

Regionalizing rainfall–runoff model parameters to predict the daily streamflow of ungauged catchments in the dry tropics

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ABSTRACT

A methodology has been derived which allows an estimate to be made of the daily streamflow at any point within the Burdekin catchment in the dry tropics of Australia. The input data requirements are daily rainfall (to drive the rainfall–runoff model) and mean average wet season rainfall, total length of streams, percent cropping and percent forest in the catchment (to regionalize the parameters of the rainfall–runoff model). The method is based on the use of a simple, lumped parameter rainfall–runoff model, IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data). Of the five parameters in the model, three have been set to constants to reflect regional conditions while the other two have been related to physio-climatic attributes of the catchment under consideration. The parameter defining total catchment water yield (c) has been estimated based on the mean average wet season rainfall, while the streamflow recession time constant (τ) has been estimated based on the total length of streams, percent cropping and percent forest in the catchment. These relationships have been shown to be applicable over a range of scales from 68–130,146 km². However, three separate relationships were required to define c in the three major physiographic regions of the Burdekin: the upper Burdekin, Bowen and Suttor/lower Burdekin. The invariance of the relationships with scale indicates that the dominant processes may be similar across a range of scales. The fact that different relationships were required for each of the three major regions indicates the geographic limitations of this regionalization approach. For most of the 24 gauged catchments within the Burdekin the regionalized rainfall–runoff models were nearly as good as or better than the rainfall–runoff models calibrated to the observed streamflow. In addition, models often performed better over the simulation period than the calibration period. This indicates that future improvements in regionalization should focus on improving the quality of input data and rainfall–runoff model conceptualization rather than on the regionalization procedure per se.

Key words | dry tropics, prediction in ungauged basins (PUB), regionalization, top-down modelling

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INTRODUCTION

Previous regionalization studies

Predicting the hydrologic response of ungauged catchments is currently one of the key problems in hydrology. It is the focus of a major research initiative of the International Association of Hydrological Sciences known as Prediction

in Ungauged Basins (PUB, Sivapalan *et al.* 2003). There are many reasons why we need to know the hydrologic response of a river at an ungauged point, ranging from civil engineering requirements such as the siting of dams and bridges, to flood forecasts to stream ecology studies.

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These practical applications are the reason that many regionalization studies deal with flood frequency analysis (Patton & Baker 1976; Reimers 1990) or low flow analysis (Chang & Boyer 1977; Gustard *et al.* 1992; Nathan & McMahon 1992).

Typically, the required aspect of hydrologic response has been predicted directly from landscape attributes (e.g. flood frequencies, NERC 1975 or low flows, Pilgrim 1987). However, a number of studies have related landscape attributes to the hydrologic response of a catchment as defined by a rainfall–runoff model. Most of these studies have met with limited success either because the model used did not adequately represent the hydrologic response of the catchment (e.g. Rosso 1984) or because the model was over-parameterized. Examples include the 18 parameter Sacramento model (Weeks & Ashkanasy 1985), the 20 parameter HBV3-ETH model (Braun & Renner 1992) and the 19 parameter MODHYDROLOG model (Chiew & McMahon 1994).

In general, models with a more parsimonious approach have met with greater success in regionalization studies (e.g. Hundecha & Bárdossy 2004). This could be due to highly parameterized models (such as those mentioned above) being more complex than is warranted based on the rather meagre input data available in ungauged and indeed most gauged catchments. This trade-off between input data availability and model complexity is discussed by Grayson & Bloschl (2000). An example of a more parsimonious approach is provided by Post & Jakeman (1996) who noted that the parameters of the IHACRES rainfall–runoff model could be related to the landscape attributes of a catchment, such as catchment slope, drainage density and area. In Post & Jakeman (1999) the authors made use of these relationships to make predictions of the daily hydrologic response of 16 small (< 1 km²) catchments in south-eastern Australia. Predictions for some of these catchments were very good; however, others were quite poor when evaluated with the Nash–Sutcliffe coefficient of determination. 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.

The current study 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 by Croke (2006). This new method allows predictions to be made of this time constant of streamflow recession in a much quicker and more accurate way than can be obtained using the IHACRES calibration techniques described in Post & Jakeman (1999).

Secondly, we are applying the regionalization technique to a dry-tropical rangeland environment—the Burdekin catchment in North Queensland (see following section). Previously, the technique had only been applied in humid catchments (Post & Jakeman 1996, 1999).

Finally, we have simplified the regionalization technique by holding constant a number of the IHACRES parameters. This has made it much easier to regionalize hydrologic response since regional relationships only need to be derived for two of the model parameters.

