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The Brigalow Catchment Study: II*. Clearing brigalow (*Acacia harpophylla*) for cropping or pasture increases runoff

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Abstract. The Brigalow Catchment Study (BCS) was established to determine the impact on hydrology when brigalow land is cleared for cropping and grazing. The paired catchment study was commenced in 1965 using catchments of approximately 15 ha, with natural vegetation dominated by brigalow scrub (*Acacia harpophylla*). Three contiguous catchments were selected near Theodore in central Queensland to represent the extensive brigalow bioregion of central and southern Queensland and northern New South Wales (~40 Mha). The hydrology of the 3 catchments was characterised during a 17-year calibration period (1965–81). The catchments were considered hydrologically similar, with sufficient data available for an empirical comparison between catchments. In 1982, two of the catchments were cleared, with one developed for cropping and the other sown to improved pasture. The third catchment was used as an uncleared control. Hydrologic characteristics were then compared for the following 21 years. In their virgin state, the catchments behaved similarly, with average annual runoff being 5% of annual rainfall. Once cleared, total runoff from the cropping catchment increased to 11% of annual rainfall and total runoff from the pasture catchment increased to 9% of annual rainfall; however, timing of the individual runoff events varied between land uses. In order to confirm that changes in hydrology were a function of land use and not just seasonal variability or sampling error, several analytic techniques were used: a simple comparison of runoff totals, comparison of events, comparison of probability of exceedance for daily runoff, and comparison of predicted and observed runoff using a water balance modelling approach.

Additional keywords: land development, hydrological change, catchment, runoff, brigalow.

Introduction

The brigalow bioregions of Queensland and New South Wales occupy 36.7 Mha, stretching from Dubbo in the south to Townsville in the north (Department of Environment and Heritage 2006). Since European settlement, 21.4 Mha (58%) of this bioregion has been cleared (National Land and Water Resources Audit 2002). In 1962, the Brigalow Land Development Fitzroy Basin Scheme commenced, resulting in the clearing of 4.5 Mha for cropping and grazing (Land Administration Commission 1968). This clearing represents 21% of all clearing in the brigalow bioregions, and represents 32% of the Fitzroy Basin Catchment area (Queensland Department of Primary Industries 1993). A full description of the Brigalow Scheme and the background for this study is presented by Cowie *et al*. (2007, this series).

When the Brigalow Development Scheme was being planned, broad-scale clearing was expected to have an impact on catchment hydrology, with a positive benefit of increased flow in local creeks and streams. In order to quantify the extent of hydrologic change, the Brigalow Catchment Study commenced in 1965. Since the study began, demand on water resources has increased dramatically, providing greater impetus for us to better understand hydrology and land use interactions in allocating scarce resources.

A number of methods for investigating hydrologic change associated with land clearing and development are described in the literature, with results being critically dependent on methodology (Siriwardena *et al*. 2006). The simplest approach is similar to that of Adamson (1976), where 2 similar catchments are selected and subjected to different treatments without calibration. The limitation to this approach is that differences in catchment runoff are solely attributed to changes in management, and any inherent difference in the catchments is ignored. Calibrated catchments such as those used in this study seek to avoid this limitation; however, variable climate sequences can still greatly alter treatment effects (Leitch and Flinn 1986; Williams *et al*. 1993; Fernandez and Garbrecht 1994). Longer term comparison seeks to minimise the effect of climate variability, but depending on the size of the catchments, hydrological change can often be masked by intrinsic catchment differences and climate variability.

Due to the complex processes associated with runoff generation, simply comparing rainfall and runoff before and after

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clearing is inadequate to detect and quantify change (Siriwardena *et al*. 2006). An alternative approach, applied in both Australia (Siriwardena *et al*. 2006) and Africa (Lørup *et al*. 1998), is to use hydrological modelling. Daily rainfall–runoff models are calibrated to observed pre-clearing runoff, and observed post-clearing runoff is then compared to the simulated pre-clearing runoff in the same period. Several analytical methodologies were applied to the 40 years of rainfall and runoff data collected from the Brigalow Catchment Study in order to confidently estimate changes in hydrology associated with clearing of brigalow lands for cropping or grazing.

The brigalow bioregion represents a large part of the landscape in northern New South Wales and Queensland which has been extensively developed for cropping or pasture. This study provides benchmark information on hydrologic changes associated with this development.

Materials and methods

Location

The Brigalow Catchment Study is located on the Queensland Department of Primary Industries and Fisheries Brigalow Research Station in the Dawson sub catchment of the Fitzroy basin, central Queensland. The Research Station (24.81°S, 149.80°E using the Geocentric Datum of Australia 1994 (Australian Government – Geoscience Australia 2007)), established in 1963, is equidistant between Theodore to the south-east and Moura to the north-east at an altitude of 151 m (Lawrence and Sinclair 1989).

Climate

The region has a subtropical climate with wet summers and low winter rainfall. Seventy percent of the annual average rainfall of 720 mm falls between October and March. Annual evaporation potential is 2133 mm, with average evaporation being at least twice the average rainfall in all months. Rainfall is highly variable, ranging from 11 mm or less in any month, to 165 mm in one day. Brigalow Research Station has an average of 3.5 days per year with minimum temperatures less than zero (Bureau of Meteorology 2005).

Soil types

Soil types in the catchments comprise associations of uniform, fine-textured, dark cracking clays (Black and Grey Vertosols), some with gilgais, and non-cracking clays (Black and Grey Dermosols), and sub-dominant soils of thin-surfaced dark and brown sodic texture contrast soils (Black and Brown Sodosols) (R. J. Tucker, pers. comm.; Isbell 1996). Clay soils (Vertosols and Dermosols) occupy approximately 70% of catchments 1 and 2, and 58% of catchment 3. Sodosols occupy the remaining area in each catchment. The soils have a plant-available water capacity ranging from 160 to 200 mm in the surface 1.4 m. A full soil description can be found in Cowie *et al*. (2007, this series).

Natural vegetation

Before clearing, the catchment site was composed of 3 major vegetation communities, identified by their most common canopy species; brigalow (*Acacia harpophylla*), brigalow–belah (*Casuarina cristata*), and brigalow–Dawson Gum (*Eucalyptus cambageana*). Understoreys of all major communities are characterised by *Geijera* sp. either exclusively, or in association with *Eremophila* sp. or *Myoporum* sp. (Johnson 2004). Projected canopy cover ranges from zero in non-vegetated areas to 100% in tree areas. Litter levels (both leaf and wood) range from 1.9 t/ha in non-vegetated areas to 29 t/ha in tree areas (Dowling *et al*. 1986).

Experimental design and instrumentation

Three contiguous catchments were identified by topographic survey. The areas of the catchments are 16.8 ha (catchment 1, C1), 11.7 ha (catchment 2, C2), and 12.7 ha (catchment 3, C3). Mean slope of the catchments is 2.5%. The catchments were good quality agricultural land, all equally suitable for cropping or grazing (Webb 1971). Each catchment was instrumented to measure runoff using a 1.2-m steel HL flume with a 3.9 by 6.1 m concrete approach box (Brakenseik *et al*. 1979) (Fig. 1). 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 (Fig. 2). As rainfall in central Queensland is summer-dominant, a water year (1 October–30 September) is used in summarising annual data.

