LOSS MODELLING FOR FLOOD ESTIMATION- A REVIEW

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COOPERATIVE RESEARCH CENTRE FOR
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PREFACE

The Cooperative Research Centre (CRC) for Catchment Hydrology's research program "Flood Hydrology" has the overall objective:

> *To improve methods for estimating flood risk and the reliability of flood forecasting, and to advance the understanding of catchment similarity and regional behaviour.*

Major improvements in the accuracy of flood estimates, and hence flood risk, could be achieved if we could better predict the proportion of storm rainfall which becomes flood runoff. Depending on initial wetness and catchment characteristics, this proportion can vary from 0% (dry catchment, porous soil) to nearly 100% (wet catchment, impervious soil).

CRC Project D1 "Improved loss modelling for design flood estimation and flood forecasting" has the goal of improving the prediction of runoff for storm events. A major factor in the adoption of this project by the CRC is the access to rainfall data (Bureau of Meteorology) and runoff data (Rural Water Corporation). The resulting database is more extensive than has been previously available in Victoria for studies of this kind, and a shining example of the cooperative arrangements within the CRC.

Earlier versions of this review by Nandakumar *et al.* set the scene for the 3 year project which began in October 1993. This document provides the background and justification for the selection of the sub-projects which comprise CRC Project D1.

R.G. Mein
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SUMMARY

This report gives a review of approaches used to estimate storm losses ie. the amount of rainfall which does not contribute to storm runoff. The coverage is for both loss estimation for use in real-time forecasting (flood warning), and for the calculation of design floods. The aim is to highlight the deficiencies in the current state-of the-art and to indicate the most promising areas of research for CRC Project D1 "Improved loss modelling for design flood estimation and flood forecasting".

The review first examines the probabilistic concepts of design losses for approaches such as: (i) median loss values, (ii) design loss values estimated from frequency analysis of rainfall and runoff, and (iii) joint probabilities between the variables involved in runoff generation. It is concluded that: (i) median loss values are used for design, but without theoretical support, (ii) design loss estimates dependant on event recurrence interval are not available for most Australian catchments, and (iii) the joint probability approach to losses deserves further investigation.

Loss estimation models can be divided into two groups: (i) the methods based on a spatially lumped response of the catchment, and (ii) point infiltration equations. For spatially lumped models, widely used methods are: (a) constant loss model, (b) initial loss-continuing loss model, (c) proportional loss model, (d) antecedent precipitation index methods and (e) SCS curve number procedure. There are a limited number of studies using the SCS curve number procedure in Australia, although it has been widely applied in the USA. The initial loss-continuing loss model is common in Australia, but the relationship between initial loss and antecedent wetness indices for real-time applications needs further investigation.

Popular point infiltration models such as the Horton equation, the Green-Ampt model and the Philip equation are considered in this review, in addition to the Richards equation which has been increasingly used in the current generation of rainfall-runoff models. It is concluded that theoretically-based point infiltration models should be considered for further investigation to determine the usefulness of current measures of soil characteristics. Approaches to take into account spatial variation of the model parameters are also discussed.

The loss models used in real-time flood forecasting include simple approaches such as initial loss combined with continuing or proportional loss rates, ϕ-index, runoff coefficient, linked with estimates of catchment conditions. In the simple models, temporal variation in losses are not considered explicitly, but can be included in a defacto way through parameter updating to match the observed hydrograph. Recent studies have demonstrated the use of Boughton's AWBM model coupled with the routing model, URBS. Similarly the TOPOG model can be coupled with the RORB model to simulate the spatial variability of losses. Further investigation of both of these models is recommended.

1. INTRODUCTION

The difference between rainfall and runoff volume (ie. "losses") has a major influence on the magnitude and shape of flood hydrographs resulting from rainfall. This report presents a review of approaches used to estimate the amount of rainfall which becomes runoff during storm events. It is concerned with both loss estimation for use in real-time forecasting (flood warning) and for calculation of design floods used to size hydraulic structures. The purpose is to highlight the deficiencies in the current state-of the-art and to indicate the most promising areas of research for CRC Project D1 "Improved loss modelling for design flood estimation and flood forecasting".

The emphasis of this review is on estimation of losses for storm events to enable the calculation of complete storm hydrographs; it is considered that current procedures for determination of design peak flows are adequately covered in Australian Rainfall and Runoff (I.E. Aust., 1987, Ch. 5). Urban catchments are not considered specifically here, for similar reasons.

Storm loss for an event is defined as the amount of precipitation that does not appear as direct runoff; it includes moisture intercepted by vegetation (interception loss), percolated into soil (infiltration) or retained by surface storage (depression). As these loss components are dependent on topography, soils, vegetation and climate, the rainfall losses exhibit both temporal and spatial variability during an event.

In this report, the concepts and derivation approaches for design losses are described in Chapter 2. Chapter 3 presents the spatially lumped design loss estimation methods in common use; point infiltration models are covered in Chapter 4. In Chapter 5, real-time forecasting requirements and loss models are reviewed. The recommendations for future research and development which emerge from this review are outlined in Chapter 6.

2. DESIGN LOSS CONCEPTS

2.1 Introduction

Many problems in hydrology involve the estimation of a flood flow with a given chance of occurrence in a specified time period; such hypothetical flow estimates are termed design floods. If an adequate period of stream discharge measurements is available for the site in question, estimates of design floods can be made using frequency analysis of the recorded data. More often, however, no flow data are available and design flood estimates are made from design storms.

Design floods are typically estimated from design storms using: (i) rational methods for peak flows, or (ii) routing models in association with loss models for flow hydrograph estimation. The first method does not take into account any physical processes involved in runoff generation; the design peak runoff rate from a catchment is related to a storm of specified intensity using runoff coefficients (Pilgrim, 1980). The current Australian Rainfall and Runoff (I.E. Aust., 1987) recommends the Probabilistic Rational Method for NSW and Victoria. This is a regional frequency procedure based on analysis of data for many sites in these states.

In the second method, a loss model is applied to convert rainfall to excess rainfall; the latter is routed using an appropriate routing model to obtain the flood hydrograph. Design flood hydrographs are needed for cases where storage is significant (dam spillway design, flood plain flows) or where the duration of flooding is required. For these applications, attention must be paid to the proper calculation of design losses.

The purpose of design loss is to achieve a flood with a given annual recurrence interval (ARI) from a design rainfall with the same ARI. Since actual losses vary from event to event, design losses can be viewed as probabilistic or statistical estimates of the most likely value.

A number of approaches to derive design losses are given in the following sections.

2.2 Design Loss Derivation Approaches

Usual approaches for estimation of a design flood using design rainfall and losses include the use of: (i) median loss values, (ii) design loss values estimated from frequency analysis of rainfall and runoff, and (iii) joint probabilities between the variables involved in runoff generation.

2.2.1 Median losses

Cordery (1970b) proposed that the design frequency of floods would be approximately equal to the frequency of the design storm by abstracting median losses obtained by analysis of storm losses in a number of observed events. I.E. Aust. (1987) recommends the use of at least three, and preferably five or more events, for such calculations.

It has been argued that median losses may not be suitable for direct design applications because:
(i) calculated loss values tend to be biased in that they are obtained from significant runoff events; large rainfalls that produce little or no runoff due to dry catchment conditions are not analysed, and
(ii) design rainfalls, in their derivation, do not represent complete storms; they come from high intensity rainfalls within longer storms (I.E. Aust., 1987).

The first can result in underestimation of design losses, eg. Waugh (1991) reported that overestimation of flood magnitudes by as much as 20% can be caused by adoption of major floods in the design loss derivation. The second may contribute to overestimation, due to subtraction of full event loss from only portions of storm events.

The use of the median loss values in design flood estimation has been recommended without theoretical support and needs further investigation (Pilgrim and Robinson, 1988).

2.2.2 Frequency analysis of rainfall and runoff

In this approach, the design loss with the "correct" ARI is derived by fitting a flood hydrograph model using a rainfall depth and runoff peak of the same ARI, the latter being obtained from frequency analyses. In this way, the combined effects of the causative variables on losses are accounted for (Pilgrim and Robinson, 1988) because, in the derivation, the derived loss converts the design rainfall with a given ARI to a design flood with the same ARI.

A number of studies (eg. Flavell and Belstead, 1986, Walsh et al., 1991, Walsh and Pilgrim, 1993) describe the derivation of design losses with different ARIs using the rainfall intensity-frequency-duration, temporal pattern and areal reduction factors published in I.E. Aust. (1987). In these analyses, design losses are typically obtained by the following steps (Walsh et al., 1991):

(i) The flood hydrograph model is first calibrated (ie. parameters fitted) using data from a number of observed events;

(ii) Peak discharge for the desired ARI is obtained from a frequency analysis of observed flood peaks;

(iii) For each of a range of duration of design storms of the same ARI, and adopting a fixed loss value of typical magnitude, peak discharges are obtained;

(iv) The critical duration of design rainfall with a given ARI is obtained from the peak of a smooth curve drawn through the points in the flood peaks vs rainfall duration plot;

(v) For the critical duration storm, the input loss value is adjusted until the calculated flood peak is equal to that obtained from the frequency curve [Step (ii)]. The resulting loss value is adopted as the design loss value.

