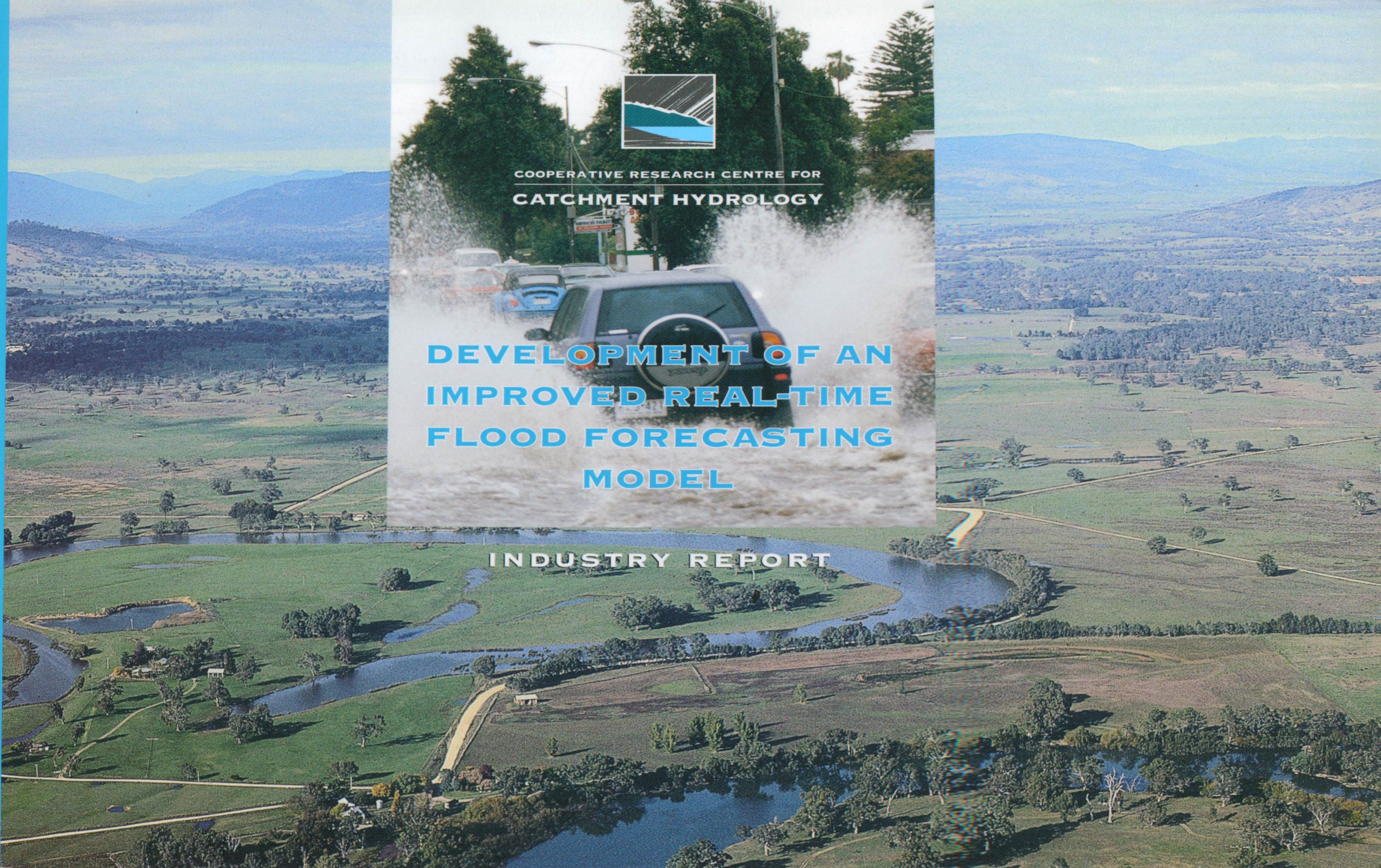

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

DEVELOPMENT OF AN IMPROVED REAL-TIME FLOOD FORECASTING MODEL

INDUSTRY REPORT

DEVELOPMENT OF AN IMPROVED REAL-TIME FLOOD FORECASTING MODEL

by

Jim Elliott

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Industry Report
Report 97/6
September 1997

Elliott, J. F. (James Francis), 1948-.
Development of an improved real-time flood forecasting model.

Bibliography.
ISBN 1 876006 22 6.

1. Flood forecasting - Mathematical models.
2. Hydrologic models.
3. Runoff-Mathematical models.
4. Rain and rainfall -Mathematical models. I. Cooperative Research Centre for Catchment Hydrology. II. Title. (Series: Report (Cooperative Research Centre for Catchment Hydrology): 97/06).

551.4890112

Keywords

Floods and Flooding
Flood Forecasting
Modelling (Hydrological)
Rainfall/Runoff Relationship
Streams (in Natural Channels)
Soil/Water Systems
Modelling (-General-)

Cooperative Research Centre for Catchment Hydrology, 1997
Centre Office
Department of Civil Engineering
Monash University
Clayton, Victoria, 3168
Australia
Tel: (03) 9905 2704 Fax: (03) 9905 5033
Home Page: http://www-civil.eng.monash.edu.au/centres/crcch/

Photographs were provided by:

- Ian Rutherfurd (front and back cover)
- The Age; including front cover insert
  (Melbourne Nov 95, Mark Wilson / The Age)

FOREWORD

This Industry Report is one of a series prepared by the CRC for Catchment Hydrology to help provide agencies and consultants in the Australian land- and water-use industry with improved ways of managing catchments.

Through this series of reports and other forms of technology transfer, industry is now able to benefit from the Centre's high-quality, comprehensive research on salinity, forest hydrology, waterway management, urban hydrology and flood hydrology.

This particular Report represents a major contribution from the CRC's flood hydrology program, and presents key findings from the project entitled 'Development of an improved real-time flood forecasting model'. (More detailed explanations and research findings from the project can be found in a separate series of Research Reports and Working Documents published by the Centre.)

The CRC welcomes feedback on the work reported here, and is keen to discuss opportunities for further collaboration with industry to expedite the process of getting research outcomes into practice.

Russell Mein

Director, Cooperative Research Centre for Catchment Hydrology

PREFACE

This report summarises an evaluation by the Cooperative Research Centre for Catchment Hydrology of recent advances in real-time rainfall-runoff models. These innovations are designed to improve the quality of flood warning services in Australia.

The models were evaluated using data from fourteen catchments in Queensland, New South Wales, Victoria, South Australia and Tasmania. Full details of the work can be found in a series of Cooperative Research Centre (CRC) Working Documents and Reports (see 'Further Reading' section).

Through this project - 'Development of an improved real-time flood forecasting model' (Project D4) – the CRC has successfully identified techniques to improve current models, and has produced new procedures for model implementation. The project has also provided an approach for evaluating the effect of such improvements, and its results provide a basis for assessment of current practice.

The work was undertaken primarily by Sri Srikanthan and Soori Sooriyakumaran at the Bureau of Meteorology, and with support from Peter Hill (data preparation), Hassan Khan (Xinanjiang and AWBM modelling) and Avijeet Ramchurn (URBS modelling). The project was guided by a reference panel comprising Russell Mein, Tom McMahon, Peter Baddiley and Geoff Crapper, along with the project research staff.

Jim Elliott

Project Leader

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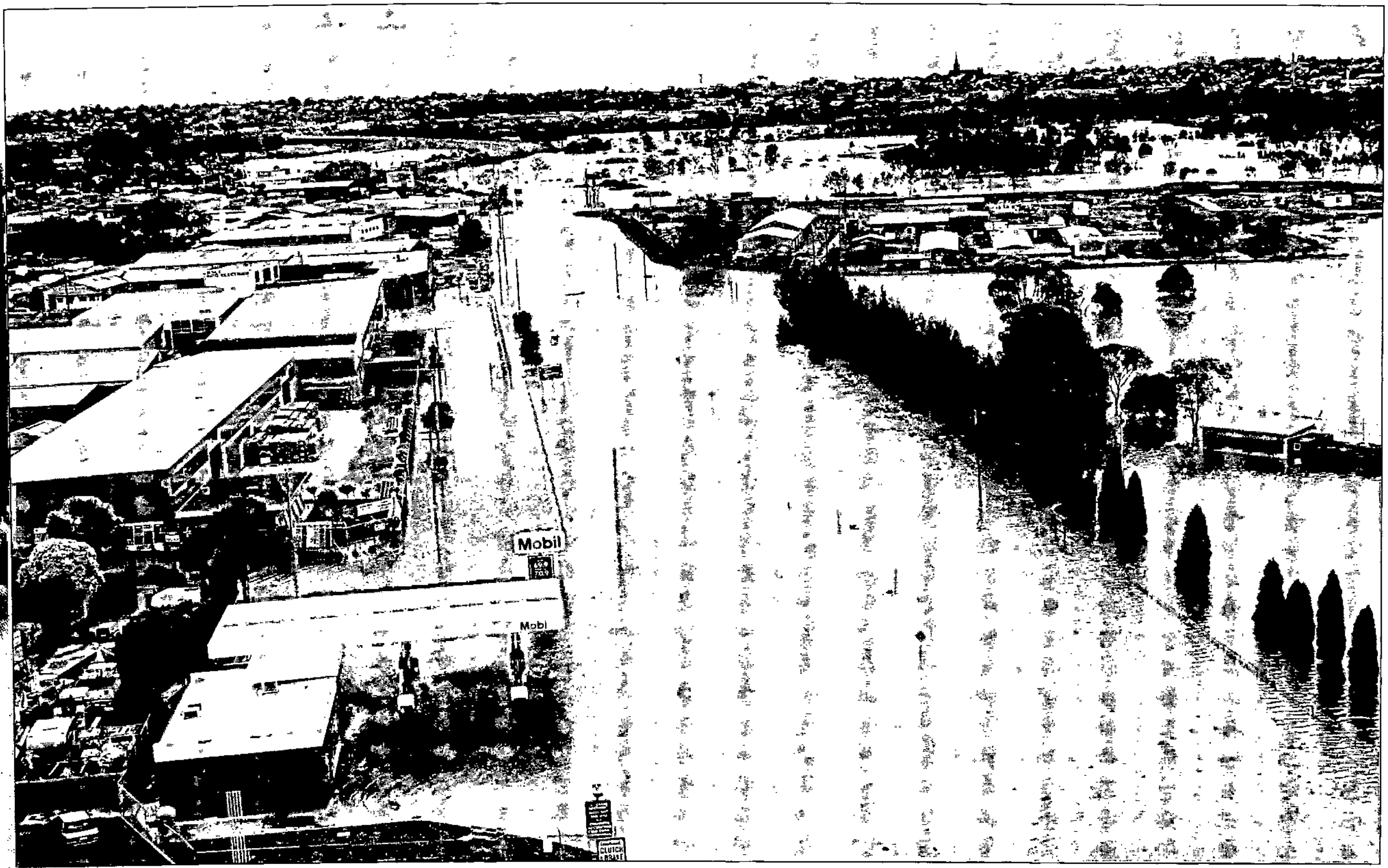


Improved forecasting will benefit the wider community. (Barwon River, Geelong, Nov 95 – John Lamb / The age.)

INTRODUCTION: FLOOD FORECASTING IN AUSTRALIA

Flooding costs the Australian economy an average $300-400 million annually. While relatively few lives are lost, floods continue to cause considerable economic and social disruption, despite significant expenditure on flood mitigation. Until recently, most of the expenditure was on structural works - levees, river diversions, and retarding basins - built to reduce the flood hazard.

More recent strategies, however, have focussed on non-structural measures. **Flood warning**, for example, involves forecasting the future flood behaviour of rivers at critical locations. Advance warnings enable agencies and people living on the flood plain to take preventative measures for reducing the risks to people, stock and property.

To be fully effective, flood warning systems must be viewed within what is termed a 'total warning' systems perspective (Figure 1), in which each system element interacts with the other elements. The system's effectiveness is determined by the effective response of the agencies and people affected by a particular flood. Accurate river forecasts are an important part of this total warning system. Thus, this project sought to evaluate the performance of recent advances in real-time flood forecasting techniques to identify improvements that could be introduced into Australian flood forecasting practice.

