A Computer Program to Determine Derived Flood Frequency Curves

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Abstract: Rainfall-based flood estimation techniques are frequently adopted in hydrologic design. This generally adopts a runoff routing model that converts a design rainfall event to a design streamflow hydrograph. Most of the existing runoff routing models are based on the Design Event Approach in that representative values of the inputs/model parameters are used to convert a rainfall depth of a given annual recurrence interval (ARI) to a flood discharge of the same ARI. This assumes that all the model inputs/parameters except the rainfall depth are probability neutral. This assumption is hardly satisfied in practical situations as the observed values of the model inputs/parameters generally show a wide variability. In contrast, a Joint Probability Approach can offer significant improvement in flood estimation by making rigorous treatment of the probabilistic aspects of the important model inputs/parameters. This paper presents a computer program written in FORTRAN that employs a Joint Probability Approach to determine derived flood frequency curves. The program requires hourly rainfall and streamflow data recorded on a catchment to identify probability distributions of four input variables: rainfall duration, rainfall intensity, rainfall temporal pattern and initial loss. The program then uses a Monte Carlo Simulation technique to simulate a large number of rainfall events from the identified probability distributions of the four input variables, which are then combined with other fixed model inputs/parameters and routed through a calibrated runoff routing model to generate streamflow hydrographs. The peaks of the simulated hydrographs are then used to construct a derived flood frequency curve.

Keywords: Computer program; Joint Probability Approach; Monte Carlo Simulation; Runoff routing model; Derived flood frequency curves

1. INTRODUCTION

Rainfall-based flood estimation techniques are frequently adopted in hydrologic design. Many of these techniques adopt runoff routing models that are based on the Design Event Approach. They use a rainfall depth of a given annual recurrence interval (ARI) in combination with representative values of other model inputs/parameters and then assume that the resulting flood has the same ARI as that of the input rainfall depth. In many cases, this assumption is unreasonable, because the observed values of the model inputs/parameters generally show a wide variability. For example, the observed initial loss values in Eastern Queensland show a wide range (0–140mm, median: 15–35mm), but a single value is adopted in the Design Event Approach [I. E. Aust., 2001]. Since, the rainfall runoff process is non-linear; the use of median values of the inputs/parameters cannot guarantee the preservation of the probability of the input rainfall depth in the final flood discharge. The arbitrary and independent treatment of various model inputs/parameters, as done with the Design Event Approach, is likely to introduce significant bias in flood estimates for a given frequency.

The Joint Probability Approach has the potential to overcome the major limitations of the Design Event Approach by considering the probability-distributed inputs and model parameters and their correlations to determine probability-distributed outputs [Eagleson, 1972; Sivapalan et al., 1996]. A new Joint Probability Approach to flood estimation has been developed recently in the Cooperative Research Centre for Catchment Hydrology [Rahman et al., 1998, 2000, 2001a & b; Weinmann et al., 1998, 2000; Hoang et al., 1999]. The advantages of the new technique are that this uses a commonly applied loss model and runoff routing model, and many of the currently available design data (e.g. rainfall intensity, rainfall temporal pattern, losses), and makes explicit allowance for dependencies between different design inputs.

The purpose of this paper is to describe a computer program written in FORTRAN that can be used to construct derived flood frequency curves based on the principles of joint probability.

2. COMPUTER PROGRAM

2.1 Scope

The adopted Joint Probability Approach considers (a) four input variables as random variables in the rainfall runoff process: rainfall duration, rainfall intensity, rainfall temporal pattern and initial loss; (b) an initial loss-continuing loss model as a runoff production function; and (c) a non-linear simple conceptual runoff routing model for hydrograph formation [Rahman et al., 1998, 2000, 2001; Weinmann et al., 1998, 2000; Hoang et al., 1999]. The historical rainfall and streamflow data on a catchment of interest are used to identify the probability distributions of the four input variables. The program generates a large set (in the order of thousands) of data from these distributions, which are used to construct net rainfall hyetographs. These are then routed through the calibrated runoff routing model to simulate streamflow hydrographs. The peaks of all the simulated hydrographs are then used to determine a derived flood frequency curve, using an appropriate probability plotting position formula.

