from 5 min to 24 h, in a large heterogeneous area on the Mediterranean side of the Iberian Peninsula. This article also assesses the influence of geographical factors (altitude, aspect and distance to the sea) on the maximum rain intensities at different time scales. The analysis is based on data collected by the Automatic Hydrological Information System between 1994 and 2007, from 147 rain gauges.

2. Material and methods

2.1. Study area and data

The study area covers the territory of the River Júcar Water Authority (42,989 km^2), in eastern Spain (Fig. 1). From a geomorphological point of view, there are three major units: (1) the mountain systems, (2) a continental plateau and (3) the coastal plain. The main mountain range is the Iberian System (oriented NW–SE), whose highest peak, Peñarroya, is 2024 m above sea level. At the south of the study area there is a second line of mountains formed by the Betic Range (direction SW–NE). The coastal plain is formed by an alluvial platform along the coastal strip, and is over 400 km long and 40 km broad at its widest section. This plain is delimited by the Iberian System to the northwest, the continental plateau to the west and the Betic Range to the south. Finally, the continental plateau is a flat surface with an average height of 650 m, which is located to the west between the aforementioned mountain ranges.

The area has a typical Mediterranean climate with hot, dry summers and mild winters. Mean annual precipitation is about 500 mm, ranging from 300 mm in the south to over 800 mm in the north. Intense rainfall events are most frequent in the autumn, and there is a secondary maximum in spring.

To assess the intensity of precipitation, rainfall data were collected by the SAIH network (Automatic Hydrological Information System) every 5 min, from 147 rain gauges. The study period spanned 14 years (1994–2007). The gauges are the tipping-bucket type rain gauges with a measurement accuracy of 0.2 mm and a minimum detection rate of 2.4 mm/h. This network came into operation in 1989, bringing a major qualitative change with respect to the traditional rain gauge network (which provides records every 24 h).

To analyse the influence of conditioning geographical factors on maximum intensities, the study is based on topographical variables (altitude and aspect) and on the linear distance to the sea of the rain gauges.

2.2. Selection of the most representative time scales

In order to find which time scales were more representative, the rainfall data, originally recorded every 5 min, were filtered and rescaled using moving averages over intervals of 15 min, 30 min, 1 h, 2 h, 3 h, 4 h, 6 h, 12 h and 24 h. The maximum intensity values were estimated in mm/h for each rain gauge at each time interval. Then, the spatial average of the maxima (to acquire a solid measure of maximum values) and the absolute maxima (to find the extremes reached) were obtained. These relationships, along with their frequencies, are known as IDF (Intensity Duration, Frequency) curves and are one of the most common tools in water engineering. In this work, however, the frequency analysis based on return periods has not been carried out, because the objective of the research is not the construction of IDF curves, but the exploration of the behaviour of the empirical maximum intensities as a function of time.

Results show four representative observation time scales: 5 min, 1 h, 6 h and 24 h. From this point onwards, the analysis only considers these four main time scales plus three support intervals (15 min, 30 min and 12 h). Data for 2, 3 and 4 h intervals were not analysed because they were redundant.

2.3. Statistical analysis of extreme intensities for each time scale

In order to confirm that maximum intensities really do have different characteristics according to the observation time scale, the spatial distribution of maximum intensity was analysed using mean comparison tests. The normality tests, carried out using the Kolmogorov–Smirnov test, showed that the maximum intensities recorded at the time intervals of 5 min, 15 min, 30 min and 1 h had normal distributions, while the distributions for the remaining intervals (6 h, 12 h and 24 h) were not normal. Parametric statistical tests to compare averages (T test for related samples) were applied for normal distributions (5-min, 15-min, 30-min and 1-h intervals) and non-parametric tests (Wilcoxon test) were applied for the remaining intervals (6 h, 12 h and 24 h) which presented non-normal distributions.

Finally, the analysis of the spatial distribution of intensities was tackled by mapping the intensity values, grouped by quartiles, for each observation interval.

2.4. Influence of geographical factors: altitude, aspect and distance to the sea

The maximum intensity values we are working with are the result of highly unsettled weather conditions enhanced by local