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A Comparison of Rainfall-Runoff Models

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Five different rainfall – runoff models including three sophisticated conceptual models (Sacramento, Stanford and Monash Models), a simple conceptual model (Boughton Model) and a black-box or purely mathematical method involving a recursive time series alogirithm were tested on three catchments in the south-west region of Western Australia. A variety of techniques were used to assess the performance of each of the models which were calibrated on about six years of data and then tested on a further six or seven years of extra data. As well as the objective comparison of the models, a subjective assessment of the user and computation aspects of model calibration is presented. All of the models except the Boughton Model performed in a satisfactory manner with the Sacramento Model and Time Series Method being given overall recommendation.

Introduction

During the past ten years, much effort has been devoted to the development of methods to relate streamflow to rainfall on a continuous basis for use in hydrologic analysis. Most of these models have been developed by a particular user who then begins to apply the model to his particular applications. It is uncommon to find models widely applied by users not associated with their development and it is rare to find a systematic comparison of models on the same catchments. With the vast array of different models currently available, it would seem obvious that these models should be objectively tested, but only two such comparisons have been reported recently.

The World Meteorological Organisation (1974) arranged to test ten different models on six rivers distributed throughout the world. The owners of each model were sent sets of concurrent rainfall and streamflow data to calibrate the model and a set of rainfall data (while W.M.O. retained the streamflow data) to test the model performance. Another study reported by Moore and Mein (1975) tested three process models on four Australian rivers. In both of these studies the catchments chosen were selected from a wide range of climatic and hydrologic conditions. This study concentrates on three catchments from one geographical region, the south-west of Western Australia (location map, Fig. 1) and examines the performance of five rainfall-runoff models on each of these catchments.

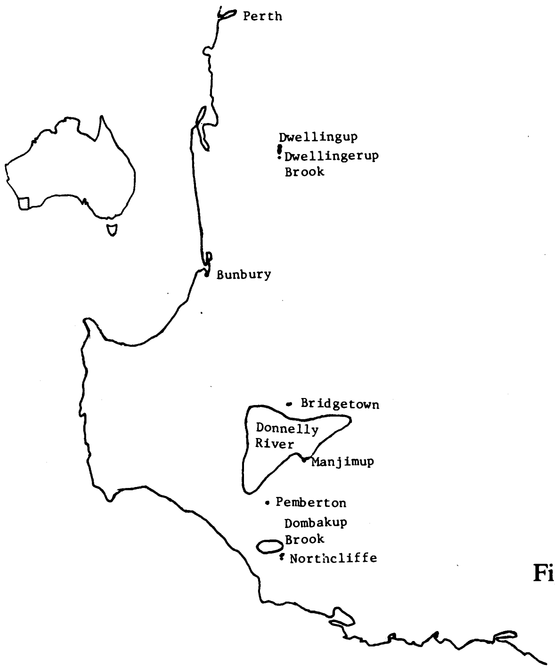

Fig. 1. Location Map.

The Region

The south-western region of Western Australia has a typical Mediterranean climate with hot dry summers and mild wet winters. The predominant winter rainfall results from the movement of cold fronts across the area with the orographic effect of the Darling Scarp producing increased rainfall along its length. Mean annual rainfall is reasonably low being about 1,200 mm along the scarp and in the extreme south-west. Mean rainfall decreases rapidly further inland at a rate of approximately 20 mm per km. The area in which the streams rise, known as the

Darling Ranges, is characterized by lateritic soils of high permeability and a drainage pattern of low relief resulting in very sluggish streamflow response. To the west the flat low lying, predominately sandy, coastal plain is separated from the ranges by an escarpment which rises sharply by some 300 m. Forests cover the upland regions but further inland to the east the forest has been cleared for sheep and cattle grazing. In the lower south-west, a variety of argricultural activity including fruit and vegetable growing and dairying is practised.

In testing rainfall-runoff models, adequate rainfall and streamflow data should be available. Evaporation data is also required. Concurrent record lengths of all data should not be less than ten years to provide a good calibration period and adequate data to independently test the model. In Western Australia, extensive collection of hydrologic data commenced only recently so there were few stream gauging stations with adequate length of continuous record.

Three rivers were chosen in the south-west for which there were good quality streamflow and rainfall records of reasonable length.

These three cover a variety of catchment types and sizes. Their properties are summarised in Table 1.

Table 1 - Catchement characteristics

River	Dombakup Brook	Donnelly Brook	Dwellingerup Brook
Number	607155	608151	614134
Catchment area (km^2)	115	805	1.35
Vegetation	karri forest (100%)	karri forest (80%)	cleared (100%)
Start of record	May 1961	Feb 1961	Apr 1960
Mean annual rainfall (mm)	1400	1140	1350
Mean annual runoff (mm)	410	230	430
Max. recorded flow (m^3/s)	69	114	2.05
Min. recorded flow (m^3/s)	.01	.02	.003

Model Descriptions

Sacramento Model

The Sacramento Model, typical of a number of explicit soil moisture accounting type models, was developed jointly by the United States National Weather Service and the California State Department of Water Resources, orginally for flood forecasting purposes; see Burnash, Ferral and McGuire (1973). The model has not been widely used elsewhere in Australia but the W.A. Public Works Department has used it on rivers in the Pilbara (Wallace 1976) and in the south-west (Murton and Wallace 1976).