It should be noted that the "correct" ARI of flood volume is not considered explicitly in the above procedure. Beard (1990) took into account the flood volumes along with flood peaks when calibrating a flood hydrograph model, and claimed that the calibrated model can be used to estimate design losses for various land-uses.

2.2.3 Joint probability approach

This approach considers joint probability of variables contributing to the flood discharge (I.E. Aust., 1987, Ch.1). The combination of the contributing stochastic variables is determined from the mathematical model used to calculate runoff. A number of examples of this approach are cited below.

Beran and Sutcliffe (1972) used the joint probabilities of rainfall and soil moisture deficit to obtain the probability distribution of rainfall excess. The rainfall excess was assumed to be the difference between rainfall depth and soil moisture deficit.

Hughes (1977) derived the distribution of runoff volume for a given runoff duration using the joint probabilities of rainfalls and loss rates. For a given runoff duration, peak flow was related to runoff volume and the time distribution of runoff; for the latter a linear relationship between peak flow and runoff volume was assumed. Using this, the exceedence probability of peak discharge was obtained using the joint probabilities of runoff volume and runoff duration.

Ahern and Weinmann (1982) used a nonlinear runoff-routing model to develop a general relationship between rainfall, catchment losses and peak flows. Using this relationship, the distribution of peak flows was determined using a joint probability analysis.

Goyen (1983) employed a joint probability approach to combine a probabilistic antecedent moisture index in the infiltration component of the Australian Representative Basin Model with rainfall probability. A routing model (RAFTS) was used to obtain the flood frequency curve using frequency curves of rainfall excess associated with rainfall temporal patterns.

To conclude, although the joint probability approach is theoretically superior to the procedures covered in Sections 2.2.1-2, problems arise due to uncertainties in the tails of the input probabilistic distributions, especially for rare events (I.E. Aust., 1987, Ch 1). The joint probability approach could be used for annual recurrence intervals in the, say 1 - 100 years range, although the complications involved in obtaining necessary probability distributions appear to limit its usefulness for routine applications.

2.3 Other Approaches

2.3.1 Continuous simulation

The approaches described in Section 2.2 above are mostly based on event modelling to derive design flood hydrographs. However, continuous modelling can also be employed to derive flood frequency curves using: (i) historical rainfall sequences, (ii) synthetic rainfall data generated using historical distributions (Bras et al., 1985), and/or (iii) data obtained from storm transposition (Bradley and Potter, 1992).

Continuous models automatically account for the antecedent condition for major storm events, and hence overcome the difficulty of separately estimating the initial conditions which affect losses. Continuous rainfall-runoff modelling is becoming increasingly popular because of model capabilities in predicting short-time interval flows and the ready availability of computer resources. With such resources, lumped deterministic models like HRCYCLE, (Porter and McMahon, 1971), the Stanford Model (Crawford and Linsley, 1966), and the Australian Representative Basin Model (Chapman, 1968) can now be used to simulate short-time interval flows.

Although the continuous modelling approach is conceptually more sound than event based approaches, it is difficult to use the former for design flood estimation in rural catchments because of the complexity involved in calibration of the model. Recently, Boughton and Carroll (1993) demonstrated the coupling of a simple continuous rainfall-runoff model (AWBM) and a flood routing event model (URBS) to simulate flood flows. This is an important development to obtain the most desirable features of both type of models.

2.3.2 Inclusion of flood volume

The use of observed relationships between flood peak and volume seems to be a worthwhile alternative to traditional flood frequency analysis of peaks alone. In design involving high return periods, the extrapolation of the frequency curve of runoff volume has been claimed to be more reliable than extrapolation of peak flows, because runoff volume generally shows less variability than peaks (Bradley and Potter, 1992). Hence, if a peak-to-volume relationship can be shown to exist, it can be used to derive more reliable flood peaks from the volume frequency curve.

Peak-to-volume relationships can be used to derive design floods (i) in the joint probability approach along with loss models (eg. Hughes, 1977) and (ii) in conjunction with frequency analysis of runoff volume or volumetric runoff coefficients. Although this approach appears to be promising in design flood estimations, further investigations are needed to confirm its use.

3. SPATIALLY LUMPED LOSS MODELS

As mentioned in Chapter 1, storm losses include interception, depression and infiltration losses which have been conceptualised in simple forms. Such conceptualised models do not consider the spatial variability or the real temporal pattern of storm losses; the model parameters are estimated using the total catchment response ie. runoff. However, spatially-lumped loss models are widely used because of their simplicity and ability to approximate catchment runoff behaviour. For example, the proportional loss rate model can be regarded as conceptualising the variable contributing area concept ie. 100% runoff from a proportion of the catchment.

Some of the most frequently used methods for spatially lumped losses include (i) constant loss rate, (ii) initial loss-continuing loss, (iii) proportional loss, (iv) antecedent precipitation index, and (v) SCS curve procedures. These are described in the following sections.

3.1 Constant Loss Rate

In this method, sometimes known as the ϕ index method, a constant loss rate is subtracted from the design storm (Figure 1). Although this model does not closely conceptualise the actual processes for many Australian regions, it can be used in catchments that produce high runoff from storms (i.e. low loss). Flavell and Belstead (1986) applied this model in a region (Kimberly region of Western Australia) with large areas of bare rock and shallow sand cover; the constant loss rate varied from 2.5 to 4.8 mm/h for a range of average recurrence intervals (ARI).

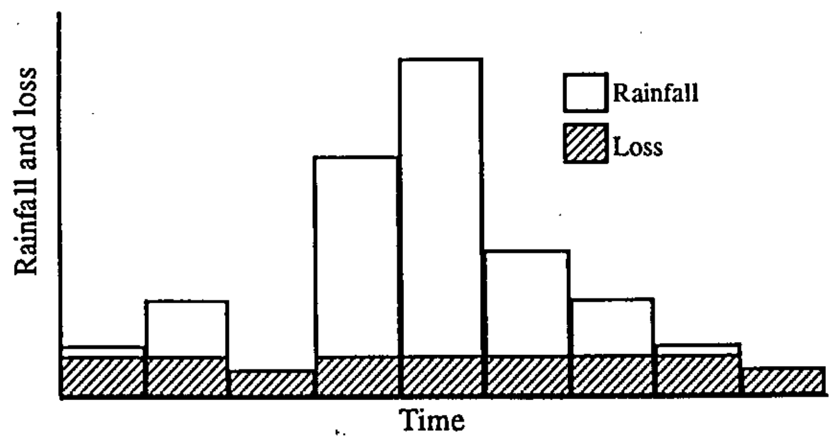

Figure 1 Constant loss model

3.2 Initial Loss-Continuing Loss (IL-CL) Model

This model (Figure 2) has been widely used in Australia (I.E. Aust., 1987), due both to its simplicity and to its generally better approximation of the temporal pattern of storm losses than the constant loss rate approach (Section 3.1). Initial loss is the loss that occurs in the early part of the storm, prior to the commencement of surface runoff. Thus, it can be considered to be composed of the interception loss, depression storage and infiltration that occurs before the soil surface saturates. Continuing loss is then the average rate of loss during the remaining period of storm.

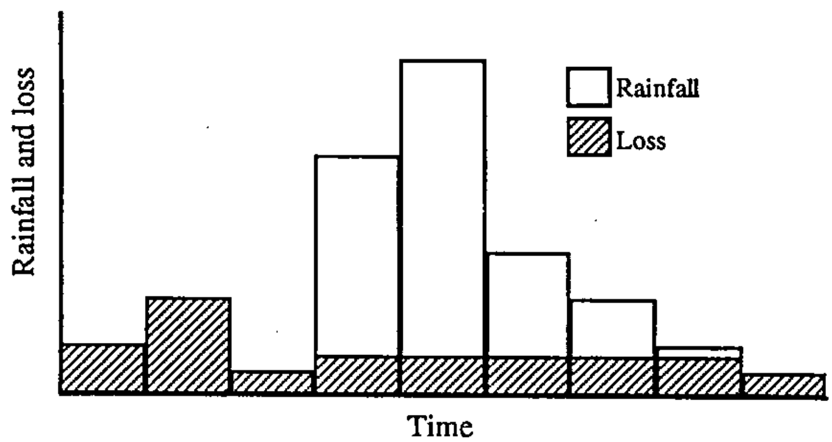

Figure 2 Initial loss-continuing loss model

Cordery (1970a) proposed Equation. 1 to calculate median IL for NSW catchments using mean annual rainfall, P (in mm) and catchment area, A (in km^2).

$$\text{Median IL} = 1.05\, A^{0.079}\ (3683\text{-}P) \qquad (1)$$

for $A < 260\ \text{km}^2$

$635\ \text{mm} < P < 1780\ \text{mm}$

Cordery found that IL was highly correlated with antecedent precipitation index, and suggested that IL is an important factor in low rainfall areas, but can be neglected in areas where mean annual rainfall is greater than 1270 mm. However, Flavell and Belstead (1986) derived initial loss values up to 84 mm for a West Australian catchment with an annual rainfall of 1420 mm, which shows the hazards of areal extrapolation of empirical equations.

