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# The effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savanna (northern Australia)

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## Abstract

The effects of three fire regimes—(1) burning early in the dry season (June), (2) burning late in the dry season (September) and (3) not burning (protected from wildfires)—on the water quality, water yield and export coefficients of three intermittent streams, which flow between December and June, have been examined in a tropical savanna in northern Australia. The study was conducted over a three year period in Kakadu National Park, and employed a comparative catchment approach though without any pre-treatment data. The canopy cover, density of riparian vegetation, litter- and ground-cover of the catchment burnt early in the dry season (catchment E, stream E) and the unburnt catchment (catchment U, stream U) were similar. Fires lit late in the dry season (catchment L, stream L) however resulted in tree mortalities, and a lower canopy cover (50% less), riparian tree density (80% less) and litter cover, and increased amounts of bare ground; thereby increasing catchment L's susceptibility to erosion. This resulted in episodic runoff events from catchment L in November and December, before continuous wet season flow. These events, absent in catchments E and U, featured high concentrations of total suspended sediment (TSS), volatile suspended sediment (VSS), N, P, Fe and Mn up to 10 times those measured later in the wet season. During continuous wet season flow between December and June, baseflow water quality of the three streams were similar. Storm runoff concentrations for N and P were also similar, however stream L storm runoff concentrations of TSS, VSS, Fe and Mn were 2–5 times higher than those measured in streams E and U. Despite this, only the export coefficients for TSS from catchment L (average 61 kg ha$^{-1}$) were significantly higher (average 2.4 times) than catchment E and U coefficients. This was attributed to the overwhelming influence of stream volume, relative to concentration, in determining stream load and hence catchment export coefficients (load/catchment area). The apparently negligible impact of the fire regimes on VSS, N, P, Fe and Mn export coefficients, and also the overall low sediment export coefficients for the three catchments which were up to 100 times less than that reported for other tropical environments, were ascribed to the low catchment slopes (average 0.5%), low soil fertility, maintenance of a protective surface gravel lag, the negligible impact of the fire regimes on water yield, and the sometimes lengthy (maximum 6 months) period between burning and runoff.

*Keywords*: Fire; Sediment; Nitrogen; Phosphorus

## 1. Introduction

Fire is a dominant feature of tropical savannas, which are characterised by a seasonal cycle of profuse vegetation growth over the wet season, followed by a period of "drought" lasting several months when

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grasses, herbs and other vegetation dries out (Gillon, 1983). Prior to human habitation of the Australian continent, wildfires in the tropical savannas (i.e. woodlands and open forests; *sensu* Mott et al., 1985) were ignited by lightning strikes during the end of the dry season, between October and December (Gill et al., 1990). Aboriginal occupation, beginning at least 50,000 years ago, has increased fire frequency and extended the duration of the fire season. Traditional fire management by Aboriginal people produced a mosaic of burnt and unburnt land (Haynes 1985), with most fires lit between June and October (Braithwaite, 1991). Over the last 150 years, European settlement has further modified the incidence of fire. Today, the current dominant fire management regime is early dry season (May–June) burning to reduce the risk of wildfires later in the 'dry' (Andersen et al., 1998), though these still occur. The most appropriate fire regime, however, to achieve land-use and social objectives, whilst maintaining the ecological integrity of the savannas is a contentious issue in Australia (Andersen et al., 1998) and elsewhere in the tropics (Gillon, 1983).

Most research into the hydrological response of catchments to burning has been conducted in subtropical and temperate climates (see reviews by Chandler et al., 1983; Attiwill, 1991; Bayley and Schindler, 1991; Scott, 1993). Exceptions, however, include experiments performed by Hudson et al. (1983a,b) into the effect of fire on the steep terrain of the Honduran pine savannas, and studies of the impact of combined clearing-felling and burning of Malaysian rainforest (Malmer, 1996). To assess the effect of fire management on the Australian tropical savanna woodlands, a landscape-scale fire experiment was undertaken (Andersen et al., 1998) at Kapalga Research Station in Kakadu National Park (Fig. 1).

The effects of fire on catchment erosion and geochemical cycling of plant nutrients are two critical issues, amongst others, addressed by this experiment (Andersen et al., 1998). Extrapolation of the findings of fire studies from other regions to the savanna woodlands of Australia was considered unwise, as the impact of catchment burning on streams varies considerably. For example, sediment loads following fire range from undetected impacts (Richter et al., 1982; Britton et al., 1993) to 100-fold increases (Brown, 1972; Wells, 1985). This reflects the range of factors which affect the hydrologic response of catchments to fire. These factors include: (1) the frequency, intensity and spatial extent of burning; (2) climate, notably rainfall pattern; (3) catchment characteristics (e.g. slope, soil, ground-cover, land-use, the proportion of vegetation burnt and its regrowth); and (4) the time interval between burning and subsequent runoff.

This paper examines the effect of three fire regimes—(1) early dry season fires, (2) late dry season fires, and (3) no fire (protected from wildfires)—on stream water quality, water yield and export coefficients at Kapalga Research Station. Sediment export represents the synthesis of catchment erosion, whilst fluvial exports of nitrogen and phosphorus are fundamental components of any catchment nutrient budget. The concentrations and loads of iron and manganese have also been determined. Elevated concentrations of these metals in water supply reservoirs can impair the aesthetic quality of potable water (WHO, 1984). Moreover, the aquatic chemistry of iron is linked to the solubility of phosphorus (Stumm and Morgan, 1981), and indirectly the trophic state of lakes. The effect of fire on some catchment vegetation features, of hydrologic significance, are also reported.

## 2. Climate, catchment descriptions and fire treatments

Kapalga Research Station (132°25′E, 12°40′S) lies in the wet/dry tropics of northern Australia (Fig. 1). Annual rainfall at Jabiru, 50 km east of the study sites, averages 1473 mm, with 66% falling between January and March, and 98% falling between October and April. Convective storms account for most of the region's rainfall, whilst larger scale weather phenomena such as cyclones and rain depressions can produce sustained rainfall lasting up to 10 days. Between December and April, rainfall exceeds evapotranspiration and the requirements for soil moisture replenishment (McDonald and McAlpine, 1991). Most streams in the region are intermittent, typically flowing between December and June.

The wet season spans two calendar years. For brevity, each wet season is referred to by the second year, when the majority of rain falls. For example, the

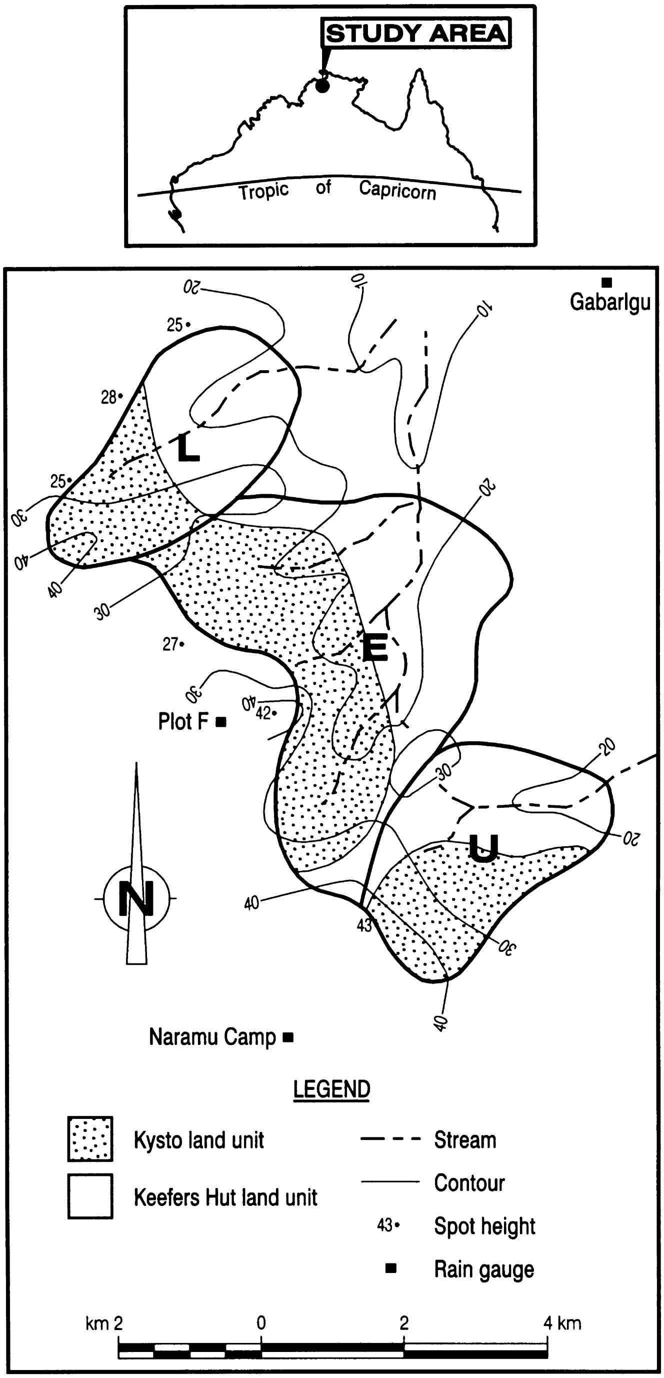

Fig. 1. Study catchments and rain gauges at Kapalga Research Station (Kakadu National Park, northern Australia). Catchment E was burnt early in the dry season (June), catchment L later in the ‘dry’ (September), whilst catchment U was protected from fires and remained unburnt.