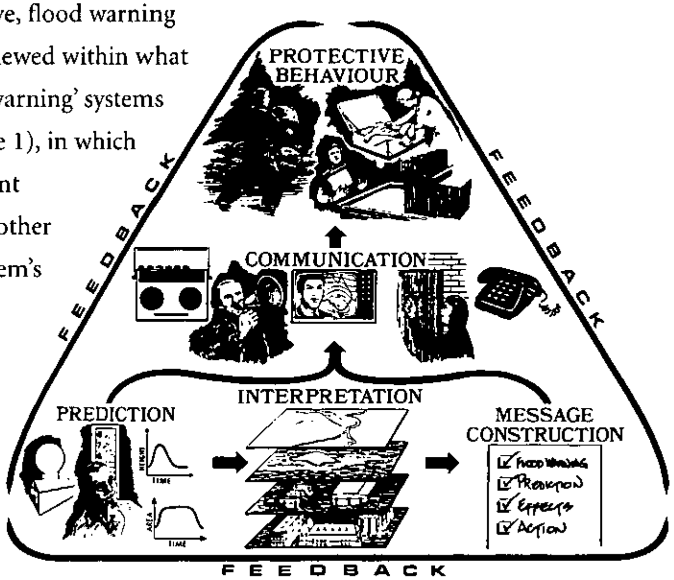


Figure 1: Overview of a 'total flood warning' system

The Bureau of Meteorology is responsible nationally for providing flood forecasting and warning services. This service is well developed in many flood-prone areas of Australia, and includes quantitative prediction systems. Very little research, however, had been undertaken since a major upgrade of the service saw the installation of improved real-time data collection systems. These new systems provide more data than ever before. It is important that the models used to prepare forecasts from that data capitalise as much as possible on this increased data availability.

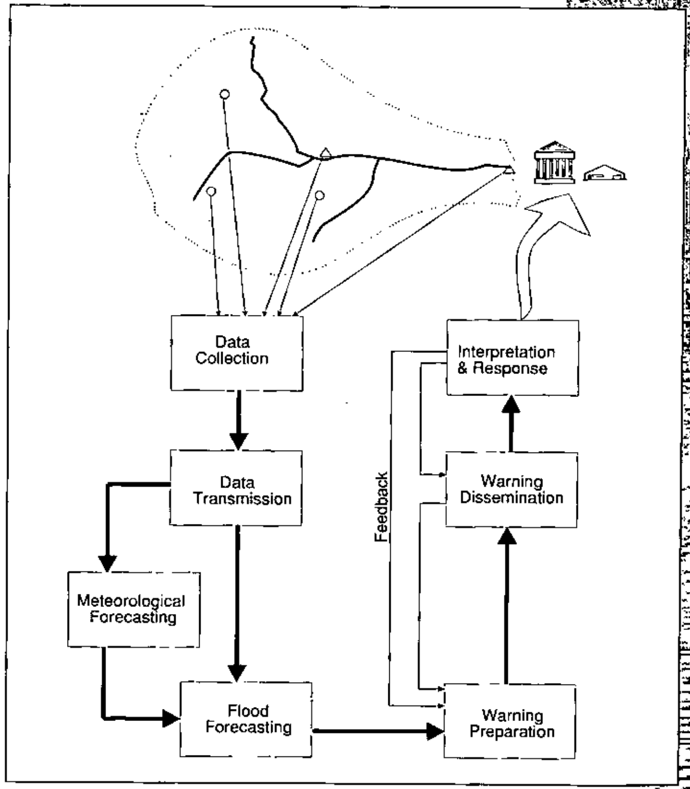


Figure 2: Components of a flood forecasting and warning system

WHAT IS FLOOD FORECASTING?

The components of a flood forecasting and warning system are shown in Figure 2.

The requirements of the system depend on the particular flood risk involved,

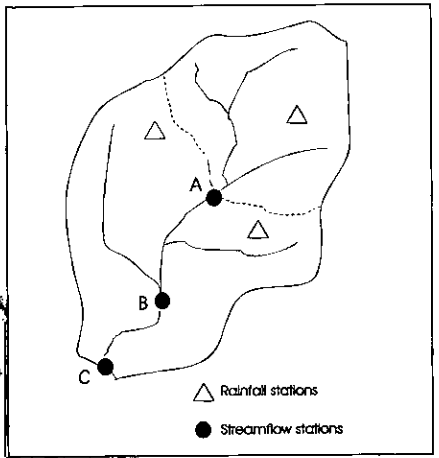


Figure 3: Typical arrangement of forecast locations and data collection networks in a catchment

but normally involve some form of hydrologic model to forecast future river levels at key locations in a river basin (Figure 3). Typically predictions will be provided for several locations (for example, locations A, B and C in diagram). Data collection stations are installed to collect and transmit rainfall or river level observations to a flood warning centre for analysis. The data is also input to the hydrologic forecasting model to predict future river levels.

Meteorological forecasting - particularly rainfall forecasts (quantitative or qualitative) – provides a vital input to the flood forecasting process. While this may add some uncertainty, the longer warning time can often be more important to emergency management agencies in preparing a response strategy to deal with future flooding.

The type of hydrologic forecasting technique used will depend on the location within the river basin, and the availability of data for use in preparing the prediction.

In the uppermost reaches of the basin (A in Figure 3), predictions must be made solely on the basis of rainfall (observed and forecast) using rainfall-runoff techniques or models. Further downstream (B and C), observations of river levels at upstream locations (A and B) can be used. In these cases, forecasting involves the use of flood-routing (hydrograph estimation from upstream flows) techniques, although rainfall-runoff models (hydrograph estimation from rainfall) may be important to forecast what is termed local area runoff (for example, between A and B). Some models integrate both types of procedure, enabling predictions to be made at a number of locations within the catchment.

Flood routing procedures are generally well established, and a technique can be readily selected to suit a particular situation. Rainfall-runoff models, however, while available in many forms, are normally less accurate. Thus improvements to this type of model would be expected to lead to greater overall benefit for a range of forecasting problems, particularly those where the catchment flood response times are short. For this reason, the CRC's D4 project focused solely on improvements to rainfall-runoff models.

OPPORTUNITIES TO IMPROVE CURRENT PRACTICE

The CRC found a significant 'gap' between current practice in Australia and that reported in the literature - almost no use has been made of objective techniques for rainfall-runoff model updating. In other words, practitioners are not taking the full opportunity provided by 'real-time' modelling to objectively use observations, made during a flood event, of the river level/flow at the location for which the forecast is being prepared. Such observations can be used to improve forecast quality for the remainder of the event.

In fact the CRC's literature review found evidence that simple models - when combined with some form of objective updating procedure - had been able to match the performance of more complex models. What needed further investigation was whether this same conclusion could be applied to Australian conditions. More specifically, the CRC set out to find whether current simple unit hydrograph and catchment routing models could be rapidly improved with some form of objective updating.

Even though simple models with some form of objective updating had been shown to perform as well as more complex models, work elsewhere suggested that this result applied more to shorter forecast lead-times. It was suggested that, for longer lead-time forecasts, there were advantages in having a sound soil-moisture accounting component in the forecasting model.

In Australia, although a range of rainfall-runoff models based on continuous soil-moisture accounting are available, their application to real-time problems has been limited. Thus the application of continuous soil-moisture accounting models, coupled with some form of objective updating technique represented a further area for CRC research. This research included testing models developed for use in other countries, but not yet evaluated under Australian conditions.

The review of the research literature and practices in other agencies also revealed that a methodology for systematically evaluating and comparing alternative forecasting models was not available. Thus the CRC set out to develop and test an evaluation strategy, involving a mix of approaches, which would be useful not only for research projects such as this, but also as a tool for forecasting agencies to evaluate current procedures and potential improvements.

To summarise, the objectives of the CRC project were to:

- develop a strategy for evaluating alternative forecasting models
- use this strategy to evaluate the effectiveness of combining an objective updating method with simple models
- evaluate the forecasting performance of continuous soil-moisture accounting models coupled with different objective updating methods (including overseas models)
- provide guidance on the choice of model and updating method from a comparison of the relative performance of models.

REAL-TIME FORECASTING AND MODEL UPDATING

The operational requirements of flood forecasting introduce differences to the hydrologic modelling approach when compared with the more common design hudrology applications. These differences are discussed in this section of the report.

REAL-TIME RAINFALL-RUNOFF MODELLING

The requirements of a forecasting model depend on its application. In some cases, an agency only needs a forecast of the highest river level (the peak); in other cases, the agency needs a forecast of the 'rising limb' to predict when critical levels will be exceeded (roads cut, levees overtopped, etc.); in yet other cases, the entire hydrograph is required.

Normally, forecasting agencies continually assess the potential of a catchment to flood under different rainfall scenarios, so that emergency management agencies have as much warning of the flooding potential as is practicable. This can be done more effectively if the flood forecaster uses a model that accurately times the start of the flood event's rise. Clearly, improvements in forecasting accuracy at all stages in a flood event will be beneficial.

Rainfall-runoff models are used to predict the height of a river at a particular forecast location following rainfall (observed and/or forecast). Most models do this in two separate stages. The first stage estimates the

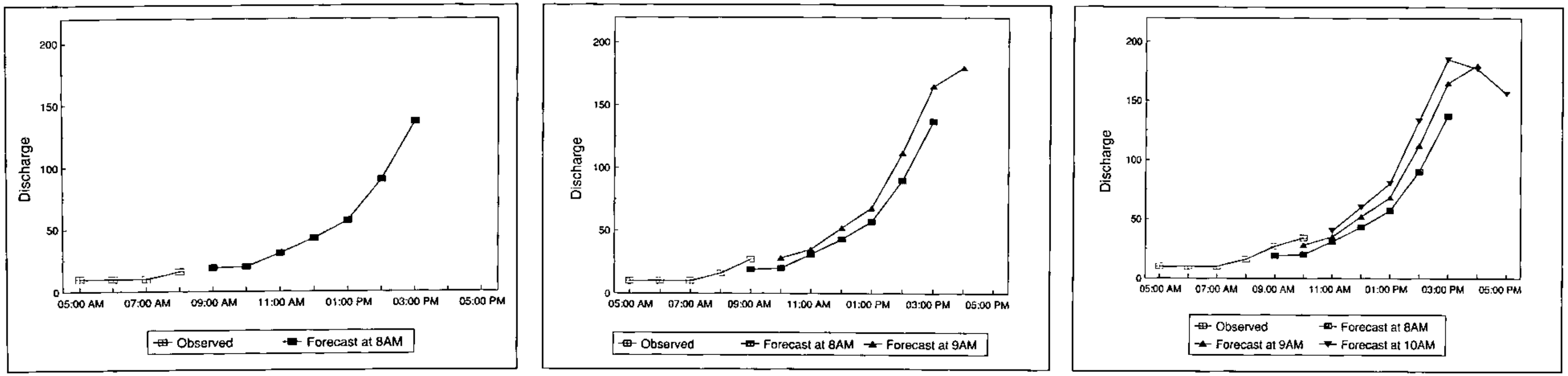
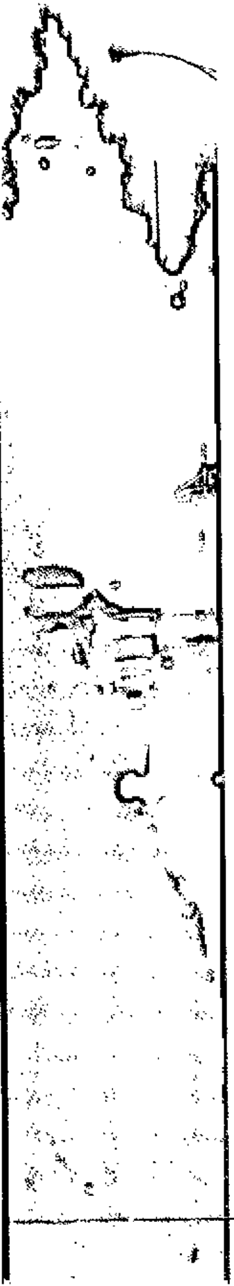


Figure 4: Example showing how real-time flood forecasting models work - (a) forecast at 8am; (b) forecast at 9am; and (c) forecast at 10am



rainfall volume that runs off the catchment (runoff), and the second stage models the effect of the catchment in distributing this runoff in time to produce the flood hydrograph at the catchment outlet (catchment model).

