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Research papers

Derived flood frequency distributions considering individual event hydrograph shapes

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A B S T R A C T

Derived in this paper is the frequency distribution of the peak discharge rate of a random runoff event from a small urban catchment. The derivation follows the derived probability distribution procedure and incorporates a catchment rainfall-runoff model with approximating shapes for individual runoff event hydrographs. In the past, only simple triangular runoff event hydrograph shapes were used, in this study approximating runoff event hydrograph shapes better representing all the possibilities are considered. The resulting closed-form mathematical equations are converted to the commonly required flood frequency distributions for use in urban stormwater management studies. The analytically determined peak discharge rates of different return periods for a wide range of hypothetical catchment conditions were compared to those determined from design storm modeling. The newly derived equations generated results that are closer to those from design storm modeling and provide a better alternative for use in urban stormwater management studies.

1. Introduction

Peak-discharge rates of different return periods from urban catchments are frequently required for the planning and design of urban stormwater management facilities. The accurate sizing of these facilities highly depends on the accuracy of these peak-discharge rates. Due to the lack of observed flow data, the required peak-discharge frequency information is often obtained from relevant rainfall data together with rainfall-runoff transformation models.

Both the design storm and the continuous simulation approaches may be used to determine the exceedence frequencies of peak discharges. The design storm approach assumes that the selected design storm and its resulting peak runoff rate have the same return period. This assumption makes the design storm approach simple to apply but with a possible sacrifice on accuracy (Adams and Howard, 1986). This is because the return period of the design storm and the resulting peak runoff rate may approximately equal to each other and there is no way to accurately calculate the exact return period of the peak runoff rate resulting from an input design storm. The continuous simulation approach uses a long and continuous rainfall record as input and transforms it into a flow rate series, a frequency analysis is then conducted to obtain the flow rates of desired exceedence frequencies. For locations where long-term rainfall records are not available, they may be synthetically generated based on limited observed rainfall data (Grimaldi et al., 2012a,b, 2013). The use of long series of actual rainfall data allows the model to include more complete meteorological conditions, properly model the soil conditions during inter-event dry periods, and therefore better establish the actual antecedent moisture conditions for individual rainfall events (Nnadi et al., 1999). The application of the continuous simulation approach is limited due to time constraints and lack of rainfall or runoff data (Quader and Guo, 2006). Instead, the design storm approach is widely applied in practice due to its simplicity. The unavailability of other simple yet accurate alternative approaches is the other reason that the design storm approach is almost universally applied in practice (Levy and McCuen, 1999; Guo and Zhuge, 2008).

In the recent decades there appeared a new approach referred to as the analytical probabilistic approach (APA). This new approach was developed to overcome the shortcomings of the design storm and continuous simulation approaches. The APA includes some of the features of the design storm and continuous simulation approaches. The APA is event-based in terms of rainfall-runoff transformation which is similar to the design storm approach; however the APA also uses long rainfall data similar to the continuous simulation approach. The APA starts by identifying and analyzing actual individual rainfall events from a long-term

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continuous rainfall record. The APA, like the other two approaches, requires some kind of frequency analysis but with different procedures. First the long continuous recorded rainfall data is segregated into individual rainfall events where each event is characterized by its volume (v), duration (t), and the dry time (referred to as the interevent time, b) that separates it from the preceding rainfall event. Then similar to the design storm approach, the frequency analysis employed by the APA is performed with the input rainfall data; however, the actual individual rainfall event's characteristics such as a rainfall event's total volume v (mm), total duration t (h) and the interevent time b (h) are subjects for frequency analysis in the APA. For the development of design storms, however, the subjects of frequency analysis are rainfall amounts fallen within preselected durations. For the continuous simulation approach, the frequency analysis is performed on the modeled runoff series in order to obtain the peak-discharge frequency distributions. For the APA, the probability distributions of runoff characteristics (peak flow and runoff volume) are derived directly from the probability distributions of the input rainfall event characteristics (Eagleson, 1972; Howard, 1976; Adams et al., 1986; Guo and Adams, 1998a,b,1999a,b; Guo, 2001; Bacchi et al., 2008; Balistrocchi et al., 2009). The APA is able to generate, in a more straightforward manner, information about prediction uncertainty, either because of parameter uncertainty, forcing uncertainty, or both. It is worth mentioning that there is another alternative approach to design storm and continuous simulation modeling which is recently developed by Mejía et al. (2014). This approach uses stochastic models and has similarities to the APA approach. One similarity is that they both use probability density functions to characterize rainfall depths. Mejía et al. (2014) used stochastic models to generate flow duration curves for urbanized watersheds, but similar stochastic approaches may be developed for peak flow frequencies. Up till now, the only approach used in actual engineering practice for the determination of the frequency distribution of peak discharge rates for small urban catchments is almost always the design storm approach. Ever since the beginning of the application of the analytical approach, it has been improving little by little due to the challenging mathematical derivation that is involved in its development.