Rainfall that falls on the catchment is considered as falling on one of two types of surface, permeable areas or impervious areas connected to the stream channel. Runoff is produced from the impervious area from any rainfall event no matter how small, but runoff occurs from the permeable area only when the rainfall intensity exceeds the infiltration rate. In this area, an initial soil moisture storage, the upper zone tension storage must be filled before water is available to enter other storages. This represents the volume of precipitation required to meet interception requirements and is water closely bound to soil particles. When this tension storage is filled, water is accumulated in the upper zone free water-storage from where water can move to deeper storage or move laterally to appear in the stream channel as interflow.

The vertically draining water, or percolation, can enter one of the three lower zone storages, the lower zone tension storage, (the depth of water held by the soil particles) and the two lower zone free water storages that are available for drainage as baseflow or subsurface outflow. These storages fill simultaneously but drain independently at different rates.

The surface runoff and interflow are routed to the catchment outlet by a nondimensional unithydrograph.

Fig. 2 illustrates the model structure.

Stanford Model

The Stanford Model was originally developed at Stanford University during the early 1960's and was successively improved until reaching the version known as the Stanford Watershed Model IV described by Crawford and Linsley (1966), the version that is now widely used. Outside of this study this model has been used in the south-eastern part of Australia by Moore and Mein (1975) and Fleming and Black (1974).

The Stanford Model attempts to model catchment processes realistically and thus is more complex than most other models of its type. Its flow chart is given in Fig. 3. Rainfall first falls on an interception storage which must be filled before water is available for other functions. After interception is satisfied, direct runoff from impervious areas is accounted for and the remaining moisture is then subject to an infiltration function that determines whether water will move to the stream as overland flow, interflow, or infiltrate into the soil. The infiltrating moisture can enter the lower zone storage (subject to evapotranspiration) or the groundwater storage (subject to drainage as baseflow). All outflow is routed to the catchment outlet using the Clark-Johnstone unithydrograph model.

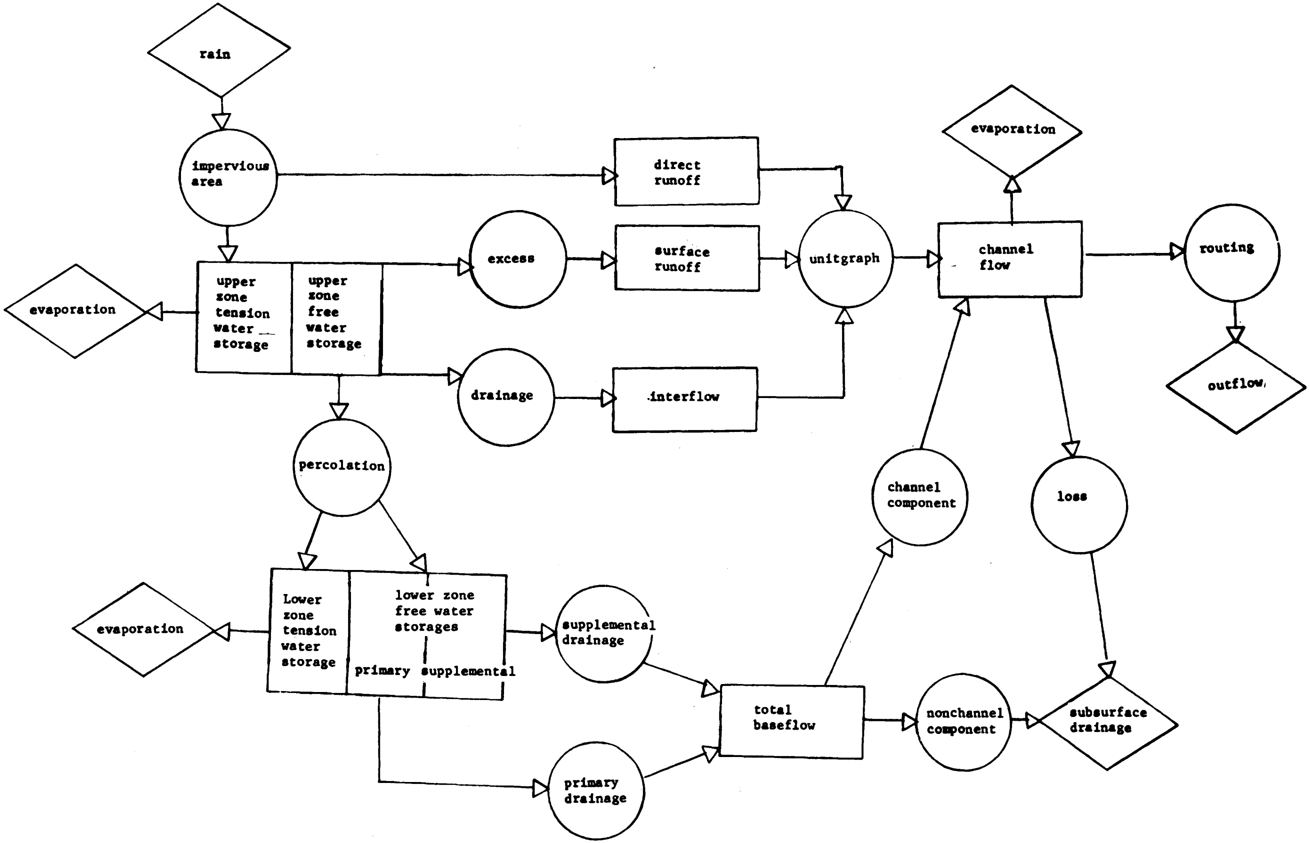

Fig. 2. Sacramento Model.

