

Predicting hydrologic response from physio-climatic attributes : an application to ungauged sub-catchments of the Burdekin River, North Queensland

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Abstract : The Burdekin is a large (140,000 km²) catchment located in the dry tropics of North Queensland, Australia. To assess the water resources of this catchment, we require a methodology which will allow us to determine the daily streamflow at any point within the catchment. To this end, we have utilised a simple, lumped parameter model, IHACRES. Of the five parameters in the model, three have been set to default values, while the other two have been related to the physio-climatic attributes of the sub-catchment under consideration. The parameter defining total catchment water yield (c) was constrained using %yield, which is related to summer precipitation, while the streamflow recession time constant (τ) was related to the total length of stream reaches in the catchment. These relationships were applicable over a range of scales from 68 km² to 130,000 km², however three separate relationships were required to define c in the three major regions of the Burdekin – the upper Burdekin, Bowen, and Belyando Suttor. This research has provided a valuable insight into the hydrologic behaviour of the Burdekin catchment, while also providing a useful methodology for water resources assessment. The invariance of the relationships with scale indicates that the dominant processes may be similar for a range of scales, while the fact that different relationships were required for each of the three major regions indicates the geographic limitations of this regionalisation approach.

Keywords : Regionalisation, surface-water hydrology, dry tropics, rainfall-runoff model

1. INTRODUCTION

This paper represents an extension of a regionalisation methodology that has been designed to allow users to predict the daily hydrologic response of ungauged catchments. It is based on assessing similarities between the catchment under assessment and nearby gauged catchments. This methodology was first presented in Post and Jakeman (1996) where it was noted that the parameters of a rainfall-runoff model, IHACRES could be related to so-called 'landscape attributes' of a catchment – such as catchment slope, drainage density and area. In Post and Jakeman (1999), the authors made use of these relationships to make predictions of the daily hydrologic response of 16 small (<1 km²) catchments in the Dandenong Mountains to the east of Melbourne. Predictions for some of these catchments were very good, however others were quite poor. To improve the quality of these

predictions, Post *et al.* (1998) proposed using simple relationships to predict the total water yield of catchments, then using this information to constrain the parameters of the rainfall-runoff model.

This paper represents an extension of this previous work in three ways:

Firstly, we make use of a new method for deriving the streamflow recession time constant (τ), developed based on an idea proposed by Croke (1992). This new method allows predictions to be made of this time constant much quicker than can be obtained using the IHACRES calibration techniques described in Post and Jakeman (1999).

Secondly, we are applying the regionalisation technique in a dry-tropical rangeland environment, the Burdekin catchment in North Queensland (see

Figure 1). Previously, the technique had only been applied in humid catchments.

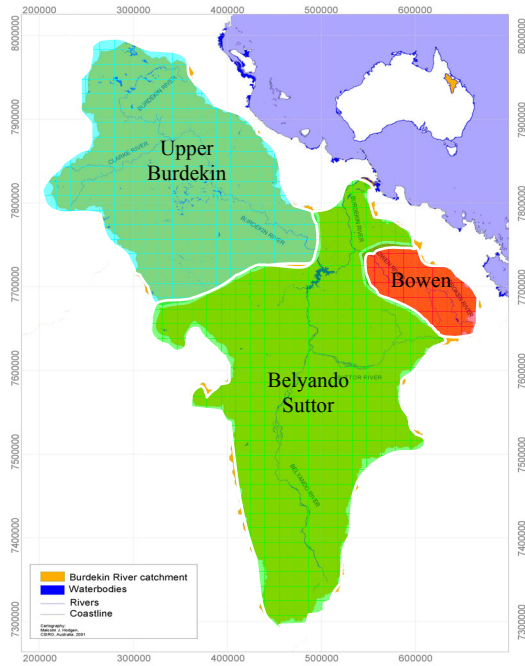


Figure 1. Location of the Burdekin catchment

Finally, we have simplified the regionalisation technique by holding constant a number of the IHACRES parameters. This allows us to make much quicker estimates of hydrologic response as well as potentially easier identification of relationships between parameters and catchment attributes, but may lead to some loss of accuracy.