For the derivation of the mathematical equations comprising the APA, the rainfall event characteristics (i.e. rainfall event volume, duration and interevent time) are generally assumed to follow exponential distributions (Eagleson 1972, 1978; Howard 1976; Adams et al. 1986; Guo and Adams 1998a,b, 1999a,b; Adams and Papa, 2000; Guo, 2001; Guo and Baetz, 2007; Zhang and Guo, 2013a,b). For many North American locations, exponential distributions were found to be appropriate for describing their rainfall characteristics (Adams and Papa, 2000; Wanielista and Yousef, 1993). In addition, the rainfall event volume and duration are assumed to be statistically independent. The APA is only applicable where the aforementioned assumptions are valid. Hassini and Guo (2016) provided a detailed procedure for testing the exponentiality of a location's rainfall event characteristics. The input rainfall statistics and catchment conditions together with the resulting closed-form mathematical equations describing the peak discharge and runoff volume frequency distributions are referred to as the analytical probabilistic models. These models are developed for stormwater management planning and design purposes (Adams and Papa, 2000); similar to continuous simulation and design storm models.

The APA was first used by Eagleson (1972) to estimate the frequency of peak stream flows using the probability density functions (pdfs) of rainfall intensity and duration, and the kinematic wave formula, which represents a functional relationship between peak stream flows and rainfall characteristics. Then it was employed for stormwater management purposes by many other researchers (e.g., Adams et al., 1986; Guo and Adams, 1998a,b, 1999a,b; Adams and Papa, 2000; Guo, 2001; Quader and Guo, 2006; Guo and Baetz, 2007; Chen and Adams, 2005, 2007; Bacchi et al., 2008; Balistrocchi et al., 2009; Zhang and Guo, 2013a; Zhang and Guo, 2013b). To estimate peak-discharge frequency distributions, Guo and Adams (1998b) developed an analytical probabilistic stormwater management model assuming that each individual runoff event hydrograph can be approximated as a triangle, the resulting model is referred to as the APSWM(Tri) model in this paper. For the development of APSWM(Tri), a hydrograph's total volume and duration is calculated first, peak discharge rate of that hydrograph is then calculated based on the assumed approximating shape of the hydrograph. Since most hydrographs have a broad peak area than a triangular hydrograph, the assumption of triangular hydrographs may result in an overestimation of peak discharge rates, especially for larger catchments and/or longer rainfall events. Although the capability of APSWM(Tri) was later expanded to include explicit channel flow routing (Guo et al., 2009) and different methods for rainfall loss calculations (Guo and Markus, 2011), the simple assumption of triangular hydrograph is always used. In order to further develop the analytical probabilistic models and increase their accuracy, other alternatives of estimating the peak-discharge rate based on more accurate hydrograph shapes for individual runoff events should be considered.

Ponce (1989) illustrated that event hydrographs may take three possible shapes depending on the catchment's time of concentration and rainfall event duration (details of these shapes will be illustrated in the next section); two of the three possible shapes can be approximated as trapezoidal and the other can be approximated as triangular. Triangular or trapezoidal hydrograph is not used as a shape of a unit hydrograph for numerical hydrologic modeling purposes; instead it is used to approximate individual event hydrographs, this is needed in order to use the derived probability distribution approach for estimating flood frequencies. The objective of this study is to derive and verify new closed-form mathematical equations describing the peak-discharge rate frequency distributions assuming that the runoff event hydrographs take the three possible shapes as suggested by Ponce (1989). The resulting analytical probabilistic model is referred to as the APSWM(Tra). The APSWM(Tri) model that was developed earlier is simplified in the approximation of individual event hydrograph shapes, the APSWM(Tra) model which is developed in this paper improves greatly on that. To verify the performance of APSWM (Tra), it is vital to investigate the estimates of peak-discharge rate frequency distributions for as many as possible different catchment conditions. Third-party reliable estimates of peak-discharge rate frequency distributions are also required for this purpose. Despite its drawbacks, the widely used design storm approach can provide results with acceptable levels of accuracy if the design storm characteristics and antecedent catchment conditions are selected properly (Guo, 2001; Guo and Zhuge, 2008). Thus the design storm results will be used in this paper as a reference to compare the two analytical models APSWM(Tra) and APSWM(Tri).

2. Peak discharge rate of a runoff event based on approximating hydrograph shapes

2.1. Runoff event volume

In the development of APSWM(Tri), the rainfall-runoff transformation is completed on an event-by-event basis. The total volume v_r (mm) of a runoff event (referred to as runoff event volume) is equal to the total rainfall volume of the input rainfall event (v) minus all the hydrologic losses that occur during the event. The