Laurenson and Pilgrim (1963) presented 150 continuing loss rate values for 24 catchments in south-eastern Australia. The values varied markedly from catchment to catchment, and were found to be significantly influenced by antecedent wetness and season. The median values of continuing loss rate for the 24 catchments were between 0 to 5 mm/h, with half of them equal to or less than 2.5 mm/h. Updated loss rate values for 54 Australian catchments are given in I.E. Aust. (1987) (Ch. 6); the distribution of derived individual loss rate values obtained from 658 events is shown in Figure 3.

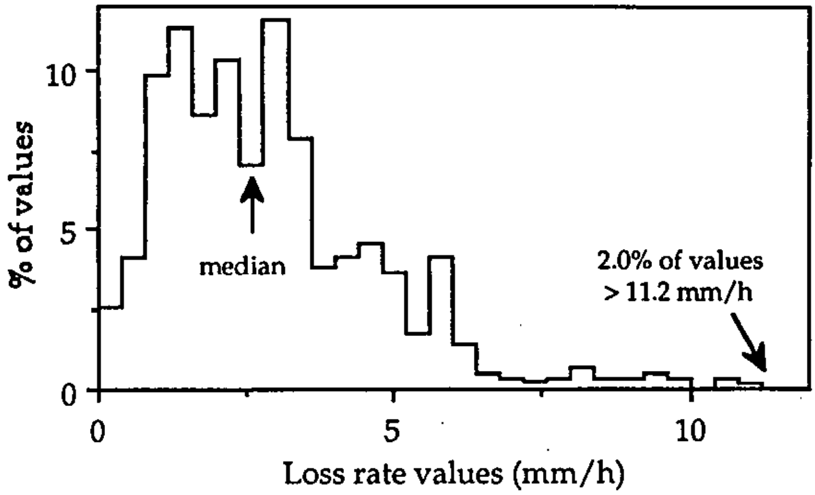

Figure 3 Frequency distribution of individual loss rate values from 54 Australian catchments [after I.E. Aust., 1987 (Ch. 6)]

Flavell and Belstead (1986) used the IL-CL model to obtain design losses for catchments in Western Australia. They found that IL decreased with ARI in the region where flooding tends to increase towards the end of winter as catchments become wetter; the rarer events are associated with high antecedent wetness. In the other regions, IL increased with ARI up to an ARI of 10 years, and then decreased! A minimum IL of 20 mm was obtained with an ARI of 2 years for loamy soil areas, and a maximum IL of 98 mm was derived with ARI of 10 years for sandy soil catchments. This indicates the broadness of the range of values of this parameter. For the same data, CL varied from 3 mm/h to 5 mm/h.

Using the design rainfall given in I.E. Aust. (1987), Walsh et al. (1991) estimated design IL values for 22 catchments in NSW. An average CL rate of 2.7 mm/h was used to obtain the IL for a range of ARIs. The derived IL values varied from 15 to 50 mm and were dependent on the degree of nonlinearity used in the flood hydrograph model (RORB). The derived IL values also showed some degree of dependency on design rainfall pattern.

3.2.1 Relationships with catchment characteristics

In their analysis of data from 27 catchments, Cordery and Pilgrim (1983) found no relationships between catchment characteristics and median continuing loss rate. It appears that the difficulty of obtaining relationships between loss model parameters and catchment characteristics are due to:

(i) the probabilistic nature of the design losses, and

(ii) the inadequacy of the loss models in conceptualising real catchment-processes both in temporally and spatially.

Further investigation is needed to account for these problems.

3.3 Proportional Loss Rate (PLR) Model

For this model, loss is assumed to be a fixed proportion of storm rainfall (Figure 4); in Australia, the approach is generally used in conjunction with an initial loss for rural catchments. The model performs well on catchments where runoff is generated from source areas, as then the runoff is proportional to the rainfall.

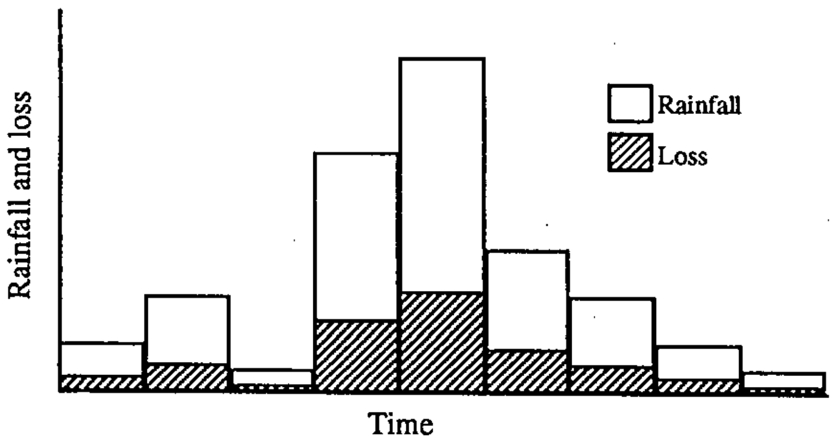

Figure 4 Proportional loss model

Harvey (1982) found that the PLR model, with an initial loss model, performed well in South Western Australia. Flavell and Belstead (1986) used the PLR model to derive design losses in forested catchments in that state. PLR was related to the stream length (L in km), the percentage of forest cleared (c), the mean annual rainfall (P in mm); the relationship for a given ARI was given in the form

$$PLR = k\ 10^{a_1 c}\ P^{a_2}\ L^{a_3} \qquad (2)$$

where k, a_1, a_2 and a_3 are constants, dependent on type of forest and soils. Most of the fitted regression equations were significant at 5.0% or a lower level for the catchments considered.

Dyer et al. (1994) compared the performance of the initial loss -proportional loss and initial loss continuing loss models on 24 catchments and found that the former gave a better fit between observed and calculated hydrographs using the RORB model.

Although proportional loss model closely simulates the source area concept, it has not been recommended in I.E. Aust. (1987), except for some regions of the Western Australia. This may be due to the lack of design information available for the PLR model as it had not been tested in rural catchments, prior to recent work. It appears that this model needs further investigation in other parts of Australia, especially in forested catchments where source area runoff generation is dominant.

In the PLR model, a constant proportional loss is usually applied. Another approach, in which a variable loss rate is used within a storm event is outlined in Section 3.4.2.

3.4 Antecedent Precipitation Index Method

As indicated in previous sections, storm losses are dependent on antecedent moisture conditions of the catchment. The antecedent precipitation index (API) is a well known measure of the initial wetness of a catchment. It is based on antecedent precipitation, adjusted for intervening evaporation losses by use of an empirical "decay" factor. Hence, in dry periods the factor is low; in wet periods the factor is high.

Different definitions of API are found in the literature (eg. NERC, 1975, Cordery, 1970b); some of these are due to differences in daily-rainfall reading times. NERC (1975) defined the API as

$$API_d = P_{d-1} + k\,P_{d-2} + k^2\,P_{d-3} + \ldots \qquad (3)$$

Cordery's(1970b) definition is

$$API_d = P_d + k\,P_{d-1} + k^2\,P_{d-2} + \ldots \qquad (4)$$

where k is an exponentially decay index and P_d is rainfall for day d. The value of k varies typically in the range 0.85 to 0.98 (Linsley et al., 1982). With lower k values the index is affected by shorter numbers of antecedent days; for most applications, 30 days is about the maximum.

NERC (1975) obtained antecedent wetness of a catchment using calculated soil moisture deficits. To account for soil moisture conditions above the field capacity of soil, which is common in the U.K. in some months, NERC (1975) proposed a short term API given by

$$API5_d = 0.5^{1/2}\,[P_{d-1} + 0.5\,P_{d-2} + (0.5^2)\,P_{d-3} + (0.5^3)\,P_{d-4} + (0.5^4)\,P_{d-5}] \qquad (5)$$

The short-term API is used in conjunction with soil moisture deficit estimated from rainfall and actual evaporation to calculate an antecedent wetness index given by

$$CWI = 125 + API5 - SMD \quad (6)$$

where SMD is soil moisture deficit.

The antecedent wetness index, CWI, can also be calculated at smaller time intervals than one day. The use of smaller time interval CWI in calculating variable loss rates during an storm event is given in Section 3.4.2.

3.4.1 Relationships between API and initial loss

As initial loss is dependent on antecedent catchment wetness, IL has been related to the API. Bureau of Meteorology (1963) obtained a linear relationship between the two values. Cordery (1970a) found that Equation. 7 is a better form of the relationship.

$$IL = IL_{max} (N)^{API} \quad (7)$$

where IL_{max} and N are parameters obtained from the data.

The decay coefficient, k in Equations. 3 and 4 is as an index of evaporation between storm events. Cordery (1970a) related k to monthly evaporation and temperature; he also introduced a seasonal variation to k in the form of a sine curve. All the seasonal relationships variation gave equally good relationships between API and IL; although these relationships appear to be promising, further investigations are needed to regionalize Cordery's findings.

3.4.2 Relationships between API and loss rates

As mentioned in the previous sections, infiltration rates are dependent on soil moisture conditions. During a storm event, the infiltration rate decreases with time due to decreases in capillary suction gradients. In the U.K. flood studies report (NERC, 1975), the variable loss rate was calculated with the following equation:

$$\text{Variable loss} = \frac{K}{CWI_t} \quad (8)$$

where CWI_t is short time interval antecedent wetness index and K is obtained from the water balance of the event as discussed below.

