The Brigalow Catchment Study: Effects of land development on peak runoff rate and its prediction in central Queensland, Australia

Craig Thornton
Scientist (Catchment Science), Queensland Department of Natural Resources and Mines, Rockhampton, Australia
E-mail: craig.thornton@DNRM.qld.gov.au

Bofu Yu
School of Engineering, Griffith University, Nathan and Gold Coast, Australia
E-mail: b.yu@griffith.edu.au

Abstract

Commencing in 1965 and continuing today, the Brigalow Catchment Study in central Queensland has measured both runoff volume and peak runoff rate from three catchments (11.7 to 16.8 ha) which were initially covered with native brigalow scrub. Thirty-eight years of data were used to assess the accuracy of three different methods for estimating peak runoff rate, and then, to quantify the changes in peak runoff rate as a result of clearing two of the three catchments for either cropping or pasture.

Three methods were used to estimate the peak runoff rate for the 3 catchments: 1) multi-variable regression; 2) Soil Conservation Service Curve Number (SCS-CN) method; and 3) Spatially Variable Infiltration model (SVIM). Regression analysis showed that peak runoff rate was strongly correlated with total runoff volume, in addition to 3 rainfall related variables. Regression method yielded the best results of the three methods tested. Estimates using the SCS-CN method were strongly correlated with observed peak runoff rate for all catchments. However, the method typically underestimated for small events and overestimated for large events. Estimates using SVIM with linear kinematic wave routing were strongly correlated with observed peak runoff rate for all catchments.

Prior to land use change, peak runoff rate from the three brigalow scrub catchments averaged 3.4 mm/hr. A significant increase in peak runoff rate from both the cropping and pasture catchments was clearly evident and attributed to land use change, with the average peak runoff rate increased by 9.1 mm/hr for the cropping catchment and 3.4 mm/hr for the pasture catchment. This equates to an increase of 263% and 164%, respectively, to estimates of their peak runoff rate had they not been cleared. Increases in the peak runoff rate were largest for smaller storm events with an average recurrence interval of less than two years under cropping and less than four years under pasture.

1. INTRODUCTION

Measurement and estimation of runoff volume (Q_{tot}) and peak runoff rate (Q_p) have been the focus of substantial hydrological research worldwide. In Queensland, large tracts of native vegetation have been cleared for agriculture, resulting in substantial hydrologic change in the landscape. Australia's longest-running paired catchment study, the Brigalow Catchment Study (BCS), was established in 1965 to monitor hydrologic change associated with land development, particularly that of the 1960s Land Development Fitzroy Basin Scheme. The Scheme was the largest Government sponsored land development initiative in Australia, resulting in the clearing of 4.5 Mha of brigalow lands for cropping or grazing (Cowie *et al,* 2007). The BCS has unequivocally shown that developing brigalow for cropping or for grazing doubles runoff volume (Thornton *et al,* 2007). However, to date, little research has been done to examine suitable techniques for estimating Q_p, or to quantify the changes in Q_p when brigalow is cleared for cropping or for grazing.

Available methods for estimation of Q_{tot} and Q_p vary both in complexity and in the applicability of their results spatially. Locally accurate site-specific models have been derived empirically from research plots (Fentie *et al*, 2002). However, location-specific and empirical models may not be suitable for use in other catchments due to input data requirements or because the scale at which the relationships were derived is not representative of runoff processes in the broader landscape. Simple models requiring fewer, easily obtainable parameters may be more readily applicable to other catchments (Boughton, 1995), but the accuracy of Q_{tot} and Q_p estimations from this method may be poor or the resolution too coarse for certain applications. Complex physical process-based models may provide accurate estimations of Q_{tot} and Q_p at suitable resolution, however the application of these models to a new location is potentially hampered by the availability of data for parameterisation (Post & Jakeman, 1999).

Objectives of the research were 1) to evaluate various methods for peak runoff estimation; 2) to determine the effect of land use change on peak runoff rate for these small rural catchments. For this paper, Q_p was estimated using three methods; (1) multi-variable regression analysis; (2) Soil Conservation Service Curve Number (SCS-CN) and graphical peak discharge methodologies; and (3) a spatially variable infiltration model (SVIM). The best of the three methods was used to estimate Q_p when data were missing. Changes in peak runoff rate due to land development were evaluated by comparing various aspects of the peak runoff rate between catchments.