The program that implements the above procedure is written in FORTRAN, and has two major parts, as described below.

2.2 Data Analysis

The program requires hourly rainfall data as basic input. A pluviograph station on or near the catchment with reasonably long record length (preferably over 20 years) is required. The program identifies independent but 'significant' rainfall events called 'complete storm'. A complete storm is defined as a period of 'significant' rainfall preceded and followed by at least six hours of no rainfall period (IY) [Hoang et al., 1999].

For each of the identified complete storms, a single storm-core is identified, defined as the most intense rainfall burst within a complete storm. The corresponding storm-core is selected as the duration with the highest rainfall intensity ratio compared to the 2-year ARI design rainfall [Hoang et al., 1999; Rahman et al., 2001a & b]. The program uses storm-cores data and identifies the probability distributions of its duration (D_c), average rainfall intensity (I_c) and temporal pattern (TP_c). As reported in Rahman et al. (2001a,b), the distribution of D_c for Victorian catchments has been found to be exponential, as shown in Figure 1.

The program expresses the distributions of rainfall intensity in the form of intensity-frequency-duration (IFD) table, as shown in Table 1. The program generates the IFD table by fitting an exponential distribution to the partial series I_c data (Rahman et al., 2001).

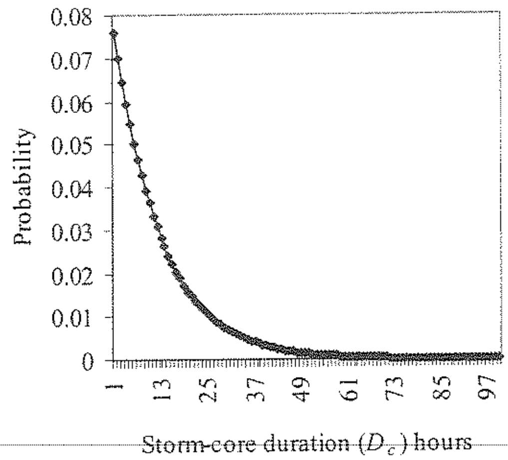

Figure 1. Distribution of storm-core duration.

Table 1. An example of IFD table (Intensities are in mm/h).

Dc (h)	ARI (years)			
	2	10	50	100
1	18.96	31.46	43.97	49.36
2	11.27	17.60	23.93	26.65
6	5.40	8.20	11.00	12.20
24	2.49	4.11	5.72	6.41
48	1.81	3.26	4.72	5.36
72	1.53	2.95	4.41	5.04
100	1.35	2.78	4.27	4.92

The program expresses rainfall temporal pattern by dimensionless mass curve, i.e. a graph of dimensionless cumulative rainfall depth versus dimensionless storm time with 10 equal time increments, as shown in Figure 2. The results from 19 pluviograph stations in Victoria indicated that the temporal patterns of rainfall depth for storm-cores (TP_c) are not dependent on season and total storm depth but on storm duration, yielding two groups: (1) up to 12 hours duration, and (2) greater than 12 hours duration [Rahman et al., 2001].

The program computes initial loss for complete storms (IL_s) and initial loss for storm-cores (IL_c) from hourly pluviograph and hourly streamflow data. The IL_s is estimated to be the rainfall that occurs prior to the commencement of surface runoff. The IL_c is the portion of IL_s that occurs within the storm-core. The value of IL_c can range from zero (when surface runoff commences before the start of the storm-core) to IL_s (when the start of the storm-core coincides with the start of the complete storm event). In computing losses, a surface runoff threshold value equal to 0.01 mm/h is used similar to Hill et al. [1996].

The program uses following relationship to estimate IL_c from IL_s

$$IL_c = IL_s[0.5 + 0.25\log_{10}(D_c)] \quad (1)$$

The distributions of IL_s for 10 catchments in Victoria have been found to be positively skewed, and a Beta distribution was used to approximate the empirical distribution of IL_s (Rahman et al., 2000).