THE BURDEKIN CATCHMENT

The Burdekin catchment with an area of 129,660 km² (Figure 1) falls within the Koppen climatic regime characterized by BSh, where BS indicates that it is semi-arid and h indicates that the coldest month averages above 0°C. It is characterized by a dry, semi-arid climate with hot temperatures (chiefly found within the tropics). This climatic regime typically occurs at slightly lower latitudes than the tropics of Capricorn and Cancer. It is found in large parts of northern Australia, as well as northern and southern Africa, India and the Middle East and small parts of Central America.

Despite this climatic regime being relatively extensive, comparatively little hydrologic research has been carried out in it. There are two main reasons for this: firstly, this climatic regime is typically found in developing countries (Australia being the major exception) and secondly, this environment has a lower population density and is not especially conducive to agriculture. In this the Burdekin catchment is similar, being characterized by low density cattle grazing.

The Burdekin catchment is similar to other catchments in BSh climates in terms of its hydrologic response. It is characterized by extremely large variability in its annual discharge (minimum of 0.4 km³, mean of 9.3 km³, maximum of 53 km³; a range of two orders of magnitude). Having a

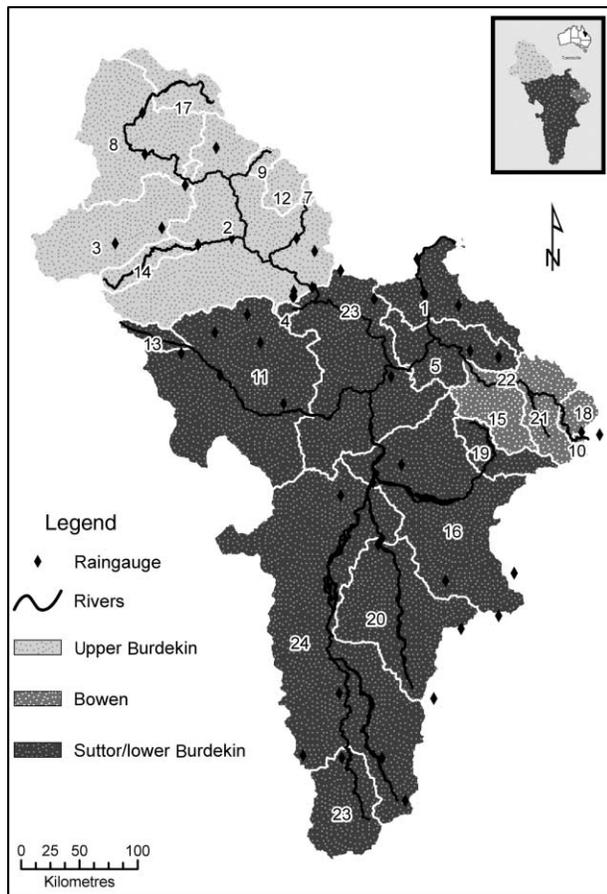


Figure 1 | Location of the Burdekin catchment and its 24 gauged catchments in three physiographic regions. The outlet of the catchment is to the northeast, through catchment #1.

distinct dry season means that the mean monthly discharge also varies dramatically, from an average of 0.03 km^3 in August to 3.1 km^3 in February, again a range of two orders of magnitude. Daily flows vary over an even greater range, with zero flow typically occurring for 18 days/year (before the dam was built in 1987) to a maximum daily flow of 32,500 cumecs and an instantaneous flow of 40,400 cumecs (on 4 April 1958). This maximum instantaneous flow from a catchment area of $129,660 \text{ km}^2$ falls within the envelope of maximum flood size encountered in other catchments throughout the world (Herschy 2002).

The Burdekin catchment can be divided into three relatively distinct physiographic regions (see Figure 1). The Suttor and lower Burdekin are generally flat with catchments in this region having an average slope of 1.05 degrees. The upper Burdekin has somewhat higher relief,

catchments in this region having an average slope of 2.56° . Finally, the Bowen has considerably more relief, with catchments in this region having an average slope of 4.49° .

METHODS

Data collection and analysis

The IHACRES model (see following section) requires as inputs daily rainfall data (to drive the model) and daily streamflow data (to calibrate). Temperature data are also typically required, but as we decided not to vary the rate of evapotranspiration (ET) based on temperature (see following section), these data were not required.

Daily streamflow data were obtained for the 24 catchments of the Burdekin shown in Figure 1 on a 0900–0900 daily time-step (to match the rainfall) from Queensland Department of Natural Resources and Water (NR&W). Rainfall data were obtained from the Bureau of Meteorology for the 45 point-patched (no missing data) rain gauges shown on Figure 1. Rainfall for each catchment was calculated using Thiessen polygons to define the contribution of each rain gauge shown in Figure 1 to each of the 24 catchments. In addition, 34 physio-climatic attributes were derived describing catchment morphology (area, elevation, slope, drainage density, etc.), landuse (percent pasture, cropland, forest, etc.) and climate (rainfall, temperature, radiation, etc.).