2. METHODS

2.1. Experimental site

The BCS is a paired, calibrated catchment study consisting of three catchments, and was established in 1965 to determine the impact on hydrology, productivity and resource condition when brigalow land is cleared for cropping and grazing. The study rationale, aims and history along with physical characteristics including location, experimental design, climate, vegetation and soils have been thoroughly documented elsewhere (Lawrence & Sinclair, 1989; Cowie *et al,* 2007; Radford *et al,* 2007; Thornton *et al,* 2007). A brief description of the site and experimental treatments follows.

The BCS (24.81^{o}S, 149.80 ^{o}E) lies in the south eastern section of the northern brigalow bioregion and is contained within the Dawson subcatchment of the Fitzroy Basin, central Queensland, Australia. The climate is a semi-arid to sub-tropical and has mean rainfall of 697 mm during the study period. Mean annual evaporation is 2100 mm/year, and exceeds mean monthly rainfall in all months.

Soil types in the catchments comprise associations of Black and Grey Vertosols, some with gilgais, Black and Grey Dermosols, and Black and Brown Sodosols (Isbell, 1996). Clay soils (Vertosols and Dermosols) occupy approximately 70% of catchments 1 and 2, and 58% of catchment 3, while Sodosols occupy the remaining area. Mean slope of the catchments is 2.5%. Before clearing, the catchment site was composed of three major vegetation communities, identified by their most common canopy species: brigalow (*Acacia harpophylla*), brigalow – belah (*Casuarina cristata*) and brigalow – Dawson Gum (*Eucalyptus cambageana*). Understories of all major communities are characterized by *Geijera spp*. either exclusively, or in association with *Eremophila spp*. or *Myoporum spp*.

Each catchment was instrumented to measure runoff using a 1.2 m steel HL flume with a 3.9 m by 6.1 m concrete approach box. Water height through the flumes was recorded using mechanical float recorders. Rainfall was recorded adjacent to each flume and at the head of the catchments.

The study has been divided into three distinct experimental stages (Table 1). During Stage I the three catchments were retained in their virgin state. Rainfall and runoff data were collected to describe differences in catchment hydrological responses to a range of weather sequences.

Stage II commenced in March1982 when catchment 2 (C2) and catchment 3 (C3) were cleared with bulldozer and chain. The fallen timber was burnt in-situ in October of the same year. Residual unburnt timber in C2 was raked to the contour line and burnt. Narrow based contour banks at 1.5m vertical spacing were constructed and a grassed waterway later established. In C3, unburnt timber was left in place, and in November 1982 the catchment was sown by throwing buffel grass seed (*Cenchrus ciliaris* cv. Biloela) on the soil surface. Catchment 1 (C1) was left untouched as a control.

In C2, cropping commenced in September 1984 with the planting of sorghum followed by nine annual wheat crops commencing in 1985. Fallow management in this period was entirely mechanical tillage.

A minimum tillage and opportunity cropping philosophy was adopted in the early 1990s and has continued with either a summer or winter crop (sorghum and wheat or barley) sown whenever soil moisture was adequate.

Grazing in C3 commenced in December 1983. Stocking rate varied between 0.29 and 0.71 head/ha (each beast typically 0.8 adult equivalent), adjusted to maintain pasture dry matter levels greater than 1000 kg/ha. There was no feed supplementation.

Table 1. The land use history of the three catchments of the Brigalow Catchment Study.

		Land use by experimental stage		
		Stage I	Stage II	Stage III
Catchment	Area (ha)	(Jan 1965 to Mar 1982)	(Mar 1982 to Sep 1984)	(Sep 1984 to Dec 2004)
1	16.8	Virgin brigalow scrub	Virgin brigalow scrub	Virgin brigalow scrub
2	11.7	Virgin brigalow scrub	Development	Cropping
3	12.7	Virgin brigalow scrub	Development	Improved pasture

2.2. Methods of analysis

Estimation of Q_p was undertaken using three methods: (1) multi-variable regression analysis; (2) Soil Conservation Service Curve Number and graphical peak discharge methodologies; and (3) a spatially variable infiltration rate model.

Multiple regression analysis was used to explore relationships between Q_p and independent variables describing climate and catchment condition. All models considered the parameters Q_{tot}, total rainfall (P), storm energy (E), storm erosivity (EI30), rainfall intensity (I) (peak intensity at 6, 10, 15, 20 and 30 min and 1, 2, 3, 4, 6, 12, 18, 24 hr intervals), antecedent rainfall total (A) (2, 3, 5, 10, 20 and 30 day), and total soil water (TSW). Each parameter was tested individually for a significant correlation (*p*-value <0.05) with Q_p. Significant parameters were then combined and an all-subsets regression performed.

