Application of Monte Carlo Simulation Technique with URBS Model for Design Flood Estimation of Large Catchments

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Abstract : The Monte Carlo simulation technique for design flood estimation, based on the Joint Probability Approach, incorporates the probabilistic nature of key input variables such as rainfall intensity, duration, temporal pattern and initial loss. URBS is a semi-distributed non-linear runoff routing model, and one of several industry models used for design flood estimation for small to very large catchments. The integration of Monte Carlo Simulation and the URBS run-off routing model, here named the URBS-Monte Carlo Simulation Technique (UMCST), has been demonstrated for small to medium sized catchments (Rahman et al., 2002a). The purpose of the paper is to extend the UMCST to large catchments containing several pluviograph stations and gauging stations. The key assumptions and methodology used to apply the UMCST to large catchments are discussed, and the flood estimates generated by the extended UMCST are compared to observed data. The paper shows that the UMCST can be applied to large catchments and be readily used by hydrologists and floodplain managers. The new technique offers greater flexibility when compared with the Design Event Approach and is based on sound probabilistic formulation. This creates an opportunity to better account for the spatial variability of flood-producing variables in large catchments. Further, the proposed technique will provide deeper insight into the hydrologic behaviour of large catchments.

Keywords: *Flood estimation; Monte Carlo Simulation; URBS; Joint Probability Approach.*

1. INTRODUCTION

A design flood is a probabilistic estimate, widely used in the design of hydraulic structures, floodplain management, environmental studies, flood insurance studies, and for various regulatory purposes. Design flood estimates have an associated average recurrence interval (ARI) or annual exceedance probability (AEP).

In Australia, most flood estimation techniques are probablistic estimates of rainfall only. The currently recommended method in Australian Rainfall and Runoff (I. E. Aust., 1987, 98) is the Design Event Approach, which has some basic limitations. More recently, a new rainfall-based design flood estimation technique, known as the Joint Probability Approach or Monte Carlo Simulation Technique, has been developed and tested in Australia (Rahman et al., 2002b, Weinmann et al., 2002). It is based on a sounder probabilistic formulation. This new approach has been integrated with the industry-based flood estimation model URBS (Carroll, 2001) and is named the URBS-Monte Carlo Simulation Technique (UMCST) (Rahman et al., 2002a).

To date, the UMCST has been applied to small to medium sized, gauged catchments. The application of the technique to large catchments is not straight forward. Ideally, it requires identification of probability distributions of various flood-producing variables at each sub-catchment level. This paper extends the UMCST method to a large gauged catchment.

2. DIFFERENCES BETWEEN DESIGN EVENT APPROACH AND MONTE CARLO SIMULATION TECHNIQUE

Both the Design Event Approach and Monte Carlo Simulation Technique have common deterministic components. These include a loss model for computing rainfall excess, and a runoff routing model for converting rainfall excess hyetograph into streamflow hydrograph. The techniques differ in their variable components, as discussed below.

2.1. Design Event Approach

The Design Event Approach considers rainfall intensity a random variable. It uses a number of trial storm durations, with fixed temporal patterns and losses, to calculate flood estimates.

The approach assumes that a design rainfall depth of a given AEP can be converted to a flood discharge of the same AEP. This is undertaken by applying 'representative' design values (e.g. storm durations, temporal patterns and losses) so that they are 'AEP neutral'.

However, the assumed correlation between the resultant flood discharge and rainfall depth cannot be supported in many cases. This is due to the non-linearity of the rainfall-runoff process and the arbitrary treatment of some flood-producing variables. This can lead to inconsistencies and significant bias in flood estimates for a given AEP.

2.2. Joint Probability Approach/Monte Carlo Simulation

In contrast, the Monte Carlo Simulation Technique treats more input variables as random. It involves simulating a large number of events from the distributions of the variables, thus eliminating the subjectivity inherent in setting representative values.

In this paper, four flood-producing variables have been represented statistically: storm duration (dc), rainfall intensity (Ic), temporal pattern (TPc) and initial loss (ILc) similar to Rahman et al., (2002b). However, the approach could be applied to all the input variables.

To provide stochastic inputs of storm duration, rainfall intensity, temporal patterns and rainfall initial loss in the Monte Carlo Simulation Technique, it is necessary to define a 'storm event'. Various characteristics of storm events can then be extracted from continuous rainfall records and/or streamflow records. The storm event definition of Hoang et al., 1999, later modified by Rahman et al., 2001 to define a storm-core event, has been employed for the purposes of this analysis.