Catchment History

Stage I. Calibration phase (January 1965–March 1982)

From 1965 to 1982, the catchments were monitored in their virgin state by collecting rainfall and runoff data. The aim of this calibration phase was to identify the inherent differences in runoff characteristics of the 3 catchments to ensure that any change in hydrology could be attributed to change in land use. This ‘paired catchment’ approach is an established method for assessing changes in hydrology, the main disadvantage being the time required for the calibration period. Data collected during a calibration period can be used to describe differences in catchment responses to a range of weather sequences. A calibration acts as a reference point for a catchment after it is cleared, as well as facilitating a comparison across catchments. Boughton (1985) analysed the first 15 years of this calibration phase and found a high level of correlation between the runoff records of the three catchments.

Stage II. Land development phase (March 1982–September 1984)

In March 1982, vegetation in C2 and C3 was cleared by bulldozer and chain, a traditional method of clearing brigalow lands. The fallen timber was burnt *in situ* in October 1982. In C2, residual unburnt timber was raked to lines on the contour, and burnt. Narrow-based contour banks, a recommended soil conservation management practice at the time, were constructed at 1.5-m vertical spacing (Fig. 2). A grassed waterway was established to carry water from the contour channels to a sediment settling pond in front of each flume. 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. Stage II hydrology was not analysed

Fig. 1. Looking into the brigalow scrub catchment (C1) at the 1.2-m HL flume outlet. Flow height recording equipment is located in the stilling wells (1, 2). Rainfall is recorded with a tipping-bucket raingauge (3).

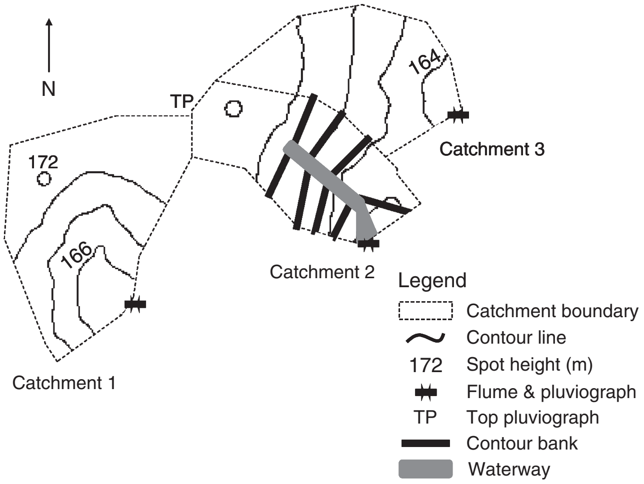

Fig. 2. Schematic diagram of the Brigalow Catchment Study showing catchment boundaries, contour banks, waterway, and the location of rainfall and runoff recording stations.

in detail due its short duration, the marked changes in catchment condition and a high incidence of equipment failure.

Stage III. Land use comparison phase (September 1984–December 2004)

In C2, the first crop sown was sorghum (September 1984), after which annual wheat was grown for 9 years. During this period fallows were managed using mechanical tillage (disc and chisel ploughs), which resulted in significant soil disturbance and low soil cover. In 1992 a minimum tillage philosophy was introduced and in 1995 opportunity cropping (sorghum and wheat) commenced with summer or winter crops planted whenever soil moisture level was adequate and the prospects of in-crop rain were reasonable (Freebairn *et al*. 2006).

The buffel grass (*Cenchrus ciliaris* cv. Biloela) pasture sown in C3 in November 1982 established well with >5 plants/m^2 and 96% groundcover achieved before grazing 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 without feed supplementation. This grazing pressure is regarded as conservative by regional standards (Dawson Catchment Coordinating Association 2004).

More detailed studies of the cropping enterprise in C2 and the grazing enterprise in C3 can be found in Radford *et al*. (2007*a*, this series).

Descriptors of catchment condition

Vegetation survey data show that before land development projected groundcover was comparable between the catchments and consistently >85%. After land development, ground cover was measured using a photographic technique similar to that of Sallaway *et al*. (1988). A camera was suspended on an overhead boom to photograph a ground area of 1.8 by 1.3 m. Images were then projected on to a 100-point grid to estimate percentage cover. Measurements were taken at strategic times such as immediately before and after tillage, at planting, flowering, and harvest, and immediately after runoff. Projected groundcover varied between 0 and 95% in C2 and always exceeded 80% in C3. Figure 3 provides views of the 3 catchments as they typically appear in midsummer in most years.

Approaches for assessing impact of land use on runoff

Given the natural variability in catchment behaviour and weather, multiple lines of evidence are used to explore hydrologic responses to land use changes.

Comparison of observed total runoff

Initial analysis compared measured total runoff between catchments before and after clearing, and attributed relative changes in runoff to land use changes. Analysis of variance was used to determine if the changes were statistically significant. A limitation to this approach is that changes may simply reflect differences in rainfall between the 2 periods. This can be quantified using C1 as a reference, as in the second approach below.

Catchment calibration and regression analysis

Two forms of regression analysis were carried out. The first approach was to regress event runoff from C2 and C3 against C1 (the reference catchment) during Stage I. An event is defined as continuous flow typically occurring from several hours to more than 3 days. Event data provided the highest resolution for comparison between catchments. A similar approach was used by Boughton (1985); however, our analysis uses a longer period of record, corrected catchment areas and hydrograph interpretation.

The resulting regression equations (presented as results) were then applied to post-clearing data to estimate runoff from C2 and C3, had they remained undisturbed. Hydrologic change was defined as the difference between the runoff measured in C2 and C3 after clearing and the runoff estimated by Eqns 1 and 2.

A second analysis compared the regression slopes of cumulative runoff plots for the 3 catchments pre and post development. A change in the regression slope for a catchment between Stages I and III was interpreted as a hydrological change.

Flow duration curves

Flow duration curves (FDCs) provide both statistical and graphical descriptions of runoff probabilities (Brown *et al.* 2005). Total daily runoff FDCs for the period of record of the 3 catchments pre- and post-clearing were generated using the HYFLOW program within HYDSTRA version 7.27.2 (Kisters 2007). Changes in runoff behaviour can be identified by comparing FDCs pre and post clearing. The FDCs for the two Stages of C1 describe differences in the weather sequence between Stages I and III.

Departure of post-clearing runoff observations from hydrological model estimates of runoff from a virgin catchment

A daily rainfall–runoff model, HowLeaky?, V2.15 (McClymont *et al.* 2006) (available from Agricultural Production Systems Research Unit, www.apsru.gov.au) based on the PERFECT model (Littleboy *et al.* 1989), was used to examine the impact of land use change on runoff and soil water. Model predictions of runoff and soil water from the 3 catchments were analysed in the same manner as the first and second approaches and provided a further assessment of the impacts of land use. By modelling the pre and post clearing records of C2 and C3 for the overall trial period, the effect of land use on runoff and soil water can be determined irrespective of inherent catchment differences and climatic sequences.

