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# Performance of grass and rainforest riparian buffers in the wet tropics, Far North Queensland. 1. Riparian hydrology

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*Abstract.* The long and intense storms of the wet tropics present extreme conditions for testing the effectiveness of riparian buffers. This study presents results of a hydrometric investigation of 4 riparian buffers on 2 commercial banana plantations in Far North Queensland, Australia. It investigates runoff generation and riparian hydrology on hillslopes with differing slopes, contributing areas, and topographic convergence. Both grass and rainforest buffers were examined. Surface and subsurface hydrology were measured for 4 wet seasons (December–April) using paired flumes, piezometers, and tensiometers. All buffers experienced large volumes of surface runoff, with peak discharges ranging from 30 L/s on planar hillslopes to 350 L/s on a highly convergent site. Event runoff : rainfall ratios ranged between 0.01 and 0.65. Grass buffers with smaller contributing areas (<0.3 ha) were able to dissipate the energy of surface runoff under all conditions. On a larger (5 ha), highly convergent hillslope, surface runoff became channelised upslope of the buffer and the vetiver hedges and grass were not able to prevent scouring of a channel through the buffer, reducing its performance. Infiltration occurred in all buffers during small events, and at the convergent buffer during large events, most likely due to the presence of deep soil fill. In contrast, exfiltration occurred in the grass buffers on planar and moderately converging slopes during large events. There, the riparian soil approached saturation and return flow and seepage were measured. Under exfiltration, soil strength may be decreased and riparian buffers are needed to decrease erosion hazard. Localised saturation was observed in the rainforest buffer beneath a planar hillslope during large events, where soils were deeper and dried out more quickly than in the adjacent grass buffer. This study documents the high runoff volumes and peak discharges on cropped slopes in the wet tropics, and evaluates riparian hydrological processes. Infiltration is unlikely to be an important buffer function in this environment, but an additional role of buffers is to reduce the erosion hazard presented by exfiltration.

*Additional keywords:* wet tropics, surface runoff.

## Introduction

The wet tropics present extreme rainfall conditions for testing the effectiveness of riparian buffers. High intensity, long duration rainfall events generate considerable volumes of surface runoff on steep, intensely cropped hillslopes. The removal of rainforest and replacement with other vegetation types has resulted in decreased infiltration and increased runoff. Ploughing, vehicle movement, and soil crusting reduce infiltration (Malmer and Grip 1990; Prove 1991 cited in Bonell and Balek 1993; Loch 1994) and cultivation may also remove the upper part of the profile and displace impeding layers to the surface (Murtha 1986; Bonell 1993).

With high runoff and disturbed soil, hillslopes become prone to rill and surface wash erosion. Traditional methods of erosion control, for example contour banks and grassed waterways have been adopted in southern and central Queensland, but not in the north. Prove *et al*. (1986) attribute this to the difficulty in achieving workable farm layouts on steep and broken topography. Riparian buffers are one water quality management tool available to landowners in this environment to help reduce pollutant delivery to streams.

Riparian buffers can reduce the effects of increased surface runoff by slowing the flow, which reduces the ability to transport sediment, promotes deposition, and prevents

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**Table 1. Characteristics of monitored hillslopes, riparian buffers, and instrumentation**

| Site | Hillslope | | | Riparian buffer | | Instrumentation |
|---|---|---|---|---|---|---|
| | Slope (%) | Area (ha) | Form | Vegetation | Width (m)[A] | |
| Gallagher's Grass (GG) | 7 | 0.2 | Planar | Signal grass | 15 | 2 San Dimas flumes (800 mm by 150 mm); 3 piezometer nests; 2 tensiometer nests |
| Gallagher's Tree (GT) | 7 | 0.2 | Planar | Remnant rainforest | 15–20 | 2 San Dimas flumes (800 mm by 150 mm); 1 piezometer nest; 2 tensiometer nests |
| Dunne's Moderate (DM) | 3 | 0.3 | Moderately convergent | Signal grass in hollow | 60 | 3 San Dimas flumes (800 mm by 250 mm) |
| Dunne's Extreme (DE) | 13 | 5.0 | Highly convergent | Steep hollow of signal grass with 4 vetiver grass hedges | 50 | 2 San Dimas flumes (1800 mm by 910 mm) |

[A]Downslope length of buffer.

erosion from occurring next to the stream. Secondly, a buffer may promote infiltration (Dillaha and Inamdar 1997), which reduces the volume and velocity of overland flow and promotes deposition. Thirdly, a permanently vegetated buffer increases soil strength to resist erosion. The significance of these processes in any environment depends strongly on the hillslope and riparian hydrology.

Little information is available on the hydrology of cropped land in tropical environments. A limited number of field studies have been undertaken in the tropics, and these have mainly examined rainforest hydrology and/or the impacts of forest clearance (e.g. Bonell and Gilmour 1978; Bonell *et al*. 1981; Elsenbeer and Vertessy 2000).

This paper reports on the hydrology of riparian buffers receiving runoff from banana plantations in the Johnstone River catchment in Far North Queensland, and a companion paper explores the water quality issues (McKergow *et al*. 2004, this issue). The key questions addressed in this paper are (*i*) what proportion of rainfall becomes surface runoff, (*ii*) what rates of surface runoff occur, and (*iii*) what hydrological processes occur in a range of buffer situations.

In this paper the term surface runoff is used for a visible flow of water over the ground surface, however produced (see overland flow, Goudie *et al*. 1994). Surface runoff may be either infiltration-excess overland flow (Hortonian; IEOF) or saturation-excess overland flow (SOF) including exfiltration or return flow (Chorley 1978). The term subsurface flow is used for all water moving through soil horizons, and may include macropore flow and displacement of soil water.

## Materials and methods

### *Study sites*

The study hillslopes are in the banana and sugarcane producing area of wet tropical Far North Queensland. They are part of the North Johnstone River catchment, which meets the coast at Innisfail (Fig. 1). Bananas are planted on steeper land in this region, while sugarcane is generally grown on the flatter land.

The average rainfall at Innisfail is 3585 mm (station 032025, 101.9 years; Bureau of Meteorology 2001). Most of the annual total rainfall occurs in the wet season, December to April, and is characterised by long duration and high intensity storms. The winter months are dry by comparison and little runoff occurs on hillslopes at this time.

Riparian buffers at 4 sites, across 2 properties, were monitored for this study (Table 1). Soils at the sites are krasnozems derived from basalt. Krasnozems are red to brown, acidic, strongly structured clay soils (50–70% clay) (Isbell 1994). A typical undisturbed profile of the Pin Gin Series includes a dark reddish brown clay loam (0–10 cm) with many aggregates (2–5 mm), which gradually changes to a dark red clay loam (10–60 cm), underlain by a light to medium clay (Murtha 1986). These soils (to 0.4–0.5 m) have high permeability and high available water storage capacity (Bonell *et al*. 1983).

