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An improved methodology for predicting the daily hydrologic response of ungauged catchments

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Abstract

In order to model fluxes of water from the land surface to the atmosphere, and from one grid cell to another in climate models, predictions of hydrologic response are required for catchments where hydrologic data are not available. A methodology has been presented previously that has the capability of producing estimates of catchment scale hydrologic response for ungauged catchments on a daily timestep (Post and Jakeman, 1998, Ecol. Mod. submitted). In the present paper, it is demonstrated that these daily predictions of hydrologic response can be improved by incorporating information about the hydrologic response of the catchment on a longer timestep. This is because the influence of large scale phenomena such as climate and vegetation may produce a similar water yield in nearby catchments, even though their daily hydrologic response may be different, due for example, to differences in drainage density. Thus, the water yield of an ungauged catchment is inferred on an inter-annual timestep, and this information is used to balance the water budget of a daily timestep rainfall-runoff model. It was found that using tree stocking densities to predict water yields for small experimental catchments in the Maroondah region of Victoria produced better results than those obtained by inferring the water balance parameter of a daily timestep rainfall-runoff model from channel gradient and catchment elongation. Good predictions of inter-annual water yield were also obtained for small experimental catchments in the H. J. Andrews, Hubbard Brook, and Coweeta long term ecological research (LTER) sites in the United States, indicating that it may be possible to produce high quality predictions of daily hydrologic response for ungauged catchments in these regions also. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Hydrologic regionalisation; Rainfall-runoff model; LTER network

Software availability

Name:	PC-IHACRES.
Contact address:	Professor Anthony Jakeman, Centre for Resource and Environmental Studies, Australian National University, Canberra, ACT 0200, Australia.
Hardware:	IBM-compatible PC 386 or higher (8 MB of RAM).
Software:	Windows 3.1 or higher.
Cost:	US$ 500.

1. Introduction

Predictions of the hydrologic response of ungauged catchments over a range of timescales may be required for a number of reasons. For example, construction of a dam may require a prediction to be made of the annual water yield of a river at an ungauged point. Conversely, for an examination of the ecological health of a river system, the frequency and duration of low flows may be of greater importance, requiring hydrologic response data on a daily or even sub-daily timestep. Similarly, the hydrologic component of a climate model may require predictions of catchment scale hydrologic response on a daily timestep. If the catchment being examined is not gauged for streamflow, these estimates must be derived using regionalisation techniques, where the catchment under consideration is assumed to behave similarly to other catchments with similar climatologies and landscape attributes. Defining 'similarity' then is something of a key issue. Previous attempts to define similarity have been based on geographical proximity (Mosley, 1981; Hughes, 1987). However, other studies have shown that geographic proximity alone is insufficient

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and catchment attributes have also been used (Acreman and Sinclair, 1986; Nathan and McMahon, 1990; Zrinji and Burn, 1994). In this study, the catchments under consideration are considered to be sufficiently similar due to their geographic proximity,as well as the similarity of their landscape attributes and hydrologic response.

In general, previous regionalisation studies which have made use of a modelling methodology have met with limited success. Major reasons for this include: (1) the lack of high quality rainfall-runoff and landscape attribute data; (2) the lack of a theoretical framework for defining hydrologically homogeneous regions; (3) uncertainties involved in representing the hydrologic response of a catchment using a rainfall-runoff model; and (4) problems in relating this hydrologic response to landscape attributes using multiple linear regression equations. The third and fourth problems arise primarily due to rainfall-runoff model deficiencies. One major deficiency is that models are typically too complex or overparameterised, meaning that their parameters cannot be estimated unambiguously, and do not have a physical interpretation. Examples include 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). The use of simpler models offsets some of these problems. However, these models generally do not define the total hydrologic response of the catchment, but rather one aspect, such as low flows (Chang and Boyer, 1977; Gustard et al., 1992; Nathan and McMahon, 1992), or flood frequencies (Patton and Baker, 1976; Reimers, 1990).

It appears that the ideal model for use in regionalisation studies would be one which accounts for the key hydrologic processes occurring in a catchment, but which avoids the problems of overparameterisation. An example of such a model may be a hybrid metric-conceptual model (Wheater et al., 1993). Here, the structure of the model is inferred from the rainfall-runoff data, but is interpretable as a system of storages and flows, which may be considered to represent storages and flows within the catchment. An example of such a model is the IHACRES model (Jakeman et al., 1990; Jakeman and Hornberger, 1993).