The method for predicting the hydrologic response of ungauged catchments presented in this paper is not the only such attempt being made. Other approaches dealing with this problem have been reviewed in Post and Jakeman (1996, 1999), and Post *et al.* (1998) and will not be repeated here.

2. METHODS

Queensland Natural Resources and Mines (NR&M) currently collect streamflow information for 25 sub-catchments of the Burdekin. These data were obtained from NR&M, and physio-climatic attributes were derived for each of these 25 sub-catchments in a GIS environment. In total, 34 physio-climatic attributes were derived describing catchment morphology (area, elevation, slope, drainage density etc), landuse (percent pasture, cropland, forest etc), and climate (precipitation, temperature, radiation etc).

A decision was made to examine the hydrologic response of these 25 catchments over the period 1980-85. This time period was chosen to avoid the influence of the Burdekin Falls Dam which was constructed in 1986. In addition, this five year period displayed a range of climatic conditions, from a very wet year in 1981, dry years in 1982 and 1985, and intermediate years in 1983 and 1984 (see Figure 2).

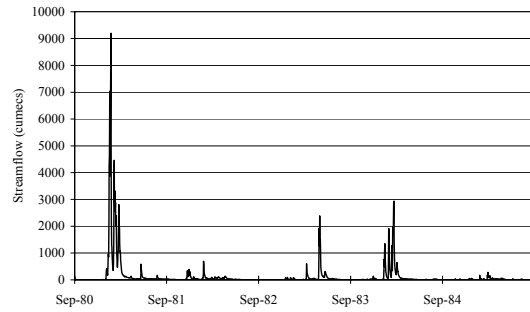


Figure 2. Streamflow for gauging station 120002, 1980-85

The lumped conceptual IHACRES rainfall-runoff model was used to define the daily hydrologic response of these 25 catchments. The model consists of two modules, a non-linear loss module to convert rainfall to effective rainfall, and a linear module to route the effective rainfall to streamflow. As shown in Figure 3, the model structure described in Post and Jakeman (1999) has been simplified through removal of one of the linear routing stores. Thus in the current version of the model, streamflow recession is considered to consist of a single exponential decay (rather than two exponential decays with different decay rates). This simplification is justified based on the streamflow response seen in the dry tropics (see Figure 2) where it can be seen that the slowflow component of streamflow is virtually absent from the observed response. However, an additional parameter (s_0) was added to account for the fact that during dry times of the year, a large rainfall will produce no streamflow response.

The calibration of the IHACRES model has also been simplified through the inclusion of a novel technique to derive the streamflow recession time constant (τ). The technique was adapted from a routine developed to determine the instrumental response of a spectrograph (Croke, 1992). The concept involves combining together a number of streamflow peaks to obtain a mean peak profile. One or more exponentials can then be fitted to the mean peak profile, thus giving the streamflow recession time constant(s). Since daily data are being used, the response curve is determined from

the peak of the flow event rather than the onset of flow or time of rainfall. For simplicity, the peak of the unit hydrograph is set to 1, rather than having a unit volume. The result is then scaled to give a volume of 1 after the profile has been fitted. It should be noted that the derived unit hydrograph is not for a pulse of rainfall, but rather is for the weighted average rainfall pattern (intensity and duration) for the storms selected. Therefore the width (full width at half maximum - FWHM) of the response curve depends on both the hydraulic properties of the catchment and the rainfall distribution of the “average” storm.

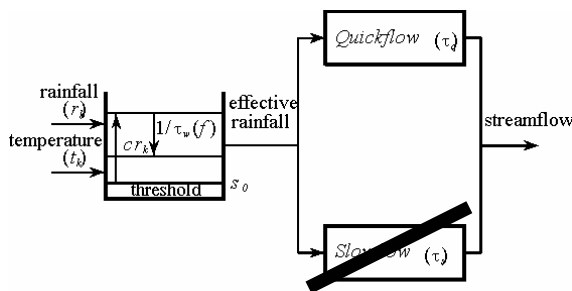


Figure 3. The modified IHACRES model

The first step in deriving the response curve from observed streamflow data is to identify isolated flow peaks with reasonably clean recession curves; that is, not contaminated significantly by previous or subsequent flow peaks. This can be done either manually, with the user supplying a list of peaks to be used; or automatically by scanning the hydrograph for peaks and selecting peaks further than some minimum separation from its nearest neighbours. The technique can be used with daily data, though hourly streamflow data is preferred as the peak width for most catchments is typically of the order of hours (Chapman, 1996). If daily data must be used, as was the case in this study, then care must be taken in fitting the response curve over the first 2-3 days after the peak. This portion of the derived response curve is affected by uncertainty in determining the actual time of peak, and whether there were any peaks within about 24 hrs of the primary peak.