Two of the catchments were adjacent hillslopes on Gallagher's property, which have been cropped continuously for 20 years and were previously unfertilised pasture (Table 1; Fig. 1). Both hillslopes drained a 7% gradient, 200-m-long planar slope planted with bananas. The current crop of bananas was planted in May 1996, in double rows perpendicular to the contours. The mounds along the rows define the boundaries of the contributing area.

The 15-m-wide riparian buffer at Gallagher's Grass (GG) was planted with signal grass (*Brachiaria decumbens*), a low-growing perennial, which forms a dense vegetation cover. The remnant rainforest riparian buffer, Gallagher's Tree (GT), was 15 to 20 m wide. The buffer had no understorey and some tree species had buttressed roots.

Two hillslope hollows, both draining into Berner Creek, were instrumented on Dunne's property (Table 1; Fig. 1). The names of these instrumented hillslopes reflect the degree of topographic convergence of flow. The hollow at Dunne's Extreme drained a 5 ha area with an average gradient of 13%. Deep soil fill has been placed in the riparian area of this small catchment. Double rows of bananas were planted perpendicular to the contours in 1994 and cropping continued across the upper part of the hollow. In May 1996 the riparian buffer was planted across the steeper foot of the hollow. A 50-m-wide signal grass buffer with 4 vetiver grass (*Vetiveria zizanioides* L.) hedges was established quickly and there was good grass cover throughout the investigation. The 4 vetiver grass hedges were located 5, 10, 25, and 45 m, respectively, below the upper flume.

Dunne's Moderate drained 0.3 ha with an average gradient of 3% and had dense signal grass cover along 60 m of gently sloping hollow (Fig. 1). The riparian buffer at Dunne's Moderate was planted in January 1996. Dunne's Moderate was ploughed in 1996, and in 1997 double rows of bananas were planted perpendicular to the contours.

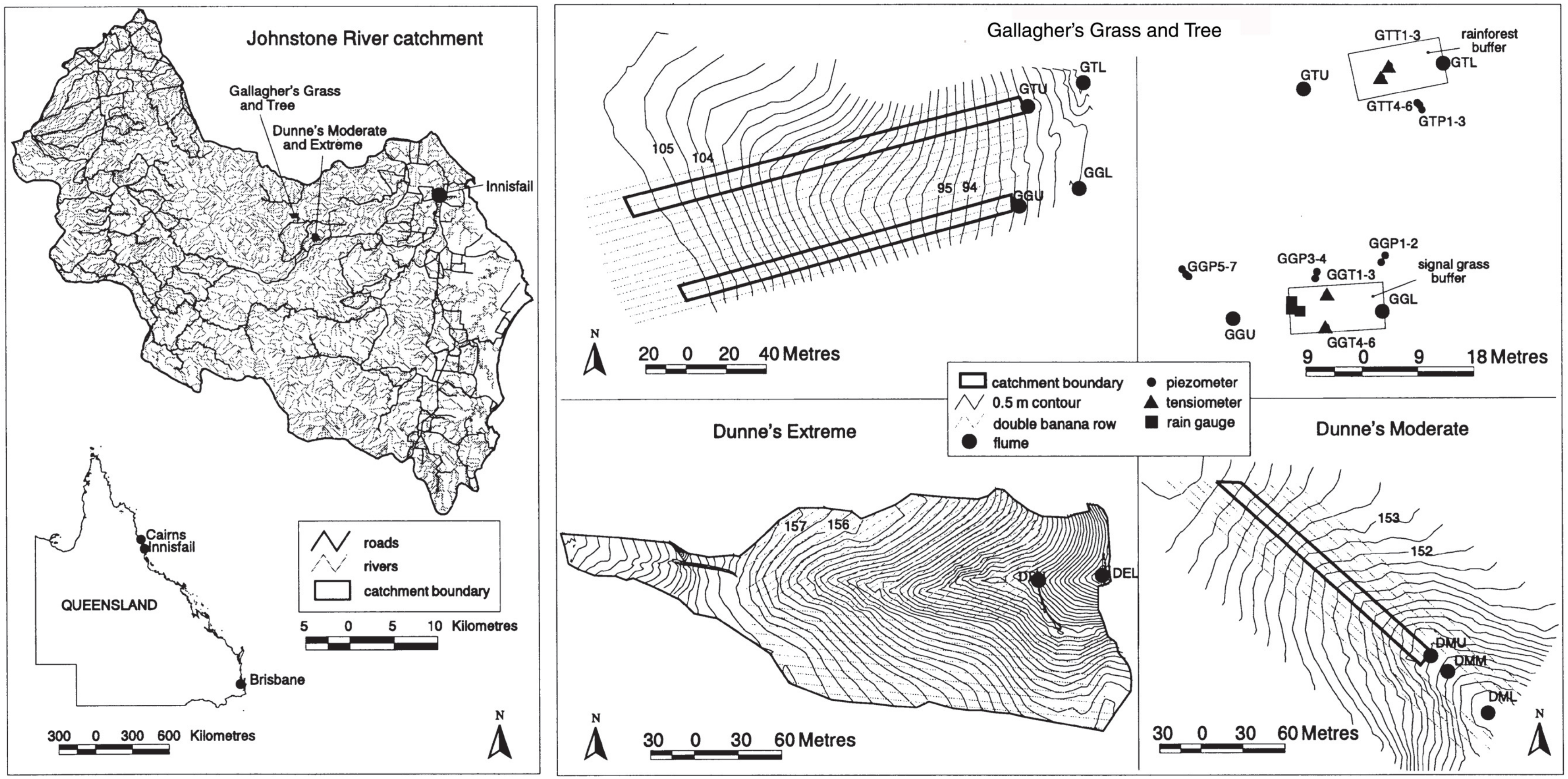


**Fig. 1.** Monitoring layouts at Gallagher's Grass (GG) and Tree (GT), and Dunne's Extreme (DE) and Moderate (DM). Runoff entering and leaving the riparian zone was measured on each hillslope at the Upper (U) and Lower (L) sites. Accompanying maps place the sites within the Johnstone River catchment and Queensland.

The signal grass buffers were all mown regularly during each wet season to prevent the clump-forming guinea grass (*Panicum maximum*) from dominating. The signal grass height varied throughout the monitoring period and between the 4 sites, but was generally 10–40 cm high.

