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Rainfall intensity–duration–frequency relationships derived from large partial duration series

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SUMMARY

A procedure is proposed for basing intensity–duration–frequency (IDF) curves on partial duration series (PDS) which are substantially larger than those commonly used for this purpose. The PDS are derived from event maxima series (EMS), composed of the maximum average intensities, over a given duration, determined for all rainfall events recorded at a station. The generalized Pareto distribution (GP) is fitted to many PDS nested within the EMS and the goodness-of-fit is determined by the Anderson–Darling test. The best fitted distribution is selected for predicting intensities associated with the given duration and with a number of recurrence intervals. This procedure was repeated for eleven rainfall durations, from 5 to 240 min, at four stations of the Israel Meteorological Service. For comparison, the GP and the generalized extreme value (GEV) distributions were fitted to annual maxima series (AMS) and the Gumbel and lognormal distributions were fitted to the PDS and to the AMS at these stations.

In almost all cases, the GP distribution well fits to ranges of PDS within an EMS, while in a few cases the best fit is fair only. Another result is that the GP distribution does not fit to AMS and to EMS. The GEV distribution well fits to most AMS, and fairly fits to the others. The Gumbel and the lognormal distributions well fit to most of the AMS and to a very few PDS. In most cases of good fits of different distributions, the predicted values by the different distributions are not much different from one another. This indicates the importance of good fit of the distribution and of the power of the AD test used for determining it. In most cases the best fit of the GP distribution is to a PDS series substantially larger than its corresponding AMS. In most cases, the standard error of the estimated 100-year intensity, through the best fitted GP to PDS, is smaller than that estimated through the GEV fitted to the corresponding AMS. All these make the proposed procedure superior to the current ones. It also enables interpolated predictions down to recurrence intervals of N/n years (N is number of years of complete records and n is PDS size). The use of large samples would reduce the sensitivity of predicted intensities to sampling variations.

Purpose

The combined effect of rainfall intensity and duration on maximum discharges of runoff from urban watersheds was first demonstrated by Kuichling (1889). The rational point for design of sewers, introduced by him, has evolved into the popular Rational Formula, in which rainfall intensity–duration–frequency relationships (IDF) play a key role (e.g., Chow, 1964; Maidment, 1993). These relationships are determined through statistical analysis of samples of records at proper meteorological stations. The accepted methodology for derivation of IDF is simple and appears satisfactory. A modest improvement is proposed here, through a substantial extension of the size of analyzed samples. This would reduce the variance of predicted intensities and the sensitivity of results to sampling variations and also improve the statistical description of frequent events.

Comparison of sampling techniques

Selection of samples for derivation of IDF follows the methodology applied in the selection of samples of maximum momentary discharges (peaks) for flood frequency analysis. There, two kinds of samples are utilized: one includes the peaks for every year in the observational period and the other includes all and only the peaks for events that exceed a given threshold. Samples of the former kind are called annual maxima series (AMS) and those of the latter kind are called partial duration series (PDS) (e.g., Jarvis et al., 1936; Langbein, 1949; Chow, 1950). In the recent decades and in applications to non-hydrological variables, the former series is also called Block Maxima and the latter series is also called Peak Over Threshold. In hydrology, the use of AMS is very popular,

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whilst that of PDS is not (e.g., Cunnane, 1973; Takeuchi, 1984; Bobee et al., 1993; Ashkar et al., 1994; Rasmussen et al., 1994; Madsen et al., 1997b; Lang et al., 1999). Some recent articles evenly consider the two kinds of sample (e.g., Katz et al., 2002; Smith, 2003; de Michele and Salvadori, 2005).

AMS are easily prepared and readily available everywhere. However, there are no common rules for preparation of PDS and their use requires a particular preparation for each case studied. The obvious relative disadvantages of the two kinds of samples are that AMS neglect certain high discharges, while PDS might suffer from serial correlation (e.g., Jarvis et al., 1936; Langbein, 1949; Taesombat and Yevjevich, 1978). The early studies considered AMS as more suitable than PDS for statistical analysis (e.g., Jarvis et al., 1936; Gumbel, 1954). This opinion has changed. Kisiel et al. (1971) stated that an event series is more informative than a monthly or an annual series. Todorovic (1978) concluded that construction of a stochastic model for AMS is hampered by many difficulties, whereas that for PDS has a solid theoretical base. Rasmussen et al. (1994) considered PDS as providing a more complete description of flood processes than AMS do. Lang et al. (1999) viewed PDS as a compromise between AMS and classical time series modeling. Recent selections are more affected by data availability (e.g., Katz et al., 2002; Smith, 2003).