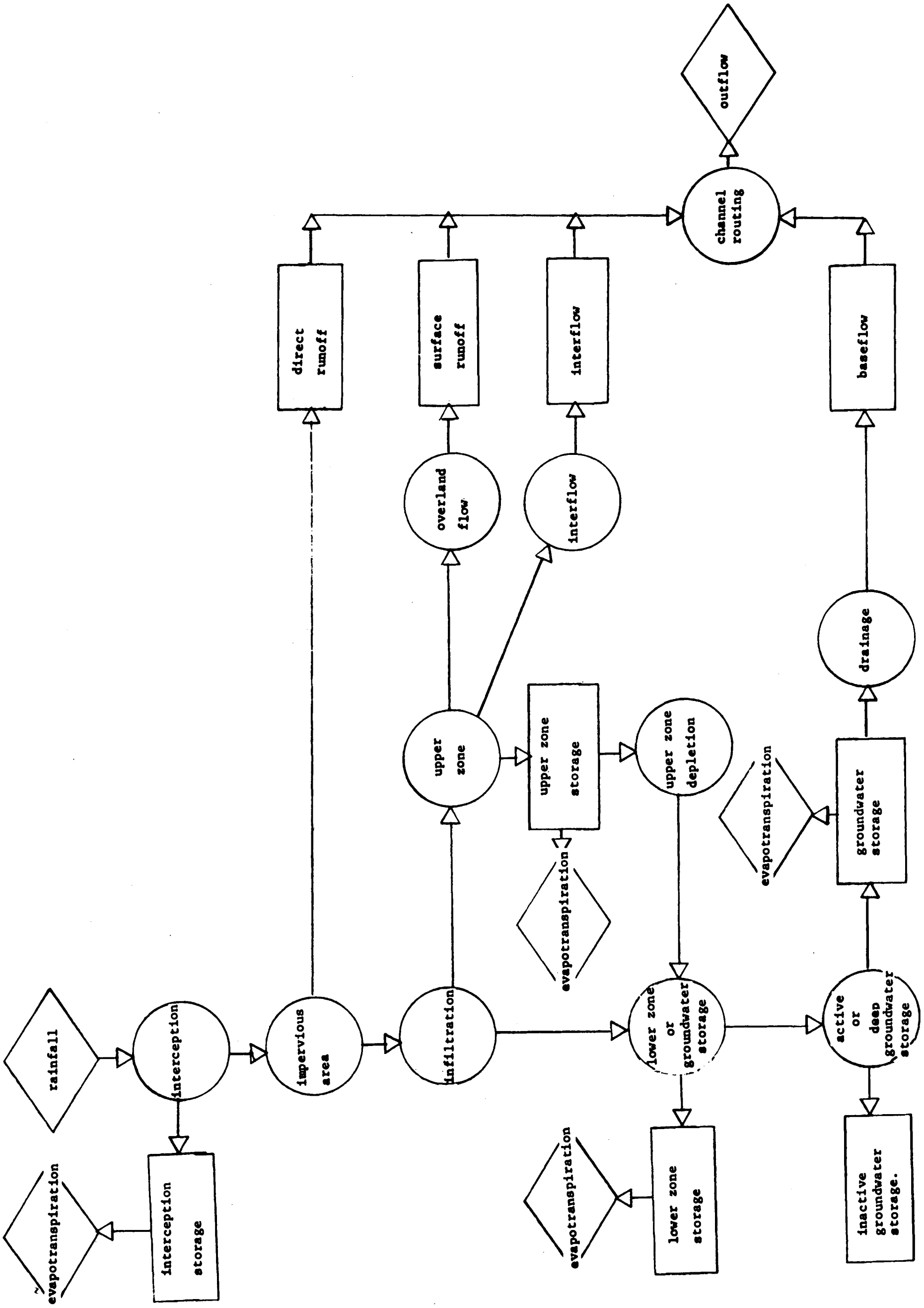

Fig. 3. Stanford Water Shed Model.

