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Monte Carlo Simulation of rainfall hyetographs for analysis and design

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SUMMARY

Observations of high intensity rainfalls have been recorded at gauging stations in many parts of the world. In some instances the resulting data sets may not be sufficient in their scope and variability for purposes of analysis or design. By directly incorporating statistical properties of hyetographs with respect to the number of events per year, storm duration, peak intensity, cumulative rainfall and rising and falling limbs we develop a fundamentally basic procedure for Monte Carlo Simulation. Rainfall from Pavia and Milano in Lombardia region and from five gauging stations in the Piemonte region of northern Italy are used in this study. Firstly, we compare the hydrologic output from our model with that from other design storm methods for validation. Secondly, depth–duration–frequency curves are obtained from historical data and corresponding functions from simulated data are compared for further validation of the procedure. By adopting this original procedure one can simulate an unlimited range of realistic hydrographs that can be used in risk assessment. The potential for extension to ungauged catchments is shown.

1. Introduction

In northern Italy, as in other areas, observations of high intensity rainfalls have been recorded during critical storms. The resulting hyetographs play a crucial role in analysis and design such as those applied to urban or agricultural drainage systems. The study of design storm hyetographs has a long history. Storm duration, average intensity, time to peak and other variables have been used in producing synthetic design hyetographs.

Rainfall records contain valuable information for analysis. However, problems arise in their usage or application mainly because of the high variability of rainfall phenomena. Besides, the way in which a rainfall event is defined is somewhat subjective. This necessitates smoothing of rainfall over time in standard methods used in generating hyetographs. The standardised rainfall profiles of Huff (1967) are based on four quartiles depending on the quarter of the storm duration during which the storm results in a peak. Those found on SCS (1986) have profiles drawn for storm durations of 6, 12 and 24 h. Such regional profiles are derived from large samples of data. Because of temporal smoothing special characteristics of local events are not accounted for. Amongst procedures based on intensity–duration–frequency (IDF) curves the Keifer and Chu (1957) approach, which become known as the "Chicago storm method", has been utilised in the design of sewers with durations of study events ranging from 3 h to 48 h in which the rainfall input is from a non-uniform hyetograph. Also in this category is the design hyetograph of Yen and Chow of triangular shape applied to small drainage areas, discussed by Chow et al. (1988) who also provide a background to methods of this type.

More recently a stochastic description of precipitation has been used in simulating rainfalls. For example, the Neyman–Scott cluster process has had many applications. See for example Le Cam (1961) and Cowpertwait (1991). Additionally, the Bartlett–Lewis rectangular pulses model has been applied (Islam et al., 1990). However, Calenda and Napolitano (1999) question the capability of stochastic point process models to reproduce historical characteristics of rainfall series for design evaluation.

Because of such shortcomings Monte Carlo Simulations techniques have been applied directly in recent years particularly to flood frequency curves. For instance, Rahman et al. (2002) made allowance for the probability-distributed nature of key flood producing variables and dependency between them to determine derived flood frequency curves based on data from the state of Victoria in Australia. Elsewhere, Aronica and Candela (2007) used Monte Carlo Simulation to derive flood frequency distributions of peak flows using a semi-distributed stochastic rainfall-runoff model applied to data from Sicily in Italy. They applied a two components extreme value distribution, the Soil Conservation Service-Curve Number (SCS-CN) method and a flood routing model.

In a case study from the state of New South Wales in Australia, Caballero and Rahman (2013) used a joint probability technique

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applied to six catchments in eastern New South Wales with a non-linear runoff routing model for Monte Carlo Simulation of streamflow hydrographs. This method is found to overcome some of the limitations of the Design Event approach currently used in Australia with respect to the assumption of available regional design data on rainfall duration, temporal patterns and losses in soil models each with their own probabilistic nature. Furthermore, in the United Kingdom, Svensson et al. (2013) applied a joint probability procedure to four different catchments in Great Britain with Monte Carlo Simulation. Previously, event-based methods had been frequently applied on the basis of pre-determined values of the input variables, such as antecedent conditions, to obtain entire flood hydrographs.

Our approach is fundamentally different and easy to apply. One difference between the previously cited four papers is that Monte Carlo Simulation is applied by us to rainfall hyetographs rather than to flood frequencies with given rainfall inputs. The objective is to provide a means of generating synthetic hyetographs. We develop and adopt a model, with parameters that are hydrologically meaningful, to meet a given practical situation. The method is relatively simple to apply.