1993 wet season refers to the period from October 1992, when the first rains fall, to May 1993 and includes the high rainfall months of January, February and March 1993.

The three study catchments lie within 6 km of each other (Fig. 1). Catchments L and U are of similar size, being 6.7 and 6.6 $km^2$, respectively. Catchment E is 18.0 $km^2$, almost three times the area of the other two catchments (Fig. 1). The terrain of the three catchments is gently undulating, with slopes averaging 0.5% (Fig. 1). The catchments are 50 km inland from the Arafura Sea coastline at an average elevation of 30 m (Fig. 1).

Intense weathering has produced soils of low fertility (Calder and Day, 1982; Day et al., 1983; Hubble et al., 1983), whilst laterisation has led to iron enrichment of the soils, and the formation of iron nodules, ironstone gravels and outcrops of ferricrete (Story et al., 1969; Isbell, 1983; Duggan, 1988). A surface veneer of ironstone gravels and sand is common. Duggan (1988) reports the soils in the region are generally well drained, though percolation can be restricted by a ferricrete horizon. Outcrops of ferricrete, and exposed parent rock, are negligible as a percentage of total area in the three catchments.

The Kapalga catchments lie on the Koolpinyah land surface which has been formed by the erosion of older surfaces comprising mainly of Late Tertiary sediments (Story et al., 1969). The upper portion belongs to the Kysto land unit (*sensu* Story et al., 1969; Fig. 1) with soils to 1 m depth (Cook, unpublished data) and classified as red and yellow Kandosols (*sensu* Isbell, 1996), whilst the lower catchment belongs to the Keefers Hut land unit (*sensu* Story et al., 1969), with deeper soils (maximum 1.5 m, Cook, unpublished data) classified as grey and brown Kandosols, arenic Rudosols and orthic Tenosols (*sensu* Isbell, 1996). The Kysto land unit comprises, respectively, 42, 45 and 53% of the catchments L, U and E. Soil clay contents range from 5–15% at the surface to 15–30% at depth, with ironstone nodules and ferruginised fragments of parent material typically increasing with depth (Cook, unpublished data).

Kandosols (*sensu* Isbell, 1996) describe soils that lack strong textural contrast, with massive or weakly structured B horizons and are not calcareous. They approximate the FAO–UNESCO (1990) Ferrosols classification. Rudosols (*sensu* Isbell, 1996) refer to soils that have negligible pedologic organisation and can be classed as FAO–Unesco Leptosols, Fluvisols, Solonchaks, Arenosols and Regosols (Isbell et al., 1997). Tenosols (*sensu* Isbell, 1996) are weakly organised, apart from the A horizons, and would be classed as mainly FAO–UNESCO (1990) Cambisols, Leptosols, Fluvisols (Isbell et al., 1997).

Catchment vegetation consists mainly of open forest, dominated by mixed *Eucalyptus* communities (Wilson et al., 1990). Canopy dominants are mainly *Eucalyptus miniata* and *E. tetrodonta*, with a range of other genera with pan-tropical affinities (e.g. *Terminalia*, *Buchanania*) comprising the canopy sub-dominants (Williams and Douglas, 1995; Russell-Smith, 1996). Crown canopy cover ranges from 30 to 80% and canopy height ranges from approximately 12 to 18 m (Williams and Douglas, 1995; Russell-Smith, 1996). Total basal area ranges from approximately 7 to 13 $m^2\,ha^{-1}$ (Cook, 1994). The under-storey is dominated by tall C4 grasses which may reach a height of up to 3 m during the wet season (Russell-Smith, 1996). The dominant grasses include annual (*Sorghum* spp.) and perennial (*Heteropogon triticeus*) species (Williams and Douglas, 1995; Russell-Smith, 1996). The grasses cure progressively throughout the dry season and provide much of the fuel for fires. The fuel loads in catchments burnt early in the dry season were about 40% lower (average 3.2 $t\,ha^{-1}$), and comprised mainly of grass (72%), compared to catchments burnt later in the ‘dry’ which featured a lower proportion of grass (41%) and higher proportion of leaf material (Williams et al., 1998).

Apart from a small number of bush tracks and unsealed roads on the catchment boundaries, there has been no clearing in the study catchments. The catchments are in a near undisturbed state.

Three fire regimes were investigated (Fig. 1): early dry season fires (catchment E, stream E) lit in June, late dry season fires lit in September (catchment L, stream L) and an unburnt catchment (U, stream U) protected from fires spreading into the catchment, though subject to lightning strikes. Experimental fires were lit annually between 1990 and 1994. Prior to this, the catchments were burnt by low intensity fires in 1988, and remained unburnt in 1989 (Williams et al., 1999). This study employed a comparative catchment approach, and assumed the three

Table 1
Fire intensity, extent of catchment burning and the proportion of ground cover burnt by fires lit early and late in the dry season at Kapalga Research Station, northern Australia

| Parameter | Year | Catchment E, burnt early in the dry season | Catchment L, burnt late in the dry season |
|---|---|---|---|
| Fire intensity (kW $m^{-1}$)[a] | 1990 | 5000 | 18 000 |
| | 1991 | 1000 | 1900 |
| | 1992 | 300 | 6000 |
| | 1993 | 1000 | 6000 |
| | 1994 | 3800 | 7000 |
| | *Average* | 2200 | 7800 |
| Estimated percentage area of each catchment burnt by experimental fires[b] | 1990 | 100 | 100 |
| | 1991 | 70 | 95 |
| | 1992 | 90 | 100 |
| | 1993 | 55 | 100 |
| | 1994 | 70 | 100 |
| | *Average* | 77 | 99 |
| Ground cover remaining after fire (% of pre-fire ground cover)[c] | 1990 | 0 | 0 |
| | 1991 | 30 | 3 |
| | 1992 | 12 | 0 |
| | 1993 | 26 | 0 |
| | 1994 | 21 | 0 |
| | *Average* | 18 | $< 1$ |

[a] Subset of data reported by Williams et al. (1998).
[b] Andersen et al. (1998, Table 2).
[c] Williams, unpublished data. See Williams et al. (1998) for details on the methods used to measure fire intensity.

catchments were not intrinsically different. Whilst the authors believe this assumption is justified, based on the catchments' common landforms and management history, the findings presented here cannot, nevertheless, be considered totally conclusive owing to the absence of pre-treatment data to evaluate the contribution made by any hydrologic differences between the catchments unrelated to the fire treatments.

The intensity of fires was measured by the Byram line of fire intensity, which is defined as the heat yield of fuel × fuel load × rate of forward spread (Byram, 1959). Fires lit early in the dry season were, on average, 78% less intense than fires lit late in the 'dry' (Table 1). The high fire intensities measured in 1990, compared to subsequent years, resulted from the accumulation of fuel since 1988. Crown fires were not observed during the study (Williams et al., 1998). The intensity of the Kapalga fires were relatively low compared with intensities of 100,000 kW $m^{-1}$ reported for forest fires in temperate Australia (Gill and Knight, 1991). Late dry season fires burnt almost the whole catchment and incinerated nearly all ground cover (Table 1). Early dry season fires, in contrast, were not as extensive (Table 1), burning between 55 and 100% of the catchment, and an average of 77% of ground cover. A smaller proportion of catchment E's riparian zone was burnt, compared to the remainder of the catchment, because these areas dried out more slowly. Fires late in the dry season, however, burnt through the riparian zone and over the dry stream beds.

