A REVIEW OF REAL-TIME FLOOD FORECASTING METHODS

A report as part of Project D4:
Development of a real-time flood forecasting model

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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 advance the understanding of catchment similarity and regional behaviour.

The issue of flood forecasting is specifically dealt with in CRC Project D4 "Development of a real-time forecasting model".

This report by "Sri" Srikanthan, Jim Elliott and Geoff Adams from the Bureau of Meteorology represents the beginning phase of Project D4. It provides a state of the art survey of flood forecasting methodology and computer packages, and presents the arguments used to choose the procedures to be investigated in the next phase.

The ultimate aim is to end up with an improved model for predicting flood levels and discharges in real-time, which utilises recent advances in model updating techniques, and which is suited for use with the Bureau's real-time data collection and operating systems. This report is an important first step in achieving that goal.

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ABSTRACT

Flood forecasting and warning systems are a cost effective means of reducing the damaging impact of floods. This report presents the results of a review of flood forecasting methods as the first phase of a project to develop an improved method for the real time forecasting of floods for use by Australian forecasting agencies.

Rainfall-runoff models and flood routing methods were reviewed. A wide range of rainfall-runoff models are available. It was concluded that the use of some form of simple soil moisture accounting model was the most promising approach to use. Real-time updating has been shown to clearly improve the accuracy of forecasting and some form of automatic, rather than subjective, updating is preferred. Two existing rainfall-runoff models; Mike11 and the Alabama Rainfall-Runoff Model were selected for further application, along with further development of the Australian Water Balance Model linked with either URBS or RORB, along with some form of real-time updating algorithm. Two adaptive unit hydrograph methods have also been recommended to capitalise on the large bank of unit hydrographs already in operational use.

Flood routing was seen as a relatively straight forward problem. The choice from among the many methods available is determined by the accuracy required and the available data. It is suggested that the simple Muskingum method be the procedure to use as a first step, moving to a variable parameter technique such as the Variable Parameter Muskingum Cunge method if greater accuracy is required.

The next phase of the project will involve direct comparison of the performance of each method on test data for local catchments. It is recommended that the project works toward the development of some form of generalised modelling framework suited to supporting the real-time application of a range of models as is done in a number of systems identified as part of the review.

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SUMMARY

This report represents the first phase of the CRC for Catchment Hydrology's Project D4, Development of a Real-Time Flood Forecasting Model. It is a review of flood forecasting methods and systems as described in both the research literature and in use by forecasting agencies in Australia and overseas. This approach was taken to explore gaps between the methods proposed at the research level and those actually being implemented. The aim of the review was to identify further research and development work required to improve the real-time hydrological modelling component of Australian flood forecasting practice.

The review first examined flood forecasting methods as reported in the literature. The methods were considered under two separate headings; rainfall-runoff methods and flood routing methods. A wide range of rainfall-runoff models of varying complexity are used throughout different countries however there is little information for making objective comparisons of performance, particularly for flood forecasting. It was generally observed that for wetter catchments simple models perform as well as complex models. Since flood forecasting mainly involves modelling the rainfall-runoff process during heavy rainfall a simple model may be adequate for most of the time. However while simple methods such as transfer function models appear to perform well for short lead time forecasting, models that incorporate some form of soil moisture accounting perform better for the longer lead times. It was concluded that the use of some form of simple soil moisture accounting model is the most promising approach. Several models are identified for further investigation.

Compared to rainfall-runoff modelling, flood routing is more straight forward. Methods ranging in complexity from the full solutions of the St Venant equations through hydrologic (Muskingum-type) methods to simple correlations are all available. Many of these methods are available as commercial software packages. Generally it is the available data and the accuracy required that become the primary determinants of the method chosen. The Muskingum method is widely used and is suggested as the procedure to use as a first step, if necessary a variable parameter approach such as the Variable Parameter Muskingum-Cunge method should be considered if greater accuracy is required.

Real-time updating has been shown in comparative studies to clearly improve the accuracy of real-time forecasting and should be considered for inclusion in all forecasting systems. The time taken for subjective updating can be prohibitive under operational conditions and so some form of automatic method is recommended. Updating either the input or the output variables is relatively easy to apply, but is limited by the degree of persistence in the updated variables and will not correct internal model errors. This shortcoming is overcome by the state updating approach however this requires that the model be reconfigured into state-space form which may not be a straightforward task. Parameter updating is not recommended since in most models the parameters are not independent. A number of updating methods are reviewed.

While not formally part of this review, the problem of rainfall forecasting is briefly addressed because of its importance to the flood forecasting problem overall. This shows that while a lot of research is being done on rainfall forecasting techniques, particularly those based on radar and satellite data and analysis, including numerical modelling, reliable quantitative precipitation forecasts are not currently possible. While some of the overseas work may be transferred to Australia, further local work needs to be done and the project should keep close contact with relevant work underway in Australian research groups.

Examples of flood forecasting systems which have integrated the flood forecasting method(s) into a system including other elements such as data processing and display and model calibration are also reviewed. These systems are structured around a framework that facilitates the inclusion of a number of different forecasting methods for real-time application as well as their non real-time calibration, giving the system flexibility to be used in a wide range of forecasting situations. The utility of this approach to the Australian situation is highlighted and a similar approach is recommended for this project.

To provide a balance to the research results, the review then looked at procedures being implemented both in Australia and overseas. Although the number of applications of recent developments in hydrological modelling to real-time flood forecasting in Australia are increasing, unit hydrographs and simple empirical procedures are still widely used. The information that was able to be collected on overseas applications was restricted to a fairly small sample and as an aid to identifying the more promising areas for further investigation, this part of the review proved to be of limited value. While there are different procedures being implemented, sometimes utilising more recently developed methods, objective comparisons between countries is difficult. This part of the review did suggest that there is scope to implement improved methods for flood forecasting in Australia particularly in areas where improved data collection systems are being installed.

From among the methods identified during the review, two existing models; MIKE11 and ARRM, have been selected for application, along with further development of the AWBM and URBS models coupled with an updating algorithm. To capitalise on the existing bank of unit hydrographs, two adaptive unit hydrograph methods are also recommended for further investigation. The investigation will involve direct comparison of the performance of each method on test data sets for local catchments using statistical criteria considered suitable for the comparison of real-time forecasting models selected from those covered in the review.

1. INTRODUCTION

1.1 Purpose of Report

The purpose of this report is to present a review of the current state of research and practice in real-time flood forecasting. The report is the first phase of a project to enhance the quality of Australian flood warning services by developing an improved method for the real-time prediction of flood levels and discharges, concentrating particularly on utilising recent advances in model updating techniques. This project is one of four projects under Program D of the research program of the Cooperative Research Centre for Catchment Hydrology. The flood forecasting method is to match operational accuracy and timeliness requirements of the forecasting agencies, particularly the Bureau of Meteorology, be compatible with existing and planned real-time data collection and operational systems and forecasting procedures, and be suited to current operational work environments. The objectives of this review are:

- to survey the literature to identify the latest research developments in the real-time flood forecasting, including model updating techniques;
- to examine forecasting techniques actually being used in forecasting agencies both within Australia and overseas and relate this to the current state of research, and
- to identify where further research and development are needed to both improve the quality of forecasting practices in Australia as well as in the real-time flood forecasting field in general.

A further aim of this report is to provide a useful resource to others working in the field of real-time flood forecasting both in Australia and overseas.

1.2 Background

Flood warning services in Australia are provided nationally by the Bureau of Meteorology, although this is undertaken in close cooperation with State and Local Government agencies. These services are provided on a regional basis through Flood Warning Centres (FWC) in the capital city of each State and the Northern Territory. Each FWC has forecasting responsibility throughout all of its region although in Western Australia and the Northern Territory, where the warning service is not as well developed, the small amount of river prediction that is done is undertaken by the State/Territory water agency. In terms of real-time modelling, this responsibility extends across a wide range of problems from quick responding catchments in the coastal areas and the headwaters of the inland rivers to the slow flowing rivers of, for example, western NSW and Queensland. This service covers over 70 river basins and forecasts are prepared for hundreds of individual locations. The area presently covered by flood warning services is shown in Figure 1.1.

Warning systems for flash flooding (defined as situations where the rain-to-flood time is 6 hours or less) are primarily the responsibility of Local Government. The Bureau role here is limited to the provision of advice and assistance in the establishment of the system as well as assistance with the development of real-time forecasting procedures. These procedures are operated by the local agency to provide localised forecasts of river behaviour. Other agencies with an interest for improved real-time hydrologic forecasting procedures include some of the larger metropolitan or regional water management agencies (eg Melbourne Water, South East Queensland Water Board, etc) who have responsibilities for flood mitigation and management, and power generation agencies such as the Hydro Electric Corporation in Tasmania who require river forecast information to optimise the management of hydro power systems.

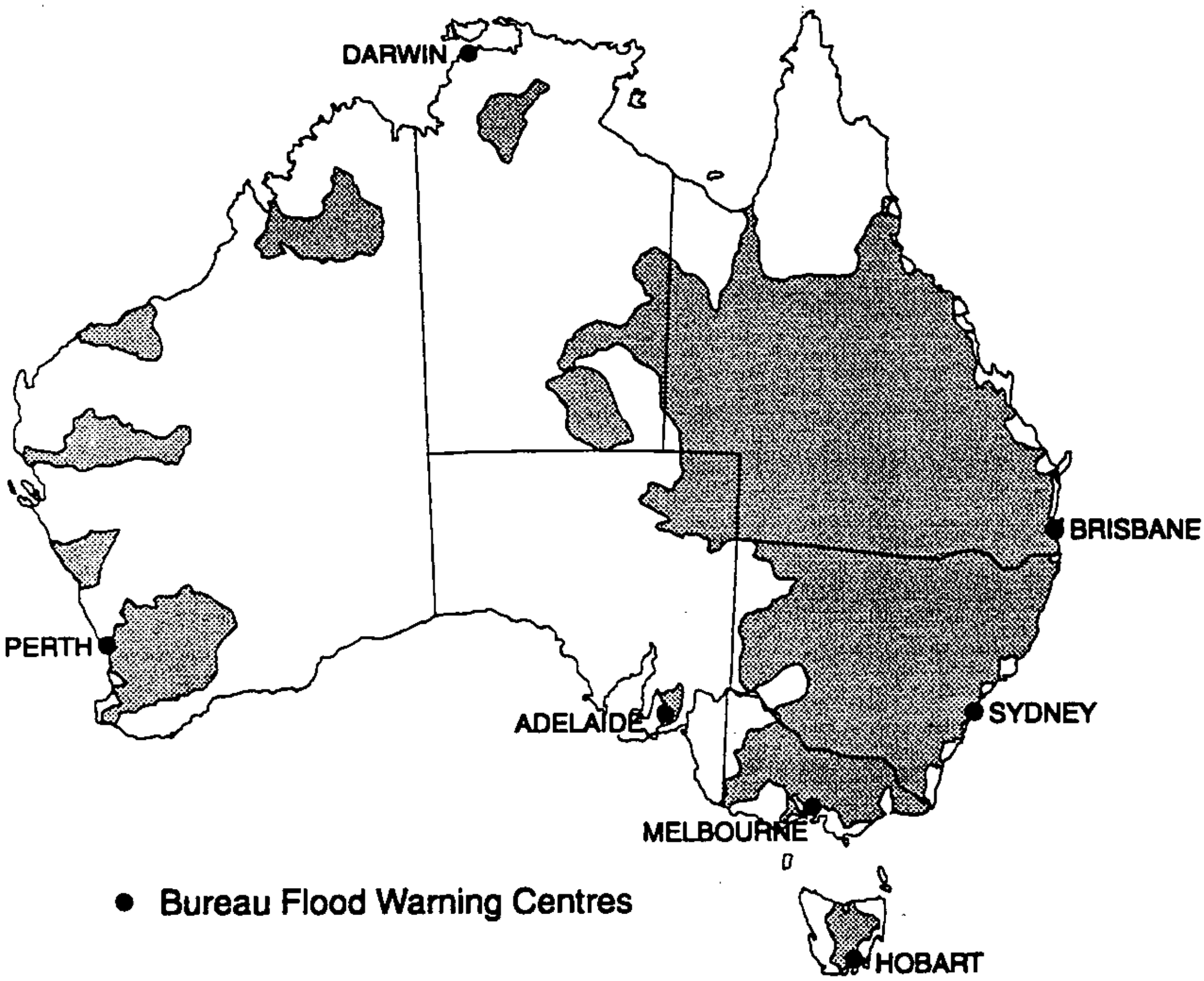


Figure 1.1 Areas covered with qualitative or quantitative flood forecasting systems.

In Australia the application of more recent advances in hydrologic modelling to the real-time flood forecasting problem has only commenced relatively recently. This has been largely because of the growing availability of real-time data collection systems with sufficient data to support the improved models, as well as the growing trend toward the non-structural approaches to flood mitigation following the failure of structural approaches to significantly arrest the growing national flood damage bill (AWRC, 1992). In the case of the Bureau of Meteorology, it was only after a Commonwealth Government decision in 1986 to upgrade national flood warning services that funds became available to modernise the existing data collection technology and develop new systems to meet the growing demand for services.

Substantial progress has been made over the five year upgrade period 1988 to 1992 with the result that now many of the more flood prone areas now have either radio or telephone based telemetry systems collecting rainfall and river level data in real-time. These systems and the real-time data management approaches adopted in the Bureau of Meteorology are described in Cock and Elliott (1989). Other systems, in particular that now operated by Melbourne Water (Giessman, 1986), have been in operation for much longer but, in a national context, these are not typical.

With the improvement in the quality of real-time data collection, has come a corresponding increase in the application of more advanced hydrological models to the real-time flood warning problem. However to date there has not been any systematic review and evaluation of alternative procedures either reported in the literature or in use in other countries with the specific aim of ensuring that flood warning systems in Australia are utilising the best real-time modelling techniques available. This project aims to address this need.

The project needs to proceed with a clear awareness of the wide range of forecasting problems and consequent real-time modelling requirements that these dictate. Apart from the vast differences in hydrology across the different flood prone areas, data collection networks differ in quality both in terms of network densities and observation accuracy and frequency; in many parts of Australia streamflow rating information at high flows is very sparse. Forecast lead time requirements differ with requirements of emergency response agencies. In the case of flash flooding, 1 to 2 hours lead time may be the goal, whereas typical lead times for larger rivers will be around 12 to 24 hours; sometimes forecasts are made for up to two weeks ahead for the slower flowing inland rivers. Forecast accuracy requirements also differ. In many cases predictions within a preset range may be sufficient, in others the exceedance of a threshold may be all that is required. Accuracy requirements also vary during the event with early warnings with longer lead times being required early in the event, being refined later as the peak level approaches. The project cannot hope to develop a single model to meet all requirements but rather keep these requirements clearly in view when evaluating the performance of each procedure investigated. It would seem that an approach that allows a range of different models to be applied to a particular forecasting problem may be most appropriate.

Improving the model is only part of the problem of achieving more accurate and timely predictions. The quality of the model output will always be limited by the quality of the inputs. In the case of rainfall, this applies both to observed and forecast inputs. The reliable provision of accurate quantitative precipitation forecasting (QPF) remains a difficult problem. While not a specific element of this review, some of the recent developments in rainfall forecasting are covered more for completeness than to identify any particular research direction. As a general problem for research this will remain a high priority but current indications suggest that it will be some time before techniques having widespread application are developed. As an element of this project however it is suggested that links be established between other research groups (notably the Bureau of Meteorology Research Centre) to integrate any developments in QPF modelling to flood forecasting models so that the direct impact of these developments can be assessed in a hydrologic forecasting context. A more immediately applicable development in the improvement of the rainfall inputs to flood forecasting models is the measurement and short term prediction of areal rainfall by radar and satellite. This technology has been operational for some time now in United States, Europe and the UK following an extensive amount of research and development work. Australia has a network of radars, disposed primarily for weather watch purposes, but also providing a good coverage of many areas of the country with a high flood risk. To date however there has been relatively little of the background research required to underpin the successful operational application of this technology to hydrological purposes. Nevertheless it is likely that much of the overseas experience can be used to accelerate the introduction of the technology to an operational tool in Australia and any work done on real-time flood modelling will need to keep the future likelihood of this form of input in mind.

Finally, this project has a practical emphasis. The ultimate product of the project is to be a modelling package that operational staff understand, find easy to use, and can be applied without the need for specialist support. In undertaking the project it is recognised that a wide range of models and systems have been proposed and reported in the literature and the development of another model is not necessarily an aim of the project. The emphasis then is to make an objective examination and selection among the existing procedures for an approach that best fits operational requirements and can be practically implemented in forecasting agencies. If, as part of this process, needs for new research are identified these will be discussed and addressed as time and resources allow. In adopting the model(s) to the needs of forecasting agencies, the differences in operation must be considered. Bureau of Meteorology Flood Warning Centres are required to prepare forecasts for a number of river basins simultaneously; each basin being different in terms of its hydrologic configuration, data network, forecasting requirements, etc. Often there is a need to run more than one model for the particular forecast point as verification. Some form of generalised structure would seem to best suit this situation. Local agencies on the other hand are mainly concerned with one river system. This provides the opportunity to "hard code" some of the features of the hydrologic model into a basin-specific forecasting program to streamline the operation. Both groups however would need to allow for the introduction of improvements that might need to be run in parallel for some time. This would also favour a more generalised structure.

1.3 Layout of the Report

The purpose of this section is to set the context for the review. Section 2 presents the review of the research literature covering rainfall-runoff modelling while section 3 presents the review of flood routing procedures. Section 4 covers the different approaches that have been used for real-time updating. Section 5 includes a brief coverage of developments in rainfall forecasting. Section 6 gives some examples of complete flood forecasting systems which, in addition to the hydrologic forecasting model, include other elements of on-line forecasting systems such as real-time data integration, processing and display. This was included to address some of the issues raised above concerning the need to produce a system to meet the operational requirements of forecasting agencies. Recognising that there is often a difference between procedures proposed in the research literature from those actually being applied, Section 7 presents a summary of some of the techniques and approaches being used by overseas forecasting agencies, as well as a summary of current techniques in use in Australia. This section also indicates where development work is underway in Australia so that the work undertaken in this project will be complementary. Finally Section 8 provides recommendations on the work to be undertaken in the investigation phase of the project, including applications of existing procedures as well as further research that is needed. A survey of various methods used in the Bureau of Meteorology Regional Offices for flood forecasting is given in Appendix A. Appendix B reviews graphical and statistical techniques that have been used for comparing the performance of the different models to assist with the evaluation of different methods. An extensive bibliography is also provided.

2. RAINFALL-RUNOFF MODELLING

Real-time forecasts of discharge, obtained by rainfall-runoff modelling, are generally less accurate than those obtained by channel routing of a hydrograph observed at an upstream gauging site. However, real-time forecasting methods based on rainfall-runoff modelling are necessary because in head water basins there is no alternative since upstream stations do not exist and in some circumstances it may yield forecasts with greater lead time. This section describes various rainfall-runoff modelling techniques used in flood forecasting.

2.1 Unit Hydrograph

The unit hydrograph approach is still used by many water authorities for flood forecasting because of its simplicity and effectiveness in representing catchment flood response. The transformation of rainfall to runoff is carried out in two steps: total rainfall is first converted to effective rainfall by subtracting the losses, then the effective rainfall is transformed into surface runoff by the unit hydrograph and the base flow is added to obtain the total runoff (Figure 2.1). A linear relationship is assumed between the surface runoff and effective rainfall. Several loss models are available and these are discussed in section 2.3.

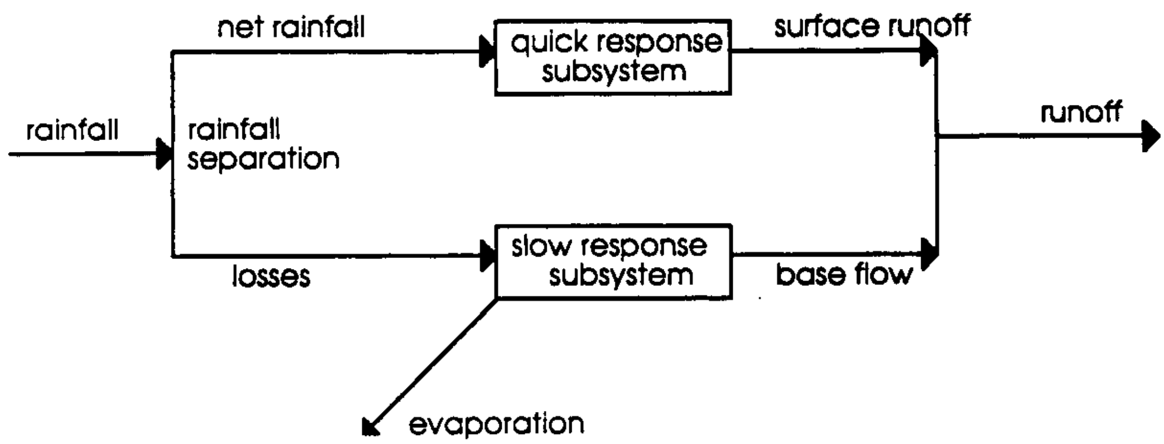


Figure 2.1 A system representation of unit hydrograph approach (Reed, 1982).

The unit hydrograph model in discrete form can be written as:

$$Q_{i+\tau} = \sum_{j=1}^{i \leq m} R_{i-j+1} \cdot U_j \qquad (2.1)$$

where

Q_i	direct runoff at time i
R_i	rainfall excess on the catchment over the time step prior to time i
U_j	T-hour unit hydrograph ordinates, j = 1, 2, ..., m
m	number of unit hydrograph ordinates
T	time step of discrete equation

τ initial lag

HEC1F (US Army Corps of Engineers, 1983) uses unit hydrograph to transform rainfall to runoff. Many of the water authorities in UK (Reed, 1984) use unit hydrograph for flood warning purposes. In the flash flood hydrologic model, ADVIS (Sweeney, 1988), forecasts are obtained by using the unit hydrograph concept and an antecedent precipitation model. A similar approach is widely used in the Bureau of Meteorology for flood warning services.

Chander and Shanker (1984) developed a unit hydrograph based forecast model which provides on-line estimation of the ϕ-index and rainfall excess as a storm progresses in time. Hino (1973) and Amirthanathan (1993) used Kalman filter in sequentially updating the parameters of a unit hydrograph model.

2.2 Non-linear Catchment Routing Models

2.2.1 RORB Model

The RORB Model is the most widely used model in Australia for design flood estimation. However, its use in real-time flood forecasting is limited, although Melbourne Water uses this method for flood forecasting in the Watts and Upper Yarra Rivers (Crapper, 1993, personal comm.).

The catchment is divided into a number of sub catchments and the catchment storage effects are represented by non-linear concentrated storages with the following storage-discharge relation:

$$S = 3600\, k\, Q^{m} \tag{2.2}$$

where S storage
Q outflow discharge
m a dimensionless exponent
k a dimensional empirical coefficient

The exponent m is a measure of the catchment's non linearity and the same value is used for all the sub catchments in the catchment.

The coefficient k is formed as the product of two factors:

$$k = k_c k_r \tag{2.3}$$

where k_c an empirical coefficient applicable to the entire catchment and stream network
k_r a dimensionless ratio (relative delay time) applicable to an individual storage

The relative delay of a storage is defined as the ratio:

$$k_{ri} = F\frac{L_i}{d_{av}} \qquad (2.4)$$

where k_{ri} relative delay time of storage i
L_i length of reach represented by storage i
d_{av} average flow distance in channel network of sub-area inflows
F a factor depending on the type of reach

The average flow distance is determined as:

$$d_{av} = \sum_{i=1}^{n}(a_i d_i)/A \qquad (2.5)$$

where a_i area of i th sub-catchment
d_i distance from the centroid of the i th sub-catchment to the outlet of the catchment
n number of sub-catchments
A total catchment area

The factor F has a value of 1.0 for natural channels and values for artificial channels are given in Laurenson and Mein (1985).

2.2.2 Watershed Bounded Network Model

The Watershed Bounded Network Model (WBNM) structure is generally similar to that for RORB, although it is based on a detailed consideration of geomorphological relations (Boyd et al., 1979, 1987). The main difference is that the WBNM has two types of storages for the two types of sub-catchments, namely, ordered basins and interbasin areas. Ordered basins are sub-catchments where no water flows into the area across catchment boundaries. The storage represents transformation of rainfall excess within the sub-catchment to the surface runoff hydrograph at the downstream end of the sub-catchment. Interbasin areas are sub-catchments with a stream draining upstream areas flowing through them. In addition to transforming rainfall excess into runoff as in ordered basins, the interbasin areas have a transmission storage which routes the upstream runoff through the stream in the interbasin area. Based on geomorphological relations, storages are related to sub-catchment areas. Linear and non-linear versions of the model are available. The rainfall excess on a given sub-catchment is routed using

$$S = K_B Q \qquad (2.6)$$

where the representative discharge is the outflow, Q, and

$$K_B = cA^{0.57}Q^{-0.23} \qquad (2.7)$$

where A - sub-catchment area (km^2)
Q - outflow discharge at downstream end of the sub-catchment (m^3s^{-1})
c - a dimensional empirical coefficient that applies to all sub-catchments.

The corresponding transmission storage parameter K_I (hours) for routing upstream runoff through main stream is given by:

$$K_I = 0.6\,K_B \tag{2.8}$$

The standard form of WBNM has only one parameter "c" to estimate.

2.2.3 RAFTS Model

The catchment is divided into a number of sub-catchments from which runoff hydrographs are produced and routed (Willing and Partners, 1984). Impervious and pervious portions of the sub-catchment can be routed separately and combined at the outlet. Each sub-catchment is represented by the non linear model developed by Laurenson (1964) consisting of a series of non linear concentrated storages with the storage-discharge relationship:

$$S = K\,Q \tag{2.9}$$

where the representative discharge is the outflow Q and

$$K = B\,Q^n \tag{2.10}$$

The sub-areas providing input to each of these storages are defined by ten isochrones at equal increments of travel time. The value of n is normally fixed at -0.285 and the main parameter of the model B is assumed to be the same for all sub-areas within a given sub-catchment, but can be varied for different sub-catchments.

The RAFTS model incorporates a more sophisticated loss routine than the other models. In addition to the initial loss- continuing loss option, the model uses the infiltration, wetting and redistribution algorithms of the Australian Representative Basins Model (Body and Goodspeed, 1979). The Muskingum-Cunge procedure is used to route the outflows from the sub-catchments through the river system. The flood forecasting system used in the ACT uses this model.