HowLeaky? was chosen because its predecessor has been tested on similar scales and land uses, and the model is readily accessible, easy to use, and transparent (Rattray *et al.* 2004). Model parameterisation was based on a combination of site-specific measured data and literature. HowLeaky? was run using the crop factor option for calculating evapotranspiration, making vegetation parameterisation efficient and stable, although more dynamic approaches may have resulted in better agreement between observed and simulated runoff values. Model validation was performed against observed runoff data and was considered against several criteria, similar to the approaches of Refsgaard and Knudsen (1996), Lørup *et al.* (1998), and Legates and McCabe (1999). Graphical comparison comprised overlay plots of simulated and observed cumulative daily runoff and scatter plots of daily and monthly runoff. Numerical evaluation compared coefficients of determination (R^2) and coefficients of efficiency (E) between simulated and observed daily runoff data (Nash and Sutcliffe 1970).

Representativeness of the experimental period—rainfall

Figure 4 presents the maximum, 75th percentile, median, 25th percentile, and minimum annual rainfall for the experimental periods and a long-term record from the nearby Brigalow Research Station (1889–2004) (NRM Enhanced Meteorological Datasets 2005). This simple analysis suggests that both wetter and more extreme drier periods have occurred in the past. Stage III of the experiment experienced greater extremes in annual rainfall than Stage I. Stage III had an annual mean 30 mm greater than Stage I but a slight reduction in rainfall per rain day due to a greater number of rain days per year (Fig. 5).

Considerations for rainfall and runoff datasets presented in this paper

Rainfall

Rainfall data presented in this paper came from the recorder at the head point of the catchments (Fig. 2). This site has a complete rainfall record, including 6-min rainfall intensity. Daily totals were determined based on 09:00 hours readings.

Runoff

Due to equipment malfunction, animal interference and extreme weather events, no runoff records were complete for the 40-year period (Table 1). Estimates from the optimised HowLeaky? simulations were used to infill missing data, allowing us to make estimates of total runoff across all catchments. No estimation procedure was reliable where missing records occurred in Stage II due to the short period of record available and the marked changes occurring within the

Fig. 3. Photographs of the 3 catchments as they typically appear in midsummer. Top shows an association of brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*) with an understorey dominated by *Geijera* sp. (C1). Centre photograph shows the cropped catchment (C2) immediately after planting. Contour banks and waterway are visible mid field. Bottom photograph shows the grazed pasture catchment (C3) looking downhill from the watering point. The catchment does not include the mature trees in the background.

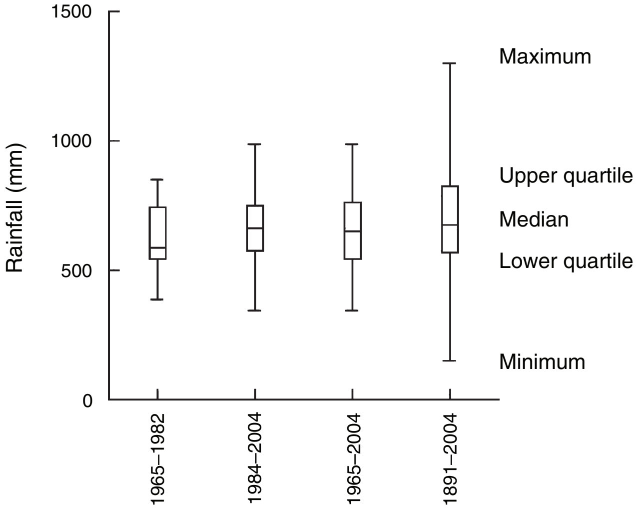

Fig. 4. Box and whisker plots of annual rainfall at the Brigalow Catchment Study site for Stages I, III, entire study period, and long-term record.

catchments. The approximately 13% failure rate is expected given the extreme operating conditions and long periods between runoff events; nevertheless, the runoff record was easily sufficient to allow sensible infilling of missing data, and comparison of catchments.

Results

Runoff observations

Stage I. Calibration phase

In their natural condition dominated by brigalow vegetation, runoff yield from the 3 catchments was approximately 5% of annual rainfall (Table 2). The highest annual runoff occurred in 1976, yielding an average of 146 mm across all catchments (17.8% of rainfall), while the lowest occurred in 1977, yielding <1 mm of runoff. Catchments 1 and 2 had an average of 2 runoff events per year, while C3 had 5 runoff events per year, although it had the lowest total runoff. The extra runoff events in C3 ranged from 0.01 to 1.23 mm, with 97% of these events producing <1 mm of runoff. Analysis of variance of log-transformed annual and monthly runoff data shows no significant difference ($P > 0.05$) in average runoff between the catchments. Runoff was strongly seasonal. Excluding the extra, small runoff events from C3, the 3 catchments showed the same monthly distribution of runoff.

When runoff occurred from all catchments simultaneously and runoff from C1 was >1.5 mm (referred to as comparable events), typical Stage I hydrographs are characterised by total runoff and peak runoff rates in the order C1 > C2 > C3. The total runoff relationship holds for 68% of comparable events, while the peak runoff rate relationship holds for 59% of comparable events. 'Typical' event hydrographs for Stage I are shown in Fig. 6.

The largest comparable event occurred in January 1978, yielding 103 mm of runoff from C1 with a peak discharge of 14.5 mm/h, 92 mm from C2 with a peak discharge of 12.7 mm/h, and 79 mm from C3 with a peak discharge of 11.3 mm/h.

Stage II. Land development phase

In the cleared but unburnt state, C2 and C3 behaved similarly to C1, with no runoff >0.5 mm occurring. After burning, reliable records were available on 2 occasions when comparable events occurred (Table 3). On both occasions C2 and C3 yielded more runoff than C1. Antecedent moisture was similar across all catchments before the second event as it occurred 3 days after the first. Catchment condition varied between C2 and C3 before both events. Although ash provided 85% cover with a mean load of 13 t/ha immediately post burning, its distribution had been altered in C2 by raking and contour bank construction. Catchment 3 had also been sown before these events, with a density of 5.1 plants/m^2 recorded during January 1983.

Stage III. Land use comparison phase

Annual measured runoff values for the 3 catchments are shown in Table 4. Average annual runoff was 32 mm

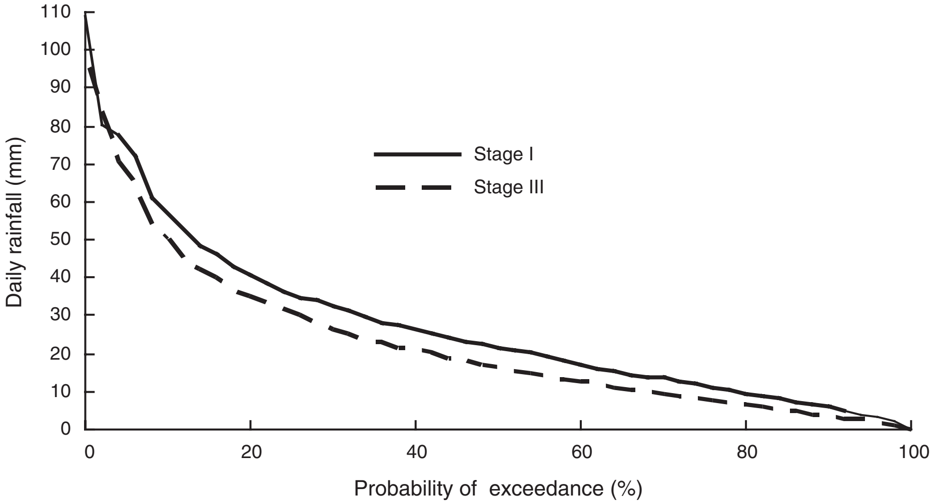

Fig. 5. Frequency distribution of daily rainfall (on rain days) for Stage I (1965–1981) and Stage III (1984–2004) showing a 4.5-mm reduction in daily rainfall over most of the distribution during Stage III.

