ELSEVIER

Ecological Modelling 123 (1999) 91–104

ECOLOGICAL MODELLING

www.elsevier.com/locate/ecolmodel

Predicting the daily streamflow of ungauged catchments in S.E. Australia by regionalising the parameters of a lumped conceptual rainfall-runoff model

David A. Post [a,*], Anthony J. Jakeman [b]

[a] *CSIRO Division of Land and Water, Davies Laboratory PMB, PO Aitkenvale, Townsville, QLD 4814, Australia*
[b] *Centre for Resource and Environmental Studies, Australian National University, Canberra, ACT 0200, Australia*

Received 18 August 1998; received in revised form 7 April 1999; accepted 10 May 1999

Abstract

Deriving relationships between catchment-scale hydrologic response and landscape attributes allows the hydrologic response of an ungauged catchment to be predicted from its landscape attributes and climate. In this study, a lumped conceptual rainfall-runoff model was applied at a daily timestep to 16 small (less than 1 km^2) catchments in the Maroondah region of Victoria, Australia. The six parameters of this model can be used to characterise the daily streamflow of the catchments. It was demonstrated in Post and Jakeman (1996) [Post, D.A., Jakeman, A.J., 1996. Relationships between catchment attributes and hydrological response characteristics in small Australian mountain ash catchments. Hydrol. Processes 10: 877–892] that these six parameters are related to the landscape attributes of the catchments. In the current paper, these relationships are quantified and used to predict the daily streamflow of each catchment from its landscape attributes and daily rainfall and temperature, as if it were ungauged for streamflow. This predicted streamflow is then compared with the observed streamflow of the catchment. These relationships may also be used to predict the daily streamflow from other, similarly sized catchments in the Maroondah region. Some of the relationships between the model parameters and landscape attributes are well defined, while others are quite poor. As a result, the predictions of daily streamflow also vary in quality. Improvement of these results can be obtained through better understanding of the controls on hydrologic response.

Keywords: Regionalisation; Rainfall-runoff model; Ungauged catchments

1. Introduction

As expressed by Goodrich and Woolhiser (1991) (p. 202), 'a detailed, process based, understanding of hydrologic response over a range of catchment scales (0.01–500 km^2) still eludes the hydrologic community'. This study represents one

* Corresponding author. Tel.: +61-7-4753-8605; fax: +61-7-4753-8650.
E-mail address: david.post@tvl.clw.csiro.au (D.A. Post)

0304-3800/99/$ - see front matter
PII: S0304-3800(99)00125-8

attempt to understand the controls on catchment-scale hydrologic response by relating that response to landscape attributes. Relationships between catchment-scale hydrologic response and landscape attributes allow a prediction to be made of the hydrologic response of an ungauged catchment (a catchment which is not gauged for streamflow), based on climatological data and a description of the landscape attributes of that catchment. Development of such relationships is an example of a regionalisation methodology and is a useful goal for a number of reasons. For example, construction of an hydrologic structure such as a bridge or dam may require a prediction to be made of the hydrologic response of a catchment at an ungauged point. Pilgrim (1987) provides examples for Australia, while NERC (1975) provides examples for the UK. For an examination of the ecological health of a river system, the frequency and duration of low flows may be of more interest, since these may be the limiting factors in supporting stream biota. If the catchment under consideration is not gauged for streamflow, these estimates must be based on some form of regionalisation, where the catchment is considered to behave similarly to another catchment (or catchments) with similar climatologies and landscape attributes. These practical applications are the reason that many regionalisation studies deal with flood frequency analysis (Patton and Baker, 1976; Reimers, 1990); or low flow analysis (Chang and Boyer, 1977; Gustard et al., 1992; Nathan and McMahon, 1992). Regionalisation is also of use in global and regional climate models, where the hydrologic response of an ungauged grid cell may be required for water and energy feedbacks in the land-atmosphere component of the climate model (Jakeman et al., 1995).

Several previous studies have related landscape attributes to the hydrologic response of a catchment as defined by a rainfall-runoff model. In general, regionalisation studies using a modelling methodology have met with only limited success. As a result, landscape attributes are commonly related directly to just one aspect of hydrologic response, such as flood frequencies (NERC, 1975; Pilgrim, 1987). While this allows an estimate to be made of one aspect of hydrologic response, it does not allow a prediction to be made of the daily streamflow of a catchment over a long period. There are two main reasons that there has been only limited success in relating the parameters of rainfall-runoff models to landscape attributes. Firstly, in some cases, the model used did not define the hydrologic response of the catchment effectively. This meant that only certain aspects of the hydrologic response could be related to landscape attributes. Examples include those studies using a unit hydrograph approach where the baseflow component of streamflow was deleted, perhaps using graphical techniques (Heerdegen and Reich, 1974; NERC, 1975; Rosso, 1984). In other studies, the model used was perhaps too complex or over-parameterised, meaning that the individual parameters of the model could not be estimated unambiguously and hence related to landscape attributes. Examples of such studies include those making use of the Stanford Watershed Model (James, 1972); the 18 parameter Sacramento model (Weeks and Ashkanasy, 1985); the 20 parameter HBV3-ETH model (Braun and Renner, 1992); the 19 parameter MODHYDROLOG model (Chiew and McMahon, 1994); and TOPMODEL (Franchini et al., 1996).

Based on the results of these previous studies, it appears that what is required is a modelling approach which accounts for the key hydrologic processes occurring in a catchment, but which avoids the problems of overparameterisation. This idea was proposed by Nash and Sutcliffe (1970) but has not received adequate recognition in the literature since that time, with many authors choosing to develop new and more highly parameterised models in an attempt to encapsulate all of the major individual hydrologic responses believed to be occurring in a catchment. Goodrich and Woolhiser (1991) agree that model simplification is justified, as long as the essential hydrologic behaviour of a catchment is retained. The usefulness of less complex parameterisations can be seen in studies by Srikanthan and Goodspeed (1988), and Servat and Dezetter (1993), both finding that landscape attributes were able to be related more readily to the parameters of less highly parameterised models, compared to models with a larger number of parameters.