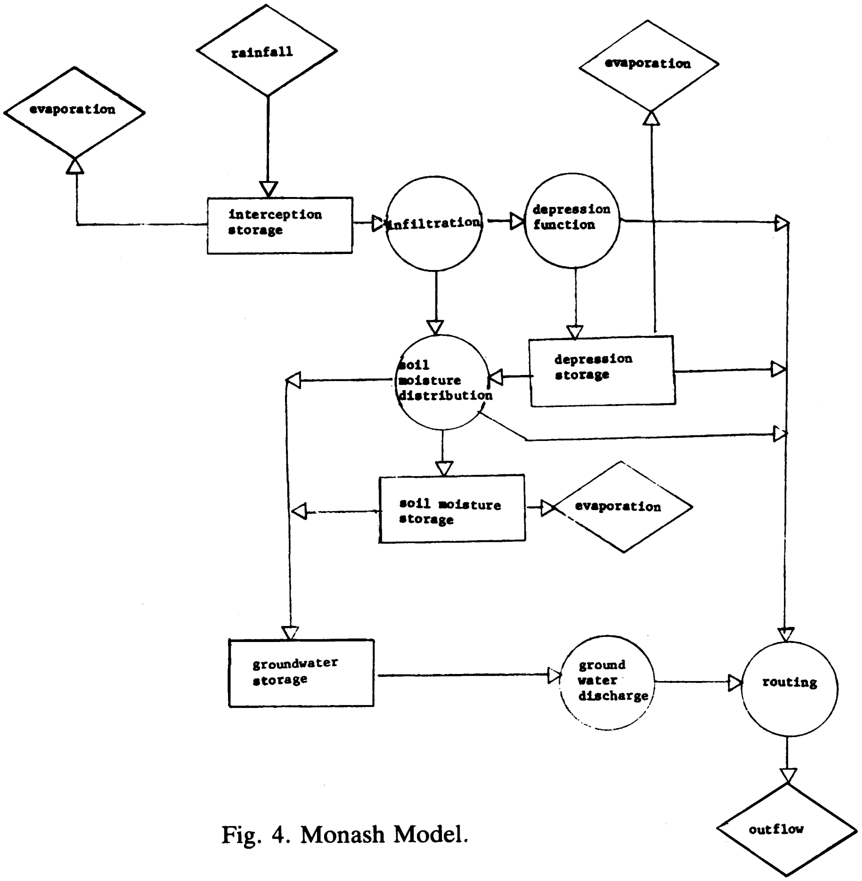

Fig. 4. Monash Model.

Monash Model

The Monash Model was developed at Monash University in Melbourne by Porter and McMahon (1971). The model has been extensively used in Victoria, (Porter and McMahon 1975) but has not previously been used in Western Australia. Like the Stanford Model, this model attempts to physically simulate the catchment processes but like the Sacramento Model is reasonably simple to understand and use. Its flow chart is given in Fig. 4. Rainfall is first subject to interception storage with excess moisture either infiltrating or flowing to the stream channel. The overland flow is subject to diversion to depression storage where the water is then subject to evaporation or infiltration. Infiltrating moisture can either enter the soil moisture storage, subject to evapotranspiration; the groundwater storage, subject to drainage as baseflow; or can immediately enter the stream channel as interflow. The soil moisture storage is of finite capacity from which overflow enters the groundwater storage which is of infinite capacity. All streamflow is routed to the catchment outlet by a nonlinear routing function.

Boughton Model

The Boughton Model was developed by Boughton (1966) in New South Wales and has since been widely used in most states of Australia except Western Australia.

The model operates on a daily time step and since it was originally developed for use on small agricultural catchments, the original version makes no provision for routing of rainfall excess or for baseflow. Since both of these processes are very important in the Western Australian rivers, the model was modified to make some allowance for them. The flow chart is shown in Fig. 5.

In the first phase of model operation, rainfall is routed through the interception, upper and drainage stores to the subsoil storage by a Horton infiltration function. Excess rainfall becomes surface runoff. Evaporation is first taken from the interception store and remaining evaporation from the upper and lower stores. In the modified program, baseflow is taken from a proportion of the subsoil storage using a single recession constant and the total surface runoff is delayed by a surface runoff storage.

Recursive Methods of Time Series Analysis

This approach to modelling the relationship between rainfall and runoff is quite different from the other four models used. It can be described as a »black box« or purely mathematical model in contrast to the other models that attempt to physically represent the catchment behaviour. Methods of time series analysis have been widely applied to other engineering problems but only rarely have been used in water resources, though recently the approach has been used in a flood warning application in Italy (Todini and Bouillot 1975) and in water quality modelling in England (Whitehead and Young 1975).

An autoregressive moving average (ARMA) representation of the impulse response of the system is adopted. This is of the form

$$(1 + \delta_1 B + \delta_2 B^2 + \cdots . \delta_r B^r) y_t = (w_0 + w_1 B + \cdots . w_s B^s) \underline{u}_{y-b} + e_t$$

where B = backward shift operator, i.e. $B^T y_t = y_{t-T}$
r = order of autoregressive term.
s = order of moving average term.
b = time lag.
δ & w = constants determined by calibration
ε_t = zero mean, normally distributed random »noise«.