Table 1. Number of runoff events during Stages I and III in each catchment and number for which data was lost due to equipment failure

Stage	Catchment	Total runoff events	Events lost
I	1	41	7
	2	39	6
	3	82	10
III	1	45	2
	2	93	5
	3	79	19

(5% of rainfall) from the brigalow scrub catchment, 72 mm (11% of rainfall) from the cropping catchment and 60 mm (9% of rainfall) from the pasture catchment. Analysis of variance of log-transformed annual and monthly runoff shows both C2 and C3 > C1 ($P < 0.05$) but C2 not significantly different from C3.

Runoff from C1 reflected the monthly distribution of rainfall. Average monthly runoff depths ranged from zero in June to 7 mm in February (Fig. 7). Runoff from the developed catchments was also seasonal and equalled or exceeded the frequency of runoff from C1 in all months (Fig. 8). From midwinter until the end of spring, C3 yielded the highest runoff. Throughout summer C2 yielded the highest runoff. March and April yielded similar runoff from C2 and C3, while May and June runoff was higher from C2. The lowest average monthly runoff was near 0, occurring in June for all catchments. The highest was 19 mm from C2 in February and 11 mm from C3 in January (Fig. 7). The largest individual runoff events were 68 mm in December 1988 from C1, 121 mm in February 1997 from C2, and 114 mm in April 1998 from C3.

Table 2. Stage I (1965–81) observed annual rainfall and runoff from the three catchments in their virgin state

Year	Annual rainfall (mm)	Catchment 1 (to remain as control)		Catchment 2 (becomes cropping)		Catchment 3 (becomes pasture)	
		No. of events	Total runoff (mm)	No. of events	Total runoff (mm)	No. of events	Total runoff (mm)
1966	591	1	0	1	0	3	2
1967	543	1	4	1	3	5	3
1968	704	1	4	1	3	2	4
1969	383	2	1	2	0	4	1
1970	451	2	0	1	0	4	1
1971	738	6	106	6	95	6	84
1972	547	1	10	1	9	2	7
1973	746	1	3	1	4	2	3
1974	785	4	42	4	40	10	41
1975	561	2	1	2	1	4	2
1976	823	4	161	4	148	6	128
1977	582	2	0	1	0	9	1
1978	848	3	112	3	100	6	83
1979	482	2	41	2	36	6	29
1980	682	4	119	4	107	6	68
1981	534	2	10	2	9	3	11
Mean	625	2	38	2	36	5	29

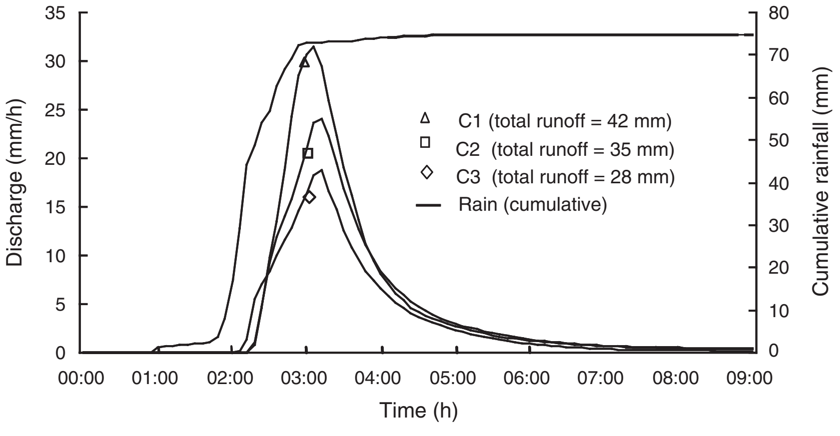

Fig. 6. Runoff hydrographs for the three catchments during a 75 mm rainfall event on 5/11/1978 (Stage 1). Vegetation in all catchments was brigalow scrub.

Table 3. Runoff data for the two measured events in Stage II, land development phase

Catchment 1 has remained brigalow scrub while catchments 2 and 3 have been cleared and burnt

Date	Rainfall (mm)	Runoff (mm) C1	C2	C3
27/04/1983	65	37	46	49
30/04/1983	135	91	92	108

Determination of hydrological change from simple comparison of observed runoff data

Determination of hydrological change during Stage II was difficult due to its short duration, dynamic changes in the condition of the catchments during development, and a high incidence of equipment failure. On the 2 occasions when comparison across the 3 catchments was possible, the catchments being developed for cropping and pasture yielded totals of 10 and 29 mm more runoff, respectively, than C1 (Table 3).

Table 4. Stage III (1985–2004) observed annual rainfall and runoff from the brigalow (C1), crop (C2), and pasture (C3) catchments and adjusted runoff for C2 and C3 using regression calibration equations 1 and 2

Year	Annual rainfall (mm)	Brigalow catchment No. of events	Runoff (mm)	Cropping catchment No. of events	Runoff (mm)	Predicted undeveloped runoff (mm)	Increase in runoff (mm)	Pasture catchment No. of events	Runoff (mm)	Predicted undeveloped runoff (mm)	Increase in runoff (mm)
1985	750	2	23	3	48	22	26	3	28	16	11
1986	587	0	0	4	4	0	4	2	0	0	0
1987	720	2	55	4	88	53	35	4	105	40	65
1988	827	2	59	2	67	56	11	2	100	42	58
1989	827	3	92	6	179	87	92	5	112	66	46
1990	651	2	23	4	64	22	42	5	46	17	30
1991	444	1	13	1	57	13	44	1	40	10	31
1992	645	2	1	7	46	1	46	3	17	0	17
1993	356	0	0	0	0	0	0	0	0	0	0
1994	492	1	8	5	49	7	42	3	39	5	34
1995	620	4	24	5	40	22	24	5	29	17	15
1996	838	4	64	4	123	61	62	8	78	46	33
1997	783	3	61	7	186	58	128	5	94	43	51
1998	987	6	121	9	231	115	116	9	287	87	200
1999	670	6	40	9	83	38	45	9	101	29	72
2000	544	0	0	2	18	0	18	1	0	0	0
2001	575	1	0	5	37	0	36	4	65	0	65
2002	686	0	0	3	8	0	8	2	2	0	2
2003	580	1	48	1	84	45	39	1	57	34	23
2004	513	2	6	4	33	6	28	2	1	4	0
Mean	655	2	32	4	72	30	42	4	60	23	38

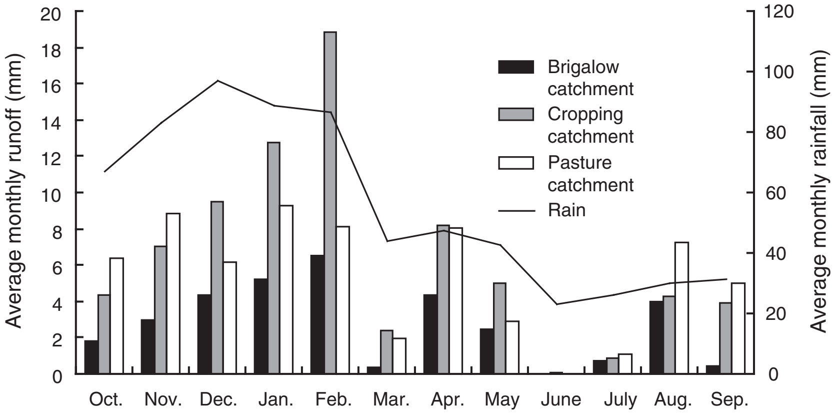

Fig. 7. Average monthly runoff from the three catchments in Stage III: runoff from both the cropping and pasture catchments exceeded that of the brigalow catchment in all months.