The application of rainfall-runoff modelling to the flood forecasting problem differs from other applications in what is termed the 'real-time' nature of the application.

Taking the example in Figure 4, at 0800 the rainfall-runoff model would be applied to the observed (and maybe forecast) rainfall data to predict future river levels for location A at 0900, 1000, and 1100 hours and so on. This might also include a forecast of the peak river level. But one hour later at 0900, the flood warning centre may receive an observation of the river level at A that may differ from the forecast at 0800. This 'error' could be due to a number of factors, including errors in the input data, model imperfections, incorrect model parameters, the model being poorly initialised for the current event, changes in catchment characteristics since the last event, or perhaps errors in determining the discharge at the forecast point.

This new observation provides an opportunity to adjust the modelling process accordingly, and to 'update' the model to improve the quality of subsequent forecasts. This updating process is made possible by the collection of information on river behaviour in 'real-time', accomplished through the use of appropriate data collection technology such as radio or telephone-based telemetry.

The current approach to updating involves subjective adjustments – usually, changes to the parameters of simple loss models (initial loss and continuing loss or proportional loss) to correct future forecasts, or some sort of subjective 'blending'.

Subjective updating can be quite effective, particularly where experienced forecasters are available to draw on their understanding of flood behaviour in catchments. This is difficult to effectively include in a mathematical model. Further, such updating can be time-consuming if the forecaster has to simultaneously handle forecasts for a number of rivers. And, because the technique relies on the experience of relatively few individuals, there is the risk that quality of service could be reduced when these staff are unavailable. For these reasons, some form of objective updating is often preferred.

MODEL UPDATING

The following four approaches can be taken to objective model updating:

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

UPDATING INPUT VARIABLES

With this approach, input variables are adjusted so that the model output matches the observed flow values. In the case of rainfall-runoff modelling, the input variable to be adjusted is normally the catchment average rainfall. Most procedures that update the input variables are interactive and of the 'trial and error' type. In most models it is difficult to determine the model input when the model output and parameters are given. Therefore, this approach was not used in this study.

UPDATING MODEL STATE VARIABLES

A typical example of model 'state' variables would be the water contents of soil-moisture stores that might be included in the model structure. Updating the model state variables involves adjusting the variables at any time during a simulation so that the model output matches the observed output. A justification for state variable updating is that errors in input are accumulated and appear as errors in the water content of stores of conceptual rainfall-runoff models which, if not corrected, will give erroneous output values for future predictions. Different approaches to model state updating are available. In this project two of the models investigated used this approach.

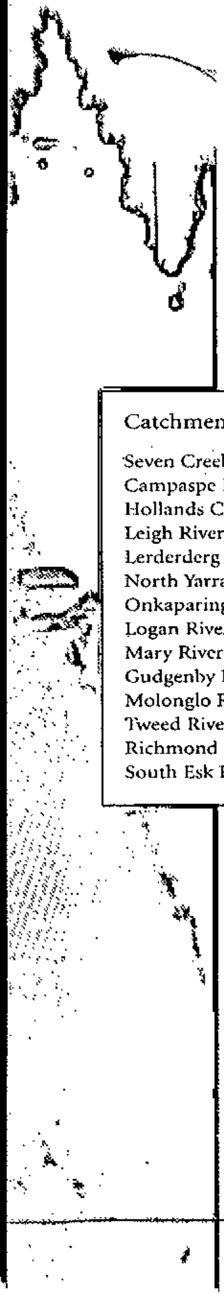
UPDATING MODEL PARAMETERS

In this approach, one or more of the model parameters are updated using the results from recent model performance. Two different methods were examined in this study: one involved converting the simple unitgraph model to a form suitable for updating using a Kalman filter approach; the other involved structuring the unitgraph model to estimate parameters at each time step through minimising an objective function.

UPDATING OUTPUT VARIABLES

This approach makes use of the difference between the model output hydrograph and the observed hydrograph, and can be used with any model. Two approaches are normally followed. A subjective 'blending' approach involves constructing a forecast hydrograph using the observed hydrograph up to the time of forecast, but adopting a smooth transition between the observed hydrograph and the model output hydrograph up to a fixed time interval (say six time periods) beyond the time of forecast, after which the model output hydrograph is used. This is similar to current practice.

An 'error correction' approach involves fitting an auto-regressive model to the time series of errors between the simulated and observed hydrographs, and using this model to forecast future errors. This approach takes advantage of the tendency for errors from rainfall-runoff models to either overestimate or underestimate the observed hydrograph. The use of error correction was used as an updating method on three of the models in this project.



MODEL EVALUATION STRATEGY

This section of the report discusses the strategy and criteria used for evaluating and comparing the performance of different models.

For the results of this project to be meaningful in the context of current practice, the evaluation process had to reflect this practice as closely as possible. This meant that:

- Catchments selected for use in the study were either headwater catchments in existing forecasting systems, or were typical of the size of these catchments, and had little or no flow regulation (Table 1 and Figure 5)

Catchment	Basin	Area (km2)	Events
Seven Creeks at Euro	Goulburn	332	6
Campaspe River at Redesdale	Campaspe	629	5
Hollands Creek at Kelfeera	Broken	451	6
Leigh River at Mt Mercer	Barwon	593	5
Lerderderg River u/s Goodman Creek Junction	Werribee	234	4
North Yarra River at Yaldara	Gawler	384	5
Onkaparinga River at Houlgraves	Onkaparinga	285	7
Logan River at Round Mountain	Logan	1270	7
Mary River at Dagan Pocket	Mary	2110	9
Gudgenby River at Nass	Murrumbidgee	388	5
Molonglo River at Burbong	Murrumbidgee	505	8
Tweed River at Uki	Tweed	275	10
Richmond River at Wiangaree	Richmond	702	9
South Esk River at Llewwlyn	Tamar	2141	9

Table 1: Details of catchments and number of events used in CRC study

- **Typical** data quality was accepted, rather than only selecting catchments and flood events that met **ideal** data quality standards. In particular, the common operational need to adjust for missing periods of data was well as the need for data interpolation was included, as were cases where the number of rainfall stations available was fewer than ideal.

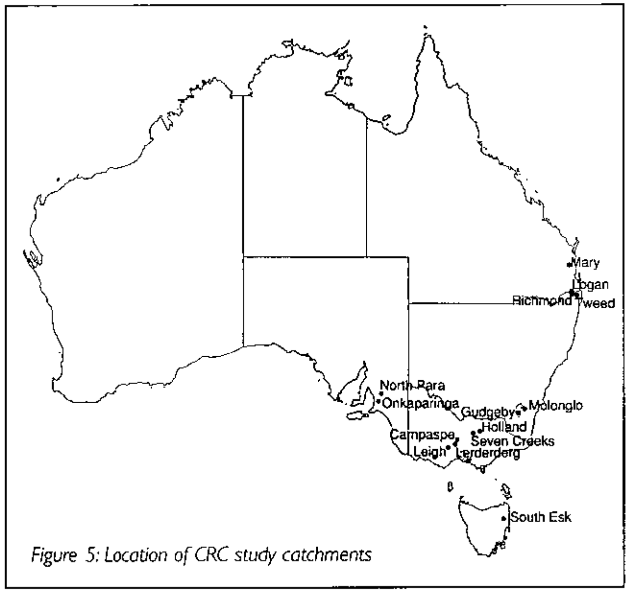


Figure 5: Location of CRC study catchments

To determine whether or not a new method is an improvement over current practice, it is necessary to have some performance standard against which the new method can be objectively compared. This could be done by using some measure of the overall accuracy achieved in current forecasting practice, and comparing the accuracy of the new method against this standard. This approach was not followed here because objective information on current performance standards is not yet available to use in this way, and it is impossible to artificially reproduce this standard adequately by simulating the real interaction between the forecaster and the forecasting model.

What is important, however, is that conclusions about relative model performance are valid. This requires the application of each model to be undertaken in the same way.

While the interaction between forecaster and forecasting model during a flood event involves considerable subjective input from the forecaster, the starting point for this subjective input is normally the result from an objective application of the model. The time taken to provide this input depends partly on the accuracy of this result. A new method, applied objectively, that proves more accurate than existing methods applied in the

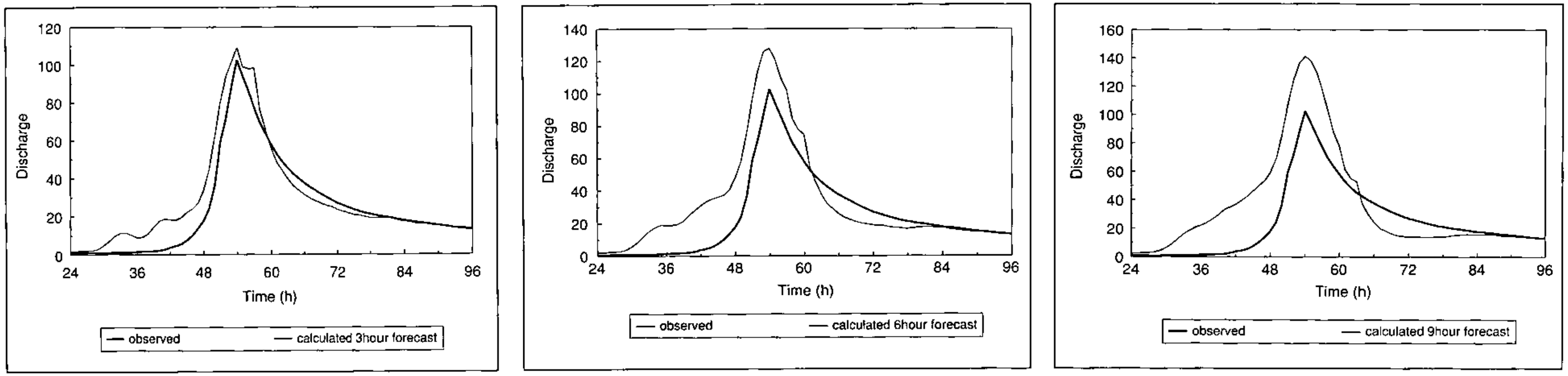


Figure 6: Fixed lead-time forecasts for Gudgenby River - (a) three-hours-ahead forecast; (b) six-hours-ahead forecast; and (c) nine-hours-ahead forecast

same way is clearly an improvement, since not only is the likelihood of the accuracy of the eventual forecast increased, but the requirement for subjective input is reduced, and the forecaster has more time to concentrate on more critical tasks, and perhaps manage additional forecast points.

The objective approach to the application of each model used in this study is described in the following section, along with the performance indicators used to quantify the difference in performance between the models investigated. Available data (event or continuous) from a catchment was split into separate calibration and verification periods, and the evaluation only carried out on results from the verification period. Again, this was done to represent the real situation.