2. The model

The model used in the present study, IHACRES, is a lumped parameter, conceptual rainfall-runoff model, based on unit hydrograph principles (Jakeman et al., 1990). An attempt is made to avoid overparameterisation by only including parameters if they can be identified from the daily rainfall and streamflow of the catchment. The model is defined by just six parameters, which together predict the daily streamflow response of a catchment (Jakeman and Hornberger, 1993). The model creates a unit hydrograph for total streamflow by defining separate unit hydrographs for quick and slowflow. During a model calibration, four of the model parameters are determined directly from the raw rainfall, streamflow and temperature data, while the other two are calibrated using a trial and error search procedure, optimising the model fit to the observed daily streamflow record. The model has been constructed to be as simple as possible, while still representing the daily streamflow of the catchment as accurately as possible. The parameters are not defined a-priori to represent individual hydrologic processes, but rather to represent the hydrologic dynamics of a number of physical processes acting together.

The model consists of two modules, a non-linear loss module to convert rainfall to effective rainfall, and a linear module to route this effective rainfall to streamflow. Effective rainfall is defined as that rainfall which eventually leaves the catchment as streamflow. Thus, all of the losses of water occur in the non-linear module. Fig. 1 is a schematic showing the structure of the model. The non-linear module is represented on the left as a storage tank representing catchment wetness. The effective rainfall is then routed through two parallel storages to produce streamflow. This model structure was identified as the most appropriate for use in this study. The equations underlying the model are to be found in Post and Jakeman (1996), while more complete descriptions of the model are in Jakeman et al. (1990) and Jakeman and Hornberger (1993). Potential applications of the model to other areas of catchment hydrology are discussed in Littlewood and Jakeman (1994).

Of the six model parameters, three relate to the non-linear module (t_w, f, and c), and three relate to the linear module (any three of t_q, t_s, v_q, v_s or h). These six parameters may be referred to as hydrologic response characteristics, as together they can be used to predict the daily hydrologic response of a catchment. They are defined as follows:

- t_w (days) is the time constant governing the rate of water loss from the catchment at 20°C.
- f varies the rate of catchment water loss due to a unit change in temperature, producing the variable $t_w(t_k)$ in Fig. 1.
- c (mm) is defined such that the total volume of modelled effective rainfall is equal to the total volume of observed streamflow. It may be re-

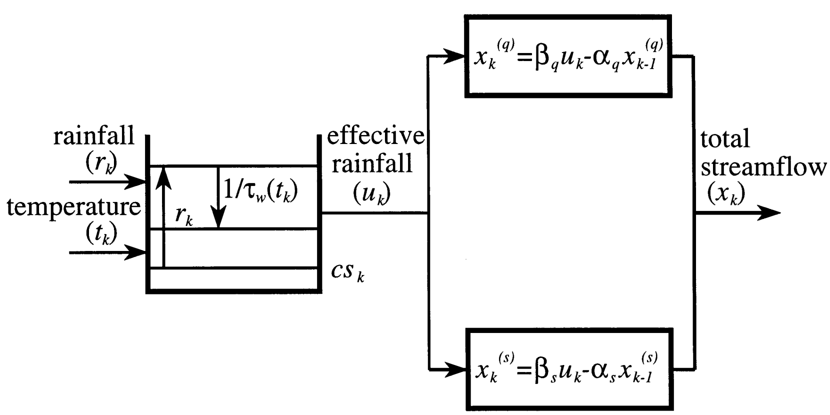

Fig. 1. Structure of the IHACRES model.

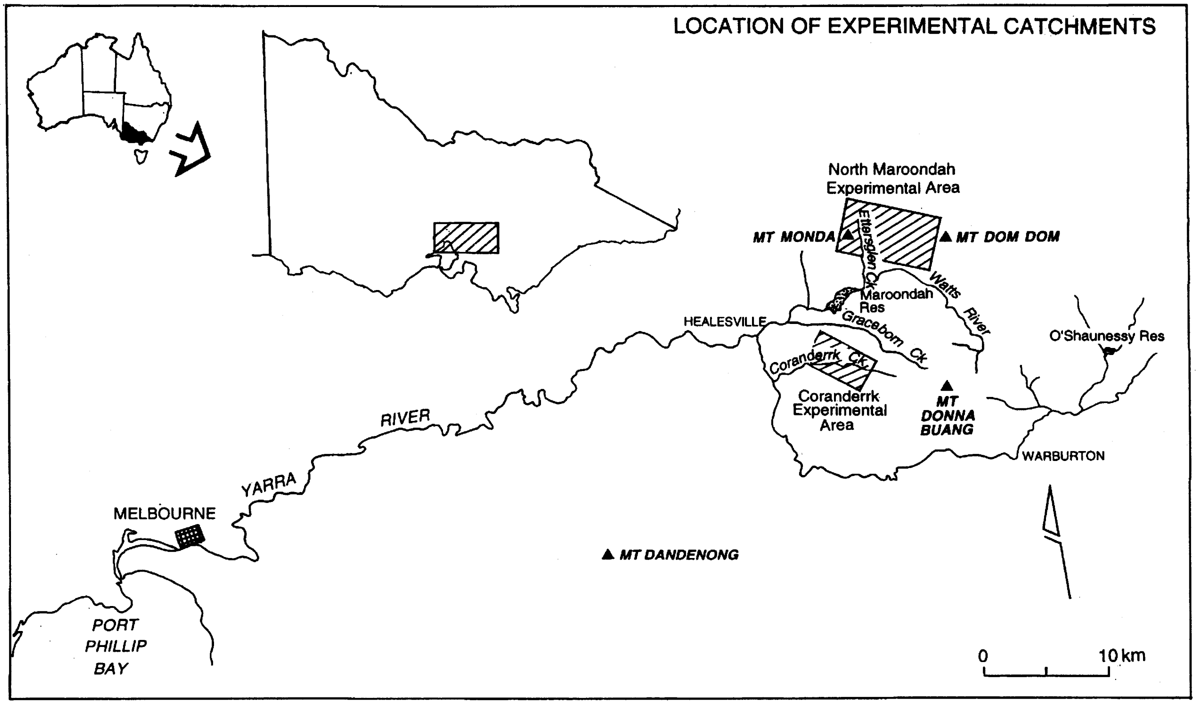

Fig. 2. Location of the experimental catchments in the Maroondah region of Victoria, Australia.

garded as the maximum volume of the non-linear store, since when the volume of the non-linear store is equal to c ($s_k = 1$ in Fig. 1), all of the observed rainfall becomes runoff.

- t_q (days) is the time constant governing the rate of quickflow recession of streamflow from the catchment (upper store in Fig. 1).
- t_s (days) is the time constant governing the rate of slowflow recession of streamflow from the catchment (lower store in Fig. 1).
- v_s is the proportion of slowflow to total flow, thus $v_s = 1 - v_q$.
- h (l/s) is the peak of the unit hydrograph resulting from a unit input of effective rainfall.