## 3. Methods

### 3.1. Rainfall, and water sample collection and analysis

Daily rainfall was measured at Naramu Camp (Fig. 1), 2 km south-west of catchment U's headwaters. Over the 1993 and 1994 wet seasons, fortnightly rainfall totals were also measured at Gabarlgu, 4 km north of the hydrograhic station on stream L, and Plot *F*, 1 km west of catchment E (Fig. 1).

At a flume on each stream, hydrographic data and water samples were collected over the 1993, 1994 and 1995 wet seasons for streams L and U, and the latter two years for stream E. Water levels were recorded continuously, and discharge calculated from a rating curve based on at least 10 gaugings over a range of discharges. Water samples were collected automatically in response to stream discharge, to sample storm events, and on average every 3 days during periods of baseflow. Between 82 and 219 samples were collected from a station over a wet season, varying with the number of storm events and the incidence of equipment failure. At least two-thirds of storms and baseflow periods were sampled in any one year for an individual stream.

Water samples were analysed by APHA (1985) standard methods for the following variables and, in parentheses, APHA method numbers: total phosphorus (424F), nitrate (418F), nitrite (418F), total Kjeldahl nitrogen (420A, 417G), and total and volatile suspended sediment. The latter approximates organic matter. Over the first two wet seasons, filterable and residual iron and manganese (303A, 304) were analysed, and summed to give total concentrations. Over the third wet season, water samples were analysed directly for total concentrations of iron and manganese (303A). The three nitrogen concentrations were summed to give total nitrogen.

### 3.2. Hydrograph separation into periods of baseflow and storm runoff

Baseflow refers to runoff derived from groundwater and soil water of longer residence time than stormflow, which refers to runoff associated with overland flow and subsurface flow of shorter residence time. These flow categories are, however, arbitrary and constitute a conceptual convenience rather than a definitive description of the source and path of water (Nathan and McMahon, 1990). The hydrographic records for the Kapalga streams have been separated into periods of baseflow, and periods comprising both stormflow and baseflow which are referred to as storm runoff. This separation method was chosen to calculate the water quality of storm runoff events and baseflow periods directly from the concentration data, and does not require separation of storm runoff into its stormflow and baseflow components and estimation of their respective concentrations. This latter method has been applied to the analysis of solutes (e.g. Lesack, 1993), but was considered inappropriate for particulates because their concentrations are influenced by in-stream processes such as sedimentation, resuspension, production of organic detritus, and stream bank erosion.

The separation methodology applied to the Kapalga hydrographs requires only two criteria; one for the commencement, and the second for the cessation of a storm runoff event. The criterion for the commencement of a storm event was defined by a rapid rise in total runoff and the proportion of stormflow, and concurrent sharp decrease in the proportion of baseflow (Fig. 2a). The proportion of total flow comprising baseflow or stormflow was determined according to Nathan and McMahon (1990), applying a filter parameter value of 0.925. The authors report their technique provides a similar stream baseflow/stormflow separation to traditional graphical techniques for a range of stream variabilities and catchment sizes, whilst being fast and objective.

Selecting a criterion for the end of a storm event is more arbitrary, as the passage from stormflow influenced water quality to baseflow influenced water quality is transitional, rather than discrete. Moreover, as a proportion of total flow, baseflow tended to increase asymptotically relative to total flow (Fig. 2b). The approach applied here was to select a proportion of total flow represented by baseflow to mark the cessation of a storm runoff event. This was based on careful examination of water quality data during and following a storm. The cessation of a storm runoff event was defined when baseflow comprised 80% of total flow (Fig. 2b), as water quality concentrations immediately preceding this value more closely resembled storm runoff water quality, rather than baseflow quality several days later. If a subsequent runoff event intervened before the 80% value was reached, a new runoff event was declared (Fig. 2c).

The volume of baseflow and storm runoff was calculated by trapezoidal integration. Selection of

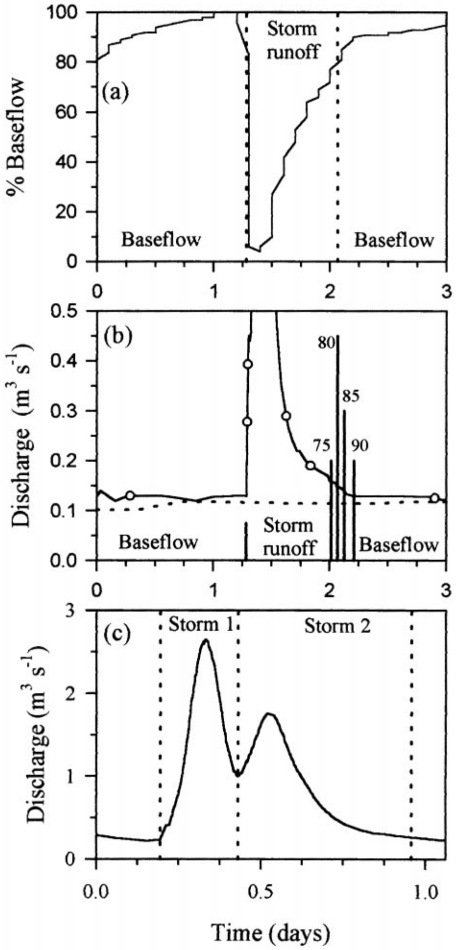

Fig. 2. Examples of hydrograph separation into periods of baseflow and storm runoff. Storm runoff comprises both stormflow and baseflow. (a) Stream L, 22 January 1995. Baseflow as a percentage of total discharge, determined by the technique of Nathan and McMahon (1990). (b) Stream L, 22 January 1995. Water sample collection (open circles), total discharge (continuous line) and baseflow discharge (dotted line). The vertical lines represent different criteria (baseflow as a percentage of total discharge) to select the cessation of storm runoff. (c) Stream L. 27–28 January 1995. Consecutive storm runoff events.

threshold values close to the 80% value varied the volume of storm runoff by approximately 6%. For example, over the 1995 wet season, the volume of storm runoff from stream L, compared to the 80% value, was 4.4% lower for a 75% threshold, and 5.3 and 8.8% higher for threshold values of 85 and 90%, respectively.

### 3.3. Estimation of storm runoff and baseflow concentrations and export coefficients

The water quality of baseflow and storm runoff periods is summarised by their volume-weighted mean concentrations. The number of samples representing a storm varied in proportion to the storm's maximum discharge; ranging from three samples for small storms to 18 samples for the largest storm runoff events. Volume-weighted mean concentrations of baseflow and storm runoff periods were calculated by trapezoidal integration, for integration periods defined by the mid-point between sample times.

Not all baseflow and storm runoff events were sampled. The quality of baseflow periods not sampled was estimated by averaging the concentration of samples collected immediately preceding and following the unsampled baseflow period. This is considered a reasonable approach because baseflow concentrations of consecutively sampled periods, for all six water quality parameters, varied by less than a factor of two.

The volume-weighted mean concentrations of unsampled storm runoff events were estimated by stepwise linear regressions. For each stream and wet season, a regression was computed for each water quality variable, where the dependent variable comprised the calculated storm volume-weighted mean concentrations from sampled storm runoff events. Five independent variables were selected based on the hydrological features of the storm and antecedent conditions. These variables were: (1) storm duration, (2) storm maximum discharge, (3) the time interval between the commencement of continuous wet season flow and the storm's maximum discharge, (4) the time interval between the discharge maxima of the storm not sampled and the preceding storm, and (5) the maximum discharge of the preceding storm.

Each regression was performed using untransformed, $\log_{10}$ transformed and $\log_{10}$–$\log_{10}$ transformed data to satisfy assumptions of normality and equal variance. All regressions were tested for statistical significance at the 5% level by an analysis of variance for the regression and its residuals. To estimate the volume-weighted concentrations of storms not sampled, the regression with the highest coefficient of determination ($R^2$) was selected. The regressions accounted for an average of 60%, and between 29 and 95%, of the variation in the dependent variable (Table 2). The collation of the data from three wet seasons for a stream did not generally improve the coefficients of determination which were on average one-third less than the average of all the individual regression $R^2$ values (Table 2).

A statistically significant regression was not determined for all water quality parameters (Table 2). In such cases, the volume-weighted mean concentration of a storm not sampled was equated to the average of all the storm volume-weighted mean concentrations for that wet season.

Wet season loads for each water quality variable were calculated by multiplying volume-weighted mean concentration and discharge volume, for each baseflow and storm runoff period, then summing over the total wet season. Annual export coefficients have been calculated by correcting loads for catchment area.