Equation. 8 is not a strict representation of physical processes, although it is considered that losses are distributed through the storm with some recognition of the changing state of the catchment (NERC, 1975).

The K value is estimated using total storm loss; NERC (1975) recommended the following equation to estimate the latter.

$$PR = 0.22(CWI-125) + 0.1\ (P-10) + SPR \qquad (9)$$

where PR - percentage of rainfall which becomes direct runoff
P - storm rainfall
SPR - standard percentage of runoff for the catchment

SPR is determined from an index of soil properties and the proportion of catchment urbanised.

Oddie et al. (1982) applied Equation. 8, with the unit hydrograph flood model, to obtain flood hydrographs for two catchments in Victoria, and found good agreement with observed and simulated flows. When total storm losses were estimated using Equation. 9, CWI failed to indicate sufficient variation with real changes in catchment wetness; this was attributed to the fact that the antecedent condition plays a more dominant role in Australian rainfall-runoff processes than in the U.K.

3.5 SCS Curve Number Method

The U.S. Soil Conservation Service (SCS) curve number procedure is widely used for estimating streamflow volumes for small to medium sized watersheds in the United States (U.S. Soil Conservation Service, 1985). It was originally developed to estimate runoff volume and peak discharge for design of soil conservation works and flood control projects, but later extended to estimate the complete hydrograph (Kumar and Jain, 1982).

The procedure, which is basically empirical, aims to provide a consistent basis for estimating the amount of runoff under varying land use and soil types (Figure 5). The primary input parameter is a runoff curve number (CN) defined in terms of soil type, antecedent moisture condition, land use treatment and hydrological condition of the catchment. The precision of the method for simulating the runoff volume is largely determined by the selection of the appropriate curve number, and accurate estimation of watershed antecedent moisture conditions.

The CN value is determined from the watershed characteristics, using tables contained in U.S. Soil Conservation Service (1985) or other texts. From this, the depth of runoff from a given rainfall is determined from Figure 5.

The CN method has been extended to calculate rates of runoff. For this, the peak discharge is estimated using a triangular approximation to the hydrograph, corresponding to a uniform rainfall excess (U.S. Soil Conservation Service, 1985). For a complex storm, rainfall excess over different time intervals may be computed separately and the resultant triangular hydrographs superimposed to obtain the peak discharge.

The SCS curve number procedure has been adapted for application to a wide range of watersheds, such as urban and semi-arid areas. (U.S. Soil Conservation Service, 1986). It has also been incorporated in a number of computer programs, such as TR-20 (U.S. Soil Conservation Service, 1975) and TR-55 (U.S. Soil Conservation Service, 1986), to estimate runoff hydrographs for rural and urban catchments.

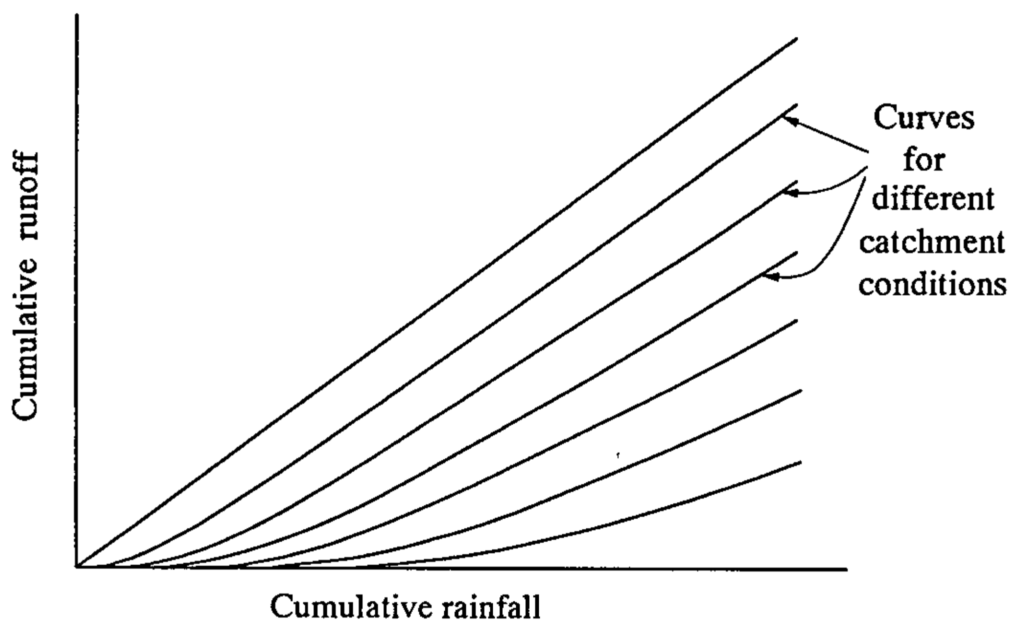

Figure 5 SCS curve relation

3.5.1 Applications of the SCS Curve Number Method

Hjelmfelt (1980, 1991) used the SCS curve number runoff equation to transform a rainfall frequency distribution to a runoff frequency distribution. The SCS runoff equation performed reasonably well for this application, for which "average catchment conditions" are appropriate. By plotting 5-day precipitation total against derived maximum potential retention, S, for various watersheds, he showed that antecedent precipitation only explains a portion of curve number variability. This highlights the importance of other watershed and storm characteristics, especially for dry conditions. The values of S determined from annual maximum events were fitted with a log normal distribution for a number of watersheds, and a reasonably good agreement between 10%, 50% and 90% probabilities against SCS tabulated values for antecedent moisture conditions (AMC) I, II and III established.

White (1988) worked with a regular-gridded network to account for areal variability, and computed the spatial variation of runoff depth. Although lower-magnitude events were predicted within a 'reasonable' range of actual storm runoff, larger storm events were highly under-estimated, even with an assumed wet antecedent conditions (AMC-III). The research also highlights the consistent under-prediction of runoff volumes in humid areas using the typically assumed median (AMC-II) curve number.

Titmarsh et al. (1989) carried out extensive testing of the SCS method, using data from 140 catchments in two regions of Eastern Australia; the procedure used was analogous to the probabilistic rational method. Peak discharges were calculated for design rainfalls by the formula based on a triangular hydrograph with dimensions as given in the US procedure. Probabilistic CN values were then derived, so as to make peak discharges estimated from the design rainfalls equal to the peak discharges determined from the frequency analysis of observed floods. Maps of the values of CN(10) were prepared for the area of study, intended for use for estimating design floods.

Titmarsh et al. (1989) also found that the probabilistic CN values were fairly weakly related to catchment characteristics, such as percentage of area of the catchment cultivated, but with a much smaller range of values than indicated by the US SCS recommendations. The relationship between CN values estimated from catchment characteristics by the US procedure, and the probabilistic values derived from Australian data, was found to be very poor.

From the above review, it is evident that the SCS curve method has not performed well in Australia; hence further investigation of this method is considered to have a low chance of success.

3.6 Adjustments for Spatial Variability

Although the loss models described in this chapter are based on the lumped response of the catchment, there have been a few attempts to include the effect of spatial variation in losses in indirect ways. Crawford and Linsley (1966), in the Stanford Watershed Model, assumed a linear cumulative distribution of potential infiltration in a time step as a function of area as shown in Figure 6. This provided for runoff from a changing proportion of the catchment at each calculation time step. Clark (1980) assumed the more general nonlinear distribution, also shown in Figure 6, but his work has yet to be adopted in practice.

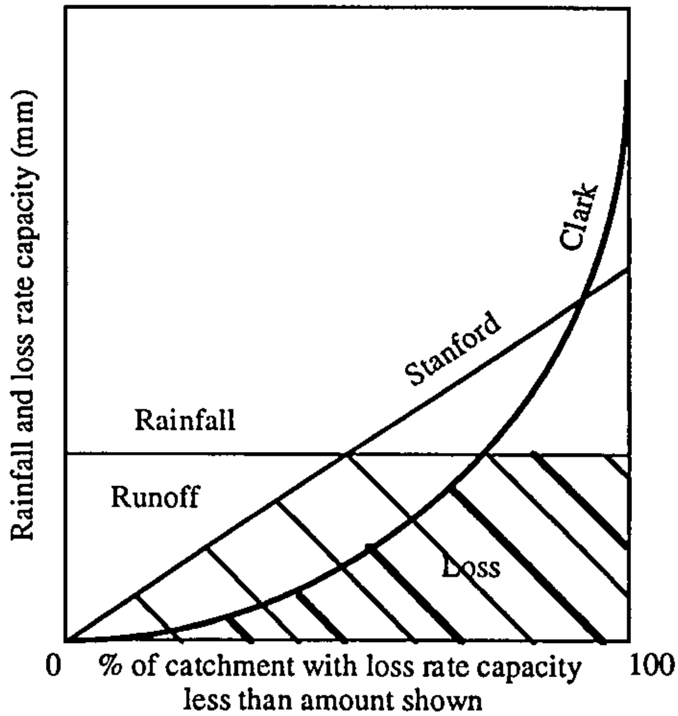

Figure 6 Relationships for areal variability of loss rate

Moore (1985) considered two approaches to take into account the spatial variability in runoff generation using probability concepts. In the first, a probability-distributed storage capacity was used. In the second, a probability-distributed infiltration capacity, similar to Crawford and Linsley's (1966) method was adopted. Although this study showed the way of adopting probability concepts in simple representation of runoff generation, further research is needed for its incorporation in more complicated hydrological processes.