*Hydrometric methods*

Intensive monitoring of hillslope runoff and riparian hydrology was conducted over 4 wet seasons between October 1996 and May 2000.

Rainfall was measured by tipping bucket and manually read rain gauges. At Gallagher's a tipping bucket gauge recorded at 3 min intervals (Hydrological Services TB3, 0.5 mm per tip) in the grass buffer at a height of 1.4 m, in order to always be above the grass. At Dunne's a weather station was installed and rainfall was recorded at 3 min intervals by an Environdata tipping bucket rain gauge (0.3 mm per tip). Gaps in the rainfall record at each site were filled with tipping bucket data from the other site corrected to manual rain gauge totals. Antecedent conditions were assessed using an Antecedent Precipitation Index of the previous 7 days rain, i.e. $API_7 = [\sum_{i=1}^{7} P_i/i]$, where $P_i$ is the rainfall on the *i*th day before the storm.

Runoff entering and leaving the riparian zone on each hillslope (Upper and Lower sites, respectively; Fig. 1) was monitored using identical San Dimas flumes (Wilm *et al.* 1938) (Table 1). San Dimas flumes were selected because of their ability to pass sediment-laden flows. Water levels were measured and recorded by floats and chart recorders (Hydrological Services AUS-1), and pressure transducers (Unidata 6508A, 0–1 m range), and data loggers (Campbell Scientific CR10x). Water levels were converted to discharge using theoretical stage–discharge rating curves (Wilm *et al.* 1938).

During large events the lower flumes at Gallagher's, particularly in the grass buffer were submerged by streamflow. During such events analysis was restricted to the periods before and after the flume was flooded.

Piezometer nests were installed at Gallagher's, as shown in Fig. 1. Three nests were installed, each containing at least 1 piezometer sitting on the weathered bedrock, at a depth of 1–4.7 m below the ground surface. A well was also installed in the grass riparian buffer at the same time (GGP1). Piezometric head and water table depth were recorded at 15 min intervals with capacitance probes and stored on data loggers (Campbell Scientific CR10x).

Tensiometers were also installed in the riparian buffers at Gallagher's. Two nests of tensiometers (Soilmoisture Equipment Jet Fill 2725 Series) were installed in each buffer (Fig. 1), and soil suctions were measured at depths of 30, 60, and 90 cm.

## Results and discussion

### *Monitoring period rainfall characteristics*

During the monitoring period rain was recorded on around 100 days during each wet season and daily rainfall totals <20 mm were common (Table 2). A significant proportion of the wet season total could also occur on consecutive days. Several events lasting a couple of days and exceeding 500 mm were recorded each wet season. For example, 533 mm of rain (21% of the total wet season rainfall) fell at Gallagher's in a 65-h period in the second wet season. Daily rainfall totals were similar at both sites (correlation coefficient 0.97), although variability was large, particularly for smaller events (<50 mm).

Short-term rainfall intensities are high in these catchments. At Gallagher's the highest 6-min total of 13.5 mm and the maximum of 21.5 mm in 12 min were measured at the start of the third wet season. Maximum 30-min and 1-h totals of 40 and 72.5 mm, respectively, were recorded at Gallagher's late in the third wet season.

**Table 2. Wet season total daily rainfall frequency**
Rainfall period is midnight to midnight

| Total | 1997–98 | 1998–99 | 1999–00 |
|---|---|---|---|
| | *Gallagher's* | | |
| <20 mm | 62 | 62 | 52 |
| 20–50 mm | 25 | 27 | 25 |
| 50–100 mm | 6 | 12 | 16 |
| >100 mm | 4 | 7 | 9 |
| Max. daily total | 307 | 315.5 | 245 |
| | *Dunne's* | | |
| <20 mm | 57 | 54 | 53 |
| 20–50 mm | 27 | 25 | 27 |
| 50–100 mm | 9 | 11 | 16 |
| >100 mm | 5 | 8 | 9 |
| Max. daily total | 336 | 309 | 245 |

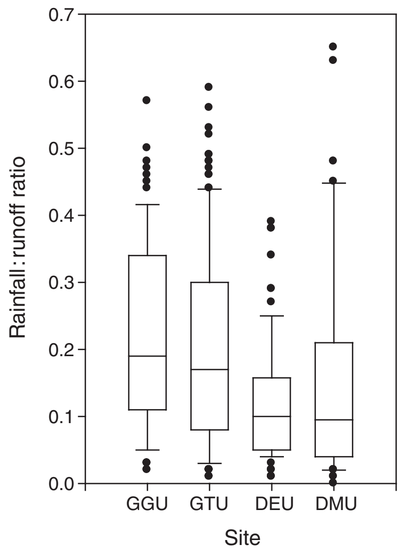


**Fig. 2.** Boxplot of hillslope surface runoff : rainfall ratios for Gallagher's Grass (GGU), Gallagher's Tree (GTU), Dunne's Extreme (DEU), and Dunne's Moderate (DMU). Box represents the median with 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outliers are dots.

### *Hillslope runoff : rainfall ratios*

Hillslope runoff : rainfall ratios were calculated for all events with good quality rainfall and runoff data. Rainfall volumes were estimated using the total rainfall depth spread over the contributing hillslope area. All sites were hillslopes so surface runoff only occurred in response to rainfall.

The proportion of rainfall becoming surface runoff varied considerably between events and sites, ranging between 0.01 and 0.65 (Fig. 2). At both Gallagher's sites runoff : rainfall ratios were typically around 0.2 (Fig. 2). In contrast, at both