WHOLE-OF-HYDROGRAPH STATISTICS

To satisfy emergency management agencies' range of requirements for information during all stages of a flood - as well as the needs of water management authorities in operating storages during these periods –

Statistic	Description
Relative mean error (RME)	Compares the mean of the difference between forecast and observed flows/levels with the mean of the observed flows/levels. Even though a smaller value is preferred, this does not always mean a good model performance since over prediction at some times can compensate for under prediction at others. A large value however does indicate a bias in the model predictions.
Root mean square error (RMSE)	An average measure of performance over the entire event. The lower the value the better the performance. As an RMS value, over and under predictions are treated equally and do not compensate each other as for the RME. A standardised RMSE, calculated as the RMSE divided by the observed peak discharge for each event, was also used.
Coefficient of determination (CD)	A measure of the association between the observed and forcast hydrographs with a value of 1 indicating perfect association, but not necessarily correspondence and a value of 0 indicating that a naive forecast of the mean flow performs as well as the model forecast. Negative values of COD are possible indicating that the varience of the forecast error is larger than the variance of the observed flows.
Coefficient of efficiency (CEF)	Measures the proportion of the variance of the observed discharges explained by the model with the best performance being the values closest to 1. If the model results are highly correlated with the observed but biased toward under or over prediction, CEF will be less than COD.
Coefficient of extrapolation (CEX)	Compares the model forecast with one made by simple linear extrapolation of the two recent observation. The closer CEX is to 1, the better the model performance compares to simple extrapolation.

Table 2: Statistics used to compare model performance

Statistic \ Lead Time	3 hour	6 hour	9 hour
Relative Mean Error	0.158	0.310	0.432
Root Mean Square Error	0.069	0.132	0.182
Coefficient of Determination	0.925	0.823	0.768
Coefficient of Efficiency	0.894	0.620	0.278
Coefficient of Extrapolation	0.215	0.113	0.026

Table 3: Model comparison statistics for Gudgenby River using error prediction scheme

statistics were used that reflect the extent to which models reproduce the full hydrograph. These 'whole-of-hydrograph' statistics are obtained by comparing the observed hydrograph with hydrographs of fixed lead-time forecasts of three, six and nine hours ahead, calculated as follows.

Each model is run hourly for each event. For each run, a forecast hydrograph is prepared from which a forecast at three, six and nine hours ahead is noted, as well as the forecast of the peak. As with similar studies done elsewhere, to reduce uncertainty introduced into the evaluation process by the use of forecast rainfall, 'perfect' rainfall (actual observed rainfall) forecasts are used throughout each application.

In this way separate hourly series of three-hour-ahead (lead), six-hour-ahead and nine-hour-ahead forecasts are obtained. Each of these three one-hourly forecast series can be compared with the corresponding observed values (Figure 6) to calculate the statistics in Table 2 (see example output in Table 3).

RELATIVE PERFORMANCE INDICATOR: AVERAGE RANK

While each of the statistics in Table 2 can be used as a model performance measure, no single measure is superior. Therefore, a ranking process was adopted to produce a simple relative performance indicator termed the 'average rank'.

Using each statistic in turn, the performance of each model can be ranked against one or more of the others. The model that performs best for each individual event, on the basis of that statistic, is ranked first (rank 1), the second-best rank 2, and so on. The model is similarly ranked for the same event using each of the other statistics. For that event, the model ranks for each statistic are averaged to produce an 'event rank' for each model. This is repeated for all events on a catchment, and the resulting event ranks are averaged to give a 'catchment rank' for each model which, in the final step of the process, can be averaged for all catchments to produce the **average rank.**

For each of the models included in this ranking process, this average rank is a measure of performance of that model relative to other models determined by using all of the measures described above over all of the catchments in the study. For this system, the lower the value of average rank, the better the relative performance of the model.

ABSOLUTE FORECAST PERFORMANCE INDICATORS

To get an indication of the absolute performance of each model, forecast accuracy expressed in terms of river level (metres) is preferred. Current measures of performance used in the Bureau of Meteorology involve summarising the accuracy of quantitative forecasts made over a period (say a year), and expressing this accuracy in terms of the relative frequency (percentage) of forecasts for all catchments falling within a certain range. This range is currently 0-0.3 m, 0.3-0.6 m, and 0.6-0.9 m.

For each catchment, histograms of forecast performance expressed in this way were generated (Figure 7) from the hourly forecasts prepared for all events (calibration or verification) using a particular model.

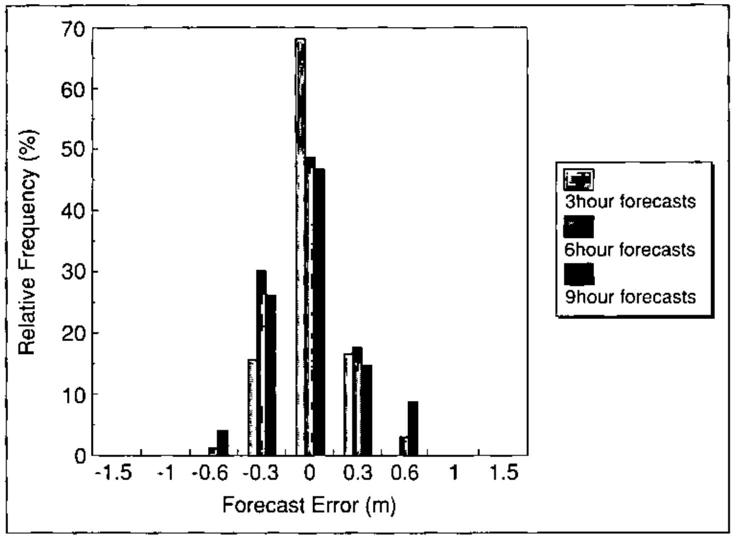


Figure 7: Histogram of forecast errors of the complete event

While these histograms can be used to rank model performance in the same way as the whole-of-hydrograph measures, they also provide an absolute performance indicator that can be more readily related to current practice. This can be done at the catchment level, by comparing the histograms of forecast accuracy from each model for that catchment directly. It can also be done – as with the model comparisons later in this report - by using an overall model performance indicator prepared by combining all forecasts produced by a model across all of the catchments. To assist model performance comparisons in this report, the indicator chosen was the percentage of time that the forecasts were within 0.3 metres of the observed river level. The histograms prepared at the catchment level have been provided in separate reports produced for each model.

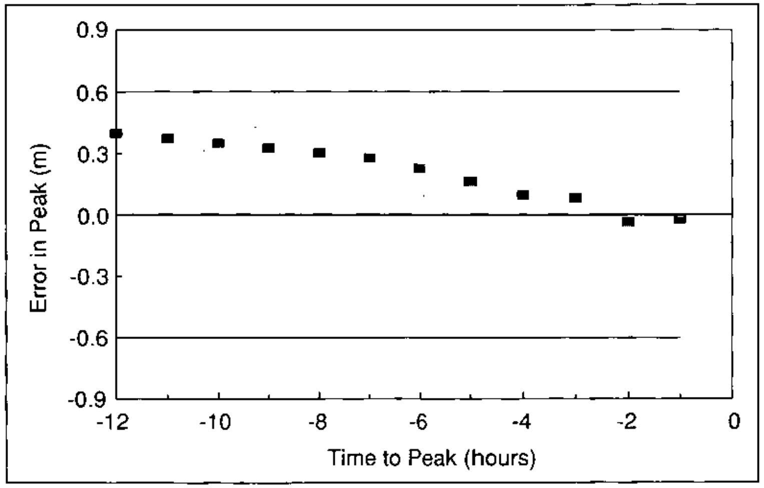


Figure 8: Variation in error in peak prediction with time-to-peak

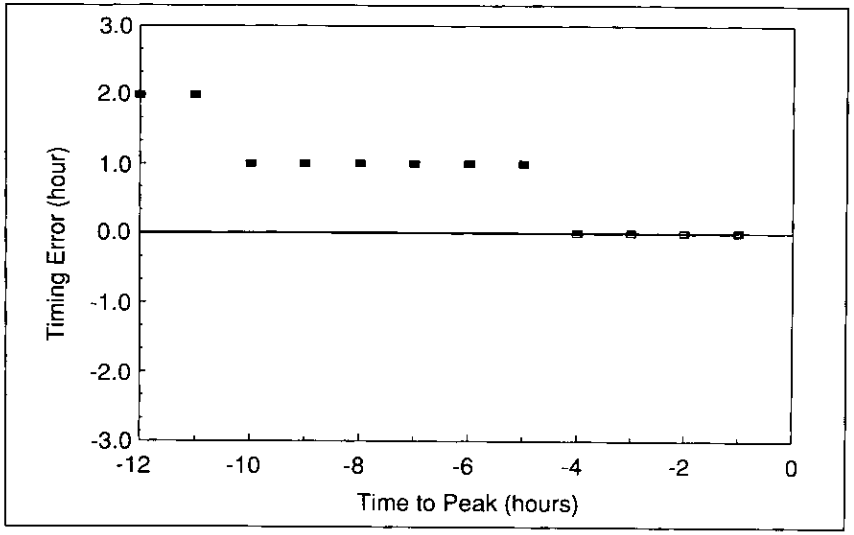


Figure 9: Variation of error in predicted peak time with time-to-peak

PEAK PERFORMANCE INDICATOR

Two plots were constructed to compare the performance of each of the models in predicting the peak level for each event.

The first (Figure 8) shows how the error in the peak prediction (under or over) changes as the prediction is made closer to the time of the peak. A performance measure from this plot is the time-in-advance of the peak at which the error is within, say, 0.6 m; the longer the time, the better the performance. The next plot shows how the predicted time-to-peak varies as the prediction is made closer to the actual time of the peak (Figure 9). A performance measure from this analysis could be the accuracy of the peak forecast made six hours prior to time-of-occurrence of the peak.

Neither of these two measures were used in model comparison. The results for each model on all catchments, however, are provided in separate CRC reports (see Further reading section, this report).

SIMPLE MODELS WITH OBJECTIVE UPDATING

In this section, we discuss the impact of adding objective updating to existing flood forecasting models, the unitgraph model, and the URBS catchment routing model.

UNITGRAPH MODEL

The current approach to flood forecasting using a unit hydrograph involves a simple loss model comprising an initial loss, and either a constant continuing loss, or a proportional loss. An average unit hydrograph and values of the loss model parameters are derived from available historical events.

With such simple loss models, it can be difficult to understand for predictive purposes the reasons for variation in loss values between events. Thus, when used operationally, the initial loss is usually estimated by observing the start of rise of the hydrograph, and using average values of the other parameters. These loss parameters can be adjusted subjectively during the event (on-line) to achieve a closer match between the observed and forecast hydrographs.

ADAPTIVE UNITGRAPH METHODS

A problem with the current approach is the variability between individual unit hydrographs derived for each of the historical storm events, as well as between the loss parameters. Adopting average values for both components of the model results in a forecasting model that should produce results for future events that, on average, will match that achieved in the calibration process (but not necessarily the best results for each individual future event).

While subjective on-line adjustment may be effective in some cases, an alternative approach is an objective method that estimates the 'best fit' parameters of this simple model for each future event. This may give better results for the event than the average values, provided it can be done reliably.

The approach used in the adaptive unit hydrograph method (ADUG) is to estimate the parameters of a simple linear model based on the unitgraph and a proportional loss model at each time-step during the event. This model estimates a new 'average' unit hydrograph and proportional loss coefficient at each time-step in such a way that the model best replicates the catchment response up to, and including, that time step. The model so derived at that point in time is assumed to offer a more accurate means of forecasting future flood levels than would the 'average' model.

An alternative approach is to again estimate 'best fit' parameters for each future event, but concentrate only on the loss model, keeping the unit hydrograph parameters constant. With this method – referred to as the Chander and Shanker method (CSM) after the researchers who suggested it - the value of the loss model (continuing or proportional) parameter can be determined at each time-step during a flood event so that the sum of squares of the deviations between the observed and computed runoff is a minimum. Again the assumption is made that the value of the loss parameter that best models the observed runoff up to a particular time-step in the current event will more accurately predict future runoff than a loss model using parameters averaged from past events.

Along with the current (non-adaptive) unitgraph model (NAUG), these two methods were compared in a pilot study based on eight Victorian catchments. Figure 10 shows that, using the relative performance indicator (average rank), the ADUG model is ranked as the best of the three models.

