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# The Brigalow Catchment Study: IV.* Clearing brigalow (*Acacia harpophylla*) for cropping or grazing increases peak runoff rate

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**Abstract.** In Queensland, Australia, large tracts of native vegetation have been cleared for agriculture, resulting in substantial hydrological changes in the landscape. Australia's longest-running paired catchment study, the Brigalow Catchment Study (BCS), was established in 1965 to monitor hydrological changes associated with land development, particularly that of the 1960s Land Development Fitzroy Basin Scheme. The BCS has unequivocally shown that developing brigalow (*Acacia harpophylla*) for cropping or for grazing doubles runoff volume. However, to date little research had been undertaken to quantify the changes in peak runoff rate when brigalow is cleared for cropping or grazing. The present study compared peak runoff rates from three brigalow catchments, two of which were subsequently cleared for cropping and pasture. Prior to land development, average peak runoff rates from the three brigalow scrub catchments were 3.2, 5 and 2 mm $h^{-1}$ for catchments 1 to 3 respectively. After development, these rates increased to 6.6 mm $h^{-1}$ from the brigalow scrub control catchment (catchment 1), 8.3 mm $h^{-1}$ from the cropping catchment (catchment 2) and 5.6 mm $h^{-1}$ from the pasture catchment (catchment 3). Peak runoff rate increased significantly from both the cropping and pasture catchments after adjusting for the underlying variation in peak runoff rate due to climatic variation between the pre- and post-development periods. The average peak runoff rate increased by 5.4 mm $h^{-1}$ (96%) for the cropping catchment and by 2.6 mm $h^{-1}$ (47%) for the pasture catchment. Increases in peak runoff rate were most prevalent in smaller events with an average recurrence interval of less than 2 years under cropping and 4 years under pasture.

**Additional keywords:** Fitzroy Basin, hydrological change, land development, land use.

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## Introduction

Estimation of peak runoff rate has been the focus of substantial hydrological research worldwide (Hawkins 1993; Dilshad and Peel 1994; Post and Jakeman 1999). Peak runoff rate is a requirement for engineering design purposes (Post and Jakeman 1999), flood estimation (Van Dijk and Bruijnzeel 2004), soil conservation (Yu *et al*. 1997, 2000*a*), water yield assessments for agriculture, urban and environmental requirements (Hawkins 1993) and as an input variable for water quality models and the design of monitoring programs (Fentie *et al*. 2002; Van Dijk and Bruijnzeel 2004).

Increases in peak runoff rate as a result of urbanisation are well documented in Australia and elsewhere in the world (Nanson and Young 1981; Du *et al*. 2012; Li *et al*. 2013; Trinh and Chui 2013; Wu *et al*. 2013; Kulkarni *et al*. 2014). The literature also reflects a body of work documenting changes in peak runoff rate as a result of land use and land cover change in both mixed land use catchments (Kuntiyawichai *et al*. 2014; Sanyal *et al*. 2014) and for specific land use changes, such as clear felling, grassland to plantation forest and forest to cultivation (Yao *et al*. 2014; Zhang *et al*. 2013; Birkinshaw *et al*. 2014; Kalantari *et al*. 2014; Tekleab *et al*. 2014).

There is a large body of literature discussing the effects of land use change on water balance and water yield (Van Lill *et al*. 1980; Bultot *et al*. 1990; Lane *et al*. 2005; Siriwardena *et al*. 2006; Thornton *et al*. 2007; Zhang *et al*. 2008; Li *et al*. 2012); however, less well documented are changes in peak runoff rate associated with land use change in Australia. This is particularly relevant to hydrological change associated with the broad-scale land clearing of the semi-arid subtropical brigalow belt bioregions in Queensland. Short-term small catchment data showed increases in peak runoff rate associated with clearing brigalow scrub for cropping or for grazed pasture (Lawrence and Sinclair 1989; Lawrence *et al*. 1991), whereas rainfall simulation studies showed that as cover in grazed pastures increases, peak runoff rate decreases, particularly for events with an average recurrence interval of less than 3 years

*Parts I, II and III of the Brigalow Catchment Study are available at *Aust. J. Soil Res.* **45**, 479–495; 496–511; 512–523.

 

(Connolly *et al*. 1997). Research has clearly identified that this limited availability of peak runoff rate data or, in the absence of data, models to estimate peak runoff rate are an impediment to soil erosion research (Silburn 2011).

The Brigalow Catchment Study (BCS) is representative of the 36.7 Mha of the brigalow bioregion in Queensland and northern New South Wales (Cowie *et al*. 2007; Thornton *et al*. 2007). Cowie *et al*. (2007) presented an overview of the study, whereas the increase in runoff amount and changes to productivity as a result of the land clearing were examined in detail in Thornton *et al*. (2007) and Radford *et al*. (2007) respectively. The present study is an extension of these papers. Hydrological modelling and erosion research in this landscape will be improved by the knowledge that clearing of virgin brigalow scrub for cropping or grazed pasture land uses has significantly increased peak runoff rate, particularly for events with an average recurrence interval of less than 2 years for cropping and 4 years for pasture.

The present study had three objectives. The first was to present long-term data on peak runoff rate from the three land uses of virgin brigalow scrub, cropping and grazed pasture at the BCS in central Queensland; the second was to quantify changes in the peak runoff rate when virgin brigalow scrub was cleared for cropping or grazed pasture using simple comparison of the observed data and by a paired, calibrated catchment study approach; and the third was to evaluate the change in peak runoff rate in relation to the annual recurrence interval of the runoff event.

## Materials and methods

### *Experimental site*

Data for the present study were collected from the long-term BCS. The BCS has been described in detail in Cowie *et al.* (2007); changes in runoff volume are given in Thornton *et al.* (2007), agronomic and soil fertility results are given in Radford *et al*. (2007) and the deep drainage component of the water balance is given in Silburn *et al*. (2009). The BCS is a paired calibrated catchment study located in the Dawson subcatchment of the Fitzroy Basin, central Queensland, Australia (Fig. 1). It consists of three catchments (C1, C2 and C3) with three distinct experimental periods (Fig. 2; Table 1; Thornton *et al*. 2010). Stage I was a calibration period where all catchments were virgin brigalow scrub. During Stage II, C2 and C3 were cleared via pulling with bulldozer and chain and the fallen timber was burnt *in situ*. Following clearing, C2 was developed for cropping and C3 was developed for improved pasture. C1 was retained as an uncleared control. Stage III allowed for land use comparison between the three catchments. During this stage, C2 was sown to grain sorghum (*Sorghum bicolour*) in 1984, followed by an annual wheat crop (*Triticum aestivum*) for 10 years, with the exception of a drought year in 1993. Following this, an opportunity cropping philosophy was adopted with either wheat or sorghum sown whenever soil water content was considered adequate. In C3, an improved pasture of buffel grass (*Cenchrus ciliaris*) was grazed at stocking rates of 0.29–0.71 head $ha^{-1}$ (each animal typically a 0.8 adult equivalent), maintaining ground cover in excess of 85%.