3. The catchments

Models were calibrated for 16 small (< 1 km^2) catchments located in the Maroondah region of Victoria, Australia. These catchments are instrumented and operated by the Melbourne Water Corporation. Fig. 2 shows the location of this region in the central highlands of Victoria, to the north-east of Melbourne. The catchments range in size from 4 to 65 ha and each is predominantly covered in mountain ash (*Eucalyptus regnans*).

The geology of the area is igneous and is described in detail in McLaughlin (1976). Soils are typically deep krasnozems formed by weathering of these igneous rocks, and have clay contents of 60–80%. It has been estimated that the soils reach to a depth of around 10–15 m (Langford and O'Shaughnessy, 1977).

The mean monthly summer temperature of this region is 17°C and the mean monthly winter temperature is 4°C. The mean annual precipitation is 1250 mm, with a slight winter maximum, 75% falling in the 8 months from April to November. Throughout the area, there is a pattern of increasing rainfall and decreasing temperature with elevation. Relative humidity during the day in summer tends to be in the range 40–60% and in winter is typically above 80% (Langford and O'Shaughnessy, 1977).

The mountain ash covering the catchments is of two distinct ages. The oldest is mature ash of 100–200 years old, with heights up to 80 m, diameters up to 4 m, and stocking rates of 30–80 trees/ha (Langford and O'Shaughnessy, 1980). The remainder of the mountain ash is regrowth from bushfires in 1939, with heights up to 50 m and stocking rates up to 400 trees/ha (Langford and O'Shaughnessy, 1977). The Coranderrk and Myrtle catchments are covered primarily in mature mountain ash forest, while the Ettercon, Black Spur and Monda catchments are covered in 1939 regrowth.

4. Model calibrations

To account for climatic variability, an attempt was made to calibrate models over the same period of record. Models for the Coranderrk catchments (Picaninny and Blue Jacket) were calibrated over the period 15 May 1959 to 16 April 1971. Models for the remainder of the catchments were calibrated over the period 24 June 1972 to 27 July 1976. A common period of record for all of the catchments was not available since forestry treatments commenced in the Coranderrk catchments before the North Maroondah catchments were instrumented. The impact of these forestry treatments on the hydrologic response of these catchments is examined in Post and Jakeman (1998).

These model calibrations were assessed in terms of their ability to reproduce the observed streamflow from an independent period of record. Model calibrations and simulations over independent periods for these 16 catchments are presented in Post (1996), while the Myrtle 2 calibration model is shown in Post and Jakeman (1996). From this analysis, it was concluded that the model is representing the hydrologic response of the 16 catchments adequately.

5. Defining the value of each hydrologic response characteristic from landscape attributes

The six model parameters can be used to define the daily streamflow of these catchments. An attempt will now be made to relate these model parameters (hydrologic response characteristics) to attributes of the landscape. Over 20 different landscape attributes were examined as possible controls on the hydrologic response of these catchments. Post (1996) contains a complete list and definitions of these attributes. Of these 20 landscape attributes, the following six were found to be important in defining catchment hydrologic response (see the following section for details):

Area: Drainage area in hectares;

Drainage density: Total length of streams per km^2 (Horton, 1932);

Elongation: The ratio of the diameter of a circle with the same area as the basin, to the basin length (Langford and O'Shaughnessy, 1977);

Gradient: The gradient of the channel, defined vertically by maximum catchment relief and horizontally by channel length;

Slope: Angle of the catchment lid from the horizontal (Lee, 1963);

Wetted area: Percentage of the catchment adjacent to the stream channel showing evidence of surface saturation (Langford and O'Shaughnessy, 1977).

Table 1 shows the values of these six landscape attributes for each of the 16 catchments.

As the relationships between the landscape attributes and hydrologic response characteristics are not necessarily linear, square root, square, *ln*, and inverse transformations (Kleinbaum et al., 1988) were performed in order to find the most appropriate relationship. For each derived equation, the number of samples was 16 and landscape attributes were included in the regression in a stepwise fashion only if they were found to be significant (Norusis, 1993). Equations (1) to (6) represent the optimum predictive equations obtained using this technique for each hydrologic response characteristic.

$$\frac{1}{c} = 2.4 \times 10^{-2}\frac{1}{\text{gradient}} + 1 \times 10^{-3}\text{elongation}^2 - 5.1 \times 10^{-4} \quad r^2 = 0.63 \tag{1}$$

$$\frac{1}{f} = -0.3\ln(\text{gradient}) + 1.4 \quad r^2 = 0.37 \tag{2}$$

$$\frac{1}{\tau_w} = -4.2 \times 10^{-2} \ln(c) + 0.3 \quad r^2 = 0.70 \qquad (3)$$

$$\frac{1}{\tau_q} = 0.4\sqrt{\text{drainage density}} - 0.2 \quad r^2 = 0.40 \qquad (4)$$

$$\frac{1}{\tau_s} = 3.4 \times 10^{-4}\,\text{slope} + 3.1 \times 10^{-3} \quad r^2 = 0.47 \qquad (5)$$

$$\sqrt{h} = 1.1 \times 10^{-2}\,\text{area} - 5 \times 10^{-3}\,\text{gradient} + 0.3 \quad r^2 = 0.94 \qquad (6)$$

Post and Jakeman (1996) and Post (1996) contain a detailed examination of the relationships between the hydrologic response characteristics and landscape attributes. Here, only a brief discussion of the underlying reasons for the relationships will be given.

Non-linear module parameters: The mass balance parameter, c is related primarily to the gradient of the catchment (Eq. (1)). This is because the mass balance of water in the catchments is related to evapotranspiration. With the vegetation cover being relatively homogeneous, and all of the catchments facing south easterly to south westerly, those with higher gradients seem to have a lower rate of water loss to evapotranspiration, presumably because of aspect related shading. The temperature modulation factor, f is also related to the gradient of the catchment (Eq. (2)). This is because in the middle of winter, catchments with steeper gradients seem to have lower rates of evapotranspiration than more gently sloping catchments, again probably due to aspect related shading. The time constant governing the rate of water loss, t_w is strongly related to the mass balance parameter, c (Equation 3). This is because t_w controls the rate at which catchment wetness, s_k, decreases between rainfall events, while c controls the amount by which s_k is increased by a rainfall event (Fig. 1). This interaction between two of the parameters may indicate a degree of over-parameterisation, even in a model with just six parameters.