The time of the peaks are then registered (set to time step 0), and the profiles checked for any subsequent flow peaks. This is done by noting where the derivative of the post-peak profile becomes positive (indicating an increase in the flow with time). In such cases, the profile is then fixed at the minimum value prior to the secondary peak until the observed flow drops below this value. This reduces the effect of subsequent peaks

on the derived response curve, but does not fully remove them. The peaks are then summed after interpolating to $1/10^{\text{th}}$ of a time step, and the peak value of the summed curve normalised to 1. This produces the raw response curve over an interval before and after the peak.

In total then the model can be fully defined by five parameters (see Figure 3) :

- c defines catchment water yield;
- τ is the streamflow recession time constant;
- τ_w is the rate of catchment drying;
- f varies the rate of catchment drying based on temperature;
- s_0 is the catchment wetness index, s_k below which no runoff will occur.

The model can be simplified further by assuming that the rate of catchment drying, f is not dependent on temperature (this is reasonable in the tropics where humidity and wind speed are far more important climatic variables than temperature in determining evapotranspiration). As a result, f can be set to zero. Also, having applied the model to the sub-catchments of the Burdekin, it was found that the result was relatively insensitive to the values of s_0 and τ_w . As a result, further simplification was achieved by using the average value of 0.09 for s_0 , and 11 days for τ_w . This then leaves us with just two parameters to predict for each catchment, c and τ .

3. PREDICTING THE VALUE OF c AND τ

3.1 Predicting water yield (c)

The IHACRES model uses the parameter c in order to balance the total water yield of the catchment. During the calibration of the model then, c is chosen such that the total volume of effective rainfall is equal to the total volume of observed streamflow. In order to be able to apply IHACRES to an ungauged catchment, we must find a way of predicting this total volume of observed streamflow. The easiest way to do this is to predict the percent yield of the catchment (defined as that percentage of rainfall that eventually becomes streamflow). Comparing the observed percent yield of the 25 gauged catchments to the physio-climatic variables, we discovered a strong relationship between percent yield and the volume of precipitation that falls in the summer months (December to February). This relationship occurs because most of the runoff occurs during these months. Heavy rainfalls in winter do not produce runoff – they do however produce scatter in the relationship between mean annual precipitation and percent yield. For this

reason, summer precipitation is a better attribute to use than mean annual precipitation. Different relationships were found to operate in the three major regions of the Burdekin (see Figure 1). Figure 4 shows these three relationships. The equations defining the regressions shown in Figure 4 are as follows :

$$\begin{aligned} \text{Upper Burdekin : } & y = 0.06x + 5.35 \quad r^2=0.88 \\ \text{Belyando Suttor : } & y = 0.12x - 8.21 \quad r^2=0.72 \\ \text{Bowen : } & y = 1.05 e^{0.01x} \quad r^2=0.85 \end{aligned}$$

Where y is the percent yield of the catchment and x is the summer precipitation.

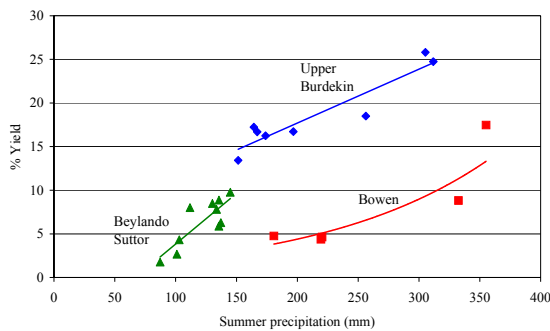


Figure 4. Predicting percent yield from summer precipitation

The different relationships for the three regions are very interesting. The linear relationships defining the upper Burdekin and Belyando Suttor are similar, and these two regions could potentially be combined using a non-linear relationship. However, the relationship for the Bowen region is very different indeed. A summer precipitation of 250 mm for example would produce around 50 mm of runoff in the upper Burdekin region (20%), but only around 15 mm in the Bowen region (6%). The reason for this difference is unknown but implies that rates of evapotranspiration (ET) are higher in the Bowen than in the upper Burdekin. This may be related to a different temporal distribution of rainfall, or differences in vegetation or catchment soil storages. The reason for this difference will be the subject of future work.