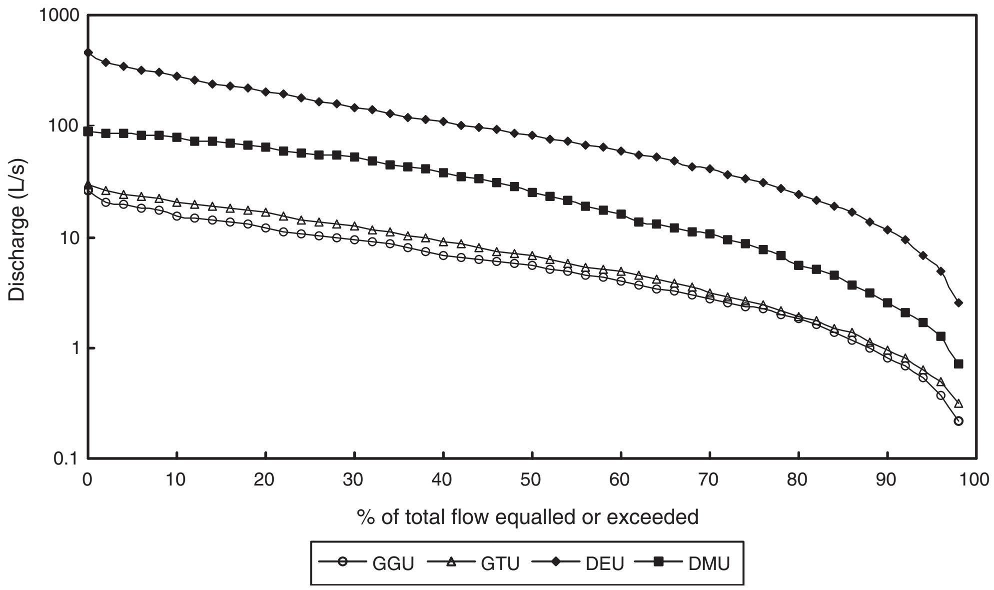


**Fig. 3.** Flow exceedance curves for surface runoff at all upper sites. Calculated using 12-min maximum discharges for the period of record: Gallagher's Grass Upper (GGU), Gallagher's Tree Upper (GTU) and Dunne's Moderate Upper (DMU) March 1997–April 2000; Dunne's Extreme Upper (DEU) December 1996–May 2000.

Dunne's sites the median runoff : rainfall ratios were around 0.1 (Fig. 2). These figures are consistent with those reported for other tropical hillslope sites in the literature (e.g. Chandler and Walter 1998; Dykes and Thornes 2000).

Many factors influence the proportion of rainfall becoming surface runoff, including rainfall total and intensity, antecedent conditions, and interception storage. Regression analysis of runoff volume with rainfall total, rainfall intensity, and $API_7$ for each of the 4 sites suggested that event rainfall total was the key variable, explaining >70% of the variation in event runoff volume. Interception storage is likely to be of limited importance, particularly during large events. Praertsak *et al*. (2001) measured interception at Dunne's during light rains in August and September 1993 and found that the plant canopy intercepted >50% of the rainfall, but of this a considerable proportion reached the ground surface as stemflow.

### *Hillslope surface runoff discharge*

A key function of buffer vegetation is to reduce the velocity of surface runoff causing sediment to settle out. The buffer vegetation must therefore be able to withstand peak runoff discharges and be able to prevent scouring.

Surface runoff discharges were similar at GG and GT upper flumes (GGU and GTU, respectively), although slightly larger at GTU (Fig. 3). This is most likely due to the slightly larger area and longer slope length contributing to flow at GTU (Fig. 1). Flows >1 L/s were recorded during only 5% of the total monitoring record. The median discharges at both sites were just over 5 L/s and even during large events peak flow rates were always <30 L/s. Runoff did not become channelised at these sites and so the full upper face of the buffers actively contributed to slowing the surface runoff.

Flow rates at both Dunne's sites were higher than those measured at Gallagher's. At Dunne's Moderate Upper, flows >1 L/s were recorded during 14% of the total monitoring period. The median flow rate was 25 L/s and peak flows were just under 90 L/s (Fig. 3).

Surface runoff discharges were considerably higher at Dunne's Extreme, owing to the large catchment area. Flows >1 L/s were recorded during 24% of the total monitoring period. The median peak runoff velocity was 81 L/s and peak flow rates were >350 L/s (Fig. 3). The flow at Dunne's Extreme became channelised and so the effective buffer face width was reduced.

The surface runoff measured on the hillslopes is likely to be a mixture of IEOF and SOF, with the relative proportions of each varying between sites and events. Infiltration-excess overland flow was observed in the inter-row areas where hard surface crusts had formed. Prove (1991 cited in Bonell and Balek 1993) provided evidence of IEOF occurring in the inter-rows of sugarcane on krasnozems in North Queensland and identified compaction by agricultural machinery as the cause.

### *Scour of buffers*

The dense buffers at Gallagher's and Dunne's Moderate were able to withstand the peak discharges and did not show any signs of scour throughout the monitoring period. The planar slopes allowed flow to disperse, assisted by the grass vegetation, which, with a low gradient slope, keeps flow velocities and depths low. Localised scouring was observed in the rainforest buffer, particularly around buttressed tree roots, which suggests that they can concentrate surface runoff into channels.

The grass buffer and vetiver hedges at Dunne's Extreme were not able to slow surface runoff sufficiently during one large event and a 30-cm-wide channel was scoured through the buffer. Under field conditions mature vetiver plants can withstand flows up to 0.6 m deep at 0.5 m/s (P. A. Dalton, pers. comm. cited in Truong *et al*. 1996), which equates to 300 L/s per m width.

By expressing discharge in terms of boundary shear stress ($\tau_b$), the sensitivity of a buffer to scour can be evaluated. Shear stress can be calculated using (Prosser 1996):

$$\tau_b = \left( \frac{g^2 s^2 \rho^3 a}{8 v^b w^{(2+b)}} \right)^{1/3} Q^{(2+b/3)}$$

where, $g$ is acceleration due to gravity (9.8 m/s), $\rho$ is density of fluid (1000 kg/m$^3$), $s$ is the sine of the gradient, $v$ is the kinematic viscosity of fluid ($1 \times 10^{-6}$ m$^2$/s), and $w$ is the width of flow. Both a and b are constants; a is the intercept on a curve of Darcy-Weisbach flow resistance plotted against Reynolds number (e.g. Figure 31.5 in Prosser 1996; assume 30000) and b the slope of the flow resistance curve (assume –0.5).

At Dunne's Extreme, the peak discharge (when the channel was scoured through the buffer) was 377 L/s (0.37 m$^3$/s). The average slope is 13%, or 7.4°, so $s$ is 0.13. A flow width of 0.3 m, gives $\tau_b$ = 2000 N/m$^2$, and for a flow width of 1 m, $\tau_b$ is 1100 N/m$^2$. Completing a similar calculation for Dunne's Moderate, which never scoured, gives $\tau_b$ = 200 N/m$^2$ (assuming $s$ = 0.03, $w$ = 1 m and Q = 0.09 m$^3$/s).

On a 13% slope with a peak discharge of 0.09 m$^3$/s, the active buffer face width would need to be at least 5 m wide to match the $\tau_b$ calculated for the grass buffer at Dunne's Moderate, which never scoured. Such a significant flow width is not possible given the topography and velocity of flow, suggesting that the buffer should be extended to the end of the crop rows in the hollow at Dunne's Extreme (Fig. 1) to reduce the risk of scour.

