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Hydrological response of Ngarradj—a seasonal stream in the wet–dry tropics, Northern Territory, Australia*

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Abstract As part of a long-term study of the impact of mining at Jabiluka on the Ngarradj catchment, an attempt has been made to estimate the baseline hydrological characteristics of the catchment. General diurnal trends and analysis of high magnitude storm events at the Ngarradj catchment during the three-year monitoring period (1998–2001) show that peak rainfall and runoff occur late in the afternoon to early in the morning. The average time taken from the start of low frequency, very intense rainfall periods to peak runoff at streamgauging stations within Ngarradj catchment ranged between 45 min and 5.2 h. These lag times were examined in relation to the hydrological and geomorphological characteristics of the catchment. The understanding of these hydrological responses has important implications for the design of an effective stream sediment monitoring regime within the Ngarradj catchment.

Key words Ngarradj catchment; wet–dry tropics; flood events; diurnal variation; hydrological response; lag time; sampling regime; digital elevation model (DEM)

INTRODUCTION

The Jabiluka uranium mine is located in the Ngarradj catchment in the wet–dry tropics of the Northern Territory, Australia (Fig. 1). Ngarradj is located in the World Heritage listed Kakadu National Park, and will be the first to be affected should any impact occur as a result of mining operations at Jabiluka.

A streamgauging network was established in 1998 to collect data on baseline sediment movement and hydrology in the Ngarradj catchment (Fig. 1). The Environmental Research Institute of the Supervising Scientist (***eriss***) installed gauging stations both upstream (Upper Main—UM; East Tributary—ET) and downstream (Swift Creek—SC) (Fig. 1) of the mine. Gauging stations were also operated for a period of time during the 1998/99 wet season at tributaries north, central and south (TN, TC and TS respectively) (Fig. 1) by Earth-Water-Life Sciences Pty Ltd (EWLS).

This paper attempts to characterize the hydrological response of streams within the Ngarradj catchment both on a long-term average basis and on an individual storm event basis. The importance of characterizing low frequency, high magnitude flood events in developing an understanding of baseline conditions of sediment movement is also examined.

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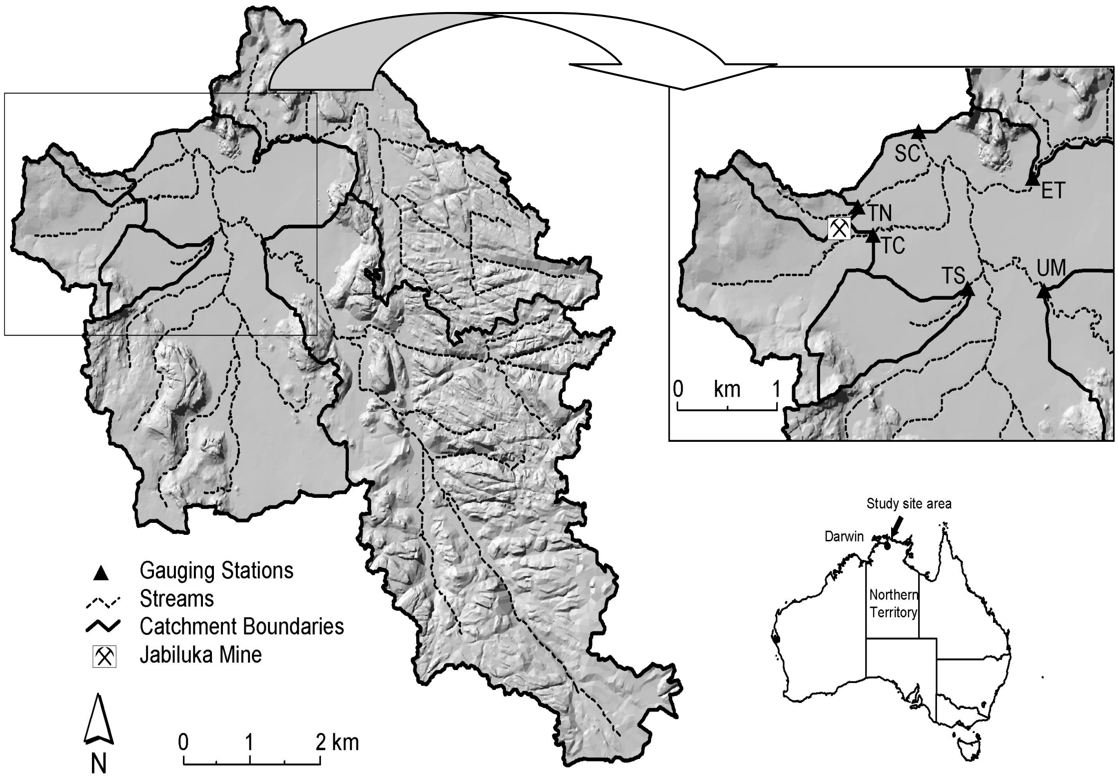