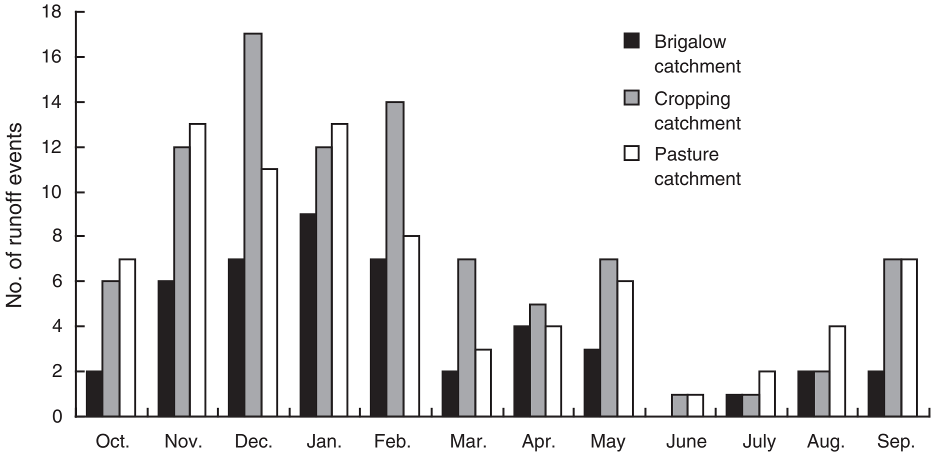

Fig. 8. Monthly distribution of runoff events from the three catchments in Stage III. The frequency was higher in both the cropping and pasture catchments compared to the brigalow catchment in all months.

Comparison of the hydrographs for the second of these events (Fig. 9) with the hydrograph from Stage I (Fig. 6) demonstrates that the hydrologic responses in C2 and C3 had changed. The 2 cleared catchments had greater peak runoff rates and faster times to rise and recession, indicating less surface storage.

In Stage III, direct comparison of runoff totals across the 3 catchments shows that average annual runoff from C2 and C3 was 40 and 28 mm greater, respectively, than C1 (Table 4). Statistically, both C2 and C3 had significantly ($P < 0.05$) greater average annual and monthly runoff than C1, but there was no significant difference between C2 and C3. The brigalow scrub catchment showed no significant difference in average annual or monthly runoff between Stages I and III.

Determination of hydrological change using calibrated catchments

The following equations describe the relationships of runoff between C2 and C3 relative to C1 during Stage I:

$$\text{C2 runoff (mm)} = \text{C1 runoff (mm)} \times 0.9539 \quad (\text{adjusted } R^2 = 0.95, n = 37) \qquad (1)$$

$$\text{C3 runoff (mm)} = \text{C1 runoff (mm)} \times 0.7176 \quad (\text{adjusted } R^2 = 0.887, n = 40) \qquad (2)$$

Intercepts and slopes of each regression equation were tested for statistical difference (from 0 and 1, respectively). The intercepts were not significantly different from zero ($P > 0.05$); however, slopes were significantly different from 1 ($P < 0.001$).

The regression equations (Eqns 1 and 2) were used to provide estimates of runoff from C2 and C3 during Stage III, had they not been cleared. Changes in catchment hydrology were determined from the difference between measured runoff and calculated runoff for the virgin condition. Estimated increases in annual average runoff were 42 mm in C2 and 38 mm in C3 (Table 4). These increases were statistically significant ($P < 0.05$). Runoff increases for the largest individual events were 81 mm from C2 and 78 mm from C3.

Visual comparison of cumulative runoff (observed data) shows that runoff from C2 and C3 was greater than C1 (Fig. 10). A regression analysis of cumulative runoff (observed data) for the 3 catchments showed that the regression

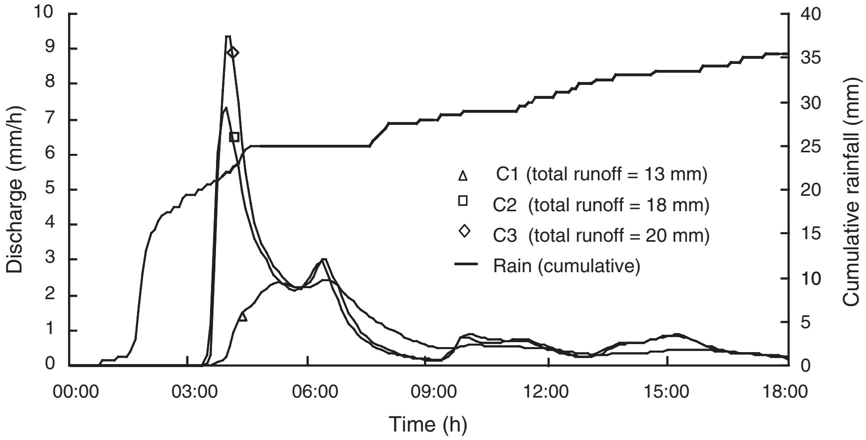

Fig. 9. Runoff hydrographs for the 3 catchments during a 37 mm rainfall event on 30/04/1983 (Stage II). Rises and recessions were more rapid once the brigalow scrub had been cleared (cf. Fig. 6).

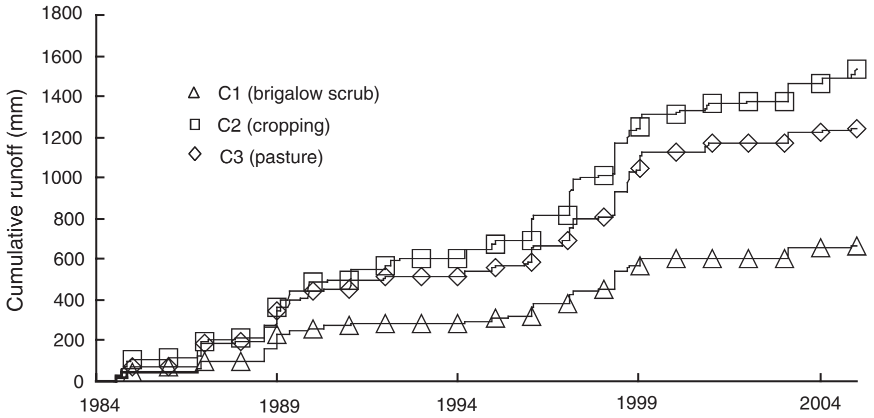

Fig. 10. Cumulative plots of observed runoff showing that runoff from the land uses of cropping and pasture was double the runoff from brigalow scrub.

slopes in Stages I and III were significantly different ($P < 0.001$) for both C2 and C3. Comparison across all 3 catchments in Stage III indicated statistically different regression slopes ($P < 0.001$) and intercepts.

