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Technical Note

Effect of temporal aggregation on the estimate of annual maximum rainfall depths for the design of hydraulic infrastructure systems

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ABSTRACT

For a few decades the local rainfall measurements are generally obtained by tipping bucket sensors, that allow to record each tipping time corresponding to a well-known rain depth. However, a considerable part of rainfall data to be used in the hydrological practice is available in aggregated form within constant time intervals. This can produce undesirable effects, like the underestimation of the annual maximum rainfall depth, H_d, associated with a given duration, d, that is the basic quantity in the development of rainfall depth-duration-frequency relationships. The errors in the evaluation of H_d from data characterized by a coarse temporal aggregation, t_a, and a procedure to reduce the non-homogeneity of the H_d series are here investigated. Our results show that for $t_a = 1$ min the underestimation is practically negligible, whereas for larger temporal aggregations with $d = t_a$ the error in a single H_d can reach values up to 50% and in a series of H_d in the average up to 17%. Relationships between the non-dimensional ratio t_a/d and the average underestimation of H_d, derived through continuous rainfall data observed in many stations of Central Italy, are presented to overcome this issue. These equations allow to improve the H_d estimates and the associated depth-duration-frequency curves at least in areas with similar climatic conditions. The effect of the correction of the H_d series on the rainfall depth-duration-frequency curves is quantified. Our results indicate that the improvements obtained by the proposed procedure are of the order of 10%.

1. Introduction

Rainfall data with relatively high time resolution are essential for many hydrologic studies, including the development of rainfall modeling (Corradini and Melone, 1989; Haile et al., 2011a), simulation of infiltration (Melone et al., 2008), representation of the mechanisms of runoff generation (Govindaraju et al., 1999), description of soil erosion (e.g. Angel et al., 2005) and even design of hydraulic infrastructure systems (Adamowski et al., 2010; Notaro et al., 2015). The last topic relies upon the determination of rainfall depth-duration-frequency relationships (Willems, 2000; Overeem et al., 2008) which require the knowledge of the annual maximum rainfall depths, H_d, accumulated over different durations, d (Koutsoyiannis et al., 1998). The time resolution of rainfall data can play a significant role, particularly in the estimation of extreme rainfalls with short duration that are of primary importance in the design of widespread hydraulic and drainage infrastructure systems (Du Plessis and Burger, 2015).

Historical rainfall data may be available with different temporal aggregations (or time resolutions), t_a, linked to the progress of recording systems through time. Currently, through tipping bucket sensors, rainfall amounts are recorded in a data-logger for each tip time associated with a fixed rainfall depth (usually 0.1 or 0.2 mm). The rain event properties are then summarized by aggregating the number of tips over a selected t_a, that can vary from 1 min to much longer time intervals.

After this aggregation procedure, rainfall analyses at temporal scales smaller than the adopted t_a cannot be derived, while for $d \geq t_a$ they can be affected by significant errors (Haile et al., 2011b).

This occurs because often in hydrological practice there is no access to basic metadata collected by hydrological agencies, particularly in the case of historical data derived from potentially inaccurate long-standing recording systems (e.g. paper rolls). The quantification of the errors in extreme rainfall amount caused by different values of d for a fixed t_a have been analyzed in several

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studies. It is well known that for d comparable with t_a the actual maximum accumulations may be underestimated (Hershfield, 1961; Weiss, 1964; Young and McEnroe, 2003; Yoo et al., 2015). Hershfield (1961) observed that for d = t_a the results obtained from an analysis based on actual maxima were closely approximated through a frequency analysis of H_d with values multiplied by 1.13. Weiss (1964), on probabilistic grounds, under the assumption of a uniform rainfall throughout the duration of interest, developed a relationship between the sampling ratio, t_a/d, and the average ratio of the real maximum rainfall accumulation for a given d to the maximum one deduced by a fixed recording interval, henceforth designated as sampling adjustment factor (SAF). Young and McEnroe (2003) used high temporal resolution data from 15 rain gauges located in the Kansas City metropolitan area to derive a single empirical relationship between SAF and sampling ratio. This relation was found to provide adjustments consistent with other empirical studies (Miller et al., 1973; Frederick et al., 1977; Huff and Angel, 1992). However, the length of the considered rainfall series (in the range 5.3–14.9 years, with average value of 9.6 years) was too limited to draw a conclusion of general validity. Yoo et al. (2015) extended the probabilistic approach presented by Weiss (1964) considering several not uniform rainfall temporal distributions that were found significantly related with the SAF. Overall, previous studies suggest that the SAF is dependent on both sampling ratio and d, with the latter that is involved because the shape of the rainfall temporal distribution is linked to it.