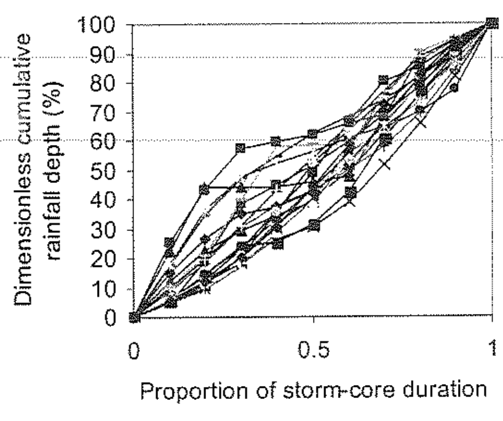

Figure 2. Dimensionless rainfall temporal patterns.

The program uses a lumped conceptual model for runoff routing in that the storage-discharge relationship is expressed by:

$$S = kQ^m \quad (2)$$

where S is catchment storage in m^3, k is a storage delay parameter in hour, Q is the rate of outflow in m^3/s and m is a non-linearity parameter (taken as 0.8 here). This model is typically applicable to small to medium sized catchments up to about 500 km^2. The program computes values of k using a number of selected observed rainfall and runoff events in a catchment. For a particular application, the user has to select an appropriate value of k from the observed values.

The inputs and outputs of the data analysis subprogram are listed in Table 2.

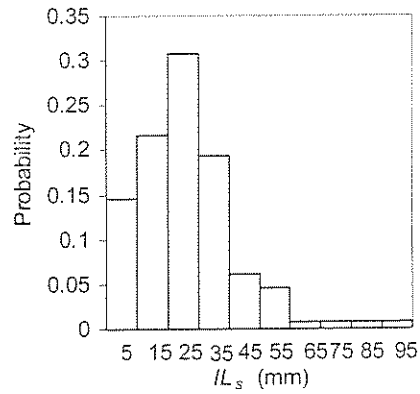

Figure 3. Distribution of initial loss IL_s.

2.3 Data Generation and Simulation

This subprogram generates a total of NG rainfall events and stores as a data file for use in the simulation of streamflow events. A rainfall event is defined by random values of D_c, I_c, TP_c and IL_c. Any significant correlation between these variables is allowed for by using conditional probability distributions. For example, the strong correlation between D_c and I_c is allowed for by first drawing a value of D_c and then a value of I_c from the conditional distribution of I_c for that duration interval.

The number of partial series rainfall events to be generated (NG) for a given catchment is obtained from the following equation:

$$NG = \lambda * NY \quad (3)$$

where λ is the average number of storm-core events per year, and NY is the number of years of data to be generated. As an example, for λ equal to 5, to simulate 2000 years of data, a total of 10,000 data points have to be generated. The selected value of λ should be similar to the average number of observed storm-cores per year at the catchment of interest using the adopted storm-core definition. The NG value should be sufficiently large to fully reflect the range of variation of inputs/parameter values in the generated output.

Table 2. Inputs and outputs of the data analysis subprogram.

Inputs/outputs	Description	Comments
Inputs:		
Hourly pluviograph and streamflow data		Greater than 20 years.
IY, f_1 and f_2	Factors used to select complete storms that can produce significant runoff	Usually, IY = 6 hours, and f_1 = 0.4 and f_2 = 0.5.
${}^2I_1$, ${}^2I_{12}$, ${}^2I_{72}$, ${}^{50}I_1$, ${}^{50}I_{12}$, ${}^{50}I_{72}$ and G	Design rainfall intensities and skewness	Used to select complete storms and storm-cores.
A	Catchment area (km^2)	Used in computation of losses.
IL, CL, k and m	An approximate values of initial loss, continuing loss, storage delay parameter and non-linearity parameter	This are required to calibrate runoff routing model for an appropriate value of k.
Outputs:		
Mean value of D_c	Mean value of storm-core duration	Used to fit exponential distribution to storm-core duration data.
IFD table	Conditional distribution of storm-core rainfall intensity (as a function of D_c)	Used to generate I_c values in the simulation.
Dimensionless temporal patterns	Data banks of TP_c (as a function of D_c)	Used to randomly sample a TP_c in the simulation.
LL, UL, Mean IL_s, SD of IL_s	Lower limit, upper limit, mean and standard deviation of observed IL_s values on the catchment	Required to fit a Beta distribution to IL_s data.
m, k	Non-linearity parameter and storage delay time k (hour)	Used by the runoff routing model. m = 0.8.