Although the above methods go some distance toward allowing for spatial variability, the model parameters do not have any predictable relationships with catchment characteristics. The use of such models to improve storm-loss predictions on Australian catchments is yet to be demonstrated.

4. METHODS BASED ON POINT INFILTRATION EQUATIONS

A number of equations have been developed for the process of water entry into soil from surface at a point (eg. Singh, 1989). Some of them are based on fitting empirical equations to infiltration data; others are analytical/numerical solutions to the complex equations for the water movement in soil (eg. Richards equation), with various simplifying assumptions. The aim of this section is to review some of the better known infiltration equations with respect to their suitability for loss-modelling.

In the following sections, an empirical infiltration equation (Horton), two theoretical equations (Philip and Green-Ampt), and numerical solutions of the Richards equation are described.

4.1 Horton Equation

Horton (1940) observed that infiltration capacity decreased with time until it reached a constant value, and described this process by the exponential equation

$$f_p = f_c + (f_0 - f_c)\, e^{-kt} \qquad (10)$$

where f_p - infiltration capacity (mm/h)

f_0 - initial infiltration capacity (mm/h)

f_c - final infiltration capacity (mm/h)

t - time (h)

k - exponential decay constant

Equation. 10 is applicable as it only stands to shallow ponded conditions, i.e. to infiltration at potential rate. However, Bauer (1974) has modified it to account for infiltration during intermittent rainfall; he obtained a starting time for simulation in terms of moisture stored in the soil assuming a drainage rate (d) in the following form.

$$d = f_c - f_c\, e^{-kt} \qquad (11)$$

The equation for the starting time of simulation is given by

$$t_s = \frac{1}{k} \ln\left(\frac{1}{1 - S_t k / f_0}\right) \qquad (12)$$

where S_t is soil moisture storage

This equation allows for recovery of infiltration capacity during intermittent rainfall and accommodates initial soil moisture conditions.

Akan (1992) expressed infiltration capacity in terms of the depth of water that has infiltrated in excess of final infiltration capacity. The modified equation is given by

$$f_p = f_0 - kF_e \qquad (13)$$

where F_e is the depth of water which has entered the soil at rates in excess of f_c. As the calculated infiltration rate is related to the moisture which has entered into soil, it can be used with rainfall intensity less than the infiltration capacity.

Akan's (1992) modification is similar to Bauer's (1974) approach, if the drainage in Equation. 12 is assumed to be equal to f_c ie. water entered into soil in excess of f_c is equal to moisture in the soil.

In Australia, Walsh and Pilgrim (1993) used the Horton model with f_c = 2.5 mm/h, k=0.2 and f_0 as a fitting parameter to obtain rainfall-excess and hence design floods; they reported results comparable with those from IL-CL model.

A number of hydrologic models use the Horton equation in their infiltration routines [eg. SWMM (Hubber et al., 1982), ILSAX (O'Loughlin, 1988), ILLUDAS (Terstriep and Stall, 1974)] due to its simplicity. The model parameters are generally obtained by calibration or from tables which relate the parameters to soil types. For example, in the ILSAX model, the model parameters are obtained from soil type using Table 1; for f_0, reduced values (Table 2) are used according to the initial moisture conditions.

Table 1 Infiltration model parameters used in ILSAX (after O'Loughlin, 1988)

Parameters	Soil type*			
	A	B	C	D
f_0 (mm/h)	250	200	125	75
f_c (mm/h)	25	13	6	3
k	2	2	2	2

* classifications given by U.S. Soil Conservation Service (1985)

Table 2 Initial infiltration rates (mm/h) with given antecedent moisture conditions (AMC)

AMC*	Soil type			
	A	B	C	D
1	250.0 (0)	200.0 (0)	125.0 (0)	75.0 (0)
2	162.3 (50)	130.1 (38)	78.0 (25)	40.9 (18)
3	83.6 (100)	66.3 (75)	33.7 (50)	7.4 (38)
4	33.1 (150)	30.7 (100)	6.6 (75)	3.0 (50)

* antecedent moisture condition is determined from 5-day rainfall in mm, given in parenthesis for each soil type.

4.2 Green-Ampt Model

Green and Ampt (1911) applied Darcy's Law assuming ponded conditions, a constant matric potential at the wetting front, and uniform moisture content and conductivity to obtain an infiltration equation given by

$$f_p = K_s \left(1 + \frac{M \psi}{F} \right) \qquad (14)$$

where f_p - infiltration capacity (mm/h)

K_s - saturated hydraulic conductivity (mm/h)

M - initial soil moisture deficit (vol/vol)

ψ - capillary suction at wetting front (mm of water)

F - cumulative infiltrated volume from beginning of event (mm)

Mein and Larson (1971) showed that the Green-Ampt (G-A) model could be adapted for a constant intensity rainfall at the surface (rather than ponded conditions); their two-stage model is given by

$$f=I, \ \text{for } F \leq F_s, I > K_s, F_s = \frac{\psi_{av} M}{(I/K_s)-1} \qquad \text{(ie. pre-ponding)} \qquad (15)$$

$$f = f_p = K_s \left(1 + \frac{M \psi_{av}}{F} \right) \text{ for } F \geq F_s, I > f_p \qquad \text{(ie. post-ponding)}$$

where I - rainfall intensity (mm/h)

f - infiltration rate (mm/h)

F_s - Volume of infiltration at the moment of surface saturation (mm)

ψ_{av} - average suction at wetting front (mm water)

Chu (1978) extended the application to an unsteady rain condition by shifting the time scale to account for the effect of cumulative infiltration before ponding time. Mein (1980) also showed that the G-A model with this modification can be successfully used with variable rainfall.

4.2.1 Parameter evaluation

The G-A model as given by Equation. 15 has three parameters: ψ_{av} , M and K_s. Several studies have dealt with the estimation of these parameters (eg. Mein, 1980, Moore et al., 1981, Rawls et al., 1983); this sub-section briefly reviews some of them.

Saturated hydraulic conductivity

Because K_S is a multiplier to other terms in the G-A equation (Equation. 14), its prediction accuracy is most sensitive to the value of this parameter. K_S can be estimated from soil type as relationships between K_S and soil texture which have been established for U.S. soils (Table 3).

Moore et al. (1981) showed that K_S should be modified for the effect of air entrapment in the field and surface conditions. In their review, they quoted that K_S could in the order 0.4 to 0.6 of measured saturated hydraulic conductivity due to the air effects. Further, they presented an equation for K_S to take into account the effects of surface seal formation.

Table 3 Green-Ampt infiltration parameters (after Rawls et al., 1993)

Soil texture class	Porosity	Wetting front soil suction head ψ (cm)	Saturated hydraulic conductivity K_S (cm/h)
Sand	0.437 (0.374-0.5000)	4.95 (0.97-25.36)	23.56
Loamy sand	0.437 (0.363-0.506)	6.13 (1.35-27.94)	5.98
Sandy loam	0.453 (0.351-0.555)	11.01 (2.67-45.47)	2.18
Loam	0.463 (0.375-0.551)	8.889 (1.33-59.58)	1.32
Silt loam	0.501 (0.420-0.582)	16.68 (2.92-95.39)	0.68
Sandy clay loam	0.398 (0.332-0.464)	21.85 (4.42-108.0)	0.30
Clay loam	0.464 (0.409-0.519)	20.88 (4.79-91.10)	0.20
Silty clay loam	0.471 (0.418-0.524)	27.30 (5.67-131.50)	0.20
Sandy clay	0.430 (0.370-0.490)	23.90 (4.08-140.2)	0.12
Silty clay	0.479 (0.425-0.533)	29.22 (6.13-139.4)	0.10
Clay	0.475 (0.427-0.523)	31.63 (6.39-156.5)	0.06

Initial moisture deficit

The moisture deficiency is the difference between the wettable soil porosity and the moisture content, both expressed as fractions of the total soil volume. The wettable soil porosity could be 0.8 to 0.9 of available porosity due to the air entrapment in the soil. Total porosity values for a range of soil textures are given Table 3.

Suction at wetting front

Mein and Larson (1971) defined the value of ψ_{av} as

$$\psi_{av} = \int_{0}^{1} \psi(k)dk \qquad (16)$$

where k is the relative hydraulic conductivity and $\psi(k)$ is the matric suction as function of k.

From Table 3, it is evident that the values of ψ_{av} fall within a range of 40 to 400 mm for most of the soil textures. However, it has been found that calculated infiltration rates are not particularly sensitive to the ψ_{av} values used (Mein, 1980).

4.2.2 Applications of G-A equations at catchment scale

Van Mullem (1991) applied the G-A model and SCS curve method to 12 catchments (area varied from 1.8 to 139 km^2). The model parameters were obtained from empirical equations related to the soil texture. A 15 bar tension level was assumed to represent the initial soil moisture conditions. It was reported that the G-A model performed better in predicting runoff volume than did the SCS curve method. However, the G-A model did not predict peak flows well; this was attributed to the errors in peak flow measurements. The G-A model underpredicted runoff volume in shallow soil catchments because soil profile filling is not taken into account in the G-A equation; the latter demonstrates the problem in modelling a shallow soil system with a one dimensional infiltration equation.