The first objective of this paper is to define, for a given duration, the length of a H_d series, observed with a given aggregation time, that is required to derive an average adjustment factor to be applied to each series element to reduce the involved original errors. Considering the random nature of H_d this is an important point, but sometimes it has not been considered in depth. We note, for example, that Young and McEnroe (2003) used series with fairly short length and did not examine the problem of their reliability in the determination of the adjustment factors. In this study we use, as a benchmark, rainfall data observed for many years with an aggregation time of 1 min. Furthermore, in the analysis performed for t_a and d of interest the series incorporate rainfall temporal distributions with a variety of shapes that included the different theoretical distributions supposed by Yoo et al. (2015). The second objective of this paper is to define a methodology to obtain homogeneous series of annual maximum rainfall depths from data derived through different temporal aggregations. This is a crucial issue because many rain gauge stations were installed in the first half of the twentieth century and their series of annual maximum rainfall depths are not homogeneous (Alexandersson, 1986; Hanssen-Bauer and Forland, 1994) as a result of many values derived from rainfall data with a coarse t_a (e.g. when a recording system on rolling paper was adopted) and the remaining ones with t_a = 1 min. The third objective of this paper is to estimate the sensitivity of the rainfall depth-duration-frequency curves to the corrections of the H_d series performed by the proposed methodology.

2. Methods

Following Burlando and Rosso (1996) and Boni et al. (2006) we provide the definition of annual maximum rainfall depth through the rainfall rate at time t, x(t), measured at a specific location. The accumulated rainfall recorded over a time interval d, $x_d(t)$, is given by:

$$x_d(t) = \int_t^{t+d} x(\xi)d\xi \tag{1}$$

The annual maximum rainfall depth over a duration d, H_d, is therefore expressed as:

$$H_d = \max[x_d(t) : t_0 < t < t_0 - d + 1 \text{ year}] \tag{2}$$

where t_0 is the starting time of each year.

To determine H_d for a specific year, the knowledge of rainfall data characterized by any $t_a \leq d$ is necessary. When d = t_a, independently of the rainfall pulse shape, the H_d value is sometimes correctly estimated (Fig. 1a) but can also be underestimated (Fig. 1b,c) with errors up to 50% (Fig. 1c). The underestimation error adopted here is directly related to both the SAF introduced by Young and McEnroe (2003) and the correction factor of Yoo et al. (2015).

Despite the inability to correctly quantify the accuracy of a given H_d value, a representation of the average error for a time series containing a large number of elements can be established.

It is well-know that for each duration d, a long H_d series is affected by an average error depending on both t_a and the shape of the rainfall pulses. In the case of rectangular pulses, the average underestimation is equal to 25%, because each error assumes with the same probability of occurrence a value in the range 0–50%. This is consistent with the theoretical results by Yoo et al. (2015). However, it is widely recognized that the H_d values are determined by heavy rainfalls of erratic shape (Balme et al., 2006; Al-Rawas and Valeo, 2009; Coutinho et al., 2014). For example, Fig. 2 shows a few sample hyetographs associated with the annual maximum rainfall rates for d = 60 min that were recorded by a rain gauge station located in Central Italy. The hyetographs exhibit irregular shapes that can be roughly considered of triangular type.

Under the assumption of a triangular rainfall pulse characterized by a duration d, the total rainfall depth, R_{pd}, is (Fig. 3a):

$$R_{pd} = \frac{dh}{2} \tag{3}$$

with h equal to the rainfall intensity peak.

When t_a = d, also with a triangular pulse the underestimation error of a single H_d is within the range 0–50%. The error associated with the possible pulse positions (Fig. 3b) is displayed in Fig. 3c. Its average value, E_a, obtained by integration through the pulse duration (see also Yoo et al., 2015) is given by:

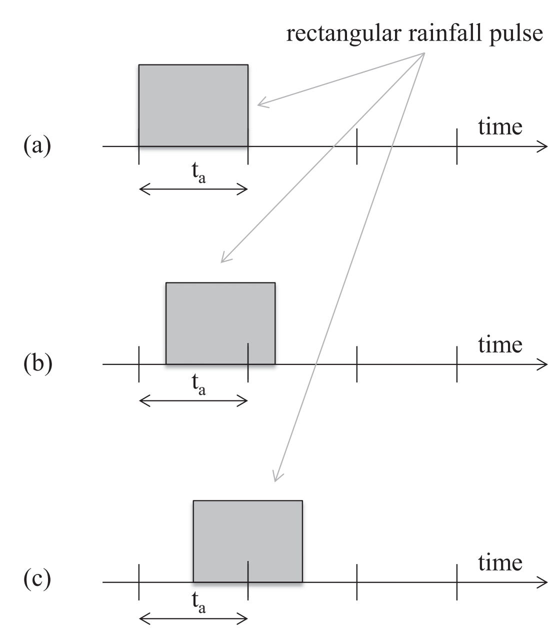

Fig. 1. Schematic representation of a rectangular rainfall pulse with duration, d, equal to the measurement aggregation time, t_a: (a) condition where a correct evaluation of the annual maximum rainfall rate of duration d, H_d, is possible; (b) condition for a generic underestimation of H_d; (c) condition for the maximum underestimation of H_d (equal to 50%).