Determination of hydrological change using flow duration curves

The FDCs were compared in the context of low and high flow conditions (Smakhtin 2001; Brown *et al.* 2005). Visual comparison of FDCs for C1 for Stages I and III shows low flows (flows exceeded for >70% of the time) had declined by 3.5 mm (28%) and high flows (flows exceeded for <5% of the time) had declined by 10 mm (22%) (Fig. 11). These changes are attributed to climatic variability, as no land use changes occurred in C1.

Visual comparison of pre-and post-clearing FDCs for C2 shows little change in low flows (Fig. 11). High flows, however, have increased by 18 mm (44%). Similar to C2, C3 shows no change in low flows when compared to its pre-clearing FDC (Fig. 11). High flows have increased by 10 mm (29%).

Given that changed rainfall characteristics in Stage III resulted in a decline in runoff for any probability level for C1, compared to Stage I, direct comparison of post-clearing FDCs from C2 and C3 with their pre-clearing FDCs will underestimate runoff increases.

Determining hydrological change using hydrological modelling

The HowLeaky? model was calibrated to predict daily runoff from each of the 3 catchments under brigalow scrub and runoff from C2 and C3 with the new land uses of cropping and pasture. Runoff Curve Number and soil profile drainage rate were the key parameters optimised in the calibration procedure. Graphical comparison of cumulative runoff plots showed good agreement with observed data. Comparison of observed and predicted cumulative runoff from C1 across all Stages shows predicted runoff to be within 1% of observed runoff. The models of C2 both pre- and post-clearing predicted cumulative runoff to within 10% of observed cumulative runoff. The C3 brigalow model

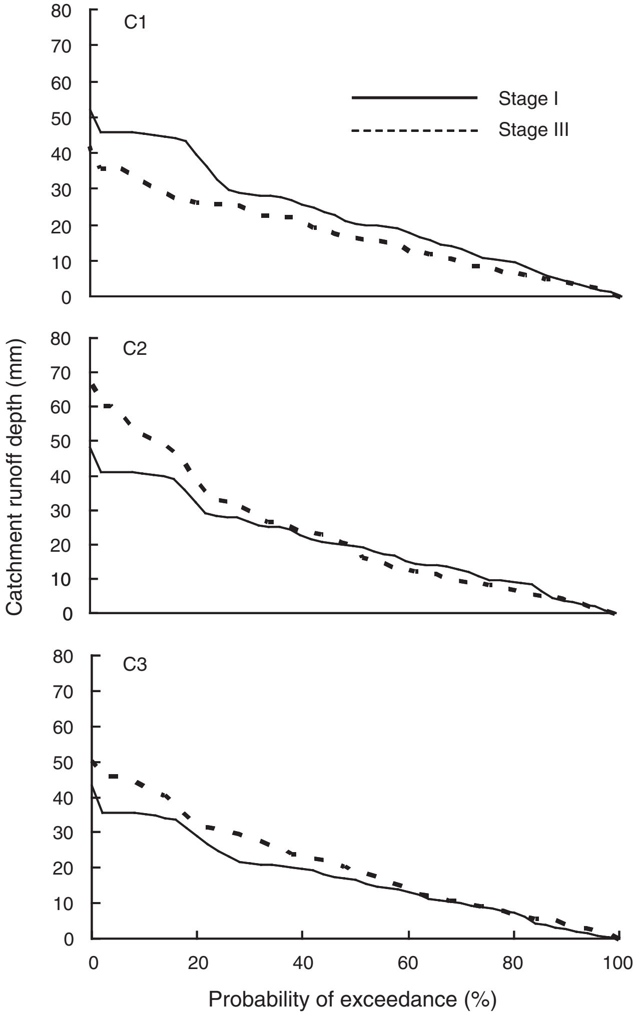

Fig. 11. Daily flow duration curves for the 3 catchments during Stages I and III. C1 shows a decline in both high and low flows in Stage III; C2 and C3 show an increase in high flows of 44% and 29% in volume, respectively.

also predicted cumulative runoff to within 10% of observed cumulative runoff. The C3 pasture model predicted cumulative runoff to within 15% of observed cumulative runoff. In each comparison missing data in the observed cumulative runoff plots were infilled with the modelled estimate.

Scatter plots of observed and predicted daily runoff for all brigalow scrub models gave coefficients of determination (R^2) of >0.9, while monthly and annual totals gave R^2 of >0.93. Scatter plots of observed and predicted daily runoff for the C2 crop and C3 pasture models gave coefficients of determination (R^2) of >0.8, while monthly and annual totals gave R^2 of >0.85. The Nash Sutcliffe coefficient of efficiency (E) was >0.95 for the 3 brigalow scrub models and for the crop and pasture models for daily, monthly, and annual totals.

Predicted annual runoff for brigalow scrub during Stage III was 36 mm from C1, 30 mm from C2, and 33 mm from C3, all between 4.5 and 5.5% of rainfall. Predicted annual runoff for cropping was 68 mm from C2 (10% of rainfall) and for pasture was 54 mm from C3 (8% of rainfall). By difference, the cropping land use produced 38 mm more annual runoff than brigalow scrub, and the pasture land use produced 21 mm more.

As for Fig. 10, visual comparison of cumulative modelled runoff shows that runoff from C2 and C3 is greater than C1 (Fig. 12). Regression analysis of cumulative plots of daily runoff for C2 and C3 shows significant difference ($P < 0.001$) between the regression slopes of each catchment as brigalow scrub and as cropping or grazing. Intercepts of the brigalow scrub models are equal to zero, while the cropping and pasture land use model intercepts are not.

HowLeaky? model predictions of soil water showed that during Stage I, there was no significant difference in total available soil water on a daily, monthly, or yearly basis across the 3 brigalow catchments ($P < 0.05$). February had the highest average soil water, but not significantly more than January ($P < 0.05$). October had the lowest average soil water and was significantly lower than the summer months, March and May ($P < 0.05$).

During Stage III the overall trend was for the new land uses to have significantly greater average monthly soil water than the original land use of brigalow. In the cropping catchment, fallow months during wheat monoculture had significantly higher average soil water than brigalow ($P < 0.05$). This trend continued for the first 2 months after planting then declined, becoming not significantly different to brigalow for the 3–5 months after planting ($P < 0.05$).

Sorghum monoculture showed a similar trend. Again, all fallow months had significantly higher average soil water than brigalow, continuing for the first month after planting ($P < 0.05$). In the second month of crop growth, soil moisture declined, becoming not significantly different to brigalow, then increased to significantly greater than brigalow for the remainder of the crop period ($P < 0.05$).

Comparison of the sorghum and wheat cropping regimes shows wheat had significantly greater average soil moisture in the summer and autumn months and significantly lower average soil moisture from midwinter through spring ($P < 0.05$).