Fig. 1 The DEM of Ngarradj catchment. Shaded relief represents the sandstone plateau.

Study area

The Ngarradj catchment, located approximately 230 km east of Darwin in the monsoon tropics climatic zone (Fig. 1), experiences a distinct wet season from October to April, and a dry season for the remainder of the year. Streamflow, as a consequence, is highly seasonal. The average annual rainfall for the region is approximately 1410 mm (Bureau of Meteorology personal communication, 2001).

Ngarradj main channel flows in a well-defined valley in a northwesterly direction from the Arnhem Land sandstone plateau to the Magela Creek flood plain with one major right bank tributary (East Tributary) (Fig. 1). Both the upper reaches of the Ngarradj main channel and East Tributary flow in essentially a bedrock confined channel on the plateau (Fig. 1). There are several left bank tributaries that drain predominantly wooded lowland areas and have significantly smaller areas of bedrock and escarpment than the main channel and East Tributary. The total catchment area of the Ngarradj catchment (upstream of SC) is approximately 43.6 km^2.

Data collection

A 0.2-mm tipping bucket raingauge was installed at each ***eriss*** gauging station within Ngarradj catchment and readings were taken at 6-min intervals. Rainfall data were also collected at 10-min intervals at Jabiluka mine (Fig. 1) by Energy Resources of Australia using a 0.5-mm tipping bucket raingauge. The total annual rainfall over the

Ngarradj catchment (September–August), determined using the Thiessen polygon method (Thiessen, 1911) to spatially average the total rainfall measured at the three ***eriss*** gauging stations and Jabiluka mine, was 1826, 2047 and 1897 mm for 1998/99, 1999/00 and 2000/01 respectively.

Stage height (m) at each gauging station was measured at 6-min intervals by a pressure transducer. Stage data collected at SC, UM and ET were converted to discharge (m^3 s^{-1}) using fitted rating tables derived in Moliere *et al*. (2001). The total average runoff for the wet season at SC, UM and ET, estimated as the area under the hydrograph, was 34 450, 16 715 and 8143 Ml respectively. On average, flow occurred at each gauging station for approximately six months of the year (December–June).

A stage activated pump sampler was installed at each ***eriss*** gauging station to obtain a "continuous" suspended sediment data set throughout the wet season hydrograph. Grab samples were also taken weekly during the period of flow.

As the EWLS gauging stations (TN, TC and TS) only operated for a period of time during the 1998/99 wet season, runoff data from these gauging stations were not used in the analysis of long-term diurnal trends or high magnitude, low frequency storm events.

DIURNAL VARIATION IN RAINFALL AND RUNOFF

The mean hourly rainfalls measured at the four raingauges during the three-year monitoring period were spatially averaged using the Thiessen polygon method to determine the diurnal cycle over the Ngarradj catchment (Fig. 2). Figure 2 shows that Ngarradj catchment rainfall exhibits a strong diurnal cycle with a peak in the late afternoon, similar to that found over the Darwin region (Li *et al*., 1996; Soman *et al*., 1995). The mean runoff in 1-h bins for three years of runoff data collected at the three gauging stations is also shown in Fig. 2.