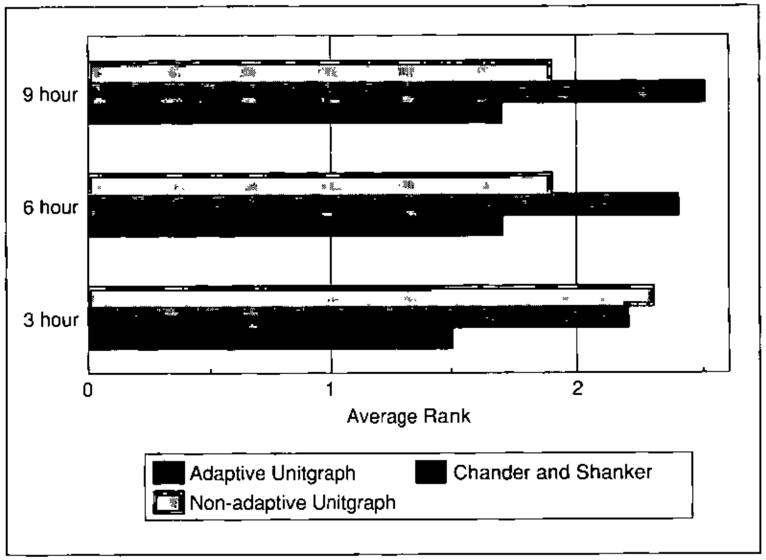


Figure 10: Comparison of forecasting performance - for three-, six-, and nine-hour lead times - of two adaptive unitgraph models and the current unitgraph model using 'average rank' (lower rank indicates better performance)

The CSM model using the different adaptive approach showed a slight improvement over the existing unitgraph model for the shorter forecast lead-times, but was overall ranked as the worst performer and was eliminated from the project.

UNIT GRAPH WITH ERROR CORRECTION

To investigate an alternative method, we compared the ADUG model and the unit-graph with the addition of an updating component using the error correction method (referred to as the ECUG model).

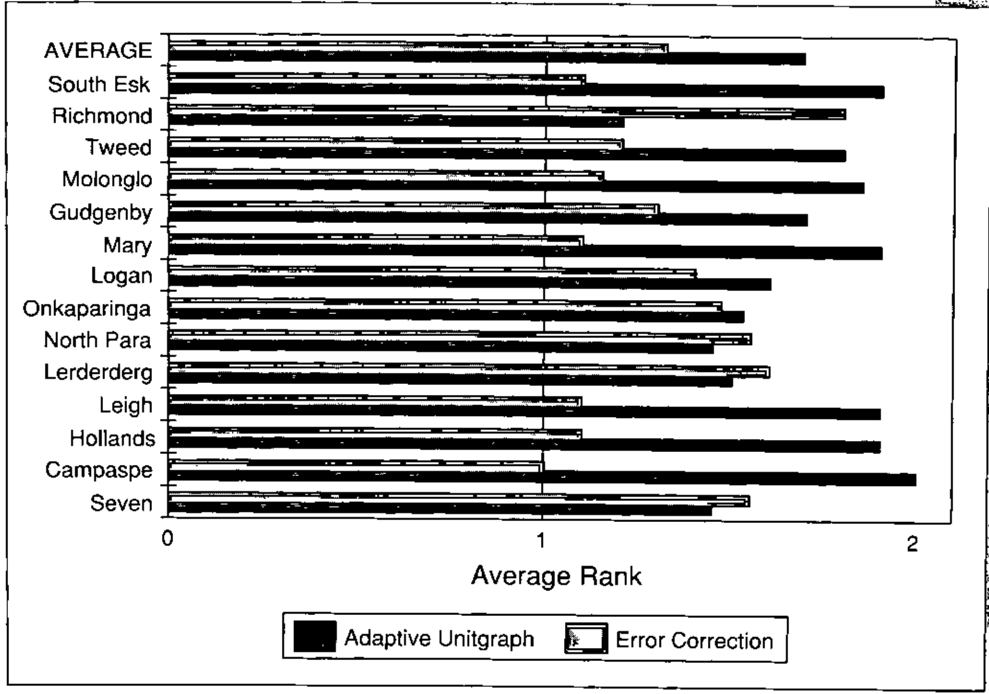


Figure 11: Comparison of adaptive unitgraph method to unitgraph with error correction for forecasts with a lead-time of three hours over 14 catchments

This comparison was carried out using data from all 14 catchments. Figure 11 shows the relative performance of the two methods of each of the catchments for three-hour lead-time forecasts. This figure does not show one model as being consistently better over all catchments, although the ECUG model, on average, gives the better result. This difference does not continue for longer lead-time forecasts (Figure 12), where both models are ranked about equal on a plot of average ranks for all catchments.

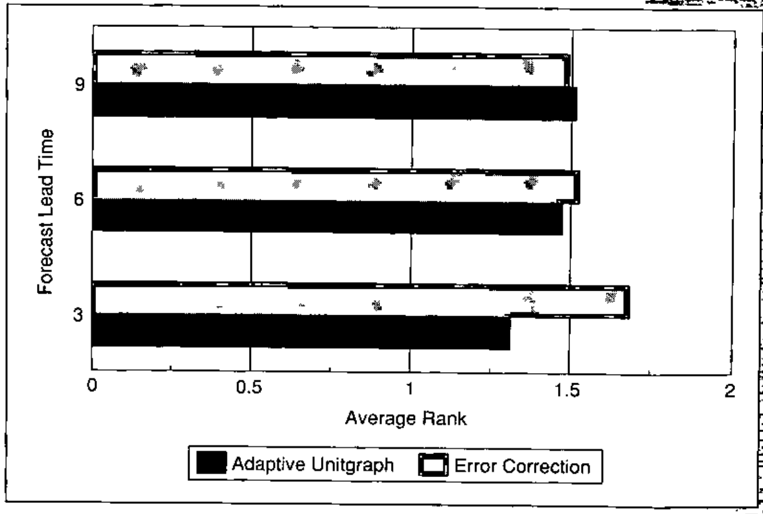
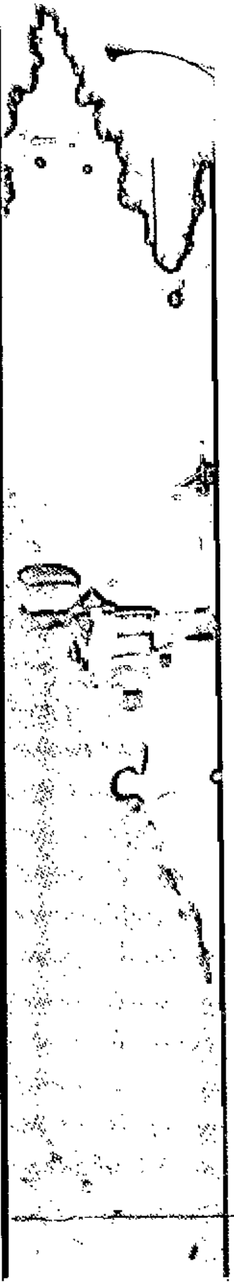


Figure 12: Comparison of average performance of adaptive unitgraph method against unit-graph with error correction over 14 catchments for three-, six-, and nine-hour forecast lead-times



THE URBS MODEL

URBS is a rainfall-runoff model that treats the drainage network of a catchment as a network model of sub-catchments (Figure 13). Rainfall excesses from each sub-catchment can be estimated using simple loss models such as initial loss and continuing loss or, as done in a separate part of this study, generated using a continuous soil-moisture accounting model.

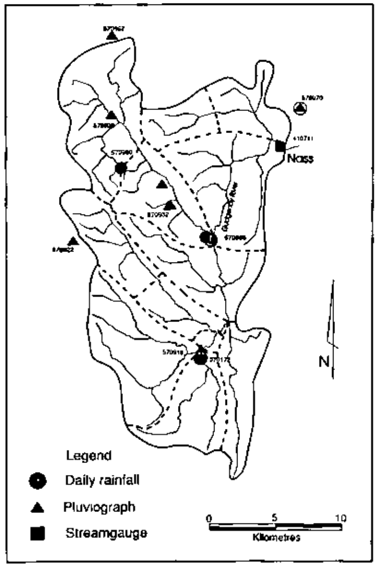


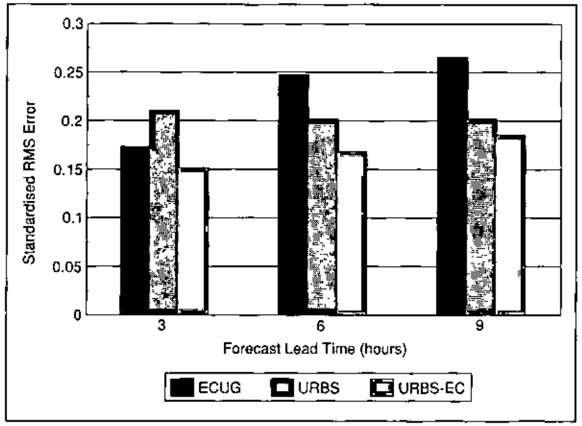
Figure 13: URBS networked catchment model

The effect of catchment storage is modelled first by routing each sub-area rainfall excess to the centroid of the sub-area, and then routing each sub-area contribution through the channel network to produce the surface-runoff hydrograph at the catchment outlet. An error correction model can then be fitted to the model as a simple updating method. The complete model is referred to as URBS-EC.

The effectiveness of adding the error correction updating model to URBS can be seen clearly in Figures 14 and 15. For the three-hour lead-time forecast, the standardised RMS error (Table 2) has been reduced by about 25 percent and the percentage of forecasts within 0.3 m has risen from just over 40 to more than 70 percent. This indicates a dramatic improvement in accuracy.

While the improvement is less significant as forecast lead-time increases, an improvement is indicated. For comparison, the results from the ECUG model are included. These reveal that this model is slightly superior to the more complex URBS model for short lead-times but, for longer lead times, URBS shows superior perfor-mance. The difference between the two methods increases with longer lead-time.

Figure 14: Effectiveness of error correction on simple models in reducing root mean square error (average model forecast performance over 14 catchments)



In terms of a modelling strategy, these results suggest that:

- flood forecasting procedures based on the standard unitgraph model can be easily improved by the addition of an error correction model to update the model output
- URBS forecasting models can also be improved by the addition of an error correction updating model
- in both cases, the benefit of the improvement will diminish for longer lead-times, but the relatively superior performance of URBS for longer lead-times would seem to justify the additional effort of replacing existing unitgraph models with URBS-EC.

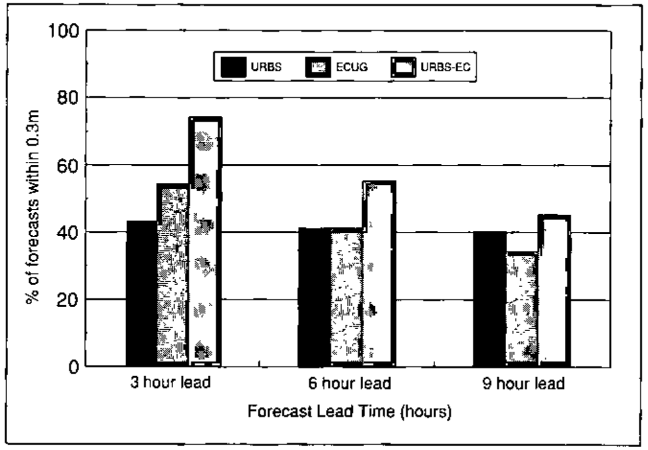


Figure 15: Effectiveness of error correction on simple models in predicting heights within specified accuracy (average model forecast performance over 14 catchments)

CONTINUOUS SOIL-MOISTURE ACCOUNTING MODELS

In the previous section, it was concluded that the addition of objective updating to simple models such as URBS and the unitgraph led to a significant improvement in forecasting performance. Both models used an event-based approach to rainfall excess prediction.

The aim of this part of the project was to determine to what extent continuous soil-moisture accounting (CSMA) models can improve this performance, and whether they provide advantages when forecasting for longer forecast lead-times, as suggested in the review.