2.2.4 URBS Model

The URBS model (Carroll, 1992) is an adaptation of the RORB compatible WT42 model (Shallcross, 1987). It is a networked model of sub-catchments. In its most basic form, the reach length characterises the storage-discharge of the catchment.

$$S = \left\{ \frac{\alpha f L_i}{(1+U_i)^2} \right\} Q^m \tag{2.11}$$

where

S	catchment and channel storage
α	channel parameter
f	reach length factor
L_i	length of reach i

U_i	fraction of urbanisation of subarea i
Q	outflow
m	catchment non-linearity parameter

The advanced version of the model separates the two types of storages. The catchment storage is assumed to be proportional to the square root of the sub-area and the channel storage is proportional to the reach length.

$$S = \left\{ \alpha f L_i + \frac{\beta A_i^{1/2}}{(1+U_i)^2} \right\} Q^m \tag{2.12}$$

where

β	catchment lag parameter
A_i	area of sub-area i

The sophisticated version of the model calculates the effects of catchment and channel routing in each sub-catchment separately. The rainfall on a sub-catchment is routed to the creek channel and then routed along a reach by using the Muskingum method.

For catchment routing:

$$S_{cmt} = \frac{\beta A_i^{1/2}}{(1+U_i)^2} I^m \tag{2.13}$$

For channel routing:

$$S_{chl} = \alpha f L_i [x I + (1-x) Q]^n \tag{2.14}$$

where

S_{cmt}	catchment storage
S_{chl}	channel storage
I	inflow into the channel from the sub-catchment
x	Muskingum parameter
n	non-linearity parameter

2.3 Loss Models

2.3.1 Constant Loss Rate (φ Index Method)

Reed (1982) has shown that a constant loss rate is workable as a real time method of rainfall separation and derived a predictive relationship for the φ index, PHI, for UK catchments as

$$PHI = 0.687\, AVER^{0.844} ROMIN^{-0.225} \tag{2.15}$$

where AVER is the average rainfall intensity and ROMIN is the runoff rate at the beginning of the event.

Chander and Shanker (1984) developed a procedure for the on-line estimation of the ϕ index. Using the unit hydrograph formulation given by Eq (2.1), the ϕ index at the kth time step is

$$PHI = \frac{\sum_{j=1}^{k}\left[\left(Q_{j+t} - \sum_{i=1}^{j} P_{j-i+1}.U_i\right)\left(\sum_{i=1}^{j} U_i\right)\right]}{\sum_{j=1}^{k}\left(\sum_{i=1}^{j} U_i\right)^2} \qquad (2.16)$$

where P is the rainfall and the other variables are defined under Eq. (2.1).

2.3.2 Variable Loss Rate

The variable loss rate concept is based on the fact the soils have limited capacity to absorb water by infiltration and the capacity decreases with increasing soil water content. The loss rate is usually described by an infiltration curve. Philip's infiltration equation is used in RAFTS (Willing and Partners, 1984) to estimate the rainfall losses.

2.3.3 Constant Proportional Loss

The unit hydrograph method of flood estimation described in Flood Studies Report (NERC, 1975) assumes a constant proportional loss model. The percentage of runoff PR corresponding to a rainfall depth of P is:

$$PR = SPR + 0.22\ (CWI - 125) + 0.1(P - 10) \qquad (2.17)$$

where SPR is a standard percentage runoff determined by soil type, land slope and land use and CWI antecedent catchment wetness index defined in terms of soil moisture deficit SMD and five day antecedent precipitation index API5 as

$$CWI = 125 - SMD + API5 \qquad (2.18)$$

2.3.4 Variable Proportional Loss

For flood forecasting applications of the unit hydrograph, a variable proportional loss rate model is suggested (NERC, 1975).

$$PR_t = k\ CWI_t \qquad (2.19)$$

where k is a parameter to be determined.

2.3.5 Initial Loss - Continuing Loss Model

This is the most widely used loss model in Australia for the estimation of design floods and also for real-time flood forecasting in the Bureau of Meteorology where the unit hydrograph method is used. No runoff is assumed to occur until a given initial loss capacity has been satisfied regardless of the rainfall intensity. The continuing loss is at a constant rate. A variation of this model is to have an initial loss followed by continuing loss consisting of a constant fraction of the rainfall in the remaining time periods.

2.3.6 Other Models

Crapper (1989) developed an initial loss model for the Jacksons Creek Catchment by correlating the initial loss obtained from RORB runs with the antecedent mean daily flows from a gauging station in the catchment. The rainfall loss model obtained was:

$$IL = \begin{cases} 133 - 23.7\,MDF + 1.24\,MDF^2 & MDF > 9\ ML\ /\ day \\ 20mm & \text{otherwise} \end{cases} \qquad (2.20)$$

where IL = initial loss (mm)
MDF = mean daily flow 7 days prior to storm event (ML / day)

In the flash flood hydrologic model, ADVIS, the effective rainfall is obtained from an API - runoff relationship (Sweeney, 1988).

A continuous soil moisture accounting model can be used to estimate the losses prior to a storm event. Boughton and Carroll (1993) applied the AWBM to estimate the effective rainfall and the resulting runoff volume was routed through the URBS model.

In a real-time flood operations model for Somerset Dam, Wivenhoe Dam and North Pine Dam, Ruffini et al. (1994) developed a procedure to estimate initial loss and continuing loss using the conceptual storage volumes and process information from the modified Sacramento model. In addition, simplified procedures for estimating the soil moisture status based on base flow and/or 7-day and 14-day antecedent rainfall have been incorporated.

2.4 Non-Linear Storage Models

2.4.1 Inflow-Storage-Outflow Model

In this model (Lambert, 1969, 1972), it is assumed that at any instant the outflow from the catchment q is uniquely related to the quantity of water S (surface water, soil moisture and ground water) stored in the catchment and that the water balance equation for the catchment is satisfied at all times.

$$q = q(S) \qquad (2.21)$$

$$\frac{dS}{dt} = p - q \qquad (2.22)$$

where p inflow
q outflow
t time.

Equations (2.20) and (2.21) coupled together form an Inflow-Storage-Outflow or ISO model. The type of the model is determined by the functional form chosen for the storage/outflow relationship (2.20).

In flood forecasting applications, p is taken as the catchment average rainfall and q the runoff from the catchment. On many catchments, there is time delay between the rainfall and the resultant runoff and this is taken into account using a pure time delay or a translation lag parameter, L.

$$\frac{dS}{dt} = p_{t-L} - q_t \tag{2.23}$$

Since $\frac{dS}{dt} = \frac{dS}{dq}\frac{dq}{dt}$, Eq (2.23) becomes:

$$\frac{dq}{dt} = (p_{t-L} - q_t)\frac{dq}{dS} \tag{2.24}$$

Bobinski and Mierkiewicz (1986) reported an application of the ISO model with a logarithmic storage-outflow relation. Rainfall loss was obtained from an exponential recession function of the antecedent precipitation index which contains two empirical parameters.

2.4.2 Isolated Event Model

In the Isolated Event model (IEM) (NERC, 1975), rainfall losses are represented explicitly using a runoff proportion, ROP. Effective rainfall (n_t) is given by:

$$n_t = ROP\ p_t \tag{2.25}$$

The runoff proportion is determined from the initial soil moisture deficit (SMD) according to:

$$ROP = PERC\ e^{-PERI.SMD} \tag{2.26}$$

Two additional parameters - time delay, L and routing coefficient AC - complete the model.

$$S = AC\sqrt{q} \tag{2.27}$$

The model equation is

$$\frac{dq}{dt} = (n_{t-L} - q_t).\frac{2\sqrt{q}}{AC} \tag{2.28}$$

2.4.3 Generalised Non linear Storage Model

A generalised non linear storage model is obtained by combining the ISO and IEM models:

$$n_t = ROP.P_t$$
$$ROP = ROP(CWI)$$
$$\frac{dq}{dt} = (n_{t-L} - q_t)\frac{dq}{dS} \quad (2.29)$$
$$\frac{dq}{dS} = \frac{dq(q)}{dS}$$

The particular type of non linear model is determined by the function chosen for ROP and dq/dS.

type I ISO Model: ROP = 1; $\frac{dq}{dS} = \frac{q}{k}$ (2.30)

type II ISO Model: ROP = 1: $\frac{dq}{dS} = \frac{1}{K}$ (2.31)

standard IEM: $ROP = PERC\ e^{-PERI.SMD}$; $\frac{dq}{dS} = \frac{2\sqrt{q}}{AC}$ (2.32)

In a modified version of IEM, pre-event runoff q_O is used to estimate ROP (Brunsdon and Sargent, 1982).

modified IEM: $ROP = a + b \ln (q_O)$; $\frac{dq}{dS} = \frac{2\sqrt{q}}{AC}$ (2.33)

An extended version of IEM was developed (O'Connell, 1980) by using a 2 parameter storage/outflow relationship and a constant runoff proportion.

extended IEM: ROP = c; $\frac{dq}{dS} = aq^b$ (2.34)

The storage routing models used for flood forecasting in the Ishikari River (Tateya et al., 1989) are expressed by:

$$S = k_1 q^{p_1} + k_2 \frac{d}{dt}(q^{p_2})$$
$$\frac{dS}{dt} = f.r - q = r_e - q \quad (2.35)$$

where S is the storage, q the direct runoff depth, r_e the rate of rainfall excess, r the rainfall, f the runoff coefficient, t the time and k_1, k_2, p_1 and p_2 are the model parameters.

Another form of a general storage routing model has the structure (Prasad, 1967)

$$S = k_1 q^p + k_2 \frac{dq}{dt} + k_3 \frac{d^2q}{dt^2}$$
$$\frac{dS}{dt} = f.r - q \qquad (2.36)$$

where k_1, k_2, k_3 and p are model parameters.

Hasebe et al (1989) compared the above two storage routing models with the filter separation AR method and the tank model for forecasting floods in Ishikari and Kokai Rivers in Japan. They concluded that the filter separation AR method is superior to the generalised storage function methods or the tank model method in the accuracy of forecasting.

2.5 Conceptual Models

2.5.1 Sacramento Model

The National Weather Service River Forecast System currently uses the Sacramento model (Figure 2.2) for explicit soil moisture accounting purposes. It is a lumped input and lumped parameter model. The soil moisture is represented by two zones. The upper zone represents the upper soil layer and interception storage while the lower zone represents the bulk of the soil moisture and ground water storage. Each zone stores water in two forms, namely, free water and tension water. Tension water is depleted by only evapotranspiration. Two lower zone free water storages are defined: primary which is slowly draining and longer lasting and supplementary which is faster draining. Both operate as linear reservoirs. The flow rate from the upper zone to the lower zone is expressed by a non linear function of the upper and lower zones. The model generates five components of flow:

- direct runoff resulting from moisture input applied to impervious areas
- surface runoff occurring when the free water storage of the upper zone gets saturated
- lateral drainage from upper zone free water
- supplementary base flow, lateral drainage from lower zone supplementary free water
- primary base flow, lateral drainage from lower zone primary free flow.

The above processes involves 17 parameters. A channel unit hydrograph and a time delay function are used to convert the runoff volume to a discharge hydrograph. The model operates at a 6-hour time step with moisture input given in volume over that period.

Kitanidis and Bras (1980) compared the results of the above model set in a state-space framework with those from an ARMAX model and found that the former is more reliable than the latter in forecasting the most important features of the hydrograph such as the beginning of the rising limb, the time and height of peak and the total water volume. For the shortest forecast lead time (6 hours), the ARMAX model performed as well as the stochastic conceptual model while for long forecast lead times, the stochastic conceptual model gave significantly better results than the ARMAX model.

The Nile Flood Early Warning System (FEWS) uses a real-time rainfall-runoff model SAMFIL (Vermuleulen and Snoeker, 1991) which is a combination of the Sacramento model with an extended Kalman filter for field data assimilation during real-time rainfall-runoff simulation (Grijsen et al, 1992). In the absence of real-time rainfall data, Meteosat TIR images are used to derive daily total Cold Cloud Duration (CCD) data for various sub catchments as a basis for rainfall estimation (Milford and Dugale, 1989). Since August, 1992 the Nile FEWS is in operation at the Ministry of Irrigation and Water Resources in Khartoum. Although full details of the performance of the FEWS were not available at the time of writing the paper, results so far look very promising.

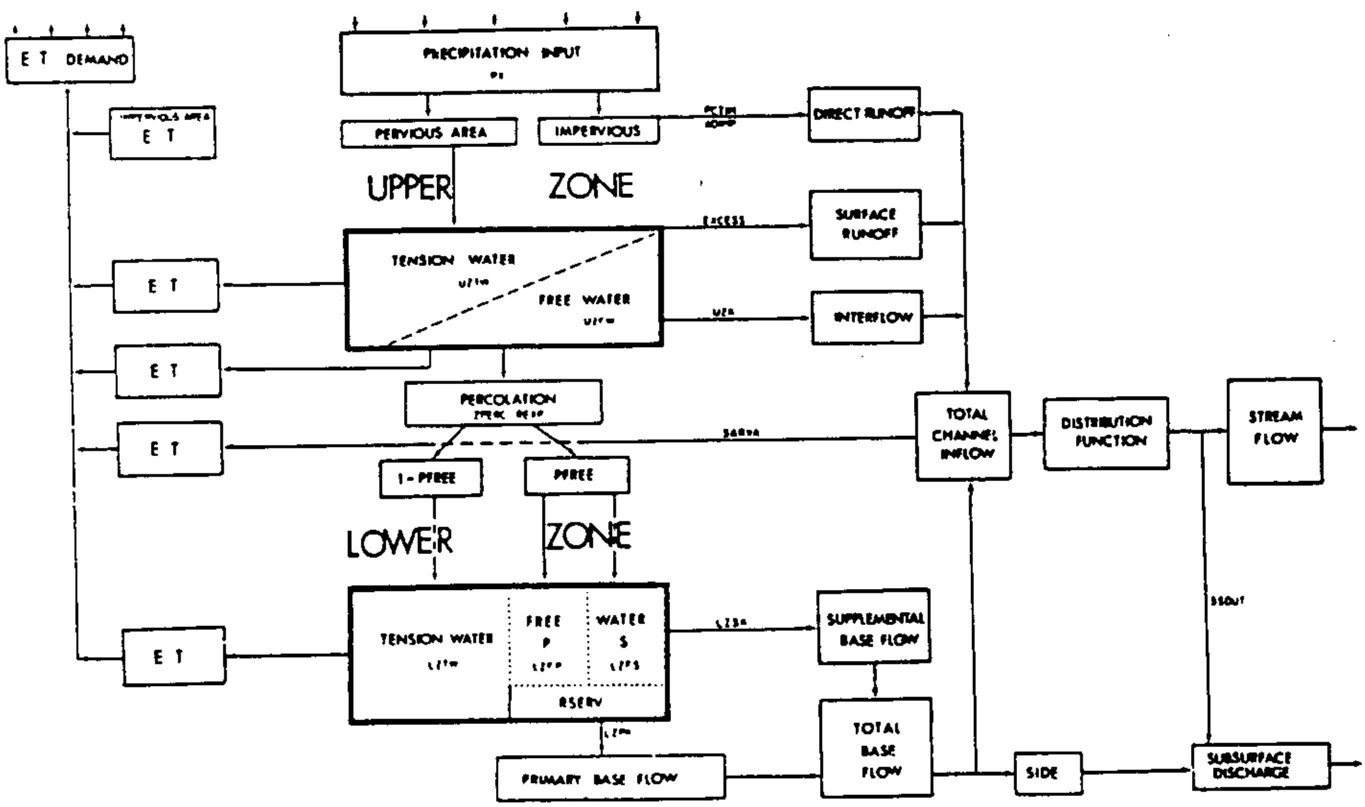


Figure 2.2 Schematic diagram of Sacramento soil moisture accounting model (Kitanidis and Bras, 1980).

A modified Sacramento model has been used in a model of the Brisbane River System to estimate the soil moisture state of the sub-catchments and base flow recession rates (Ruffini et al., 1994).

2.5.2 IPH-II Model

The IPH-II model is formulated as a lumped model and does not take into account channel routing. It is applied in catchments where channel routing is not important. Input to the model are rainfall and potential evaporation in the catchment. Four basic algorithms are used: evaporation and interception losses, flow separation, surface and ground water routing and parameter optimisation (Bertoni et al, 1992). The model parameters which can be optimised are:

- I_0 maximum soil infiltration capacity (Horton's method)
- I_b minimum soil infiltration capacity (Horton's method)
- h parameter characterising soil type (defining infiltration delay)
- K_{sup} parameter characterising runoff lag time (using Clarke's method)
- K_{sub} parameter characterising ground water flow lag time (modelled as a simple linear reservoir)
- R_{max} depth of interception storage

Bertoni et al (1992) used the IPH-II model for real-time flood forecasting and a simplified stochastic model to forecast the future rainfall. The method was tested using 17 years of data from a small catchment (the River Ray at Grendon Underwood, U.K.). The results showed that a simple method to forecast rain falling during the next few hours may help to improve real-time discharge estimates.

2.5.3 The Australian Water Balance Model

The Australian Water Balance Model (AWBM) is a saturation overland flow model which allows for variable source areas of surface runoff in different storms and in different periods in a single storm (Boughton, 1993). The structure of the model is shown in Figure 2.3. Three stores are used to represent different values of surface storage capacity over a catchment area. This allows for different source areas of surface runoff. The recharge of base flow storage takes place when surface runoff is occurring and is a fixed proportion of the amount of surface runoff.

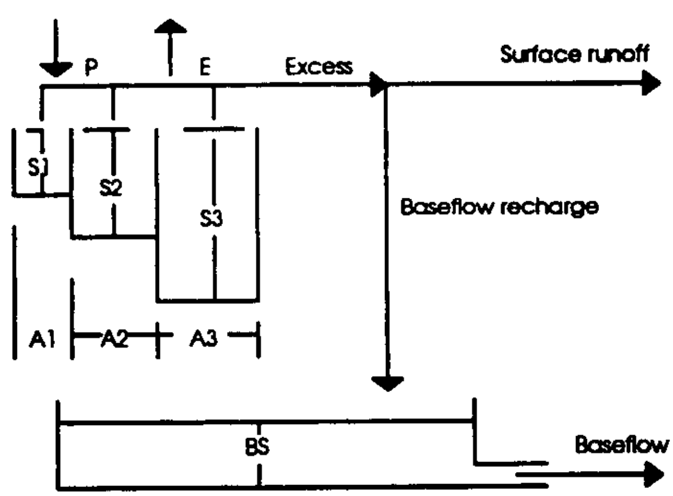


Figure 2.3 Structure of AWBM.

Boughton and Carroll (1993) applied this model combined with a flood hydrograph model (URBS) to Oxley Creek. The results from the combined model was claimed to be considerably better than those from both the URBS and unit hydrograph models based on the assumption of antecedent wetness of the catchment.

2.5.4 NAM Model

The NAM model is a lumped conceptual soil moisture accounting model which computes the runoff from a catchment by continually accounting for the moisture content in five different but mutually interrelated surface and sub surface storages. The structure of the model is shown in Figure 2.4. Input data is required in the form of mean areal rainfall, evaporation and (only if snow occurs) temperature time series. It has been successfully applied for rainfall-runoff modelling in more than 10 countries throughout the world (Refsgaard *et al*, 1988).

van Kalken and Havno (1992) applied this model to Kelani Ganga Catchment in Sri Lanka to determine the present level of flood protection in Colombo and the rest of the catchment. A trial forecast of the 1989 flood event was carried out using the NAM generated runoff based on eight rain gauges and the measured discharges at Glencorse were used to update the forecasts. The travel time of major flood waves from Glencorse to Colombo is about 50 hours. The predicted water levels in Colombo were within 10 cm of the recorded values with almost no phase errors.

The NAM model in conjunction with the System 11 model was applied to two large catchments in India for flood forecasting up to 48 hours . The one day ahead forecasts showed good agreement with the recorded flows for both the low flow events and flood events. The two days ahead forecasts showed a fair agreement. A closer examination of the forecasts revealed that the forecasts were quite reliable during the recession part of the hydrograph while the two days ahead forecasts underestimated the flows in the rising limb, because zero rainfall was usually assumed during the 12-48 hour period. It was concluded that the two days ahead forecasts can be improved only if the rainfall forecasts becomes more reliable.

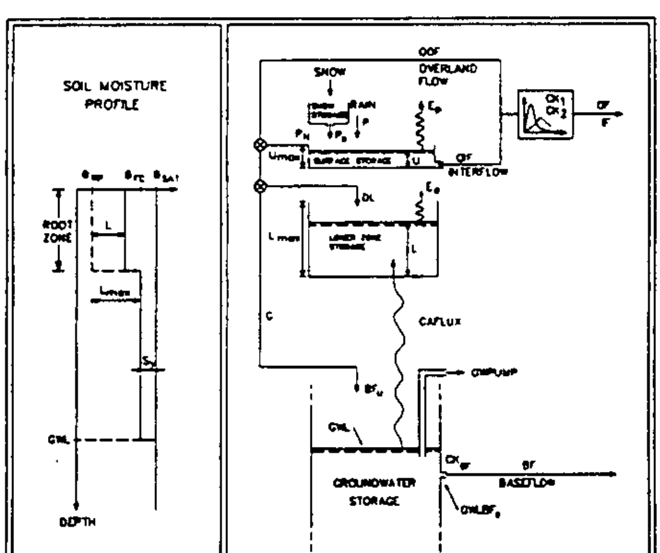


Figure 2.4 Structure of NAM rainfall runoff model (van Kalken and Havno 1992).

2.5.5 The HBV Model

The HBV model developed by Bergstrom (1976, 1992) at the Swedish Meteorological and Hydrological Institute (SMHI) has been shown to give good estimates of runoff from several Scandinavian catchments (Lundberg, 1982). It uses sub-catchments as primary hydrological units and within these an area-elevation distribution and a crude classification of land use are made (Figure 2.5). The model has a number of free parameters which are found by calibration. With only one sub-catchment and one type of vegetation, the model has altogether 12 parameters. The model has been applied in more than 30 countries world wide.

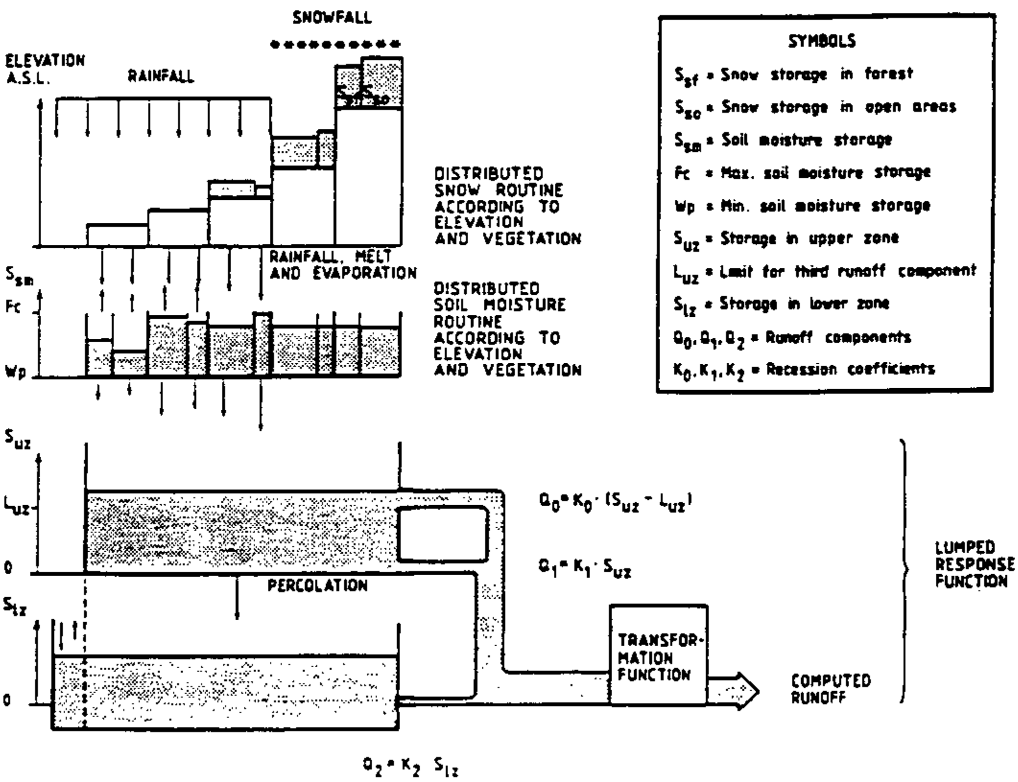


Figure 2.5 The general structure of SMHI version of the HBV model when applied to one sub-basin (Bergstrom, 1992).

2.5.6 Tank Model

The tank model proposed by Sugawara (1979) is a lumped model having a simple structure and is widely used in Japan. It consists of a number of tanks stacked on top of another as shown in Figure 2.6. Goto et al. (1993) used a four tank configuration to model the Ping River (Thailand) catchment. This model was combined with an ARIMA(2,1,0) model to obtain 1- to 3-day ahead forecasts.

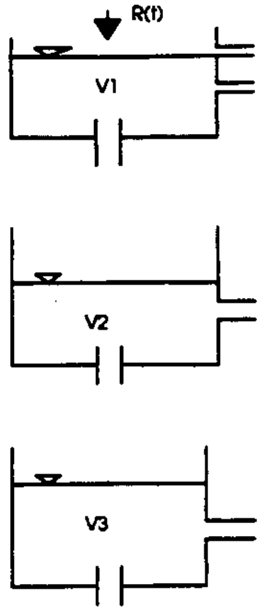


Figure 2.6. Tank model structure.

2.5.7 Probability Distributed Model

The probability distributed model (PDM) transforms rainfall and evaporation data to flow at catchment outlet (Figure 2.7). The runoff production at a point is controlled by the absorption capacity of soil to take up water. The spatial variation of the soil capacity to take up water is described by a probability distribution. The probability distributed store model is used to partition rainfall into direct runoff, ground water recharge and soil moisture storage (Moore and Jones, 1991). Direct runoff is routed through a fast response system while the ground water recharge from soil water drainage is routed through a slow response system. Both routing systems can be defined by a variety of non-linear storage reservoirs.