At the beginning, the program generates a value of D_c from the fitted exponential distribution. Next, a random value of ARI is generated. For the given D_c and ARI values, an I_c value is then read from the IFD table for the site of interest, using linear interpolation with respect to both log(D_c) and log(ARI).

For temporal pattern, the program randomly selects a historic temporal pattern recorded at the site of interest, depending on the previously generated D_c value. The procedure is repeated NG times to sample NG temporal patterns. Next, the program generates IL_c value by first generating an IL_s value from the Beta distribution fitted to the IL_s data from observed events at the site of interest. The generated IL_s value is then converted to IL_c value, using Equation 1. The procedure is repeated NG times to generate NG values of IL_c.

In addition to these four stochastic inputs, the simulation of streamflow hydrographs requires a number of fixed inputs as shown in Table 3.Finally, the program converts the generated rainfall events to streamflow events using the necessary fixed and stochastic inputs. Each generated rainfall event is converted to an input runoff hydrograph for the catchment and then routed through the single storage model to obtain a simulated flood hydrograph at the catchment outlet. The peak of each of the NG simulated hydrographs is stored and used by the program to determine a derived flood frequency curve.The program uses a non-parametric method to construct the derived flood frequency curve from the NG simulated partial series flood peaks. The operation of the program is illustrated in Figure 4. The inputs and outputs of the data generation and simulation subprogram are provided in Table 3.

Table 3. Inputs and outputs of the data generation and simulation subprogram.

Inputs/outputs	Description	Comments
Inputs:		
λ	Average number of storm-core events per year	A value of 4 to 6 may be appropriate.
NY	Number of years of data to be generated	A value of 2000 years may be appropriate for up to 100 year ARI flood.
CL	A representative value of continuing loss in mm/h	An appropriate value may be selected from the calibration results of the runoff routing model.
A	Catchment area (km^2)	
k	Storage delay time (hours)	
Output:		
Q	Peak of the simulated streamflow hydrographs (m^3/s)	

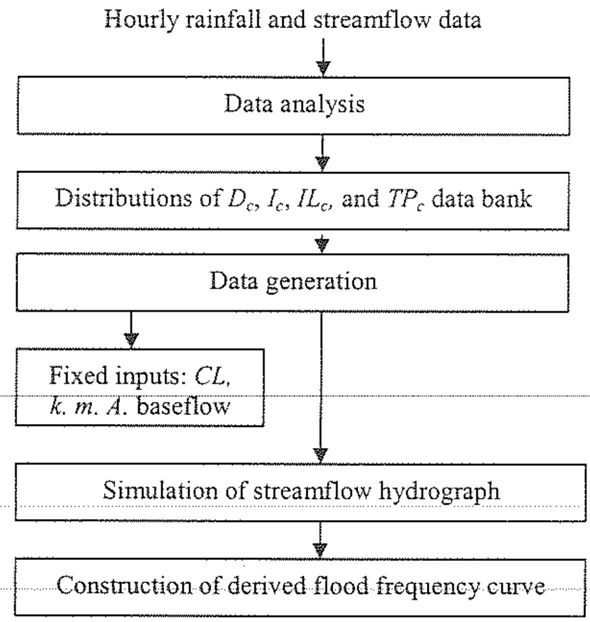

Figure 4. Operation of the program to construct derived flood frequency curve.

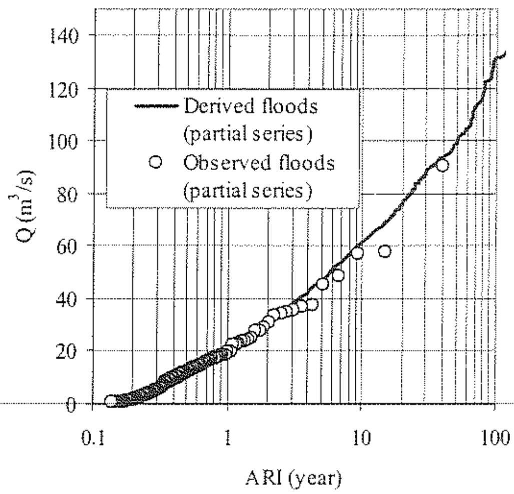

Figure 5. Derived flood frequency curve for Boggy Creek in Victoria [from Rahman et al., 2001].