Post and Jakeman (1998) presented a regionalisation approach which allowed predictions to be made of the hydrologic response of ungauged catchments in the Maroondah region of Victoria, Australia, based on relationships between the IHACRES model parameters and landscape attributes such as drainage density, catchment slope, catchment area, and channel gradient. In this paper, an extension of this approach will be presented, where the IHACRES model is used to determine the shape of the daily streamflow hydrograph, but the total volume of streamflow is determined by comparing the inter-annual water yield of the catchment to nearby catchments. Thus, water yield information is used to constrain the IHACRES model and improve its predictive capability.

The major problem in such an approach is that high quality hydrologic and climatologic data are required for a number of ‘similar’ catchments before predictions can be made of the hydrologic response of an ungauged catchment in a region. In order to solve this problem, a study is currently being carried out which attempts to identify the underlying controls on hydrologic response across a range of regions. If these controls are similar or vary in some systematic way between regions, it should be possible to derive relationships for ungauged catchments in regions which do not have a large number (or potentially any) gauged catchments within them.

2. The IHACRES model

This 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. As a result, all of the losses of water occur in the non-linear module. In the non-linear module, an antecedent precipitation index, s_k is calculated at each timestep as an internal state variable. The index s_k is given by

$$s_k = \frac{r_k}{c} + \left[1 - \frac{1}{\tau_w(t_k)}\right] s_{k-1} \tag{1}$$

In Eq. (1), c is defined such that the total volume of modelled effective rainfall is equal to the total volume of observed streamflow. It may be regarded as the maximum volume of the non-linear catchment store, since when the volume of the non-linear store is equal to c ($s_k = 1$), all of the observed rainfall, r_k, becomes runoff; $\tau_w(t_k)$ is the time constant (days) of catchment losses at daily mean temperature t_k (°C) according to

$$\tau_w(t_k) = \tau_w \exp(20f - t_k f) \tag{2}$$

In (2), τ_w is the time constant (days) of catchment losses at 20°C and f is a factor describing the effect of a unit change in temperature on the loss rate. Effective rainfall u_k is then calculated according to

$$u_k = \tfrac{1}{2}(s_k + s_{k-1}) r_k \tag{3}$$

Once the effective rainfall has been calculated, the total unit hydrograph is determined by parameterising and discretising the following linear convolution as a configuration of linear reservoirs:

$$y(t) = \int_0^t h(t-s)u(s)\mathrm{d}s \tag{4}$$

where $y(t)$ is observed streamflow, $u(s)$ is effective rainfall and $h(t)$ is the unit hydrograph. The parameters describing the unit hydrograph are determined by a simple refined version of the instrumental variable technique. Its advantages in this context are described in Jakeman et al. (1990). 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. Effective rainfall is then routed through two parallel storages to produce streamflow. This model structure was identified as the most appropriate for use in the Maroondah catchments. The model used here has six parameters in total, three related to the non-linear component (τ_w, f and c as defined above), and three related to the linear component; τ_q and τ_s are the recession time constants for quickflow and slowflow, and ν_s is the proportion of slowflow to total flow.

3. Maroondah catchments

The Maroondah catchments are located in the central highlands of Victoria in south-eastern Australia. Fig. 2 shows the location of this region to the north-east of Melbourne. There are 17 monitored catchments, ranging in size from 4 to 65 ha. The elevations of the weirs range from 232 to 835 m. Mean monthly temperatures vary from 4°C in July to 17°C in January. Average annual precipitation is 1250 mm, with a slight winter maximum, 75% falling in the 8 months from April to November. Snowpack accumulation is minimal. The dominant canopy vegetation is mountain ash (an evergreen Eucalypt species). The quality of both the rainfall and streamflow records is regarded as excellent (Langford and O'Shaughnessy, 1980).

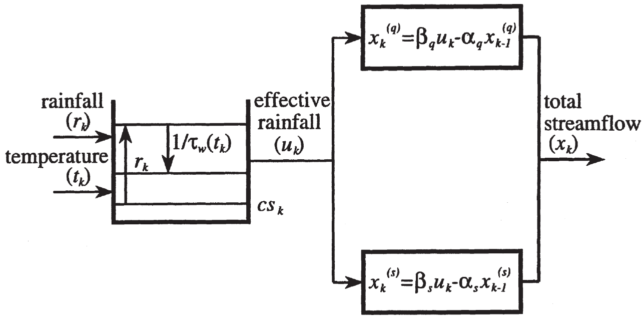

Fig. 1. Structure of the IHACRES model.