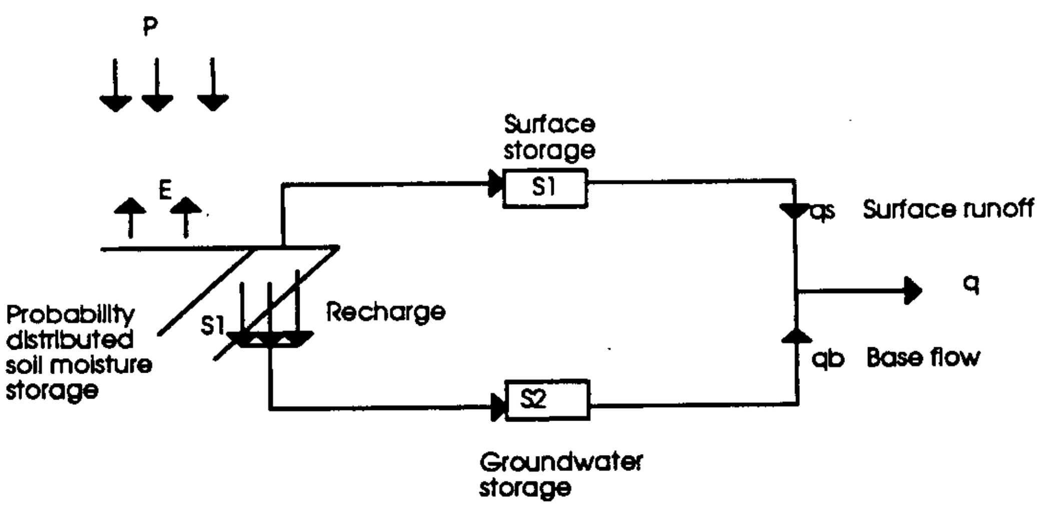


Figure 2.7 Probability distributed model.

2.5.8 The Alabama Rainfall-Runoff Model

The Alabama Rainfall-Runoff Model (ARRM) is a conceptual state-space model cast in a stochastic framework (Henry et al, 1988). It uses the Green-Ampt method for infiltration, exponential decay for interflow and ground water contributions and lumped parameter kinematic routing for overland and channel flows. The stochastic model is built on

- the deterministic model equations to which noise terms are appended
- a set of measurement equations which relate observed flow rates to state variables and to which the noise terms are appended.

The model equations are obtained by the application of the conservation of mass to an appropriate control volume in a manner that yields the rate of change of the state variable under consideration.

The first state equation (ponding equation) is obtained by applying conservation of mass to the inflow, outflow and change in storage of the ponded water with a depth of X_1 and lumped kinematic routing of overland flow:

$$\frac{dX_1}{dt} = r - I - CS.X_1^{EXS} \tag{2.37}$$

where

r	the rainfall rate
I	the infiltration rate
CS	the coefficient in Manning's equation for overland flow

The Green-Ampt method is used to estimate the infiltration. The second state equation (infiltration equation) is:

$$(\Theta_s - \Theta_i)\frac{dX_2}{dt} = I - ET - \frac{2.3}{\Delta t_1} X_2 (\Theta_s - \Theta_i) \tag{2.38}$$

where

$(\Theta_s - \Theta_i)$	the fillable porosity
I	the infiltration rate
ET	evapotranspiration
Δt_1	the time for the interflow to decrease to 90%

The time varying infiltration demand is given by:

$$I_d = \frac{K(\Psi + X_2 + X_1)}{X_2} \tag{2.39}$$

where

X_2	the depth to the wetting front

K the hydraulic conductivity

Ψ the difference in suction head across the front

After ponding, the infiltration is I_d and the rate P available for infiltration is

$$P = r + X_1 / \Delta t \tag{2.40}$$

where

Δt the time interval used for integrating the state equations

$$\begin{aligned} I &= I_d \quad \text{when } I_d \le P \\ I &= P \quad \text{otherwise} \end{aligned} \tag{2.41}$$

The evapotranspiration is taken as linearly proportional to the depth of the wetting front.

$$\begin{aligned} ET &= X_2 . \frac{PET}{ELMAX} \quad \text{when } X_2 \le ELMAX \\ ET &= PET \quad \text{otherwise} \end{aligned} \tag{2.42}$$

where ELMAX is the depth below which no evapotranspiration will occur.

The state equation for the groundwater variable is:

$$\frac{dX_3}{dt} = \frac{2.3}{\Delta t_1} PERC.X_2(\Theta_s - \Theta_i) - \frac{2.3}{\Delta t_2} X_3 - RK.X_3 \tag{2.43}$$

where

PERC	the fraction of the wetting front outflow going to ground water
Δt_2	the time for the flow rate from ground water to decrease 90%
RK	the coefficient of losses to deeper aquifers.

In ARRM, it is assumed that the overland flow, interflow and groundwater flow into collector creeks before flowing to a river channel. The equation for the collector creek storage X_4 is:

$$\frac{dX_4}{dt} = r.ARC + \frac{2.3}{\Delta t_1}(1 - PERC)X_2(\Theta_s - \Theta_i) + \frac{2.3}{\Delta t_2} X_3 + CS.X_1^{EXS} - CCR.X_4^{EXCR} \tag{2.44}$$

where

CCR	the coefficient in Manning's equation for the creeks
EXCR	the exponent in Manning's equation for the creeks
ARC	the surface area of creeks as a fraction of the catchment area

Water flows from the collector creeks to the river reaches where a lumped kinematic routing is applied. The state equation for the rate of change in storage X_i in the i^{th} river reach is:

$$\frac{dX_i}{dt} = r.ACH + CCR.X_4^{EXCR}.PROP_i + CCH.X_{i-1}^{EXCH} - CCH.X_i^{EXCH} \tag{2.45}$$

where

$PROP_i$	the proportion of the total creek flow going into the current reach
CCH	the coefficient in Manning's equation for the river reach
EXCH	the exponent in Manning's equation
ACH	surface area of the river reach as a fraction of the catchment area.

Finally, the reservoir equation is:

$$\frac{X_R}{dt} = CCH_i . X_i^{EXCH} + CCR . X_4^{EXCH} . PROP_R + r . ARCH - q_{out} \qquad (2.46)$$

where

$CCH_i . X_i^{EXCH}$	the sum of flows from all tributary reaches flowing into the reservoir
$PROP_R$	the proportion of the collector creek flow which goes directly into the reservoir
ARCH	the area of the reservoir as a fraction of the total catchment area
q_{out}	controlled outflow plus that over the spillway.

The application of the model to real-time modelling of Coosa river above Rome, Georgia shows that ARRM can be effective in flood control operations.

2.6 Spatially Distributed Models

A brief mention of spatially distributed models is included for completeness. To date these models have seen little application to operational use such as flood forecasting and are used more commonly as research tools.

2.6.1 SIMPLE Model

SIMPLE is a process-based hydrologic model to simulate the hydrologic budget of a catchment (Kouwen, 1988). Because the model is aimed at flood forecasting using radar rainfall data, only the most dominant hydrologic processes affecting flood flows are included. These are interception, surface storage, infiltration, interflow, overland flow and base flow. The rainfall, streamflow and catchment data are stored and processed in a square grid coordinate system. The total inflow to the river system is found by adding the surface runoff from both the pervious and impervious areas, the interflow and the base flow. A storage routing technique is used to route the water through the channel system.

SIMPLE features an automatic pattern search optimisation algorithm to determine which combination of parameters best fit measured conditions. The parameters for optimisation are: soil permeability, overland flow roughness, channel roughness, depression storage, and an upper zone depletion factor. In the operational mode, the calibration option is used to determine the initial soil moisture based on real-time measurements of streamflow.

Tao and Kouwen (1989) applied the SIMPLE model for the Grand River Basin, Ontario (10 km x 10 km grid) with and without Landsat input. Four events were chosen for parameter estimation using the automatic pattern search optimisation algorithm. The results were analysed by comparing the total volume of runoff, peak flow rate and time to peak of the simulated and measured flows. From the results, it was concluded that the distributed land cover information improves the flood forecasting with SIMPLE for the Grand River Basin and Landsat can provide the satisfactory land-cover classification needed by a rainfall-runoff model.

2.6.2 The TOPOG Model

The TOPOG is a contour based model (O'Loughlin et al., 1989) developed at the Australian Centre for Catchment Hydrology for use on hill slope catchments. A hill slope catchment is divided into a number of elements by a set of contour and flow lines. All the elements between a pair of flow lines constitute a flow strip. The saturated flow depth in each element depends on the local slope, transmissivity, upstream contributing flow, rainfall on the element and evaporation from the element. If the flow rate exceeds the transmissivity, the element will be saturated.

So far this model has been run on small catchments with contour intervals of 1m. Preliminary studies (Mein and O'Loughlin, 1991) with output from TOPOG support the concept of a flood forecasting procedure in which runoff producing areas are initially determined by the base flow level and updated using cumulative rainfall during a storm.

2.6.3 TOPMODEL

The grid based TOPMODEL is based on three assumptions (Beven and Kirkby, 1979; Beven and Wood, 1983):

(i) surface runoff is generated when precipitation falls on a saturated portion of the catchment;

(ii) subsurface flow at a given location depends on the saturation deficit at that point;

(iii) saturated hydraulic conductivity exponentially decreases with depth in the upper soil layers.

Digital terrain data is preprocessed to obtain the catchment or sub-catchment distribution of a topographic index $\ln(a/\tan\beta)$, where a is the cumulative upslope area draining through a point (per unit contour length) and β is the local slope angle.

Borga and Di Luzio (1992) used this model to investigate the effect of rainfall estimation accuracy on streamflow hydrograph for a mountainous catchment in Italy. In the worst case, the combination of a 16 % error in the cumulative basin average rainfall value and a 35 % increase in the coefficient of variation generated an error of 58 % in the peak flow magnitude.

2.6.4 The SHE Model

The SHE model, a physically based distributed catchment modelling system, is produced jointly by the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (Abbott et al, 1986b). The movement of water within a catchment is modelled either by finite difference representations of the equations of mass, momentum and energy or by empirical equations derived from independent experimental research. Spatial distribution of catchment parameters, rainfall input and hydrologic response is achieved in the horizontal direction by set of orthogonal grid network and in the vertical direction by a column of horizontal layers at each grid square. Each of the primary processes of the hydrological cycle is modelled separately, viz

- interception by Rutter accounting procedure
- evapotranspiration by Penman-Monteith equation
- overland and channel flow by simplifications of the St Venant equations
- unsaturated zone flow by Richard's equation
- saturated zone flow by the two dimensional Boussineq equations
- snow melt by an energy budget method.

Overall control of the parallel running of the components is managed by a FRAME component. Application of the SHE model requires large amounts of parametric and input data some of which, like crop parameters, may be time dependent. Considerable computing resources are required to handle large arrays and to perform iterative solutions.

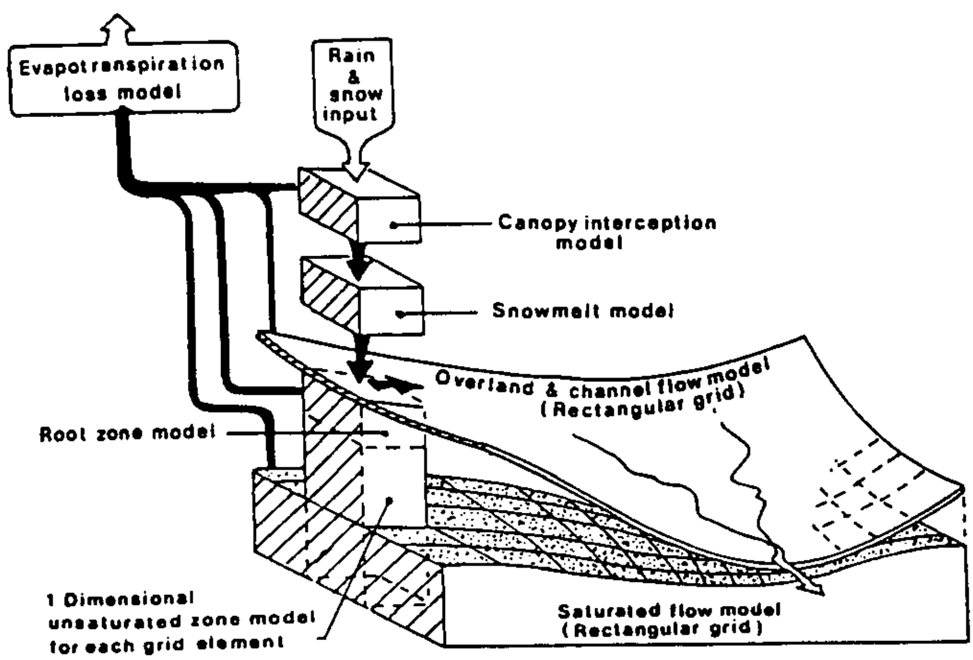


Figure 2.8 Schematic representation of the structure of the SHE model (Abbott et al, 1986).

2.7 Transfer Function Models

Transfer function models give forecasts based on recent and previously observed rainfall and flow. The general form of a transfer function model is (Troch et al, 1991):

$$y_k = \frac{B(z^{-1})}{A(z^{-1})} u_{k-d} + \frac{D(z^{-1})}{C(z^{-1})} e_k \qquad (2.47)$$

where u_k is the input sequence, y_k is the output sequence and e_k represents white noise with variance σ^2. $A(z^{-1})$, $B(z^{-1})$, $C(z^{-1})$ and $D(z^{-1})$ are polynomials of order n and d is the lag time of the process. The estimation of the model parameters is carried out via the generation of an instrumental variable (IV) sequence ζ_k (Young, 1974). The major problem with the IV method is the generation of suitable instrumental variables. Young (1965) suggests to use an auxiliary model of the process to generate ζ_k.

$$\zeta_k = \frac{\tilde{B}(z^{-1})}{\tilde{A}(z^{-1})} u_{k-d} \qquad (2.48)$$

where $\tilde{A}(z^{-1})$ and $\tilde{B}(z^{-1})$ are polynomials with parameters chosen in some reasonable manner. A recursive solution to the IV equations is:

$$\hat{\Theta}_k = \hat{\Theta}_{k-1} \hat{k}_k [z_k^T \hat{\Theta}_k - y_k] \qquad (2.49)$$

$$\hat{k}_k = \hat{P}_{k-1} \hat{x}_k [\delta_k + z_k^T \hat{P}_{k-1} \hat{x}_k]^{-1} \qquad (2.50)$$

$$\hat{P}_k = \frac{1}{\delta_k} \left\{ \hat{P}_{k-1} - \hat{P}_{k-1} \hat{x}_k [\delta_k + z_k^T \hat{P}_{k-1} \hat{x}_k]^{-1} z_k^T \hat{P}_{k-1} \right\} \qquad (2.51)$$

where $\hat{\Theta}_k$ is the estimated parameter vector at time k and z_k and $\hat{x}_k$ defined as

$$z_k^T = [-y_{k-1}, \ldots, -y_{k-n}; u_{k-d}, \ldots, u_{k-d-n}] \qquad (2.52)$$

$$\hat{x}_k^T = [-\zeta_{k-1}, \ldots, -\zeta_{k-n}; u_{k-d}, \ldots, u_{k-d-n}] \qquad (2.53)$$

The scaler δ_k is called the forgetting factor and is calculated recursively as

$$\delta_k = \lambda_o \delta_{k-1} + (1 - \lambda_o)\delta \qquad (2.54)$$

with δ, λ_o and δ_o additional parameters chosen by the modeller.

2.7.1 Modelling Parametric Variations

Instead of assuming parametric invariance, assume that the parameters vary according to a random walk model:

$$\Theta_{k+1} = \Theta_k + \varepsilon_k \tag{2.55}$$

where ε_k is a white noise vector with zero mean and covariance matrix Q. In the case of random walk model, the IV algorithm becomes:

$$\hat{\Theta}_k = \hat{\Theta}_{k-1} - \hat{k}_k[z_k^T\hat{\Theta}_k - y_k] \tag{2.56}$$

$$\hat{k}_k = \hat{P}_{k|k-1}\hat{x}_k[\delta_k + z_k^T\hat{P}_{k|k-1}\hat{x}_k]^{-1} \tag{2.57}$$

$$\hat{P}_{k|k-1} = \hat{P}_{k-1} + Q \tag{2.58}$$

$$\hat{P}_k = \frac{1}{\delta_k}\left\{\hat{P}_{k|k-1} - \hat{P}_{k|k-1}\hat{x}_k[\delta_k + z_k^T\hat{P}_{k|k-1}\hat{x}_k]^{-1} z_k^T\hat{P}_{k|k-1}\right\} \tag{2.59}$$

Troch et al. (1991) applied the above two adaptive modelling approaches to several sub catchments of the River Meuse. It was found that the additive Q matrix approach generally leads to better forecasting performance for isolated storm events. However, the peak of the hydrograph is usually overestimated. The choice of the Q matrix is rather critical to the performance of the adaptive model and further research is recommended to develop an objective selection criteria for Q.

Harpin (1982), Powell (1985) and Owens (1986) have demonstrated that both rainfall-runoff and flood wave transformation processes can be satisfactorily simulated by single input-single output (SISO) transfer function models with the structure given below:

$$y_t - a_1y_{t-1} - a_2y_{t-2} - \ldots - a_py_{t-p} = b_1u_{t-1} + b_2u_{t-2} + \ldots + b_qu_{t-q} \tag{2.60}$$

where	y_t	flow at time t
	u_{t-1}	rainfall at time t-1
and	a, b	parameters

Harpin (1982) and Cluckie and Ede (1985) found that the recursive least squares estimator (RLS) to be adequate for the estimation of parameters for use in a real-time model. In the case of a catchment where catchment response lags rainfall input, a pure time delay can be incorporated into the model.

Due to their size, large river catchments are composed of several distinct sub catchments over which the precipitation and surface characteristics may vary considerably. Multiple input-single output (MISO) transfer function models or a cluster of SISO transfer function models can be used to model large catchments. The basic equation in the semi-distributed models with m inputs is

$$A(z)y_t = \sum_{i=1}^{m} B_i(z).u_t \tag{2.61}$$

where $A(z) = 1 - a_1z^{-1} - a_2z^{-2} - \ldots - a_pz^{-p}$

$B_i(z) = b_{i1}z^{-1} + b_{i2}z^{-2} + \ldots + b_{iq}z^{-q}$

z^{-1} is the backward shift operator.

A mutually interactive state parameter algorithm was used to develop multi-day forecasts of river flows resulting from combined snow melt and precipitation for the Sturgeon River, Ontario (Fitch and McBean, 1991). It was found that 1-day and 2-day ahead forecasts were good, but the longer term forecasts were found to be poor. Good initial parameter estimates are shown to be essential for optimal forecasting performance.

Iritz (1992) applied a self-tuning predictor for flow forecasting where upstream discharge and excess rainfall data together were used as inputs. Excess rainfall was estimated by approximate expressions and was routed by a linear cascade model.

Amirthanathan (1989) compared the following four sequential optimal filtering techniques for forecasting flow at a downstream site from measured flows at three upstream sites.

Time varying regression model
Method considering discharge as a state variable
MISP technique (two filters in parallel)
Instrumental variable method

The performance of the above four adaptive methods were found to be similar. When compared with the results from a deterministic model based on the St Venant equations, the adaptive methods gave better 1-day ahead forecast while the 2- and 3-day ahead forecasts were similar.

Bobinski and Mierkiewicz (1986) observed that the transfer function model using discharges failed to give good forecasts when the process trend changes sharply, eg. at the beginning of the hydrograph or in the vicinity of the peak. The mass curve (S - curve) was chosen instead of discharge and this improved the forecasts. Underestimation on the rising limb and overestimation on the peak and early recession were also present in the S-curve forecast model. However, the transition from underestimation to over estimation did not seem so rapid as in the case of direct flow forecasting.

2.8 Statistical Methods

Long-term and short-term operational discharges of the River Rhine are based on regression analysis with snow cover, precipitation, lake storages and previous flows as the dependent variables (Spreafico, 1982). Bidwell (1979) developed a flood forecasting procedure for the Klang River at Kuala Lumpur based on a multiple input, autoregressive moving average model. The model was calibrated by stepwise multiple regression.

2.8.1 Constrained Linear Systems

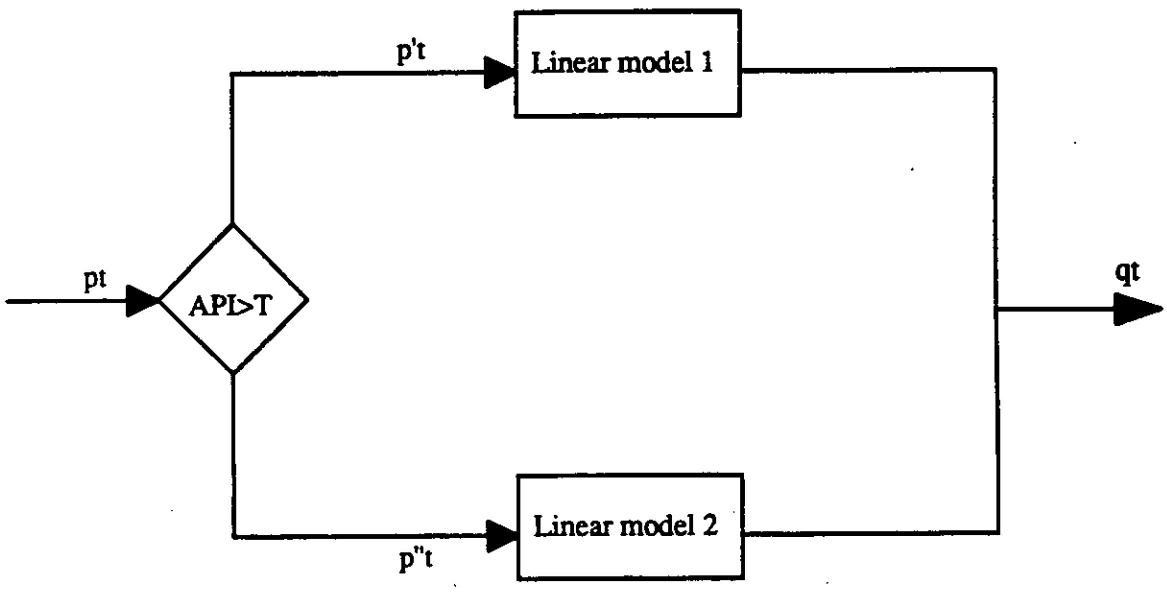
Natale and Todini (1977) developed a constrained linear systems (CLS) approach which is flexible, stable and allows multiple inputs. A set of constraints that can be deduced from the physics of the hydrologic system are imposed to reduce the high sensitivity of the classical estimators to errors in the available data. One of the basic ideas of CLS is that the precipitation

p_t is transformed into runoff q_t by a series of mutually exclusive linear systems depending on the initial conditions of the soil.

For the Ombrone River model (Todini, 1978), only two linear systems represented the rainfall-runoff process, depending on the value of the antecedent precipitation index (API).

$$API_t = K.API_{t-1} + p_{t-1} \tag{2.62}$$

where K is an exponential decay factor. The logic scheme of CLS is shown in Figure 2.9. The parameters of the model are estimated by constrained quadratic programming.



$$p_t = p'_t + p''_t \quad \forall\ t$$

Figure 2.9 CLS model scheme.

2.8.2 IHACRES Model

The IHACRES model, jointly developed by the Institute of Hydrology, U.K. and the Centre for Resource and Environmental Studies in the Australian National University, is similar to the above model in the sense that it partitions the runoff into quick flow and slow flow components [Jakeman et al (1990)]. The rainfall excess is obtained from the rainfall by a non-linear relationship. The runoff components are modelled by autoregressive models.

2.8.3 Filter Separation AR Method

The runoff series is first separated into shorter- and longer-period runoff component series by a numerical filter. Each sub-system is expressed by an AR model. The effective rainfall component for each sub-system are inversely estimated sequentially from the separated component time series. Runoff is predicted by using the inversely estimated past rainfall and the extrapolated future rainfall.

2.9 Other Models

Corradini and Melone (1986) presented an adaptive rainfall-runoff model for real-time forecasting in large catchments. It is based on a framework characterised by an ensemble of spatially homogeneous units, with the transformation from effective rainfall to direct runoff described by the Clarke translation-routing procedure. Evolution in time of infiltration is estimated, in terms of saturated hydraulic conductivity, K_s, and sorptivity parameter, S, through a representation of its pre-ponding and post-ponding stages. Spatial variability of infiltration is represented by the corresponding rainfall variability and using spatially equivalent values for K_s and S. The on-line correction of flow forecast involves the updating of the S parameter and of a runoff-scaling factor (C). The model performance was evaluated by using errors on peak runoff ε and persistence coefficient V. The model was applied to actual events observed on a large Italian basin (area 4147 km^2) and the flow forecasts for lead-times (L) up to 6 h generally compared sufficiently well with the observations. For L = 6 h, the mean values of ε and V were 10 % and 0.67 respectively.

Brath et al (1989) investigated the effects of scale on basin response. The basin response was modelled through a distributed approach using a GIS describing soil type, land use and topography. The results showed that increasing the scale of aggregation of absorption model resulted in smoothing the flood hydrograph and underestimating the flood volume.

2.10 Model Comparisons

There are not many comparisons of flood forecasting models while there are a number of comparisons of the performance of rainfall-runoff models for simulating the whole time series. In a recent study (WMO, 1992), a number of hydrologic models were compared under simulated real-time conditions. The models exhibited a wide range of accuracy and this was attributed partly to the accuracy of the basic simulations and partly to the efficiency of the updating routines for the various models. No definite conclusions were made on the relative performance of models because of the small sample sizes and other limitations.

Chiew et al (1993) compared six rainfall-runoff modelling approaches - simple polynomial equation, simple process equation (tanh equation), simple time series equation (Tsykin,1985), complex time-series model (IHACRES), simple conceptual model (SFB), (Boughton, 1984) and complex conceptual model (MODHYDROLOG), (Chiew and McMahon, 1991) - using data from eight catchments. The performance of the models were assessed based on their ability to simulate daily, monthly and annual flows. It was concluded that the use of a complex conceptual rainfall-runoff model is essential for the successful simulation of daily flows.

Franchini and Pacciani (1991) compared the performance of seven conceptual rainfall-runoff models using hourly data for the Sieve catchment, Italy for a four month period. The models used are:

1. STANFORD IV model
2. SACRAMENTO model
3. TANK model
4. APIC model
5. SSAR model
6. XINANJIANG model
7. ARNO model

It was observed that with the exception of the APIC model, all the models produced similar and equally valid results in spite of the wide range of structural complexity. However, the degree of complexity played a significant role in the calibration phase. The difficulties encountered during the calibration were closely related to the number of parameters and to the greater or lesser ease of visualising the meaning of various parameters and their interactions. It was concluded that a conceptual model must balance the desire for simplicity on the one hand, with the need to respect the physics of the problem on the other.

Bacchi and Brath (1989) analysed the issue of the choice between off-line and on-line use of lumped conceptual models for real-time flood forecasting in the presence of errors in areal rainfall input. The analysis showed that continuous recalibration can result in biased and highly variable parameter estimates if rainfall measurements are corrupted by noise.