Curve Number (CN) and graphical peak discharge (GPD) method for estimation was undertaken using locally calculated CN values, time of concentration calculated using the SCS lag method, a type II rainfall distribution, and equation based calculation of unit peak discharge (USDA NRCS, 1986). Spatially Variable Infiltration model (VIR) estimations were undertaken on a 15 minute time step, also using time the of concentration calculated by the SCS lag method, and with a linear solution to the kinematic wave approximation used to route rainfall excess to the catchment outlet (Yu 1997; Yu *et al* 1997).

Evaluation of changes in peak runoff rate due to land development using a simple comparison of observed data and calibrated catchment analysis followed the approach of Thornton *et al* (2007).

3. RESULTS

Equations 1 to 3 describe the multiple regression models developed for each catchment during Stage III. Events with Q_p > 1 mm/hr were better estimated than events with Q_p < 1 mm/hr (Figure 1). Irrespective of catchment or stage, Q_{tot} gave the best correlation of an individual variable with Q_p. Models with the single variable Q_{tot} resulted in a significant regressions for all catchments (p-value <0.001) with minor or no reduction in R^2 (0.93, 0.80 and 0.83 for C1, C2 and C3 respectively) compared to multi-variable models.

$$\text{C1 Stage 3} \log Q_p = 0.7095 \times \log Q_{tot} + 0.02266 \times I_{2hr} - 0.491 \quad (R^2 = 0.93) \quad (1)$$

$$\text{C2 Stage 3} \log Q_p = 0.7966 \times \log Q_{tot} - 0.02568 \times P + 0.1192 \times E \quad (R^2 = 0.89) \quad (2)$$

$$\text{C3 Stage 3} \log Q_p = 0.5692 \times \log Q_{tot} + 0.01832 \times I_{1hr} - 0.3335 \quad (R^2 = 0.87) \quad (3)$$

The GPD method gave good estimations of Q_p across all catchments and stages (Figure 2). Linear regression analysis gave R^2 >0.7 in all instances. These high R^2 values disguise the fact that the method typically under-estimates Q_p in small events and over-estimates Q_p in large events. On average, in events where $Q_{p\text{-observed}}$ >5 mm/hr, 71% of estimations were greater than the observed data.

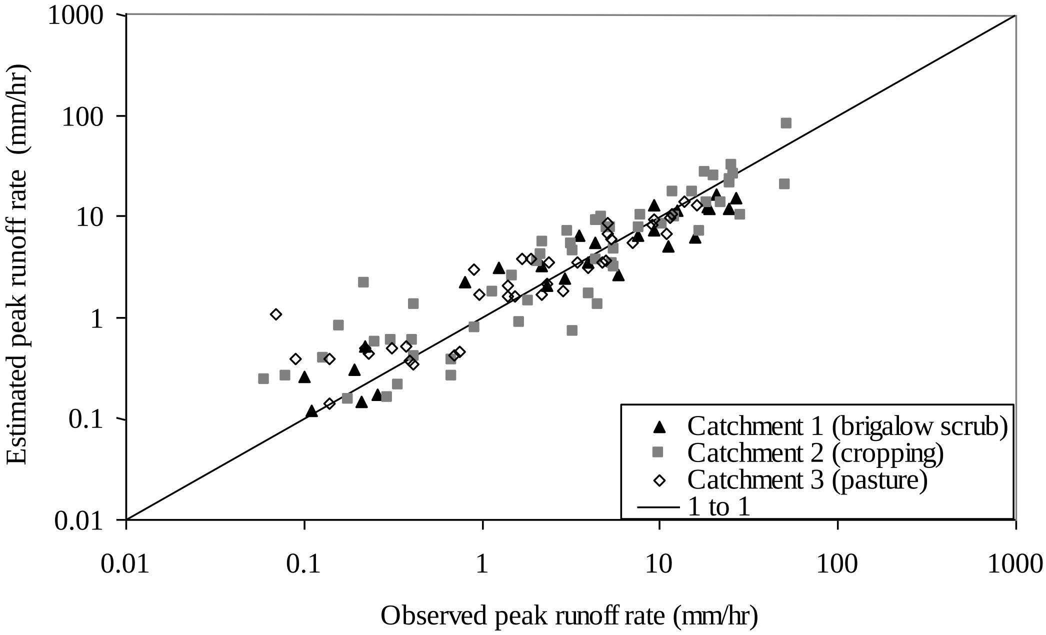

Figure 1. Observed peak runoff rate compared with estimated peak runoff rate using multiple regression models (Equations 1 to 3) for the three catchments during Stage III.