The hydrologic response of these 24 catchments was examined (and rainfall-runoff models calibrated) over the period 1980–1985. This time period was chosen for two reasons: firstly, to avoid the influence of the Burdekin Falls Dam which was constructed in 1986 and secondly, 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. The period 1975–1980 was a wetter period (see Figure 2) and was therefore chosen as the simulation period of the model, in order to test it in a different climatic regime to that over which it was calibrated.

The IHACRES model

The structure of the IHACRES model is driven by the available data and therefore may be considered to be a

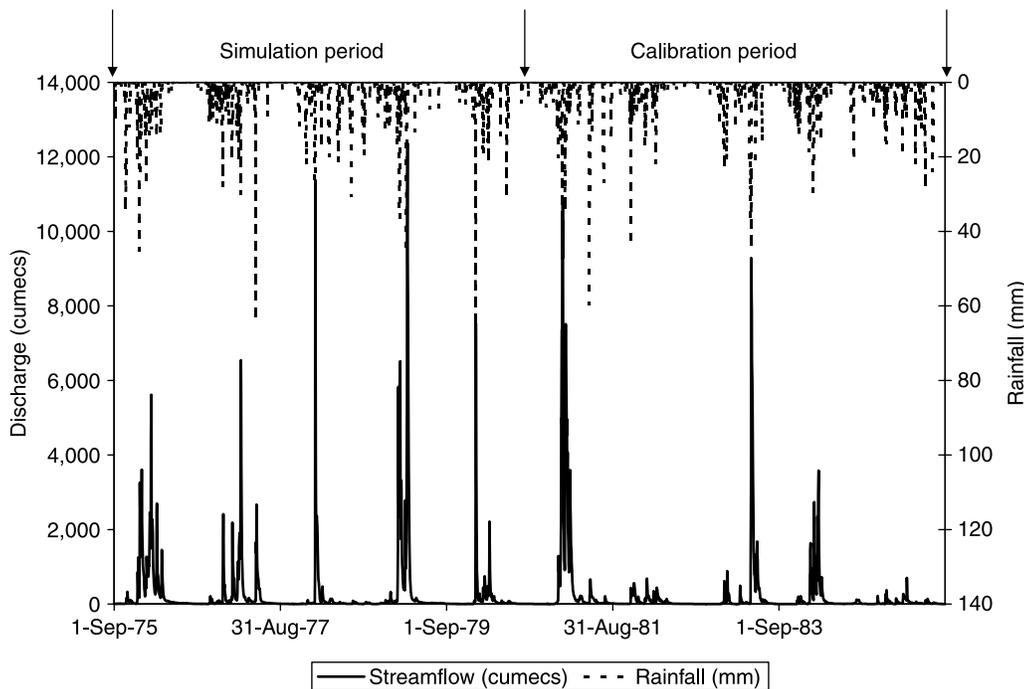


Figure 2 | Daily observed rainfall and discharge from the Burdekin catchment 1975–1985.

top-down model as defined by Post *et al.* (2005). The model consists of two modules, a nonlinear loss module to convert rainfall to effective rainfall and a linear module to route the effective rainfall to streamflow (Figure 3). Rainfall acts to fill the soil moisture store (s_k) in the nonlinear module by an amount equal to r_k/c . This nonlinear store is then reduced by evapotranspiration and drainage on each time-step by the function $1/\tau_w(f)$. The effective rainfall, calculated as $r_k \times s_k$, is then routed through the linear store(s) shown on

the right-hand side of Figure 3. A full description of the model can be found in Jakeman *et al.* (1990).

The model has been included in a number of model comparison studies (Chiew *et al.* 1993; Ye *et al.* 1997) which have shown that the model, while having only a few parameters, is generally able to represent the hydrologic response of a number of catchments as well as more highly parameterized models. Studies examining the use of the model to regionalize hydrologic response from landscape

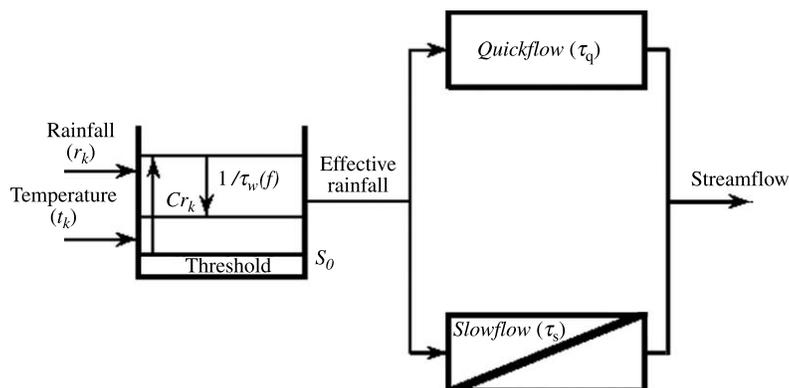


Figure 3 | The IHACRES model; note that in these catchments there is no slowflow component.

attributes (Post & Jakeman 1996, 1999; Kokkonen *et al.* 2003; Croke *et al.* 2004) have shown that the model parameters are generally related to landscape attributes.