Four continuous soil-moisture accounting models were investigated:

- the **Australian Water Balance Model** (AWBM), chosen because it was developed for Australian conditions, and had shown promising results when coupled with a catchment-routing model for flood forecasting purposes
- the **Xinanjiang Model,** chosen as an alternative soil-moisture accounting procedure to the AWBM, and also as a model used for flood forecasting operations overseas
- the **Probability Distributed Moisture** (PDM) model, chosen as a recent model developed specifically for real-time flood forecasting, and used in operational applications in the UK and elsewhere
- the **Sacramento (Hydrologic Forecast System or HFS) Model,** chosen as an advanced state updating model developed specifically for application in the US National Weather Service forecasting offices, which has given good results in other comparison tests.

The first two models had to be modified to suit real-time flood forecasting applications by the addition of a catchment routing model and a simple updating procedure. The last two were already available in a form suited to real-time flood forecasting, and included more complex state updating procedures.

This section reports on the evaluation of the first three models over all 14 catchments. The Sacramento model has a different soil-moisture accounting structure to these three and, in its state-space form in the HFS, is much more complex to calibrate and apply. Although the model was applied to six catchments, the results are not presented in any detail in this report, but are used to make some preliminary conclusions about its relative performance.

Full details of each of the models used can be found in the 'further reading' section. Only a brief description of the main features and differences between models is provided here.

THE AUSTRALIAN WATER BALANCE MODEL (AWBM)

The Australian Water Balance Model (AWBM) is a simple model that transforms daily or hourly rainfall to

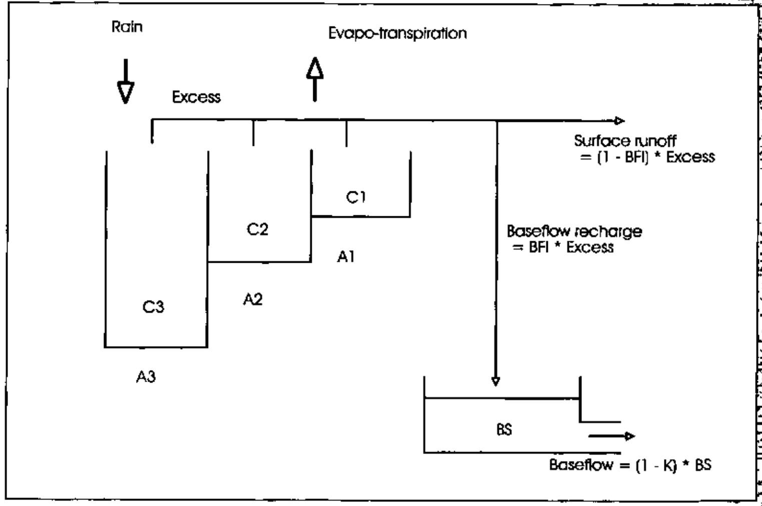


Figure 16: The Australian Water Balance Model (AWBM)

runoff. The model uses three surface stores (capacity C1, C2 and C3) to simulate partial areas (A1, A2 and A3) of runoff (Figure 16). The water balance of each surface store is calculated independently of the others. At each time-step, the daily or hourly rainfall is added to each of the three surface moisture stores and evapotranspiration is subtracted from each store.

Surface runoff and recharge of baseflow storage occur when one or more of the stores is over-filled and overflow occurs. If the value of moisture in any store becomes negative, it is set to zero. If the value of moisture in any store exceeds the capacity of the store, the excess moisture becomes runoff and the store is set to capacity. When runoff occurs from any store, part of the runoff (BFI) becomes recharge of the baseflow store (BS). The remainder of the runoff is the surface runoff.

For this project, the rainfall excess output from AWBM was used with the non-linear catchment routing model URBS to produce a catchment output hydrograph, which was updated using an error correction method. This model is referred to as AWBMU.

THE PROBABILITY DISTRIBUTED MOISTURE (PDM) MODEL

The Probability Distributed Moisture (PDM) model is also based on the concept of soil storage capacity varying across a catchment, but instead of representing this variation by three stores as in the AWBM, PDM uses a population of stores of capacity represented by a probability. For the PDM model, as for Xinanjiang, the cumulative probability distribution referred to as the Pareto distribution was used (Figure 17).

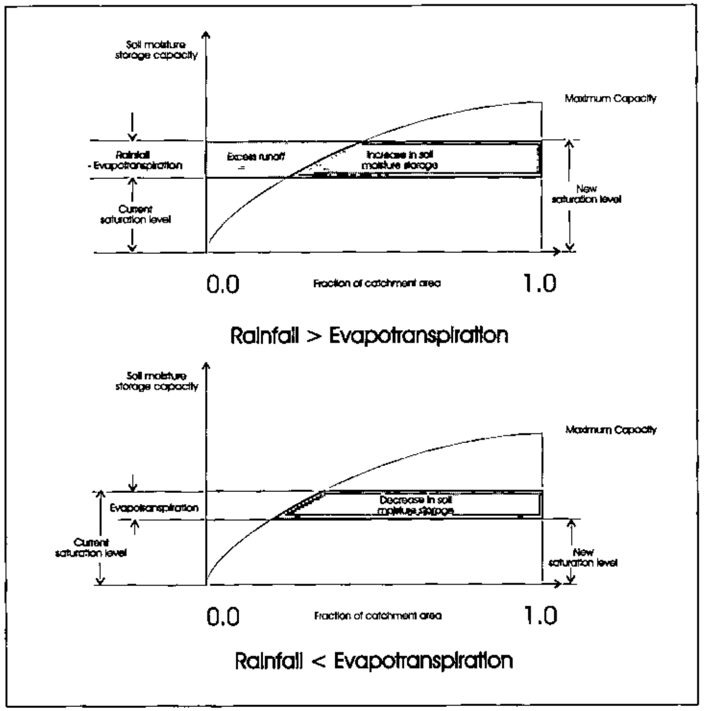


Figure 17: Soil moisture capacity distribution curves for PDM and Xinanjiang models

Unlike AWBM where the stores do not interact, the PDM model allows this interaction to represent a redistribution of soil moisture between stores (Figure 17). This difference leads to other differences in the way rainfall and evapotranspiration are used to model changes in soil moisture, and in the production of rainfall excess when compared with AWBM. The rainfall excess (direct runoff) is routed through a catchment surface storage system, while the groundwater recharge from soil water drainage is routed through a groundwater storage system (Figure 18). Both routing systems can be defined by a variety of non-linear storage reservoirs.

The updating methods used with the PDM model were an error correction approach (PDMEC) and the application of a form of state updating termed 'empirical state updating' (PDMSU) where the 'error' is apportioned between the surface and groundwater stores (S1 and S2 in Figure 18) in proportion to their contribution to total flow.

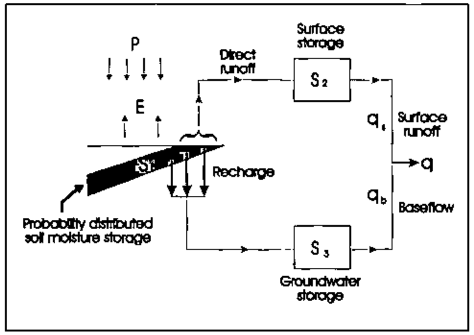


Figure 18: The Probability Distributed Moisture (PDM) model

THE XINANJIANG MODEL

Like PDM, the Xinanjiang model represents the variation of soil storage capacity across a catchment by a continuous function (Figure 17), and allows interaction between the different soil stores. There are some differences in the way in which rainfall and evapotranspiration is used to calculate rainfall excess, but otherwise both models handle their soil-moisture accounting procedure in the same way.

Although later versions of the model use the unit hydrograph for catchment routing and additional parameters for interflow and baseflow, only the soil-moisture accounting component was used for this study, with the URBS model being used for catchment routing. The updating was done using an ARMA model for error prediction. This model is referred to as XINANU.

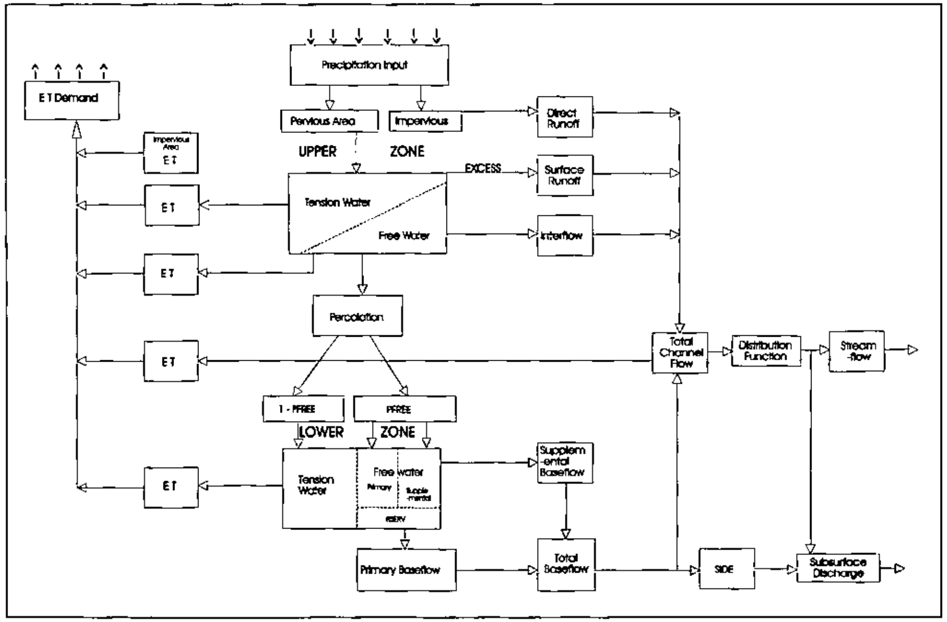


Figure 19: Schematic description of the Sacramento soil-moisture accounting model (from Kitanadis, P.K. and Bras, R.L., 1980)

THE HYDROLOGIC FORECAST SYSTEM (HFS)

The HFS is a system designed specifically for the real-time prediction of streamflow in headwater basins using an adaptation of the Sacramento soil-water accounting model as its central component. This model differs from the other three described above by not including any specific spatial variation of soil storage capacities across the catchment. It does, however, have a more detailed structure that accounts for moisture movement vertically within the catchment soil profile (Figure 19).

Including the catchment and channel routing components, there are more than 20 parameters in the model. The system provides for real-time updating using a state-updating approach, which includes a further 19 parameters. Although the system is powerful, it needs considerable expertise to calibrate and apply. As discussed earlier, this system was only applied to six catchments and, without further work, the results could only be considered preliminary and are not reported.

DO CSMA MODELS ADD VALUE?

The results from application of both event-based models (ECUG and URBS-EC) and the four continuous soil-moisture accounting models (PDMSU, PDMEC, AWBMU, XINANU) are summarised in Figures 20 and 21. These figures show the values of each of the performance measures

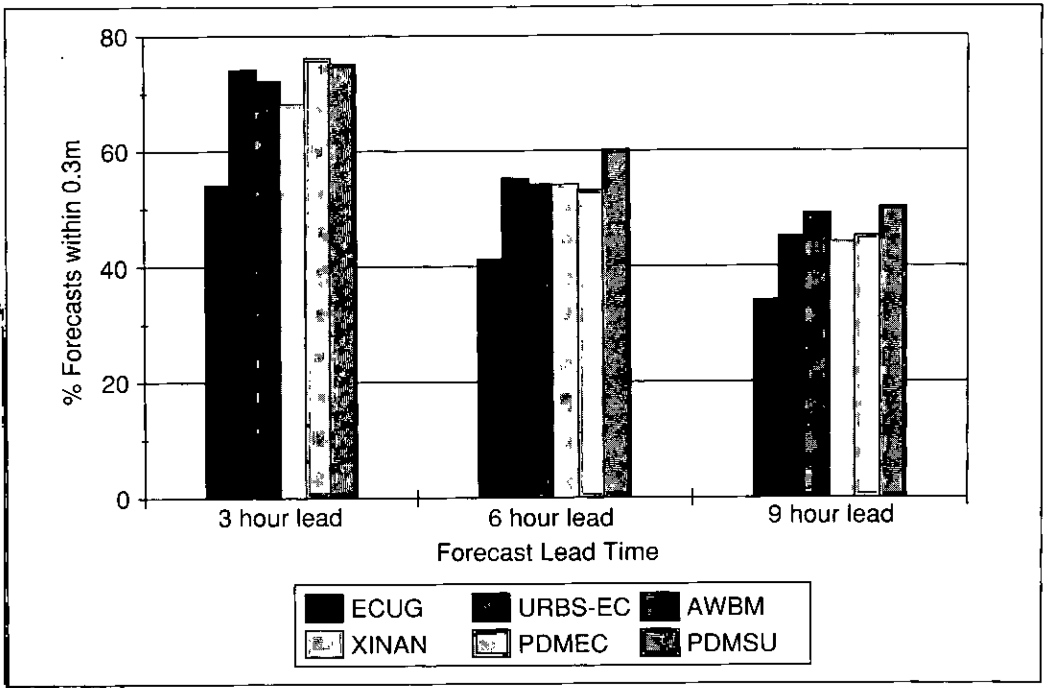


Figure 20: Comparison of model average performance in predicting heights within specified accuracy

averaged for all verification events on each catchment, thus representing the overall performance of each model.