3.1. Original predictions

The IHACRES model has previously been applied to 13 of the catchments in this region by Post and Jakeman (1998). This study found that the values of the six model parameters were able to be inferred from the landscape attributes of the catchments. As a result, predictions of the daily hydrologic response of catchments in this region were made, as if the catchment under consideration were ungauged for streamflow. As can be seen from column 1 in Table 1, the predictions of streamflow on an annual water yield basis range from a 39% underprediction (for Myrtle 2), to a 31% overprediction (for Ettercon 2). Thus, while the model is capable of predicting the shape of the streamflow hydrograph with reasonable accuracy for most of the catchments, the total volume of streamflow is not predicted well for some of the catchments. Fig. 3 illustrates this, showing the observed and predicted daily streamflow for the Myrtle 2 catchment. It can be seen from Fig. 3 that the shape of the observed and predicted streamflow hydrographs are similar, however, the prediction is significantly underestimating the total volume of streamflow. These predictions of inter-annual water yield were made by relating the IHACRES model parameter representing the maximum volume of the non-linear store, c, to the gradient of the stream channel and the catchment elongation (Post and Jakeman, 1998).

3.2. Inter-annual water yield predictions

An alternative methodology is hereby proposed for deriving the value of c, whereby an attempt is made to infer the inter-annual water yield of an ungauged catchment by examining the percent runoff of nearby catchments. The value of c can then be determined such that the total volume of modelled streamflow is equal to the total volume of streamflow inferred by this regionalisation technique.

While all of the catchments in this region have a similar cover of mountain ash, there are two distinct ages of trees, with Picaninny, Blue Jacket, and Myrtle 1 and 2 covered in old growth mountain ash, and the remainder of the catchments covered in regrowth mountain ash from bush fires in 1939. Fig. 4 shows the relationship between the percentage runoff of each catchment, and the stocking rate of trees in stems per hectare. It reflects this difference in vegetation age, with two distinct regressions for the two ages of mountain ash forest. From Fig. 4, relationships may be derived which predict the water yield of a catchment in this region from rainfall and knowledge of the stocking density of mountain ash in the catchment. The relationship for old growth mountain ash forest is given by

$$\%\,\text{runoff} = -\,0.318\,\text{stocking} + 58.41 \tag{5}$$

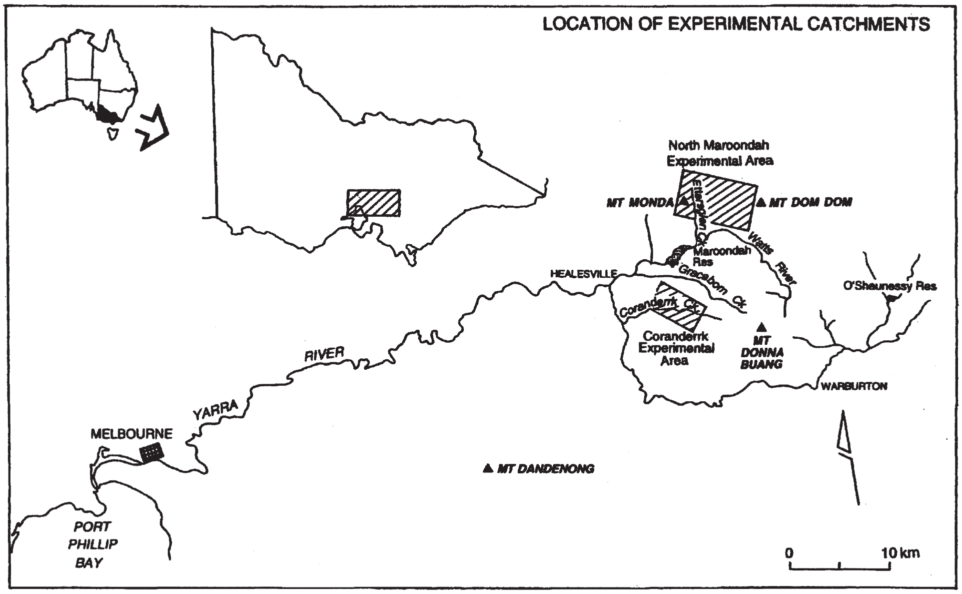

Fig. 2. Location of the experimental catchments in the Maroondah region of Victoria, Australia.