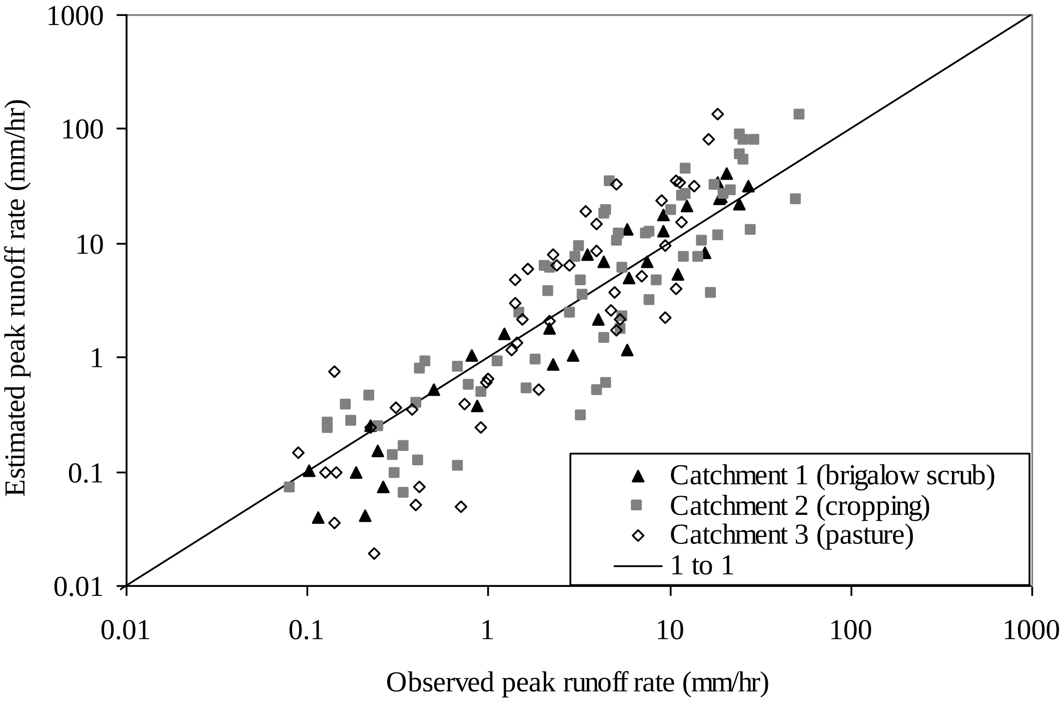

Figure 2. Observed peak runoff rate compared to GPD method estimated peak runoff rate for the three catchments during Stage III.

The SVIM method gave better estimates of Q_p compared to the GPD method, with linear regression analysis giving R^2 >0.8 for all catchments in Stage III (Figure 3). However, the lag in the routing component was too short, with 94% of all routed peaks occurring prior to the observed peak.