Linear module parameters: The quickflow recession time constant, t_q is related to the drainage density of the catchment (Eq. (4)). This is because water will find its way to stream more quickly in catchments with a higher drainage density. The slowflow recession time constant, t_s is related to the slope of the catchment (Eq. (5)). This is because, given the similar soils and geology of these catchments, it would be expected that deep subsurface water be expelled more quickly in steeply sloping catchments. The peak of the unit

Table 1
Landscape attributes for each of the 16 Maroondah catchments

Catchment	Area (ha)	Drainage density (km/km^2)	Elongation	Gradient (°)	Slope (°)	Wetted area (%)
Picaninny	52.8	1.62	0.55	33.3	37.8	0.91
Blue Jacket	64.8	2.53	0.59	18.3	36.6	3.07
Myrtle 1	25.2	3.94	1.13	10.5	19.9	5.78
Myrtle 2	30.5	3.25	0.86	11.6	21.0	3.57
Ettercon 1	11.6	3.75	0.92	6.6	7.0	4.20
Ettercon 2	8.8	4.02	0.70	5.6	6.9	5.90
Ettercon 3	15.0	3.92	1.62	12.0	13.0	3.59
Ettercon 4	9.0	2.46	1.14	15.6	16.0	3.85
Monda 1	6.2	4.16	1.55	17.5	10.0	4.22
Monda 2	4.0	3.97	0.60	31.6	22.0	4.05
Monda 3	7.3	3.46	0.85	21.8	20.0	3.37
Monda 4	6.3	3.29	0.74	21.1	23.0	3.15
Black Spur 1	17.0	1.38	1.19	17.1	7.0	1.44
Black Spur 2	9.6	3.63	1.26	11.8	15.0	5.17
Black Spur 3	7.7	3.76	0.81	13.1	14.0	3.36
Black Spur 4	9.8	2.67	0.52	20.0	17.0	1.11

Table 2
Calibrated (and predicted) values of the hydrologic response characteristics and goodness of fit of the resultant predicted streamflow

Catchment	c (mm)	f	t_w (days)	t_q (days)	t_s (days)	h (l/s)	D	Average annual water yield error (%)
Picaninny	1213 (2110)	3.0 (2.9)	15 (47)	4.2 (3.3)	56 (68)	0.48 (0.46)	0.68	16
Blue Jacket	567 (906)	2.0 (1.9)	17 (18)	2.1 (2.7)	73 (61)	0.81 (0.79)	0.45	−37
Myrtle 1	208 (336)	1.7 (1.4)	6 (10)	1.9 (1.8)	117 (101)	0.30 (0.25)	0.71	−17
Myrtle 2	285 (437)	0.9 (1.6)	17 (11)	2.1 (2.1)	146 (96)	0.24 (0.32)	0.07	−39
Ettercon 1	206 (268)	1.5 (1.1)	8 (9)	2.0 (1.9)	119 (205)	0.10 (0.15)	0.42	−28
Ettercon 2	305 (176)	1.2 (1.1)	10 (8)	1.9 (1.8)	131 (201)	0.16 (0.12)	0.58	31
Ettercon 3	767 (367)	1.3 (1.5)	19 (11)	1.7 (1.8)	142 (133)	0.20 (0.15)	0.39	43
Ettercon 4	438 (408)	1.9 (1.7)	14 (11)	2.0 (2.7)	163 (116)	0.08 (0.09)	0.62	−19
Monda 1	262 (332)	1.3 (1.9)	10 (10)	1.8 (1.7)	241 (149)	0.07 (0.07)	0.62	1
Monda 2	2712 (1408)	2.9 (2.7)	89 (26)	1.3 (1.9)	161 (92)	0.03 (0.03)	0.46	−11
Monda 3	1020 (703)	4.2 (2.0)	15 (15)	1.5 (2.0)	89 (103)	0.05 (0.07)	0.61	−21
Monda 4	781 (818)	4.0 (2.0)	17 (16)	3.8 (2.0)	52 (99)	0.02 (0.07)	0.20	−47
Black Spur 1	2144 (369)	3.3 (1.7)	53 (11)	1.3 (4.3)	166 (188)	0.11 (0.15)	−1.53	27
Black Spur 2	273 (316)	1.4 (1.5)	8 (10)	2.1 (1.9)	181 (120)	0.14 (0.11)	0.69	9
Black Spur 3	652 (479)	1.4 (1.6)	20 (12)	2.3 (1.8)	217 (124)	0.09 (0.09)	0.72	−4
Black Spur 4	691 (1097)	1.2 (2.1)	11 (20)	3.0 (2.4)	79 (117)	0.19 (0.08)	0.27	48

hydrograph, h is strongly related to the area of the catchment (Eq. (6)). This is because larger catchments produce a greater peak of runoff (l/s) than smaller catchments. Because of this excellent relationship, it was decided to use h as the third parameter to define the linear module, rather than v_q or v_s which were not well related to landscape attributes.

It will be seen from Eqs. (1)–(6) that half of the relationships defining the model parameters in terms of one or more landscape attributes are poor, displaying a large degree of scatter and thus low values of r^2. There are a number of reasons for this. Firstly, more than one landscape attribute will affect each aspect of the hydrologic response of a catchment. However, with only 16 catchments, only one or at most two of the landscape attributes were found to be significant in each multiple linear regression equation. Secondly, the model is an imperfect representation of reality and thus each model parameter is only a representation of the actual hydrologic response, making it difficult to relate to landscape attributes. Thirdly, these catchments have very similar landscape attributes and climate, meaning that their hydrologic response is also very similar. As a result, the landscape attribute controlling each aspect of hydrologic response does not vary greatly between catchments. For example, while vegetation has a strong influence on evapotranspiration, it does not appear in the regression equations since it does not vary significantly between catchments.

6. Predicting the daily streamflow of ungauged catchments

Sixteen versions of Eqs. (1)–(6) were derived, each one treating a different catchment as if it were ungauged and excluding it from the relationship. In this way, predictions were made of the hydrologic response characteristics for each of the 16 catchments as if they were ungauged for streamflow. Table 2 shows the calibrated and predicted values of the six hydrologic response characteristics for all 16 catchments. As these six hydrologic response characteristics fully define the IHACRES model, the predictions can be used in conjunction with the daily rainfall and temperature time series to predict the daily streamflow of each catchment as if it were ungauged for streamflow. Since these catchments are in fact gauged, this predicted daily streamflow may be compared to the observed daily streamflow in order to assess the accuracy of the predictions. Table 2 shows the coefficient of determination, D for the predicted compared to observed streamflow, as well as the average difference in annual water yield between the observed and predicted streamflow. The coefficient of determination, D is defined by:

$$D = 1 - \frac{\sum(y_k - x_k)^2}{\sum(y_k - y)^2}$$

where y_k is the observed streamflow at timestep k, y is the mean observed streamflow, and x_k is the modelled streamflow. As the model fit improves, D approaches unity.