Table 1
Original and new percent error in the prediction of inter-annual water yield for the Maroondah catchments

Catchment	Original water yield error (%)	New water yield error (%)
Picaninny	16	78
Blue Jacket	−37	−40
Myrtle 1	−17	−10
Myrtle 2	−39	10
Ettercon 1	−28	−13
Ettercon 2	31	11
Ettercon 4	−19	−24
Monda 1	1	−4
Monda 2	−11	2
Monda 3	−21	−2
Black Spur 1	27	23
Black Spur 2	9	−7
Black Spur 3	−4	14

while for 1939 regrowth mountain ash, the relationship is given by

$$\% \text{ runoff} = -0.048 \text{ stocking} + 54.22 \quad (6)$$

As expected, as the stocking density of trees increases, the percentage runoff (and therefore water yield) of the catchments decreases.

In order to make predictions of the water yield of each of the 16 experimental catchments as if they were ungauged for streamflow, the catchment under consideration must be removed from the set of catchments for which the regression equation is derived. As a result, the coefficients in Eqs. (5) and (6) differ slightly from those used when predicting the percentage runoff (and therefore water yield) of each catchment.

Column 2 of Table 1 shows the percentage error in the water yield of these catchments when inferred from the relationships with stocking density. It will be seen that the percentage errors are all either about the same or significantly better than the predictions obtained by relating c to channel gradient (column 1), for all of the catchments except Picaninny. This is because Picaninny displays an unusually low water yield based on its stocking density (Fig. 2). When Picaninny is considered to be ungauged and removed from the relationship, the relationship based on Blue Jacket and Myrtle 1 and 2 produces a considerable error when applied to Picaninny. This may be due to an error in the calculated stocking density, differences in the precipitation received by Blue Jacket and Picaninny (the same precipitation is assumed for both catchments), or the influence of other unmeasured landscape attributes in Picaninny.

Fig. 5 shows the improvement obtained on a daily timestep when the inferred inter-annual water yield of Myrtle 2 is used to constrain the IHACRES model (compared to Fig. 3). From Table 1 it can be seen that improved predictions were also made for Myrtle 1, Ettercon 1 and 2, Monda 2 and 3, and Black Spur 1 and 2. The predictions for Blue Jacket, Ettercon 4, Monda 1 and Black Spur 3 were only slightly poorer than the original predictions.

4. Application to LTER catchments

Having determined that this technique can be used to predict the daily streamflow of ungauged catchments in the Maroondah region of Victoria, Australia, a study is now being carried out which attempts to extend these results to catchments in other regions. By understanding

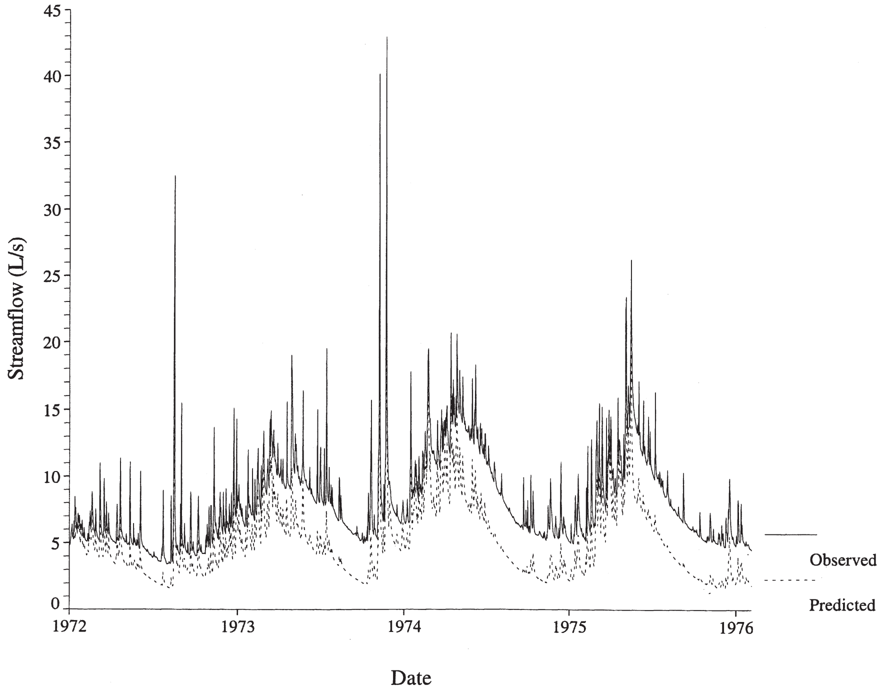

Fig. 3. Streamflow for Myrtle 2 when c is predicted from gradient and elongation.