Model calibration and simulation

As shown in Figure 3, the model structure described in Post & Jakeman (1999) was simplified through removal of one of the linear routing stores. In the version of the model used here, streamflow recession is therefore considered to consist of a single exponential decay (rather than two exponential decays in parallel). This simplification is justified based on the streamflow response seen in the dry tropics (see, for example, Figure 2) where it can be seen that the slowflow component of streamflow is virtually absent from the observed response. τ_q and τ_s in Figure 3 have therefore been replaced by a single decay constant, τ .

An additional parameter, the soil moisture threshold (s_0), was added to the nonlinear loss module to account for the fact that during dry times of the year, a large rainfall event will produce no streamflow response.

The model used in dry tropical environments with no slowflow can then be fully defined by five parameters (see Figure 3):

- c is a mass balance parameter and therefore 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; and
- s_0 is the catchment wetness index below which no runoff will occur.

Application of the IHACRES model to a number of the Burdekin catchments showed that the values of s_0 and τ_w did not vary greatly (not shown here). To aid in the regionalization process, the values of these parameters were therefore set to 0.09 and 11, respectively. This means that when the soil moisture coefficient drops below 0.09 (on a scale of 0 to 1) no runoff is produced and the time for the soil moisture coefficient to drop to $1/e$ of its peak value is 11 days. In addition, in the dry tropics where water availability, relative humidity and wind speed are of greater importance in determining the rate of evapotranspiration

than temperature, the value of f was set to zero. This means that the rate of drying in these catchments is the same all year round.

This then leaves us with just two parameters to be calibrated for each catchment: τ and c . The value of the streamflow recession time constant τ was derived directly from the streamflow data using a technique developed by Croke (2006), while the value of c was derived by ensuring that the volume of modelled streamflow equalled the volume of observed streamflow for each catchment over the calibration period 1980–1985. This was done for all 24 catchments in turn.

Model simulation runs were then carried out over the period 1975–1980. That is, the values of the model parameters τ and c derived over the period 1980–1985 were applied to the period 1975–1980 and the resultant streamflow compared with the observed streamflow for that period.

Results of model calibrations and simulations

In order to evaluate model performance, the Nash–Sutcliffe efficiency E was calculated on the daily streamflow (Nash & Sutcliffe 1970). This is defined as:

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

where y_k is the observed streamflow, x_k is the modelled streamflow and \hat{y} is the mean of the observed streamflow. This measure of model efficiency is preferable to the simple square of the correlation coefficient (r^2) as it measures the difference between observation and prediction rather than the (possibly scaled) relationship between the two. Thus an r^2 of 1.0 can be achieved even if all of the predictions are (say) half the magnitude of the observations. Model efficiency E therefore offers greater power to discriminate good from poor models.

The range of calibrated parameter values τ and c are listed in Table 1, where catchment # 1 has the best calibration E followed by catchment # 2, down to catchment #24 which has the worst calibration E . The calibration E , along with the corresponding simulation E for the period 1975–1980, is shown in Figure 4.

Table 1 | List of stream gauging stations in the Burdekin catchment with calibration model parameter values, ordered from best to worst in terms of the model calibration E over the period 1980–1985

Catchment #	Area (km ²)	Percent yield (%)	Description	τ (days)	c (mm)
1	130,146	8.8	Burdekin River @ Clare	5.00	450
2	36,145	17.2	Burdekin River @ Sellheim	2.86	329
3	17,217	16.7	Burdekin River @ Mount Fullstop	1.67	368
4	194	6.3	Broughton River @ Oak Meadows	0.56	841
5	125,746	7.8	Burdekin River @ Dalbeg	4.00	490
6	114,521	8.5	Burdekin River @ Hydro Site*	4.00	472
7	175	25.8	Keelbottom Creek @ Keelbottom	1.67	584
8	10,507	16.2	Burdekin River @ Blue Range	1.43	375
9	466	24.7	Running River @ Mt Bradley	1.25	469
10	68	17.5	Broken River @ Old Racecourse	1.43	677
11	15,912	5.9	Cape River @ Inland Highway	2.22	782
12	1,216	18.5	Star River @ Larooona	1.25	595
13	826	9.8	Cape River @ Pentland	1.00	600
14	1,384	13.4	Basalt River @ Bluff Downs	1.25	482
15	7,045	4.8	Bowen River @ Myuna	1.25	853
16	50,411	4.3	Suttor River @ St Anns	3.33	643
17	2,314	16.7	Burdekin River @ Lake Lucy Dam Site**	2.00	475
18	1,033	8.8	Broken River @ Urannah	1.25	1183
19	1,947	8.0	Suttor River @ Eaglefield	0.83	784
20	8,025	3.6	Mistake Creek @ Twin Hills	1.43	866
21	4,126	4.6	Bowen River @ Pump Station	1.43	1080
22	4,180	4.4	Bowen River @ Jacks Ck	1.25	1114
23	4,145	1.8	Native Companion Creek @ Violet Grove	1.00	1034
24	35,536	2.7	Belyando River @ Gregory Dev Rd***	1.00	830