It can be seen from Table 2 that the accuracy of the predictions of the hydrologic response characteristics varies greatly. These inaccuracies lead to the errors in the prediction of streamflow and annual water yield shown in the last two columns of Table 2. Additionally, Figs. 3–6 show the predicted and observed streamflow for the Coranderrk, Myrtle, Ettercon, Monda, and Black Spur catchments, respectively. These streamflows were predicted without calibrating the model to the observed streamflow record of that catchment.

The large errors in the predicted values of some of the hydrologic response characteristics have led to poor predictions of daily streamflow for some of the catchments, yet surprisingly good predictions for others (Figs. 3–6). For example, the streamflow for Picaninny is predicted well (Fig. 3(a)), despite the very poor prediction of t_w for that catchment. This is because the over-prediction of t_w is balanced by the over-prediction of c, leading to a good prediction of water yield (defined by a combination of c, f, and t_w). Where the errors in the predicted values of the water yield parameters do not act to cancel each other, the consequent prediction of water yield is poor. See for example Myrtle 2, where the over-prediction of c and under-prediction of t_w combine to under-predict total water yield by 39%. A more efficient method may be to predict the water yield of an ungauged catchment by directly relating it to landscape attributes, and then constraining the values of these three parameters to produce this yield (Post et al., 1998b).

Predictions of the linear module parameters (t_q, t_s, and h) are in general much better. This is reflected by the similarities in the shape of the observed and predicted hydrographs, even when the volumes are predicted poorly. This is probably due to the similarly shaped hydrographs for these 16 catchments (Figs. 3–6), making it easier to regionalise their response. The notable exceptions are Black Spur 1, Ettercon 1, and Monda 4. The predicted response for Black Spur 1 (Fig. 6(a)) is too flashy, resulting from the over-prediction of t_q, due to the poor correlation between it and drainage density in this catchment. Conversely, the predicted responses for Ettercon 1 (Fig. 4(a)) and Monda 4 (Fig. 5(d)) are too flat, not capturing the seasonality of the observed response. This is due to the over-prediction of t_s for Ettercon 1 and h for Monda 4. This is because Monda 4 (and to a lesser extent Ettercon 1) displays a larger degree of seasonality compared to the other catchments.

7. Conclusions

For these 16 catchments in the Maroondah region of Victoria, six landscape attributes (drainage density, catchment slope, channel gradient, wetted area, elongation, and area) were used to predict the values of the six hydrologic response characteristics defining the IHACRES model. Each of the 16 catchments in turn was considered to be ungauged, and a prediction made of the daily streamflow of that catchment, based on the relationships between landscape attributes and hydrologic response characteristics derived using the other 15 catchments. These predictions of daily streamflow ranged from very good to poor (Figs. 3–6). This range of results is due in part to errors in the representation of hydrologic response by the IHACRES model, combined with the limited availability of appropriate landscape

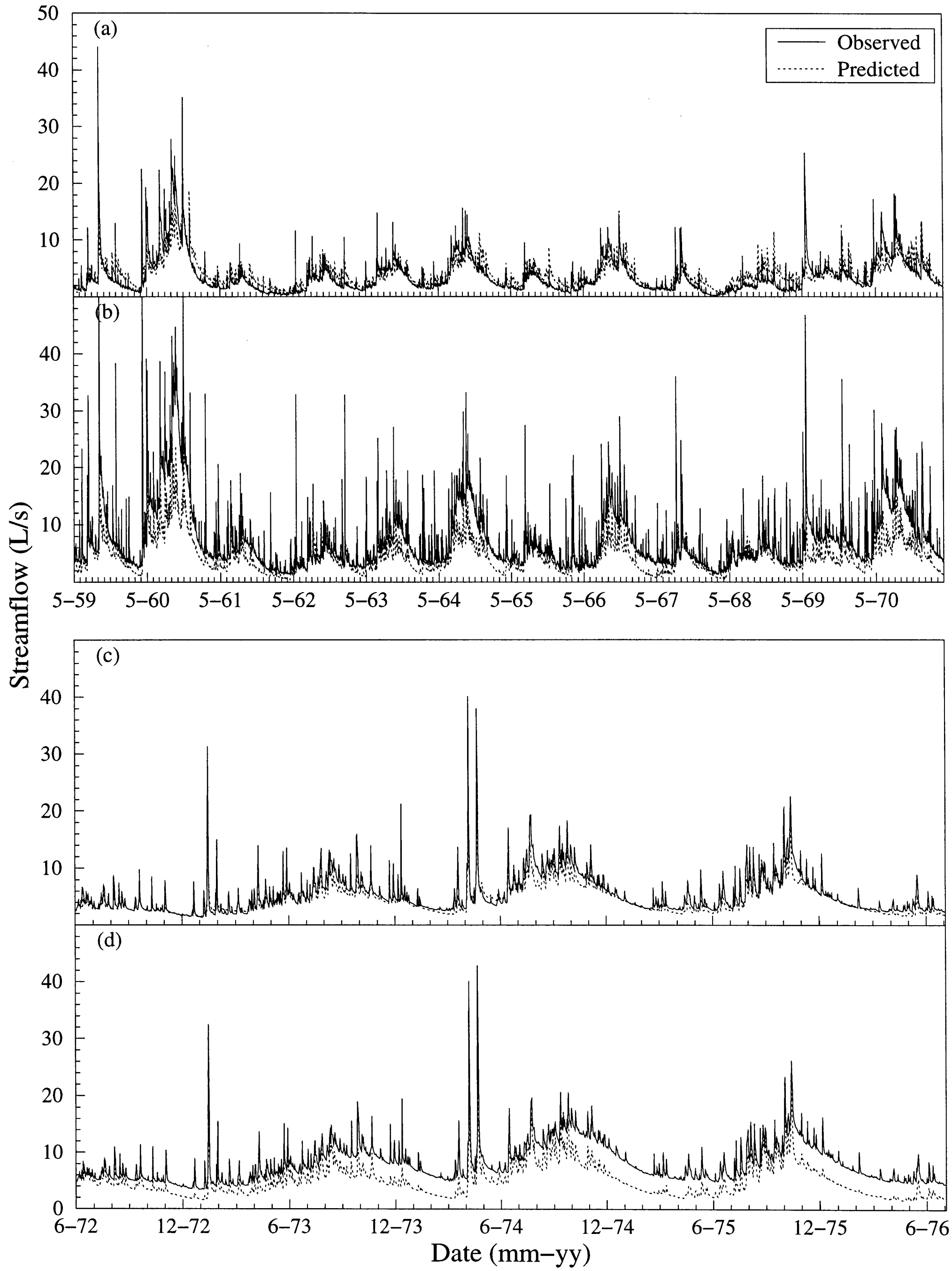

Fig. 3. Predicted and observed streamflow for (a) Picaninny; (b) Blue Jacket; (c) Myrtle 1; (d) Myrtle 2.