Puente and Bras (1987a) investigated whether soil moisture accounting models are necessary to guarantee reliable forecasts by comparing the performances of two alternative models: one with and one without a soil moisture component. Results from a case study suggested that given observations of rainfall and discharge only, the soil moisture component could be bypassed and still reasonable flow forecasts could be obtained. Rainfall predictions play an important role in runoff forecasting. If rainfall is under predicted, the soil component may be bypassed and still get good results. A soil component is needed if rainfall is over predicted (Puente, 1988).

2.11 Summary

A number of rainfall-runoff models of different complexity are used in various parts of the world for transforming rainfall to runoff. It was generally observed that for wetter catchments, simple models give similar flows to those from complex models. Since flood forecasting involves modelling the rainfall-runoff process during heavy rainfalls, a simple model might be adequate. In addition, updating of state and or output variables will improve the ability of these models to predict runoff even if the initial predictions at the beginning of the rising limb are not satisfactory. Although forecasting accuracy is enhanced by an improved modelling of catchment response, Puente and Bras (1987a) argue that a complex soil moisture accounting is not essential in achieving good overall forecasts. Even though transfer function models perform well for short lead time forecasting, they do not perform as well as the soil moisture accounting models for long lead time forecasts.

The major problem in rainfall-runoff modelling is the calibration of model parameters. In addition to parameter inter-dependence, another drawback is the dependence of parameters on the data used. For example, if the rainfall and runoff data were measured for 20 years, calibration of model parameters might result in two sets of parameters: one using 10 years and the other using 20 years. Thus, for a catchment one can obtain a number of sets of parameters according to seasons, data availability, time period chosen for calibration, etc. Each set of parameters represent a different "model" of the catchment for that method and is referred to as a multi-model approach (Cunge *et al*, 1992). On the other hand, different methods can be used on the same catchment and this approach is referred to as multi-method. From experience, it was found that a method performs well on some catchments and not so well on others. Hence, it is worthwhile to have a number of suitable methods and then to choose the one which is applicable to a particular catchment at a particular time.

The unit hydrograph method is simple and effective in transforming effective rainfall to runoff. The major problem with this method is the estimation of losses and a successful outcome from the Project D1 will enhance the results from the unit hydrograph method. There is not a lot of difference in performance of non-linear models (Malone and Cordery, 1989) and it is suggested to consider the URBS model as Boughton and Carroll (1993) have some success in combining this with AWBM model. Sacramento model is too complex in terms of the number of parameters and the need to run continuously to get good results. The SIMPLE model is grid based and it will not be effective without spatially distributed catchment data and input data from radar or satellite. In the TANK model, the representation of runoff transformation appears very abstract and does not have any physical correspondence. In the HBV model, a catchment is sub-divided according to altitude as well and it appears that this model is to be more suited to catchments with snow melt component. The NAM model is similar to HBV in terms of complexity and is preferred over HBV as the former is being used currently in Australia. The statistical models CLS, IHACRES and filter separation AR method are similar in nature to transfer function models except for partitioning the flow into two or more component flows. In summary, simple models like the unit hydrograph method, AWBM, ARRM and NAM are considered to be adequate for modelling the rainfall-runoff process for real-time flood forecasting purposes.

3. FLOOD ROUTING

Flood routing offers a satisfactory means of flood forecasting for long river systems. In this section, different flood routing methods are discussed. For this approach to be successful, the travel time of flood peaks from upstream to the downstream site needs to be long enough to allow adequate period of warning. The flood routing methods can be classified under four headings: experience methods, statistical methods, hydrologic routing methods and hydraulic routing methods.

3.1 Experience Methods

A survey of water authorities in Britain (Reed, 1984) reflected the importance of experience methods as a fall back technique of most authorities. These methods rely on the assumption that future floods occur in a similar manner to that occurred previously. An experienced flood forecaster assesses the expected floods based on levels upstream and/or the depth and duration of heavy rainfall. This approach is also commonly used in Australia.

3.2 Statistical Methods

3.2.1 Correlation Methods

Correlation between upstream and downstream river levels are used to forecast the flood levels at the downstream site. The downstream river levels are plotted against the upstream river levels and a best fit line is drawn through the points either by eye or using the method of least squares. These methods are widely used by flood forecasting agencies in Australia.

3.2.2 Statistical Routing Methods

The general form of the forecasting equation is

$$\hat{Q}_d(t+d) = F(Q_u(t-kT), Q_d(t-kT)) \tag{3.1}$$

where d is the forecasting horizon, T the measurement period, k an integer and Q_d and Q_u are the downstream and upstream flows.

Masmoudi and Habaieb (1993) applied seven statistical-routing models to the Medjerdah River, Tunisia for forecasting the extreme flood events at Jendouba for different forecasting horizons. The models used were linear functions with constant coefficients.

(i) The finite difference regression method (FDR):

$$\begin{aligned} Y(t) &= Q_d(t) - Q_d(t-T) \\ \hat{Y}(t+d) &= c_1 Y(t) + c_2 Y(t-d) \\ \hat{Q}_d(t+d) &= \hat{Y}(t+d) + Q_d(t+d-T) \end{aligned} \tag{3.2}$$

where

$$c_1 = \frac{\rho_1(1-\rho_2)}{(1-\rho_1^2)} \quad \text{and} \quad c_2 = \frac{(\rho_2-\rho_1^2)}{(1-\rho_1^2)}$$

in which ρ_1 and ρ_2 are the autocorrelation coefficients for forecasting horizons d and 2d respectively.

(ii) The Muskingum with extrapolation method (ME):

$$\hat{Q}_d(t+d) = c_1Q_u(t) + c_2(2Q_u(t) - Q_u(t-d)) + c_3Q_d(t) \tag{3.3}$$

The least squares method was used to estimate the coefficients with the constraint that the sum of the coefficients to be equal to one.

(iii) The regression with an upstream point method (RU)

$$\hat{Q}_d(t+d) = c_1Q_u(t+d-t_p) + c_2Q_d(t) + c_3Q_d(t-d) \tag{3.4}$$

where t_p is a pure time delay between upstream and downstream flows. The least squares method was used to estimate the coefficients as in (ii).

(iv) The competition models (CP)

The forecasting is carried out using the above models in parallel and the adopted forecast corresponds to that of the model which minimises the criterion:

$$\mathbf{E}_i(t) = |E_i(t)| + |E_i(t-T)|/3 + |E_i(t-2T)|/6 \tag{3.5}$$

where E_i is the forecast error of the model i at time t. Two competition models were used: the first one (CP1) uses the models FDR, ME and RU and the second (CP2) uses only the models ME and RU.

(v) The mixed models (MIX)

The forecasted value corresponds to the weighted sum of the individual forecasts from the above models that run in parallel.

$$\hat{Q}_d(t+d) = \frac{\sum_i a_i\hat{Q}_{di}(t+d)}{\sum_i a_i} \tag{3.6}$$

where a_i is taken to be identical and equal to one. Here again two mixed models were used: the first one (MIX1) uses the models FDR, ME and RU and the second (MIX2) uses only the models ME and RU as in (iv).

The coefficients used for forecasting were estimated using the last event of the same season. A multi-criteria analysis was used to rank the performance of the above seven models when applied to a sample of 17 flood events recorded on the Medjerdah River. Mixed models seemed to be the best for short (2, 4 h) as well as for long (6, 8 h) forecast lead times.

Yapo et al (1993) used a Markov chain flow model for short-term streamflow forecasting in which the forecasts were given as ranges of streamflow values. Three types of flood forecasts are proposed: the threshold forecast, the maximum probable event (MPE) forecast and the regression forecast. The threshold forecast is defined as:

$$\begin{array}{lll} \text{If } P_{iN} > p_0 & \text{Decision} = \text{Warning} \\ \text{If } P_{iN} \leq p_0 & \text{Decision} = \text{No warning} \end{array} \tag{3.7}$$

where p_0 is the threshold probability, N the flood state and i the current state.

The MPE forecast selects the streamflow range, $\hat{X}_{t+1}$, where the next streamflow is most likely to occur:

$$\hat{X}_{t+1} = \left\{ j: \max_j P_{ij} \right\} \tag{3.8}$$

where j represents the state of the streamflow at time t+1.

The regression forecast is defined as

$$\hat{x}_{t+1} = \sum_{j=1}^{N} P_{ij} \overline{x}_j \tag{3.9}$$

where $\overline{x}_j$ is the average streamflow in state j.

3.3 Hydrologic Routing Methods

Hydrologic routing methods are based on the continuity equation and storage-discharge relationships.

3.3.1 Muskingum Method

The equation of continuity for a river reach in terms of storage S, inflow I and outflow Q is

$$\frac{dS}{dt} = I - Q \tag{3.10}$$

The storage in a river reach is given by the Muskingum equation

$$S = K[Q + x(I - Q)] \tag{3.11}$$

where

K storage coefficient (units of time)
x weighting factor (dimensionless)

Combining equations (3.10) and (3.11), outflow Q_2 from the reach after a time interval Δt is given by

$$Q_2 = C_0 I_2 + C_1 I_1 + C_2 Q_2 \tag{3.12}$$

where

$$\begin{aligned} C_0 &= -(Kx - \Delta t/2)/(K - Kx + \Delta t/2) \\ C_1 &= \ (Kx + \Delta t/2)/(K - Kx + \Delta t/2) \\ C_2 &= \ (K - Kx - \Delta t/2)/(K - Kx + \Delta t/2) \end{aligned} \tag{3.13}$$

The coefficients C_i sum to unity satisfying the continuity equation. Various graphical and analytical methods have been used to estimate the Muskingum parameters K and x.

A reach is usually defined by upstream and downstream gauging stations. The lateral inflow can be included by dividing the reach into a number of sub-reaches. In this case, the value of K for the sub-reaches is obtained by apportioning the reach value by sub-reach lengths while the same value of x is used for all the sub-reaches.

O'Donnell (1985) proposed a three parameter Muskingum model for lateral inflow which is proportional to the main channel inflow. The parameters are estimated by the method of least squares. Khan (1993) extended the basic single inflow-single outflow model to a multiple inflow-single outflow form which also incorporates ungauged lateral inflow. For m tributaries with inflows $I^{(1)}, I^{(2)}, \ldots, I^{(m)}$, the routing equation becomes:

$$Q_{j+1} = \sum_{k=1}^{m} C_1^{(k)} I_j^{(k)} + \sum_{k=1}^{m} C_2^{(k)} I_{j+1}^{(k)} + C_3 Q_j \tag{3.14}$$

where $C_1^{(k)}, C_2^{(k)}$, k= 1, ..., m are the various coefficients associated with the tributary inflows. The least squares regression can be used to estimate the coefficients.

3.3.2 Muskingum-Cunge Method

With an appropriate choice of sub-reach length Δx and routing period Δt, Cunge (1969) showed that the Muskingum equation can provide a good approximation to solution of the linear diffusion equation:

$$\frac{\partial Q}{\partial t} + \omega \frac{\partial Q}{\partial x} = \mu \frac{\partial^2 Q}{\partial x^2} \tag{3.15}$$

where $Q \equiv Q(x,t)$ is the flow at distance x and time t, ω the kinematic wave speed and μ the diffusion parameter.

From Cunge's analysis, the outflow at the downstream site at time $t+\Delta t$ is given by

$$Q_2 = c_0 I_2 + c_1 I_1 + c_2 Q_1 \tag{3.16}$$

where

$$c_0 = -(\omega\Delta x - 2\mu - \omega^2\Delta t)/(\omega\Delta x + 2\mu + \omega^2\Delta t)$$
$$c_1 = (\omega\Delta x - 2\mu + \omega^2\Delta t)/(\omega\Delta x + 2\mu + \omega^2\Delta t) \qquad (3.17)$$
$$c_2 = (\omega\Delta x + 2\mu - \omega^2\Delta t)/(\omega\Delta x + 2\mu + \omega^2\Delta t)$$

and the space and time steps are chosen such that

$$\Delta t \geq 1.625\mu/\omega^2 \quad \text{and} \quad 2.6 \leq \Delta x \leq 1.6\Delta t \qquad (3.18)$$

The following additional condition on the time step is imposed to define the upstream hydrograph adequately.

$$\Delta t \leq 0.2T_R \qquad (3.19)$$

where T_R is the shortest hydrograph rise time that is likely to be of concern.

Details of estimating ω and μ from channel geometry and observed flood peak travel times are given in Reed (1984) and Price (1973).

3.3.3 Variable Parameter Muskingum-Cunge Method

A major weakness in the Muskingum-Cunge method is the assumption that the wave speed is independent of flow. In the variable parameter Muskingum-Cunge (VPMC) method, both the wave speed parameter ω and the diffusion parameter μ are allowed to vary with the flow. Calibration of VPMC method is carried out by evaluating ω and μ for a range of flows for both within bank and out-of-bank conditions. In practice, some adjustment is made to the wave speed-discharge relationship by trial routings with the model (Miller and Cunge, 1975; Ponce and Yevjevich, 1978).

3.3.4 Nonlinear Reservoir-type Channel Routing Method

Georgakakos and Bras (1980, 1982) presented a conceptual, nonlinear reservoir-type channel routing model. A river channel is divided into n reaches according to the homogeneity of their hydrogeomorphological properties. Each of the reaches stores and releases water according to a nonlinear function of the form:

$$Q_i(t) = a_i S_i^m(t) \qquad i = 1, 2, \ldots, n \qquad (3.20)$$

where

$S_i(t)$ volume of water in storage in the i^{th} reach
$Q_i(t)$ outflow from the same reach
m, a_i model parameters.

The continuity equation completes the model description.

$$\frac{dS_i(t)}{dt} = I_i(t) - Q_i(t) \qquad i = 1, 2, \ldots, n \qquad (3.21)$$

where $I_i(t)$ lumped inflow in the i^{th} reach.

The nonlinear model is transformed into an equivalent linear model through statistical linearisation for applying filtering and optimal estimation techniques.

3.4 Hydraulic Routing Methods

Hydraulic routing methods are based on the numerical solution of the general one-dimensional St Venant equations.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{3.22}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\alpha\frac{Q^2}{A}\right)+gA\frac{\partial y}{\partial x}+gA(S_f-S_0)=qV \tag{3.23}$$

Kinematic wave

Diffusive wave

Dynamic wave

where

A	flow area
g	acceleration due to gravity
Q	discharge
q	lateral inflow per unit length of channel
S_f	friction slope
S_0	bed slope
t	time
V	entering velocity in the x direction of lateral inflow
x	horizontal distance
y	water depth
α	momentum distribution coefficient

Several numerical methods are available to solve the above set of equations at finite incremental values of x and t. The finite difference methods can be grouped into four categories (Weinmann and Laurenson, 1977):

(i) Finite difference schemes that solve the characteristic equations using a curvilinear characteristic grid

(ii) Explicit finite difference scheme for the characteristic equations using a rectangular x-t grid

(iii) Explicit finite difference schemes for the original equations using a rectangular grid

(iv) Implicit finite difference schemes for the original equations using a rectangular grid

In explicit schemes, Q and y at a given point (x,t) are found explicitly, while implicit schemes use sets of simultaneous equations to find Q and y at several x values for a given t value. In explicit schemes, the size of the time step is limited by the stability criterion

$$\Delta t \leq \frac{\Delta x}{Q/A+\sqrt{gy}} \tag{3.24}$$

Implicit models are not subjected to this stability criterion. Amein and Fang (1969) claimed that implicit schemes are the only schemes suited to deal with large variations in flow characteristics between adjacent channel sections. In System 11 model, a time-centred implicit scheme is used to solve the St Venant equations. Takasao et al (1993) used a four-point numerical scheme with the Newton iteration technique.

If the fully dynamic wave description is not required, approximations are made to save computer time. Kinematic wave and diffusive wave approximations are indicated in equation (3.23).

3.4.1 Kinematic Wave Method

Under this approximation, the St Venant equations can be combined into one equation, commonly referred to as the kinematic wave equation (Lighthill and Whitham, 1955):

$$\frac{1}{\omega}\frac{\partial Q}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{3.25}$$

where ω is the kinematic wave speed which is treated as constant in linear models and variable in non-linear models. For a given discharge Q at a particular location, ω is obtained from the Kleitz-Seddon law (Weinmann and Laurenson, 1977):

$$\omega=\left(\frac{dQ}{dA}\right)_x=\frac{1}{B}\left(\frac{dQ}{dy}\right)_x \tag{3.26}$$

Both the explicit and implicit schemes can be applied to obtain the solution. The stability criterion for the explicit scheme is less severe than before.

$$\Delta t \leq \frac{\Delta x}{c} \tag{3.27}$$

3.4.2 Diffusion Wave Method

This method is based on the continuity equation (3.22) and the indicated part of momentum equation (3.23). Both the explicit and implicit schemes can be used to solve the equations. By using a linearisation, the two equations can be combined into a single equation of the convective diffusion type (Price, 1973):

$$\frac{\partial Q}{\partial t}+\omega\frac{\partial Q}{\partial x}=\mu\frac{\partial^2 Q}{\partial x^2} \tag{3.28}$$

where ω is the wave speed parameter and μ the diffusion parameter. Price (1973) proposed analytical expressions for the computation of ω and μ in irregular channels.

As discussed earlier, Cunge (1969) has shown that with the appropriate choice of space and time steps, Muskingum method can provide a good approximation to the equation (3.28) (See Section 3.3.2).

3.5 Summary

Compared to rainfall-runoff modelling, flood routing appears to be less complicated. Franchini and Pacciani (1991) agreed with the following statement of Cordova and Rodriguez-Iturbe (1983): " ... the problem is more *what* to route than *how* to route". A number of techniques of varying degree of sophistication are available to route a flood wave down a river channel. Depending on the accuracy required and the availability of data, one can choose methods ranging in complexity from simple hydrologic routing to the more complex numerical solutions to St Venant equations. As a first step, one should consider using Muskingum or the variable parameter Muskingum-Cunge method for flood routing. If this fails to provide satisfactory results, then a full dynamic wave model has to be used. Some of the computer software packages available for runoff routing are: System 11, NETFIL, RUBICON, DWOPER/NETWORK, FLUCOMP.

4. REAL-TIME CORRECTION

A major problem which often occurs in real-time flood forecasting is that the forecasted value is different from the observed value when the latter becomes available. This difference is due to

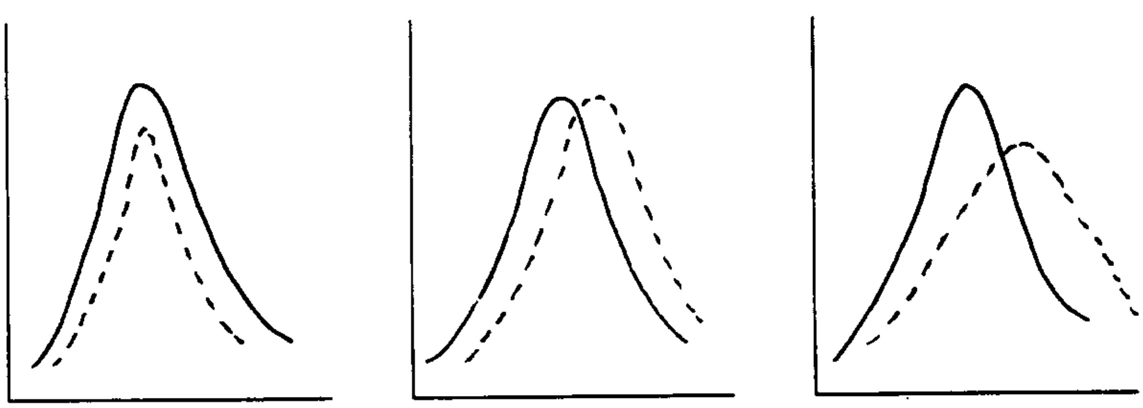
- errors induced by input data
- model imperfections
- inappropriate model parameters
- model is poorly initialised for the current event
- changes in catchment characteristics with time
- errors in the determination of discharge at the gauging station

Serban and Askew (1991) defined three basic types of error between simulated and observed hydrographs (Figure 4.1):

(a) volume or amplitude error, generally due to improper modelling of losses or errors in input data;

(b) errors in the timing of the simulated and observed hydrographs or phase errors mainly induced by the routing component of the model;

(c) hydrograph shape errors mainly induced by the transfer component of the model; for instance a unit hydrograph.



(a) amplitude errors (b) phase errors (c) shape errors

Figure 4.1 Three types of errors between the computed (---) and observed (—) hydrographs.

In practice, various combinations of the above three types of errors can occur. For application in real time, updating procedures have been developed which take account of the errors between the computed and observed discharges to correct the values computed by the forecasting models. Four different approaches can be used;

- updating input variables
- updating state variables
- updating model parameters
- updating output variables

4.1 Updating Input Variables

In this approach, input variables are updated to match the observed flow values. The primary variables that may be updated are rainfall and air temperature (where snow melt is modelled). Most procedures which update input variables are interactive and of the "trial and error" type because with most models it is difficult to determine the model input when the model output and parameters are given. The main steps in this procedure to be carried out at each forecasting moment are (Serban and Askew, 1991):

- computation of error between the measured and simulated hydrograph
- comparison of the error with a pre-defined acceptable level of error
- selection of the input variables to be adjusted, the adjustment increment for each variable and the maximum number of increments allowed in any computation period
- rerun of the model using the adjusted input variables.

In the WMO intercomparison project (WMO, 1992), three models (HBV, Sweden; TANK, Japan and SSARR, USA) updated only the model inputs (rainfall and snow melt or air temperature) while one model (CEQEAU, Canada) updated both the input (rainfall and snow melt) and output (discharge).

Cluckie et al (1990) employed an automatic technique in the transfer function model whereby forecast error is used to update a model scaling factor (Δ). The scaling factor acts as a real-time rainfall correction factor and applied on the rainfall terms as:

$$y_t = a_1 y_{t-1} + a_2 y_{t-2} + \dots +_p y_{t-p} + \Delta\{ b_1 u_{t-1} + b_2 u_{t-2} + \dots + b_q u_{t-q}\} \qquad (4.1)$$

and updated in real-time as given below:

$$\Delta_t = \mu\Delta_{t-1} + (1 - \mu)\frac{y_t - \{a_1 y_{t-1} + a_2 y_{t-2} + \ldots + a_p y_{t-p}\}}{b_1 u_{t-1} + b_2 u_{t-2} + \ldots + b_q u_{t-q}} \quad (4.2)$$

where μ is a parameter.

4.2 Updating State Variables

Using this approach requires that the catchment outflow or some other observable quantity acts as a state variable so that a telemetered observation can be used to update the state of the model directly. One justification for state variable updating is that errors in input are accumulated and appear as errors in the water content of the stores of the conceptual rainfall-runoff models which, if not corrected, will give erroneous output values. The amount of water stored in the conceptual stores is often updated by means of a Kalman filter to linear models or an extended Kalman filter to non-linear models. The Kalman filter can be integrated with transfer function models of the ARMA type (Wood and Szollosi-Nagy, 1978) or with the conceptual hydrological models such as the HFS model (Georgakakos et al, 1988) and the NAMKAL model (Refsgaard *et al*, 1988).

The application of Kalman filter to a physical system requires a description of the system dynamics as a system of linear equations of the form

$$X_{j+1} = \Phi X_j + \Gamma U_j + W_j \quad (4.3)$$

and a definition of a measurement equation of the form

$$Z_j = HX_j + V_j \quad (4.4)$$

where X a vector of state variables
U a vector containing input variables
Φ transition matrix
Γ input adjustment matrix
W modelling error vector
Z measurement vector
H measurement selection matrix
V measurement error vector

The matrices Φ, Γ and H can be constant or variable in time. The errors V and W are considered independent and normally distributed.

$$V \sim N(0,R); \quad W \sim N(0,Q); \quad E[V_i, W^T_j] = 0$$

The covariance matrix for the estimation errors is defined as

$$P_{j|j-1} = E[(X_j - \hat{X}_{j|j-1})(X_j - \hat{X}_{j|j-1})^T] \quad (4.5)$$

Once the initial values for X_o and P_o are established, the equations for the forecasting and updating are given below:

Forecasting at time j

state forecast	$\hat{X}_{j+1|j} = \Phi\hat{X}_{j|j} + \Gamma U_j$	(4.6)
measurement forecast	$\hat{Z}_{j+i|j} = H\hat{X}_{j+1|j}$	(4.7)
state forecast error covariance	$P_{j+1|j} = \Phi P_{j|j}\,\Phi^T + Q$	(4.8)

Forecast updating using the measurement at time j+1

correction matrix or Kalman gain	$K_{j+1} = P_{j+1|j}\,H^T[HP_{j+1|j}H^T + R]^{-1}$	(4.9)
state update	$\hat{X}_{j+1|j+1} = \hat{X}_{j+1|j} + K_{j+1}[Zj+1 - H\hat{X}_{j+1|j}]$	(4.10)
state forecast error covariance	$P_{j+1|j+1} = P_{j+1|j} - K_{j+1}HP_{j+1|j}$	(4.11)

The algorithm is repeated by substituting into equations (4.6) and (4.8) the estimated values of the state vector $\hat{X}_{j+1|j+1}$ and of the error covariance $P_{j+1|j+1}$ obtained from equations (4.10) and (4.11).

Good estimates of the system and measurement noise are essential if an optimal estimate of the state vector is to be provided by the Kalman filter. If the measurement noise is much larger than the system noise, less weight will be given to any new measurements in the updating of the state vector. This can lead to filter divergence. If the system noise is too large relative to the measurement noise, the filtered estimates will closely follow the measurements such that the filtered and measured estimates are essentially the same.

The effect of imperfect initial estimates of the system can be minimised by starting the estimation procedure well in advance of the initial period for which forecasts are required. This allows the filter to become tuned so that initial poor estimates of state have an opportunity to be damped out (Burn and McBean, 1985).

Puente and Bras (1987b) investigated the practical use of non linear filters on the Sacramento model using the data from the Bird Creek, Oklahama. The non linear filters used were:

- extended Kalman filter
- iterated extended Kalman filter
- extended linear filter smoother
- iterated linear filter smoother

The results emphasised the importance of the assumed noise component of the catchment model and depending on such noises, runoff predictions could range from excellent to unacceptable. When effective, the extended Kalman filter was found to be as good as the more complicated filters. Although smoothing algorithms lead to improvements, their computational burden might be unacceptable.

Moore (1986) presented simple state correction techniques which typically consist of a rule for weighting the amount of change needed to different model states in order to match or nearly match the latest observations. These have been adopted in the RFFS in preference to more formal Kalman filter based state correction methods because the latter have no outstanding advantages and are considerably more complex to implement (Moore et al, 1990).