Aston and Dunin (1979) applied the Green-Ampt model coupled with a surface runoff model under unsteady rainfall conditions and obtained excellent agreement between observed and simulated runoff volumes from a 5 ha catchment. For this simulation, they used saturated hydraulic conductivity values measured at the catchment and ψ_{av} estimated from sorptivity measurements.

Chu (1978) used the Green-Ampt equation for unsteady rainfall and obtained good agreement between predicted rainfall excess and observed runoff from a 46 ha catchment. James et al. (1992) applied the G-A equation and SCS curve method using 23 storms in seven catchments. He reported that the G-A equation performed better in predicting rainfall excess when the rainfall was greater than 25 mm.

4.2.3 Accounting for spatial variability

Rajendran and Mein (1986) accounted for spatial variability of infiltration rates in a catchment by using a scaling factor applied to saturated hydraulic conductivity. The scaling factor was log normally distributed with mean of one and standard deviation σ. The distribution was used to determine the area of catchment represented by soil of a given K_s; runoff tended to occur from the low K_s subareas (source areas). In 11 catchments with area ranging from 0.12 to 259 km^2, the value of σ obtained from optimization varied from 0 to 20. Except for summer events, runoff volumes were well predicted. Although this approach takes into account the spatial variability of infiltration, it does not consider the effect of rainfall excess from one subarea flowing to, and infiltrating on another. On this point, Smith and Hebbert (1979) showed that relative positions of ponding regions are important in determining the catchment infiltration loss.

4.3 Philip Equation

For a homogeneous soil with a uniform initial moisture content and ponded conditions at the surface, Philip (1957) obtained a series solution to the Richard equation (see Section 4.4). For most conditions, two terms are a sufficient approximation, resulting in

$$F = St^{1/2} + At \qquad (17)$$

where parameters S and A are functions of both soil water diffusivity the initial water content, and ponded depth and t is time. Parameter S is termed sorptivity.

The Philip equation has been incorporated in a number of rainfall-runoff models ie. ARBM (Chapman, 1968), Monash Model (Porter and McMahon, 1971). Goyen used the ARBM model to derive the antecedent soil moisture distribution to estimate design floods using a joint probability approach.

4.3.1 Parameter estimation

Parameter values of the Philip equation have been related to soil texture as they have physical meaning. Several conflicting interpretations of the parameter A have been reported, ranging from 1/3 K_s to K_s (Singh, 1989).

Parameters S and A can be estimated from the following equations using the soil properties given in Table 3 (Rawls and Brakensiek, 1989).

$$S = [2(\psi_0 + \psi)(v-\theta)(K_s)]^{1/2} \quad (18)$$

$A = K_s$

where v - porosity

θ - initial water content (v/v)

ψ_0 - depth of ponded water (cm)

ψ - wetting front suction (cm)

4.3.2 Spatial variability

Spatial variability in infiltration has been demonstrated in a number of studies using the Philip infiltration equation. Sharma and Seely (1979) used Monte-Carlo simulation method to evaluate the effect of spatial variability of parameters S and A; the distribution of both parameters was assumed to be log-normal. The simulations showed that rainfall excess increased with increasing variability of the parameters S and A; the effect of the latter was quantitatively much smaller. Thus they concluded that an average infiltration curve based on average parameters would underpredict rainfall excess.

Maller and Sharma (1980) studied the effect of spatial variability of the parameters S and A on ponding time using analytical methods. For log-normally distributed parameters, the predicted ponding time was also found to have the same distribution. As the log-normal distribution is highly skewed and long tailed there is high probability that ponding of some areas of the catchment will occur quite late. This will affect the catchment rainfall excess dependent on location of such areas (Smith and Hebbert, 1979).

Sharma et al. (1980) showed that similar media concept can be used to model spatial variability in the infiltration. The assumption that the scaling factors are log-normally distributed was validated using infiltrometer tests at 26 sites in a 9.6 ha catchment.

4.4 Richards Equation

Richards equation is a physically based mathematical model of flow in porous media, derived by combining Darcy's law and the continuity equation. The one-dimensional form of the Richards equation for derivation of vertical unsaturated soil moisture flow is given by

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k(\Psi)\left(\frac{\partial \Psi}{\partial z} - 1\right)\right] \tag{19}$$

where θ - volumetric water content

t - time

z - space coordinate in vertical direction

k - hydraulic conductivity of soil

ψ - total matric potential

The Richards equation provides a commonly accepted basis for detailed studies of soil water movement, but computational complexity to solve the equation, and the difficulties of obtaining the required soil hydraulic properties, have limited the extent of wider applications. Simulating field conditions for infiltration is highly complicated, since the initial and boundary conditions are not constant and soil characteristics vary with time and space.

In recent years, more practical methods of obtaining soil hydraulic properties have been developed (eg. Kool et al., 1985), and computational limitations are decreasing due to enhanced computer capabilities; hence, the numerical solution of Richards equation is becoming more attractive. A further development is of more efficient finite difference solutions for Richards equation (eg. Campbell, 1985; Ross, 1990a).

4.4.1 Models adopting the Richards equation

Numerical solutions to Richards equation have been incorporated into several physically based computer packages which simulate individual hydrological processes, the purpose being to model the unsaturated vertical soil moisture flow under various field conditions.

The SHE (Systems Hydrològique Europeen) model is an advanced physically-based, distributed, catchment modelling system in which unsaturated soil moisture flow from ground water to phreatic surface is modelled by one-dimensional Richards equation (Abbott et al., 1986). The expanded equation solved includes a source/sink term as follows.

$$C\frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial \Psi}{\partial z}\right) + \frac{\partial K}{\partial z} - S(z) \tag{20}$$

where	$\psi(\theta,z)$	- Soil matric potential
	t	- time
	z	- vertical space coordinate
	C	- $\partial\theta/\partial\psi$ = soil water capacity
	θ	- volumetric water content
	$K(\theta,z)$	- hydraulic conductivity
	S(z)	- Source / Sink term for root extraction and soil evaporation

Functional relationships for $K(\theta,z)$ and $\psi(\theta,z)$ are required to solve the equation. The equation itself is numerically solved by a finite difference technique with an iterative implicit scheme. The time step is determined in proportion to the rainfall/irrigation intensity and as a function of the soil dryness. In general, time steps range from 1 hour during periods with no rainfall or irrigation, to 2-3 minutes under changing wetting or drying conditions; at each time step the solution is checked for a proper mass balance and, if this is not satisfactory, the solution is repeated with smaller time steps. The distance steps in the vertical are chosen according to the required resolution and usually in the range of 5-50 cm.

TOPOG is another hydrological model developed by CSIRO Division of Water Resources (CSIRO, 1992). The soil moisture distribution in TOPOG is modelled by a 'mixed' form of the Richards equation, numerically solved using Crank-Nicolson scheme through the Kirchhoff transformation. The Newton-Raphson method is adopted to achieve the convergence of the solution and the Broadbridge and White (1987, 1988) soil hydraulic model adopted to improve numeric stability. TOPOG model can handle layered soils, ponded conditions and can incorporate evaporation/transpiration processes with various boundary conditions.

The computer package SWIM provides a numerical solution of the Richards equation for cases involving infiltration, redistribution and evapotranspiration of soil water (Ross, 1990b). It can handle layered or uniform soils, unsaturated, saturated and ponded conditions, and different vegetation types. Simplifications are that soils are non-swelling, hysteresis and vapour flow are ignored, and that soil properties can be expressed by power-type equations.

4.5 Discussion

Richards equation

Models described in this chapter along with some form of interception and depression loss models would better predict the temporal distribution in storm losses than those given in Chapter 3. Although numerical solutions to the Richards equation are quite accurate in predicting infiltration losses, this approach is not really suitable for design applications because

(i) the input data (such as the soil moisture characteristic) are not commonly available and (ii) the solution methods are computationally demanding.

Horton, Green-Ampt and Philip equations

Although the Horton equation is empirical, its parameters have been indirectly related to soil characteristics (Section 4.1). The parameters of the Philip and the Green-Ampt equations have physical meaning, so that relationships between them and soil textures have been established (eg. Rawls and Brakensiek, 1989). In addition, the Philip and Green-Ampt equations have successfully modelled the storm losses at catchment scale (Van Mullem, 1991, James et al., 1992). Their use could be an option for improved loss modelling given that spatial variability of model parameters can be taken into account.

Spatial variability

The equations described in previous sections are based on point infiltration; they may fail to simulate actual catchment loss because of spatial variability of both the parameters and runoff generation mechanisms. Storm runoff can be considered as generated by three distinct mechanisms (Beven, 1986). The first is the infiltration excess storm flow or Hortonian flow which can be predicted using the models described in this chapter. The second is saturation overland flow which is the surface runoff on saturated areas caused by subsurface flows due to the topographic heterogeneity (eg. O'Loughlin, 1986, Beven, 1986). The third is subsurface storm flow.

A limited number of studies have taken into account the spatial variability in runoff generation. Beven (1986) considered all three mechanisms in deriving flood frequencies using a model based on terrain analysis. Mein and O'Loughlin (1991) used a steady state wetness index model (TOPOG) to identify the fraction of saturated area in a catchment which is related to base flow. From these studies, it is evident that any realistic loss modelling approach should account for saturation overland flow.