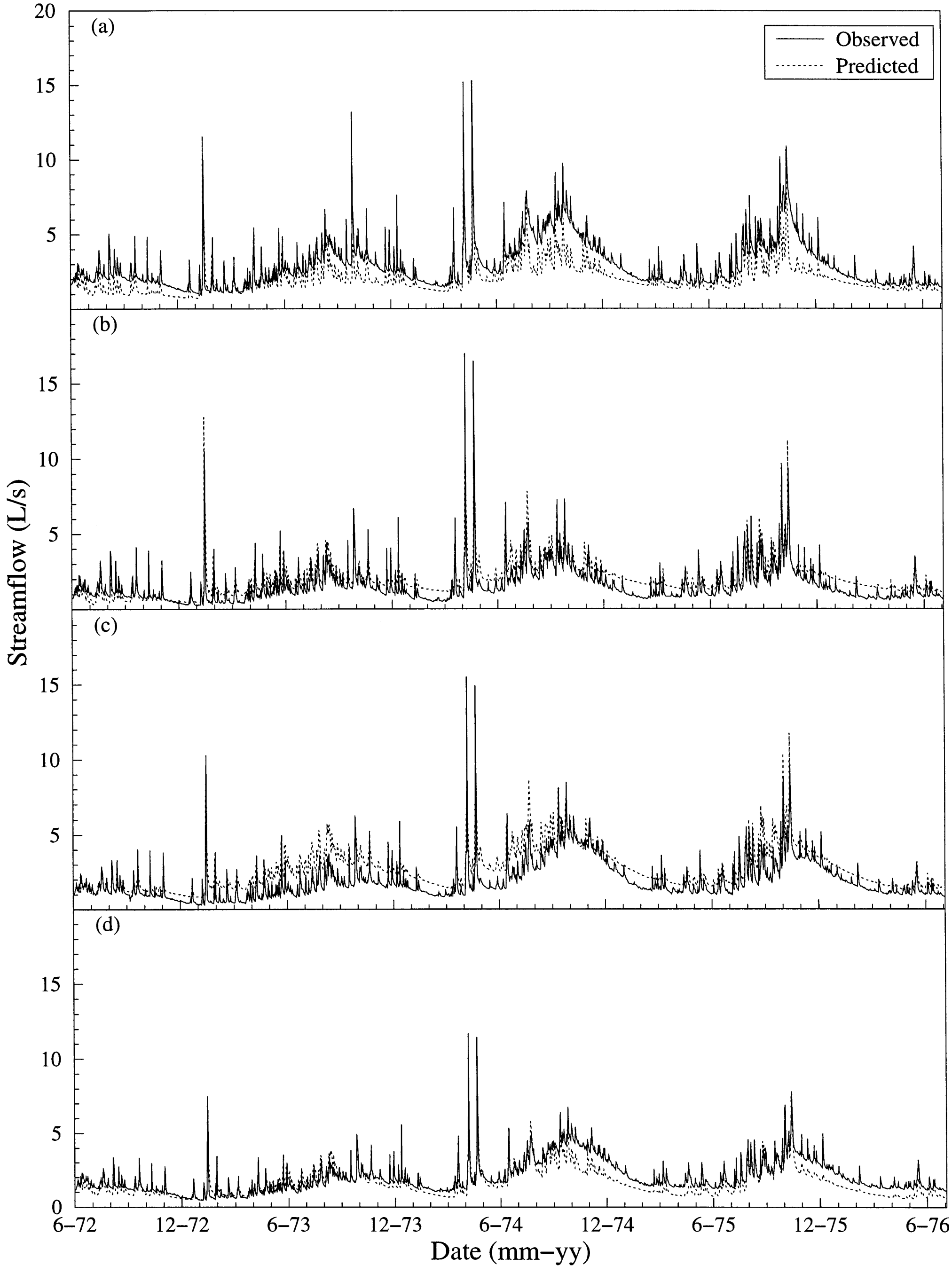

Fig. 4. Predicted and observed streamflow for (a) Ettercon 1; (b) Ettercon 2; (c) Ettercon 3; (d) Ettercon 4.

attributes. For example, quickflow was observed to recede very rapidly in Black Spur 1, despite its low drainage density. This was almost certainly due to the impact of some unmeasured feature of the landscape in that catchment.

This study has shown that regional relationships between hydrologic response characteristics and landscape attributes can be used in order to make a prediction of the daily streamflow of an ungauged catchment from an appropriate rainfall and temperature time series. However, some of