In a grid-based distributed model, downstream flow is simulated by a coefficient equation having a single parameter transfer function model of the form (Cluckie et al 1990):

$$Q(t) = A.Q(t-1) + B.I(t) + B.I(t-1) \quad (4.12)$$

where $Q(t)$ outflow at river reach
$I(t)$ inflow at river reach
A, B parameters ($A + 2B = 1$)

State updating is used to update the inflow at each river reach using the observed flow at the outlet. The basic assumption is that error in the outflow $Q(t)$ is attributable to the inflow $I(t)$ and that $Q(t-1)$ and $I(t-1)$ are correct because they have been updated in the previous step. When the observed flow $\mathit{Q(t)}$ is available, the estimated inflow $I(t)$ can be updated as:

$$\mathit{I(t)} = (1 + \beta).I(t) \quad (4.13)$$

where β $[\mathit{Q(t)} - Q(t)] / B.I(t)$ and
$\mathit{I(t)}$ inflow at river reach after updating.

4.3 Updating Model Parameters

For this approach, one or more of the model parameters are updated in the light of recent model performance. At least three methods for real time updating of estimates of conceptual model parameters have been considered. They include:

(i) adoption of model to 'state-space' form (Kitanidis and Bras, 1978);

(ii) the use of iterative optimization techniques (Tucci and Clarke, 1980);

(iii) the direct minimisation of an objective function explicit in the parameters to be estimated (Chander and Shanker, 1984).

The first of these techniques tends to make the model more complex, while the last is limited to very simple models. The use of iterative optimization techniques encountered difficulties because inconsistent parameter values were obtained. There are several explanations for this occurrence, the main one being the effects of parameters' interdependence (Mandeville et al, 1970), the existence of different minima on the surface associated with the objective function (Johnstone and Pilgrim, 1976), errors in rain and/or streamflow observations (Schultz, 1986) and model deficiencies in adapting to the features of the physical system modelled (Moore, 1986).

Corradini and Melone (1986) employed a trial-and error procedure to estimate the sorptivity parameter S of their model so that an objective function is minimised. Another parameter, C, named the runoff-scaling factor, is used to take account of the residual error in the computed flow at the time of forecast, caused by the type of objective function selected. In reality, the procedure associated with the estimation of S at each time step of the forecast appears to be costly in terms of computer operation time and S is updated only when C lies outside the range 0.7 to 1.3.

4.4 Updating Output Variables

The difference between computed and observed flows is used to update the output variables. Output variables that may be updated include discharge, flood volume, hydrograph shape and lateral inflow. This is done by simply blending in the observed values (as in HEC1F model) or by predicting the errors in future based on auto regressive models (UBC, CEQUEAU, SMAR, and NAMS11 models).

In the first approach, the computed runoff hydrograph is blended with the observed hydrograph. A blended hydrograph consists of the observed hydrograph up to the time-of-forecast, a transition from the observed to the computed hydrograph for six time intervals following the time-of-forecast and the computed hydrograph from the end of transition to the remainder of the forecast period (Charley and Peters, 1988). The blended hydrograph is used in subsequent routing computations.

In the second approach, an auto regressive model is fitted to the errors, "e", between the computed and measured hydrographs:

$$e_j = a_1 e_{j-1} + a_2 e_{j-2} + \dots + a_p e_{j-p} + \varepsilon_j \qquad (4.14)$$

where p order of the auto regressive model
$a_1, a_2, \dots, a_p$ coefficients of the auto regressive model
ε_j residual errors.

Lundberg (1982) used an autoregressive (AR) model to model the residuals of the HBV model for the Eman Catchment in Sweden. The AR model gave considerable improvements for real short time forecasting, but for long term (10 days or more) forecasting, no improvement was achieved compared to the model. Separation of the error functions for high and low discharges did not give any further improvement.

The updating procedure used in the NAM-S11 model is based on "error prediction" simulating the deviations between measured and simulated runoff through a linear auto regressive model (Refsgaard, 1988). The simulated deviation is used to adjust the streamflows simulated by NAM prior to the routing by System 11 (a hydrodynamic river model). In the recent version of this model MIKE11, the updating procedure takes account of both the amplitude and phase errors.

4.5 Mutually Interactive State-Parameter Estimation

The Mutually Interactive State-Parameter (MISP) algorithm performs the state/parameter estimation using two interacting Kalman filters of different size. The first Kalman filter performs the minimum variance state estimation given the parameter set. The second filter performs the minimum variation estimation of parameters given the state estimate both at the present and previous time step (Todini, 1978).

4.6 Summary

Updating enables one to correct any errors in input variables such as rainfall and to adjust the initial states of a model in order to improve the model output. Updating is important for increasing the accuracy of real-time flood forecasting and appropriate updating techniques should be considered for inclusion in all forecasting systems (WMO, 1992). It was observed during the course of the 1987 WMO workshop (WMO, 1987) that subjective updating of model states and parameters requires a considerable amount of time and this makes it difficult in operational conditions where timely forecasts are required for a number of rivers.

Updating input or output variables is relatively easy to apply. Effectiveness of this form of updating depends on the degree of persistence in the updated variables and this method of updating may not correct errors in the internal working of the model. State correction provides a conceptually more appealing updating method by adjusting the state variables of a model to achieve agreement between observed and forecasted discharges. However, Kalman filter formulation is more complicated especially for complex models and this has resulted in the use of deterministic rules being applied to update the model states. The choice and correct application of an updating procedure can be as important as the choice of model (Serban and Askew, 1991). Parameter updating is not recommended (Serban and Askew, 1991) because in most models the parameters are not independent and the modification of one parameter would require the modification of other parameters. In addition, parameter updating in the presence of input errors may result in parameter estimates that are biased or physically unrealistic (Bacchi and Brath, 1989).

5. RAINFALL FORECASTING

In cases where the concentration time falls between three and five hours, rainfall forecasts are required to provide adequate lead time(Georgakakos and Kavvas, 1987; Brath *et al*, 1989; Foufoula-Georgiou and Georgakakos, 1989). Using a transfer function model with a lag time L, L step ahead forecasts of river flow Q can be based on the measured rainfall up to time t (time "now"). If the desired forecast horizon is H, then future rainfall up to time t+H-L has to be known. Currently available operational procedures for quantitative precipitation forecasting (QPF) are reviewed in Belloq (1980), Georgakakos and Hudlow (1984), Brown (1987), Georgakakos and Kavvas (1987) and Browning and Collier (1989). It is outside the scope of this report to review these procedures, however for completeness a broad overview of the different approaches is given.

5.1 Deterministic Method

Georgakakos and Bras (1982) developed a physically based non linear precipitation model in state-space form. The model uses observed or forecast values of temperature, pressure, and dew point temperature (wind speed if orography is important). Cloud microphysics gives expressions for the precipitation rate as a function of the input variables, the model state and the storm invariant parameters. Pseudo adiabatic condensation gives the input rate in the cloud column. A Kalman filter (Bras and Rodriguez-Iturbe, 1985) updates the model state in real-time from observations of surface precipitation. Tests of the formulated stochastic-dynamic precipitation model with operationally available hourly data have revealed consistently good predictions of precipitation at an observation station when the input variables are obtained from the same station. This model is being used by the NWS Warning and Forecast Offices for flash flood warning.

A similar forecasting framework including radar data was recently investigated by Seo and Smith (1992) and Georgakakos and Krajewski (1991). A two-dimensional formulation of a statistical-dynamic approach was investigated by Lee and Georgakakos (1990) and Lee (1991).

5.2 Statistical Method

Reed (1982, 1984) found that a simple auto regressive model was useful in forecasting rainfall up to 3 hours ahead. The model adopted to forecast rainfall for the Rhonda Catchment in the U. K. relates the rainfall in the next period to the rainfalls in the last and the previous period as

$$RF_{next} = 0.8RF_{last} - 0.2RF_{previous} \qquad (5.1)$$

where RF denotes the point rainfall.

Hino and Kim (1986) forecasted future effective rainfall rather than gross rainfall. Since the effective rainfall component for the longer-period runoff $u_i^{(1)}$ varies slowly as a result of the smoothing process of infiltration, the future longer-period component of effective rainfalls were predicted by the simple extrapolation formula:

$$u_{i+L}^{(l)} = \rho_L^{(l)} u_i^{(l)} \tag{5.2}$$

where L is the lead time.

As the shorter-period rainfall component $u_i^{(s)}$ fluctuates rapidly, a smoothed value was extrapolated.

$$u_{i+L}^{(s)} = \rho_L^{(s)} \left[\frac{1}{n} \sum_{j=1}^{n} u_{i-j+1}^{(s)} \right] \tag{5.3}$$

where n is the number of terms of summation. The values of $\rho_L^{(l)}$ and $\rho_L^{(s)}$ were empirical and were chosen as 0.8.

Hino and Kim (1986) applied this procedure to Kanna River, Japan and were able to obtain good forecasts up to a lead time of 5 or 6 hours.

Statistical analysis of historical storm events can result in a real-time prediction model for rainfall distribution (Croley *et al*, 1978, Creutin and Obled, 1980). Other rainfall generation models as described by Bras and Rodriguez-Iturbe (1976) and Jakubowski (1988) are designed for simulation purposes and are difficult to transform into a real-time operational model.

Bertoni *et al* (1992) used a transition probability model to forecast rainfall. Historical storm data recorded at a station are classified into states which divide the range of rainfall variation into a sequence of r non-overlapping intervals. The one-step transition probabilities are estimated from:

$$p_{ij} = f_{ij} / \sum_{j=1}^{r} f_{ij} \qquad i, j = 1, 2, \ldots, r \tag{5.4}$$

where f_{ij} is the frequency of transition from state i to state j.

Separate state transition matrices were determined for each season. For a small catchment in UK (18.6 km^2), rainfall forecasts were derived for lead time varying from 1 to 3 hours corresponding to non-exceedance probabilities of 50, 75 and 90 %. It was observed that for a non-exceedance probability of 50 %, the probabilistic forecasts were almost always better than the zero rainfall assumptions.

5.3 Radar Method

Recently, a lot of attention is being paid to weather radar as an aid to flood forecasting. Very short period (up to 6 hours) forecasts of rainfall in the U.K. have been made routinely using linear extrapolation of the motion of radar echoes. The system within which this is done is known as FRONTIERS (Collier, 1991). Forecasts for 3 - 18 hours ahead are being made using numerical weather prediction models. Cluckie and Owens (1987) investigated the performance of transfer function models using quantitative rainfall forecasts up to 6 hours ahead generated by the FRONTIERS system. They concluded that the FRONTIERS data generally provide a helpful forecast and could be useful to the hydrologist. Klatt and Schultz (1983) introduced a stochastic approach for forecasting rainfall based on weather radar information. With the aid of the probabilistic model, future rainfall is estimated according to its depth and duration and the chosen probability of non-exceedance.

Elvander (1976) carried out a series of experiments to forecast rainfall using three different techniques: a cross correlation method, tracking individual echoes using a linear least squares extrapolation of the motion of the echo centroid and a technique involving the tracking of individual echoes by considering the entire echo complex. It was concluded that the cross correlation model was the most effective when used with zero tilt reflectivity data while the linear least squares interpolation of echo centroids was the most effective method when the data on the vertically integrated liquid water content was used. These conclusions were based on forecasts up to 90 minutes ahead using instantaneous pictures at both 10 and 30 minutes intervals of convective rainfall. Using data smoothed over a grid length of 20 km for one case of frontal rainfall, Hill *et al* (1977) demonstrated that a cross correlation procedure provided quite successful forecasts up to 6 hours ahead. However, Browning *et al* (1974) and Hill and Browning (1979) showed significant differential motion of mesoscale precipitation areas within frontal systems for which this technique is not suited.

The SCOUT II.0 (Einfalt *et al*, 1991) method is an urban hydrology oriented forecasting technique. Since the emphasis is on heavy rainfall, a threshold for echo definition is fixed after a statistical intensity analysis of the whole image, leading to a selection of the heavy rainfall areas.

Anderson (1991) developed an advective model to obtain the probability of accumulated precipitation at a point. The source area upwind of the forecasting point is advected over it using the 850 hPa forecasted wind.

5.4 Numerical Weather Prediction Method

Conventional Numerical Weather Prediction (NWP) models represent explicitly only the large scale features of the weather and are best suited to providing forecasts of a general nature for periods beyond 12 hours ahead. Mesoscale NWP models, representing features of the weather on smaller scales of tens to hundreds of kilometres provide greater detail for the forecast period a few hours to 18 hours ahead. Thus for forecasts up to a few hours ahead, a better forecast is often achievable by observing the detailed distribution and movement of weather patterns and assuming that they will continue to travel without change over the very short period (up to 2 hours) concerned. This is known as nowcasting. The quality of the forecasts depends upon the lead time for which linear extrapolation is valid. For example, linear extrapolation may be very useful for forecasting the passage of frontal systems many hours ahead but for individual showers may only be useful for up to 20 minutes or so.

Although several types of non-linear forecasting procedures have been developed, the most reliable and generally applicable are procedures based on numerical models of the atmosphere. Such models may enhance the use of weather data in two ways (Collier, 1991):

- by providing data such as wind fields with which to aid the extrapolation radar echoes
- by using the radar data as an integral part of the model data assimilation procedure defining the initial humidity field.

The regional weather forecast models operate at present with meshes in the range of 250 x 250 km and the average quantitative precipitation forecast (QPF) estimated over these mesh sizes cannot be used effectively on catchments with sizes varying from 100 to 1000 km^2, particularly when the orographical effects strongly modify the spatial distribution of the rainfall field. The recent development of limited area models (LAMs) (Lazic and Telenta, 1990) and the use of eta coordinates in order to account for the presence of orography (Black, 1988, Mesinger *et al*, 1988) have introduced new possibilities of interaction between the regional and mesoscale weather forecast models and the operational real-time flood forecasts. These LAMs can operate on mesh sizes of 10 x 10 km by nesting them to the mesoscale weather models.

5.5 Neural Network

French *et al* (1992) developed a neural network to forecast rainfall intensity fields with a lead time of 1 hour using only the current field as input. It was shown that a neural network with a proper structure performed rainfall forecasting with an accuracy comparable or slightly higher than typical existing methods such as persistence and nowcasting.

5.6 Summary

Rainfall is usually assumed to be zero from the time of forecast to the forecast time and this results in considerable under estimation of discharges especially during the rising limb of a hydrograph. Rainfall forecasts are essential to forecast in small, mountainous catchments and for long lead times. Also, adequate estimation of areal rainfall from point measurements is essential. Radar rainfall can be used to improve the spatial coverage of the rainfall field and a number of research groups overseas are working on rainfall forecasting from radar data.

It can be seen from the above overview that reliable QPF is not possible at this moment. A lot of research work is being done to forecast rainfall based on radar, satellite and LAMs. The current status in Australia is that the numerical based precipitation forecasts produced by the Bureau of Meteorology have a resolution of 75 to 150 km grid at the surface and hence provide a very broad scale indication of the likely regions of rainfall. While the likely rainfall regions forecasted by the models are generally a good indication, the rainfall quantities are less reliable and extreme rainfall events are rarely correctly forecasted by the models (Farrel, 1993). Objective techniques using extrapolation of system motion from radar/satellite imagery have not yet been developed for operational use in Australia.

6. FLOOD FORECASTING SYSTEMS

The review in sections 2 and 3 was of the various flood forecasting methods that are available. This section reviews published examples of flood forecasting systems which, in addition to a forecasting method, include other elements such as data preparation as well as having, in some cases, a generalised framework to support a number of different methods.

6.1 River Flow Forecasting System

The Institute of Hydrology designed and developed a River Flow Forecasting System (RFFS) for use by the Yorkshire Region of the National Rivers Authority (NRA) (Moore and Jones, 1991). The system has been configured to make forecasts at 115 forecast points on the Ouse River Network and the other river networks within the 13 500 km^2 of the NRA Yorkshire Region. This has required the specification of 208 forecast requirement and 89 model component files. A total of 16 model algorithms are used and there is a requirement for 49 profiles. There are 1578 state variables of which 488 relate directly to the hydraulic model of the tidal Ouse.

An Information Control Algorithm (ICA) controls the flow of data required to make the forecasts and selects the model algorithms to be used. A set of description files describe a particular configuration of the forecast points within a river system. These files take two forms:

(i) a model component file which defines the form of model structure and data inputs to make forecasts

(ii) a forecast requirement file which defines for each forecast point the model component to be used to obtain the forecast for that point, the type of forecast and the connectivity with other model components.

A model component is made up of a number of model algorithms (Figure 6.1). The connectivity between the model components (Figure 6.2) allows the ICA to represent river systems with complex configurations.

The Probability Distributed Model (PDM) is used to transform rainfall and evaporation data into flow at the catchment outlet. A generalised form of kinematic wave (KW) model which makes allowance for varying wave speeds with discharge is used for flow routing. The pragmatic snow melt model, PACK, is used to represent the snow melt processes. The hydraulic model used for tidal modelling is based on the United States National Weather Service's DWOPER/NETWORK program (Fread, 1985) which employs a four point implicit scheme to solve the St Venant equations. Two forms of updating of model forecasts are used: state correction for the PDM rainfall-runoff model and ARMA error prediction for KW and the hydraulic models.

The kernel software of the RFFS is used as the basis of the White Cart Water Flood Forecasting system to provide flood warning to the southern parts of Glasgow (Anderson, *et al*, 1992). The RFFS kernel software is being currently developed for a pilot flood forecasting system in Hong Kong for the Indus basin (70 Km^2) in the New Territories. A strategy for the implementation of the RFFS throughout the Anglian region of the NRA is being developed (Moore *et al*, 1992).

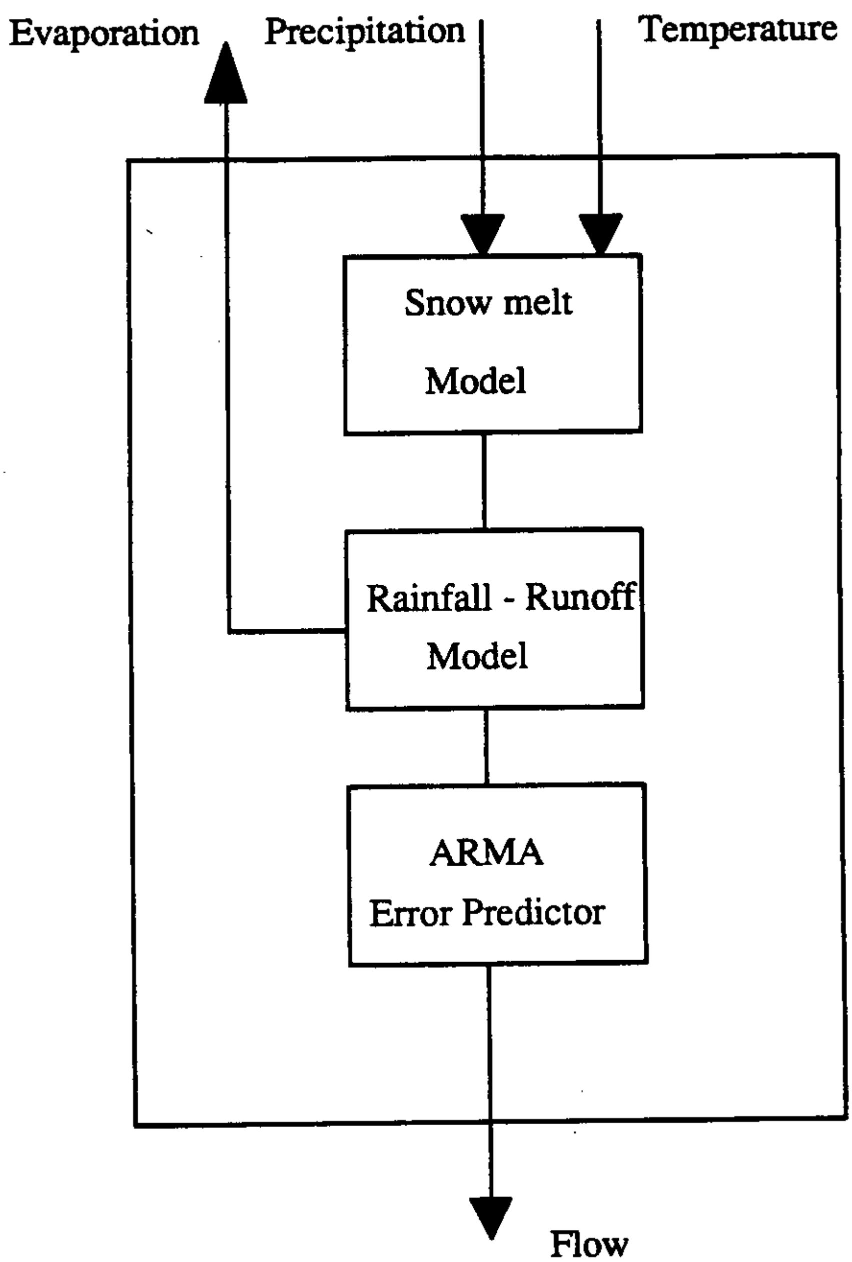


Figure 6.1 A model component and its associated model algorithms (Moore and Jones, 1991).

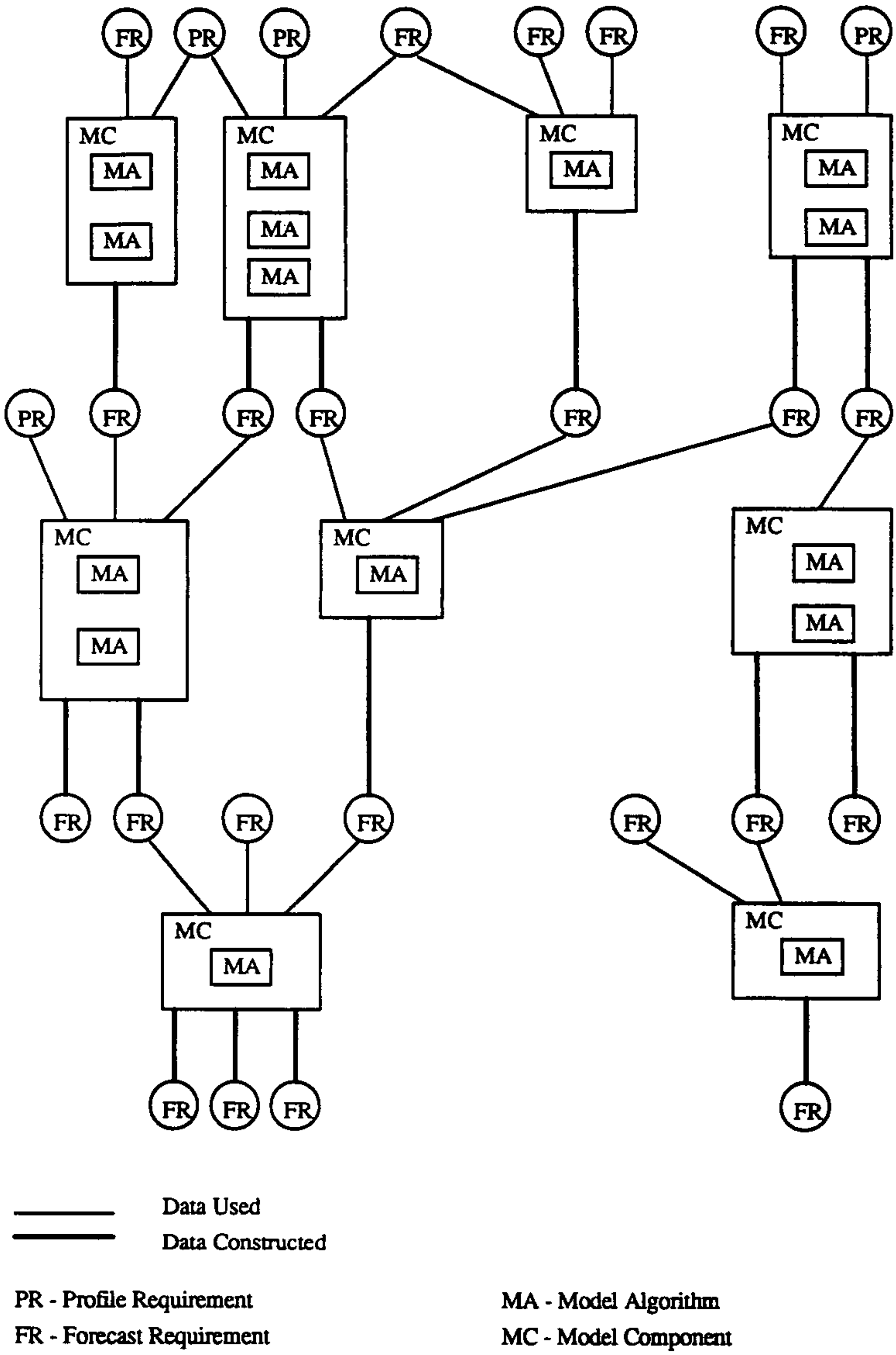


Figure 6.2 Connectivity between model components (Moore and Jones, 1991).

6.2 MIKE11 FF

The Danish Hydraulic Institute's flood forecasting modelling system is MIKE 11 FF model which consists of the following components (DHI, 1990):

- a real-time data management system with direct access data bases and user-designed data entry menus
- calculation of mean areal rainfall from point rainfall in a number of sub catchments within the area
- calculation of discharge from water level and rating curves or rating tables
- the NAM rainfall-runoff model to calculate sub-catchment inflow to the river system
- the hydrodynamic model SYSTEM 11 for routing the river flow and predicting water levels and inflow to reservoirs
- an automatic updating procedure which utilises the measured and/or calculated discharge or water levels for minimising the differences between observed and simulated flow/water levels at the time of forecast
- specification of quantitative precipitation forecasts and predictions of boundary inflow in the forecast period
- log file reporting of daily forecasts including accumulated inflow at user-selected sites.

The MIKE 11 FF can be used with either a manually based or a fully automatic data collection and processing system. In the first case, data entry takes place manually through menus while in the second case, a real-time data link has to be established to the telemetry system.

6.3 The Nile River Flood Early Warning System

The Nile FEWS has three main components (Grijsen *et al*, 1992):

(i) a Primary Data User Station (PDUS) with relevant software for receiving and processing Meteosat TIR images on a half hourly basis (AUTOSAT/ARCS).

(ii) a communication system for real-time transmission of water levels to the Flood Warning Centre in Khartoum.

(iii) a computerised Flood Warning System, consisting of a set of mathematical models (SAMFIL/NETFIL) and a temporary data base with an appropriate user interface.