### *Infiltration–exfiltration*

Infiltration may be a desirable buffer function as it reduces the sediment transport capacity by decreasing the surface runoff volume. In this study infiltration was detected by a reduction in runoff volume between the upper and lower flumes, and exfiltration was identified by an increase in runoff volume. For both Gallagher's sites the data were combined with tensiometer and piezometer measurements.

Sites with deeper riparian soils are more likely to encourage infiltration, although 100% infiltration is unlikely, except during small events. Many small rainfall events generated runoff only at the upper flumes, and no corresponding response was recorded at the lower flumes. These events were typically in response to 1–20 mm of rainfall and generally resulted in <100 L of runoff at the upper flumes.

Large events dominate the annual rainfall totals in this environment. The remainder of this paper focuses on these events as they exhibit the greatest riparian response. The sites are discussed in order along a continuum from infiltration- to exfiltration-dominated large events.

Dunne's Extreme was the only site where infiltration occurred consistently, even during large events. A large proportion of the runoff passing through the upper flume at Dunne's Extreme infiltrated within the first 15 m of the buffer. The proportion of surface runoff infiltrating varied between and within events. This hollow has soil fill at least 3 m deep, which can absorb surface runoff.

Figure 4 shows the rainfall and runoff associated with a cyclone in late December 1997. This was the first daily rainfall total >50 mm in the second wet season and antecedent conditions were dry ($API_7$ = 21 mm). A rainfall total of 550 mm was recorded during the period and maximum 1-h rainfall intensity was 78.3 mm. The runoff:rainfall ratio at the upper flume was 0.12. Infiltration of surface runoff between the upper and lower flumes was large, with 45% (4440 m$^3$) of the surface runoff flowing through the upper flume not flowing through the lower flume.

By comparing the peak flow rates at the upper and lower flumes we can estimate the maximum infiltration rate. The peak discharges were 351 and 270 L/s at the upper and lower flumes, respectively. For individual peaks, the difference varied between 50 and 70 L/s. The distance between the flumes is 49 m and assuming an active flow width of 1 m, this gives an area of around 50 m$^2$. Therefore, the effective infiltration rate is in the order of 3600–5000 mm/h. During the subsequent cyclone 8 days later (400 mm over 60 h), about 20% (2260 m$^3$) of the flow infiltrated under moister antecedent conditions ($API_7$ = 50 mm). The difference in peak discharges varied between 10 and 30 L/s, which equates to an effective infiltration rate of 700–2000 mm/h. These calculated infiltration rates are consistent with topsoil (0–0.1 m) hydraulic conductivities of 2275–6030 mm/h measured in other Pin Gin Series soils nearby (Bonell *et al*. 1983).

Despite the high infiltration rates, it is likely that the surface runoff velocities are too high during large events for all of the runoff to infiltrate even if soil storage is available.

Many cropped areas in the Johnstone River catchment have undergone landscape modification on a large scale. At Dunne's Extreme deep soil fill has been placed in the riparian buffer, increasing its ability to absorb surface runoff. Considerable volumes of surface runoff were able to infiltrate between the upper and lower flumes and this may

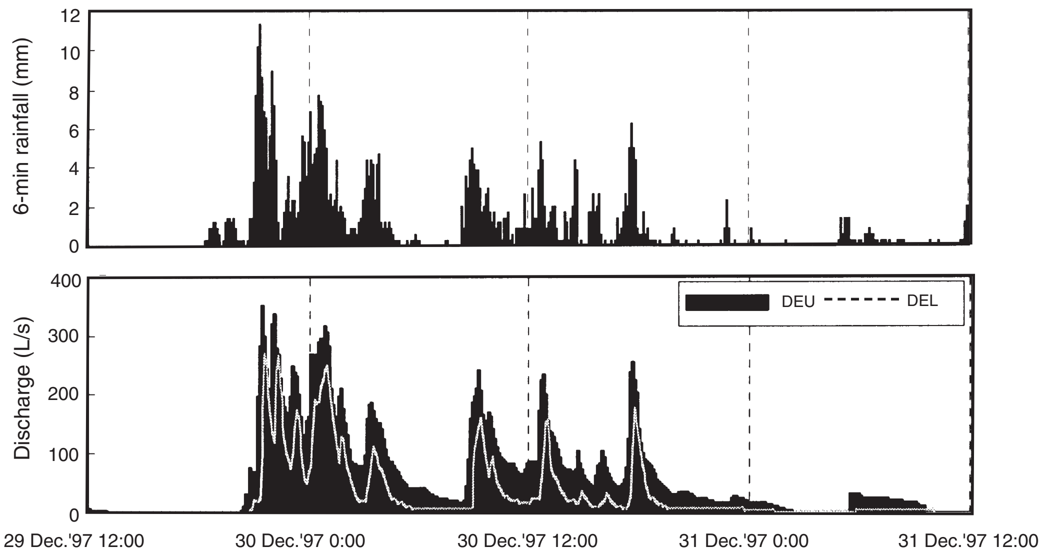


**Fig. 4.** Six-minute rainfall totals at Dunne's and Dunne's Extreme Upper (DEU) and Lower (DEL) hydrographs for the 550-mm event in late December 1997.

help improve surface runoff water quality by reducing the pollutant load, but may add to the subsurface pollutant load. Vegetation cover is required to protect filled areas in this environment, as large gullies have formed by mass failure.

In the rainforest buffer, flow through the lower flume was generally greater than that measured at the upper flume during large events. However, the difference is similar to the volume of rainfall added by direct precipitation to the buffer. This suggests that only a small quantity of localised return flow may have occurred in the rainforest buffer.

A tropical cyclone in February 1999 delivered a total of 517 mm of rain over a 45-h period. The maximum 1-h rainfall intensity was 50.5 mm and the antecedent conditions were moist ($API_7$ = 50 mm). During the event a total rainfall volume of 1143 $m^3$ fell on the crop, of which 33% became surface runoff at the upper flume. The peak discharge at the upper flume was 15 L/s. During the entire event a total volume of 372 $m^3$ passed through the upper flume and an additional 86 $m^3$ passed through the lower flume. This additional volume is similar to the volume added by direct precipitation onto the rainforest buffer (77.5 $m^3$). During the event, saturation was localised and temporary, occurring at 1 tensiometer nest [GTT4 (30 cm) and GTT6 (90 cm)]. The soil profile at the other tensiometer nest (GTT1 and GTT3) remained unsaturated throughout the event (Fig. 5*c*,*d*).

Localised saturation of the surface soil occurred in the rainforest buffer, particularly during large events. Two mechanisms may explain this localised saturation. Firstly, the soil permeability above 30 cm may have acted as a temporary throttle on infiltration and led to the development of localised saturation, as observed by Bonell *et al*. (1981). An alternative is that localised saturation and increases in surface runoff within the buffer could be due to stemflow.