### 3.4. Vegetation surveys

Canopy cover in the catchments was assessed in December 1993. At three sites in each catchment (including at least both land units) six measurements of percentage canopy cover were made using a convex, hemispherical densiometer (Model-A, Forest Densiometers, Bartlesville, Oklahoma, USA). The densiometer was held at a height of approximately 1 m, and an average was taken of four readings made at right angles to each other (Lemmon, 1957).

In October 1994, woody vegetation was sampled in the middle and lower reaches of stream L and U. At each reach, four quadrats (two on each bank) were located within a randomly selected 200 m section. Each quadrat enclosed an area of 0.06 ha, running 30 m along the bank and 20 m away from the bank. To calculate tree density, all woody vegetation above 1 m height was counted in each quadrat.

### 3.5. Statistical tests

Paired-sample *t*-tests (Zar, 1974) have been conducted to test the hypothesis that the difference between stream L and U variable values, over three wet seasons ($n = 3$), is zero, assuming these differences are normally distributed about zero. This test was chosen, in preference to the standard *t*-test which tests equality of means, to take into account inter-annual influences associated with wet season rainfall. Stream E has not been included in these tests because it was represented by only two wet seasons of data.

Vegetation and storm water quality data have been analysed by single and multiple ANOVAs, and *t*-tests (Zar, 1974). To satisfy the assumptions of normality and equal variance, the data has been $\log_{10}$ transformed. All tests were performed at a 5% level of significance. Multiple comparisons have been conducted for statistically significant ANOVAs by the Tukey procedure (Zar, 1974) to determine which variable means differ.

## 4. Results

### 4.1. Catchment and riparian vegetation

Canopy cover was significantly different between the three catchments (one-way ANOVA, $p = 0.017$), with cover in catchment L about half that in catchments E and U (Fig. 3a; $L < E = U$, Tukey's test, $p < 0.05$). This difference was attributable to high tree mortality in catchment L caused by fire (Williams et al., 1999).

Although not quantified during the wet season, bare ground cover was higher in catchment L, relative to catchments E and U. The loss of litter cover by burning in catchment L was compensated to some extent however, by leaf fall caused by canopy scorching.

Tree density in the riparian zone was significantly different in catchments L and U, with density in catchment U five times the density in catchment L (Fig. 3b; three-way ANOVA, $p < 0.001$). A survey of the riparian woody vegetation in catchment E was undertaken in 1997, after the catchment continued to be burnt annually early in the dry season. Although not directly comparable to the surveys conducted in 1993, results indicate that riparian tree density is similar to catchment U (Douglas, unpublished data).

### 4.2. Rainfall and stream discharge

Total annual rainfall for the 1993, 1994 and 1995 wet seasons averaged, respectively, 1476, 1336 and 1652 mm (Table 3). The predominance of rainfall by convective storms, and their sometimes small rainfall

Table 2

Stepwise linear regressions, using an entry criterion of $F = 4.0$, to determine the volume-weighted mean concentration of unsampled storms for TSS (total suspended sediment), VSS (volatile suspended sediment), P, N, Fe and Mn. The regression analyses tests for the statistically significant contribution of five independent variables, listed below (A,B,C,D,E). The regressions were performed on untransformed and transformed data (see below). Each regression's variables are listed with the cumulative regression coefficient of determination ($R^2$), in order of their decreasing contribution to $R^2$. The probability of each regression is also presented. A regression was not selected when an analysis of variance for the regression and its residuals exceeded 0.05. The early burnt catchment was lit in June, whilst the late burnt catchment was lit in September[a]

| | Early burn, 1994 | Early burn, 1995 | Early burn, both years | Late burn, 1993 | Late burn, 1994 | Late burn, 1995 | Late burn, all years | Unburnt, 1994 | Unburnt, 1994 | Unburnt, 1995 | Unburnt, all years |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TSS | A: 0.51<br>E: 0.72<br>$p = 0.03$ | C: 0.71<br>$p < 0.001$ | C: 0.31<br>D: 0.57<br>$p < 0.001$ | D$^{*}$: 0.41<br>C$^{*}$: 0.64<br>B$^{*}$: 0.80<br>$p = 0.046$ | A: 0.36<br>$p = 0.05$ | A$^{*}$: 0.40<br>C$^{*}$: 0.65<br>$p = 0.005$ | A$^{*}$: 0.24<br>B$^{*}$ :0.36<br>C$^{*}$: 0.53<br>D$^{*}$: 0.59<br>$p = 0.001$ | C$^{*}$: 0.93<br>$p < 0.001$ | D$^{**}$: 0.64<br>A$^{**}$: 0.82<br>$p = 0.002$ | C: 0.41<br>B: 0.72<br>A: 0.78<br>$p < 0.001$ | C$^{**}$: 0.39<br>$p < 0.001$ |
| VSS | A$^{*}$: 0.79<br>$p = 0.001$ | C: 0.34<br>$p = 0.011$ | D$^{*}$: 0.40<br>A$^{*}$: 0.57<br>$p = 0.001$ | A$^{*}$: 0.49<br>C$^{*}$: 0.73<br>$p = 0.028$ | A$^{**}$: 0.57<br>B$^{**}$: 0.079<br>C$^{**}$: 0.87<br>$p = 0.006$ | No regr. | A$^{*}$: 0.25<br>B$^{*}$: 0.40<br>C$^{*}$: 0.45<br>D$^{*}$: 0.52<br>$p = 0.029$ | C: 0.69<br>$p < 0.001$ | E: 0.62<br>A: 0.85<br>$p = 0.015$ | C: 0.31<br>B: 0.48<br>$p = 0.014$ | B: 0.44<br>E: 0.50<br>$p < 0.001$ |
| P | A: 0.45<br>$p = 0.047$ | A$^{*}$: 0.59<br>$p < 0.001$ | A$^{**}$: 0.30<br>E$^{**}$: 0.43<br>$p = 0.006$ | No regr. | A$^{*}$: 0.59<br>$p = 0.006$ | A$^{*}$: 0.45<br>C$^{*}$: 0.59<br>$p = 0.042$ | A$^{*}$: 0.31<br>D$^{*}$: 0.38<br>$p = 0.045$ | No regr. | A$^{**}$: 0.68<br>$p = 0.003$ | E$^{*}$: 0.29<br>$p = 0.022$ | A$^{**}$: 0.35<br>$p < 0.001$ |
| N | D$^{**}$: 0.51<br>$p = 0.030$ | A$^{**}$: 0.32<br>$p = 0.014$ | A: 0.22<br>D: 0.34<br>$p = 0.046$ | A$^{*}$: 0.92<br>C$^{*}$: 0.95<br>$p = 0.049$ | E$^{**}$: 0.35<br>B$^{**}$: 0.57<br>D$^{**}$: 0.78<br>$p = 0.009$ | A$^{**}$: 0.41<br>B$^{**}$: 0.56<br>$p = 0.039$ | A$^{*}$: 0.51<br>D$^{*}$: 0.62<br>$p = 0.001$ | C$^{**}$: 0.27<br>A$^{**}$: 0.47<br>E$^{**}$: 0.63<br>$p = 0.015$ | A$^{*}$: 0.42<br>$p = 0.042$ | B$^{*}$: 0.34<br>$p = 0.012$ | B$^{**}$: 0.26<br>$p < 0.001$ |
| Fe | No regr. | E: 0.23<br>C: 0.43<br>$p = 0.017$ | D$^{**}$: 0.18<br>$p = 0.028$ | D$^{*}$: 0.39<br>$p = 0.048$ | B$^{**}$: 0.33<br>$p = 0.062$ | C$^{**}$: 0.28<br>A$^{**}$: 0.50<br>B$^{**}$: 0.71<br>$p = 0.008$ | C$^{*}$: 0.14<br>D$^{*}$: 0.23<br>$p = 0.002$ | No regr. | E: 0.50<br>C: 0.73<br>$p = 0.048$ | B: 0.29<br>$p = 0.022$ | No. regr. |
| Mn | D: 0.84<br>$p < 0.001$ | No regr. | D$^{**}$: 0.23<br>$p = 0.011$ | C$^{**}$: 0.39<br>$p = 0.017$ | No regr. | A: 0.26<br>C: 0.47<br>$p = 0.019$ | C$^{**}$: 0.09<br>$p = 0.048$ | No regr. | C: 0.52<br>$p = 0.020$ | A$^{**}$: 0.57<br>D$^{**}$: 0.71<br>$p = 0.001$ | No regr. |

[a] Regression variables: A = Time interval between the commencement of continuous wet season flow and storm discharge maximum; B = Time interval between the discharge maxima of the preceding and unsampled storms; C = Storm maximum discharge; D = Maximum discharge of preceding storm; E = Storm duration. Transformations: $^{*}$ = independent variables $\log_{10}$ transformed; $^{**}$ = both independent and dependent variables $\log_{10}$ transformed.