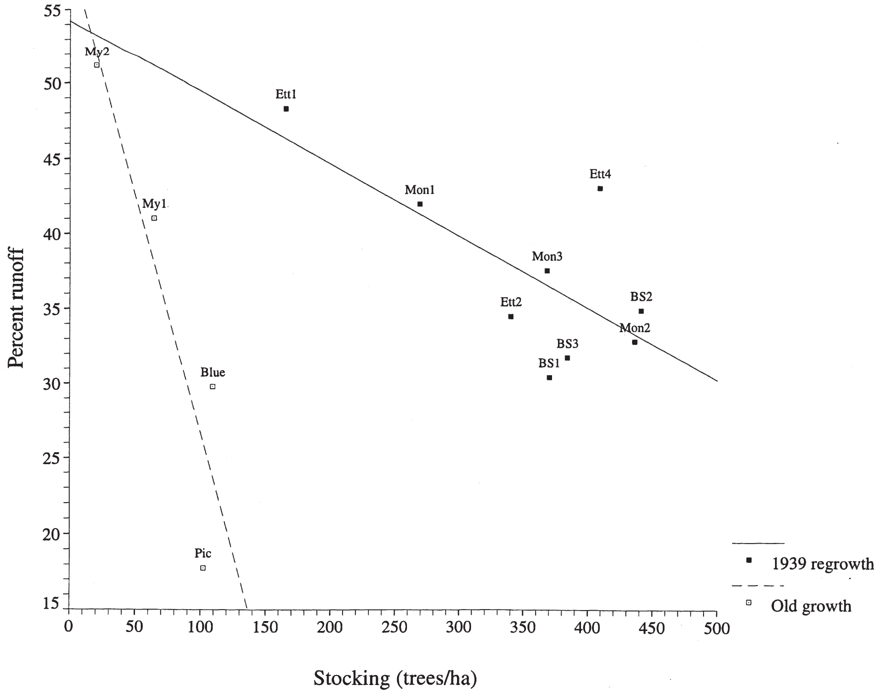

Fig. 4. Relationship between percentage runoff and stocking density for the Maroondah catchments.

the controls on hydrologic response in a variety of regions, it is hoped to derive relationships which can be used to predict the hydrologic response of ungauged catchments, even if nearby gauged catchments are not available. This extended study encompasses a number of sites across the United States, as can be seen from Fig. 6. Data from three of these sites have been examined thus far: Hubbard Brook (HBR) in New Hampshire; H.J. Andrews (HJA) in Oregon; and Coweeta (CWT) in North Carolina. Results from these three sites will be presented here. Sites shown in Fig. 6 and still under analysis include Caspar Creek (CAS) and San Dimas (SND) in California; Reynolds Creek (RCR) in Idaho; Walnut Gulch (WLG) in Arizona; Konza Prairie (KNZ)

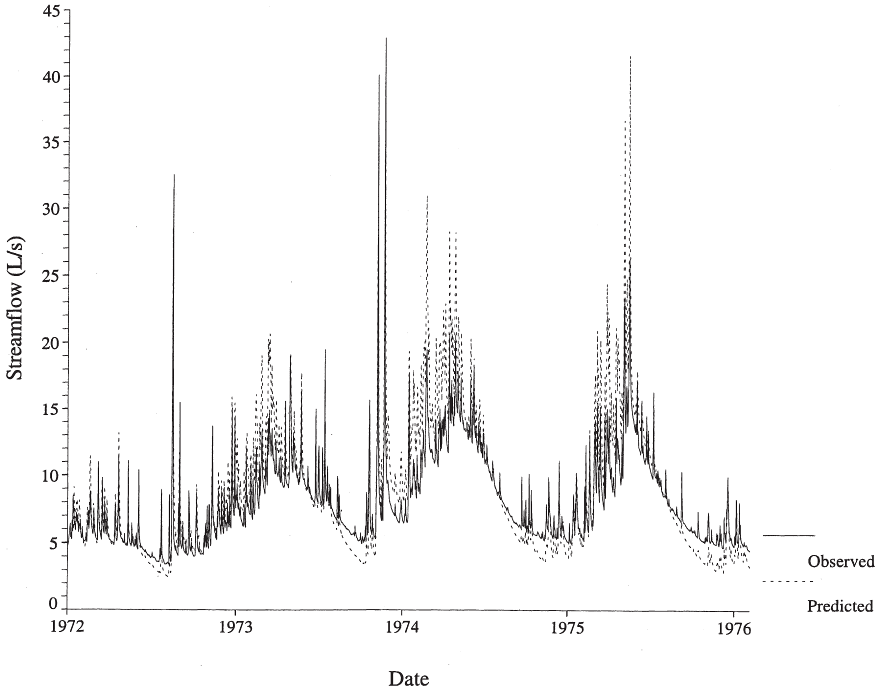

Fig. 5. Streamflow for Myrtle 2 when water yield is predicted from stocking density.