From the extracted storm event data, as defined by Rahman et al., 2001, storm-cores are analysed to yield the stochastic inputs of duration, intensity and temporal patterns. Losses are obtained from the comparison of concurrent storm event and streamflow event data. The detailed procedure can be found in Rahman et al. (2001). The outcomes from the process can be summarised as follows:

(a) A probability distribution of storm core durations, dc, is developed which is typically exponential.

(b) A conditional distribution (Ic/dc) expressed in the form of Intensity-frequency duration (IFD) curves.

(c) Dimensionless temporal patterns (TPc) based on the observed storm-core rainfall patterns.

(d) A probability distribution of ILs, the storm event initial loss, generally assumed as a four-parameter Beta distribution. The value of ILs is transformed to storm-core initial loss (ILc) value by an empirical relationship.

The Monte Carlo Simulation Technique has been developed and tested in small to medium sized gauged catchments in Victoria and Queensland (e.g. Rahman et al., 1998; 2001, 2002a, b, c, d; Weinmann et al., 1998, 2002; Hoang et al., 1999; 2001).

3. URBS MODEL

URBS is a runoff-routing networked model of sub-catchments based on centroidal inflows. URBS has a similar catchment discretisation to that of the RORB model (Laurenson and Mein, 1997). An important feature of the URBS model is the ability to split the hydrograph routing into catchment and channel components. The URBS model is used extensively throughout Australia for flood forecasting and design event modelling. Further information on the URBS model is contained in Carroll (2001).

3.1. URBS-Monte Carlo Simulation Technique

UMCST integrates the probablistic and deterministic approaches described above. The integration of the Monte Carlo Simulation Technique with URBS is described in detail in Rahman et al. (2002a) but can be summarised as follows:

(a) Randomly select a set of dc, Ic, TPc and ILc, which defines a stochastic runoff event.

(b) Select inputs representing continuing loss (CL) and URBS model calibration parameters.

(c) Combine the stochastic inputs and fixed inputs to form a stochastic event.

(d) Repeat N times, to generate N stochastic events, N is typically greater than 10,000.

(e) Conduct a non-parametric frequency analysis of the generated peak discharges.

4. STUDY CATCHMENT AND DATA

The UMCST method was applied to the North Johnstone River Catchment in North Queensland. Its catchment area is approximately 1000 km^2. The topography of the catchment varies significantly from the highly elevated Atherton Tablelands to the lowlands.

Continuous rainfall data has been sourced from fourteen ALERT stations across the entire catchment. Approximately seven years of continuous rainfall data are available for each station. Streamflow data was sourced for Tung Oil, a continuous stream gauging located at the downstream end of the North Johnstone River catchment. This information was used to estimate the probability distributions of dc, Ic, ILc and to prepare the database of dimensionless temporal patterns (TPc).

5. RESULTS

5.1. Rainfall Analysis

The statistics of the storm-core events and storm-core durations (dc) are listed in Table 1. The observed distribution of Corsi's ALERT rainfall station storm-core durations is illustrated in Figure 1 and is typical of an exponential distribution. The conditional distribution of storm-core rainfall intensity (Ic) is represented in the form of intensity-frequency-duration (IFD) tables, generated from the ALERT rainfall stations an example of which is shown in Figure 2. Since the ALERT rainfall stations have a very short record, the developed IFD curves for ARIs greater than 20 years are subject to large error. However, the regional method such as CRC-FORGE (Nandakumar et al., 1997) can be incorporated with the at-site IFD curves developed to obtain more reliable IFD data. This has been left for future research.

Table 1. Statistics of the storm-core durations (d_c) at the 14 ALERT rainfall stations.

Alert Station I.D.	ALERT Station Name	Observed Events	Average Events per year	Statistics of Storm-Core Durations (d_c) – hours		
				Mean	Standard Deviation	Skewness
2500	Millaa Millaa	32	5	17	22	1
2510	Malanda	33	5	14	19	2
2515	Topaz	37	5	33	51	3
2520	McKell Rd	30	4	12	16	2
2525	Greenhaven	19	4	16	23	1
2530	Bartle View	26	4	17	27	3
2535	Sutties Creek	25	4	11	20	3
2540	Crawford's Lookout	24	4	19	30	3
2545	Menavale	34	5	15	21	2
2550	Corsi's	29	4	14	21	2
2555	Central Mill	37	5	14	21	2
2560	Nerada	24	4	13	18	2
2565	Tung Oil	38	5	16	22	2
2570	Innisfail	41	6	15	23	2