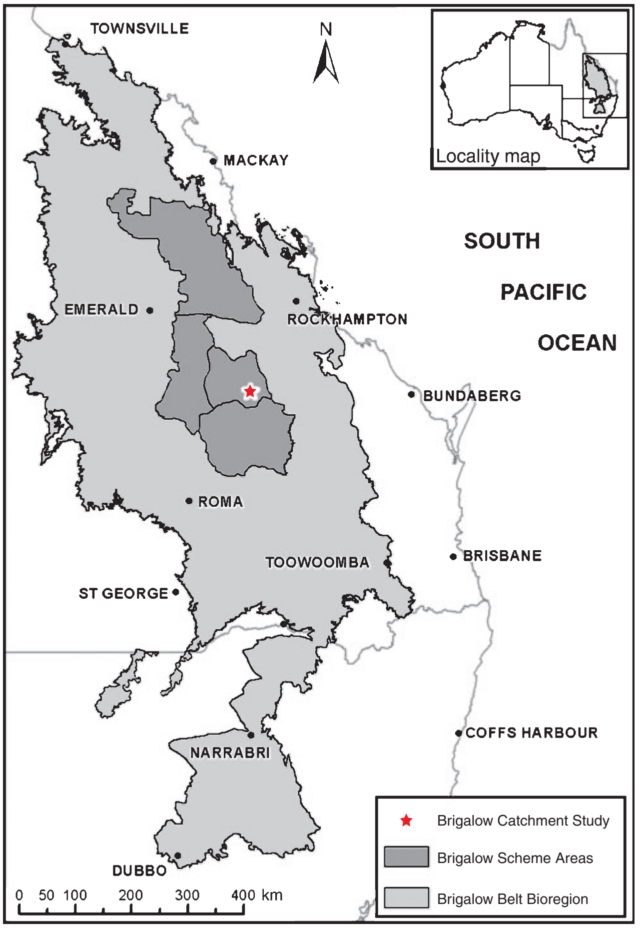


**Fig. 1.** Locality map of the Brigalow Catchment Study, central Queensland, Australia.

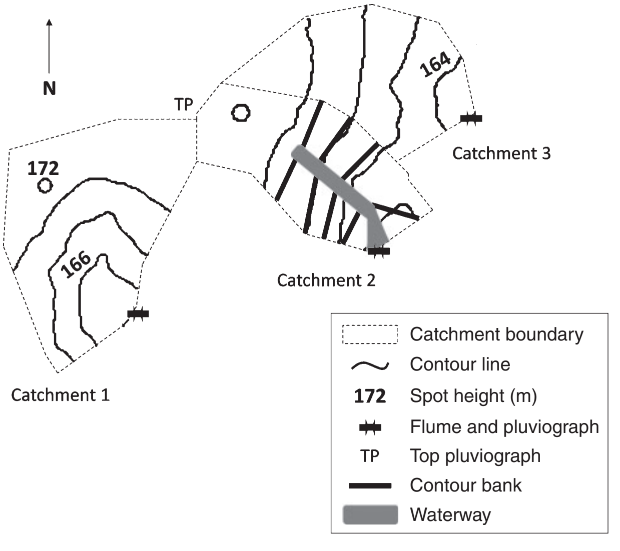


**Fig. 2.** Schematic diagram of the Brigalow Catchment Study showing catchment boundaries, contour banks, waterways and the location of rainfall and runoff recording stations.

**Table 1. Land use history of the three catchments of the Brigalow Catchment Study**

Stage I, January 1965–March 1982; Stage II, March 1982–September 1984; Stage III, September 1984–December 2004

| Catchment | Area (ha) | Land use by experimental stage: Stage I | Stage II | Stage III |
|---|---|---|---|---|
| C1 | 16.8 | Native brigalow | Native brigalow | Native brigalow |
| C2 | 11.7 | Native brigalow | Development | Cropping |
| C3 | 12.7 | Native brigalow | Development | Improved pasture |

### *Data*

The instrumentation of the study is described in Thornton *et al*. (2007). Rainfall data used in the present study were collected from a 0.5-mm tipping bucket recorder located at the head point of the catchments. Each catchment was instrumented to measure runoff using a 1.2-m steel HL flume with a 3.9 × 6.1 m concrete approach box located at the outlet point of each catchment (Brakenseik *et al*. 1979). Water height through the flumes was recorded using mechanical float recorders. Total runoff ($Q_{tot}$), total rainfall ($P_{tot}$) and total soil water (TSW) data are the same as presented in Thornton *et al*. (2007). Raw data were stored and manipulated using the Hydstra database (Hydstra/TS Time Series Data Management version V10.4, Kisters; www.kisters.com.au, accessed 17 August 2015). Peak runoff rate ($Q_p$) was calculated on an event basis from the observed instantaneous peak height. An event was defined as one or more rain days that produced runoff, separated from other events by at least 1 day without rainfall. The technique of Rosewell (1986) was used to provide estimates of storm energy ($E_{tot}$) from observed tipping bucket rainfall intensity data. Storm erosivity ($EI_{30}$) was calculated as the product of storm energy and peak 30-min rainfall intensity (Yu and Rosewell 1998). Rainfall intensity ($I$) was calculated as the peak intensity over the specified time period within the event. Antecedent rainfall ($A$) was calculated as the sum of daily rainfall totals over the specified interval until 0900 hours on the day the event commenced. A surrogate parameter for roughness was generated for C2 during Stage III by calculating total rainfall from planting or cultivation to the commencement of runoff. This parameter is a reflection of the decay in soil surface roughness over time due to rainfall (Guzha 2004; Ndiaye *et al*. 2005).

### *Dealing with missing data*

Because of equipment malfunction, animal interference and extreme weather events, no catchment had a complete runoff record for the 40-year period. The average failure rate for the study was 11%. Prior to any analysis, where measurements of $Q_p$ were missing from the dataset they were estimated using multiple regression models developed using locally collected data. This approach was consistent with that used in similar studies at both the BCS and other sites (Thornton *et al*. 2007; Freebairn *et al*. 2009). To assess the sensitivity of the results due to the inclusion of estimated data, each of the analyses contributing to the three objectives of the present study were repeated excluding all the data containing estimated peak runoff rates.