An important aspect in the selection is the accuracy of discharges predicted through statistical distributions fitted to the samples. Cunnane (1973) estimated that in order to be more efficient, the size of PDS should be at least 1.65 times larger than that of its corresponding AMS. Tavares and Da Silva (1983) found that the estimated variance of flood magnitude associated with a given return period (quantile) can be underestimated (or overestimated) by Cunnane's (1973) approximation if the average number of events in a year is larger (or smaller) than 2. According to them, the advantage of PDS is strongly conditioned on the assumption of serial independence of the magnitudes. Buishand (1990) estimated the bias and variance of quantile estimates from PDS through certain models for arrival times and for magnitude distribution. Martins and Stedinger (2001) found that the precision of flood quantiles derived from PDS is insensitive to the arrival rate.

Pikand (1975) has shown that the generalized Pareto (GP) distribution is a limiting form for the distribution of independent exceedances over high thresholds (i.e., PDS). Smith (1984) has shown that for a large number of events in a year, the generalized extreme value (GEV) distribution is a limiting form for the distribution of annual maxima series (AMS). Assuming Poissonian count of the number of events in a year, certain relationships exist between the parameters of the corresponding GP and GEV distributions (e.g., Wang, 1991; Smith, 2003). One of these relationships is that the shape parameters of the two distributions are equal to each other.

Madsen et al. (1997a) concluded that PDS/GP is more efficient for quantile estimation than AMS/GEV and that homogeneous grouping is simpler for PDS than that for AMS. Madsen et al. (1997b) concluded that, in general, one should use PDS–MOM for negative shapes of the distribution fitted (i.e., heavy tailed), PDS with exponentially distributed magnitudes for close to zero shape parameter, AMS–MOM for moderately positive shapes and PDS–ML for large positive shapes (i.e., light tailed) [MOM, PWM and ML are methods for fitting distributions to data]. Presuming that heavy tailed distributions are most common in hydrology, they preferred PDS for at-site quantile estimations. It should be explained here that heavy and light tails reflect the rate of increase of the physical variable as its exceedance probability declines. Heavy tailed distributions increase faster, and light tailed ones increase slower, than the exponential rate.

Threshold selection

The threshold associated with a PDS may affect its properties. The lower its level the larger the PDS size and possibly more serially correlated are its members. A larger series would be less sensitive to sampling variations, but a more serially correlated sample might be less suitable for the commonly practiced probabilistic analysis. In early works, the recommended threshold was equal to, or a little lower than the minimum annual peak (Jarvis et al., 1936). In a long record, however, the threshold was usually raised so that on average only three or four floods a year are included (Langbein, 1949). Chow (1964) and Koutsoyiannis (2004) proposed selection of threshold for which the size of associated PDS is equal to the number of years on record. Cunnane (1973) and Taesombat and Yevjevich (1978) recommended that the size of PDS be at least 1.65 times the number of years on record. Todorovic (1981) observed that, in practice, the threshold was selected to obtain, on average, no more than 3 events per year. Tavares and Da Silva (1983) preferred sizes larger than 2 events per year. Buishand (1989) examined series with a fixed number of peaks. Barrett (1992) selected the threshold as a little higher than the minimum annual maximum discharge, thus generating series of about 5 events per year. Trefry et al. (2005) selected series that have, on average, 2 events per year.

Kavvas (1982) selected the threshold as about equal to bankful discharge. Ben-Zvi and Cohen (1983) selected thresholds where the flow velocity ceases to be sensitive to the discharge. Ashkar and Rousselle (1983a) preferred selection on mathematical, rather than on physical or economic, grounds.

Another approach for threshold selection is by inspection the properties of its associated PDS. Pikand (1975) recommended selection of the largest PDS that maintains the assumptions underlying the GP distribution. Ashkar and Rousselle (1987) concluded that the arrivals of runoff events are Poissonian, and in accordance with the properties of this process they proposed selection of the threshold where equality exists between the mean and the variance of the number of events in a year. McCuen et al. (1993) followed this recommendation. Smith (1987) selected the threshold where a linear relationship commences between mean exceedance and threshold values. Begueria (2005) recommended selection of thresholds where the linear relationship between these variables ends. Ben-Zvi (1994) proposed selection where a selected statistical distribution best fits the PDS.

The above studies concern PDS of peak runoff discharges. Those concerning rainfall intensities are substantially fewer. Bell (1969) used PDS for which the lowest value has a return period shorter than 1 year. Van Montfort and Witter (1986) examined PDS having, on average, 1–10 events per year. Madsen et al. (2002) used common thresholds for all the stations in their study region, and the associated PDS contained, on average, 2.5–3.2 events per year. Substantially larger PDS are considered in the present study.

Statistical methods

The study aims at demonstrating that rainfall intensities can be well predicted through fit of a distribution to large PDS. In order to concentrate on the series size issue, the statistical methods proposed by Ben-Zvi (1994) with respect to runoff discharges are applied here. These include fit of the generalized Pareto (GP) distribution by the Probability Weighted Moments (PWM) method to PDS nested within an EMS, use of the Anderson–Darling (AD) goodness-of-fit test and selection of the PDS to which the distribution best fits. An EMS of rainfall intensities is composed of maximum average intensities, over a given rainfall duration, for all events recorded at a station.