3. APPLICATION

The program takes about 40 minutes on a Pentium 500 computer to obtain derived flood frequency curve at a catchment. The present version of the program is applicable to small to medium sized catchment with a maximum size of 500 km^2. The derived flood frequency curve for Boggy Creek catchment in Victoria using the described computer program is shown in Figure 5.

4. CONCLUSION

A computer program is described that can be used to determine derived flood frequency curve for small to medium sized catchments. The program accounts for the probability-distributed nature of rainfall duration, rainfall intensity, rainfall temporal pattern and initial loss and their correlations in an explicit manner in simulating rainfall and streamflow events. The program generates a large number of rainfall events and uses a simple conceptual non-linear runoff routing model to produce streamflow hydrographs. The simulated flood peaks are used to determine derived flood frequency curve at the catchment of interest. The program needs further development before it can be applied to larger catchments.

5. ACKNOWLEDGMENTS

Part of the program was developed and tested by the author in the CRC for Catchment Hydrology, Department of Civil Engineering, Monash University. The author thanks Mr Erwin Weinmann, Monash University and Ms Tam Hoang, Bureau of Meteorology for their suggestions in developing the program.

6. REFERENCES

Eagleson, P.S., Dynamics of flood frequency, *Water Resources Research, 8*, 4, 878-898, 1972.

Hill, P. I., U.K. Maheepala, R.G. Mein and P.E. Weinmann, Empirical analysis of data to derive losses for design flood estimation in south-eastern Australia. CRC Report 96/5, CRC for Catchment Hydrology, Dept. of Civil Eng., Monash University, 1996.

Institution of Engineers Australia, Australian rainfall and runoff - a guide to flood estimation, 2001.

Hoang, T.M.T., A. Rahman, P.E. Weinmann, E.M. Laurenson and R.J. Nathan, Joint probability description of design rainfalls. Proc. Hydro. and Water Resour. Symp., I.E. Aust., Brisbane, Vol. 1, 379-384, 1999.

Rahman, A., T.M.T. Hoang, P.E. Weinmann and E.M. Laurenson, Joint probability approaches to design flood estimation: a review. Report 98/8, CRC for Catchment Hydrology, Monash University, Australia, 1998.

Rahman, A., P.E. Weinmann, R.G. Mein, Probabilistic nature of initial losses and its impacts on design flood estimates. Proc. 3rd Intl. Hydrology and Water Resources Symp., I.E. Aust., Perth, Western Australia, Vol. 1, 71-75, 2000.

Rahman, A., P.E. Weinmann, T.M.T. Hoang, E.M. Laurenson and R.J. Nathan, Monte Carlo simulation of flood frequency curves from rainfall. Report 01/4. CRC for Catchment Hydrology, Dept. of Civil Eng., Monash University, 2001a.

Rahman, A., P.E. Weinmann, T.M.T. Hoang and E.M. Laurenson, Monte Carlo simulation of flood frequency curves from rainfall. *Journal of Hydrology* (In press), 2001b.

Sivapalan, M., G. Bloschl and D. Gutknecht, Process controls on flood frequency. 1. Derived flood frequency. Centre for Water Research Environmental Dynamics Report, ED 1158 MS, Department of Civil Eng., The University of Western Australia, 1996.

Weinmann, P. E., A. Rahman, T.M.T. Hoang, E. M. Laurenson, R. J. Nathan, A new modelling framework for design flood estimation. Proc. Intl. Conference on Hydraulics in Civil Engineering, Adelaide, Australia, 1998.

Weinmann, P. E., A. Rahman, T.M.T. Hoang, E. M. Laurenson, R. J. Nathan, Monte Carlo simulation of flood frequency curves from rainfall – the way ahead. Proc. 3rd Intl. Hydro. and Water Resour. Symp., Perth, Western Australia, Vol. 1, 564-569, 2000.