Although a number of models [eg. TOPOG (CSIRO, 1992), TOPMODEL (Beven, 1986)] capable of predicting saturated regions are available, they have not been utilised to date to improve design loss predictions. These models could be used to understand and identify the important loss mechanisms which can be incorporated in design loss estimation procedures.

Another approach is to consider spatial variability in the infiltration parameters themselves, which can be accounted for using: (i) scaling factors (eg. Rajendran and Mein, 1986) and (ii) Monte-Carlo simulation (eg. Smith and Hebbert, 1979, Sharma and Seely, 1979). Further investigation of both of these methods is needed to improve design loss estimation.

5. LOSS ESTIMATION FOR REAL-TIME FLOOD FORECASTING

The loss models used for real-time forecasting are discussed in the review report for another CRC Project in the Flood Hydrology Program (Srikanthan et al., 1994). Here only a brief review is provided, for completeness. The major aim is to examine the suitability and adaptability of loss models currently used in practice, and how these models estimate and account for the temporal and areal variation of losses over the catchment in real time.

In this chapter, an overview of real-time flood forecasting is given in Section 5.1. In Section 5.2, the applications of some of the loss models (described in Chapters 3 and 4) for real-time forecasting are reviewed.

5.1. Overview of Real-Time Flood Forecasting

The steps followed in real-time forecasting are similar to those used in the design storm method of flood estimation. In design applications, *design* hyetographs and *design* loss rates are used. However, in real-time forecasting, the *actual* (or forecasted) rainfall hyetograph over the catchment is combined with a model of losses to determine the rainfall excess for input to a runoff-routing model (eg. unit graph, runoff routing, kinematic wave). The estimation of hydrographs in real-time may include a feedback component for the correction of forecasts according to the discrepancies observed in earlier forecasts.

If the forecast lead time is shorter than the hydrologic response time of the catchment, the flood forecast should be based on observed rainfall data transmitted to the forecast centre, and adaptive rainfall-runoff models, which are capable of tracking parameter variation in real time, would be most appropriate for formulating the forecast. Rainfall-runoff adaptive models include unit hydrograph based linear models (Chander and Shanker, 1984, Corradini et al., 1987), non-linear runoff routing models such as RORB (Knee and Falkland, 1989, Crapper, 1989, Avery, 1989), transfer function-noise models (Goring, 1986) and conceptual models (Kitanidis and Bras, 1980; Tucci and Clarke, 1980). Conceptual models make use of explicit soil moisture accounting through allocation of water into various stores; however their use is limited in practice due to complexity and computational effort, along with the problem of estimating values for the large number of parameters involved.

Updating in real time

In simple models, the correction of forecasts is based on errors in earlier forecasts, and achieved interactively by adjusting either input or model parameters. In the latter case, it may be the loss parameters which are adjusted. The U. S. National Weather Service (NWS) and HEC1F models adopt a simple 'blending' procedure in which error between observed and calculated hydrographs is linearly distributed over the next forecasting time steps (Hudlow, 1988; Peters and Ely, 1985). Blending techniques do not correct the underlying cause of discrepancy, but they are objective and easy to implement. More simple techniques, such as adjustment of volumetric runoff coefficient (Simpson et al., 1980) and adjustment of mean areal precipitation (Peck et al., 1980) have also been proposed as updating techniques for hydrological forecasts.

Some models adopt techniques to optimise model parameters in successive forecasting time steps. Recursive techniques, such as application of the Kalman filter to non-linear conceptual catchment models for parameter estimation and model forecast updating, have gained prominence in recent times.

5.2. Loss Models Adopted in Real-Time Flood Forecasting

The most commonly adopted loss models in real-time flood forecasting are the continuing or proportional loss rate models combined with initial loss, constant loss rate (ϕ-index method), antecedent precipitation index methods or point infiltration models. Applications of these models are reviewed below.

5.2.1. Initial loss and continuing/proportional loss models

Spatially lumped loss models for initial loss, combined either with continuing loss or proportional loss rate, have achieved wide adoption in real-time flood forecasting, mainly due to the simplicity and ease of application. Surface runoff catchment models, such as HEC1F (Peters and Ely, 1985), RORB (Crapper, 1989, Knee and Falkland, 1989, Avery, 1989) and RAFTS (Peddie and Ball, 1993, Knee and Falkland, 1989) which incorporate the above loss models, are used by a number of agencies to forecast runoff hydrographs in real time.

HEC1F

The HEC1F computer model employs a unit hydrograph procedure and hydrologic routing to simulate runoff from a sub-divided basin; it is used to make short-to-medium term runoff forecasts (Peters and Ely, 1985). In applications, the initial and continuing loss parameters are optimised together with other model parameters, using the observed flood hydrographs at headwater sub-basins or index areas. These parameters are then adopted for computation of flood hydrographs for the whole catchment downstream. Routed and combined hydrographs at each gauged location are 'blended' with observed hydrographs prior to subsequent routing and forecasting. The capability is also provided in HEC1F to reinstate the initial loss after a period of no precipitation with a simple moisture deficit calculation.

RORB

The RORB computer program has several applications in Australia in real-time flood forecasting (Crapper, 1989; Knee and Falkland, 1989; Avery 1989). Being a spatially distributed model, it has a potential advantage over procedures using a lumped unitgraph. In applications, calibrated model parameters for the basin are adopted, and forecast updating is basically carried out through adjustments to the loss model parameters. Historical storm events can be used to correlate calibrated loss parameters with antecedent conditions for use at the beginning of a storm event. In application of the RORB program for real-time flood forecasting, the antecedent precipitation index is used to estimate the initial loss parameter; Crapper (1989) has developed a second order predictor equation for initial loss as a function of seven day antecedent mean daily flow for Jackson Creek at Gisborn. As the storm progresses the discrepancy between calculated and observed hydrographs at each gauging station is corrected by making adjustments either to continuing loss rate or proportional loss rate. Avery (1989) observed broad scatter in continuing loss rates as the storm proceeds. A constant base flow is usually assumed throughout the storm period.

RAFTS

The RAFTS computer model, which has a similar model structure as RORB, has also found use in real-time flood forecasting in Australia (Knee and Falkland, 1989). In applications, the initial and continuing loss model has been used due to it's simplicity, although RAFTS has the facility to use the more complex Philip's infiltration equation. Knee and Falkland (1989) compared the performance and suitability of the RORB and RAFTS computer models for real-time flood forecasting and recommended the latter, due to availability of extra options and flexibility of the model, although both models produced similar results.

5.2.2 Constant loss rate

The simplest infiltration model is the ϕ-index, which is the average rainfall loss rate needed to make the mass of rainfall equals the volume of rainfall-excess equal to the volume of surface runoff. Chander and Shanker (1984) adopted a simple unitgraph procedure for real-time flood forecasting with on-line estimation of the constant loss rate and rainfall excess. The first estimate of constant loss rate is calculated to match the computed flow at the end of the first time step with the observed flow. In each subsequent step, the constant loss rate is updated to match calculated and observed hydrographs; the current best estimate of constant loss rate at any time step is used in determining rainfall excess for forecasting for the next step.

Corradini et al. (1986) developed a semi-distributed adaptive model for real-time flood forecasting, based on Clark's (1945) procedure, using calibrated parameters for the catchment. In his application, the basin was divided into isochrones of travel time; rainfall and losses are represented by preserving their variations from one zone to another. The distribution of losses in space is assumed to be proportional to rainfall-rate, and their evolution in time is represented by the constant loss rate.

As the constant loss rate method does not allow initial loss or depression storage during rainless periods, matching the initial rise of the observed hydrograph can be difficult.

5.2.3 Antecedent precipitation index methods

The API method was commonly used in the USA for flood forecasting, with a co-axial graphical correlation method with parameters such as API, time of the year, and storm duration (Linsley et al., 1982); a considerable amount of data is required for the preparation of the empirical graphical relations. Even today, the U.S. Weather Bureau's NWSRFS flood forecasting model still retains the API type relationship as an alternative loss model.

In Australia, the Bureau of Meteorology also used the API concept, in which a correlated relationship of initial loss against an antecedent precipitation index is used in flood forecasting procedures (Bureau of Meteorology, 1963). The loss models incorporated in the Melbourne's flood warning system include fitted regression relationship between API and mean catchment loss rate for various rainfall durations (Giesemann, 1986). In applications, the above loss models are applied to routing models such as unit hydrograph, or non-linear runoff-routing models (eg. RORB) to formulate the forecasted hydrograph. Other approaches such as "Soil Moisture Index" (SMI) adopted in the SSARR model (US Army Corps of Engineers, 1975) are also used in practice.

5.2.4 Point infiltration equations

Kitanidis and Bras (1980) used the NWSRFS model, which incorporates the Sacramento model for continuous soil moisture accounting to illustrate the application of the Kalman filter technique to parameter optimisation and forecast updating within a stochastic process framework. The infiltration process is modelled by a Horton-type percolation function, which depends on relative water storages in the upper and lower soil zones. The NWSRFS model uses a simple flow adjustment and a 'blending' procedure for forecast updating.