All regression models for the estimation of $Q_p$ considered the parameters $Q_{tot}$, $P_{tot}$, $E_{tot}$, $EI_{30}$, $I$ (peak intensity over 6-, 10-, 15-, 20- and 30-min and 1-, 2-, 3-, 4-, 6-, 12-, 18- and 24-h intervals), $A$ (2, 3, 5, 10, 20 and 30 days) and TSW. An additional parameter describing roughness was included for C2 during Stage III. Events that did not have a full parameter set were excluded from the analysis. Each parameter was tested individually for a significant correlation ($P < 0.05$) with dependent parameter $Q_p$. Significant parameters were then combined and an all-subsets regression performed using the statistical software program GENSTAT v14.1 (VSN International; www.vsni.co.uk/software/genstat/, accessed 17 August 2015). The final models only included significant constants and coefficients and, in the case of peak intensities and antecedent rainfall, only one parameter from the time interval best correlated with $Q_p$.

Because $Q_p$ was not normally distributed, log transformation, $\log(Q_p + 1)$, was performed to allow for valid statistical testing. Where the prefix 'log' is specified, it indicates that this transformation has been applied. To allow numerical evaluation of $Q_p$ regression models, a split sample approach was used. The models were developed on data collected in odd years and then tested on $Q_p$ data collected in even years. Model performance could then be assessed by comparisons between the observed and estimated data using numerical indicators adjusted $R^2$ and the coefficient of efficiency, $E$ (Nash and Sutcliffe 1970).

The coefficient of determination is generally defined as:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \quad (1)$$

where $SS_{tot}$ is the total sum of squares and $SS_{res}$ is the residual sum of squares. $R^2$ measures the fraction of the total variation that can be explained by the model, whereas $r^2$ is the squared coefficient of correlation, defined as the fraction of the variation in the values of a variable $y$ that is explained by the least-squares regression of $y$ on a variable $x$ (Moore and McCabe 1993). Adjusted $R^2$ is defined as:

$$\text{Adjusted } R^2 = 1 - \frac{SS_{res}/(n-p-1)}{SS_{tot}/(n-1)} \quad (2)$$

where $n$ is the number of observations and $p$ is the number of explanatory variables. Adjusted $R^2$ has the advantage over the statistic $r^2$ in that it takes into account of the number of explanatory variables that have been used in the model, thus preventing inflation in $R^2$ by including non-significant independent variables in the regression.

The coefficient of efficiency, $E$ (Eqn 3), expresses the proportion of variance of the observed data that can be accounted for directly by the estimated data as follows:

$$E = 1 - \frac{\sum (Q_{Obs} - Q_{Est})^2}{\sum (Q_{Obs} - \bar{Q}_{Obs})^2} \quad (3)$$

where $Q_{Obs}$ is the observed peak runoff rate, $Q_{Est}$ is the estimated peak runoff rate and $\bar{Q}_{Obs}$ is the average observed peak runoff rate. This is a better indicator of model performance than the statistic $r^2$, which has been shown to be insensitive to additive and proportional differences between observed and estimated data (Legates and McCabe 1999). Values of $E$ range from 1 to $-\infty$. An $E$ value of 1 means perfect agreement between the observed and estimated data, an $E$ value of 0 means that the modelled estimate is no better a predictor than a value equal to the observed average and a negative $E$ value means that the modelled estimate is a worse predictor than an estimation made using the average of the observed data (Chiew and McMahon 1993; Legates and McCabe 1999; Yu *et al*. 2000*b*). For linear regression models, statistic $r^2$ and $E$ are identical in value; both indicate the fraction of total variation that can be explained by the linear regression model. However, $E$, the coefficient of efficiency, is a much more general indicator of model performance and applicable to all kinds of models when the output of the model can be compared with observations.

To develop a multiple regression model for brigalow scrub catchments describing a general relationship between $Q_p$ and locally measured descriptors of climate and land use, estimation of $Q_p$ was undertaken by pooling all Stage I data from the three catchments. Because no land use change occurred in C1, the pooled Stage I model was applied to C1 Stage III data. Because daily rainfall characteristics were not consistent between the stages (Thornton *et al*. 2007) and land use change had occurred in C2 and C3, individual models were also developed for C2 and C3.

### Analytical methods

Analysis of variance (ANOVA) was performed using Genstat v14.1 (VSN International) to determine whether the peak runoff rates from each catchment were significantly different ($P < 0.05$) between Stages I and III. Assuming that no change in the drivers of runoff (such as rainfall) occurred, a significant difference between Stages I and III in observed $Q_p$ from C2 or C3 would suggest that land development affects $Q_p$.

Because the study is a paired calibrated catchment design, a more rigorous analysis than a simple comparison of observed data was undertaken. Using the approach of Thornton *et al*. (2007), preclearing $Q_p$ data from C2 and C3 were regressed against $Q_p$ data from C1. This regression results in equations to estimate $Q_p$ for C2 and C3, given the measured $Q_p$ for C1. This process is referred to as 'calibrating the catchments'. This calibration was used after clearing to estimate $Q_p$ for C2 and C3 had they remained uncleared. Differences between the observed $Q_p$ for C2 and C3 in Stage III and estimates of $Q_p$ had the catchments remained uncleared, calculated using the calibration equations, can then be attributed to land use change. This paired calibrated catchment design removes the influence of factors other than land use change on $Q_p$ (Bosch and Hewlett 1982; Wang *et al*. 2012), including removal of the effects of climate, climate change, geology, soil and topography.

A partial series analysis was undertaken to investigate changes in $Q_p$ for a given recurrence interval. The partial series of $Q_p$ for each catchment in both Stages I and III was determined (Claps and Laio 2003). The series were ranked, and the ratios of C2 : C1 and C3 : C1 in Stages I and III were obtained. Implicit in this approach is the assumption that observed peak discharge of the same rank for the same period would have an identical average recurrence interval. These ratios were plotted against an average recurrence interval and fitted with an exponential curve. Comparison of the Stage I and III curves for each pair of catchments shows the change in $Q_p$ for a given average recurrence interval with land development regardless of changes in climatic sequence.

## Results

### Multiple regression models for estimation of missing peak runoff rate data

Results of regression analysis of the individual parameters against $Q_p$ are given in Table 2. The parameter $\log Q_{tot}$ was the best correlated individual parameter to $Q_p$.

#### Stage I

Log-transformed $Q_{tot}$ gave the best correlation of an individual parameter with $Q_p$. Parameters for intensity $<I_{2\,h}$ were not significant in any analysis. The whole-of-stage model estimated $Q_p$ using the parameters $\log Q_{tot}$ and $A_{2\ day}$ ($R^2 = 0.94$, $P < 0.001$, $n = 45$; Eqn 4). Individual catchment models for C1 (Eqn 5) reduced $R^2$ by 0.12, whereas individual catchment models for C2 improved $R^2$ by 0.02 (Eqn 6). The individual catchment model for C3 gave no improvement in $R^2$ (Eqn 7).