Some basic calculations can be done to estimate the volume of water required to saturate the rainforest riparian buffer. The soil is over 3 m deep, but the different soil horizons do not respond in the same manner. The response at GTP1 was attenuated and delayed, which indicates a much less conductive horizon at depth and a loose vertical coupling between the surface and subsurface horizons. GTP2 shows a more event-based response (e.g. Fig. 5*e*) and so a depth of 2.3 m, over which the water table responds, is used. Assuming the porosity is around 0.5 (krasnozem bulk densities are commonly 1–1.4 g/$cm^3$ below 30 cm and particle densities vary between 2.3 and 2.6 g/$cm^3$; Lepsch 1989; Spain *et al*. 1989), field capacity is 0.2, and residual water 0.1, the available storage ranges between 20 and 40% of the soil volume. Including the buffer dimensions gives a total soil volume of 345 $m^3$ (15 m by 10 m by 2.3 m deep), which gives a water storage range of 70–140 $m^3$ in the buffer depending on the antecedent soil moisture. Over the entire event, the volume difference between the upper and lower flumes was 30 $m^3$ and the estimated volume of direct precipitation onto the buffer was an additional 30 $m^3$. This combined volume could have infiltrated without the buffer soil saturating.

The piezometer data provide additional evidence that the riparian buffer is not prone to saturation. The piezometric head rises gradually during each wet season and only the large events cause large responses. For example, during the tropical cyclone shown in Fig. 5 the piezometric head rose slowly and peaked after the surface runoff peak.

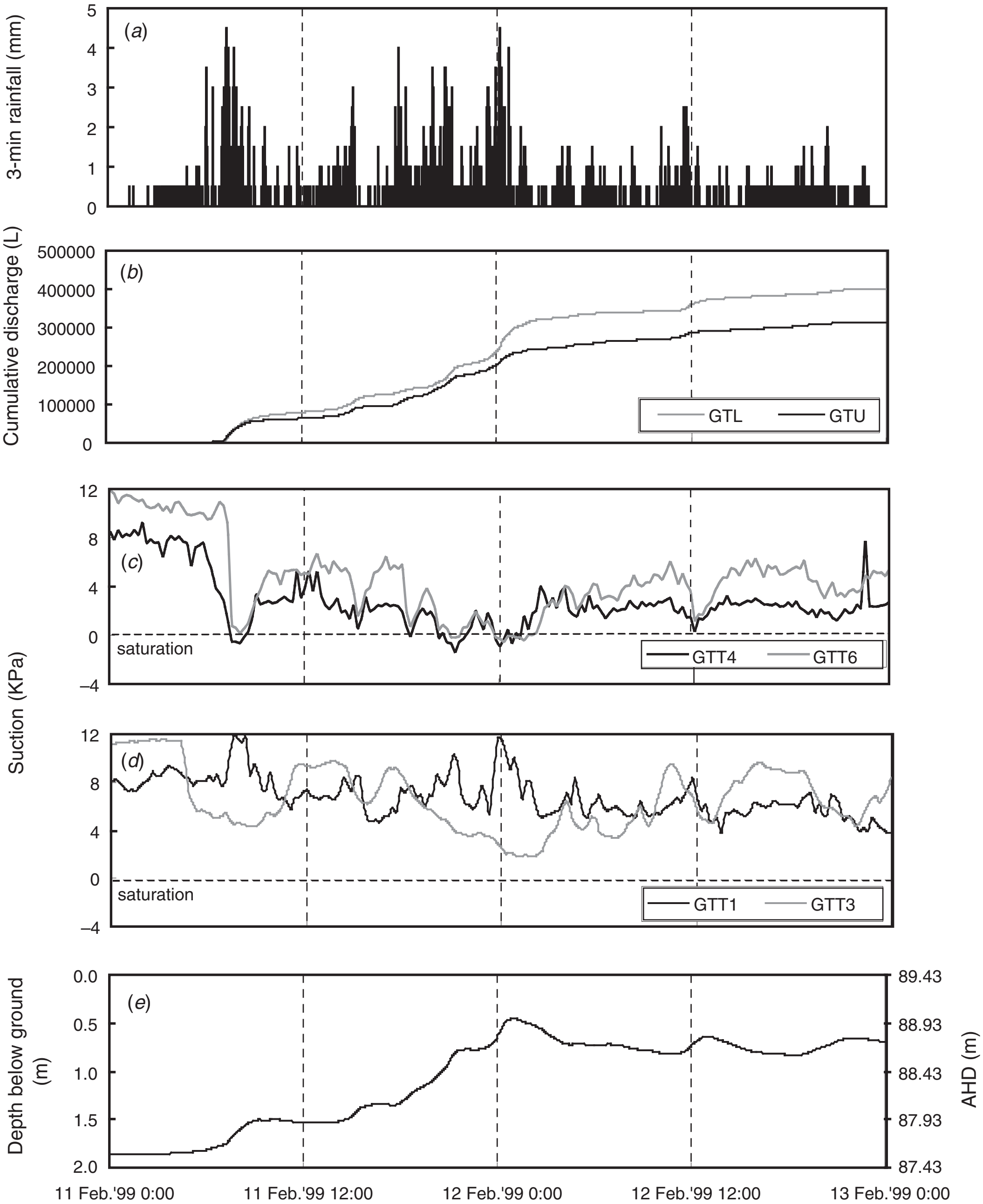


**Fig. 5.** (*a*) Rainfall, (*b*) cumulative runoff (Gallagher's Tree Upper (GTU) and Lower (GTL)), (*c*) tensiometer suction at GTT4 (30 cm), GTT6 (90 cm), and (*d*) GTT1 (30 cm) and GTT3 (90 cm), and (*e*) piezometric head (GTP2) in the rainforest buffer during Cyclone Rona, 11–13 February 1999.

Soils in the remnant rainforest buffer were drier than the soils in the adjacent grass buffer. After rainfall events the soil between 30 and 90 cm depth dried out rapidly, most likely due to higher water demand.

Exfiltration was measured at 2 of our sites, Gallagher's Grass and Dunne's Moderate, during large events. More runoff was measured at the lower flumes than the upper flumes.

Return flow (or exfiltration) was common at Gallagher's Grass during large events. The largest event at Gallagher's during the monitoring period occurred in December 1997, and caused the most extensive flooding witnessed by the landowners. Over the 4-day period a total rainfall of 603 mm was recorded. The maximum 1-h rainfall intensity was 55.5 mm and the antecedent conditions were dry ($API_7$ = 18 mm). The runoff:rainfall ratio at the upper flume was 0.22 and the peak discharge was 20 L/s (Fig. 6).