Corradini and Melone (1986) adopted the Clark routing procedure. Their effective rainfall was based on a time varying point rainfall infiltration model, representing pre-ponding and post ponding stages through the model parameters of rainfall intensity, saturated hydraulic conductivity, K_S, and sorptivity parameter, S. For infiltration rates less than soil infiltration capacity, a temporal redistribution of rainfall was used. Variability of infiltration in space was incorporated through spatial variability in the rainfall pattern and using spatially "equivalent" values of K_S and S. On-line correction of flow forecast was then carried out by updating the S parameter and a runoff scaling factor.

A number of more simpler soil moisture accounting conceptual models, with smaller numbers of model parameters, have been proposed (Marivoet and Vandewiele , 1980; Tucci and Clarke, 1980). In these models, infiltration is modelled according to the Horton equation. Forecast updating, using an auto-regressive moving average process (ARMA model) is a fairly common technique with this type of model.

5.2.5 Discussion

Loss models adopted for real-time flood forecasting have usually been simple lumped models, such as initial loss combined with continuing or proportional loss rates, ϕ-index, runoff coefficient, and API-relationships. In most cases, temporal variation in losses has not been considered, but included in a defacto way through parameter updating to match the observed hydrograph. The more "advanced" conceptual models, which have gained prominence in recent times in flood forecasting, include loss models which are capable of modelling temporal variation. However difficulties in parameter optimisation and in updating have continued to limit their use.

5.3 Coupled Rainfall-Runoff and Runoff-Routing Models

Mein and O'Loughlin (1991) and Boughton and Carrol (1993) have proposed that coupled rainfall-runoff and runoff-routing models can be used to estimate rainfall-excess and flow hydrograph in real time.

5.3.1 TOPOG/RORB

Mein and O'Loughlin (1991) suggests a novel approach to account for the spatial and temporal variability of losses in real-time flood forecasting, in which the TOPOG model is used to predict the size and location of the runoff producing areas of the catchment, with increasing rainfall, as a function of pre-storm baseflow.

TOPOG is a distributed parameter hydrologic modelling framework and composed of a kernel and several application modules; the first contains a suite of terrain analysis routines which generates element network of the catchment and the second was designed for water balance modelling in the element network under steady-state and transient assumptions (CSIRO, 1992).

In the steady-state model, soil moisture is redistributed by saturated subsurface flow under topographic gradients. The wetness of a catchment is indicated by a wetness index. The steady-state wetness index (O'Loughlin, 1986) is given by

$$W_S = \frac{1}{MbT} \int q\,dA \qquad (21)$$

where M is the slope of the element, b is the length of contour at the base of the element, T is the local transmissivity, A is the upslope catchment area and q is the net subsurface drainage flux.

A value of W_S of unity indicates complete saturation of the soil profile. Mein and O'Loughlin (1991) related baseflow with saturated area estimated using the TOPOG model and uses this information in the RORB model as percentage runoff coefficients for corresponding sub-areas to produce the predicted runoff hydrograph. Mag and Mein (1994) demonstrate how the TOPOG output can be input into the RORB model. This approach has yet to be tested with real-time applications, however.

5.3.2 AWBM/URBS

Boughton and Carroll (1993) have combined the AWBM water balance model (Boughton, 1993) with the URBS runoff routing model (Carroll, 1992). AWBM is a partial-area saturation overland flow model, which allows modelling in hourly/daily steps for spatially and temporally variable source areas of surface runoff. The partial area concept is modelled by adopting different soil storage capacities over a catchment area, with computation based on a conceptual soil moisture accounting procedure.

As shown in Figure 7, this model uses three capacities which allow for different source areas of surface runoff. Surface runoff occurs when one or more of the stores is over-filled and overflow occurs. A fixed proportion of the surface runoff is diverted recharge of baseflow storage; baseflow discharge at time step t is proportional to that at time step t-1.

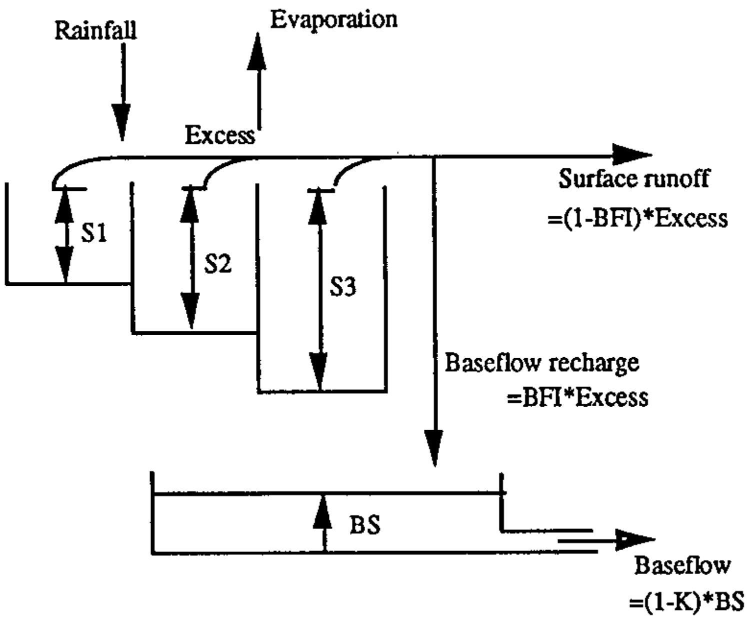

Figure 7 Schematic diagram of AWBM model (after Boughton, 1993)

The rainfall excess from partial areas of the catchment calculated from the calibrated AWBM model is routed by the URBS model to calculate the forecasted flood hydrograph.

5.3.3 Discussion

The coupled rainfall-runoff and runoff-routing model approach overcomes the problem of estimating antecedent conditions for actual storms, and seems to hold considerable promise in the real-time flood estimation area. It is a field where further research and development could show a worthwhile return.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter presents a number of research areas on loss modelling, identified from the review given in the previous chapters. These are divided into three groups: (i) empirical analysis of data, (ii) identifying the parameters which are important for loss modelling (ie. improve our understanding) and (iii) development and/or testing of alternative loss models.

6.1 Empirical Analysis of Data

Virtually all of the recommended loss models in I.E. Aust. (1987) are based on empirical analyses of data. Since the CRC has, through its partners, access to extensive data holdings, the following research activities have the potential for improved parameter estimates.

(1) *Derivation of loss model parameters for different average recurrence intervals (ARI), involving the analysis of concurrent records of rainfall and runoff for a number of catchments (see Section 2.2.1). The research envisaged would include an investigation of the validity of using median values for design losses (as opposed to other measures of central tendency).*

(2) *Relating initial loss to an antecedent wetness index, dependent on both antecedent rainfall and evaporation. Relationships, such as those proposed by Cordery (1970a and b) for an antecedent precipitation index, can be re-examined with a much more extensive data set (Section 3.4). The relationship between loss parameters and the level of base flow at the start of the event (as a surrogate for catchment wetness) is worth further study.*

6.2 Identifying Parameters Important for Loss Modelling

The research tasks recommended below are aimed at developing a better understanding of the areal and temporal variability of losses; this is important for both estimation of design floods and real-time flood forecasting.

(3) *Further examination of the relationships between loss parameters of existing loss models and catchment characteristics such as vegetation, topography and soils (Section 3.2.1).*

(4) *Identification of saturated regions, and use of contributing area concepts, to calculate losses (Sections 4.5 and 5.3). Saturation regions could be identified by topographical analysis using the TOPOG model, or with information from remote sensing and GIS.*

6.3 Development and/or Testing of Alternative Loss Models

Here, the purpose is to apply and test procedures not commonly used in conventional loss estimation. The methods include frequency analysis, application of a point loss model at various catchment scales, and use of continuous models for both data generation and real-time estimates.

(5) *Frequency analysis of volumetric runoff coefficients derived from rainfall/runoff data; there is a potential to use this in conjunction with an assigned temporal pattern of losses for the duration of the event. The peak-to-volume relationships could also be used to derive the frequency curve for peak flows (Section 2.3.2).*

(6) *The Green-Ampt infiltration equation applied at catchment scale to estimate infiltration losses using parameters obtained from soil texture (Section 4.2).*

A number of options to introduce the spatial variability in runoff generation can be investigated. They are:

- (6.1) *subdivision of the catchments into a number of homogeneous sub-areas, and combining the calculated runoff from each.*
- (6.2) *use of a contributing area related to rainfall intensity and antecedent conditions (Section 3.6)*
- (6.3) *use of probability distributions of infiltration parameters (Section 3.6).*

(7) *Continuous simulation modelling to generate long periods of runoff data for a catchment (Section 2.3.1), using recorded rainfall and evaporation data as input. A distribution of loss parameters can be derived from the input and output from the model.*

[It should be noted that estimation of design event losses is not necessary if continuous simulation is used, as flood frequency analysis can be applied to the model output. However this method is potentially useful to derive loss data for hydrologically homogeneous regions.]

(8) *Continuous models can be applied for direct loss estimation. They achieve this by updating catchment condition on a daily basis, with daily climatic data. The AWBM (Boughton, 1993) is a recent development which appears to have considerable potential for the estimation of rainfall excess volumes in real time (Section 5.3).*

(9) *The TOPOG model can indicate saturated areas from which runoff originates; this can be used in real-time applications. The research would include the prediction of initial conditions, and updating of size and location of areas as the storm proceeds (Section 5.3).*

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