Stage I:

$$\log(Q_p+1) = 0.6616 \times \log(Q_{tot}+1) + 0.0063 \times A_{2day}\ (R^2 = 0.94, P < 0.001) \quad (4)$$

C1 Stage I:

$$\log(Q_p+1) = 0.5424 \times \log(Q_{tot}+1)\ (R^2 = 0.82, P < 0.001) \quad (5)$$

C2 Stage I:

$$\log(Q_p+1) = 0.8483 \times \log(Q_{tot}+1) - 0.0188 \times P_{tot} + 0.0787 \times E_{tot}\ (R^2 = 0.96, P < 0.001) \quad (6)$$

C3 Stage I:

$$\log(Q_p+1) = 0.5767 \times \log(Q_{tot}+1) + 0.0122 \times E_{tot} + 0.0073 \times A_{2day}\ (R^2 = 0.94, P < 0.001) \quad (7)$$

Although the whole-of-stage three-parameter regression model gave an $R^2$ of 0.94, it must be noted that a model using the single parameter $\log Q_{tot}$ also resulted in a significant regression ($P < 0.001$) with only a minor reduction in $R^2$ ($R^2 = 0.93$). An assessment of model performance using a split-sample approach gave an $R^2$ of 0.89 or greater and $E$ values of 0.35 or greater for all catchments.

#### Stage III

Log-transformed $Q_{tot}$ continued to be the best correlated individual parameter (Table 2). The parameter for roughness was not significant in any analysis. Antecedent rainfall had no significant correlation with $Q_p$ for any of the three catchments. Because no land use change occurred in C1, the parameters used in the whole-of-stage model for Stage I

**Table 2. Adjusted coefficients of determination ($R^2$) for regression analysis of the individual parameters against the response parameter $\log Q_p$ (peak runoff rate)**

$\log Q_{tot}$, total runoff; $P_{tot}$, total rainfall; $E_{tot}$, storm energy; $EI_{30}$, storm erosivity; TSW, total soil water

| Catchment | $\log Q_{tot}$ (mm) | $P_{tot}$ (mm) | $E_{tot}$ (MJ ha$^{-1}$ mm$^{-1}$) | EI$_{30}$ (mm h$^{-1}$) | TSW (mm) | Rainfall intensity (peak mm per time interval) 10 min | 15 min | 1 h | 2 h | 3 h | 4 h | 6 h | 12 h | 18 h | 24 h | Antecedent rainfall (mm) 2 days | 3 days | 5 days | 10 days | 20 days | 30 days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stage I | | | | | | | | | | | | | | | | | | | | | |
| All | 0.93 | 0.52 | 0.47 | 0.10 | 0.22 | NS | NS | NS | 0.14 | 0.24 | 0.25 | 0.33 | 0.39 | 0.42 | 0.47 | 0.28 | 0.19 | 0.24 | 0.14 | 0.15 | 0.21 |
| 1 | 0.82 | 0.00 | 0.02 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | 0.11 | 0.11 | NS | NS | NS | NS | NS | NS |
| 2 | 0.94 | 0.53 | 0.46 | NS | 0.29 | NS | NS | NS | NS | NS | NS | 0.31 | 0.40 | 0.41 | 0.46 | NS | NS | NS | NS | NS | NS |
| 3 | 0.93 | 0.47 | 0.48 | 0.26 | NS | NS | NS | NS | 0.24 | 0.34 | 0.35 | 0.40 | 0.46 | 0.48 | 0.53 | 0.33 | 0.23 | 0.29 | 0.15 | NS | NS |
| Stage III | | | | | | | | | | | | | | | | | | | | | |
| 1 | 0.82 | 0.35 | 0.46 | 0.03 | NS | NS | NS | NS | 0.04 | 0.19 | 0.23 | 0.30 | 0.45 | 0.43 | 0.41 | NS | NS | NS | NS | NS | NS |
| 2 | 0.68 | 0.06 | 0.23 | NS | NS | NS | NS | NS | NS | NS | NS | 0.06 | NS | 0.06 | NS | NS | NS | NS | NS | NS | NS |
| 3 | 0.76 | 0.18 | 0.45 | 0.33 | NS | 0.41 | 0.31 | 0.27 | 0.28 | 0.28 | 0.12 | 0.01 | 0.04 | 0.00 | NS | NS | NS | NS | NS | NS | NS |

were applied to C1 Stage III data. The regression remained significant ($P < 0.001$, $R^2 = 0.85$); however, the parameter $A_{2\ day}$ was no longer significant ($P = 0.111$). Individual catchment regression models were also developed for Stage III (Eqns 8–10). Events with $Q_p > 1$ mm h$^{-1}$ were better estimated than events with $Q_p < 1$ mm h$^{-1}$ (Fig. 3).

C1 Stage III:

$$\log(Q_p + 1) = 0.6767 \times \log(Q_{tot} + 1)\ (R^2 = 0.82, P < 0.001) \quad (8)$$

C2 Stage III:

$$\log(Q_p + 1) = 0.815 \times \log(Q_{tot} + 1) - 0.0238 \times P + 0.1096 \times E\ (R^2 = 0.75, P < 0.001) \quad (9)$$

C3 Stage III:

$$\log(Q_p + 1) = 0.466 \times \log(Q_{tot} + 1) + 0.0006 \times EI_{30}\ (R^2 = 0.92, P < 0.001) \quad (10)$$

As for Stage I, models with the single parameter $\log Q_{tot}$ resulted in significant regressions for all catchments ($P < 0.001$). Compared with multiple variable models, the single variable models reduced $R^2$ to 0.68 for C2 and 0.76 for C3. An assessment of model performance using a split-sample approach gave an $R^2$ of 0.87 or greater and $E$ values of 0.67 or greater for all catchments.

In total, there were 315 runoff events for the three catchments during Stage I and III. Of these, there were 35 events (11%) with missing peak runoff rate data. Regression Eqns 5–10 were used to estimate peak runoff rates for these 35 events with missing data in order to have a complete dataset on peak runoff rate for comparison purposes.

### *Peak runoff rate observations*

Average observed $Q_p$ for the three catchments in both Stages I and III are given in Table 3. Average $Q_p$ for the three catchments excluding estimated $Q_p$ data decreased the average C1 $Q_p$ by 0.3 mm h$^{-1}$ while increasing the average C2 and C3 $Q_p$ by 0.2 and 1.5 mm h$^{-1}$ respectively.