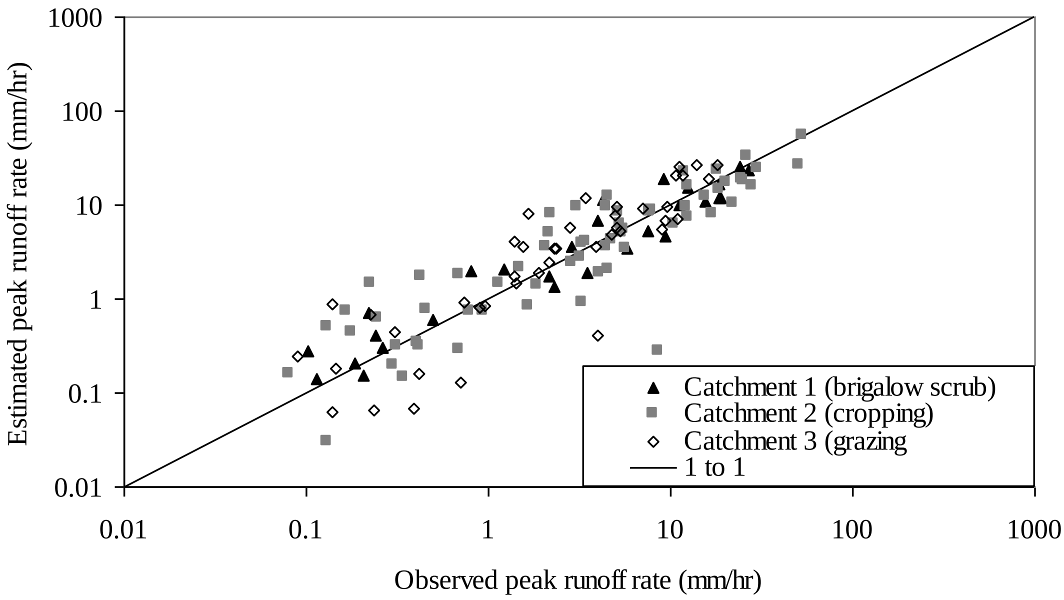

Figure 3. Observed peak runoff rate compared to the VIR method estimated peak runoff rate for the three catchments during Stage III.

Average observed Q_p for the three catchments in both Stage I and III are shown in Table 2 using the complete data set. Analysis of variance of observed Q_p showed a significant increase in average Q_p between Stage I and III for all catchments (p-value <0.05). Regression analysis showed strong correlation of Q_p between the catchments in Stage I (Figure 4) (Equations 4 and 5).

Table 2. Summary of observed peak runoff rate.

Catchment	Stage	Total number of events	Average Q_p (mm/hr)	Maximum Q_p (mm/hr)
1	I	36	3.0	31.7
	III	37	6.6	27.0
2	I	34	4.8	33.5
	III	72	14.7	52.7
3	I	73	1.9	28.7
	III	60	8.8	50.2

$$\log Q_p \text{ C2 (mm/hr)} = \log Q_p \text{C1(mm/hr)} \times 0.9431 \qquad (R^2 = 0.99,\ n = 25) \qquad (4)$$

$$\log Q_p \text{ C3 (mm/hr)} = \log Q_p \text{C1(mm/hr)} \times 0.8176 + 0.2303 \qquad (R^2 = 0.92,\ n = 24) \qquad (5)$$

However, the correlation was much weaker In Stage III (Figure 4) (Equations 6 and 7).

$$\log Q_p \text{ C2 (mm/hr)} = \log Q_p \text{C1(mm/hr)} \times 0.686 + 1.289 \qquad (R^2 = 0.50,\ n = 32) \qquad (6)$$

$$\log Q_p \text{ C3 (mm/hr)} = \log Q_p \text{C1(mm/hr)} \times 0.499 + 1.185 \qquad (R^2 = 0.36,\ n = 19) \qquad (7)$$

Equations 4 and 5 were used to estimate Q_p from C2 and C3 in Stage III, had they not been cleared. Both catchments showed a trend of larger observed Q_p than that estimated by their pre-clearing behaviour (Figure 4). In C2, 94% of events had a higher Q_p while in C3, 80% of events had a higher Q_p. Observed average Q_p from C2 was 14.7 mm/hr, an increase of 9.1 mm/hr from its estimated Q_p of 5.6 mm/hr had it not been cleared, while the observed average Q_p from C3 was 8.8 mm/hr, an increase of 3.4 mm/hr from its estimated Q_p of 5.4 mm/hr had it not been cleared. The maximum increase in Q_p was 43 mm/hr in C2 and 34 mm/hr in C3.

In addition to direct comparison of the Q_p for the same set of storm events, partial series of peak runoff rates were prepared for each catchment in each of the two stages. For given average recurrence interval, the ratios of C2 over C1 and C3 over C1 show the change in peak runoff rate with the same frequency of occurrence (Figure 5). It is clear that the change in Q_p with land development is most prominent in events with a short average recurrence interval (Figure 5). Under cropping, events with an average recurrence interval greater than two years had similar ratios between the two stages, indicating less change in Q_p with land development during large storm events. Grazed pasture exhibited a similar trend, with little change in the ratios of Q_p for events with an average recurrence interval greater than four years.