Buffel grass pasture maintained significantly higher average soil water than brigalow ($P < 0.05$) in all months. Within the pasture catchment there was no significant difference in average monthly soil water throughout the year ($P > 0.05$).

Comparing multiple lines of evidence supporting hydrological change

The 4 lines of evidence used to examine hydrological change are in agreement and support the conclusion that runoff has increased with the clearing of land for cropping or grazing (Table 5). Analysis of flow duration curves indicates that hydrologic change is mostly expressed in the larger runoff events.

Had the trial relied upon a single catchment to estimate hydrology changes associated with a change in land use for the same research period, climate effects would have been confounded with land clearing effects. Annual runoff increase due to land clearing for cropping or grazing would have been underestimated by 6 mm. Even if multiple catchments had been used, but no calibration period included, inherent differences in catchment hydrology would not have been described. While the 3 catchments can be considered good pairs, a significant

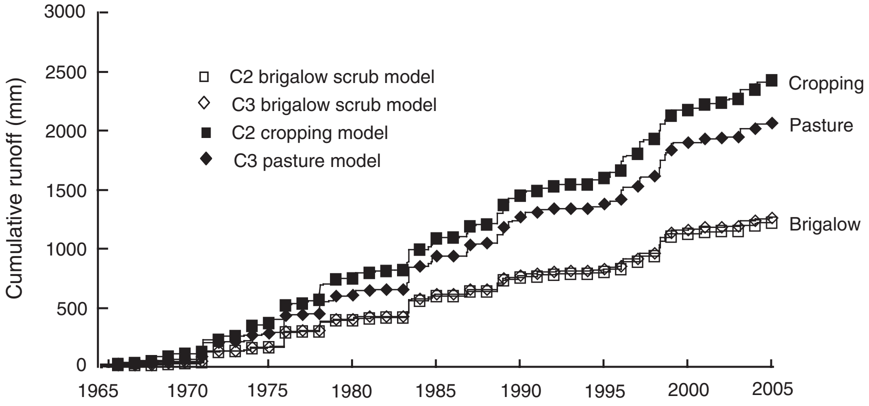

Fig. 12. Cumulative runoff estimates derived from a daily water balance model (HowLeaky?; McClymont *et al.* 2006) showing that runoff from the land uses of cropping and pasture was double the runoff of brigalow scrub.

Table 5. Summary of evidence used to investigate hydrological change in the period 1984–2004

Method of analysis	Runoff increase C2 (cropping)	C3 (pasture)
Observed runoff	40 mm/year	28 mm/year
Calibrated runoff	42 mm/year	38 mm/year
Hydrological modelling	38 mm/year	21 mm/year
Daily flow duration curves (during high flows)	18 mm/day	13 mm/day

calibration effort was required to determine that C2 and C3 had 5% and 24% less runoff under brigalow scrub, respectively. Clearly these intrinsic catchment differences would confound any interpretation of catchment data.

Climatic variability can also skew results of a paired, calibrated catchment design if the observation period is too short. Three-year moving averages of annual runoff from C1 vary from nil to greater than double the 39-year average. The 10-year moving average provides a better estimate, but still ranges from half to one and a half times the long-term average. Hydrological modelling was valuable in estimating missing data and can also be used to provide a synthetic long-term record in order to overcome some of the issues of collecting a representative sample of climatic conditions. However, sufficient data must be available for adequate model calibration, regardless of detailed catchment characterisation or model structure.

Discussion

This study has shown that natural brigalow vegetation in central Queensland yields an average of 5% of annual rainfall as runoff. Developing these landscapes for agriculture more than doubled the runoff component of the water balance at a small catchment scale (10–15 ha), increasing both the frequency and magnitude of runoff. Both of these findings are reflected in the responses of larger catchments; in the nearby Comet River catchment Siriwardena *et al.* (2006) found that before the extensive land development of the Brigalow Scheme, runoff from the undeveloped catchment was 4.2% of annual rainfall. Once developed for agriculture, runoff increased by 40%. It is notable that the Siriwardena paper is one of a very few internationally to demonstrate this phenomenon for larger catchments.

Comparison of runoff from virgin brigalow catchments with other Australian landscapes

Runoff yield from brigalow vegetation is similar to that of eucalypt woodlands in the tropical, subtropical, and grassland areas of Queensland and the Northern Territory. Runoff from eucalypt woodlands in rainfall zones of 550–1250 mm varies, with observations of runoff <0.5% of rainfall (Dilshad and Jonauskas 1992) but more typically 3–4% of rainfall (Prebble and Stirk 1988; Bonell and Williams 1989; Williams *et al.* 1993). These observations have been made in summer and summer-dominant rainfall zones, similar to that of the brigalow bioregion (Bureau of Meteorology 2005).

Runoff from brigalow catchments immediately after clearing

Runoff from the catchments after clearing, but before burning, was similar to the undeveloped brigalow catchment. This can be explained by several factors. First, the catchment condition during this time was similar to its pre-clearing condition with high levels of cover and surface roughness, both of which minimise runoff (Freebairn and Wockner 1986; Carroll *et al.* 1996, 1997; Dilshad *et al.* 1996). Second, rainfall during this period was below average. Only one sizeable rainfall event (25 mm) occurred in the 213-day period.

After burning, the cleared catchments could be expected to run off more than brigalow scrub, as burning reduces cover and increases surface sealing (Mallik *et al.* 1984; Valzano *et al.* 1997; Mills and Fey 2004).

While the land development phase lasted only 2.5 years, hydrograph analysis indicated decreased surface storage and higher overland flow velocities associated with land clearing for cropping or pasture. The 2 event comparisons presented suggest that the short-term runoff increase immediately after clearing is lower than the long-term increase resulting from the new land uses.

Runoff increase with land development

Runoff increase with land development is consistent with Northern Territory research showing increased runoff when grazed pasture replaced eucalypt woodlands (Dilshad and Jonauskas 1992). Water balance modelling in Queensland also supports this conclusion, showing increased runoff from cleared grazed pasture (Williams *et al.* 1993).

Other studies in Queensland show decreased runoff from grazed pasture after clearing, using both water balance modelling (Scanlan and McIvor 1993) and runoff plots (McIvor *et al.* 1995), but these studies compared cleared grazed pastures to uncleared grazed woodlands. As grazing increases runoff from pasture (Scanlan *et al.* 1996), it can also be expected to increase runoff from woodland.

While other studies have compared the effects of land use and management on runoff, few have done so since the time of clearing. Comparisons of runoff from cropping and grazing land uses on catchments previously cropped typically show runoff from cropping to be twice that of pasture (Silburn *et al.* in press). It is likely that the lower runoff from pasture is a result of its ameliorative effects on soil structure previously degraded by cropping, rather than an inherent characteristic of the land use.

Comments on the possible drivers of hydrological change

Given that virgin brigalow is an opportunistic and perennial water user and maintains high cover and low soil water levels (Tunstall 1973), all of which inhibit runoff, clearing could be expected to increase runoff. What was unexpected is the similar average annual runoff increase in the cropping and pasture catchments, given that their management, patterns of water use, and levels of cover differ greatly, and under cropping vary widely through the year.