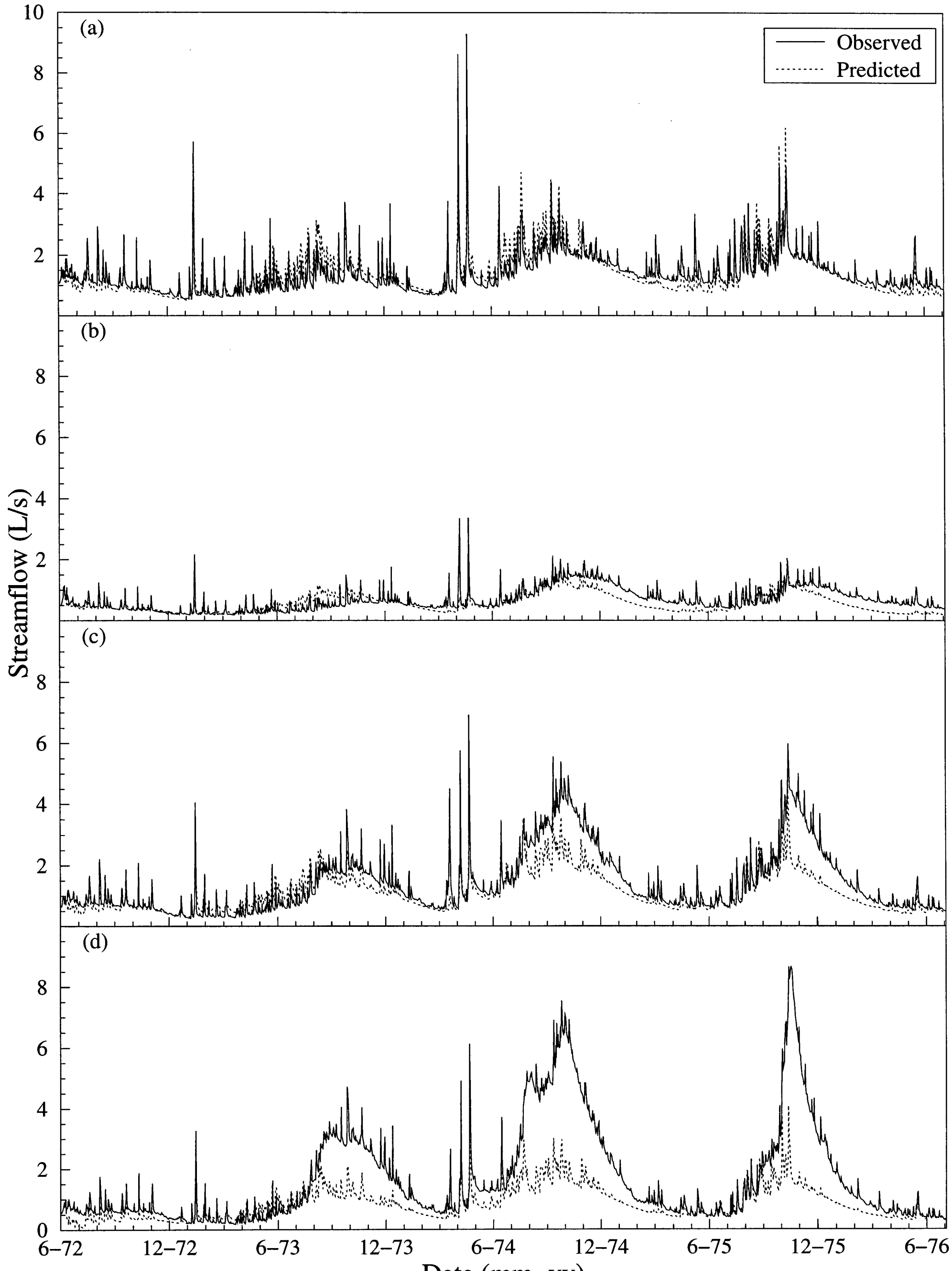

Fig. 5. Predicted and observed streamflow for (a) Monda 1; (b) Monda 2; (c) Monda 3; (d) Monda 4.

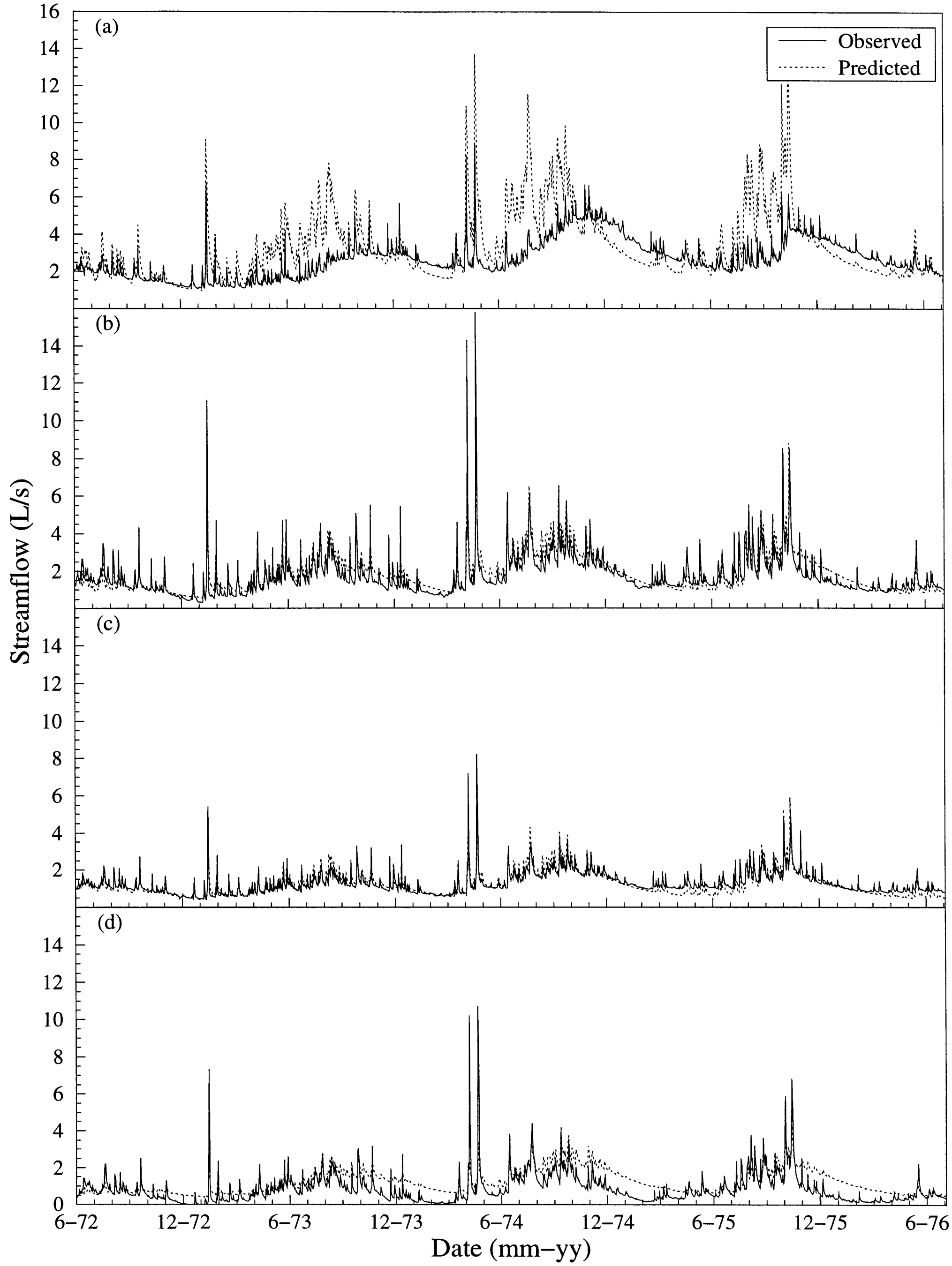

Fig. 6. Predicted and observed streamflow for (a) Black Spur 1; (b) Black Spur 2; (c) Black Spur 3; (d) Black Spur 4.

the streamflow hydrographs resulting from these predictions were poor, indicating that the relationships between the landscape attributes and hydrologic response characteristics are not understood sufficiently well. The fact that reasonable results were obtained for many of the catchments is probably due to the similarity of these catchments, both in terms of their landscape attributes and hydrologic response. A better understanding of the dominant controls on hydrologic response (Post et al., 1998a) may lead to improved results.