*Flow data only available 23/12/77 +

** Rainfall data only available 1/1/77+

*** Flow data only available 9/8/76 +

The IHACRES model represents the hydrologic response of 12 of the catchments reasonably well ($E > 0.5$). For example, see the model calibrated on catchment # 12 over the 1975 water year in Figure 5. For the poorer models, the model generally produces flow at the correct times but the shape of the modelled streamflow does not match the observed streamflow (see catchment #16 in Figure 6, for example). This is due to errors in calibrating the value of τ over the calibration period and could well be due to inadequate rainfall data. For the poorest models, the model both produces flow at the wrong times and the shape of the model hydrograph does not resemble the observed hydrograph (see the poorest fit, catchment #24 in Figure 7, for example).

For 11 of the 12 ‘good’ catchment models, the simulation fit (1975–1980) is almost as good as, or slightly better than, the calibration fit (1980–1985) (see Figure 4). This indicates that the model is performing well over an independent period, but also that the observed rainfall and streamflow time series for these catchments are at least of adequate quality during both the calibration and simulation period.

For the 12 ‘poor’ catchment models, the quality of the simulation fit is similar to the quality of the calibration fit in 4 cases. For another 6 catchments, the simulation model fit is actually significantly better than the calibration model fit (see Figure 4), while the simulation fit is significantly worse than the calibration model fit for only 2 catchment models.

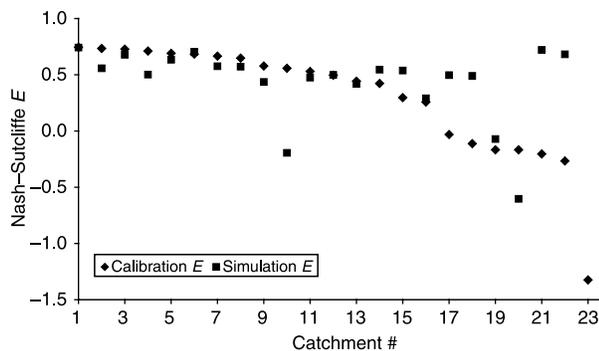


Figure 4 | Calibration and simulation E for the 24 Burdekin catchments; note simulation E for catchment #23 is off the graph at -5.0 .

These results indicate that one possible cause of the poor model calibrations for these 12 catchments is the inadequacy of the rainfall and/or streamflow time series during the model calibration period. In addition, 21 of the 24 catchments are wetter during the simulation period than the calibration period, so it might be expected that the simulation E would be higher than the calibration E . This is not the whole story, however, as three of the catchments with higher simulation E have lower rainfall during the simulation period.

Regionalizing catchment water yield

The IHACRES model uses the parameter c in order to balance the total water yield of the catchment. During the calibration of the model described in *Model calibration and simulation*, c was chosen such that the total volume of effective rainfall equalled the total volume of observed

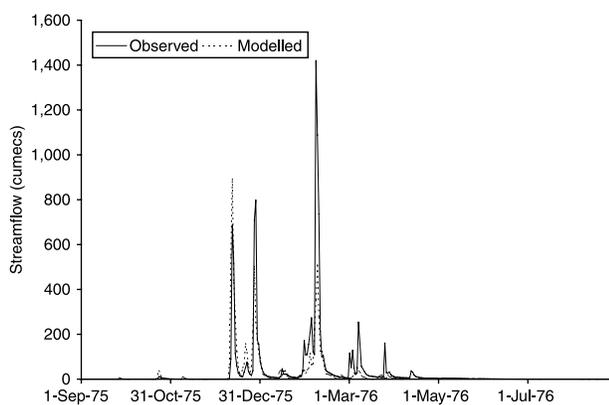


Figure 5 | Observed and modelled streamflow for the poorest of the 'good' 12 models, catchment #12 over part of the model simulation period.

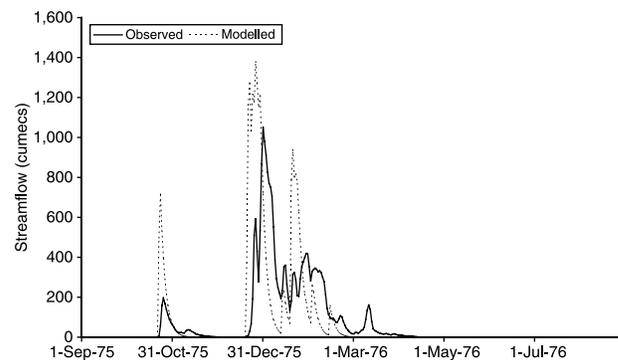


Figure 6 | Observed and modelled streamflow for one of the 'poor' models, catchment #16 over part of the model simulation period.