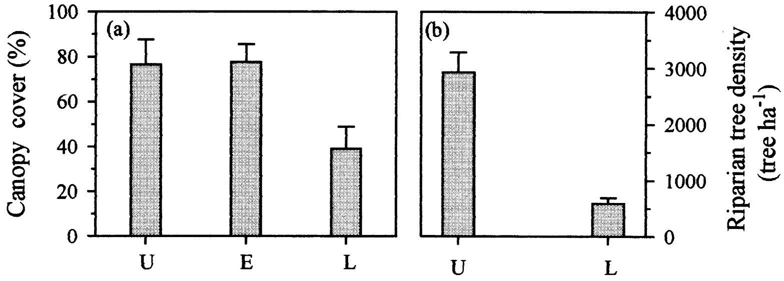

Fig. 3. Mean and standard deviation of (a) canopy cover and (b) riparian tree density for catchments U (unburnt catchment), L (burnt late in the dry season) and E (burnt early in the dry season). No data is presented for catchment E riparian vegetation.

area and seemingly random paths, produced considerable spatial variation of rainfall totals (Table 3), varying by as much as 583 mm over a wet season despite their close proximity. This was also evident when hydrographs for the three streams were compared, as major storm runoff events in one stream were not always accompanied by events of similar magnitude, or not all, in the other two streams.

As is characteristic of the region's climate, rainfall was not recorded between May and September, with the first wet season storms occurring in October (Fig. 4). Continuous wet season flow in the three streams commenced between late December and early January, and ended between mid-May and late June (Fig. 4). Stream L, however, also featured nine episodic runoff events in November and December, preceding continuous wet season discharge (Fig. 4) each wet season. These events did not occur in streams E and U.

The catchments produced varying water yields within and between wet seasons (Fig. 5). No consistent or pronounced difference in water yield is discernible between the catchments. Moreover, the proportion of total discharge defined as storm runoff was much the same between wet seasons, excluding stream E in 1994 and stream L in 1995 (Fig. 5). This is supported by statistical tests for streams L and U total wet season yield (paired-sample *t*-test; $p = 0.29$), and the proportion of stream total discharge defined as storm discharge (paired-sample *t*-test; $p = 0.75$).

### 4.3. Stream water quality

Episodic runoff events from catchment L carried ash and high concentrations of all the water quality variables tested. The volume-weighted mean concentrations of these events were as much as 10 times higher than those measured later in the wet season in stream L (Figs. 6–8). The volume of episodic runoff events in stream L was relatively small though, averaging 0.23% of total annual discharge. Due to their relatively high concentrations however, these storms contributed a disproportionally large amount to the total annual mass of each parameter exported from catchment L. On average, episodic runoff events exported 5% of TSS, 3% of VSS and P, and 2% of N, Fe and Mn annual total load.

The mean and standard deviation of volume-weighted mean concentrations of sampled storms are presented in Figs. 6–8. ANOVAs have been performed for each water quality variable to compare the concentrations for each wet season and catchment.

Table 3
Annual rainfall (mm) for three stations close to the Kapalga catchments E, L and U (see Fig. 1 for locations). Annual period commences September 1

| Annual period | Naramu Camp | Gabarlgu | Plot *F* | Average | Maximum minus minium rainfall |
|---|---|---|---|---|---|
| 1992/93 | 1363 | 1241 | 1824 | 1476 | 583 |
| 1993/94 | 1407 | 1180 | 1336 | 1336 | 227 |
| 1994/95 | 1652 | | | 1652 | |

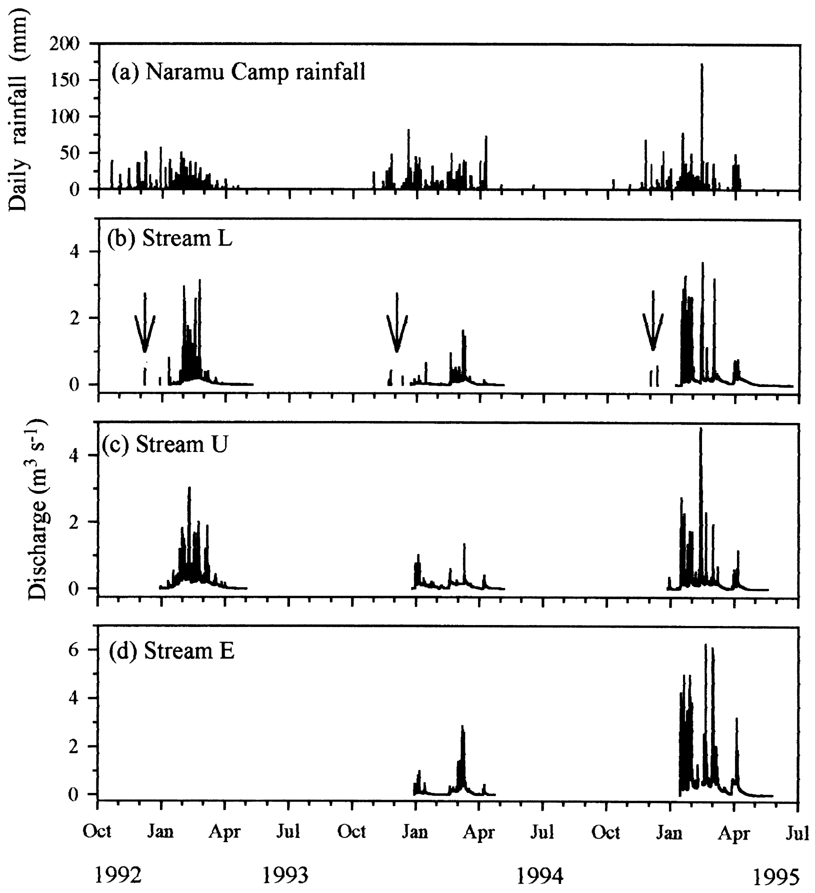

Fig. 4. (a) Total daily rainfall and hydrographs for (b) stream L (catchment burnt late in the dry season), (c) stream U (unburnt catchment), (d) stream E (catchment burnt early in the dry season). Arrows indicate episodic runoff events in stream L. These did not occur in the other streams.

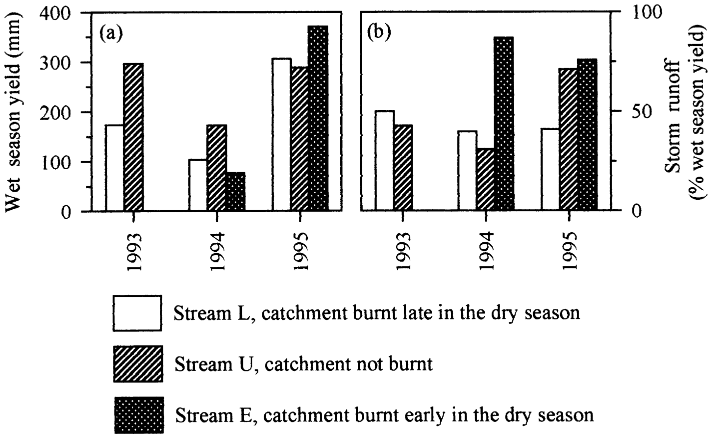

Fig. 5. (a) Total wet season yields for catchments L (burnt late in the dry season), U (unburnt) and E (burnt early in the dry season). (b) Total wet season runoff volume as a percentage of total wet season volume.