The problem of model identification consists in the determination of the most appropriate values of r, s and b. This can be done by analysing a rough approximation of the response of the system as described by Box and Jenkins (1970). Then

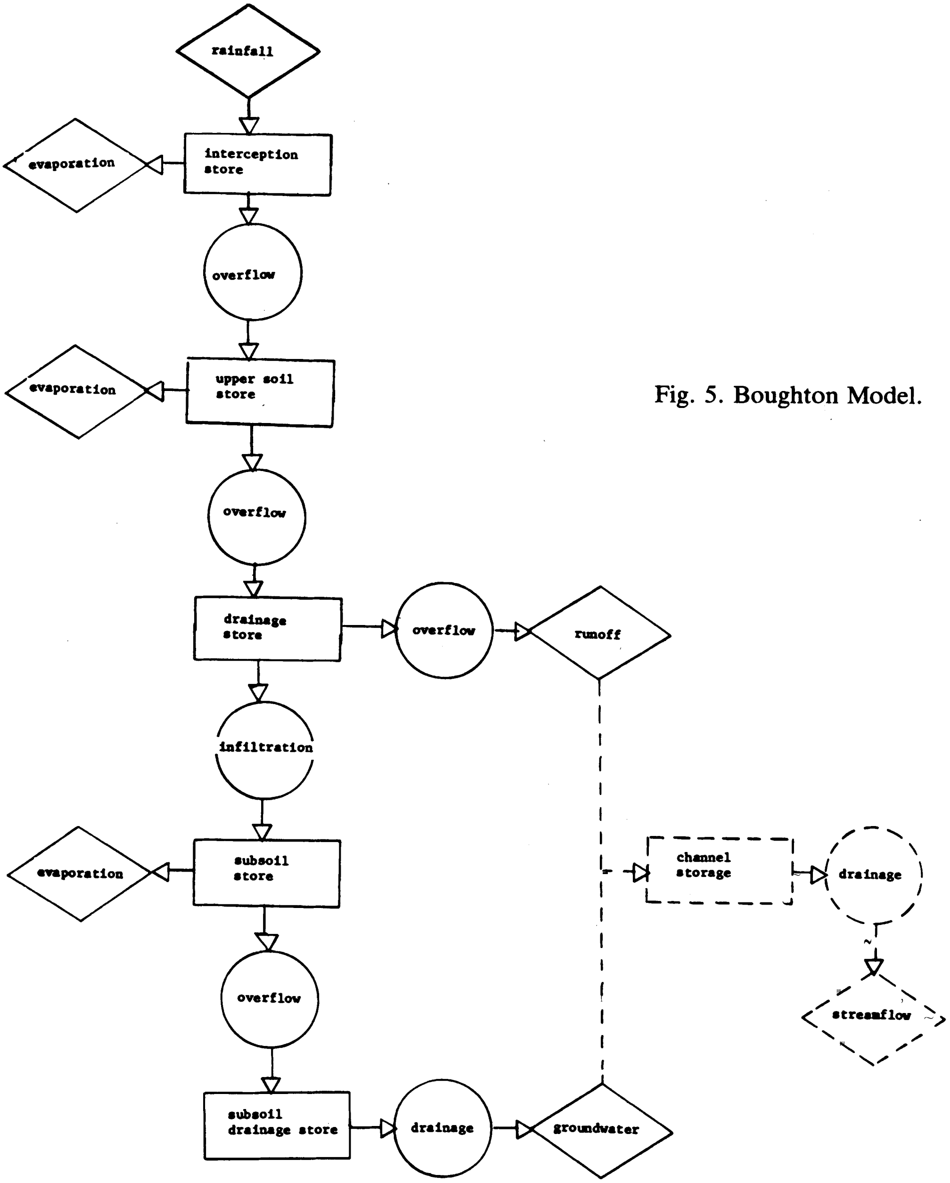

Fig. 5. Boughton Model.

using a recursive least squares instrumental variable algorithm (Young 1974) the variation of the parameters with time can be studied. A secondary identification phase is then considered where various empirical rainfall adjustment procedures can be evaluated to find the one that best transforms the time series into a time invariant parameter form. This transformed series is then used with the instrumental variable algorithm to estimate the time invariant parameters.

Comparison of General Usage

The main criteria used in calibration were:

1) mean flow
2) coefficient of variation of residual of errors and
3) subjective comparison of hydrographs.

The mean flow indicates the overall model water balance and the coefficient of variation of residual of errors provides an objective measure of the differences between recorded and calculated hydrographs. However, a subjective comparison allows the user to adjust selected parameters to improve individual flow components such as surface runoff from a wet catchment, baseflow etc. The general optimisation strategy was therefore to use subjective comparisons of hydrographs while also keeping the objective measures in mind. An automatic optimisation routine was not used.

Since routine hydrologic studies do not normally allow choice in data selection, this study (which was attempting to represent the normal situation) used the first half of the recorded period of data for calibration in each case. Even though this may not show the models to their best advantage, it represents the normal situation in hydrologic investigation and does provide a fair comparison between models.

This section will now consider general usage of each model before tabulating selected numerical results for each river.

The Sacramento Model was the easiest of the three more complex models to use since the effect of varying parameters could be partly predicted and each parameter had a well defined purpose. The baseflow routine was very good and gave excellent control over the shape of the baseflow recession curve. For the two larger catchments, this model performed the best and there was little difference between results from the calibration and testing periods. In the case of Dwellingerup Brook though, there were some floods in the testing period that were larger than any in the calibration period. For these events the simulation was poor and all the storages overflowed. This problem was caused by the fact that the moisture storages are finite in size. Thus even though the Sacramento Model is capable of very good results, the finite storage sizes should lead the user to be careful.