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 the percentage of rainfall which eventually becomes streamflow). The percent yield of a catchment is an important characteristic and one that has received significant attention in the literature. The Budyko curve shows that the percent yield of a catchment can be related to the ratio of potential evapotranspiration to precipitation, as discussed in *Wagener et al. (2007)*. Such is the importance of this characteristic that some authors (*Yadav et al. 2007*, for example) have suggested that it is more robust to predict it and other characteristics of catchment response, rather than model parameters from catchment attributes.

Comparing the observed percent yield of the 24 gauged catchments to the physio-climatic variables, we discovered a strong relationship between percent yield and the volume

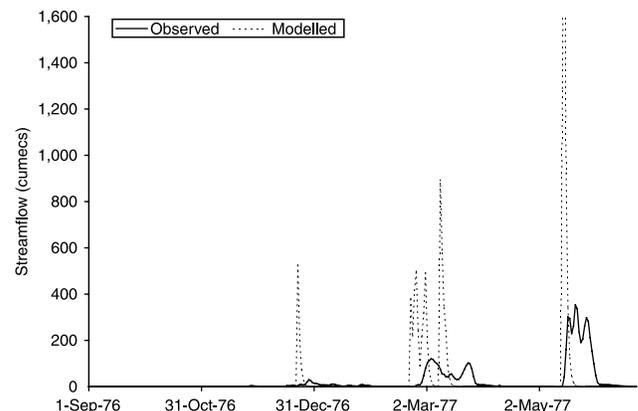


Figure 7 | Observed and modelled streamflow for the poorest model, catchment #24 over part of the model simulation period.

of rainfall that falls during the wet season (December to February). This relationship occurs because most of the runoff occurs during these months and therefore percent yield is dominated by rainfall falling at this time. Because of the very dry conditions and consequent low soil moisture, the small amount of rainfall that does fall in winter does not produce significant amounts of runoff; making use of data on rainfall that occurs during this time of the year does not improve our predictions of percent yield. For this reason, wet season rainfall is a better attribute to use than mean annual rainfall. Different relationships were found to operate in the three major physiographic regions of the Burdekin (see Figure 1). Figure 8 shows these three relationships. The equations defining the regressions shown in Figure 8 are as follows:

$$\text{Upper Burdekin : } y = 0.06x + 5.35 \quad r^2 = 0.088$$

$$\text{Suttor/lower Burdekin : } y = 0.12x - 8.21 \quad r^2 = 0.72$$

$$\text{Bowen : } y = 1.05e^{0.001x} \quad r^2 = 0.85$$

where y is the percent yield of the catchment and x is the long-term mean wet season rainfall.

It is interesting that three different relationships were found for the three main physiographic regions of the Burdekin. Upon inspection of Figure 8, the linear relationships defining the upper Burdekin and Suttor/lower Burdekin are similar, and these two regions could potentially be combined using one nonlinear relationship. However, the relationship for the Bowen region is very different from the other two. A long-term average summer

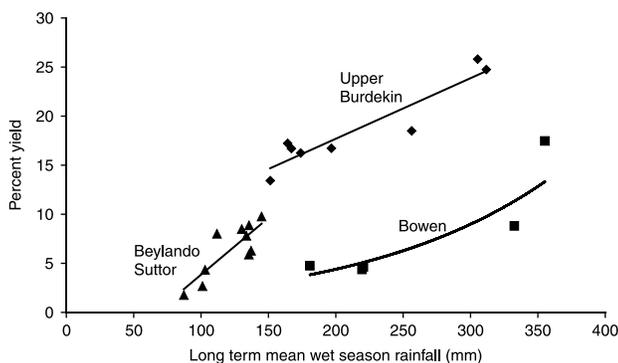


Figure 8 | Predicting percent yield from wet season rainfall.

rainfall of 250 mm, for example, would be expected to produce around 50 mm of runoff in the upper Burdekin region (20% yield) but only around 15 mm in the Bowen region (6% yield). This implies that rates of ET are higher in the Bowen than elsewhere in the Burdekin catchment (assuming no losses due to groundwater). This may be related to a different temporal distribution of rainfall, differences in vegetation or catchment soil storages.

Regionalizing streamflow recession time constant

The second parameter which must be regionalized before we can predict the daily streamflow of ungauged catchments is τ , the streamflow recession time constant. To do this, the value of τ derived for the 24 gauged catchments was compared to the physio-climatic attributes of those catchments. A relationship was discovered between τ and the total length of streams within the catchment. This relationship is shown in Figure 9. This relationship occurs because the major factor controlling travel time is the total length of streams that the water must pass along to reach the catchment outlet. In these relatively large catchments, this is more important than the time taken for rain to pass from where it falls into a stream via overland or subsurface flow.