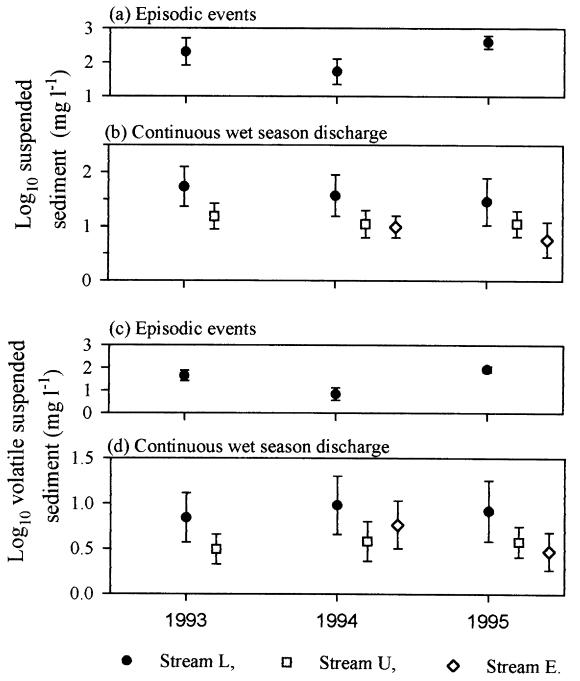

Fig. 6. Kapalga streams L (catchment burnt late in the dry season), U (unburnt catchment) and E (burnt early in the dry season) mean and standard deviation of $\log_{10}$ transformed volume-weighted storm concentrations of total (a, b) and volatile (c, d) suspended sediment concentrations for episodic runoff events (a, c; stream L only), and continuous wet season continuous discharge (b, d). Note: $\log_{10}$ scale of *Y*-axis (i.e. 2 = 100).

Two-way ANOVAs, where year (1994, 1995) and catchment (E, L, U) are factors (Table 4), found catchment L concentrations to be significantly higher than the other two catchments for all variables except P and N. Wet season was a significant factor for only P and Mn (Table 4). This pattern was also evident for streams L and U for the 1993 wet season (Table 4), with significant differences being found for TSS, VSS, P, and Fe. The same analyses for base flow water quality data (Fig. 9) revealed no statistically significant differences between the three catchments or wet seasons.

To assess the overall water quality of storms and calculate their export coefficients, the water quality of storms not sampled has been inferred from linear regressions. These explained, on average, 57% of the variability of storm water quality for stream E, and 61% for streams L and U (Table 2). No pronounced differences were discernible between the regressions for the three streams, suggesting the hydrologic processes determining stream water quality are similar between the catchments. However, the range of regression models needed to predict storm runoff water quality indicates the complex interactions between storm water quality and catchment hydrology.

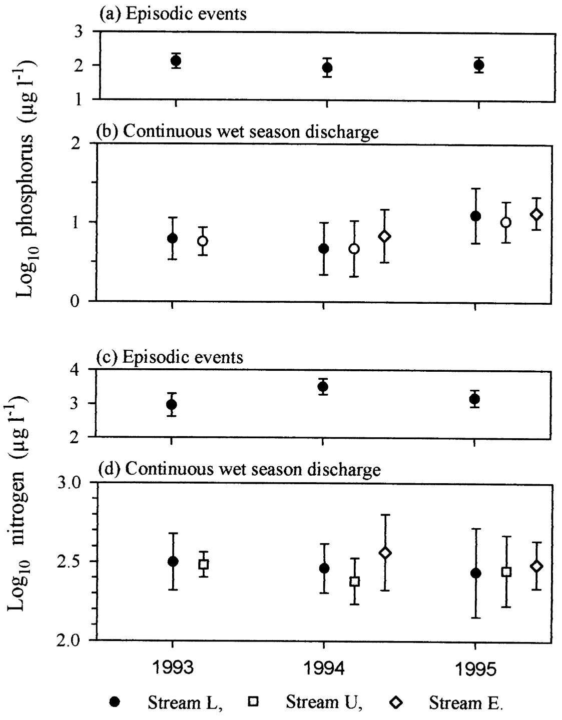

Fig. 7. Kapalga streams L (catchment burnt late in the dry season), U (unburnt catchment) and E (burnt early in the dry season) mean and standard deviation of $\log_{10}$ transformed volume-weighted storm phosphorus (a, b) and nitrogen (c, d) concentrations for episodic runoff events (a, c; stream L only), and continuous wet season continuous discharge (b, d). Note: $\log_{10}$ scale of *Y*-axis (i.e. 2 = 100).

The amount of variability explained by the regressions differed markedly between water quality variables. The largest proportion explained was for TSS and VSS concentrations (mean $R^2 \approx 70\%$), followed by P, N and Mn (mean $R^2 \approx 56\%$), then Fe (mean $R^2 = 48\%$). With the exception of P, concentrations of the water quality parameters were not explained by any one independent variable. Overall, the "time interval between the commencement of wet season flow and storm maximum discharge" and "stream maximum discharge” appeared most frequently in statistically significant regressions, occurring in one-third of regression equations. In the case of phosphorus, most regressions employed the “time interval between the commencement of wet season flow and storm maximum discharge” variable, though with various transformations, indicating a catchment “wash-off” or “exhaustion” effect.

Annual export coefficients varied by at least a factor of two between wet seasons (Fig. 10). This is ascribed to variation in stream discharge volume rather than the concentration of water quality variables, as linear regressions of export coefficient (dependent variable) and stream volume (independent variable) explained an overall average of 82% of the variation in annual export coefficients (Table 5). The remaining percentage is explained by variations in water quality variable concentration. The predominance of volume, rather than concentration, in determining catchment exports coefficients concurs with that reported elsewhere (e.g. Grobler and Silberbauer, 1985; Crosser, 1989). Most of the stream load (overall average 69%) was transported during storm runoff (Table 6), rather than baseflow.

Despite the high proportion of load transported by storm runoff and the higher storm runoff concentrations for stream L (Figs. 6–8) for most of the water quality variables, only TSS export coefficients

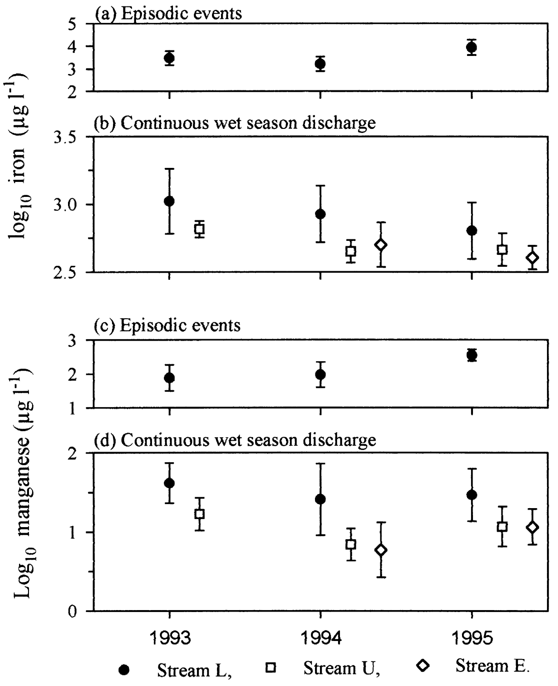

Fig. 8. Kapalga streams L (catchment burnt late in the dry season), U (unburnt catchment) and E (burnt early in the dry season) mean and standard deviation of $\log_{10}$ transformed volume-weighted storm iron (a, b) and manganese (c, d) concentrations for episodic runoff events (a, c; stream L only), and continuous wet season continuous discharge (b, d). Note, $\log_{10}$ scale of $Y$-axis (i.e. $2 = 100$).

Table 4

Statistical tests of catchment and wet season effects on ($\log_{10}$ transformed) storm volume-weighted mean concentrations for total suspended sediment (TSS), volatile suspended sediment (VSS), phosphorus, nitrogen, iron and manganese

| | TSS | VSS | P | N | Fe | Mn |
|---|---|---|---|---|---|---|
| (a) Student’s $t$-tests for 1993 stream L and U storm water quality data. Probability that effect is due to chance | | | | | | |
| Hypothesis for each test: no effect of catchment on mean concentrations | | | | | | |
| Probability of difference between catchments | <0.001 | <0.001 | 0.15 | 0.26 | 0.001 | <0.001 |
| (b) Two-way ANOVA for streams E, L and U; 1994 and 1995 data. Probability that effect is due to chance | | | | | | |
| Hypothesis 1[a] (catchments) | <0.001 | <0.001 | 0.18 | 0.14 | <0.001 | <0.001 |
| Hypothesis 2[b] (wet season) | 0.17 | 0.06 | <0.001 | 0.95 | 0.09 | 0.003 |
| Interaction[c] | 0.39 | 0.09 | 0.08 | 0.46 | 0.33 | 0.43 |
| Significant ($P < 0.05$) pairwise multiple comparisons for significant ANOVA tests (Tukey test) | | | | | | |
| Catchment | L and U;<br>L and E | L and U;<br>L and E | | | L and U;<br>L and E | L and U;<br>L and E |
| Wet season | | | 1994, 1995 | | | 1994, 1995 |

[a] Hypothesis 1: there is no effect of catchment on mean concentration.