The Stanford Model, in contrast, is much more difficult to use, mainly because many input parameters are required to calculate the actual parameters used in model processes. This meant that it took more optimising runs to calibrate the Stanford Model. Results for the larger catchments, Dombakup Brook and Donnelly River, were almost as good as those obtained with the Sacramento Model, while the simulation for Dwellingerup Brook was better. The advantage of the Stanford Model is that its storages are infinite in size although adding water becomes more difficult as they fill. The main difficulty with the Stanford Model is its complexity, but once calibrated it is capable of very good quality simulation.

The Monash Model, though not as simple as the Sacramento Model, was quite straightforward to use. Its baseflow routine was not quite as successful as the Sacramento Model's but was adequate. The nonlinear routing function had only a small effect on the very damped response from these catchments. Results for Dombakup Brook and Donnelly River, though not as good as the other models, were acceptable. The main difference was with Dwellingerup Brook where the model performed well in contrast to the other two models. The large floods were accounted for by the infinite sized groundwater storage so that the calculated runoff volumes were of the correct magnitude. Adding extra water to the groundwater storage did not completely remove the water from the runoff hydrograph but distributed the error by providing extra baseflow for some time after the flood.

The Boughton Model, even after the modifications that had been made to it, was still not very successful. The model was only slightly simpler to use than the other three process models so could not be regarded as a fast and simple method. The major reason for its poor simulation is the lack of storage delay routines, even in the modified version of the program. Thus the Boughton Model, even though it has been used successfully in other areas of Australia, is not applicable in the south-west of Western Australia where stream response is sluggish.

The method of time series analysis was found to be reasonably straightforward to use and required a limited amount of computer time. Its results on the two larger catchments were quite good though baseflow was poorly modelled. With Dwellingerup Brook where baseflow was an extremely important component the modelling was completely unacceptable. This black box method can therefore only be recommended on catchments where baseflow is relatively unimportant.

Statistical Comparison

The most straightforward way to compare models is to compare the quality of simulation. Since streamflow provides a large amount of data of a range of types, it is difficult to find one particular test that will objectively test the whole record. Thus a variety of different statistics and tests must be assessed and a subjective decision made on the basis of these results. A variety of tests, many described by Aitken (1973), were utilized in this study.

The major property that a rainfall-runoff model should have is that it should preserve the mean and standard deviation of the recorded hydrograph. Two other statistical parameters commonly used are the coefficient of variation of residual of errors, C_y and the ratio of relative error to the mean, R, which are defined as

$$C_y = \frac{[\frac{1}{n}\sum (y_c - y_r)^2]^{\frac{1}{2}}}{\bar{y}_r} \qquad (1)$$

and

$$R \equiv \frac{\sum(y_c - y_r)}{n\,\bar{y}_r} \qquad (2)$$

where $\bar{y}_r$ is the mean recorded flow and y_c and y_r are the calculated and recorded flows respectively.

The significance of the numerical value of C_y can be assessed by an analysis of the following form. If the error in y_c is assumed to be a constant, k, then

$$y_c = (1+k)\,y_r \qquad (3)$$

Substituting this expression for y_c into Eq. (1) gives

$$C_y = \frac{k\,(\sum y_r^2/n)^{\frac{1}{2}}}{\bar{y}_r}$$

or

$$C_y = \frac{k\,E\,(y_r^2)}{\bar{y}_r} \qquad (4)$$

where $E(y^2_r)$ is the expected or mean square value of the recorded flow.

Now the amount that $E(y^2_r)$ differs from $\bar{y}^2_r$ depends on the standard deviation S_r of the recorded flows where the unbiased estimate is

$$S_r = \left[\frac{\sum(y_r - \bar{y}_r)^2}{n-1}\right]^{\frac{1}{2}} \qquad (5)$$

which rearranged gives

$$\frac{\sum(y_r)^2}{n} = \frac{(n-1)S_r^2}{n} + \bar{y}_r^2 \qquad (6)$$

Combining Eqs. (6) and (4), and introducing the coefficient of variance ($C_v = S_r/\bar{y}_r$) gives

$$C_y = k\left(\frac{n-1}{n}\,C_v^2 + 1\right)^{\frac{1}{4}} \qquad (7)$$

This formulation is of course only valid for a constant error k, but a similar analysis with variable errors shows that this value of k indicates the maximum error of the model and is therefore useful in comparisons between models and rivers. For example it shows that for the total data period of Dombakup Brook, the Sacramento Model simulation is equivalent to a constant error af 37% for the daily results and 18% for the monthly results.

These statistics are generally calculated separately for the calibration and verification periods to test for any divergence, as given in Tables 2, 3 and 4. A limitation of these tests is that they are affected more by large floods than by low flows.

Another useful numerical test which partially overcomes this difficulty is the one sample runs test (Siegel 1956) recommended by Aitken (1973) who states: »To determine quickly the existence of a systematic error in a model the simple sign test is the most suitable approach and should always be used«. The technique is based on the number of runs of residuals of the same sign which the data set exhibits. The magnitude of the residuals has no effect on the results, but the total number of runs gives an indication of whether the sample is random or not. If few runs occur, a time trend due to lack of independence is suggested while too many runs may indicate systematic cyclical fluctuation.