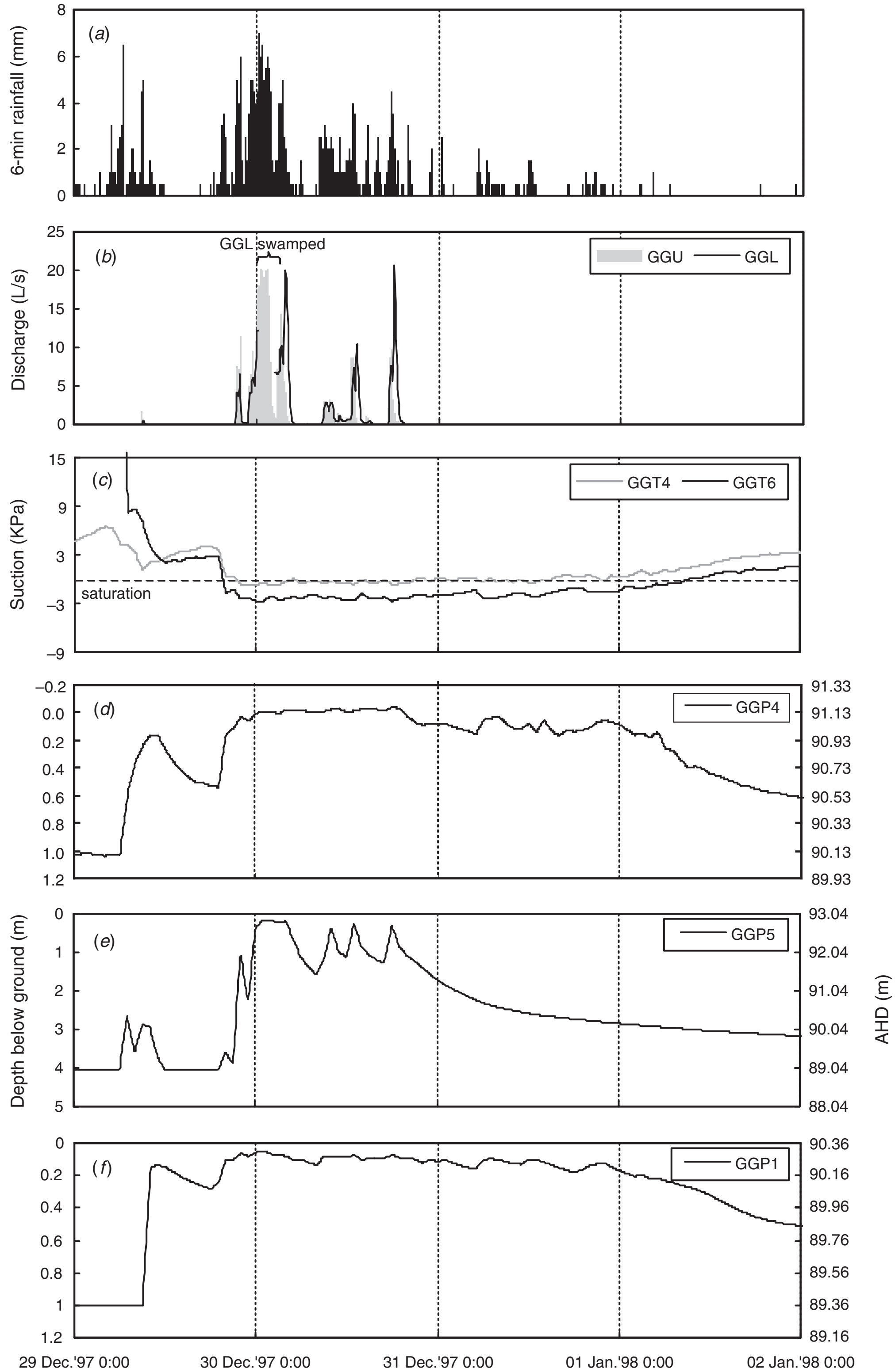


**Fig. 6.** (*a*) Rainfall, (*b*) runoff, (*c*) soil suction (GGT4 and GTT6), and (*d*) piezometric head within the riparian buffer (GGP4), (*e*) on the hillslope (GGP5), and (*f*) water table in the grass riparian buffer (GGP1) during 2 cyclones in late 1997–early 1998.

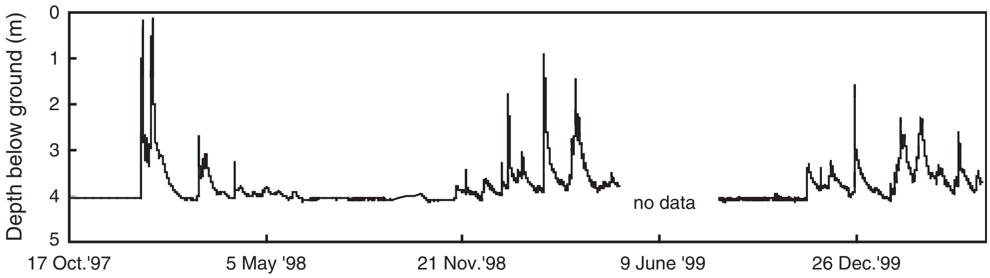


**Fig. 7.** Piezometric head in the hillslope piezometer GGP5 at Gallagher's Grass. The period October 1997–May 2000 is shown; the first wet season's data were lost due to logger battery failure.

The initial rain (74 mm between 0406 and 1048 hours) on the morning of 29 December did not result in much surface runoff, but there was a large subsurface response. Half of the 1055 L measured at the upper flume infiltrated before it reached the lower flume (Fig. 6*b*). A subsurface response was measured between 0600 and 0700 hours in the piezometers near the buffer edge (GGP4) and in the crop (GGP5) (Fig. 6*d–e*). The deeper tensiometers (90 cm) also responded before the shallower tensiometers, suggesting that they were saturated from below (Fig. 6*c*). The first near-stream subsurface response occurred between 0800 and 0900 hours when the water table rose to within 10 cm of the surface (GGP1) (Fig. 6*f*).

In the second surface runoff event, late on 29 December, runoff was still able to infiltrate into the buffer soil; 32% more runoff (17080 L) passed through the upper flume than the lower flume. The buffer soil was saturated by 2245 hours (Fig. 6*c*) and the saturation expanded upslope into the crop, where the head at GGP5 was within 30 cm of the soil surface for 4 h (Fig. 6*e*). During this 4-h period the saturation was sourced from below as the vertical hydraulic gradient between GGP7 and GGP6 was positive.