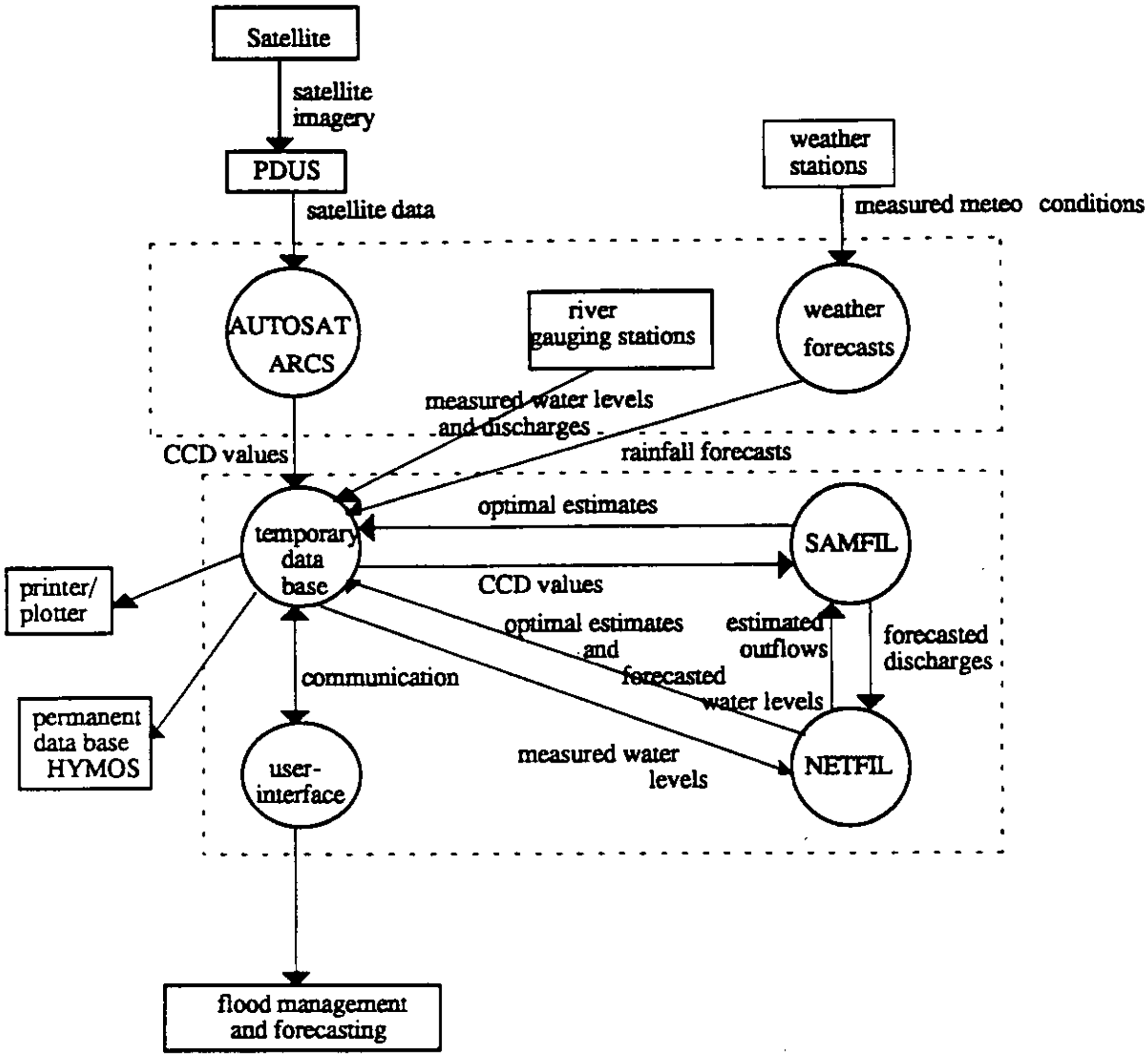


Figure 6.3 Structure of the Nile Flood Early Warning System (Grijsen *et al*, 1992)

The rainfall-runoff model SAMFIL is used to obtain the inflows from the catchments to the main river channels and the unsteady flow simulation model NETFIL is used to route the inflows down the main river network.

Forecasts are made for a ten days ahead. This is approximately the lead time between rainfall events in the upper catchments and the rise in water level at Dongola on the Main Nile River in the north of Sudan while the lead time for Khartoum is about six days. About three days are gained by run forecasting for the upper catchments of Blue Nile and Atbara rivers.

6.4 Hydrologic Forecasting System

The Hydrological Forecasting System (HFS/SPH) is an integrated software environment designed to execute the typical tasks involved in real-time flood forecasting (Cunge *et al*, 1992). This system was developed and applied for the first time to the real-time forecasting of Fuchun River levels and discharges. (LHF, 1991). It is claimed that due to its design and modular structure, it can be installed and used on-line at any forecasting site equipped with a data collection network, communication and data acquisition system. A catchment is divided into a number of communicating cells which are identified as hydrologically homogeneous sub-catchments or in the case of a network flow model, as elementary reaches of a river system. The user can combine forecasts either by selecting different methods for the same sub-catchments for comparison purposes or by modelling different sub-catchments by different methods. The recent version of the HFS methods library includes:

- the conceptual lumped rainfall-runoff models XIARNO (Todini & Partners, 1988; Zhao, 1977) and CLS (Natale and Todini, 1976)
- full dynamic wave model ONDYN (Cunge *et al*, 1980)
- time series model ARIMA (Box and Jenkins, 1976) and seasonal multiple regression model (Morrison, 1976)
- double Kalman filter MISP model for updating (Todini, 1978a)

Functional architecture of the HFS model is shown in Figure 6.4 The modelling capacity can be easily extended by incorporating other models into the system. It is a menu driven software package written entirely in Fortran 77 and C languages and is designed for a graphical work station environment under UNIX (SCO UNIX) operation system. The user interface uses a GKS graphics library and its hydrological data base is developed using the ORACLE database.

6.5 HEC1F

HEC1F was developed for real-time flood forecasting and flood control operations (Peters and Ely, 1985). It is a component of a software package that includes data acquisition and management (HECDSS), precipitation analysis, streamflow forecasting, reservoir system analysis and graphical display of data and simulation results (HEC, 1983). HEC1F is intended for short-term forecasts of flood runoff. It does not provide a continuous accounting of soil moisture and is therefore not suitable for long-term forecasting.

HEC1F makes use of two primary capabilities of HEC-1:

- parameter estimation to estimate loss rate, unit hydrograph and base flow in real-time.
- rainfall-runoff simulation using unit hydrograph and hydrologic routing procedures.

Real-time parameter estimation is generally limited to gauged headwater sub-basins. Application of HEC1F to large catchments is a two step process requiring two separate applications of the program (HEC, 1989). The first step is to estimate the parameters and calculate runoff hydrographs for gauged headwater sub-catchments. The second step consists of the following:

- runoff hydrographs are calculated for all ungauged sub-catchments using user-defined runoff parameters.

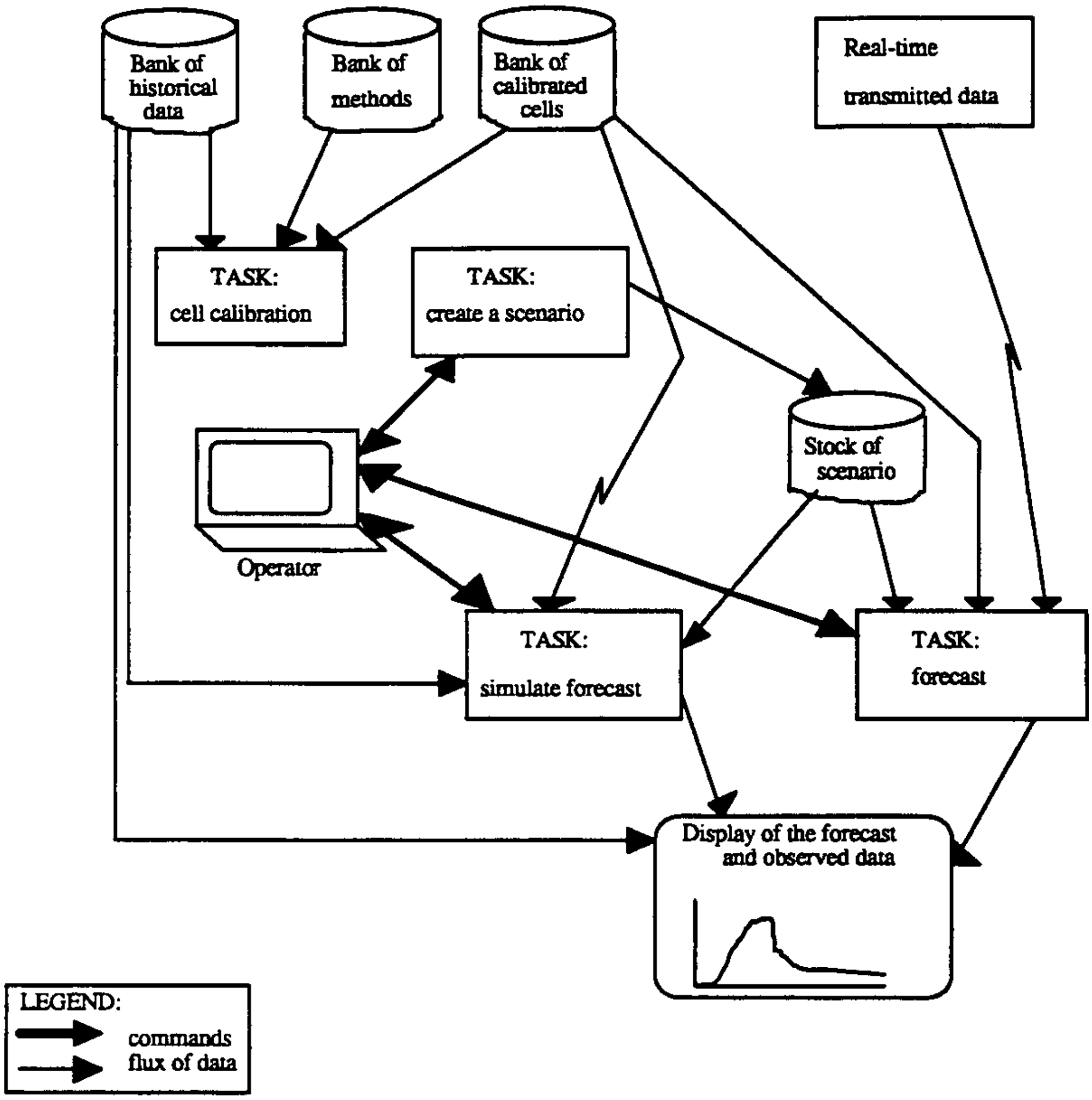


Figure 6.4 HFS functional architecture (Cunge *et al*, 1992).

- hydrographs are routed and combined throughout the basin.
- hydrographs are blended at each gauge prior to subsequent routing and combining operations.

6.6 National Weather Service River Forecasting System

The National Weather Service has developed a computerised system of hydrologic forecast procedures known as the National Weather Service River Forecasting System (NWSRFS). The NWSRFS is composed of (Hudlow, 1988):

- a system of models
- utility programs and data entry, preprocessing and processing modules to establish and maintain data files and assemble and prepare data
- a Hydrologic Command Language (HCL) to provide the forecaster with the flexibility for specifying forecast instructions and options control.

The hydrologic modelling capabilities within the NSWRFS include hydrologic models which simulate the runoff and routing processes, a reservoir model allowing simulation of reservoir operations and hydraulic models which utilise the continuity and momentum equations.

The soil moisture accounting system is based on the Sacramento Model. The model consists of a number of parameters to model the basic hydrologic processes in the soil mantle as they convert rainfall to runoff. The model must be run continuously as running it intermittently will destroy the model's ability to account for the soil moisture changes over time and will seriously compromise the ability of the model to produce accurate streamflow forecasts. A dynamic wave routing model known as the NWS Dynamic Wave Operational Model, DWOPER, is used to rout the flow through complex river systems.

6.7 EFFORTS

The EFFORTS package, a real-time flood forecasting system, has been designed on the basis of fully automatic data management and forecast result analysis. All data updates, reliability verification, sampling and reconstruction and mathematical processing for simulation or forecasting all occur automatically without human intervention (CEC, 1993b). The database used is ORACLE while the entire system has been developed in OS/2. Several hundred sensors can be managed on a 386 class personal computer.

The data currently used by the package are rainfall, temperature, water level, discharge and evapotranspiration. These data are analysed in advance to eliminate possible transmission and recording errors (validation phase). They are then processed to obtain a time-continuous series of values (sampling phase). Finally, they are reconstructed to eliminate any missing data (reconstruction phase). In real-time forecasting, a function has been introduced allowing an extrapolation model to be activated to obtain an estimate of the incoming data over the whole of the forecast period.

Outflow from sub-catchments is obtained from the ARNO model (CEC, 1993b) associated with a filter (MISP) which represents the stochastic component of the flood forecast system. The hydraulic flood propagation model PAB is used to determine the flood levels in various cross sections and establish the flood risk.

6.8 WATFLOOD

WATFLOOD (Kouwen, 1993) is an integrated set of computer programs for flood forecasting in catchments with response time varying from one hour to several weeks. There are computer programs to:

- create catchment files based on catchment characteristics
- convert radar constant altitude precipitation index maps to rainfall maps
- calibrate radar data with ground level rain gauge data in real-time environment
- perform simulation of the hydrology of a catchment
- plot the flow forecast at various scales.

While the WATFLOOD system has been designed to optimally use remotely sensed data, conventional data can be readily used to set up and operate the system. However, this does not allow the full potential of the model to be realised.

7. AUSTRALIAN AND OVERSEAS FLOOD FORECASTING APPLICATIONS

This section of the report looks at current flood forecasting systems both in Australia and overseas and the different forecasting methods being applied. This is to assess the extent to which the different methods reviewed in earlier sections of the report have found their way into forecasting practice as well as to identify overseas practices that have potential application in Australia. The issue of forecasting system performance is also discussed both to provide a basis for assessing the potential improvement offered by any new forecasting method as well as using relative forecasting performance to identify overseas applications that may have potential application in Australia.

7.1 Australian Applications

7.1.1 Bureau of Meteorology

As described in Section 1, the Bureau of Meteorology has a national responsibility for the provision of flood warning services. These services are provided through Flood Warning Centres in the Regional Offices in each State and the Northern Territory. In Western Australia and the NT the river prediction is undertaken by the respective State/Territory water agency. In the other States the majority of the prediction is done by the Bureau. The flood forecasting techniques currently in use in Bureau Flood Warning Centres include:

- empirical correlations; both for estimating peak river level from rainfall data as well as river peak height and peak travel-time correlations;
- unit hydrograph modelling procedures, including a range of simple loss models (API-Initial Loss, IL-continuing loss, proportional loss);
- experience methods based on analogues with past flood behaviour;
- hydrologic (Muskingum-type) flood routing and tributary combination procedures;
- non-linear network models (RORB, RAFTS, URBS); which have been used in both rainfall-runoff and river routing applications.

Unit hydrograph, network models and the hydrologic routing techniques are normally applied through computer programs. In some cases these programs are linked directly to the real-time data collection system, in others the data is manually entered. The empirical techniques are applied manually. Following the recent upgrading of real-time data collection systems in many of the Bureau catchments, more "on-line" systems have been developed. This work has mainly been done in Queensland and involves the development of direct interfaces between the real-time data base and URBS (Carroll, 1992) and the unit hydrograph model. No objective updating procedures are used, although adjustments are made to the forecasts during the flood event either subjectively through experience or by a direct adjustment of the rainfall loss parameters (for example) to produce a better match with the observed data, particularly at the start of rise of the hydrograph. In some of the routing models (eg URBS) the substitution of observed flows at the upstream nodes of the network for the model calculated flows has been used as a simple form of updating.

Appendix A contains a summary of the different procedures currently being used by the Bureau in Queensland, New South Wales, Victoria and Tasmania. In South Australia preliminary unit hydrographs and peak stage correlations have been developed for the Gawler and Onkaparinga Rivers. In Western Australia the WA Water Authority use a mix of empirical procedures and models developed from flood plain management studies for up to 10 basins, while in the Northern Territory the Power and Water Authority rely on 6 river stage correlations to forecast for the Todd, Katherine/Daly and Victoria Rivers. In considering the data in Appendix A it should be recognised that there are a number of techniques used to meet the forecasting requirements in each basin. Separate techniques will be used to forecast each segment of the river system, with often more than one technique for each segment being used as either a backup or to suit the characteristics of different flood event situations.

Table 7.1 summarises the detail in Appendix A. This table shows the number of basins with flood forecasting systems and the number of each type of technique or the number basins within which the technique is used. The extent to which empirical methods are used for both rainfall based and river based forecasting is illustrated, as is the heavy dependence on the unit hydrograph (UH) as a rainfall routing model.

Table 7.1 Summary of Forecasting Techniques Used in Bureau of Meteorology Flood Warning Centres

State	No of	Rainfall Data Based Technique			River Data Based Technique	
	Basins	Empirical	UH (a)	URBS/RORB	Hydrologic (b)	Empirical
Qld	32	109 (c)	16	11	8	24 (d)
NSW	27	21 (d)	83	4	33	27 (d)
Vic	20		4		4 (d)	13 (d)
Tas	10	8	14			15

Notes:

(a) Includes simple loss models
(b) Includes use of URBS model for flood routing
(c) All IL-API relations
(d) Number of basins in which type of technique is used

7.1.2 Other Agencies

A number of other agencies in Australia have an involvement in real-time flood forecasting and related modelling. A summary of these activities is presented in the following paragraphs.

Melbourne Water are involved in real-time flood prediction in and around the Melbourne metropolitan area. Flood prediction systems are operated in coordination with the Bureau of Meteorology who assist with rainfall forecast information and dissemination of the flood forecast information through warnings to the public and emergency services. Flood forecasting procedures are predominantly empirical formulae developed from historical data and/or hydrological models to form relationships between catchment wetness, current and predicted rainfall and flows in the waterways (Giessman, 1986). These systems are applied both manually and through computer programs using data from an extensive polled telemetry system. Recently a real-time version of RORB has been developed for the Watts River, Upper Yarra Dam and Diamond Creek catchments, and a model for the Maribyrnong River is under development.

The ACT Electricity and Water Authority operate a real-time data collection and flood warning system for the areas of the Queanbeyan and Molonglo Rivers flowing into the ACT (Falkland, 1989). As part of this system, the RAFTS model is run as a real-time flood prediction technique (Knee and Falkland, 1989). Data input for the model is prepared from hydrologic data stored in the HYDSYS data base and updated hourly by automatic polling of gauging stations. Work is currently underway to develop a Windows version of this system to improve the real-time access to the data and the linkages between the data base and the forecasting model. The graphical interface will provide instant access to information by simply clicking on a node representing a specific location.

Ruffini et al (1994) describe the work being done by Queensland Department of Primary Industries, Water Resources on the development of a real-time flood forecasting model for the Brisbane and Pine River catchments. This model has been developed for the South East Queensland Water Board and will be used for the operation of flood mitigation storages and to assist with flood warning in conjunction with the Bureau of Meteorology. The model is based on an early version of the runoff routing model (WT42) and uses loss models developed from calibrated versions of the Sacramento rainfall-runoff model.

In Tasmania, the Hydro-Electric Commission are developing a Windows NT modelling system based around the hydrologic data collection system HYDROL (Wilson, 1993). This work is aimed at developing a very flexible modelling system suited to the implementation of a range of different forecasting models and to be adapted to different river and water management systems. The system will be used to provide real-time inflow forecasts to HEC storages to assist with managing the hydro-power generation system. URBS (Carroll, 1992) and the AWBM (Boughton, 1993) are expected to form the basis of the initial hydrologic modelling applications to the system.

A number of local councils have been progressing the development of real-time modelling capabilities for use with ALERT flood data collection systems installed in conjunction with the Bureau of Meteorology. The NSW Public Works Department have developed a RORB model for the Tweed Valley, NSW (Avery, 1989), which has been available for use with ALERT data by the Tweed Shire council for about 2 years, although there has been little opportunity to date to use the model in a real-time flood forecasting situation. The Shoalhaven City Council have recently engaged Wollongong University to carry out a study of the application of the Sacramento model as a forecasting model for two sub catchments of the Shoalhaven River. Wyong council have engaged a consultant to develop a flood forecasting model based on Mike-11 and linked to the ALERT data base. The NSW Department of Water Resources has developed a flow (not flood) forecasting model to assist with water management decisions in the North-West Rivers area of NSW. This model, known as the North West Rivers Flow Forecasting Model (NWFLOW) is used to forecast daily streamflows at 57 locations along the rivers and creeks in the area, and allows the operator to forecast the likely effects of upstream water use on streamflows at critical downstream locations (DWR, 1993).

As part of the development of the Brownhill Creek flood warning system in the Adelaide Hills, a post graduate student has been engaged in the Masters Program in Civil and Environmental Engineering at the University of Adelaide to develop a real-time flood forecasting model using data from the recently installed ALERT system. This model may eventually be extended to other flash flood catchments in South Australia.

7.2 Overseas Applications

The information for this part of the review was collected by direct survey of contacts in forecasting agencies overseas as well as the use of available published material. It does not purport to be a complete summary as it was recognised that it would be unrealistic to attempt to contact every overseas agency with some activity in real-time flood forecasting. The information presented for the USA, UK, New Zealand and Canada has been summarised from published material as referenced. The information for the remaining countries is a summary of the response to a circular letter to the respective Members of the World Meteorological Organisation Commission for Hydrology (CHy), the UN specialised agency for operational hydrology.

7.2.1 USA

The US National Weather Service is responsible for the national flood warning service in the USA. The 13 River Forecast Centres (RFC) have the primary responsibility to prepare hydrologic guidance, including site specific river and flood forecasts and advisories. Each RFC area of responsibility is organised along river basin boundaries and provides flood warning services through networks of Weather Service Offices and Weather Service Forecast Offices who, along with other agencies, provide the RFC with the hydrologic data that is the basis of the river forecasts.

Since 1971 the National Weather Service has been implementing the National Weather Service River Forecast System (NWSRFS) which consists of a series of computer programs that process data and model physical processes. Hudlow (1988) describes the operation of the NWSRFS as centering around an operations table, consisting of a list of hydrologic procedures (operations) and the user-specified sequence in which the operations are to be performed. the operations included as part of NWSRFS Version 5 are listed in Table 7.2. A segment (group of operations performed as a unit) normally includes the operations necessary to compute the flow at a forecast point. To accommodate large river systems with many forecast points, segments are combined into various groupings and a forecast run could consist of the execution of single segment or a group of segments. This approach provides the forecaster with the flexibility to choose the appropriate mix of procedures to match the needs of each river. The modular framework and the well defined linkages between operations and the driver program allows new procedures to be added with minimum difficulty. It has typically been run as a batch program by forecasters at the RFC, submitted to the central computer facility over dedicated communication lines. As part of the modernisation of the NWS, computer facilities in each RFC will be upgraded and the batch version of the NWSRFS replaced by an interactive version run on-site at the RFC (Wiele and Smith, 1991). An overview of the interactive concepts behind the new NWSRFS are described by Adams (1991) and Page (1991)

Hudlow (1988) also describes plans to implement new developments in real-time forecasting techniques including an estimation theory updating procedure (Georgakakos, 1983) and a general purpose time series analysis-state space modelling - filtering - parameter estimation package, including an integrated hydrometeorological forecast system (Georgakakos, 1984; Georgakakos and Hudlow, 1985).

Table 7.2 Operations Available in NWSRFS Version 5 (From (Hudlow, 1988))

1	Temperature index snow accumulation and ablation model
2	Sacramento soil-moisture accounting model
3	Antecedent Precipitation Index (API) rainfall-runoff models used in the Missouri Basin, Ohio
4	Unit hydrograph with a constant and variable base flow option
5	Lag and K, Muskingum, layered coefficient, and Tatum routing procedures
6	Dynamic Wave Routing Model (DWOPER)
7	Reservoir model that allows the user to select and combine thirteen modes of regulation to simulate the operation of a single, independently controlled reservoir
8	Stage/discharge conversion using single-valued rating curves with log or hydraulic extensions
9	Simple flow adjustment and blend procedure
10	Simplified channel loss procedure
11	Computation of mean discharge from instantaneous values
12	Set time series values to zero
13	Add and subtract time series
14	Weight time series
15	Change the time interval of a time series
16	Plot instantaneous discharge
17	Operational hydrograph display
18	General time series plot
19	Daily flow plots (calibration use only)
20	Statistics package (calibration)

The forecast component of the NWSRFS consists of models that simulate snow accumulation and ablation, average evapotranspiration, base flow, interflow and surface runoff, reservoir operations, and river routing. Several different models are available for most types of processes. Wiele and Smith (1991) describe how the river systems in each RFC area of responsibility is subdivided into forecast groups and river segments, and how the NWSRFS is applied successively to each segment. Updating is provided through modifications applied to segments where the simulation shows an unacceptable departure from the observed flows. One approach is to modify observed data, for example automatically reported river stages may be clearly inconsistent with neighbouring values, may show no variation over time, or extend beyond an acceptable range. Adjustments to empirical rainfall runoff models can be made to more closely match actual event conditions to the average conditions used in the calibration, or unit hydrograph shapes may be adjusted to account for local variability in rainfall intensity. Alternatively blending procedures can be used which are essentially graphical adjustments that gradually adjust the forecast flow to match the observed flow within (say) 6-8 time periods.

7.2.2 United Kingdom

The National Rivers Authority (NRA) is responsible for forecasting flood risk for England and Wales. The NRA liaises closely with police, local authorities and emergency services to ensure that people living in areas at risk are warned. The NRA flood warning service operates through its 10 Regions. As an example of one of these regions, the procedures used in the Severn-Trent region are described.

The operational flow forecasting system used in the Severn-Trent Region is a well integrated system of real-time hydrological data collection and processing, forecast modelling and presentation, and provides for on-line access by a range of remote users involved in forecast dissemination and response. The system also includes an alarm monitoring and response facility through which remotely generated alarms can be displayed as well as retransmitted to duty officers, and can initiate outstation polling (Dobson, 1991).

The forecasting model used includes a conceptual rainfall-runoff model that uses rainfall from the telemetry system, with the optional blending with radar data, as input. Snow melt modelling is also included. The model includes a simple soil-moisture accounting process and a cascade of two non-linear reservoirs to simulate the runoff response function. The simple conceptual flow routing model used works by lagging and attenuating flows using simple algorithms, with allowance for static floodplain storage. The model is flexible and reliable despite having no direct hydrodynamic effects. A third model uses information observed in the latest 6 hours to update model forecasts using a very pragmatic "blending" approach. The forecasting models are described further in Dobson and Davies (1990).