For larger samples, the expected number of runs can be shown to be normally distributed with

$$\text{mean} = \mu r = \frac{2n_1 n_2}{n_1 + n_2} + 1 \qquad (8)$$

$$\text{and standard deviation} = \sigma r = \left[\frac{2n_1 n_2 (2n_1 n_2 - n_1 - n_2)}{(n_1 + n_2)^2 (n_1 + n_2 - 1)} \right]^{\frac{1}{2}} \qquad (9)$$

where n_1 = number of positive residuals
and n_2 = number of negative residuals.

The standard normal variate

$$z = \frac{r - \mu r}{\sigma r} \qquad (10)$$

(where r = number of runs)

is normally distributed with zero mean and unit variance under the null hypothesis that the order of signs of residuals is random. The significance of the computed value of z can be determined from the normal distribution.

If we accept a null hypothesis based on the Chi-square two tailed test and adopt a significance level of 0.05 then values of $|z|>1.96$ indicate that the number of runs are significantly different from that expected for random errors and it is concluded that the model is producing a systematic error.

This test has been used to compare the models considered here and the values of z are given in Tables 2, 3 and 4 for the monthly results. In nearly all cases, the test suggests that there are systematic errors.

Table 2 - Dombakup Brook results

	Sacramento Model	Stanford Model	Monash Model	Boughton Model	Time Series Analysis
Calibration period (recorded mean daily flow ≡ 152m^3 x 10^3)					
Daily mean flow	164	170	170	159	138
R	0.08	0.12	0.12	0.04	–0.10
C$_y$ (monthly)	0.26	0.31	0.43	0.51	0.48
C$_y$ (daily)	0.70	0.72	0.79	1.16	0.79
z (monthly)	–1.61	–4.30	–2.83	–	–4.59
Verification period (recorded mean daily flow = 114m^3 x 10^3)					
Daily mean flow	106	101	107	79	89
R	–0.07	–0.11	–0.06	–0.31	–0.22
C$_y$ (monthly)	0.31	0.53	0.40	0.79	0.48
C$_y$ (daily)	0.76	0.91	0.76	1.24	0.77
z (monthly)	–6.40	–3.62	–3.51	–	–1.75
k (monthly)	0.18	0.41	0.24	0.64	0.39
k (daily)	0.37	0.44	0.37	0.60	0.37
Number of iterations	34	56	25	16	–

Table 3 - Donnelly River Results

	Sacramento Model	Stanford Model	Monash Model	Boughton Model	Time Series Analysis
Calibration period (recorded mean daily flow = 513.5m^3 x 10^3)					
Daily mean flow	510	547	519	528	512
R	–0.01	0.06	0.01	0.03	0.00
C$_y$ (monthly)	0.23	0.30	0.40	0.73	0.38
C$_y$ (daily)	0.50	0.52	0.59	1.00	0.54
z (monthly)	–0.98	–3.74	–4.18	–	–4.46
Verification period (recorded mean daily flow ≡ 354.9m^3 x 10^3)					
Daily mean flow	304	304	324	217	365
R	–0.14	–0.14	–0.09	–0.40	0.03
C$_y$ (monthly)	0.38	0.48	0.46	1.59	0.43
C$_y$ (daily)	0.50	0.61	0.60	1.89	0.73
z (monthly)	–4.61	–4.52	–4.95	–	–2.78
k (monthly)	0.23	0.28	0.27	0.64	0.25
k (daily)	0.45	0.33	0.33	0.68	0.39
Number of iterations	30	56	24	15	–

Table 4 - Dwellingerup Brook results

	Sacramento Model	Stanford Model	Monash Model	Boughton Model	Time Series Analysis
Calibration period (recorded mean daily flow = 1.60m^3 x 10^3)					
Daily mean flow	1.62	1.54	1.58	1.57	1.37
R	0.01	–0.04	–0.01	0.02	–0.14
C_y (monthly)	0.26	0.24	0.21	0.52	0.49
C_y (daily)	0.42	0.43	0.51	0.63	0.58
z (monthly)	–2.89	1.67	–5.24	–	–3.58
Total period (recorded mean daily flow = 1.53m^3 x 10^3)					
Daily mean flow	1.76	1.87	1.89	1.86	1.43
R	0.15	0.14	0.15	–0.13	–0.10
C_y (monthly)	0.61	0.39	0.35	0.60	0.56
C_y (daily)	1.31	0.73	0.67	0.87	0.70
z (monthly)	–6.32	–6.43	–8.16	–	–6.36
k (monthly)	0.51	0.33	0.29	0.50	0.43
k (daily)	0.93	0.92	0.52	0.68	0.50
Number of iterations	32	35	30	22	–

A limitation of this test occurs in those situations where the streamflow is characterized by extended periods of baseflow. In these cases even a small discrepancy in model simulation results in long runs of either positive or negative errors. This occurs in Western Australia where there is little or no summer rainfall and

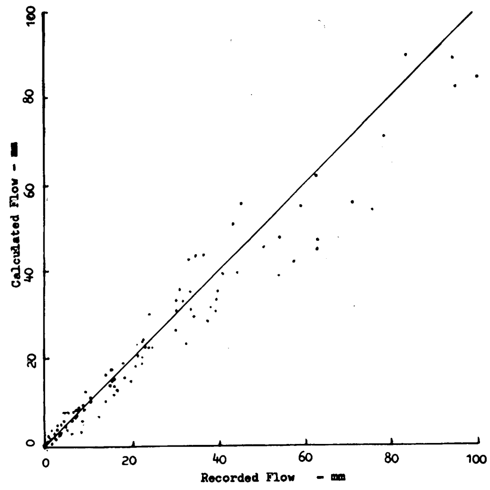

Fig. 6. Sacramento Model – Donnelly River, observed vs calculated monthly flow.