The runoff rates and volumes at both flumes were substantial, but as the lower flume was swamped for 2 h, we cannot compare totals for the entire period. However, during the last surface runoff event (from 1724 hours 30 December; Fig. 6*b*), nearly 3 times more runoff was measured at the lower flume (47.7 $m^3$) than the upper flume (17.7 $m^3$). The difference in runoff volumes exceeds the maximum possible input from direct precipitation (10.4 $m^3$) and so there is evidence of return flow exiting from the buffer soil. Runoff was still able to infiltrate within the crop at this time. A hydraulic gradient of –0.15 to –0.2 developed between GGP6 and GGP7 during the second input of rain (late on 29 December), with water flowing into the soil from the surface.

Exfiltration occurred frequently in the riparian buffer, but expansion of the saturated wedge up into the cropped area occurred only during large events or prolonged periods of rainfall. The piezometric head was recorded within 2 m of the ground surface in the hillslope piezometers only on 6 occasions during the second to fourth wet seasons, as shown in Fig. 7.

The soil in the grass buffer has an average depth of 1 m. So using the same method and values as before, a reasonable estimate of the total storage volume is 30–60 $m^3$ depending on antecedent conditions. Much of the actual storage volume is filled shortly after rainfall starts, which suggests that macropores may deliver rainfall rapidly to the riparian soils. Work by McShane (unpublished, cited in Prove *et al.* 1994) at a cropped site nearby indicated that macropores contributed as much as 25% of flow at saturation in the 0–60 cm zone. The top 10–15 cm of the soil profile also consists of large (>2 mm) loosely packed aggregates, which may encourage infiltration and may be the reason why the water table does not come completely to the surface and drops rapidly after rainfall ceases.

During larger events exfiltration was recorded in the lower segment of the grass riparian buffer at Dunne's Moderate. After large events or several consecutive days with daily totals >50 mm, seepage was observed after the rain had stopped. For example, during a 5-day period in April 2000, runoff continued to pass through the lower flume (DML) well after the rain had stopped (Fig. 8). A total of 352 mm of rain fell during the 34.5 h after midnight 6 April, and of this 282 mm fell in the main event. The maximum 1-h rainfall intensity was 72.5 mm and antecedent conditions were moist ($API_7$ = 32.5 mm). Seepage flowed through the flume at a rate of 1.5 L/s for 4 days after the event on 8 April 2000. Observations show that the seepage area typically extended 10–15 m upslope of the lower flume (DML). Shallow soils and bedrock constriction are the most likely cause of seepage in the lower buffer. Bedrock is exposed at the surface 10 m downslope of the lower flume.

Saturated riparian areas may present a high erosion risk if they are cropped instead of being protected by good grass cover. Positive pore water pressures accompanying return flow and seepage may reduce soil strength and in the most extreme cases lead to mass soil failure and gully erosion (Huang and Laften 1996; Bryan *et al.* 1998). Under these conditions a buffer's main function is to prevent erosion by displacing cropping from the riparian area.

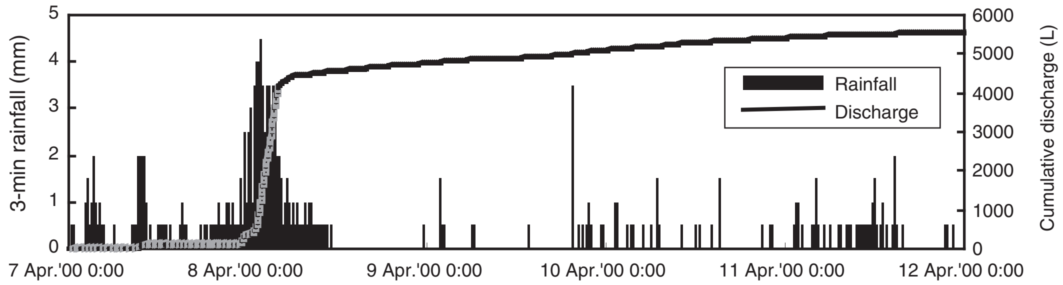


**Fig. 8.** Cumulative surface runoff and seepage at Dunne's Moderate Lower (DML) and rainfall from Gallagher's over a 5-day period in April 2000. No rainfall data were available for Dunne's during this event.

## Conclusions

Hydrometric methods were used to evaluate the proportion of rainfall becoming surface runoff, surface runoff discharges, and the hydrological processes occurring in the buffers. Surface runoff was only measured during rainfall events in these hillslope catchments. Between 1 and 65% of rainfall became surface runoff and event rainfall total was the key factor determining the runoff volume, rather than antecedent conditions or rainfall intensity.

This study documents the high runoff volumes and peak discharges occurring under current cropping practices in the wet tropics. On planar 7% slopes peak discharges from slope lengths of 200 m were always <30 L/s. In contrast, peak surface runoff discharges from a 5 ha convergent catchment were >350 L/s. Such conditions are not ideal for maximising riparian buffer performance. The grass buffer and vetiver hedges in this catchment were not able to reduce runoff velocities or disperse flow sufficiently in one large event and a channel was scoured through the buffer. The high discharges and channelised flow will decrease the buffer's performance and for it to be more successful it should be extended to the end of the crop rows.

Infiltration is a desirable buffer function as it reduces the sediment transport capacity by decreasing the surface runoff volume. This study showed that infiltration of surface runoff is unlikely to be an important riparian buffer function in the wet tropics. All runoff infiltrated into the riparian soils during small events, but during large events, which dominate the surface runoff volume, infiltration was generally limited. This may be due to high surface runoff velocities, which may reduce the ability of runoff to infiltrate, even if there is available soil storage.

Infiltration of surface runoff into the riparian soil was considerable in the large (5 ha) convergent catchment, most likely as the result of deep soil fill (>3 m deep). The proportion of surface runoff infiltrating varied during and between events, and during large events estimated infiltration rates were 700–5000 mm/h. Runoff volumes were so large and concentrated, however, that significant runoff still reached the stream.

Exfiltration dominated the riparian hydrology of 2 buffers during large events. Saturation overland flow, return flow, and seepage increased the volume of surface runoff flowing through the buffers. This was in places where soil depth was relatively shallow. Under these conditions an important function of grass riparian buffers is to reduce the risk of mass failure, rill, and gully erosion.

This study documents the high surface runoff volumes and discharges generated on cropped land in the wet tropics. It also suggests that infiltration may not be an important buffer function in this environment, but highlights the additional role that riparian buffers can play in protecting riparian lands from erosion risk due to exfiltration.

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