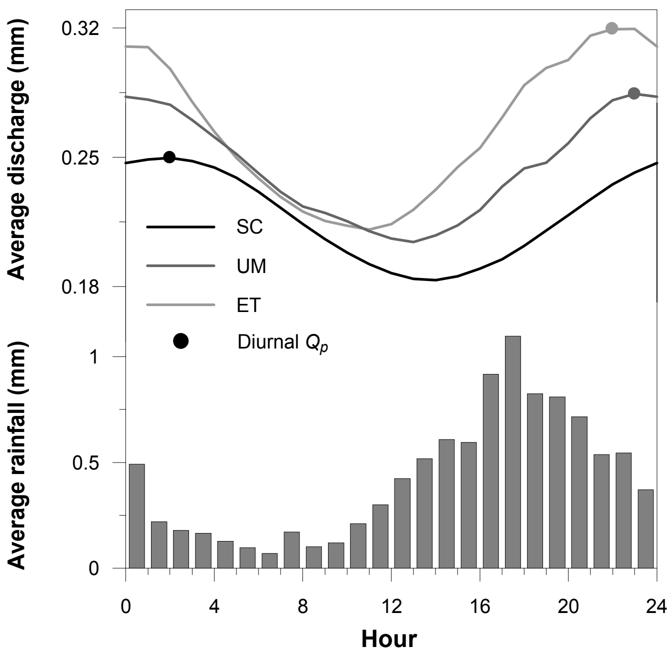

Fig. 2 Diurnal variation of mean catchment rainfall and runoff at each gauging station.

The mean hourly runoffs measured at the three ***eriss*** gauging stations exhibit a strong diurnal cycle with a peak late in the evening to early in the morning (Fig. 2). The average peak in runoff (Q_p) at SC, UM and ET occurs at approximately 03:00, 24:00 and 23:00 h respectively, corresponding to a "lag time" from the peak in rainfall of approximately 9, 6 and 5 h respectively (Fig. 2). The minimum runoff at SC, UM and ET is expected to occur at approximately 15:00, 14:00 and 12:00 h respectively (Fig. 2).

RUNOFF RESPONSE ON AN EVENT BASIS

A selection of the largest flood events observed during the three-year monitoring period at each ***eriss*** gauging station were used to characterize the runoff response to rainfall events on an individual event basis.

In the selection of the flood events a suitable criterion for independence of successive peaks (Hoggan, 1997) was applied where two flood peaks were considered to be independent if separated by periods of baseflow. The baseflow at each gauging station was determined by applying the Lyne and Hollick digital filter (Nathan & McMahon, 1990) to the three years of observed discharge data. For events separated by a period of baseflow it is interpreted that overland flow from the catchment has ceased.

The 10 largest flood events, in terms of peak discharge (Q_p), that occurred at each gauging station during the three-year monitoring period are shown in Table 1. The total rainfall, duration and maximum rainfall intensity (over a 60-min duration) of each rainfall period attributing to the flood peak are also given in Table 1. Tabulated intensity–frequency–duration (IFD) data for the Ngarradj catchment region (Bureau of Meteorology personal communication, 2000) for a 60-min duration were used to estimate the average recurrence interval (ARI) for each of the 10 rainfall events (Table 1).

The 10 rainfall events occurred between approximately 11:00 and 24:00 h (Table 1), with an average start of rainfall time of 18:43 h, which corresponds well to the overall diurnal cycle of rainfall over the Ngarradj catchment (Fig. 2). The average time of Q_p at SC, UM and ET for the 10 events was approximately 00:15, 23:30 and 22:30 h

Table 1 The 10 largest flood events during the three-year monitoring period.