7.2.3 Canada

Flood forecasting and warning in Canada involves a network of five provincial streamflow forecast centres across the country (Environment Canada, 1993). The approach in each province differs in response to the local needs and types of flooding. The province of Ontario will be used here as an example of one approach.

Ontario has decentralised its forecasting system and put much of the responsibility in the hands of the 38 Conservation Authorities and eight Ministry of Natural Resources regional offices. The Streamflow Forecast Centre is responsible for assisting the Conservation Authorities in planning and establishing systems and providing early alerts of threatening weather systems. One of these authorities, the Grand River Conservation Authority has developed the Grand River Flood Forecasting System which is described in the following paragraphs.

The objective of this system is to provide flood warnings to the flood prone communities in the basin as well as operate three major dams to mitigate the effects of floods. The system consists of a hydrologic data collection network, supplemented by telexed meteorological forecast information from the Atmospheric Environment Service and a videotex computer service providing weather maps as well as radar coverage, and various flood forecasting models.

Snow melt modelling aside, the primary flood forecast models used are:

(a) stage relation curves;
(b) hydrologic routing forecast model; and
(c) Grand River Integrated Flood Forecast Model.

The use of stage relation curves is a simple graphical method used for predicting downstream flood levels and requires only water level measurements from upstream and downstream gauges (Nedeco, 1959). This procedure has been found to give satisfactory results, although the assumption of no significant flow between the upstream and downstream points can be a limitation and seasonal changes in channel characteristics can result in shifts in the curves.

The hydrologic routing forecast model is used to forecast streamflow using hourly observed flows and reservoir water levels. The river system is divided into reaches defined by the location of the streamflow gauges and the observed flows are routed through the system by the Muskingum method, adjusting at each stage for local inflow. This method is independent of rainfall or snow melt data and tends to underestimate flows because of assumptions about local and headwater inflows.

The Grand River Integrated Flood Forecast System (GRIFFS) is a real-time streamflow forecasting model including rainfall-runoff modelling and combined rainfall-snowmelt modelling. The hydrologic routines in GRIFFS are based on the Guelph All Weather Storm-Event Runoff Model (GAWSER) with features that include; a modified Green-Ampt infiltration routine, Muskingum-Cunge channel routing routine, enhanced reservoir routing options, and overland flow routing routine and a subsurface routing routine (Environment Canada, 1989). The model is run using hourly input data and parameters are adjusted during the start-up period so that the first rise of the hydrograph is modelled correctly. The user can interact with the model during forecasting to substitute observed data for simulated data at upstream locations as a form of updating. Current work involves the incorporation of real-time radar rainfall data into the forecast model using the ground based telemetered rain gauge as ground truth (Kouwen, 1988), although this has not yet been implemented operationally.

7.2.4 New Zealand

In New Zealand regional councils are responsible for operating flood forecasting systems and associated day-to-day monitoring of river flows and rainfalls. A survey undertaken by Pearson and Jordan (1991) revealed that most forecasting methods used can be classed as "manual", that is, they involve a substantial amount of judgement on the part of the forecaster. For a few rivers however forecasting methods are more objective with the application of rainfall-runoff models and flow routing models taking much of the uncertainty out of forecasting. The "automatic" procedures used by the regional councils include linear systems approaches (Goring, 1984); conceptual catchment storage rainfall-runoff models; multiple linear regressions of flood peaks on moving average rainfall data (Rae and Wadsworth, 1990); empirical procedures using RORB (Griffiths et al, 1989), and HEC1 unit hydrograph rainfall-runoff models (US Army Corps of Engineers, 1973).

The second part of the survey was concerned with obtaining details of forecasting performance in recent floods and analysing these figures to draw conclusions on the reliability of current forecasting practices. Using a measure of reliability defined as the flood peak being both within 20% of the actual peak and made at least 3 hours before the actual peak, automatic procedures were shown to be considerably more reliable than manual methods, although it was acknowledged that the sample size of the survey was quite small.

7.2.5 Sweden

The agency responsible for hydrological forecasting in Sweden is the Swedish Meteorological and Hydrological Institute (SMHI) (Persson, 1989). Two forecasting methods are used; a regression method and a simple conceptual model, the HBV model. The regression method involves a multiple regression relationship between runoff volume and the precipitation at a number of stations in or near the catchment area. The method has been used only in northern Sweden and mainly in the upper and western parts of the river basins. Where the station density is low, an areal precipitation index derived from precipitation maps is used. This method is used for 43 catchments.

The HBV model is a simple conceptual model that uses only precipitation and air temperature as daily input data. Standard monthly values are used for potential evapotranspiration calculated using Penman's formula. The operational hydrological forecasting service based on this model started in 1976. The model is used to make forecasts for about 50 basins (Persson, 1989). About 100 forecasts are made every year at SMHI, with 1 to 10 forecasts in each basin per year on average. The system is also used by some water power companies, with some of the forecasting being conducted at the company offices.

The model is run continuously through the year for each basin, although it is used for forecasting almost solely during the winter and spring seasons. The model is used for two different types of forecast; the short range (5-7 days ahead) forecast using forecast precipitation and temperature, and a long range forecast made using 10 to 20 years of historical data to develop probability distributions of runoff sequences. Some updating is done by adjusting the input data (usually the temperature), but never the model parameters. This updating procedure was initially a manual iterative procedure but recently a semi-automatic procedure has been introduced where the correction to give agreement between recorded and observed hydrographs for a selected period is determined automatically.

7.2.6 Italy

Tomasino (1993) reports on the experiences of ENEL S.p.a., the Italian Electricity Board, who have an interest in the better management of hydro-electric reservoirs during flood periods. This problem is being addressed for two basins; one 6000 sq km for which forecasts are made up to 12 hours ahead, and a 300 sq km basin where hourly forecasts are required. Due to the geomorphology of the area, rainfall-runoff models have to run at hourly or 30 minute time steps. The hydrological rainfall-runoff models implemented are based on two different approaches; black box statistical modelling based mainly on the Constrained Linear System (CLS) model (Todini, 1978), and a conceptual semi-distributed model based on a version of the Xinanjiang model described by Franchini and Pacciani (1991). The problem of updating is addressed by correction of the forecasts rather than updating or recalibration of model parameters. The model predictions are directly corrected (or updated) by means of Kalman filtering or by the MISP (Mutually Interactive State-Parameter Algorithm) (Todini, 1978). The model forecasts are updated at each time step based on the differences between observed and forecasted flows at previous N steps (usually N<6).

Arno River forecasting system refers to the real-time data acquisition system of the Arno River. A real-time flood forecasting and warning system has been developed using the ARNO model to protect the city of Florence (CEC, 1993a). The Po River Forecasting System, developed for the Po River in Italy, is based on flood routing models combined to a stochastic component by means of the MISP algorithm (Todini, 1978a).

7.2.7 Poland

The river forecasting systems in Poland using rainfall-runoff models have been operational since 1975 and are operated by the Operational Hydrology Division of the Institute of Meteorology and Water Management. The rainfall-runoff models used have evolved from initially more complex conceptual models to the present systems based on simple but physically realistic models using efficient updating procedures. Two simple models used are the ISO model (Lambert, 1972) with a logarithmic storage-outflow relation, and the Nash cascade (Nash, 1960), the parameters of which are estimated via the geomorphological instantaneous unit hydrograph theory developed by Rodriguez-Iturbe and Valdes (1979). The ISO model has the advantage of simplicity however without adequate net rainfall estimation it performs poorly. An S-curve forecast procedure, using a ARMA-type transfer function model coupled with a linear Kalman filter for updating has been used with encouraging results. For updating flow forecasts, the linear Kalman filter enjoys considerable popularity in Poland and has been used for several years.

The performance of the simple models has been found, practically, to be as good as that of complex models, and are far more economical (Bobinski and Mierkiewicz, 1986). More recently a partial area model has been developed and applied to four mountain rivers in Poland (Bobinski *et al*, 1993). This model is to be linked with an atmosphere-land surface mesoscale model to improve the atmosphere-land surface component of the model.

7.2.8 Switzerland

The Swiss National Hydrological and Geological Survey is the federal agency responsible for hydrological forecasting in Switzerland. Since 1986 that agency has calculated and distributed forecasts for the Swiss part of the Rhine basin to power companies, river navigation, local public authorities responsible for flood control, and foreign authorities downstream responsible for flood forecasting and warning. The flood warning system is based on automatic water level alarm gauges and a year-round discharge forecasting system. This system is operated in close cooperation with the Swiss Meteorological Institute in Zurich who provide real-time (hourly) rainfall and temperature data, access to the radar-rainfall network, and quantitative precipitation and temperature forecasts for 72 hours from a high resolution nested numerical model. Discharge forecasts are calculated for three days ahead every working day, but increasing to 2-3 times every day during floods. Rainfall-radar data are now only used in a qualitative manner, but with the new generation Doppler radar in 1995 this will become a quantitative input. A nowcasting procedure is also planned to forecast rainfall for 2 to 3 hours. This will be an important input as there is only 8 to 12 hours from the top of the river basin to the border of Switzerland.

The forecasting model used is described by Lang *et al* (1987). The whole river basin is divided into the sub-basins of the different tributary rivers and lakes, taking into account the real-time network of river gauging stations. Individual forecasts are established for each of these sub-basins, beginning with the uppermost catchments. The river forecasting model is composed of four components and provides a forecast of discharge one-step ahead. The model is normally run at hourly time steps. The four components of the model account for the forecast inflow to the sub-basin from upstream, an estimate of the surface runoff from the sub-basin using an empirical approach to estimate the effective precipitation, an estimate of the recession flow from the sub-basin from the previous time step, and an autoregressive component relating the runoff directly to its antecedent value. The forecasting procedure also includes a snow melt and lake modelling component. No objective updating procedure is used although the forecast is recalculated every 1-2 hours with new observed data so this is unlikely to offer much improvement. There are plans to replace the forecasting model early in 1994 by the HBV model (Bergstrom, 1992).

7.2.9 Thailand

The Thai Meteorological Department, through the Hydrometeorology Division, is the government agency responsible for real-time flood forecasting and warning in Thailand (Uthaisang, 1993). The current real-time hydrological modelling practices as used for flood forecasting are carried out in the Pasak, Prachin Buri and Nan river basins, based on a Discrete Linear Cascade Model (DLCM). This model uses a series of linear reservoirs to represent a river reach and has two parameters; the number of reservoirs in the reach, and the travel time or storage coefficient of each reservoir. The error residuals of the deterministic part are modelled by a continuous error adjustment method to update forecasts. Downstream stage and discharge data are computed from upstream data and model parameters. Lead time of forecasting ranges from 1 to 6 days.

7.3 Flood Forecasting System Performance

The objective of a flood *warning* system is to enable and persuade people and organisations to take action to increase safety and reduce the economic and social costs of flooding. Flood *forecasting* is one component of this system and the performance of this component is a function of the timeliness and accuracy of the river prediction and the degree to which this prediction meets the requirement of emergency service and response agencies. Total system performance is affected by many factors which can cloud the role played by accurate forecasts, however it is clear that improvements in forecasting accuracy will have a positive influence on the total system. Measures of the effectiveness of hydrologic forecasts have been reviewed by Zevin (1983) including the different measures of accuracy used by agencies. These are normally limited to some simple statistical indicator derived from differences between observed and modelled river levels/flows and different indicators are used by the various agencies which makes comparison difficult. In an attempt to promote the systematic collection of information on performance, a strategy for monitoring the performance of individual flood forecasting systems is proposed by WMO (1990). This system known as MOFFS (Management Overview of Flood Forecasting Systems) is applied to the total flood forecasting system, not just the modelling component, and has not yet been fully implemented.

7.3.1 Performance of Australian Forecasting Systems

To date in Australia there has been no systematic reporting of the performance of flood forecasting systems on a national basis. Ideally the performance of the forecasting system (not the warning system) should include some reconciliation of the system output with forecasting requirements. In Australia flood forecasting requirements are normally determined in conjunction with emergency services and local response agencies. While these vary for different locations they are normally expressed in terms of the number of hours warning of peak heights or the height exceeding particular critical threshold levels. An example of the forecasting requirements for two locations on the Hunter River (NSW) are given in Table 7.3.

Table 7.3 Example of Flood Forecasting Requirements

Station	Flood Classifications (m)			Flood Forecasting Requirements	
	Minor	Moderate	Major		
Singleton	9.0	10.5	12.0	a.	require 18-24 hours warning of peak height if less than 9.0 metres
				b.	require 12 hours warning of peak height if greater than 9.0 metres
				c.	evacuation routes are cut at 12.8 metres.
Belmore Bridge	6.1	9.1	10.7	a.	6.1 metres at Belmore bridge equates to approx 7.5 metres at Maitland
				b.	require 12 hours warning of 6.1 to 7.3 metres
				c.	require 24-48 hours warning of heights greater than 7.3 metres
				d.	require 24-48 hours of peak heights
				e.	Maitland levee protects to 12.5 metres (equates approx to 10.7 metres at Belmore Bridge).

7.3.2 Australian Forecasting Accuracy

An indication of the general level of accuracy being achieved is shown in Figure 7.1 which shows the average level of accuracy of river height prediction in the New South Wales Flood Warning Centre for the period 1988 to 1992.

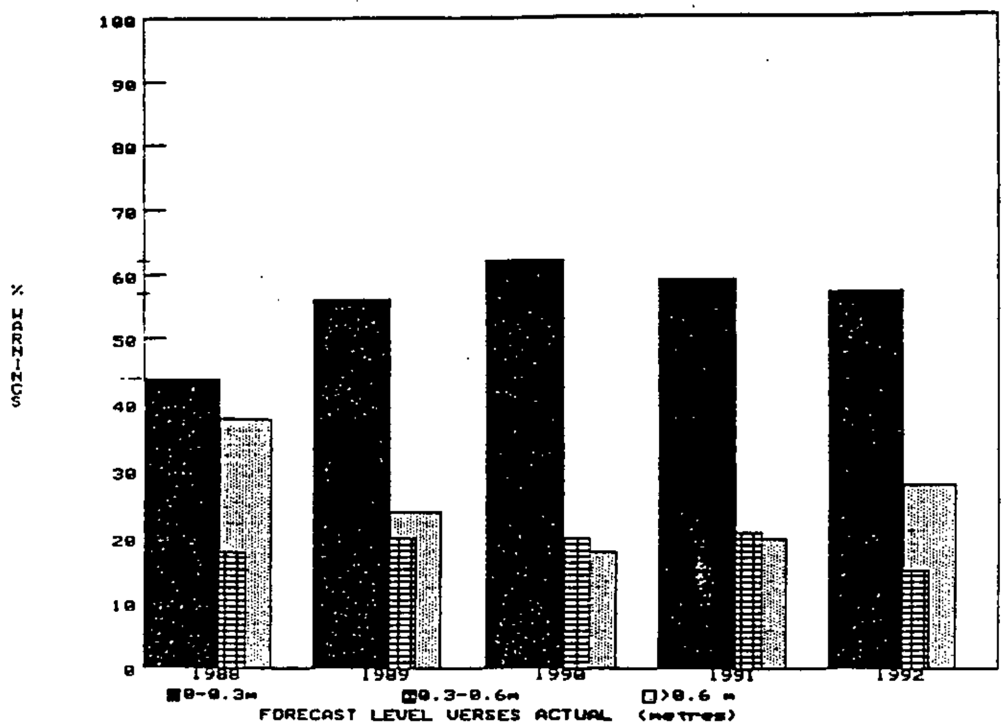


Figure 7.1 Summary of Forecast Accuracy NSW Bureau of Meteorology Flood Warning Centre, 1988-92

These figures have been averaged across all river basins with flooding during each year. Similar figures are available for Queensland. In other regions, reports on the performance of the flood forecasting system are prepared after selected events. Without an indication of lead time or an appreciation of how well the forecast requirements were met, accuracy is not a particularly meaningful indicator of forecast quality. Ideally these figures should be assessed in terms of how well the warning requirement was met in each case. However these requirements are not presently as refined as the example in Table 7.3 and this form of performance reporting is not possible on a systematic basis.

7.3.3 Performance of Overseas Forecasting Systems

The review of overseas forecasting practices reported here did not specifically seek objective information about the quality of forecasting in each country. As discussed above, forecasting performance is not measured simply and it is difficult to make comparisons between agencies without using some common system. What may be considered acceptable performance in one application may not be adequate in another. Furthermore the quality of river prediction is influenced by other factors besides the real-time model used; in particular the quality of data inputs has a major influence and this varies between countries. Before any conclusions can be drawn about the transferability of any apparent improved level of performance by a particular system, the interdependence between the model and the data network, and the relative impacts of their respective contributions to improved performance needs to be examined carefully. This can be a difficult task. This makes comparison between countries and judgements about the merit of different forecasting methods potentially unreliable, unless appropriate attention is paid to understanding the impacts of the other elements of the forecasting system on forecast quality.

The review of the effectiveness of hydrologic forecasts cited earlier by Zevin (1983) reported on forecasting accuracies in some overseas countries. These are summarised in Table 7.4 and are included here for information and are not intended to be used as a basis for comparison.

Table 7.4 Summary of Forecast Accuracy for Overseas Forecasting Agencies (from Zevin (1983).

Country	Agency	Forecast Accuracy	Comment
Brazil	CESP - Sao Paulo	< 10%	
	DNOS - Rio de Janeiro	Largest errors in 4 week forecasts (up to 0.6m)	
Canada	Environment New Brunswick	1 day flow forecast +/- 10%; stage forecast +/- 0.2m	Acceptable accuracy levels
	Environment Quebec	10% - 1 day ahead 20% - 2 day ahead 35% - 3 day ahead	
	Manitoba Ministry of Natural Resources	Good < 22% Fair 22-37% Poor > 37%	Performance categories
Hungary	VITUKI - Tisza River	0.4-0.9m for 1-4 day forecasts in upper basin areas; 0.15-0.5m for 2-5 day forecasts in mid-lower basin	RMS errors since 1979.
	VITUKI - Danube	2 day ahead 0.15-0.3m 97% time; 3 day ahead 0.25-0.4m 97% time; 4 day ahead 0.40-0.65m 97% time.	Use coefficient of efficiency (η) to categorise forecasts as Good ($\eta > 0.85$), Acceptable ($0.6 < \eta < 0.86$)
India		Within 0.15m in more than 85% cases	
USA	13 points in central US	<1% of forecasts in error by 0.5m	

7.4 Summary

As an aid to identify more promising areas for investigation, this part of the review has proved of limited value. While different procedures are being used, these are being implemented within flood forecasting systems established to meet the needs of those areas and to suit the organisational arrangements set up in each case to provide flood warning services.

Conclusions from this review are made cautiously because it is limited in coverage however a number of points can be made.

While there are exceptions in a number of individual cases, the review did suggest however that there is still a gap between the techniques in the research literature and those in widespread use in forecasting agencies. Why this is so is not clear; it could be because the work needed to transfer research results into a working system suited to the requirements of operational agencies has not been done, or it could be that forecasting agencies are aware of the techniques but don't consider the potential improvements justify the investment required in their implementation. Some combination of both reasons is most likely to be the case. This project provides an opportunity and some resources to help bridge this gap.

Compared to many systems overseas, data collection networks in Australia have, on average, been of lower quality and the forecasting methods in common use have matched the capabilities of these systems. It is interesting that, despite better data collection networks, simple methods are still used to some extent in other countries, including the United States. However when judged against methods currently being implemented as well as those planned for future implementation, recent moves in Australia to introduce more hydrologically based procedures through the work with URBS, RORB and the RAFTS modelling in particular to match improvements in local data networks, is clearly consistent with overseas directions and this project is timely both to help accelerate this work as well as assist with the systematic identification of alternatives from among those identified in the review.

8. RECOMMENDATIONS ON FURTHER WORK AND FUTURE RESEARCH NEEDS

This section presents recommendations on the areas for further investigation in the project and identifies a number of areas where further research is needed.

8.1 Australian Forecasting Requirements

As mentioned earlier, flood forecasts are currently provided for hundreds of locations throughout over 70 river basins in all areas of Australia. Quantitative forecasts are normally limited to the larger river basins with response times typically of 6 hours or more, and forecast lead times usually vary from 6 to 24 or 48 hours ahead, with longer lead times on some of the slower moving rivers. In urban areas, flash flooding of small creeks and drainage systems is a particular risk where only short lead times are possible, often relying on meteorological forecast information. Currently only very generalised warnings are given for this type of flooding.

The real-time modelling requirement in each case is different, with flash flooding commonly involving shorter lead times and more frequent updating compared to the longer lead time forecasts in the more rural areas. A recent feasibility study on the provision of improved flash flood warning services for the Sydney-Newcastle-Wollongong region in New South Wales identified the importance of adequate radar-rainfall measurement and forecasting systems, including appropriate real-time data collection and on-line processing systems to the development of an improved service. While hydrologic modelling was identified as a component of this system, the critical elements were the need for radar based weather monitoring and forecasting as well as an efficient public warning and dissemination system. With flash flooding the difficulty is more often locating where flooding will occur than in estimating the particular water level. Because of the dependance on forecast rainfall, the quality of inputs to the hydrologic models may not be high, so simple robust models suited to automatic operation, producing forecasts for relatively short lead times should meet the majority of requirements.

For the larger rivers with longer potential lead times, the response component of the warning system is more sensitive to the quality of the river prediction and it is in these situations where the potential benefit of improved river prediction can be immediately realised. Recent efforts, particularly in New South Wales, to encourage response groups to better define their requirements have been encouraging and will place growing demand on the quality (accuracy and timeliness) of river predictions. For long, slow flowing rivers such as those in western New South Wales and Queensland simple flood routing methods are normally adequate and the quality of the real-time data collection often becomes more critical than model accuracy in determining the ultimate quality of the river prediction. Forecasting for catchment areas with response times up to about 36-48 hours requires some form of rainfall-runoff modelling. These could either be catchments in headwater areas of larger catchments or local inflow situations along the longer rivers. While the quality of real-time data collection is again a critical factor, model accuracy plays a much more important part and the implementation of improved rainfall-runoff models has potential to yield significant benefits to existing flood warning systems.

A requirement noted in section 1 was the potential need for some form of generalised modelling framework to facilitate the application of different models as needs change and forecasting methods evolve. This framework has been provided in the US NWSRFS system for example (section 7) and section 6 reviews a number of sytems developed recently that provide this flexibility. Adopting such an approach is seen as an essential element of the modelling system developed in this project if the future operational needs of central forecasting agencies like the Bureau of Meteorology are to be met efficiently. These systems provide a framework that integrates routines for the calibration of models as well as supporting their real-time application, using a modular and generic design approach to allow the use of a wide choice of hydrologic forecasting models and procedures. From section 6 it appears that the RFFS system (Moore and Jones, 1991) is the most promising example to investigate further and it is recommended that this approach be investigated for application as the overall flood forecasting modelling framework to support the development of improved forecasting models in Australia.

Flood forecasting is also undertaken by a number of large regional water agencies (eg Melbourne Water, South East Queensland Water Board, etc) as well as by local government agencies as part of the cooperative provision of flood warning services under national policy guidelines. Unlike Bureau Flood Warning Centres, these agencies are normally only concerned with a single river system. Many local government agencies have a particular need for robust models to meet their river prediction needs that can operate reliably without the need for the support of hydrolgy specialists who are generally not as available in these smaller agencies. As the real-time data collection systems are often shared between the local agencies and FWC and since the FWC interacts with the local agencies during floods, these models ideally will be suited to operation in an open computing environment and within the same overall hydrologic modelling and data management framework described above to facilitate sharing and the cost-effective use of available resources.

8.2 Methods Recommended for Further Investigation

As might have been expected, this review has not clearly identified one forecasting method as being clearly superior to others. From the review it is considered that the most promising approach to rainfall-runoff modelling for real-time flood forecasting from among the techniques currently available is the combination of a simple conceptual soil-moisture accounting model and an objective updating procedure. Although there is little by way of comparative studies available, results of exercises such as that undertaken by WMO (WMO, 1992) and the published results of the application of different models suggests that simple models, when coupled with some form of updating procedure, perform as well as the more complex models. A clear conclusion from the WMO exercise was that inclusion of some form of updating was important for increasing the accuracy of all models tested. Some form of automatic updating is preferred as it was noted that subjective updating procedures may be too time consuming for real-time application. Approaches such as ARMA methods have been shown to perform as well the more complex conceptual models (Kitanadis and Bras, 1980) for the short forecast lead times, however some form of soil moisture accounting approach appears to offer advantages for the longer lead times. This is supported by the finding of the WMO comparison (WMO, 1992) where all modellers considered it necessary to have a good simulation model to achieve consistently good results for the longer lead times as well as Chiew *et al* (1993) who identified the importance of a good conceptual basis to successfully simulating daily flow sequences.

A simple model such as NAM, as used in the Mike-11 modelling system fits the above requirements and has been used succesfully in many applications overseas and in Australia. There are other models that also fit this category, but these don't seem to have had such widespread use. It is recommended that the NAM model, with its existing updating algorithm, be investigated and its performance compared to existing forecasting procedures.

A shortcoming of updating approaches based on adjustment of output variable (such as used in NAM) is that errors in the model for the particular event being forecast are left without correction for subsequent forecasts during the event. The Alabama Rainfall Runoff Model (ARRM) (Henry *et al*, 1988) is a simple model set up in state-space form with an updating procedure that adjusts the model state at each time step. As it fis the above basic requirements and as an example of an alternative updating approach, it is recommended that this model also be investigated and included in the comparison.

As an Australian development and recognising the promising results in the work to date (Boughton and Carrol, 1993) it is also recommended that the combination of AWBM and URBS, linked with an updating technique also be included in the comparison. URBS has an advantage over other available non-linear routing models in that, while it has a similar routing feature to RORB, it is configured in a form that is particularly suited to real-time application. Because of the large number of RORB model calibrations available and the progress with the real-time use of RORB by Melbourne Water in particular, a comparison between the performances of RORB and URBS will be useful.

The simplest approach to updating for the AWBM-URBS combination would be the use of one of the algorithms decribed in section 4.4 based on adjustments to the output variables or error prediction. This avoids the need to reconfigure the model into the state-space form required for other approaches. It is recommended that one of the algorithms from section 4.4 be selected and coded as a module for application to the AWBM-URBS model, but also for general application to other models (for example as an alternative to the current approach used in NAM).