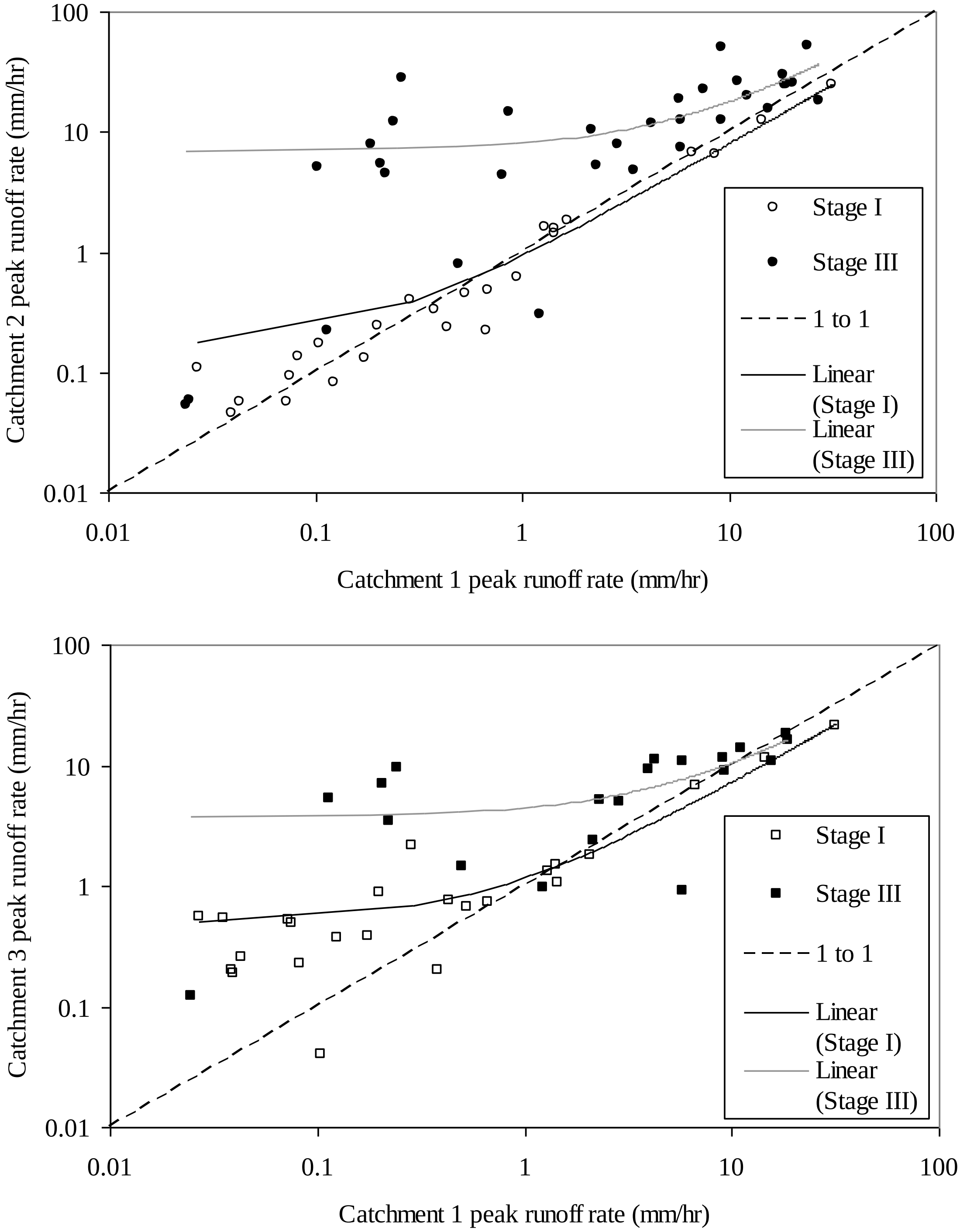

Figure 4. Peak runoff rate for C2 and C3 compared to C both pre- and post-clearing.