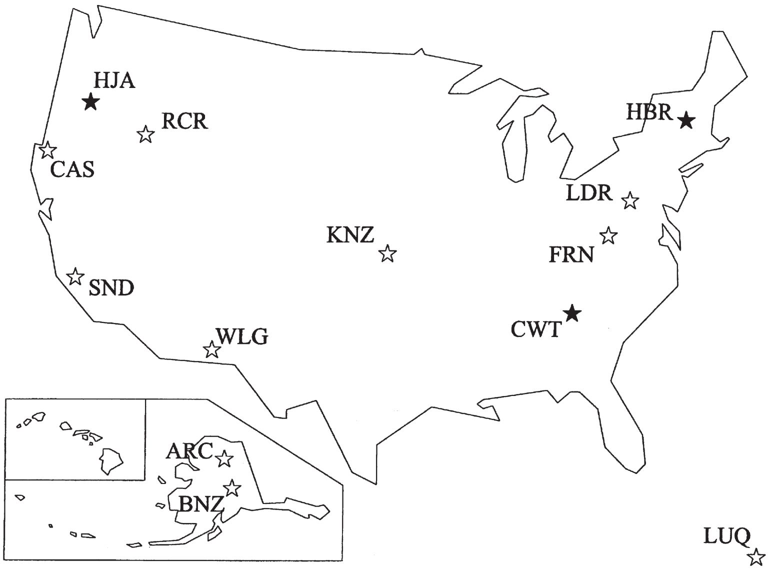

Fig. 6. Location of the experimental catchments in the United States. Filled stars represent the sites examined in the present paper. The names of the sites are given in the text.

in Kansas; Leading Ridge (LDR) in Pennsylvania; Fernow (FRN) in West Virginia; Luquillo (LUQ) in Puerto Rico; and Arctic Tundra (ARC) and Bonanza Creek (BNZ) in Alaska.

4.1. Hubbard Brook LTER

The Hubbard Brook LTER site is located in the White Mountains of New Hampshire, in the north-eastern United States (see Fig. 6). It consists of nine monitored catchments, ranging in size from 12 to 76 ha. The elevations of the weirs range from 442 to 619 m. The climate of the area is humid-continental, with a mean monthly air temperature of − 9°C in January and 19°C in July. Average annual precipitation is 1310 mm and is evenly distributed throughout the year. The winter snowpack accumulates to around 1.5 m in depth. The dominant vegetation consists of deciduous northern hardwoods (beech, sugar maple and yellow birch). A description of the Hubbard Brook LTER site is given in Likens et al. (1977).

In this study, six of the catchments were selected for analysis, as they had a common period of record from 1 June 1969 to 31 May 1983. Using a similar methodology as was applied to the Maroondah catchments, the water yield of each of these six catchments was predicted as if it was ungauged by comparing it to the other five catchments. Because of the homogeneity of these six catchments, excellent predictions of percentage runoff were obtained for each catchment by simply taking the mean of the percentage runoff for the other five catchments. Table 2 shows the observed water yield for each catchment, along with the percentage error of the predicted water yield.

Comparison of the errors in the predictions of water yield for Hubbard Brook from Table 2 with those of the Maroondah catchments from Table 1 show that the predictions for Hubbard Brook are far better. This is primarily due to the homogeneity of the Hubbard Brook catchments, where the mean percentage runoff of the other five catchments provides an excellent prediction of the water yield of the ungauged catchment. Conversely, in the more heterogeneous Maroondah catchments, a relationship between percentage runoff and stocking density was required. This implies that the predictions of daily streamflow for the Hubbard Brook catchments should be of similarly high quality, as long as the timing of the snowmelt in these catchments can be captured adequately.