3.2 Predicting streamflow recession time constant (τ)

Again, in order to apply IHACRES to ungauged catchments, we must derive a procedure to determine the value of τ from physio-climatic attributes. The value of τ derived for the 25 gauged catchments was thus compared to the physio-climatic attributes of those catchments. A

relationship was discovered between the streamflow recession time constant, τ and the total length of stream reaches (*length*) within the catchment. This relationship is shown in Figure 5.

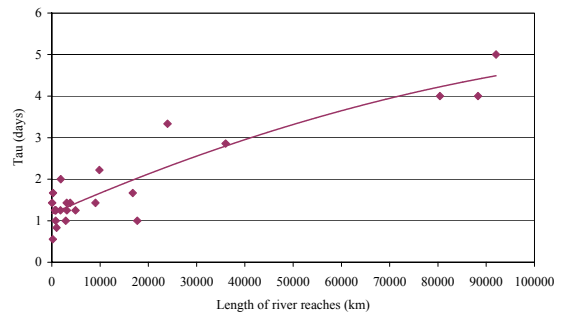


Figure 5. Predicting the streamflow recession time constant from length of river reaches

This relationship was further improved by adding the variables percent of the catchment under cropping (*crop*), and percent of the catchment under forest (*forest*) into the relationship as follows :

$$\tau = 3.46 \times 10^{-5} \text{length} + 0.696 \text{crop} + 0.020 \text{forest} - 0.416 \quad r^2=0.91$$

In this relationship, *length* accounts for 62% of the variance in τ , *crop* accounts for 21%, and *forest* 17%. The positive coefficients indicate that the greater the length of stream reaches, amount of cropping, and amount of forest, the longer is the streamflow time constant (it takes longer for a rainfall input to reach the outlet of the catchment).

4. RESULTS

As we have decided to adopt catchment average values of $f = 0$, $s_0 = 0.09$, and $\tau_w = 11$, and have derived a procedure above for predicting c from summer precipitation and τ from length of stream reaches, percent cropping, and percent forest, we can now derive an IHACRES rainfall-runoff model for any point in the catchment.

As we have 25 gauged points in the catchment, we can compare our predictions of streamflow with observed streamflow at these points in order to assess the accuracy of this regionalisation technique. Table 1 shows the accuracy of the predicted values of percent yield and τ across the 25 gauged catchments. In general, the predicted values of percent yield are within 20% of the observations. The exceptions are mostly for catchments with very low values of percent yield, which are difficult to predict accurately. Given the very low percent yields for these catchments

however (ranging from 1.8% to 25.8%), these predictions are quite good. The case for τ is similar, with the predicted values being within 0.7 days of the observations.

Catchment	Obs. % yield	Pred. % yield	Obs. τ	Pred. τ
120002	17.23	15.49	2.86	2.39
120006	8.87	7.94	5.00	4.69
120008	7.81	7.70	4.00	4.41
120014	6.28	8.12	0.56	0.53
120015	8.49	7.29	4.00	4.18
120102	25.81	24.19	1.67	1.47
120106	13.43	14.69	1.25	1.36
120107	16.24	16.08	1.43	1.71
120110	16.70	15.66	1.67	1.95
120112	18.50	21.17	1.25	1.23
120120	24.74	24.59	1.25	1.32
120121	16.73	17.49	2.00	1.58
120205	4.75	3.80	1.25	1.15
120207	8.81	11.17	1.25	1.49
120209	4.38	5.00	1.25	1.35
120216	17.47	13.12	1.43	1.52
120299	4.64	5.04	1.43	1.35
120301	2.67	3.83	1.00	1.49
120302	5.89	7.93	2.22	1.45
120303	4.33	4.05	3.33	2.67
120304	8.01	5.10	0.83	0.77
120305	1.76	2.18	1.00	1.00
120307	9.77	9.05	1.00	1.31
120309	3.64	4.33	1.43	1.98
120002	17.23	15.49	2.86	2.39

Table 1. Observed versus predicted values

These predictions of τ and percent yield are now being used in conjunction with the IHACRES model to predict daily streamflow for the 25 gauged catchments in the Burdekin. These results will be reported in a subsequent paper. As an example however, Figure 6 shows the observed and predicted streamflow for catchment 120002 (an intermediate sized catchment draining the upper Burdekin). The prediction of streamflow for this catchment is very good, with an r^2 of 0.71.