[b] Hypothesis 2: there is no effect of wet season on mean concentration.

[c] Hypothesis 3: there is no interaction of catchment and wet season on mean concentration.

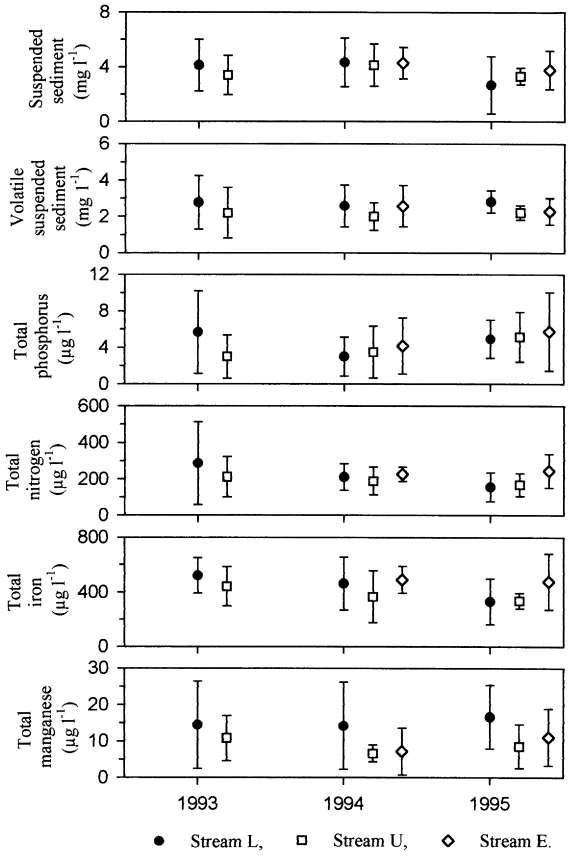

Fig. 9. Kapalga streams L (catchment burnt late in the dry season), U (unburnt catchment) and E (catchment burnt early in the dry season) mean and standard deviation of volume-weighted concentrations for periods of baseflow, 1993–1995. (a) total suspended sediment, (b) volatile suspended sediment, (c) phosphorus, (d) nitrogen, (e) iron and (f) manganese.

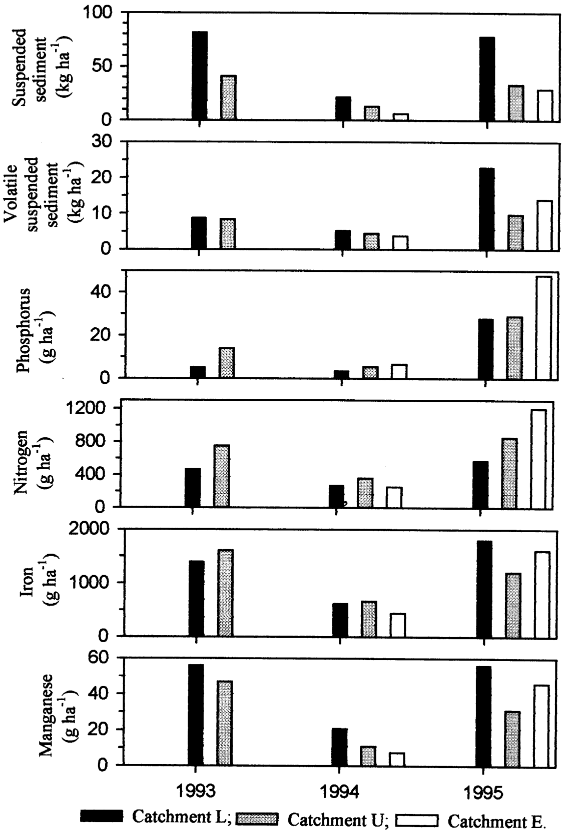

Fig. 10. Annual suspended sediment, volatile suspended sediment, P, N, Fe and Mn export coefficients for Kapalga catchments L (burnt late in the dry season), U (unburnt) and E (burnt early in the dry season).

(Fig. 10) were significantly higher (average 2.4 times; paired-sample $t$-test, $p < 0.018$) from catchment L than catchment U, and by inference catchment E which had similar coefficients to catchment U. Export coefficients for VSS, P, N, Fe and Mn did not differ significantly between catchments.

## 5. Discussion

### *5.1. Catchment yield and storm runoff*

Increased water yield, due to reduced evapotranspiration, is a commonly reported effect of fire on catchment hydrology (Chandler et al., 1983; Lindley et al., 1988; Lavabre et al., 1993; Scott, 1993), and is analogous to increased water yields caused by catchment clearing (see Bosch and Hewlett, 1982; Sahin and Hall, 1996). In this study, however, no clear evidence exists for higher water yields from the burnt catchments, either as baseflow or storm runoff, although this could be expected from catchment L owing to its lower canopy cover, relative to catchments E and U, and decreased rainfall interception and evapotranspiration from tree foliage.

The marked variability of catchment water yields most likely reflects the spatial variability of rainfall from discrete convective storms as these comprise most of the region's rainfall, compared to larger scale weather phenomena such as rainfall depressions.

Table 5
Regression coefficients ($R^2$) between stream load (dependent variable) and runoff volume for 1993, 1994 and 1995 wet seasons. Least-squares method, $n = 3$ for each water quality variable (regressions for stream E could not be calculated as only two wet seasons of data were collected). A high $R^2$ value indicates that much of the inter-annual load variation is attributable to variation in volume, whereas the remainder $(1 - R^2)$ indicates the proportion of load variation attributable to volume-weighted mean concentrations. Where the regression coefficient is almost 1.00, variation is ascribed mainly to runoff volume because the mean water quality variable concentrations were almost the same for each wet season

| Wet season | Suspended sediment | | Volatile suspended sediment | | Phosphorus | | Nitrogen | | Iron | | Manganese | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | L | U | L | U | L | U | L | U | L | U | L | U |
| Storm, $R^2$ | 0.97 | 0.77 | 0.99 | 0.99 | 0.95 | 0.93 | 0.97 | 0.99 | 0.96 | 0.88 | 0.61 | 0.73 |
| Base, $R^2$ | 0.15 | 0.98 | 0.03 | 0.99 | 0.10 | 0.17 | 0.63 | 0.99 | 0.26 | 0.98 | 0.96 | 0.86 |
| Total, $R^2$ | 0.64 | 0.96 | 0.93 | 0.96 | 0.85 | 0.57 | 0.91 | 0.94 | 0.90 | 0.94 | 0.68 | 0.85 |

A study by Sun (1998) employing a dense network of rain gauges, 200 km west of the Kapalga catchments but sharing the same climate, found the correlation between total rainfall and distance between rain gauges to decrease markedly with increasing distance when compared to a reference gauge. For example, one hour rainfall totals were correlated 0.7 at a distance of 2.5 km and 0.5 at a distance of 9 km when compared to a reference point. Such variability of rainfall, and the absence of pre-experimental data, reduces the study's ability to detect the impact of fire regime on catchment yields.

Decreased tree evapotranspiration in catchment L was probably countered by high losses through grasses. Higher rates of evapotranspiration from grasses (including *Sorghum* spp.), compared with the dominant woodland tree species in the region, have been measured by Hutley (Northern Territory University, unpublished data) and determined from a water balance study (Cook et al., 1998). Bowman et al. (1988) found grass cover increased inversely with canopy cover in Kakadu National Park, following regular burning late in the dry season. This is supported by field observations of greater grass cover in catchment L during the wet season, compared to catchments E and U. Overall, the net effect of burning late in the dry season on catchment L's water yield seems to be negligible.