4.2. H.J. Andrews LTER

The H.J. Andrews LTER site is located in the Cascade mountains of Oregon, in the north-western United States (see Fig. 6). It consists of eight monitored streams, ranging in size from 9 to 101 ha. The elevations of the weirs range from 442 to 955 m. Mean monthly air temperature ranges from 1°C in January to 19°C in July. Average annual precipitation is 2200 mm, with a distinct winter maximum, 80% falling between October and March. A snowpack develops during winter, but is not as large as that at Hubbard Brook. The coniferous Douglas Fir is the dominant vegetation species. A description of the H.J. Andrews may be found in Van Cleve and Martin (1991).

Table 2
Observed annual water yield and percentage error in the prediction of annual water yield for the Hubbard Brook catchments

Catchment	Observed annual water yield (mm)	Predicted water yield error (%)
HBR WS01	890.4	− 1.2
HBR WS03	882.2	0.3
HBR WS05	885.1	2.1
HBR WS06	920.0	1.7
HBR WS07	972.1	− 3.3
HBR WS08	942.3	0.4

In this study, the catchments were divided into two groups, one with a common period of record ranging from 1 October 1957 to 31 July 1962 consisting of WS01, 02 and 03. The other common period from 1 October 1968 to 30 September 1973 consisted of WS02, 06, 07, 08, 09 and 10. Note that WS02 is a long-term control and could therefore be included in both groups. For the two groups, percentage runoff was predicted for each catchment, assuming that it was the same for all the catchments in the group. The results of this analysis are shown in Table 3.

It can be seen from Table 3 that the errors in the prediction of water yield for the H.J. Andrews catchments are far greater than those for the Hubbard Brook catchments. This reflects the greater heterogeneity of the H.J. Andrews catchments. It should be possible to reduce these errors by incorporating information explaining the differences in water yield between the catchments, such as was done for the Maroondah catchments using stocking density. Additionally, a recent re-examination of data from these catchments suggests that the calibration curves for WS 6, 7 and 8 may have errors associated with them. This would partly explain the large errors in predicted water yield for these catchments.

4.3. Coweeta LTER

The Coweeta LTER site is located in the Smoky Mountains of North Carolina, in the south-eastern United States (see Fig. 6). It consists of 17 monitored streams, ranging in size from 9 to 61 ha. The elevations of the weirs range from 696 to 1061 m. Average annual precipitation is 1870 mm at lower elevations, increasing to 2500 mm at higher elevations. This precipitation is relatively evenly spread throughout the year, with a slight maximum in March, and minimum in October. Snow

Table 3
Observed annual water yield and percentage error in the prediction of annual water yield for the H.J. Andrews catchments

Catchment	Observed annual water yield (mm)	Predicted water yield error (%)
HJA WS01	1321.1	8.5
HJA WS02	1510.6	− 11.4
HJA WS03	1355.6	4.4
HJA WS06	1585.2	− 16.8
HJA WS07	1113.9	26.5
HJA WS08	1411.4	− 4.1
HJA WS09	1330.7	11.0
HJA WS10	1571.5	− 9.0
HJA WS02	1435.7	1.4

contributes less than 2% to total precipitation, much less than at H.J. Andrews or Hubbard Brook. Mean monthly air temperature ranges from 3°C in January to 22°C in July. Deciduous oak species are the dominant canopy vegetation, with an abundant evergreen understorey consisting of rhododendron and mountain laurel. This vegetation is more similar to that at Hubbard Brook, than to the mainly fir-dominated H.J. Andrews forest. A description of the Coweeta site is to be found in Swank and Crossley (1988).

In this study, six of the control catchments were selected which have a common period ranging from 1 May 1947 to 30 April 1958. The mean annual water yield of these catchments are shown in Table 4. It will be seen from Table 4 that the annual water yields of the Coweeta catchments cover a far greater range than the annual water yields of any of the other catchments examined. Because of the heterogeneity of these catchments, it is not reasonable to assume that the catchment under consideration behaves similarly to the other five catchments. Thus, a relationship was derived between percentage runoff and the precipitation received by the catchments. This relationship is shown in Fig. 7. It can be seen that catchments receiving a higher precipitation also tend to have a higher percentage runoff. Other factors such as vegetation may influence this relationship since catchments with higher precipitations are also found at higher elevations.

Predictions were made of the water yield of each catchment as if it were ungauged for streamflow by using the relationship between precipitation and percentage runoff derived for the other five catchments. The percentage errors in these predictions are shown in Table 4. The predictions are generally good, with the exceptions of WS27 and WS36. This is due to the higher than expected percentage runoff for WS36 as can be seen from Fig. 4. This higher percentage runoff is probably due to the influence of another landscape attribute such as vegetation. This hypothesis will be examined when further information on the landscape attributes of the Coweeta catchments are analysed. However, even without this additional information, inter-annual water yields are being predicted to within 15%, which is better than was obtained for a number of the Maroondah catchments.