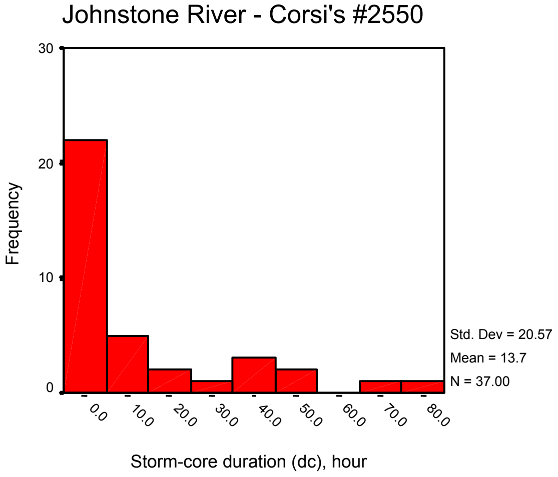

Figure 1. Distribution of storm-core duration (d_c)

Johnstone River – Corsi's #2550

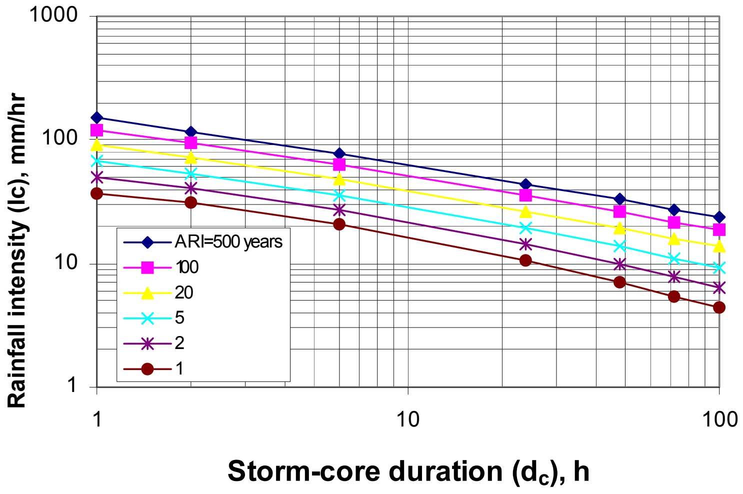

Figure 2. IFD Curve – Corsi's Alert Station #2550

The observed storm-core rainfall temporal patterns (TPc), in the form of dimensionless mass curves, were extracted for each ALERT rainfall station. These temporal patterns were 'pooled' from all the ALERT stations and were divided into two groups: a) up to twelve hours duration and b) greater than twelve hours duration. Temporal patterns were selected randomly from the pooled data depending on the value of dc as outlined by Rahman et al. 2001. Alternatively the stochastic generation of temporal patterns as proposed by Hoang (2001) could be adopted and applied to the UMCST.

The initial loss analysis was undertaken for the North Johnstone River catchment using the Tung Oil stream gauge data. Catchment average rainfall was estimated by using ALERT rainfall station data and 'Thiessen Polygon weightings'. The observed storm event initial losses (ILs) are summarised in Table 2 and illustrated in Figure 3.

The initial storm core loss value (ILc) was estimated using the relationship adopted by Rahman et al. (2002d).

Table 2. Statistics of Initial Losses (IL_c) for North Johnstone River

Name	Observed Events	Events per year	Statistics of Initial Losses (IL_s) – mm				
			Mean	St. Dev.	Skewness	Min.	Max.
North Johnstone	38	5	14	15	4	1	93

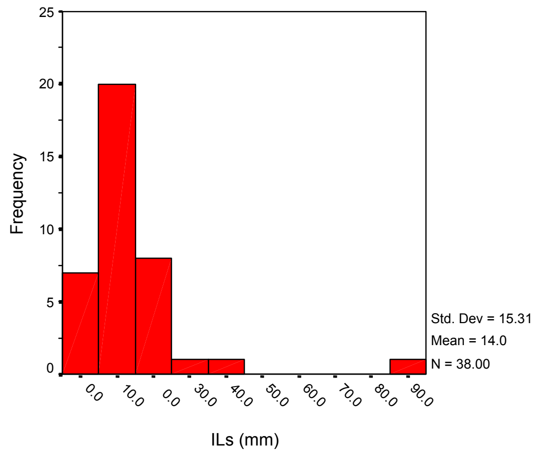

Figure 3. Probability distribution of Initial Loss (IL_s) for the North Johnstone River

5.2. Calibration of URBS Model

A calibrated URBS runoff routing model of the Johnstone River was obtained from the Bureau of Meteorology, Brisbane Office. The URBS model comprises 42 sub-areas and uses the 'SPLIT' model routine that routes the sub-catchment runoff and channel runoff separately.

5.3. URBS - Monte Carlo Simulation

An ALERT rainfall station was assigned to each of the URBS model sub-catchments. A single run involves following steps:

(a) The simulation starts with generation of a dc value from the fitted exponential distribution, which is assumed constant for all sub-catchments.