The evidence for determining whether CSMA models add any value is not clear. Figure 20 suggests that overall there is little gain from the addition of either the AWBM or the Xinanjiang models to the URBS-EC event-based model, although all models showed superior performance to the unitgraph based model (ECUG). Both PDM models performed slightly better than the others, but for three-hour lead-times only, with PDMSU performing best for six- and nine-hour lead times.

Figure 21 on the other hand shows that all of the CSMA models reduced the average standardised RMS error values achieved with the event-based models by around 20-30 percent for all forecast lead-times, which is quite significant.

When the variation in results from the different catchments is examined (Figure 22), it appears that this improvement may have been achieved by significant improvements on one or two catchments only.

Another positive feature of the performance of CSMA models noted during their calibration was that they appeared useful in modelling the initial rise of the flood hydrograph. The event-based models on the other hand all required this initial rise to begin before modelling commenced. While not a specific evaluation criterion, this feature is useful at the early stages of a flood event, and is noted as an advantage of the CSMA models.

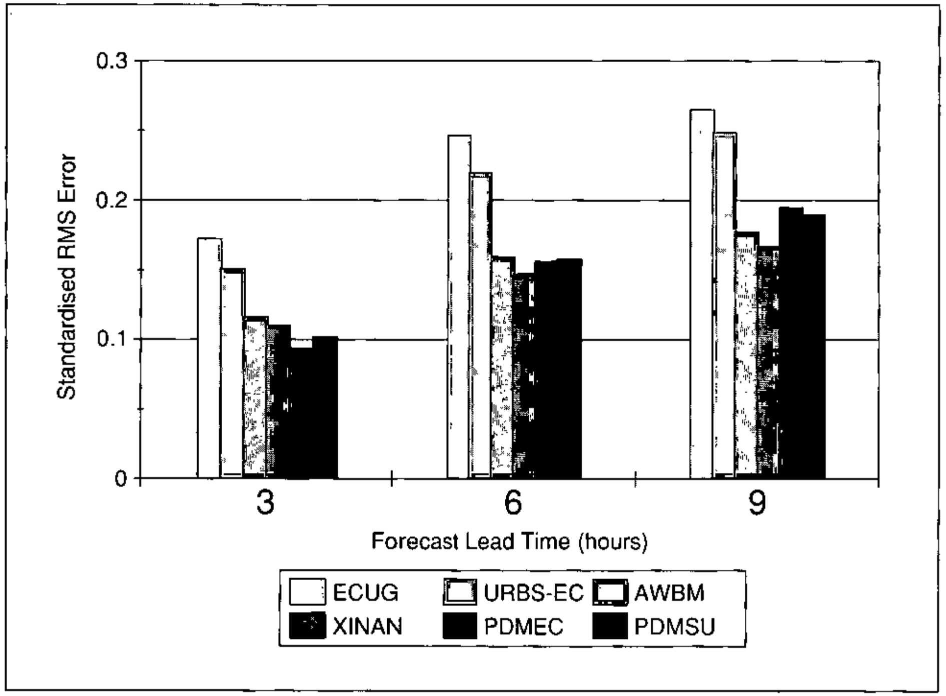


Figure 21: Comparison of model average performance in reproducing the hydrograph shape through the use of root mean square error (RMSE)

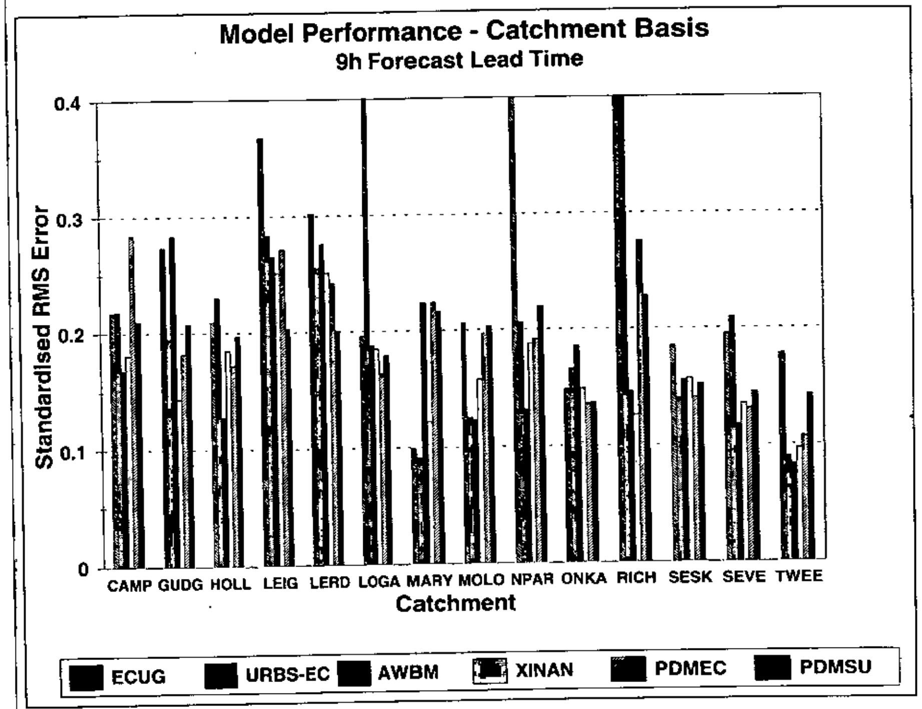


Figure 22: Relative performance of the models on a catchment-wide basis for a nine-hour-forecast lead-time

In terms of impact on modelling strategy, the general result does not provide convincing evidence to recommend adding a CSMA model to all existing event-based approaches. However, the variation between catchments (Figure 22) - in particular the dramatic improvement these models made in one or two cases, and the result presented in Figure 21, supporting the finding in the review that CSMA models sustain an improved performance over the longer lead times - would seem to justify further investigating the application of either of the CSMA models to current systems on a case-by-case basis.

No significant difference was noted between the different forms of updating (error correction and empirical state updating) to recommend one over the other.

CONCLUSIONS

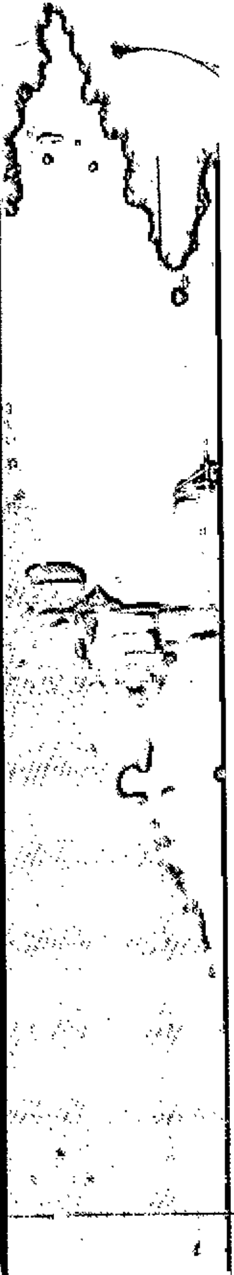
From a review and evaluation of recent advances in real-time flood forecasting modelling, the CRC has identified improvements that can be made to current flood forecasting practice in Australia. These include immediate improvements to existing procedures, and guidance on the application of new methods.

Software has been developed to apply the different procedures, and a systematic evaluation strategy established to assess and monitor the performance of any improvement once introduced. The experience gained from the project provides a basis for assessing the standard of real-time flood forecast modelling in Australia, in the context of recent research and practice elsewhere.

In terms of existing forecasting systems, this project has demonstrated that the addition of a simple updating procedure (error correction) to existing unitgraph based models (ECUG) and URBS rainfall-runoff models (URBS-EC) can lead to improvements in forecast accuracy, particularly for shorter forecast lead-times. The results for the URBS-EC model suggested that the advantage of the objective updating was sustained for longer lead-times.

This improvement may be less significant on the larger catchments, where longer forecast lead-times are normally required. It may be that a longer modelling time-step than the one hour used so far would be used for these catchments, and the three time-step-ahead improvement would translate into a more significant time advantage.

Two new real-time forecasting models (AWBMU and XINANU), both based on continuous soil-moisture accounting approaches, have been formulated and tested and, by some performance measures at least, showed



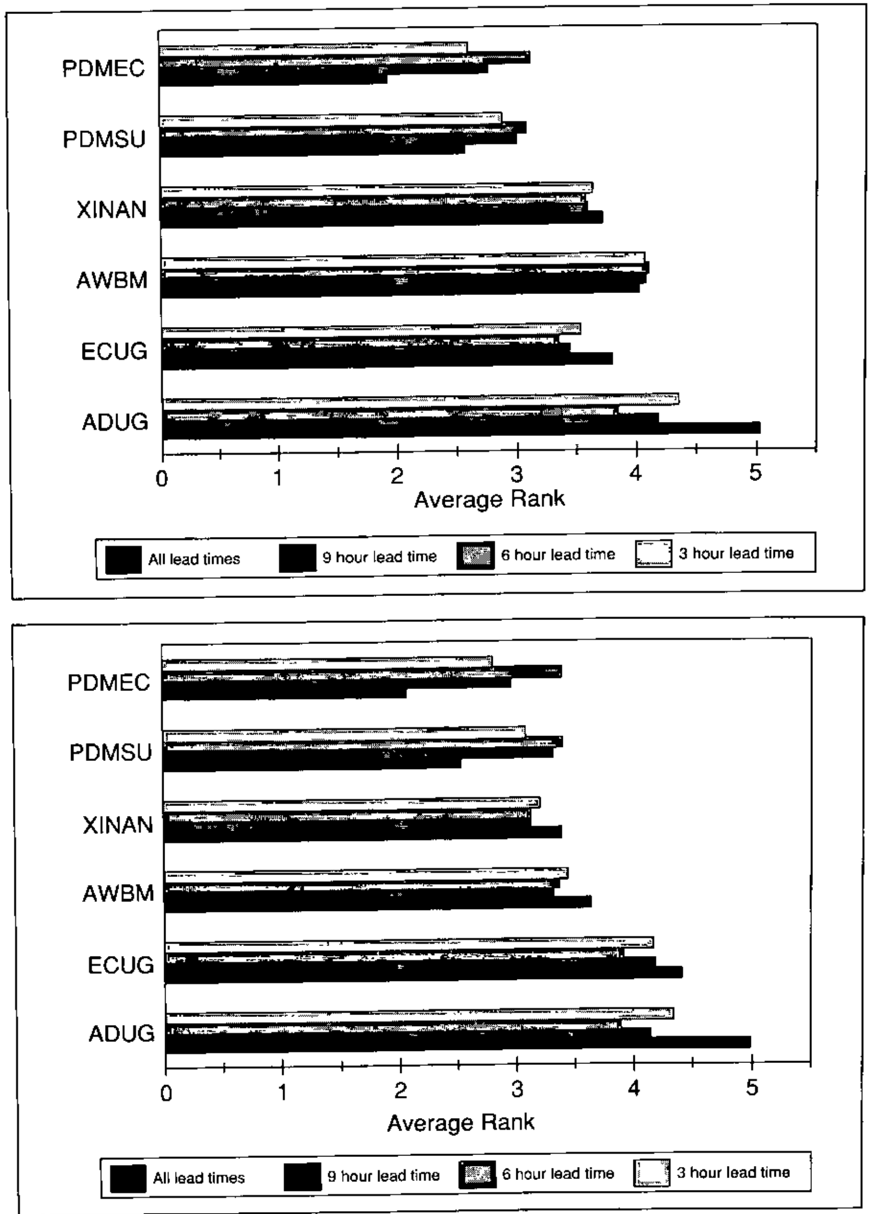


Figure 23: Overall model performance based on average rank for (a) calibration events and (b) verification events

a promising improvement over current event-based methods (with updating) for all forecast lead-times. These improvements could be introduced relatively easily and software has been developed to support this.