The simplicity of our approach can be gauged from the step-by-step procedure given in the following section. We believe that it makes a significant improvement over existing methods in the way rainfall data are used. The novelty of the work is seen particularly in the manner in which all hyetograph characteristics, and not a chosen few, are utilised. In practice, it contrasts with some of the difficulties in the application of other procedures cited and possible limitations of requisite data.

Furthermore, there is potential for many types of applications. Simulation of unsteady flows in channels, for example, is currently used in the design of drainage networks. Synthetic or design hyetographs are inputs to a mathematical model in such cases. An extensive simulation analysis requires the generation of synthetic rainfalls applying the Monte Carlo procedure.

Previously, Natale and Savi (2007) addressed the perennial problem of flooding in Rome caused by the river Tiber by using a rainfall – runoff model for Monte Carlo Simulation. They started with a stochastic rainfall model (Kottegoda et al., 2003) with randomly given initial conditions of soil and storage.

In the next section on Data and Analysis we show initially how events are defined and how hyetographs are derived from the events. Firstly we present the procedure for simulating rainfall at the Cascina Scala rainfall station in Pavia, Italy. The record of observations at this site is representative of the critical storm events in the district of Pavia which is part of the Lombardia region in northern Italy. All rainfall stations are shown in Fig. 1.

Secondly, we present results of the application to Monviso station in Milano which is also in Lombardia. Ten years of rainfall data are available at this stations. The results for Pavia and Milano are comparable as expected.

Thirdly we present the application for simulating rainfall in a part of Piemonte region based on five stations. The range of values of the estimated parameters for the simulation procedure is quite narrow compared to those from the Lombardia region. Consequently we propose a simple regional procedure that can be used to extend to ungauged sites.

By using a commercial package (not part of our work) a rainfall – runoff model is applied at the Pavia station. This is compared favourably with the output from other cited models. It gives the first validation of our model.

Depth–duration–frequency curves obtained from historical data are compared with corresponding functions from simulated data. These curves are applied to a range of return periods. This gives the second validation to the method.

In the two following sections we utilise all hyetograph characteristics and properties. This are accounted for firstly in the analysis and secondly in the procedure for Monte Carlo Simulation.

2. Data and analysis

The analysis and modelling are firstly applied to rainfall of the experimental urban watershed measurements of high intensity at the Cascina Scala rainfall station in Pavia, in the region of Lombardia in Italy (see Papiri et al., 2008) from 1989 to 2006 for which we select 38 events in 16 years. Examples of rainfall events are shown in Fig. 2. The criteria for the selection of events is that the durations are not less than 20 min and the cumulative rainfall exceeds 25 mm; also the events are separated by a minimum interval of 10 h. Table 1 gives a list of main rainfall events in Pavia. Each event results in 1 or more hyetographs given by numbers 1, 2, 3 and so on in successive rows of Table 1. The events seen in Fig. 2 result in 1, 2 or 3 hyetographs, respectively. Each hyetograph corresponds to a separate gust of rainfall. The lower limit of rainfall intensity in the data used is 0.05 mm/min. Also, the time unit for rainfall measurement is 1 min. The hyetographs are separated by dry periods as shown in Fig. 2(a). For each hyetograph, Table 1 gives the duration in minutes of wet and dry runs, peak intensity in mm/min, position of peak intensity in

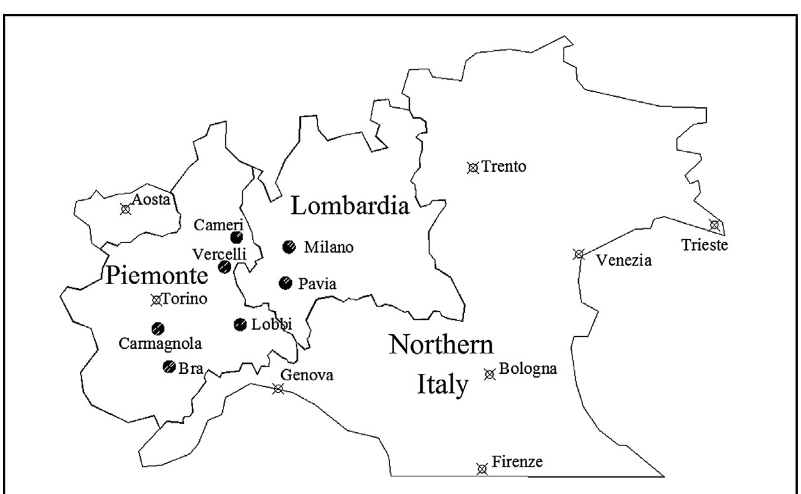

Fig. 1. Location of rainfall stations.