(b) Using the dc value, and a randomly selected value of ARI, a value of Ic is generated using the IFD table for each sub-catchment. The ARI is assumed to be constant for all sub-catchments.

(c) A random TPc is then selected from the pooled TPc data, based on a value of dc. The TPc selected is constant for all sub-catchments.

(d) The value of ILs is then generated from the fitted Beta distribution and converted to ILc value using Equation 1. The value of ILc is assumed to be constant for all sub-catchments

To convert point rainfall into areal rainfall an areal reduction factor is applied based on the area of the catchment following the approach by Siriwardena and Weinmann (1996). A constant continuing loss (CL) was applied.

The above steps allow formulation of the 'rainfall hyetograph', which is then routed through the calibrated URBS model to produce a runoff hydrograph. This process is repeated 10,000 times. The peaks of the 10,000 simulated flood hydrographs are then analysed using a non-parametric frequency analysis. The simulation time was just over one hour on a Pentium II 733 MHz personal computer.

5.4. Comparison of Results

The stream gauging station Tung Oil, representing the North Johnstone River catchment, has been used for comparison of the UMCST modelling results. Partial series peak discharge data from the Department of Natural Resources and Mines (DNRM, 2003) were used.

Overall, the comparison of peak flow rates between observed and simulated data is quite reasonable over a range of frequencies. There is some overestimation at the higher frequencies but generally the simulated values provide a good fit, as illustrated in Figure 4.

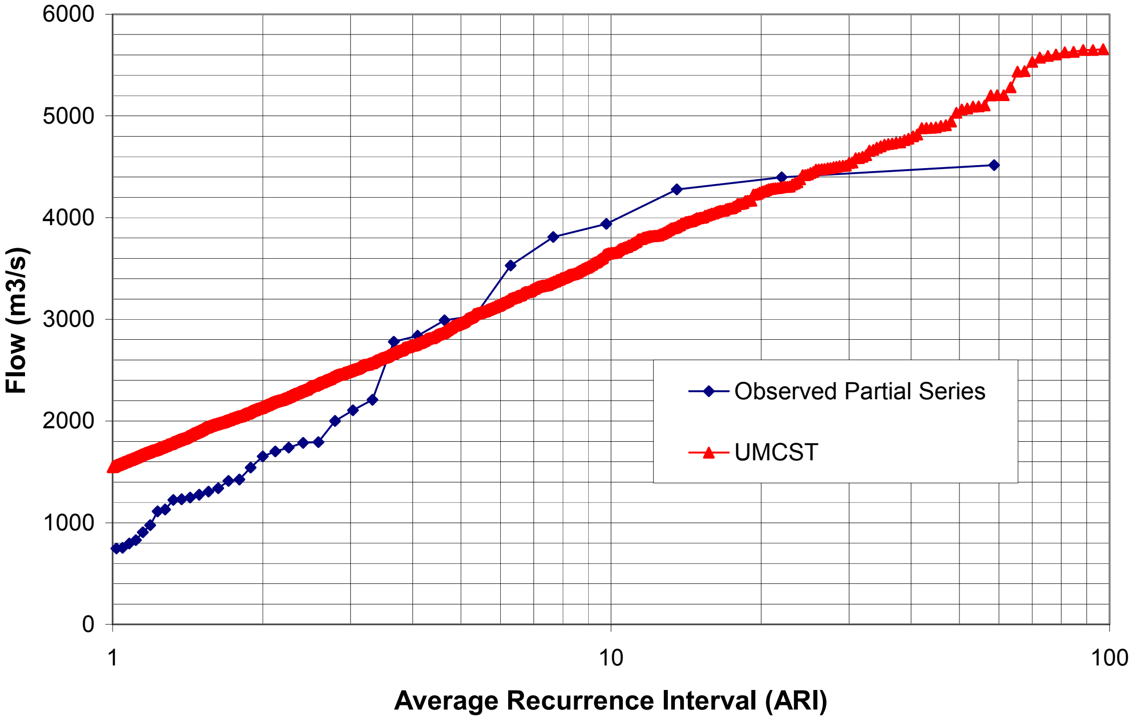

Figure 4: Flood Frequency Analysis of Tung Oil #112104

6. CONCLUSIONS

The paper describes how UMCST can be applied to a large catchment. It is concluded that it is quite feasible to apply UMCST to large catchments with multiple rainfall stations and multiple stream gauges. It is also concluded from the investigation that it is feasible to vary both the initial loss and storm duration across sub-catchments. Indeed, the new technique has the capability to vary any input variable for each sub-catchment.

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