Therefore, it is recommended that, where practitioners seek to further improve their systems, an investigation into using one of these two soil-moisture accounting models would be the most promising next step.

Two models considered to represent the state-of-the-art of real-time modelling practice in the UK (PDM) and the USA (HFS) were applied and evaluated under Australian conditions. The PDM model was applied to all catchments, but the HFS was only applied to a sample. This work showed that both models could further improve current practice, but more experience is required to fully exploit their potential - further work on this within the Bureau of Meteorology is recommended.

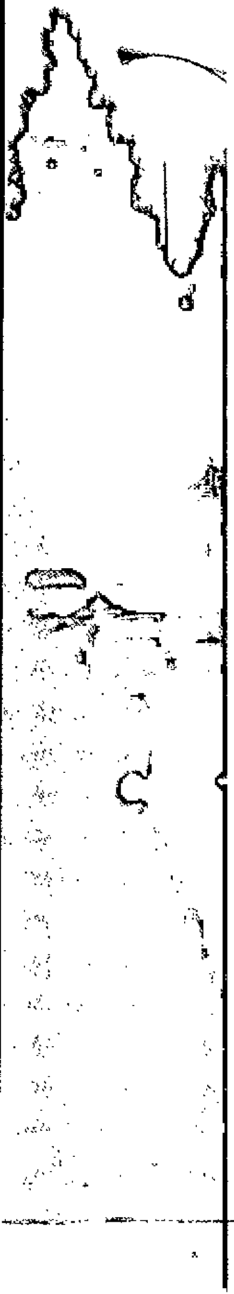
While more experience and expertise with these models may lead to better results than has been achieved so far, it was encouraging to see that results coming from models currently used for flood forecasting in Australia compared favourably with these more complex procedures.

Although not performing as well as other models, the adaptive unitgraph (ADUG) model was considered to be a useful forecasting technique in situations where little or no data is available. Careful guidance would be needed, however, as the model was found to require specialised 'tuning' for each catchment, and guidelines would need to be prepared before it could be implemented more widely.

These conclusions have been drawn from an examination of values of the various indicators of model performance averaged across all 14 catchments. An examination of the results at the single catchment level will reveal exceptions to these conclusions, implying that different models perform better on a given catchment. Without further detailed examination of the results, the reasons for this variation cannot be explained.

Thus the practitioner needs to adopt a flexible approach in selecting the most suitable model. The 'hierarchy' of incremental improvements contained in the above conclusions are a guide. While any attempt to rank the different models into some order based on the different performance indicators may not be conclusive, in some cases it may assist model selection. With the 'average rank' approach discussed earlier in the report, an attempt at ranking a selection of the models produced the result shown in Figure 23.

Finally, by systematically testing and comparing existing procedures with those identified in the research literature and in use elsewhere, this CRC project has provided a good benchmark of what can be achieved by applying a selection of 'best practice' approaches to Australian flood forecasting practice. This provides a sound basis for the industry to make judgements about the overall standard of practice in Australia, and to guide and monitor the direction of future improvements.



FURTHER READING

Amirthanathan, G.E. (1996) Adaptive linear models for real-time flood forecasting. Report 96/3, CRC for Catchment Hydrology, Melbourne.

Boughton, W.C. (1993) A hydrograph-based model for estimating the water yield of ungauged catchments. Hydrology and Water Resources Symposium, June/July 1993, pp. 317-24.

Boughton, W.C. and Carroll, D.G. (1993) A simple combined water balance/flood hydrograph model. Hydrology and Water Resources Symposium, June/July 1993, pp. 289-303.

Box, G. P. and Jenkins, G. M. (1976) Time Series Analysis, Forecasting and Control, Holden-Day, San Francisco.

Carroll, D. G. (1992) URBS: The Urbanised Catchment Runoff Routing Model. Brisbane City Council.

Carroll, D. G. (1994) Aspects of the URBS runoff routing model. Hydrology and Water Resources Symposium, November, IEAust.

Chander, S. and Shanker, H. (1984) Unit hydrograph based forecast model. Hydrol. Sci. J. 29:279-291.

Cock, R.A. and Elliott, J. F. (1989) Flood warning and real-time data collection in Australia. Hydrology and Water Resources Symposium, Christchurch, NZ, November, pp. 28-32.

Crapper, G.C.A. (1989) Development of a real-time reservoir routing flood warning procedure using the RORB model. Hydrology and Water Resources Symposium, Christchurch NZ, November, pp. 23-30.

Georgakakos, K.P. and Smith G. F. (1990) On inproved hydrologic forecasting: Results from a WMO real-time forecasting experiment. J. Hydrol. 114: 17-45.

Georgakakos, K. P., Rajaram H. and Li S. G. (1988) On improved operational hydrologic forecasting of streamflows. IIHR Report No. 325, Development Civil and Environmental Engineering & Iowa Institute of Hydralic Research, University of Iowa.

Hudlow, M. D. (1988) Technological developments in real-time operational hydrologic forecasting in the United States. In: R. L. Bras, M. Hino, P. K. Kitanidis and K Takeuchi (Eds), Hydrologic Research: The U.S./Japan experience. J. Hydrol., 102: 69-92.

Kitanidis, P. K. and Bras, R. L. (1978) Real time forecasting of river flows. Department Civil Engineering, Cambridge, Rep. No. 235 M.I.T.

Kitanidis P. K. and Bras R. L. (1980) Real-time forecasting with a conceptual hydrologic model. 1: Analysis of uncertainty. Water Resources Research 16: 1025-33.

Kitanidis, P. K. and Bras, R. L. (1980) Real-time forecasting with a conceptual hydrologic model. 2: Applications and results. Water Resources Research, 16: 1034-44.

Laurenson, E. L. (1964) A catchment storage model for runoff routing. J. Hydrol. 2:141-163.

Laurenson, E. M. and Mein, R. G. (1985) RORB - Version 3 Runoff routing program: User Manual, Second Edition, Dept. Civil Engineering, Monash University.

Malone, T.A. and Cordery I. (1989) An assessment of network models in flood forecasting. In: New Directions in Surface Water Modelling, Proceedings of the Baltimore Symposium.

Malone, T.A. (1994) Forecasting Mary River floods. 25th Congress of International Association of Hydrogeologists / International Hydrology and Water Resources Symposium , November, IEAust, pp. 223-28.

Masmoudi, M. and Habaieb, H. (1993) The performance of some real-time statistical flood forecasting models seen through multicriteria analysis. Water Resources Management, 7: 57-67.

Mein, R. G. and O'Loughlin, E. M. (1991) New approach for flood forecasting. In: International Hydrology and Water Resources Symposium, IEAust. National Conf Publ. No 92/22, pp. 219-24.

Moore, R.J. (1985) The probability-distributed principle and runoff-prediction at point and basin scales. Hydrol. Sciences Journal 30(2): 273-97.

Moore, R.J. (1986) Advances in real-time flood forecasting practice. In: Symposium on Flood Warning Systems, Winter Meeting of the River Engineering Section, Institution of Water Engineers and Scientists, pp. 1-23.

Moore, R J. and Jones, D.A. (1991) A river flow forecasting system for region-wide application. in: MAFF Conference of River and Coastal Engineers, Loughborough University, pp. 1-12.

Puente, C.E. (1988). What is necessary to forecast river flows reliably? Proc. Third Water Resources Operations Management Workshop, Fort Collins, CO, pp. 210-26.

Puente, C.E. and Bras, R.L. (1987a). Are soil moisture accounting models needed for the real time forecasting of river flows? Engineering Hydrology Symposium, August. Sponsored by the Hydraulics Division of the ASCE.

Serban, P. and Askew, A. J. (1991) Hydrological forecasting and updating procedures. In: 20th General Assembly Int. Union of Geodesy and Geophysics, Vienna, Austria, pp. 357-369.

Srikanthan, R., Elliott, J. F. and Adams, G. A. (1994) A review of real-time flood forecasting methods. Report 94/1, CRC for Catchment Hydrology, Melbourne.

Srikanthan, R., Sooriyakumaran, P., Elliott, J.F. and Hill, P.I.(1996) Comparison of two adaptive unit hydrograph methods for real-time flood forecasting. Working Document, 96/2, CRC for Catchment Hydrology, Melbourne.

Srikanthan, R., Sooriyakumaran, P., Hill, P.I. and Elliott, J.F. (In press) Development of a real-time flood forecasting model: 1. Data sets. Working Document, CRC for Catchment Hydrology, Melbourne.

Srikanthan, R., Sooriyakumaran, P., Khan, M.H. and Elliott, J.F. (In press) Development of a real-time flood forecasting model: 2. Evaluation of unit hydrograph models. Working Document, CRC for Catchment Hydrology, Melbourne.

Srikanthan, R., Khan, M.H., Sooriyakumaran, P. and Elliott, J.F. (In press) Development of a real-time flood forecasting model: 3. Evaluation of the AWBM-URBS model. Working Document, CRC for Catchment Hydrology, Melbourne.

Srikanthan, R., Khan, M.H., Sooriyakumaran, P. and Elliott, J.F. (In press) Development of a real-time flood forecasting model: 4. Evaluation of the Xinanjiang- URBS model. Working Document, CRC for Catchment Hydrology, Melbourne.

Srikanthan, R., Sooriyakumaran, P. and Elliott, J. F. (In press) Development of a real-time flood forecasting model: 5. Evaluation of the probability distributed model. Working Document, CRC for Catchment Hydrology, Melbourne.

Srikanthan, R., Ramchurn, A., Sooriyakumaran, P., and Elliott, J.F. (In press) Development of a real-time flood forecasting model: 6. Evaluation of the initial loss-continuing loss-URBS model. Working Document, CRC for Catchment Hydrology, Melbourne.

World Meteorological Organisation (WMO) (1987) Real-time intercomparison of hydrological models. WMO, Report of Workshop held inVancouver, Canada, July/August.

World Meteorological Organisation (WMO) (1992) Simulated real-time intercomparison of hydrological models. WMO Operational Hydrology Report No. 38 (WMO No. 779).

Young, P. (1974) Recursive approaches to time series analysis. Institute of Mathematics and Its Applications.

Zhao, R.-J, Zhang, Y.-L, Fang, L.-R., Liu, X.-R. and Zhang, Q.-S. (1980) The Xinanjiang model. Hydrological Forecasting, Proceedings Oxford Symposium, IASH 129, pp. 351-56.

Zhao, R.-J. (1992) The Xinanjiang model applied in China. J. Hydrology 135: 371-81.

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Established and supported under the Australian Government's Cooperative Research Centres Program

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

A cooperative venture between:
Bureau of Meteorology
CSIRO Land and Water
Department of Natural Resources and Environment, Vic
Goulburn-Murray Water
Melbourne Water
Monash University
Murray-Darling Basin Commission
Southern Rural Water
The University of Melbourne
Wimmera-Mallee Water

Associates:
Department of Land and Water Conservation, NSW
Department of Natural Resources, Qld
Hydro-Electric Corporation, Tas
State Forests of NSW

Centre Office
Department of Civil Engineering
Monash University
Clayton, Victoria 3168 Australia