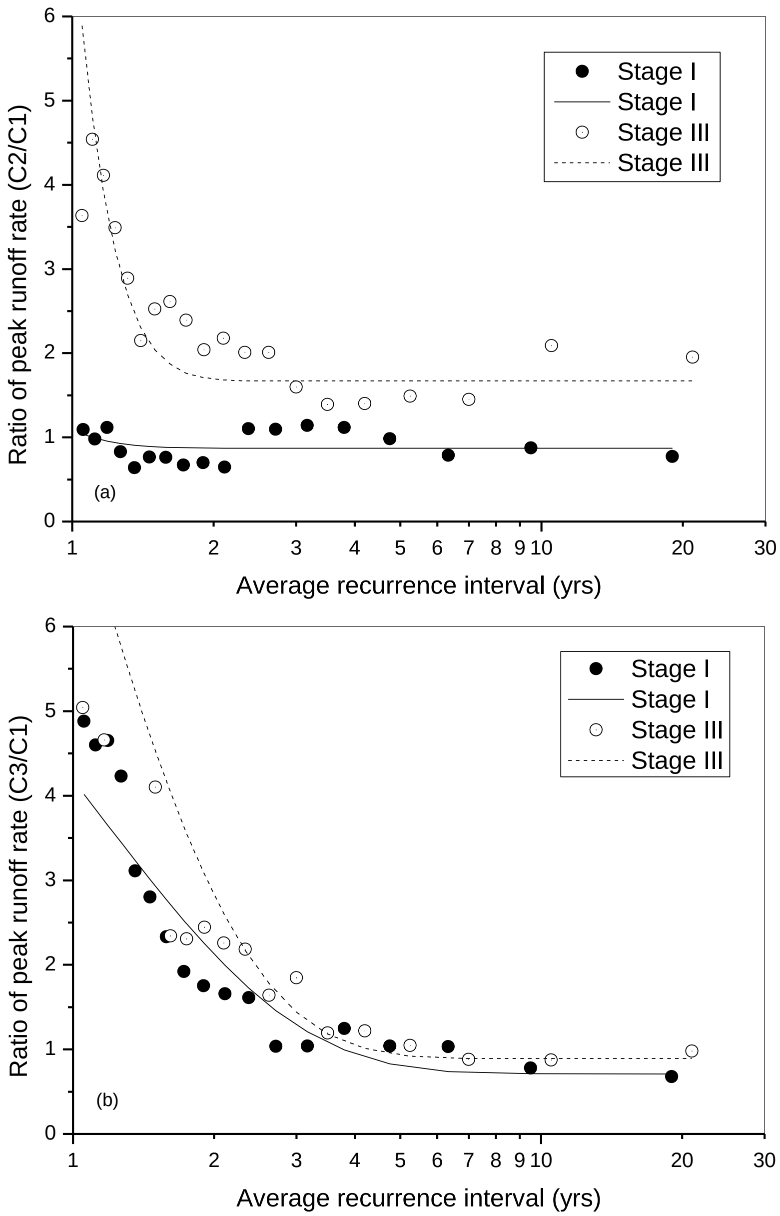

Figure 5. Ratios of peak runoff rate for C2:C1 and C3:C1 pre- and post-clearing.

4. DISCUSSION

Numerical assessment of model performance using R^2 indicates that the site-specific multiple regression models gave the best estimation of Q_p, followed by the SVIM and the SCS-CN methods. This assessment clearly indicates that multiple regression models have given the best estimations of Q_p, when data on observed peak runoff rate are available for model calibration, and when a method is needed to fill in the missing data. For ungauged sites, SVIM and the SCS-CN methods can be used to estimate peak runoff rate when data on rainfall intensity and catchment characteristics are available,

The literature shows that changes in Q_{tot} generally change Q_p (Leitch & Flinn, 1986; Bari & Smettem, 2006), and that the direction of change in Q_{tot} is generally mirrored by the change in Q_p (Rallison, 1982). As development of brigalow scrub to either cropping or pasture has been shown to have increased Q_{tot}, it would be expected that Q_p would also increase due to land use change. A simple comparison of observed Q_p data in this paper did show an increase in Q_p. Calibrated catchment methodology supported this, showing land use change increased average Q_p by 9.1 mm/hr to 14.7 mm/hr for the cropping catchment (C2) and by 3.4 mm/hr to 8.9 mm/hr for the pasture catchment (C3).

This supports the earlier conclusions of Lawrence & Sinclair (1989) who, when analysing study data from 1984 to 1987, found average increases in Q_p of 9.5 mm/hr in C2 and 4.3 mm/hr in C3. This trend is reflected internationally, where typically, higher Q_p are observed from agricultural watersheds compared to forested watersheds (Cox *et al*, 2006). Events with an average recurrence interval of less than two years showed the greatest increase in Q_p when brigalow land was developed for cropping, while events with an average recurrence interval of less than four years showed the greatest increase when brigalow land was developed for grazing.

5. ACKNOWLEDGEMENTS

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