References

Braun, L.N., Renner, C.B., 1992. Application of a conceptual runoff model in different physiographic regions of Switzerland. Hydrol. Sci. J. 37 (3), 217–231.

Chang, M., Boyer, D.C., 1977. Estimates of low flows using watershed and climatic parameters. Water Resour. Res. 13 (6), 997–1001.

Chiew, F.H.S., McMahon, T.A., 1994. Application of the daily rainfall-runoff model MODHYDROLOG to 28 Australian catchments. J. Hydrol. 153, 383–416.

Franchini, M., Wendling, J., Obled, C., Todini, E., 1996. Physical interpretation and sensitivity analysis of the TOPMODEL. J. Hydrol. 175, 293–338.

Goodrich, D.C., Woolhiser, D.A., 1991. Catchment hydrology. Reviews of Geophysics, Supplement. April 1991. US National Report to International Union of Geodesy and Geophysics, 1987–1990, pp. 202–209.

Gustard, A., Bullock, A., Dixon, J.M., 1992. Low flow estimation in the United Kingdom. Institute of Hydrology Report 108.

Heerdegen, R.G., Reich, B.M., 1974. Unit hydrographs for catchments of different sizes and dissimilar regions. J. Hydrol. 22, 143–153.

Horton, R.E., 1932. Drainage basin characteristics. Trans. Am. Geophys. Union 13, 350.

Jakeman, A.J., Hornberger, G.M., 1993. How much complexity is warranted in a rainfall-runoff model? Water Resour. Res. 29 (8), 2637–2649.

Jakeman, A.J., Littlewood, I.G., Whitehead, P.G., 1990. Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. J. Hydrol. 117, 275–300.

Jakeman, A.J., Oglesby, R.J., Hansen, D.P., Post, D.A., Schreider, S. Yu, Taylor, J.A., Larson, J.W., Hornberger, G.M., 1995. Modelling land surface–atmosphere interactions and water resource impacts: alternative approaches. Second International Conference on GEWEX in Asia and GAME, March 6–10, pp. 215–218.

James, L.D., 1972. Hydrologic modeling, parameter estimation, and watershed characteristics. J. Hydrol. 17, 283–307.

Kleinbaum, D.G., Kupper, L.L., And Muller, K.E., 1988. Applied Regression Analysis and Other Multivariable Methods. PWS-Kent, Boston.

Langford, K.J., O'Shaughnessy, P.J., 1977. First progress report-North Maroondah. Report MMBW-W-0005. MMBW, Melbourne, p. 340.

Langford, K.J., O'Shaughnessy, P.J., 1980. Second progress report-Coranderrk. Report MMBW-W-0010. MMBW, Melbourne, p. 394.

Lee, R., 1963. Evaluation of solar beam irradiation as a climatic parameter of mountain watersheds. Hydrology Paper No. 2. Colorado State University, Fort Collins, p. 50.

Littlewood, I.G., Jakeman, A.J., 1994. A new method of rainfall-runoff modelling and its applications in catchment hydrology. In: Zanetti, P. (Ed.), Environmental Modelling, vol. 2. Computational Mechanics Publications, Southampton, pp. 143–171.

McLaughlin, J.W., 1976. Upper Devonian to lower Carboniferous provinces, Central Victorian cauldron volcanic province. In: J.C. Douglas and J.A. Ferguson (Eds.), Geology of Victoria. Special Publication No 5, Geological Society of Australia, pp. 81–98.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part 1: a discussion of principles. J. Hydrol. 10, 282–290.

Nathan, R.J., McMahon, T.A., 1992. Estimating low flow characteristics in ungauged catchments. Water Res. Manage. 6, 85–100.

NERC, 1975. Flood Studies Report. Natural Environment Research Council, London.

Norusis, M.J., 1993. SPSS for Windows Base System Users Guide Release 6.0. SPSS, Chicago.

Patton, P.C., Baker, V.R., 1976. Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. Water Resour. Res. 12 (5), 941–952.

Pilgrim, D.H., 1987. Australian Rainfall and Runoff, vol. 1. Institution of Engineers Australia, Canberra.

Post, D.A., 1996. Identification of relationships between catchment-scale hydrologic response and landscape attributes. Ph.D diss. Australian National University, Canberra.

Post, D.A., Jakeman, A.J., 1996. Relationships between catchment attributes and hydrological response characteristics in small Australian mountain ash catchments. Hydrol. Processes 10, 877–892.

Post, D.A., Jakeman, A.J., 1998. Using a lumped conceptual rainfall-runoff model to predict the hydrologic impact of forestry treatments. Canadian Water Resources Association 51st Annual Conference, June 10–12, Victoria, BC, pp. 2–7.

Post, D.A., Grant, G.E., Jones, J.A., 1998a. New developments in ecological hydrology expand research opportunities. Eos 79 (43), 517, 526.

Post, D.A., Jones, J.A., Grant, G.E., 1998b. An improved methodology for predicting the daily hydrologic response of ungauged catchments through regionalisation. Environ. Model. Software 13, 395–403.

Reimers, W., 1990. Estimating hydrological parameters from basin characteristics for large semiarid catchments. Regionalization in Hydrology. IAHS Publication No. 191: 187–194.

Rosso, R., 1984. Nash model relation to Horton order ratios. Water Resour. Res. 20 (7), 914–920.
Servat, E., Dezetter, A., 1993. Rainfall-runoff modelling and water resources assessment in northwestern Ivory Coast. Tentative extension to ungauged catchments. J. Hydrol. 148, 231–248.
Srikanthan, R., Goodspeed, M.J., 1988. Regionalization of conceptual model parameters for meso-scale catchments in the Hunter Valley. Hydrology and Water Resources Symposium, ANU, Canberra, 1 February, Institution of Engineers, Australia, pp. 85–90.
Weeks, W.D., Ashkanasy, N.M., 1985. Regional parameters for the Sacramento model: a case study. Trans. Inst. Eng. Aust. CE27 (3), 305–313.