Our regionalized predictions of τ were improved by including the percent of the catchment under cropping and percent of the catchment under forest into the relationship. These relationships indicate that the greater the percent of either cropping or forest in the catchment, the longer the travel time of water to the catchment outlet. For cropping, this could well indicate the impact of irrigated agriculture

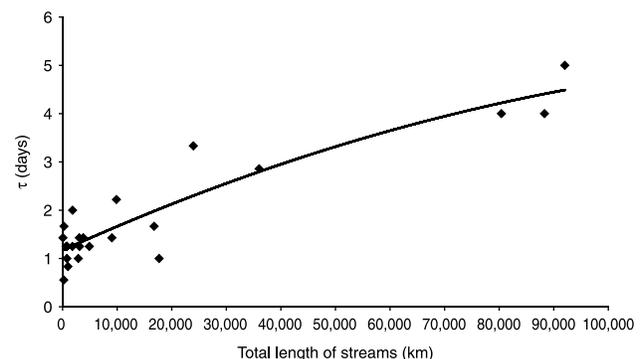


Figure 9 | Predicting the streamflow recession time constant τ from total length of streams (km).

on travel time, where water diverted for irrigation will take longer to reach the catchment outlet (irrigated cotton is grown in the Burdekin catchment). A similar explanation for the impact of forests on travel time is more problematic; however, the impact of forests is much less than agriculture as can be seen by the relative magnitude of the coefficients in the equation below.

$$\tau = 3.46 \times 10^{-5} l + 0.696 c_r + 0.020 f_o - 0.416; \quad r^2 = 0.91$$

where τ is the streamflow recession time constant, l is the total length of streams and c_r and f_o are the percentage of catchment under cropping and forest, respectively. In this relationship, l accounts for 62% of the variance in τ , c accounts for 21% and f 17%.

RESULTS OF HYDROLOGIC REGIONALIZATION

Comparison of observed and predicted values of water yield

Figure 10 shows the accuracy of the regionalized values of mean annual streamflow across the 24 gauged catchments. In general, the predicted values of mean annual streamflow are within 20% of the observations. The poorest prediction is for catchment # 10 with an observed streamflow of 310 mm and regionalized streamflow of 240 mm. This catchment is the smallest in area by quite some amount at 68 km² (the next smallest is 175 km²), indicating that this technique may break down at very small catchment areas. This may be related to the regionalization procedure being

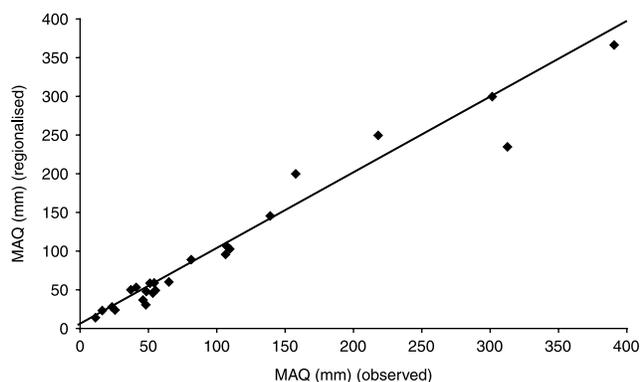


Figure 10 | Observed and regionalized values of mean annual streamflow for each of the 24 gauged catchments for the calibration period (1:1 line shown for comparison).

inappropriate at small catchment areas. Alternatively, rainfall measurements are likely to be poorer for small catchments, being based on just one raingauge. In the case of catchment #10, the raingauge is not actually located within the catchment. In general, for larger catchments, the predictions of mean annual streamflow are good.

Comparison of observed and predicted values of streamflow recession

Figure 11 shows the accuracy of the regionalized values of the streamflow recession time constant τ across the 24 gauged catchments. All of the predicted values of τ are within 0.7 days of the observations.

Comparison of observed, calibrated and regionalized daily streamflow

A model was derived for each of the 24 catchments using the regionalized values of c and τ along with the Burdekin catchment average values of s_0 (0.09) and τ_w (11 days). The daily E of these regionalized models was then compared to that for the calibrated (1980–1985) and simulated (1975–1980) models. This comparison is shown in Figure 12 which contains the same data as Figure 4 but with E for the regionalized models added.