Soil water

If soil water was the key factor governing runoff in these systems, we would expect the land use that maintained the highest soil water content would run off the most. This is supported by the overall trend of modelled soil water in the cropping and pasture land uses to be significantly greater than brigalow scrub.

With annual crops in central Queensland, soil water is generally allowed to accumulate for 7–8 months of weed-free fallow. Furthermore, water use in the early and late stages of the 4–5 months of crop growth is low. This annual water-use pattern suggests that the cropping catchment should run off more than the perennial brigalow catchment. This was the observed outcome, most noticeably in all 14 runoff events in February, when rain fell during a summer fallow or when a summer crop was at an early growth stage.

Using the same reasoning, the perennial pasture catchment should run off somewhat similarly to the perennial brigalow catchment. This was not observed. While buffel grass is a perennial species, in central Queensland it has an active growing season from mid spring to mid autumn and remains in a dormant state from late autumn to early spring (Hacker and Waite 2001). If rainfall occurs outside this active growing season, the dormant plant is less able to maintain a soil water deficit and runoff is more likely. This may be compounded by its susceptibility to frost. As 50% of foliage on buffel grass is killed at −2°C (Ivory and Whiteman 1978), in most years frost damage is likely to greatly reduce the soil water use of the pasture. Grazing management with high utilisation of pasture would have a similar effect, particularly if heavy grazing occurs during a dry summer and into winter. In relation to soil water use, buffel grass in central Queensland behaves like a summer annual, with runoff responses similar to a cropped system. These runoff responses are most noticeable from August to November.

Cover

If cover is the key factor governing runoff in these systems, brigalow would run off least ($>$85% cover), followed by pasture ($>$80%), and then cropping (0–95%). On an annual basis, this was the observed outcome; however, the increase in average annual runoff was only 4 mm greater for the cropping catchment than the pasture catchment.

Infiltration

Infiltration rate has been shown to decline in cropped soils as a result of cultivation (Bell *et al.* 1997; Connolly *et al.* 1997) and in grazed pastures as a result of hoof impact (Proffitt *et al.* 1995; Daniel *et al.* 2002). Since runoff is equal to rainfall less infiltration (Connolly *et al.* 1997), diminished infiltration in the cropped and pasture catchments should increase runoff. As ley pasture has been shown to increase infiltration in degraded cropping soils (Bell *et al.* 1997; Connolly *et al.* 1998) it is unlikely that the similar runoff responses in the cropped and pasture catchments are solely a result of diminished infiltration capacity.

Soil compaction

High soil water content is an important factor driving runoff (Adamson 1976), and once a soil profile is full, cover has little effect on infiltration (Swartz 1966; Freebairn and Boughton 1985; Carroll *et al.* 1996, 1997). Similarly, cover can be high and infiltration poor if soil structural problems exist. Soil compaction has been identified as a direct contributor to runoff increase (Young and Voorhees 1982; Rohde 2005), and it has been associated with reduced infiltration and plant-available water capacity (Li *et al.* 2001; Tullberg *et al.* 2001), leading to increased runoff. Within central Queensland, total runoff increased from 108 to 175 mm in a 4-year period on an annually compacted vertosol (Rohde 2005). Similar increases were found on a vertosol in south-east Queensland where mean annual runoff was 44% higher in compacted than uncompacted controlled traffic plots (Tullberg *et al.* 2001).

A similar level of compaction is likely to have occurred in both the cropping and pasture catchments. In minimum tillage cropping systems, 85% of the cropped area can be compacted by machinery in 1 year's cropping, and the effects can last for up to 5 years (Tullberg 2005; Radford *et al.* 2007*b*). A period of 21 years of cropping including 15 years of traditional tillage would have left the entire cropped area highly compacted. In the pasture catchment, stocking rate was 0.29–0.71 head/ha with the hoof impacts of each animal compacting an area of 0.01 ha/day (Farris 1954). Theoretically, this grazing pressure results in the entire catchment area receiving hoof impact in 7 months of grazing. Given that the pressures exerted on the soil by cattle are similar to those of light tractors (Ceballos *et al.* 2000), the hoof impacts of grazing for 21 years may be equivalent to 40 tractor passes. This level of compaction is similar to the level imposed on the cropping catchment due to the cumulative effects of planting and harvesting operations. Compaction in both treatment catchments may be acting as a throttle to infiltration, leading to similar runoff increases despite quite different seasonal cover levels.

So why has runoff increased?

When Brigalow scrub was cleared for cropping or pasture, runoff increased to approximately 10% of annual rainfall. This increase in runoff reflects water use patterns that are much more seasonal than natural vegetation, as indicated by the HowLeaky? soil water predictions. For example, buffel grass pasture is active in the summer, and dormant in the winter. Winter crops rely on water stored in the soil over summer fallows, albeit inefficiently, to sustain crop growth in the typically dry winter growing periods. Summer crops similarly rely on stored soil water, although their short growing season of 100–140 days coincides more with the rainfall pattern. In all cases with annual cropping or introduced pasture, significant periods of the year do not have transpiring plants to extract water from depth. We suspect this change in water use pattern is the dominant mechanism responsible for hydrologic change, with soil cover, structural decline, and surface roughness being secondary factors.

Are these results reflective of the wider landscape and what are the implications?

Elsewhere in central Queensland, it is likely that increases in runoff from both cropping and grazing are greater than measured at this site. Opportunity cropping and minimum till practices have been adopted on only 75% of the farming area of central Queensland, and zero-till farming accounts for only half of this area (Australian Bureau of Statistics 2003). The grazing intensity we imposed, while at industry-recommended levels (Partridge and Miller 1991; Partridge 2000), is more conservative than that used on the majority of local commercial enterprises (Dawson Catchment Coordinating Association 2004).

Additionally, there are large variations in rainfall, and thus runoff, over time in central Queensland. This is evident in that the largest individual runoff event produced from the brigalow catchment in Stage III is only 70% of that produced in Stage 1. Given this variability, it is likely that the maximum individual event runoff increases of 81 mm from the cropping catchment and 78 mm from the pasture catchment will be exceeded in the future during wetter periods.

The implications of these findings for agricultural production are that opportunities for additional crop and pasture growth will be missed due to water lost to runoff. The increased reliability of dams and local stream flow for livestock water and irrigation may compensate for these production losses. It is important to note that any increase in stream flow as a result of land development has already been accounted for in the Water Resource Plans of the Department of Natural Resources & Water (Natural Resources & Water 2007). These plans are based on data primarily collected since 1960 and therefore incorporate any increases in stream flow.

The implications for the environment include increased risks of erosion and transport of nutrients and agricultural chemicals off site as a result of clearing for cropping or grazing. There is also potential for the flow in nearby creeks and rivers to occur in different seasons compared with the former brigalow landscape. Such a change may have biodiversity impacts on species and systems reliant on the native flow regime. The increased runoff may prove beneficial in enhancing groundwater recharge.

Conclusions

Developing brigalow lands for cropping or for grazing on improved pasture increases the frequency and volume of runoff compared to the natural system. The seasonal distribution of the runoff also changes, and differs according to the new system of land use. The key drivers of changes in hydrology are primarily changes in water use patterns but also changes in soil compaction, soil cover, soil structural decline and surface roughness.

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