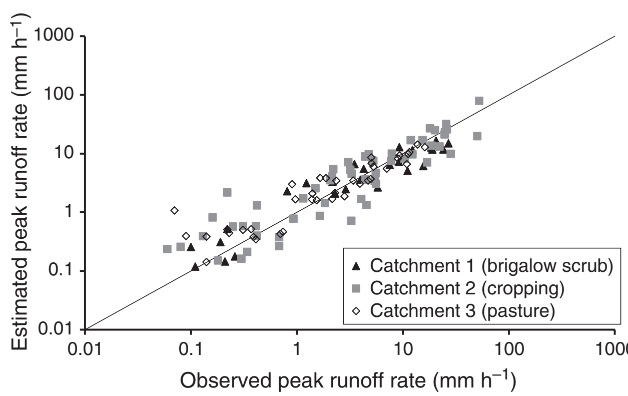


**Fig. 3.** Observed versus estimated peak runoff rate using regression Eqns 8–10 for the three catchments during Stage III.

**Table 3. Summary of observed peak runoff rate data**

| Catchment | Stage | Total no. events | No. events with missing data | Average peak runoff rate ($mm\,h^{-1}$) | Maximum peak runoff rate ($mm\,h^{-1}$) |
|---|---|---|---|---|---|
| 1 | I | 36 | 6 | 3.2 | 31.7 |
| | III | 37 | 3 | 6.6 | 27.0 |
| 2 | I | 34 | 3 | 5.0 | 33.5 |
| | III | 72 | 1 | 8.3 | 52.7 |
| 3 | I | 73 | 7 | 2.0 | 28.7 |
| | III | 63 | 15 | 5.6 | 50.2 |

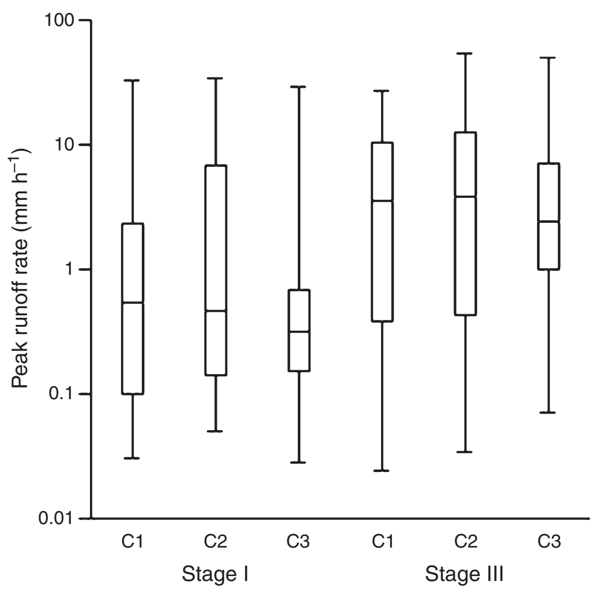


**Fig. 4.** Box and whisker plots of observed peak runoff rate data from Catchments 1, 2 and 3 (C1, C2 and C3 respectively) during Stages I and III. The boxes span the interquartile range, with the horizontal line indicating the median; the whiskers extend to minimum and maximum values.

Box and whisker plots provide basic analyses of the observed data, which is typically skewed towards low runoff rates, with maximum runoff rates up to an order of magnitude greater than the average (Fig. 4).

During Stage I, C1 and C2 shared similar skewed distributions of $Q_p$, with events <5 $mm\,h^{-1}$ occurring most frequently (Fig. 4). Events <5 $mm\,h^{-1}$ accounted for 29 events in C1 and 23 events in C2. However, C3 had 67 events with $Q_p < 5\,mm\,h^{-1}$. When directly comparing average $Q_p$ between catchments, the effect of these events on the C3 average must be taken into consideration. Maximum values of $Q_p$ for each catchment were similar, with 31.7, 33.5 and 28.7 $mm\,h^{-1}$ in C1, C2 and C3 respectively (Table 3). Average annual (hydrological year, October–September) $Q_p$ data are given in Table 4. ANOVA of log $Q_p$ showed no significant differences between C1 and C2; however, both were significantly different from C3 ($P < 0.05$), largely because of the much larger number of runoff events recorded for C3 than the other two catchments during Stage I.

During Stage III, all catchments continued to have a skewed distribution, with events <5 $mm\,h^{-1}$ occurring most frequently (Fig. 4). Maximum values of $Q_p$ decreased to 27 $mm\,h^{-1}$ for

**Table 4. Stage I (1965–1982) observed annual peak runoff rates from the three catchments all in their native, undeveloped state as virgin brigalow scrub**

| Year | C1 (brigalow) | | C2 (brigalow) | | C3 (brigalow) | |
|---|---|---|---|---|---|---|
| | Average | Maximum | Average | Maximum | Average | Maximum |
| 1965[A] | 6.3[B] | 12.4[B] | 5.4[B] | 10.6[B] | 5.0[A] | 9.5[B] |
| 1966 | 0.3 | 0.3 | 0.4 | 0.4 | 0.9 | 2.2 |
| 1967 | 0.7 | 0.7 | 0.5 | 0.5 | 0.3 | 0.4 |
| 1968 | 0.9 | 0.9 | 0.6 | 0.6 | 0.3[A] | 0.7 |
| 1969 | 0.3 | 0.7 | 0.2 | 0.2 | 0.4 | 0.7 |
| 1970 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 |
| 1971 | 5.9[B] | 11.0 | 6.2[B] | 9.2 | 3.6[A] | 8.7 |
| 1972 | 1.4 | 1.4 | 1.4 | 1.4 | 0.8 | 1.5 |
| 1973 | 1.3 | 1.3 | 1.6 | 1.6 | 0.8 | 1.3 |
| 1974 | 2.3 | 6.7 | 2.3 | 6.8 | 1.0 | 6.9 |
| 1975 | 0.3 | 0.4 | 0.2 | 0.2 | 0.4 | 0.8 |
| 1976 | 1.4[B] | 2.9 | 20.5 | 33.5 | 10.8 | 28.7 |
| 1977 | 0.0 | 0.0 | 0 | 0 | 0.2 | 0.5 |
| 1978 | 4.1 | 14.5 | 3.7 | 12.7 | 1.8 | 11.3 |
| 1979 | 16.0 | 31.7 | 12.4 | 24.5 | 5.7 | 21.5 |
| 1980 | 2.7[B] | 8.6 | 4.5 | 10.8 | 1.0[B] | 4.2 |
| 1981 | 1.9[B] | 2.1[B] | 1.4[B] | 1.9 | 1.1[B] | 1.8 |
| 1982[A] | 0 | 0 | 0 | 0 | 0.3 | 0.6 |
| Average | 2.5 | 5.3 | 3.4 | 6.4 | 1.9 | 5.6 |

[A]Incomplete hydrological year.
[B]An estimation of event data is included in this value.