Episodic runoff events, early in the wet season, were characteristic of stream L, but absent in streams

Table 6
Percentage of wet season load transported by storm runoff (see Methods for definition) in Kapalga streams L, E and U. The remaining percentage was transported by baseflow

| Wet season | L | U | E | L | U | E |
|---|---|---|---|---|---|---|
| | Suspended sediment | | | Volatile Suspended sediment | | |
| 1993 | 92 | 71 | | 81 | 61 | |
| 1994 | 79 | 56 | 94 | 57 | 47 | 91 |
| 1995 | 89 | 92 | 88 | 73 | 81 | 82 |
| Average | 87 | 73 | 91 | 70 | 63 | 87 |
| | Phosphorus | | | Nitrogen | | |
| 1993 | 44 | 54 | | 58 | 53 | |
| 1994 | 30 | 58 | 91 | 53 | 36 | 91 |
| 1995 | 52 | 82 | 83 | 65 | 85 | 85 |
| Average | 42 | 65 | 87 | 59 | 58 | 58 |
| | Iron | | | Manganese | | |
| 1993 | 67 | 51 | | 78 | 50 | |
| 1994 | 59 | 37 | 87 | 66 | 36 | 89 |
| 1995 | 69 | 79 | 75 | 78 | 78 | 79 |
| Average | 65 | 56 | 81 | 74 | 55 | 84 |

E and U. Two factors, both associated with intense fires, probably account for the occurrence of these events. Firstly, catchment L's lower litter cover and higher percentage of bare ground, and reduced resistance to overland flow. Secondly, catchment L's lower canopy cover, and consequent reduced rainfall interception, relative to catchments E and U. Elsewhere, increased stormflows have been related to water repellent soils that were induced by severe fires (see Scott and Van Wyk, 1990). But we did not test for this, and it is doubtful that regular burning at Kapalga allows for the accumulation of fuel loads and severe fire that are typically associated with such more marked hydrological responses.

Episodic storm runoff, before continuous wet season flow, has been recorded, albeit infrequently, in other catchments with similar vegetation to catchments E and U (Townsend, unpublished data). Consequently, it is likely that burning late in the dry season has increased the frequency of these events, relative to catchments E and U, assuming there are no overriding intrinsic differences between the catchments. Hydrograhic data collected in the 4 years following the cessation of the Kapalga fire experiment (Townsend, unpublished data) provides evidence that the frequency of these episodic events were indirectly related to the fire regimes of the study catchments. Since May 1995, catchment L's fire regime has been replaced by occasional wet season burns to kill grass seedlings and early dry season burns to encourage revegetation, whilst the fire regimes of catchments E and U have been maintained. Over this 4-year period, only two pre-wet season episodic events were recorded in catchment L, and none in catchments E and U. It is likely the re-establishment of ground- and litter-cover, and a 50% increase in canopy cover has protected catchment L from rainfall impact and inhibited overland flow, thereby reducing the frequency of episodic events. These observations partly support the conclusions of Duggan (1988, 1994), discussed in detail below, who emphasised the significance of pre-wet season ground- and litter-cover in preventing soil erosion.

### 5.2. Stream water quality and export coefficients

Volume-weighted mean concentrations and annual export coefficients for the Kapalga streams are, for the most part, within an order of magnitude of values reported for other catchments in the region with negligible human activity (Hart et al., 1987; Duggan, 1988, 1994; Padovan, 1997). Higher TSS coefficients calculated by Duggan (27–583 kg ha$^{-1}$) are ascribed to different catchment relief and parent geology, which include sandstone uplands with average slopes of 5%. Such areas are not found in the Kapalga catchments. Nitrogen, phosphorus and suspended sediment export coefficients from the Kapalga catchments are up to 2 orders of magnitude less than that reported for other tropical regions (see Hudson et al., 1983a; Lesack et al., 1984; Lewis, 1986; Saunders and Lewis, 1988; Lewis and Saunders, 1989), and ascribed to the low fertility of the Kapalga soils, low slopes, long history of weathering and the negligible human disturbance of the catchments.

The higher concentrations of TSS, VSS, Fe and Mn in stream L, relative to streams E and U, could be due to the following characteristics of catchment L: (1) the dislodgement of soil by rainfall impact, associated with the catchment's lower canopy cover; (2) greater overland transport of sediment attributable to the loss of litter cover and riparian vegetation, and greater area of bare ground; and (3) greater susceptibility of stream banks to erosion associated with their reduced riparian vegetation. There is no evidence of higher storm discharge maxima in stream L, when compared with stream U which drains a similar catchment area (Fig. 5), and thereby higher erosive energy in stream L.

An insight into erosion in the region can be gained from erosion pin studies undertaken by Duggan (1988, 1994) who examined the relationship between soil loss and the following: soil type, slope angle (0.1–5%) and length, foliage-, ground- and litter-cover in the lowlands of Kakadu National Park. She concluded that erosion rates were mainly related ($R^2 = 0.57$) to pre-wet season litter cover whilst the other factors listed were uncorrelated to soil loss. In addition to litter cover, Duggan (1988, 1994) also emphasised the significance of soil surface gravel lag (a covering of gravel sized particles) in reducing erosion by restricting the detachment and entrainment of finer, underlying soil particles. When this is disturbed, for example by mining and construction activities, suspended sediment exports increase by more than 2 orders of magnitude (Duggan, 1988), even on slopes as low as 3%. The higher sediment export coefficients from catchment L, which were only double those of the other catchments, indicate the catchment's gravel lag has not been significantly disturbed, even after three consecutive years of annual burning. This is probably due to the negligible human activity in the Kapalga catchment. The doubling of catchment erosion at Kapalga compares with 3-fold (Roose, 1971, cited Gillon, 1983) and 50-fold (Granier and Cabanis, 1976, cited Gillon, 1983) increases in soil loss following burning in grazed African tropical savannas.

The much lower density of riparian vegetation in catchment L (compared with catchment U) probably contributes to the greater sediment export from this catchment. Riparian vegetation is known to reduce sediment input to streams (Peterjohn and Correll, 1984; Naiman and Décamps, 1990) by stabilising stream banks and sediment within the riparian zone itself, or by trapping sediment that has been transported from areas beyond the riparian zone.

The oxidation of organic matter by fire is rarely complete (Chandler et al., 1983). At Kapalga Research Station, Cook (1994) has reported the ash remaining after early dry season fires (including catchment E) contained high concentrations of nitrogen (≈1%) and phosphorus (≈0.1%). This ash, however, did not have a significant impact on stream E's water quality during the first few storm runoff events, as its water quality was similar to stream U. The water quality of the first few runoff events from catchment L, in contrast, featured ash and high concentrations of all water quality parameters.

The different impact of ash on the water quality of streams E and L is most likely due to their fire regimes. Because the concentration of phosphorus in ash tends to increase with fire intensity (Chandler et al., 1983), the impact of ash bound phosphorus on stream L water quality would also be expected to be greater, though this may be mitigated to some extent by the lower mass of phosphorus remaining. Importantly, the longer time interval between burning and storm runoff in catchment E, relative to catchment L, would be expected to increase the likelihood of phosphorus dispersion by wind, and leaching into the soil profile.

Burning often increases phosphorus loads, due to either elevated water yield and/or phosphorus concentrations (Tiedemann et al., 1978; Schindler et al., 1980; Leitch et al., 1983; Maass et al., 1988; Belillas and Roda, 1993). The Kapalga phosphorus export coefficients indicate no pronounced differences between the three catchments and their fire regimes. Additional small losses of phosphorus carried by stream L's episodic events, equivalent to 2% of the total load, if maintained over many years, however, may reduce the phosphorus reserves of the catchment unless replaced by increased accession by wet and dry precipitation. The negligible effect of burning on annual phosphorus exports, compared to other studies, probably reflects the low fertility of the regions' soils and its small phosphorus reserves for erosive transport. Phosphorus is usually particulate bound (Tiessen, 1995), yet increased sediment loads were not matched by proportionally higher phosphorus exports.

Nitrogen is the nutrient most vulnerable to depletion by burning because large amounts are volatilised and lost to the atmosphere (Chandler et al., 1983). In contrast, phosphorus lost to the atmosphere with fine ash particles is returned later by wet and dry precipitation. Cook (1994) has suggested nitrogen lost by early dry season fires at Kapalga Research Station is not totally replaced by precipitation and biological fixation. This imbalance is likely to be even greater for fires occurring late in the dry season, owing to the increased loss of nitrogen with fire intensity (see Chandler et al., 1983). Nitrogen export coefficients were often lower from catchment L compared to catchments E and U (Fig. 10) owing mainly to variations in water yield, which have not been shown to be significantly affected by fire regime.

## 6. Conclusions

Despite the range of the fire regimes investigated—early (low intensity) and late (high intensity) dry season fires, and no burning—the study has not detected marked differences in catchment export coefficients for P, Fe, Mn and VSS. Suspended sediment export coefficients, however, were 2.4 times higher from the catchment burnt late in the dry season, when fires increased the catchment's vulnerability to erosion, principally by reducing its ground-, litter- and canopy cover. Low catchment slopes, low soil fertility, the maintenance of a protective surface layer of gravel, negligible impact of the fire regimes on water yield, and the sometimes lengthy period between burning and runoff have mitigated the impact of catchment burning on sediment, nutrients, iron and manganese exports from the Kapalga catchments.

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