For 11 of the 12 ‘good’ catchment models, the regionalized model performs nearly as well as or better than the calibrated model over both the calibration and simulation periods. In addition, the shape of the regionalized models is very similar to the calibrated models seen in

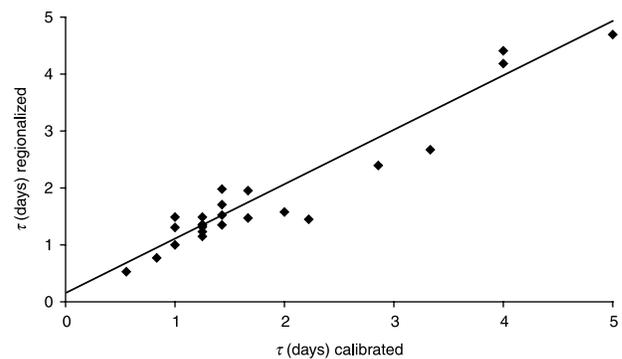


Figure 11 | Calibrated and regionalized values of the streamflow recession time constant τ for each of the 24 gauged catchments (1:1 line shown for comparison).

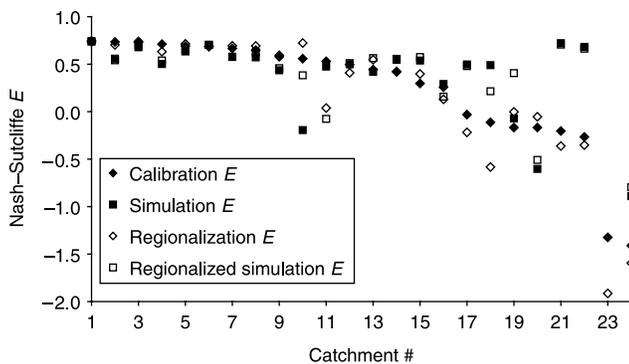


Figure 12 | Nash–Sutcliffe E values obtained for all 24 catchments for calibration and simulation runs (filled symbols) and model runs with regionalized parameter values (open symbols). Note regionalized simulation E for catchment #23 is off the graph at -6.4 .

Figures 5–7. The exception is catchment #11 where the regionalized model performs significantly poorer than the calibrated model. Conversely, for catchment #10, the regionalized model performs significantly better than the calibrated model over both the calibration and simulation period. This indicates that it was probably the model and not the data for catchment #10 which was inadequate.

For the 12 ‘poor’ catchment models, the regionalized model performed about as well as the calibrated model in 7 of the catchments, somewhat poorer in 3 of the catchments and somewhat better in 2 of the catchments (see Figure 12). Similar results for regionalized models compared to calibrated models were found by Merz & Bloschl (2004).

These results indicate that either the input data are of poor quality or the regionally constant values of s_0 and τ_w are inadequate, producing poor fits to some catchments. The regionalization procedure has not, in most cases, produced significantly poorer models than was produced by calibrating the models to the observed rainfall and streamflow time series.

Six of the simulation model fits were significantly better than the calibration model fits. It therefore appears that for these catchments (at least) it was the quality of the input rainfall data during the calibration period which caused problems, and not the quality of the rainfall–runoff model parameters s_0 and τ_w .

This would indicate that to produce real improvements in prediction in ungauged basins, more effort needs to be put into the calibration of models and the collection of

better quality rainfall data. Even simple regionalization procedures such as those employed here have allowed the regionalization of rainfall–runoff model parameters to ungauged catchments.

CONCLUSIONS

The model derived in this study provides a way to predict daily streamflow from daily rainfall at any point within the Burdekin catchment, knowing only the mean average wet season rainfall, stream length and percent cropping/percent forest in the catchment. These data are publicly available from Queensland Department of Natural Resources and Water (<http://www.nrw.qld.gov.au/>). This was carried out by holding three of the five IHACRES model parameters constant (the rate of catchment drying τ_w , the impact of temperature on catchment drying f and the threshold soil moisture s_0), and relating the mass balance parameter c to wet season rainfall and the streamflow recession time constant τ to stream length and percent cropping/percent forest.

The model may be applicable to other streams in the dry tropics of Australia and elsewhere in the world if the required input data are available. However, the relationship for predicting percent water yield from mean annual wet season rainfall required three separate equations—one each for the Upper Burdekin, Suttor/lower Burdekin, and Bowen regions. Conversely, just one relationship was needed to predict the streamflow recession time constant, but it required the inclusion of three predictive variables (stream length, percent cropping and percent forest).

Additionally, use of the model in more humid catchments, particularly those with a significant slowflow component, would most likely produce poor results as the processes operating in these catchments are likely to be quite different from those in the dry tropics.

These caveats on model applicability to other areas indicate the problems inherent in scaling or regionalizing into data-poor areas. Only by understanding the dominant processes active in a region can we regionalize relationships, either from other scales or other regions. Despite these caveats, however, the fact that the model regionalization produced as good a result as the model calibration

indicates that improvements in the prediction of hydrologic response in ungauged basins requires more work to be done on model calibration as opposed to model regionalization. In addition, since the main impediment to producing a good model fit in many catchments appears to be poor quality rainfall data, improvements in model calibration may be more likely to come from improvements in the quality of the rainfall input data, rather than improvements in model structure.

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