C1, but nearly doubled for C2 and C3 to 53 and 50 $mm\,h^{-1}$ respectively. Again, ANOVA of log $Q_p$ showed no significant differences between C1 and C2; however, both were significantly different from C3 ($P < 0.05$).

Average annual (hydrological year, October–September) $Q_p$ data are given in Table 5. All catchments exhibited an increase in average $Q_p$ in Stage III compared with Stage I. ANOVA of observed log $Q_p$ confirmed significant differences between Stages I and III for all catchments ($P < 0.05$).

### *Determining changes in peak runoff rate using a calibrated catchments approach*

Regression analysis showed strong correlation of log $Q_p$ between the catchments in Stage I (Fig. 5; Eqns 11, 12):

$$\log(Q_pC2 + 1)(\mathrm{mm\,h^{-1}}) = \log(Q_pC1 + 1)(\mathrm{mm\,h^{-1}}) \times 0.9431\ (R^2 = 0.99, P < 0.001, n = 25) \quad (11)$$

$$\log(Q_pC3 + 1)(\mathrm{mm\,h^{-1}}) = \log(Q_pC1 + 1)(\mathrm{mm\,h^{-1}}) \times 0.8176 + 0.2303\ (R^2 = 0.92, P < 0.001, n = 24) \quad (12)$$

However, in Stage III the correlation was much weaker (Fig. 5; Eqns 13, 14):

$$\log(Q_pC2 + 1)(\mathrm{mm\,h^{-1}}) = \log(Q_pC1 + 1)(\mathrm{mm\,h^{-1}}) \times 0.686 + 1.289\ (R^2 = 0.50, P < 0.001, n = 32) \quad (13)$$

$$\log(Q_pC3 + 1)(\mathrm{mm\,h^{-1}}) = \log(Q_pC1 + 1)(\mathrm{mm\,h^{-1}}) \times 0.499 + 1.185\ (R^2 = 0.36, P = 0.003, n = 19) \quad (14)$$

Each pair of equations was then tested for statistical differences between the stages. Eqns 11 and 13 had no

**Table 5. Stage III (1985–2004) observed annual peak runoff rates from the brigalow, cropping and pasture catchments and estimated preclearing runoff from the cropping and pasture catchments using regression calibration Eqns 11 and 12**

Max., maximum

| Year | Peak runoff rate (mm $h^{-1}$) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 (brigalow) | | C2 (cropping) | | | | | | C3 (pasture) | | | | | |
| | Mean | Max. | Mean | Max. | Estimated | | | | Mean | Max. | Estimated | | | |
| | | | | | Stage I mean | Stage I max. | Mean increase | Increase for observed max. | | | Stage I mean | Stage I max. | Mean increase | Increase for observed max. |
| 1985[B] | 5.0[A] | 9.2 | 33.7 | 50.5 | 4.3 | 7.9 | 29.4 | 42.6 | 4.6 | 11.6 | 4.2 | 7.4 | 1.8 | 4.2 |
| 1986 | 0 | 0 | 1.6 | 4.1 | 0 | 0 | 1.6 | 4.1 | 1.1[A] | 1.1[A] | 0 | 0 | 1.1 | 1.1 |
| 1987 | 8.3 | 12.3 | 9.5 | 20.2 | 7.2 | 10.5 | 5.9 | 9.7 | 8.6[A] | 21.4[A] | 6.7 | 9.5 | 5.3 | 11.9 |
| 1988 | 13.6 | 27.0 | 11.7 | 18.0 | 11.2 | 22.2 | 0.5 | –4.2 | 19.1 | 31.1 | 9.3 | 18.2 | 9.8 | 12.9 |
| 1989 | 8.3 | 20.6 | 7.2 | 25.7 | 7.0 | 17.1 | 3.0 | 8.6 | 5.2[A] | 13.8[A] | 6.3 | 14.5 | 1.4 | –0.8 |
| 1990 | 4.8[A] | 5.5[A] | 15.3[A] | 25.1 | 4.2 | 3.5 | 7.4 | 21.6 | 4.3 | 9.3 | 4.3 | 3.7 | 2.2 | 5.6 |
| 1991 | 11.1 | 11.1 | 26.1 | 26.1 | 9.5 | 9.5 | 16.6 | 16.6 | 13.8 | 13.8 | 8.7 | 8.7 | 5.1 | 5.1 |
| 1992 | 0.2 | 0.2 | 3.8 | 7.9 | 0.2 | 0.2 | 3.7 | 7.7 | 2.8 | 5.0 | 0 | 0 | 2.8 | 5.0 |
| 1993 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1994 | 2.2 | 2.2 | 6.8 | 10.4 | 2.0 | 2.0 | 5.9 | 8.4 | 2.4 | 2.4 | 2.2 | 2.2 | 0.1 | 0.1 |
| 1995 | 2.7 | 5.9 | 7.5 | 14.7 | 2.4 | 0.8 | 5.1 | 13.9 | 1.9[A] | 3.1[A] | 2.5 | 5.1 | –0.7 | –2.0 |
| 1996 | 8.6 | 18.6 | 10.1 | 24.8 | 7.2 | 15.5 | 2.9 | 9.2 | 4.4 | 16.2 | 6.4 | 13.3 | 1.2 | 2.8 |
| 1997 | 10.7 | 24.2 | 15.1 | 52.7 | 8.9 | 19.9 | 11.3 | 32.8 | 12.6[A] | 50.2[A] | 7.8 | 16.6 | 7.9 | 33.6 |
| 1998 | 6.1[A] | 19.0 | 6.5 | 29.9 | 5.2 | 15.4 | 3.2 | 14.4 | 5.0 | 18.2 | 5.5 | 13.3 | 1.3 | 4.9 |
| 1999 | 3.0 | 5.8 | 7.0 | 12.4 | 2.7 | 5.1 | 5.6 | 7.3 | 6.0 | 10.8 | 2.8 | 5.1 | 4.6 | 5.7 |
| 2000 | 0 | 0 | 2.6 | 3.4 | 0 | 0 | 2.6 | 3.4 | 2.3 | 4.4 | 0 | 0 | 2.3 | 4.4 |
| 2001 | 0.1 | 0.1 | 4.6 | 8.5 | 0.1 | 0.0 | 4.6 | 8.5 | 2.6 | 4.0 | 0.4 | 0 | 2.4 | 4.0 |
| 2002 | 0 | 0 | 0.3 | 0.7 | 0 | 0 | 0.3 | 0.7 | 0.2 | 0.4 | 0 | 0 | 0.2 | 0.4 |
| 2003 | 9.3 | 9.3 | 12.3 | 12.3 | 8.0 | 8.0 | 4.3 | 4.3 | 9.0 | 9.0 | 7.5 | 7.5 | 1.5 | 1.5 |
| 2004 | 5.8 | 5.8 | 7.9 | 18.7 | 5.1 | 5.1 | 6.2 | 13.6 | 0.9 | 0.9 | 5.0 | 5.0 | –4.1 | –4.1 |
| 2005[B] | 2.9 | 2.9 | 4.7 | 7.8 | 2.6 | 2.6 | 3.8 | 5.2 | 5.0 | 5.0 | 2.8 | 2.8 | 2.2 | 2.2 |
| Average | 4.9 | 8.7 | 9.3 | 17.8 | 4.2 | 6.9 | 5.9 | 10.9 | 5.3 | 11.0 | 3.9 | 6.3 | 2.3 | 4.7 |