Time rainfall commenced	Total rainfall (mm)	Maximum intensity (mm h^{-1}) [ARI (years)]	Rainfall duration (min)	Q_p (SC) (m^3 s^{-1})	Q_p (UM) (m^3 s^{-1})	Q_p (ET) (m^3 s^{-1})
30 Jan. 99, 22:00 h	51	51.0 [1.5]	63	20.74	15.00	8.51
11 Mar. 99, 19:48 h	66	65.9 [4.3]	54	22.25	14.70	8.39
28 Dec. 99, 21:42 h	82	60.6 [3.0]	90	18.14	12.15	7.89
21 Mar. 00, 19:24 h	65	65.3 [4.2]	53	17.07	9.93	7.81
22 Feb. 01, 23:54 h	55	57.5 [2.4]	48	18.97	12.27	7.20
Short duration mean	**64**	**60.1 [2.9]**	**61.6**	**19.43**	**12.81**	**7.96**
9 Feb. 99, 17:18 h	66	25.0 [0.2]	297	20.48	13.41	8.43
9 Jan. 01, 10:54 h	87	26.5 [0.3]	410	20.61	12.83	8.21
16 Jan. 01, 16:36 h	50	23.1 [0.2]	157	17.95	11.92	7.64
18 Jan. 01, 19:30 h	36	28.0 [0.3]	100	19.80	13.05	8.00
13 Feb. 01, 16:06 h	47	41.8 [0.8]	110	20.56	12.90	8.03
Long duration mean	**57**	**28.9 [0.3]**	**214.7**	**19.88**	**12.82**	**8.06**

respectively, which also corresponds well to the general trend in mean runoff at each site (Fig. 2).

Table 1 shows that there are two well-defined storm types that contribute to a major flood peak. Flood peaks during the three-year monitoring period were attributed to either (a) a short, intense rainfall period, or (b) a relatively constant and less intense rainfall period over a long duration. Total rainfall and Q_p values of the two storm types, however, were generally similar (Table 1). Examples of both storm types are shown in Fig. 3. The resultant hydrograph at UM is also shown (Fig. 3).

Each of the first five flood events listed in Table 1 were ranked amongst the most intense rainfall periods observed during 1998–2001. The two largest flood peaks at SC and UM were a result of these very short, intense rainfall periods (Table 1).

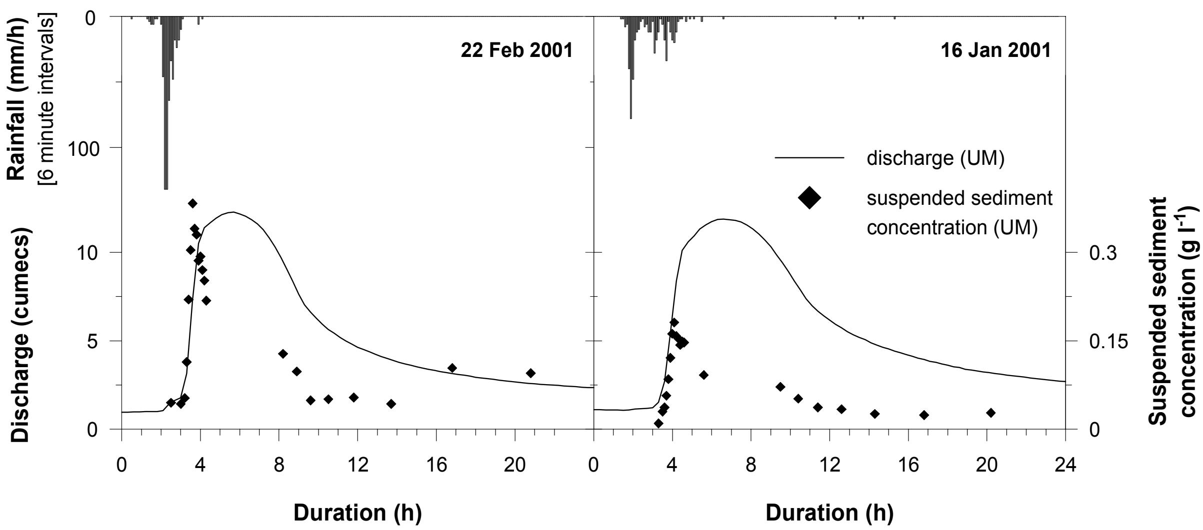

Fig. 3 An example of the two storm types that contribute to a flood peak—the short, intense rainfall period (*left*) and the longer, less intense rainfall period (*right*).