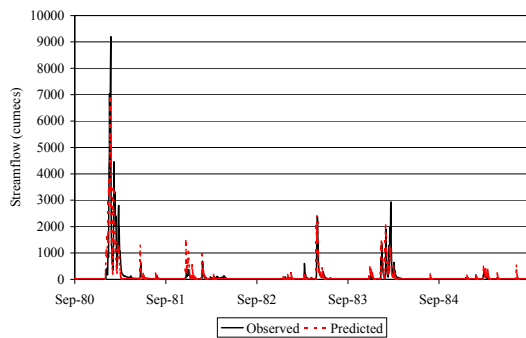


Figure 6. Observed and predicted streamflow for gauging station 120002, 1980-85

Figure 7 shows the observed and modelled data for catchment 120002 again, this time showing the data in the form of a scatter diagram. This Figure shows that in general we are under-estimating the peakflows, with the largest four streamflow peaks being under-estimated. At smaller streamflow values however, there is an even distribution of model under- and over-estimates.

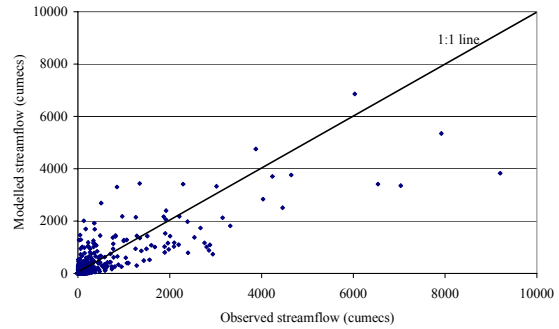


Figure 7. Scatter plot of observed and predicted streamflow

5. CONCLUSIONS

This paper has presented a methodology which allows us to predict the daily streamflow at any point within the Burdekin catchment in the dry tropics of North Queensland, Australia. The data requirements to make this prediction are daily precipitation for the catchment of interest (to drive the rainfall-runoff model), total length of stream reaches in the catchment, summer precipitation, percent cropland and percent forest within the catchment. These latter four variables are available as GIS overlays, while daily precipitation can be derived from the 411 Bureau of Meteorology rainfall stations which are currently operating in the Burdekin catchment.

However, it has been shown that relationships for predicting percent yield varies within the scale of the Burdekin catchment, with three separate relationships needing to be derived – one for the Upper Burdekin, one for the Belyando Sutor, and one for the Bowen region. Conversely, just one relationship was needed to predict the streamflow recession time constant but it required the inclusion of three predictive variables – length of stream reaches, percent cropping, and percent forest.

We believe that this variability indicates the dangers inherent in scaling or regionalising into data-poor areas. Only by understanding the

dominant processes active in a region can we regionalise relationships, either from other scales or other regions.

6. ACKNOWLEDGMENTS

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7. REFERENCES

- Chapman, T. G. 1996. Unitgraph identification from streamflow data. *Hydrol. Proc.* **10** : 773-782.
- Croke, B. F. W. 1992. CNO Abundances of globular cluster giants. *PhD Thesis*, University of New South Wales.
- Post, D. A. and Jakeman, A. J. 1996. Relationships between physical descriptors and hydrologic response characteristics in small Australian mountain ash catchments. *Hydrol. Proc.* **10** : 877-892.
- Post, D. A. and Jakeman, A. J. 1999. Predicting the daily streamflow of ungauged catchments in S. E. Australia by regionalising the parameters of a lumped conceptual rainfall-runoff model. *Ecol. Mod.* **123** : 91-104.
- Post, D. A., Jones, J. A. and Grant, G. E. 1998. An improved methodology for predicting the daily hydrologic response of ungauged catchments. *Env. Mod. Soft.* **13** : 395-403.