[A]An estimation of event data is included in this value.

[B]Incomplete hydrological year.

significant difference in slope ($P = 0.112$); however, the intercepts were significantly different ($P < 0.001$). Eqns 11 and 14 had significantly different slopes ($P = 0.038$) and intercepts ($P < 0.001$). This shows that there have been significant changes in the $Q_p$ relationships of C1 and C2, as well as C1 and C3, between Stages I and III.

Eqns 11 and 12 for Stage I were used to estimate $Q_p$ from C2 and C3 in Stage III had they not been cleared. Both catchments showed a trend for larger observed $Q_p$ than that estimated by their preclearing behaviour. In C2, 94% of events had a higher $Q_p$, whereas in C3 80% of events had a higher $Q_p$. Observed average $Q_p$ from C2 was 8.3 mm h$^{-1}$, an increase of 2.7 mm h$^{-1}$ from its estimated $Q_p$ of 5.6 mm h$^{-1}$ (using Eqn 11), had it not been cleared. However, because the cleared catchment now produced runoff when it would not have in its uncleared condition, the average of observed $Q_p$ minus estimated $Q_p$, including events where estimated $Q_p$ is zero, gave an average increase of 5.4 mm h$^{-1}$. Similarly, observed average $Q_p$ from C3 was 5.6 mm h$^{-1}$, an increase of 0.2 mm h$^{-1}$ from its estimated $Q_p$ of 5.4 mm h$^{-1}$ (using Eqn 12), had it not been cleared. However, average of observed $Q_p$ minus estimated $Q_p$, including events where estimated $Q_p$ is zero, gave an average increase of 2.6 mm h$^{-1}$. Excluding estimated $Q_p$ data, the average of observed $Q_p$ minus estimated $Q_p$, including events where estimated $Q_p$ is zero, gave an average increase of 5.2 mm h$^{-1}$ from C2 and 2.1 mm h$^{-1}$ from C3.The maximum increase in $Q_p$ was 43 and 34 mm h$^{-1}$ in C2 and C3 respectively. Average annual $Q_p$ increased by 5.9 mm h$^{-1}$ from C2 and 2.3 mm h$^{-1}$ from C3 (Table 5).

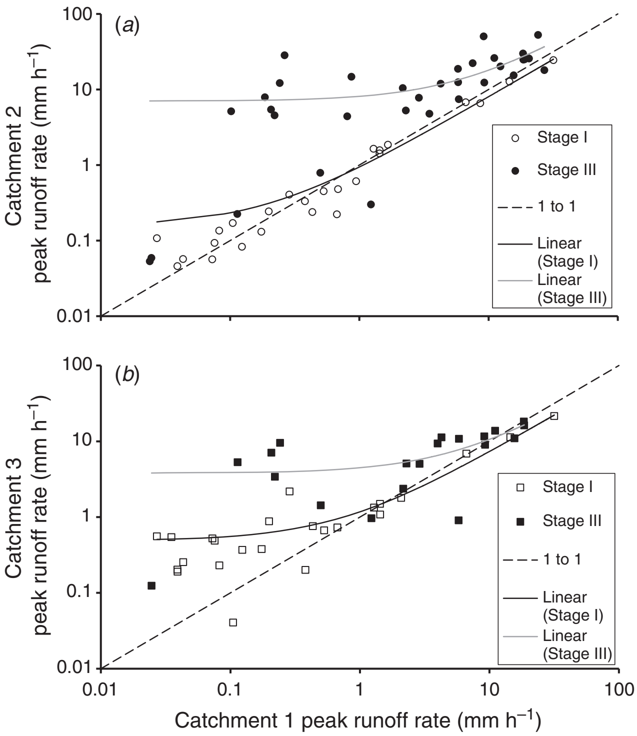


**Fig. 5.** Peak runoff rate for (*a*) Catchment 2 and (*b*) Catchment 3 compared with Catchment 1 before (Stage I) and after (Stage III) clearing.

### *Determining changes in peak runoff rate using a partial series analysis*

The fitted exponential curves describing the ratios of C2 : C1 partial series and C3 : C1 partial series in Stages I and III show that change in $Q_p$ with land development is most prominent in events with a short average recurrence interval (Fig. 6). Under cropping, events with an average recurrence interval >2 years showed similar ratios to Stage I, indicating little change in $Q_p$ with land development in larger events. Grazed pasture exhibited a similar trend, with little change in the ratios of $Q_p$ for events with an average recurrence interval >4 years. Ratios are used for the same frequency of occurrence in lieu of direct comparison of $Q_p$ for the same storm event for the three catchments.

Only one partial series ratio (C3 : C1 in Stage I) contained estimated $Q_p$ data. To examine the effect of this data point on the fitted curve (Fig. 7), the estimated parameter values for a curve fitted to the entire dataset were compared with those for a curve fitted to the observed data excluding the only estimated data point. The form of the equation of the curves is given in Eqn 15, the equation to the curve fitted to the entire dataset is given in Eqn 16 and the equation to the curve fitted to the