RELATIONSHIP BETWEEN LAG TIME AND CATCHMENT CHARACTERISTICS

The average lag time in Q_p of high intensity rainfall events at SC, UM and ET were used to determine a relationship between lag time and catchment characteristics. The estimation of lag times for these events is relatively accurate given that for these storm events: (a) the commencement time of the rainfall period is well-defined; (b) rainfall period is short and intense; and (c) resultant peak runoff is only attributable to the intense rainfall period.

During the three-year monitoring period there were seven rainfall–runoff events that occurred at all three gauging stations with an intensity greater than 44.6 mm h^{-1} (over a 60-min duration), which corresponds to a 1:1 year event at Ngarradj catchment (Bureau of Meteorology personal communication, 2000). Five of these events contributed to the flood events described in Table 1. The extra two selected storm events occurred early in the wet season (25 December 1998 and 1 December 1999) and resulted in relatively minor peak discharge events, particularly downstream at SC, as the catchment was relatively unsaturated (resulting in high infiltration rates).

The average time taken from the start of rainfall to Q_p at SC, UM and ET for the seven rainfall events was approximately 5.2, 3.7 and 3.1 h respectively (Table 2).

In order to determine a reliable and statistically significant relationship between lag time and catchment characteristics, runoff data collected at TN, TC and TS during the 1998/99 wet season (EWLS personal communication, 2001) were included in the analysis. During 1998/99 there were only three storm events with an intensity corresponding to a 1:1 year event at Ngarradj catchment. To establish a reasonable estimate of lag time for TN, TC and TS, eight rainfall–runoff events that occurred during 1998/99 with an intensity greater than 24 mm h^{-1} were selected for analysis. The average time rainfall commenced for the eight intense events was approximately 20:30 h. The average time taken from the start of rainfall to Q_p at TN, TC and TS for the eight events was approximately 46, 57 and 84 min respectively (Table 2). The average lag time at SC, UM and ET for these same eight rainfall events during 1998/99 was almost identical to that derived above for the seven most intense events observed during the three-year monitoring period (Table 2).

Table 2 Lag times and catchment characteristics.

Site	Mean lag time in Q_p (h) [SD (h)]	Area (km^2)	Perimeter (km)	Flow length (km)	Mean slope (%)	Mean channel slope (%)	Mean lag time in peak C (h) [SD (h)]
SC	5.2 [0.9]	43.61	62.28	13.71	13.4	8.49	3.8 [2.5]
UM	3.7 [0.6]	18.79	45.62	10.97	18.5	10.54	3.1 [1.6]
ET	3.1 [0.9]	8.46	29.01	7.87	14.5	8.53	2.4 [1.1]
TC	0.95 [0.2]	1.91	9.96	2.72	6.6	2.93	-
TN	0.76 [0.5]	0.34	4.36	1.67	8.4	5.34	-
TS	1.4 [0.5]	0.93	5.95	2.27	5.8	1.15	-

The lag time recorded at each gauging station was related to several catchment characteristics including catchment area, catchment perimeter, length of the longest catchment flow path, mean catchment slope and mean channel slope. These parameters were derived from a digital elevation model (DEM) of the Ngarradj catchment that was produced on a 5 m grid which has a relative vertical accuracy of ±0.5 m and relative horizontal accuracy of ±2 m. Preprocessing of the DEM involved the application of pit-filling and stream-burning algorithms to ensure that the model was both hydrologically and hydrographically correct. The final parameters were derived using the spatial analyst extension of the ESRI ArcView® 3.2 GIS software package.