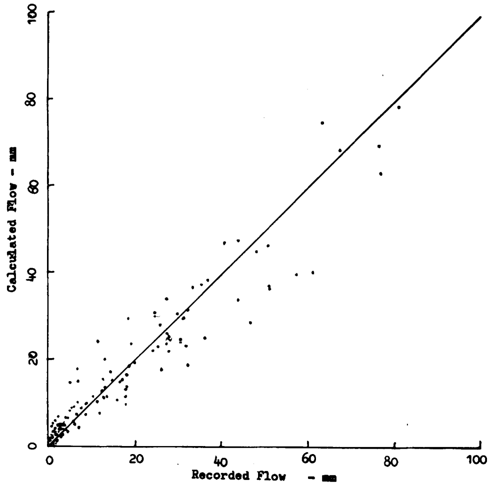

Fig. 7. Stanford Model – Donnelly River, observed vs calculated monthly flow.

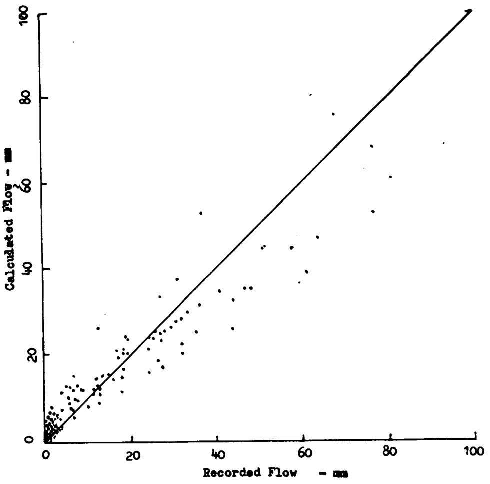

Fig.8. Monash Model – Donnelly River, observed vs calculated monthly flow.

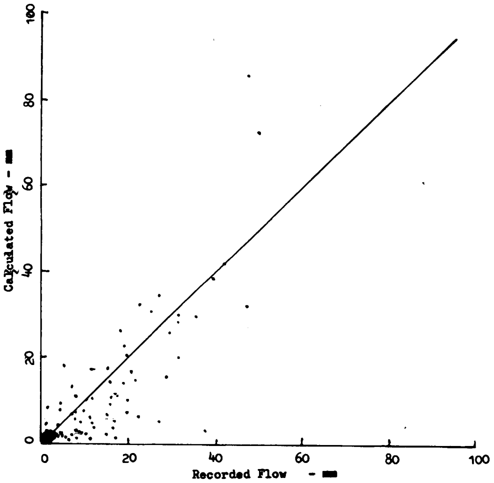

Fig.9. Boughton Model – Donnelly River, observed vs calculated monthly flow.

baseflow predominates for long periods. Hence the results of this test are not as significant as the absolute value of z might suggest. In fact it should only be used comparatively. Here it indicates that the Sacramento Model produced the least systematic error.

Graphical methods are commonly used to test the model's performance with low flows. Probably the best graphical method is to compare recorded and calculated flow duration curves but residual mass curves and scatter diagrams are also

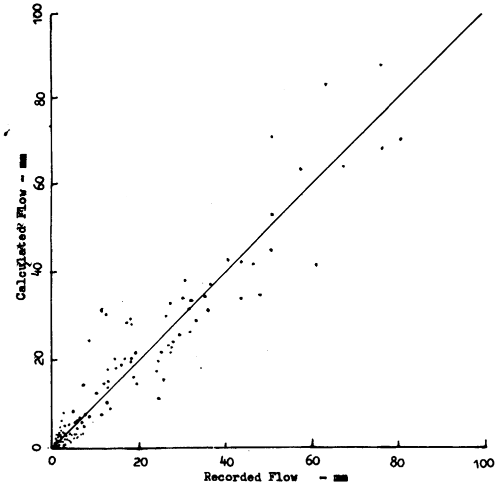

Fig. 10. Time series analysis – Donnelly River, observed vs calculated monthly flow.

valuable. Scatter diagrams for the Donnelly River results are given in Figs. 6 to 10. They indicate the relative performance of each of the models. Other considerations in assessing a model include the difficulty involved in using it and computer considerations such as core storage, computer time and number of iterations.

Conclusion

Of the five models tested, the Boughton Model was the only one found to be unacceptable. This was because of the vast difference between these rivers and the catchments for which this model was developed. It is more difficult to choose between the other four models, especially on the two larger rivers where there is very little difference between any of the models. Considering these rivers, either the Sacramento Model, because of its straightforward structure and overall good performance or the method of time series analysis, because of its simplicity, are recommended. With Dwellingerup Brook though, these models perform poorly; the Sacramento Model because of its finite storages and the time series model because of its lack of provision for baseflow. Both Stanford and Monash Models perform better on this river with the Monash Model being marginally better.

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