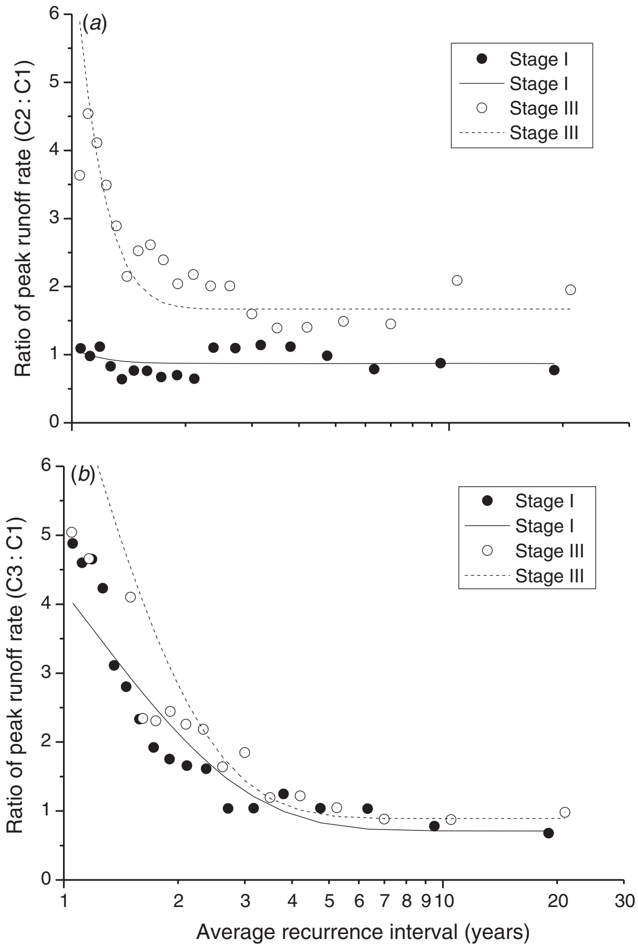


**Fig. 6.** Peak runoff rate ratios of Catchment (C) 2 : C1 and C3 : C1 before (Stage I) and after (Stage III) clearing.

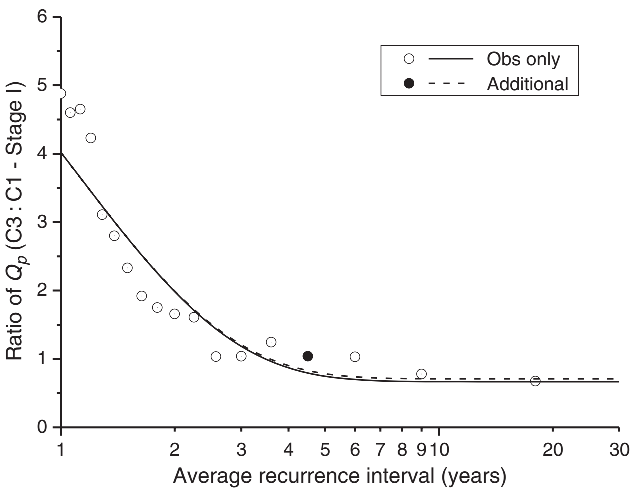


**Fig. 7.** Preclearing peak runoff rate ($Q_p$) ratios of Catchment (C) 3 : C1 showing that the additional data point for the estimated $Q_p$ has little effect on the fitted curve. Obs, observed.

observed data excluding the estimated data point is given in Eqn 17.

$$Y = a + b^{(-kx)} \quad (15)$$

$$Y = 0.709 + 8.52^{(-0.946x)} \ (R^2 = 0.7, P < 0.001, \text{s.e. of } a = 0.465, \text{s.e. of } b = 2.33, \text{s.e. of } k = 0.338) \quad (16)$$

$$Y = 0.667 + 8.53^{(-0.934x)} \ (R^2 = 0.69, P < 0.001, \text{s.e. of } a = 0.515, \text{s.e. of } b = 2.34, \text{s.e. of } k = 0.345) \quad (17)$$

The small differences in the estimated parameter values compared with their standard errors indicate that the fitted curves were essentially the same and that the data point containing estimated $Q_p$ data had no significant effect on the relationship between the average recurrence interval and the ratio of peak runoff rate.

## Discussion

Comparison of observed $Q_p$ data using calibrated catchments showed that land development increased average $Q_p$ from 2.9 to 8.3 mm h$^{-1}$ for the cropping catchment (C2) and from 3 to 5.6 mm h$^{-1}$ for the pasture catchment (C3). The maximum increase in $Q_p$ for C2 and C3 was 43 and 34 mm h$^{-1}$ respectively. This supports the earlier conclusions of Lawrence and Sinclair (1989) and Lawrence *et al*. (1991), who, when analysing study data from 1984 to 1987, found average increases in $Q_p$ in C2 and C3 of 9.5 and 4.3 mm h$^{-1}$ respectively. Events with an average recurrence interval <2 years showed the greatest increase in $Q_p$ when brigalow land was developed for cropping, whereas events with an average recurrence interval <4 years showed the greatest increase when brigalow land was developed for grazing. All these analyses were insensitive to the inclusion of estimated $Q_p$ data.

The literature shows that changes in runoff volume are generally associated with changes in the peak rate (Leitch and Flinn 1986; Bari and Smettem 2006) and that the direction of change in runoff volume is generally mirrored by the change in peak rate (Rallison 1982). Data from the present study agree, and show that land development increases both $Q_{tot}$ and $Q_p$ (Thornton *et al*. 2007). This agreement supports the application of these concepts to brigalow landscapes in central Queensland.

As found in the present study, the magnitude of the increase has been highly variable (Boughton 1970; Gilmour 1977; Mackay and Cornish 1982). Higher $Q_p$ from the land uses of cropping and pasture compared with virgin brigalow are also seen in other land use comparisons, such as those of Cox *et al.* (2006), who showed greater $Q_p$ from agricultural watersheds compared with forested watersheds. Events with low $Q_p$ similar to brigalow occurred under both cropping and pasture. In the cropping catchment, these events occurred during ratoon sorghum crops and dry fallow periods, which would be expected to maintain similar soil moisture as the brigalow catchment. In the pasture catchment, the one low $Q_p$ event occurred after 54 days of no substantial rainfall following an extremely wet summer. The actively growing high biomass pasture would have had a high water use potential, again resulting in similar soil moisture as the brigalow catchment. Because soil moisture is a key driver of runoff (Thornton *et al.* 2007), and hence $Q_p$, in this landscape, it is not surprising that all catchments yielded similar low $Q_p$ in these instances.

## Conclusion

The aims of the present study were to quantify changes in $Q_p$ as a result of land development using a simple comparison of observed data, a paired calibrated catchment analysis and a partial series analysis. Simple comparison of observed data showed that the clearing of virgin brigalow scrub for cropping or pasture land uses has significantly increased the peak runoff rate of overland flow events. Using a calibrated catchment approach, the magnitude of the increase was 96% for cropping and 47% for pasture, based on observed data and calibrated predictions of their preclearing behaviour combined with the best available method of estimating missing data as determined in this study. After development, peak runoff rates from cropping showed greater variability than those from pasture. Partial series analysis showed that the smaller events with an average recurrence interval <2 years for cropping and <4 years for pasture had the greatest increases in peak runoff rate.

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