The hydrological response of a catchment was characterized by examining the geomorphologic structure of a catchment. Rodriguez-Iturbe & Rinaldo (1997) suggested that the time-to-peak is related to stream length, channel density and constant drift velocity. A sensitivity analysis between observed lag times and various catchment characteristics (Table 2) showed that within the Ngarradj catchment, stream length and mean channel slope were the most significant factors in predicting lag time at each catchment outlet. The relationship of lag time (t_L) as a function of stream length (L) and mean channel slope (S_C) is given in equation (1).

$$t_L = 0.57\, L^{0.983}\, S_C^{-0.187} \qquad (r^2 = 0.97;\ p = 0.006) \qquad (1)$$

Figure 4 shows the relationship between observed and predicted lag times using equation (1) for each of the gauging stations within Ngarradj catchment for an individual storm event.

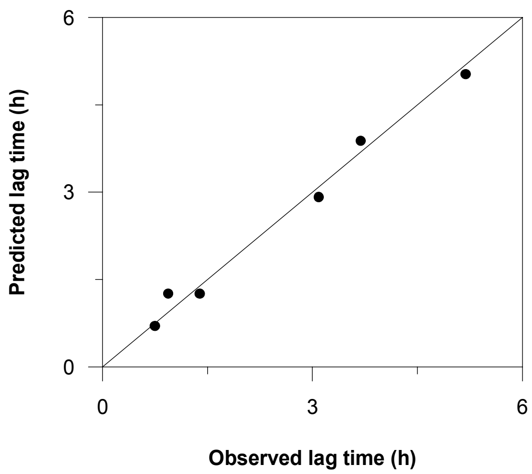

Fig. 4 Relationship between observed and predicted lag times (equation (1)). The 1:1 line is also shown.

IMPLICATIONS

The understanding of the diurnal cycle of rainfall over the Ngarradj catchment and the corresponding lag time for Q_p after a storm event has important implications for stream monitoring sampling within the Ngarradj catchment.

The application of either a fixed time, opportunistic or flow proportional sampling programme to the examination of long-term hydrology and sediment transport would give significantly different results. For example, at each ***eriss*** gauging station during the three-year monitoring period suspended sediment concentration, *C*, data were collected throughout the hydrograph by a stage activated pump sampler and from weekly grab samples. Table 3 shows that, in this case, the weekly mid-morning to mid-afternoon grab-sampling regime underestimates both the average and, in particular, the maximum background *C* in the stream at each gauging station.

General diurnal trends and analysis of high magnitude storm events show that peak rainfall and runoff occur in the late afternoon to early morning in the Ngarradj catchment. Five of the 10 flood events in Table 1 had complete *C* data collected throughout the event hydrograph at each station. Average lag times in peak *C* (Table 2) show that peak *C* occurs at the flow front. Sedigraphs for two flood events at UM showing the peak *C* occurring during the rising stage of the hydrograph are given in Fig. 3.

Table 3 Suspended sediment concentration (*C*) data from two sampling programmes.

Gauging station	Stage activated pump sampler: Mean *C* (g l^{-1}) [maximum *C* (g l^{-1})]	Weekly grab sample: Mean *C* (g l^{-1}) [maximum *C* (g l^{-1})]	Mean time of collection (h) [range of collection times (h)]
SC	0.047 [0.438]	0.035 [0.234]	12:30 [8:30–16:00]
UM	0.063 [0.567]	0.041 [0.262]	10:30 [7:20–15:20]
ET	0.085 [1.346]	0.035 [0.095]	11:00 [8:10–15:50]

These hydrological responses, therefore, need to be considered when establishing a monitoring regime to assess such issues as the impact of the Jabiluka mine on suspended sediment loads in streams within Ngarradj catchment.

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