As indicated above there are a number of other models that could be included in the comparison, however this will be limited by available resources. Another approach that has been used by a number of models involves a simple partitioning of the catchment response into "quick" and "slow" response components. Dependant on available resources it is recommended that examples of this form of model (eg CLS, IHACRES, filter separation AR method) could also be considered for further investigation.

The major area where the forecasting methods reviewed in section 2 differed was in the approach used to estimate runoff from rainfall. A unit hydrograph or unit hydrograph-type approach was commonly used to route rainfall excess, with spatial variability being handled either by applying a lumped model to small sub-catchments or the use of some form of network model. Modelling rainfall excess remains one of the most difficult modelling problems in hydrology generally, and is identified from this review as the component of the real-time modelling process that needs further research. This research is the subject of Project D1, "Improved loss modelling for design flood estimation and flood forecasting".

The unit hydrograph method is still widely used and, in view of the current bank of unit hydrographs available in forecasting offices, this approach should be included in future investigations. The adaptive unit hydrograph method (Amirthanathan, 1993) has been investigated for some Australian catchments with promising results. It is recommended that this investigation continue and that the model be included in the comparison. An alternative approach is that developed by Chander and Shanker (1984) involving on-line computation of rainfall excess. As this approach could make direct use of existing unit hydrographs, it is recommended that it be further investigated.

The SIMPLE model, as used in the WATFLOOD system, may be considered at a later stage. This model is not favoured at this initial stage of the project since it has been configured to suit remotely sensed inputs (radar and satellite) which will be an advantage at some later stage when these inputs can be more readily interfaced, however these inputs are not readily available as yet in Australia. Furthermore, the model has not the same widespread use as NAM (Mike11). The HBV model was another model considered, however this model has been developed with the particular requirements of the Nordic countries in mind and, while the number of applications in other parts of the world is growing, was not considered to have any particular advantage in the climatic regimes of flood prone areas of Australia.

Flood routing methods are generally well developed and selection of a method is determined more often by the availablity of data. Muskingum-type methods have been favored for their simplicity and real-time forecasting versions of these have been developed. For this project it is not recommended that any development work be undertaken in this area. Where a flood routing module is included as part of the method being investigated (eg Mike11) this will be used. Otherwise one of the Muskingum-type methods will be adopted within the generalised approach recommended. Alternative flood routing models could be eventually incorporated as options in the system as it evolves.

8.3 Evaluation of Alternative Methods

From the earlier discussions it is apparent that it is difficult to establish a benchmark from existing performance information against which potential improvements in forecasting models can be easily assessed. The approach recommended for this project is to efectively simulate the operational modelling sequence to generate a series of forecasts at different lead times for a number of historical events and, using a selection of the statistics suggested in the review of model evaluation techniques reported in Appendix B, make objective comparisons between methods. The baseline for this comparison would be the existing forecasting technique for the selected catchment. This would be repeated for several catchments representing a range of forecasting problems.

8.4 Summary

In summary then, the approaches recommended for further investigation are:

(a) the adaptive unit hydrograph modelling work of Amirthanathan (1993), and the unit hydrograph-based model of Chander and Shanker (1984).

(b) a combination of either AWBM and URBS (Boughton and Carrol, 1993) or AWBM and RORB, but coupled with an updating algorithm chosen from the approaches described in section 4,

(c) the Mike11 model,

(d) the Alabama Rainfall Runoff Model (ARRM),

The comparison/evaluation of each of the above be based on their respective performance on a selected set of catchments and include comparison with existing forecasting procedures.

As a framework for future development, calibration and real-time application of flood forecasting methods, the approach embodied in RFFS (Moore and Jones, 1991) be further investigated.

8.5 Future Research Areas

The following areas have been identified as requiring further research.

(a) The brief review of rainfall forecasting methods in section 5 noted some of the applications of radar estimates of rainfall, both as real-time measurements and short term forecasts, to flood forecasting modelling systems. Forecasting models need to be adapted to utilise this form of input. A project that is aimed at implementing some of the existing technologies for processing radar data and interfacing this data to hydrologic forecasting models under Australian conditions is seen as a high priority for future research.

(b) Quantitative forecasts of precipitation are required to improve the lead times of flood forecasts. This is particularly important for the the short response time catchments. Noting the difficulty of this forecasting problem and the assessment that significant breakthroughs in the development of a robust operational method are not on the immediate horizon, it is recommended that links be established between this project and the current research in precipitation forecasting to provide the hydrological framework for testing improvements.

(c) Poor quality rating curves restrict the application of hydrologic modelling techniques to many forecasting problems. The review failed to identify any recent developments in either flood routing techniques that work with river levels not flows, or techniques that model river levels (not flow volumes) from rainfall inputs. This is another area where further research is needed.

(d) Operational forecasters still rely on subjective experience, based largely on the pattern of river behaviour in past floods. Despite advances in real-time modelling, it is likely that forecasters will always require some form of re-presentation of data from past events in an analogue form. The potential for an application of recent developments in "expert systems" to assist here seems high and is suggested as another area where further research could be considered.

(e) The application of neural networks to real-time flood forecasting.

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APPENDIX A

Table A.1 Flood forecasting techniques and methods used in Queensland Regional Office

Basin	Rainfall Data Based				River Data Based			
	API /IL	Regression	Unit Hydro -graph	URBS	Regression	Peak Stage	Lag & Route	UR
South Coast	2			1				
Logan-Albert	5		2	2		*		
Brisbane	11	*	5	1		*	1	
Pine	2							
Maroochy	2							
Noosa	1							
Mary	10		1	1		*		
Burrum						*		
Burnett	6					*		
Kolan	1					*		
Fitzroy	12					*		
Pioneer	2		1	1		*	1	
Proserpine	1							
Don	1			1		*		
Burdekin	5			1	1	*	1	
Haughton	1		1	1		*	1	
Herbert	3		1	1		*		
Tully	1		1					
Johnstone	2		2			*	1	
Barron	3					*		
Condamine	11		2	1		*		
Border	8					*		
Moonie	2					*		
Warrego	1					*		
Paroo	2					*		
Bulloo	2					*		
Cooper	3					*		
Diamantina	2					*		
Georgina	4					*		
Flinders	3					*		
Norman								
Gilbert								

* used extensively

Table shows number of applications of each technique/method in each basin

Table A.2 Flood forecasting techniques and methods used in NSW Regional Office

Basin	Rainfall Based		River Based		Network Model
	Empirical	Unit Hydro -graph	Empirical	Hydrologic	
Tweed	*	*	*	*	RORB
Richmond	*	*	*	*	RORB
Clarence	*	*	*	*	
Macleay	*	*	*		RORB
Hunter	*	*	*		
Nepean-Hawkesbury	*	*	*	*	
Georges	*	*	*	*	RAFTS
Murrumbidgee	*	*	*	*	
Murray			*		
Warrego			*		
Shoalhaven	*	*	*	*	
Macintyre	*	*	*		
Barwon			*		
Darling			*		
Gwydir	*	*	*		
Namoi	*	*	*	*	
Castlereagh	*	*	*		
Macquarie	*	*	*		
Bogan	*	*	*		
Lachlan	*	*	*	*	
Culgoa			*		
Molonglo	*	*	*	*	
Manning	*	*	*		
Bellinger	*	*	*		
Hastings	*	*	*	*	
Moruya	*	*	*		
Paroo			*		

* used in the basin

Table A.3 Flood forecasting techniques and methods used in Victoria Regional Office

Basin	Rainfall Based		River Based		Network Model
	Empirical	Unit hydro -graph	Empirical	Hydrologic	
Cann-Genoa					
Snowy			*		
Mitchell			*		
Latrobe			*		
Avon			*		
Thompson-Macalister			*	*	
Yarra		*		*	
Maribyrnong		*		*	
Werribee		*			
Barwon		*	*	*	
Glenelg					
Upper Murray					
Murray			*		
Kiewa					
Ovens & King			*		
Broken			*		
Goulburn			*		
Campaspe			*		
Loddon					
Avoca			*		
Wimmera			*		

* used in the basin

Table A.4 Flood forecasting techniques and methods used in Tasmania Regional Office

Basin	Rainfall Based		River Based		Network Model
	Empirical	Unit hydro - graph	Empirical	Hydrologic	
Derwent	2	2	1		(a)
Huon	1	1			
Forth			1		
Mersey			2		
South Esk	2	4	5		
North Esk	1	1			
Meander	1	1	2		
Jordan		1			
Coal					
Macquarie	2	2	4		

Notes:

(a) The Hydro-Electric Corporation uses Mike-11 to forecast inflows to storages.

Table shows number of applications of each technique/method in each basin

APPENDIX B - MODEL EVALUATION TECHNIQUES

B. MODEL EVALUATION TECHNIQUES

This section of the report reviews the literature on criteria and methods used for comparing hydrological models. The following criteria are generally considered important in real-time flood forecasting:

- time to peak
- peak height (or discharge)
- time threshold levels, such as minor, moderate and major flood levels, are exceeded, and the time river level falls below critical levels for flood recovery etc.

Hydrological models are generally compared using combinations of graphical plots, numerical or statistical techniques and graphs of model statistics.

B.1 Graphical Techniques

A visual comparison of graphical plots of observed and modelled flows are used in many studies to assess the performance of hydrological models. This gives a quick assessment of how the models perform with regard to low flows as well as high flows for the whole record under consideration. Scatter plots are also used in some studies (WMO 1975, Weeks and Hebbert, 1980 Porter et al, 1988). This is mainly to determine the bias in the modelled values (ie over prediction or under prediction based on the 45^{o} degree line).

B.2 Numerical Techniques

B.2.1 Mean Error

Forecast error is given by

$$\varepsilon_L(i) = Q_{f,L}(i) - Q_{obs}(i) \qquad (B.1)$$

where

$Q_{f,L}(i)$	forecasted flow for lead time L for forecast i
$Q_{obs}(i)$	actual observed flow for lead time L for forecast i
L	lead time

Mean Error of forecast (WMO, 1987) or mean of residuals (Cunge et at, 1992) is given by

$$ME_L = \frac{1}{N}\sum_{i=1}^{N}\varepsilon_L(i) \qquad (B.2)$$

where

N number of forecasts made

Relative Mean Error of forecast is defined as

$$RME_L = \frac{ME_L}{\overline{Q}_{obs}} \qquad (B.3)$$

where

$\overline{Q}_{obs}$ mean observed discharge

This statistic was used by WMO (1975) and Weeks and Hebbert (1980). Even though a smaller value for this is preferred, a small value for this statistic does not always mean good model performance as the over prediction at certain times can be compensated by under predictions at some other times. However, a large value will indicate a bias in the model predictions. This statistic is preferred to ME_L as the former removes the scale effect and makes comparison easier.

Mean Relative Error of forecast (WMO, 1987) is given by

$$MRE_L = \frac{1}{N}\sum_{i=1}^{N}\frac{\varepsilon_L(i)}{Q_{obs}(i)} \tag{B.4}$$

In this case, each forecast error is standardised by the observed discharge.

The Relative Mean Absolute Error (RMAE) is defined as

$$RMAE_L = \frac{\sum_{i=1}^{N}|\varepsilon_L(i)|}{N\overline{Q}_{obs}} \tag{B.5}$$

and used in WMO (1975). A small value of this statistic means good model performance.

B.2.2 Root Mean Square Error

The Root Mean Square Errors (RMSE) is defined as (WMO, 1992)

$$RMSE_L = \sqrt{\frac{\sum_{i=1}^{N}\varepsilon_L(i)^2}{N}} \tag{B.6}$$

For each model and each event, $RMSE_1$, $RMSE_2$, ... were computed and averaged over all events and lead times. The smaller the value of RMSE, the better the performance of the model.

Kitanidis and Bras (1980) plotted RMSE as a time series for 6- and 12-hour forecast lead time. Hasebe et al (1989) called this statistic "the error of prediction" and plotted for visual comparison.

Troch et al (1991) and Singh and Majumdar (1993) calculated the RMSE separately for rising limb only in addition to the overall flood event.

A number of variations of this statistic have been used in the literature. The RMSE was divided by the mean of the observed flows, $\overline{Q}_{obs}$, and the resulting quantity was referred to as the coefficient of variation of the residuals (WMO, 1975; Weeks and Hebbert, 1980).

$$\text{Coefficient of variation of residuals} = \text{RMSE}_L \,/\, \overline{Q}_{obs} \tag{B.7}$$

This is really a standardised RMSE rather than a coefficient of variation of residuals.

Masmoudi and Habaieb (1993) divided the RMSE by the observed peak Q_o^{max} and referred to the result as the forecasting precision.

$$S_L = \text{RMSE}_L \,/\, Q_o^{max} \tag{B.8}$$

Cunge et al (1992) defined the Standard Deviation of residuals as

$$SD_L = \sqrt{\frac{\sum_{i=1}^{N} \varepsilon_L(i)^2 - N.ME_L^2}{N-1}} \tag{B.9}$$

Cunge et al (1992) also defined Root Mean Square Percent Error as

$$RMSPE_L = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{\varepsilon_L(i)}{Q_{obs}(i)}\right]^2}.100 \tag{B.10}$$

Another variation of Eq (B.6) is to use a power other than 2 [for instance 0.2 used in Chiew et al (1993)] or to weight the error terms (Bertoni et al, 1992; Porter et al, 1988). The weights are generally used to give more importance to low flows and this is not relevant to the present study which deals with floods or high flows.

B.2.3 Normalised Peak Error

The Normalised Peak Error (NPE) is defined as (Masmoudi and Habaieb, 1993):

$$NPE = \frac{Q_f^{max} - Q_o^{max}}{Q_o^{max}} \tag{B.11}$$

where

Q_f^{max} forecasted peak discharge
Q_o^{max} observed peak discharge

Cunge et al (1992) expressed this as a percentage. A smaller value means a good model. Singh and Majumdar (1993) used a weighted average absolute errors in peak for comparison in which the weight being the ratio of the peak to average discharge..

A variation of the error in peak is the ratio of the forecasted and observed peaks.

$$PR = Q_f^{max} \,/\, Q_o^{max} \tag{B.12}$$

Malone and Cordery (1989) used the mean and standard deviation of the ratio of the forecasted to observed peak discharges.

B.2.4 Peak Timing Error

The difference in the time of occurrence of the forecasted peak and the observed discharge is referred to as the Peak Timing Error (PTE).

$$PTE = t_f^{max} - t_o^{max} \quad (B.13)$$

where

t_f^{max} time of occurrence of forecasted peak discharge

t_o^{max} time of occurrence of observed peak discharge

Cunge et al (1992) referred to this as the peak phase error while Masmoudi and Habaieb (1993) referred to this as the peak delay error. Troch et al (1991) defined the time-at-peak error as |PTE|. Malone and Cordery (1989) used the mean and standard deviation of the ratio of the forecasted to observed time to peak discharges.

B.2.5 Coefficient of Determination

Coefficient of determination, a measure of association between observed and forecasted discharges (Aitken, 1973), is defined by

$$D_L = (S_{obs} - S_{est}) / S_{obs} \quad (B.14)$$

where

$$S_{obs} = \sum_{i=1}^{N} \left[Q_{obs}(i) - \overline{Q}_{obs}\right]^2$$

$$S_{est} = \sum_{i=1}^{N} \left[Q_{obs}(i) - Q_{est,L}(i)\right]^2$$

$Q_{est,L}(i)$ estimated discharge obtained from the regression of $Q_{obs}(i)$ on $Q_{f,L}(i)$.

The coefficient of determination will always be less than unity. A value of D_L close to one indicates good results. Even though this is a good measure of association between observed and forecasted values, it does not indicate systematic errors.

B.2.6 Coefficient of Efficiency

The coefficient of efficiency of a model is defined as the proportion of the variance of the observed discharges accounted for by the model (Nash and Sutcliffe, 1970).

$$E_L = (S_{obs} - S) / S_{obs} \quad (B.15)$$

where

$$S = \sum_{i=1}^{N} \varepsilon_L(i)^2 \quad \text{and } S_{obs} \text{ as defined above.}$$

The value of this statistic will be always less than unity. If the results from the model are highly correlated with the observed values but biased, then the value of E_L will be less than D_L.

B.2.7 Coefficient of Persistence

In real time a no-model forecast is better represented by the latest observed value of the discharge. A coefficient of persistence for real-time models can be defined as (Kitanidis and Bras, 1980):

$$P_L = 1 - S / \sum_{i=1}^{N} \left[Q_{obs}(i) - Q_{obs}(i - L) \right]^2 \qquad \text{(B.16)}$$

P_L is a function of the lead time and is always less than 1. The coefficient of persistence compares the forecasts of the model with the forecasts obtained by assuming that the process is a Wiener process in which case the best estimate for the future is given by the latest measurement (Kitanidis and Bras, 1980). Amirthanathan (1989) and Corradini (1991) used this for model comparison.

B.2.8 Coefficient of Extrapolation

A useful evaluation of the forecasting capability of a model can be achieved by comparing with the forecasts obtained through simple extrapolations, such as linear extrapolation, from recent observations of the discharges. A coefficient of extrapolation is defined as (Kitanidis and Bras, 1980):

$$L_L = 1 - S / \sum_{i=1}^{N} \left[Q_{obs}(i) - Q_{ext,L}(i) \right]^2 \qquad \text{(B.17)}$$

where $Q_{ext,L}(i)$ is the forecast corresponding to the straight line fitted to the two most recent observations of the discharge $Q_o(i - L)$ and $Q_o(i - L - 1)$.

B.2.9 Accumulated Volume Errors

A simple way to estimate these errors is by computing the mean and variance (Kitanidis and Bras, 1980). The mean value is indicative of the presence of biases while the variance gives the spread of the errors.

$$\overline{Q}_{f,L} = \frac{1}{N} \sum_{1}^{N} Q_{f,L}(i) \qquad \text{(B.18)}$$

$$VAR_L = \frac{1}{N-1} \sum_{1}^{N} \left[Q_{f,L}(i) - \overline{Q}_{f,L} \right]^2 \qquad \text{(B.19)}$$

B.2.10 Theil's Inequality Statistic

Cunge et al (1992) calculated the Theil's inequality statistics from (Pindyck and Rubinfeld, 1981):

$$U_L = \frac{RMSE}{\sqrt{\frac{1}{N}\sum_{i=1}^{N} Q_{o,L}^2(i)} + \sqrt{\frac{1}{N}\sum_{i=1}^{N} Q_{f,L}^2(i)}} \quad \text{(B.20)}$$

The value of U_L always falls in the range [0,1] and it expresses the goodness of fit between the model and the observed series. If U_L tends to zero, then there is a good fit between the model results and observed series. Otherwise the model's predictive features are questionable and the forecasts can be skewed (Cunge et al, 1992).

Theil's coefficient can be decomposed into three proportions indicating the sources of errors:

- Bias Proportion $UM_L = (\overline{Q}_{f,L} - \overline{Q}_{obs})^2 / RMSE$ (B.21)
- Variance proportion $US_L = (SQ_{f,L} - SQ_{obs})^2 / RMSE$ (B.22)
- Covariance proportion $UC_L = 2(1-r) SQ_{f,L} . SQ_{obs} / RMSE$ (B.23)

where

SQ_{obs}	standard deviation of the observed values
$SQ_{f,L}$	standard deviation of the forecasted values
r	correlation coefficient between the observed and the forecasted values.

The UM_L component indicates a systematic error and if $UM_L > 0.2$ then a systematic bias is present and the model should be revised. The US_L represents the variance proportion and UC_L represents the remaining model error (unsystematic error). The most desirable distribution of the Theil's inequality coefficient values is obtained when $U_L \rightarrow 0$, $UM_L \rightarrow 0$, $US_L \rightarrow 0$ and $UC_L \rightarrow 1$.

B.2.11 Two-criterion objective Function

To assess the performance of a model on flood prediction, Yapo et al (1993) proposed a two-criterion objective function F( ) = [P(FA), P(M)] where the probability of occurrence of false alarms, P(FA), and misses (non-prediction of floods), P(M), can be estimated from

$$\hat{P}(FA) = \frac{N(FA)}{N(NF) + N(FA)} \quad \text{(B.24)}$$

$$\hat{P}(M) = \frac{N(M)}{N(F) + N(M)} \quad \text{(B.25)}$$

Where

N(F)	the number of correct predictions of the flood levels
N(NF)	the number of correct predictions of the non-flood levels
N(M)	the number of misses
N(FA)	the number of false alarms

The function F( ) explicitly represents the forecaster's desire to simultaneously minimise both the probability of false alarms and that of failing to issue warnings.

B.3 Model Comparison Approach

It can be seen from the above that there exists a large number of numerical indices for model comparison. Each of the indices reflect a different feature of model performance, so there is a need to combine all or some of the indices to obtain a single quantity. This quantity will enable the models to be ranked in order of performance. The approach to achieve this varies from the simple or weighted summing of the indices or their ranking to the more formal multi criteria approach.

B.3.1 Simple Combination of Indices

Porter et al (1988) devised a ranking procedure to facilitate the comparison of three rainfall-runoff models. The following four statistical indicators were selected:

- a standardised weighted sum of squares of differences (WSS)
- the coefficient of efficiency (E)
- the percentage error in total runoff (ERR)
- the coefficient of determination (D)

Each model was ranked from 1 to 3 according to each of the three statistics, with 3 being awarded as the best result. As each of the above indicator reflect something different about the model performance, three measures were computed based on the ranking of these statistics with different weighting assigned to each.. The three measures are:

- WSS (WSS)
- 2*WSS + 2*E + ERR +D (COMPOSITE)
- 4*WSS + 3*E + 2*ERR + D (ALTERNATIVE)

For the 28 catchments considered, neutral scores are WSS = 56, COMPOSITE = 336 and ALTERNATIVE = 560. Scores greater than these are desirable.

B.3.2 Multi criteria Approach

Masmoudi and Habaieb (1993) used a multi criteria analysis to rank the models. They used the following three statistics for each event j and each forecast horizon L.

- the L-step ahead forecasting precision S_j^L
- the normalised peak error NPE_j^L
- the peak delay error PTE_j^L

The mean and variances of the above three statistics constitute the six criteria used in the multi criteria approach. Models which minimise the precision criterion are not very good for peak error and vice-versa and the performance of models for short lead time forecasts are not so good for long lead time forecasts. The choice of the best model should result from a cross-compromise between the six criteria and the forecasting lead times. The PROMETHEE method was used and improved to solve the problem (Masmoudi and Habaieb 1993).

Let $\{a_1, ..., a_n\}$ be a set of n alternatives and $\{c_1, ..., c_m\}$ be a set of m criteria. If $g_i(j)$ is the value of the criterion for the alternative a_j and p_i is the weight of that criterion i, a preferences relation can be defined as:

$$P(i,j) = \frac{1}{P}\sum p_k . F_k(i,j) \qquad \text{(B.26)}$$

where $P = \Sigma\, p_i$ and $F_k(i,j)$ takes its value according to the type of the criterion given below.

Type 1: strict criterion

$$F_k(i,j) = 1 \quad \text{if } g_k(j) > g_k(i) \qquad \text{(B.27)}$$
$$= 0 \quad \text{otherwise}$$

Type 2: criterion with indifference threshold q

$$F_k(i,j) = 1 \quad \text{if } g_k(j) > g_k(i) + q \qquad \text{(B.28)}$$
$$= 0 \quad \text{otherwise}$$

Type 3: criterion with linear threshold q

$$F_k(i,j) = 1 \quad \text{if } g_k(j) > g_k(i) + q$$
$$= [\, g_k(i) - g_k(j)] / q \quad \text{if } 0 < g_k(j) - g_k(i) < q \qquad \text{(B.29)}$$
$$= 0 \quad \text{otherwise}$$

For each alternative, the following three indices are calculated

$$\phi^+(j) = \sum_i P(i,j) \qquad \text{(B.30)}$$

$$\phi^{-}(j)=\sum_{i}P(j,i) \tag{B.31}$$

$$\phi^{t}(j)=\phi^{+}(j)-\phi^{-}(j) \tag{B.32}$$

The best alternative is the one that has the maximum value for $\phi^{+}(j)$ and minimum value of $\phi^{-}(j)$. Such an alternative does not always exist, so a ranking according to $\phi^{t}(j)$ is adopted.

Instead of this, Masmoudi and Habaieb (1993) defined normalised indices and distances that allow ranking in a more standardised way.

$$p^{+}(i)=\frac{1}{n-1}\sum_{j\neq i}P(i,j) \tag{B.33}$$

$$p^{-}(i)=1-\frac{1}{n-1}\sum_{j\neq i}P(j,i) \tag{B.34}$$

$$p^{t}(i)=\frac{p^{+}(i)+p^{-}(i)}{2} \tag{B.35}$$

$$d_{1}(i)=\sqrt{\frac{[p^{+}(i)-p^{+*}]^{2}+[p^{-}(i)-p^{-*}]^{2}}{2}} \tag{B.36}$$

$$d_{2}(i)=\sqrt{\frac{\{p^{+}(i)\}^{2}+\{p^{-}(i)\}^{2}}{2}} \tag{B.37}$$

where

$p^{+*}=\max\{p^{+}(i)\}$ and $p^{-*}=\max\{p^{-}(i)\}$, $i=1,\ldots,n$.

- $p^{+}(i)$ a measure of the degree of preference of alternative i over all other alternatives,
- $p^{-}(i)$ a measure of the degree of preference of all other alternatives over alternative i,
- $p^{t}(i)$ a net preference index of alternative i,
- $d_{1}(i)$ the normalised distance of alternative i to the optimum alternative,
- $d_{2}(i)$ a normalised absolute index of optimality which has a value between 0 (worst alternative) and 1 (best alternative).

B.4 Methods for Comparing Flood Forecasting Models

Flood forecasting model performance can vary significantly with different catchments, and even with different events and lead times within a given catchment. Model comparison methods examining different aspects of model behaviour may yield different rankings of model performance. Even model comparison methods examining similar aspects of model behaviour may rank model performances differently due to slight differences in criterion formulation.

It is suggested to use a number of relevant numerical indices along with graphical plots of forecasted and observed discharges. The numerical indices suggested for different lead times are as follows:

- root mean square error (RMSE) or standardised RMSE or Theil's Statistic (U)
- relative mean error (RME)
- Normalised peak error (NPE) or peak ratio (PR)
- Peak timing error (PTE)
- Coefficient of persistence (P)
- Coefficient of extrapolation (L)
- Coefficient of determination (D)
- Coefficient of efficiency (E)

Wherever possible the above indices should be calculated for the whole event as well as for the rising limb of the flood hydrograph.

If the indices provide inconsistent results, a simple ranking or the multicriteria approach is suggested to identify the best performing model.

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