Table 4
Observed annual water yield and percentage error in the prediction of annual water yield for the Coweeta catchments

Catchment	Observed annual water yield (mm)	Predicted water yield error (%)
CWT WS02	844.0	5.4
CWT WS14	1004.7	− 2.8
CWT WS18	1013.5	1.1
CWT WS27	1683.6	13.1
CWT WS32	1392.6	6.2
CWT WS36	1745.4	− 15.1

5. Conclusions

A methodology was presented in Post and Jakeman (1998) for making predictions of daily streamflow for catchments in a region by relating the parameters of the IHACRES rainfall-runoff model to measurable landscape attributes. In this paper, this methodology has been extended by demonstrating that more accurate predictions of streamflow are obtained by predicting the maximum value of the non-linear store in the model by inferring the inter-annual water yield of the catchment under examination from nearby catchments. If the catchments under consideration are sufficiently homogeneous, these water yield predictions may be obtained by simply taking the mean percentage runoff of nearby catchments. This was shown to be true for the Hubbard Brook catchments. Conversely, if there is considerable heterogeneity between the catchments under consideration, then a relationship can be derived that predicts percentage runoff from relevant landscape attributes such as stocking density (Maroondah catchments) or precipitation (Coweeta catchments).

Applying this methodology to catchments from three LTER sites in the United States has led to generally better predictions of water yield than were obtained for the Maroondah catchments in Australia. This indicates that regionalisation of the hydrologic response characteristics defining the IHACRES model should lead to ungauged predictions of daily streamflow for these LTER sites which are at least as good as those obtained for the Maroondah catchments in Australia. For those sites where annual water yield varied considerably between catchments, precipitation and stocking density were found to be important in determining percentage runoff. Data from the other sites shown in Fig. 6 are currently being analysed. From this analysis, it is hoped to identify the factors which are important in determining the hydrologic response of catchments, firstly at an inter-annual timestep, and ultimately at a daily timestep, as has previously been obtained for the Maroondah catchments. These factors should allow predictions to be made of the hydrologic response of ungauged catchments, even those in regions where gauged catchments are not available.

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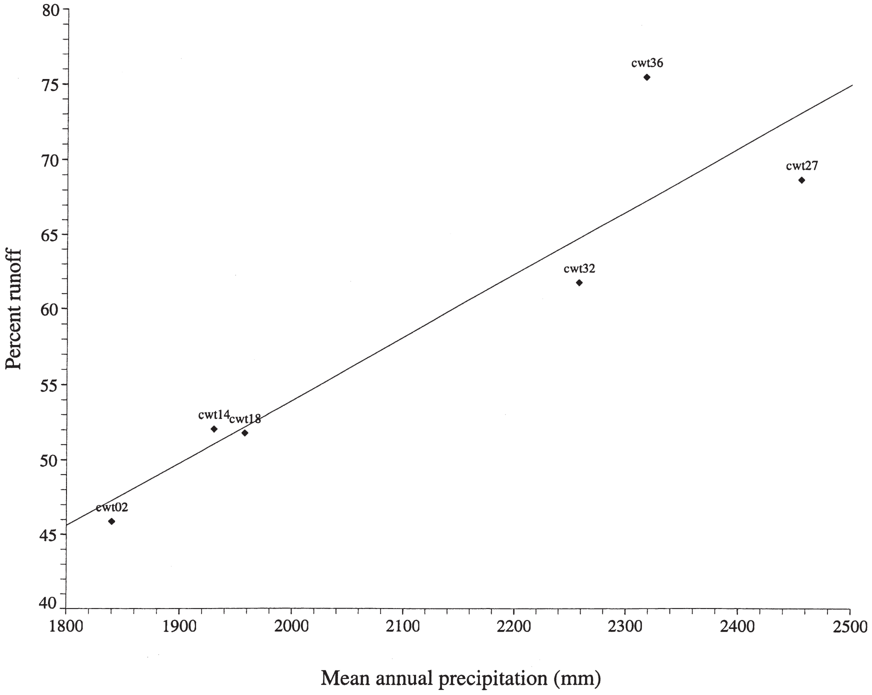

Fig. 7. Relationship between mean annual precipitation and percentage runoff for the Coweeta catchments.

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