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Hydrology and water quality of the Ngarradj catchment, Northern Territory: 2002/2003 Wet season monitoring

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1 Introduction

The Jabiluka uranium mine is located in the catchment of Ngarradj[1] in the wet dry tropics of the Northern Territory, Australia (fig 1.1). Ngarradj is a major downstream right-bank tributary of Magela Creek, which flows directly into the Magela Creek floodplain. The Magela Creek and floodplain are listed as Wetlands of International Importance under the Ramsar Convention and recognised under the World Heritage Convention.

The Ngarradj catchment will be the first to be affected should any impact occur as a result of mining operations at Jabiluka. In 1998 the Environmental Research Institute of the Supervising Scientist (***eriss***) established a stream gauging network to develop an understanding of contemporaneous catchment baseline conditions of sediment movement and hydrology in the Ngarradj catchment (fig 1.1). Stream gauging stations were installed upstream (Upper Main – UM; East Tributary – ET) and downstream (Swift Creek – SC) (fig 1.1) of the mine in order to assess possible impacts associated with mining at Jabiluka (Erskine et al 2001). Gauging stations were also operated at tributaries North, Central and South (TN, TC and TS respectively) (fig 1.1) by Energy Resources of Australia (ERA). No data were collected from the ERA gauging stations during the 2002-03 wet season.

This report describes the hydrology and water quality data collected from the three stream gauging stations within the Ngarradj catchment during the 2002-03 Wet season. The data were collected as part of the long-term study on the impact of mining at Jabiluka on the Ngarradj catchment.

1.1 Study area

The Ngarradj catchment is located approximately 230 km east of Darwin and 20 km north-east of Jabiru (fig 1.1). Oenpelli, Arnhem Land, is a further 20 km north-east of the Ngarradj catchment. Located in the monsoon tropics climatic zone, the catchment experiences a distinct wet season from October to April, and a dry season for the remainder of the year. Stream flow, as a consequence, is highly seasonal. The average annual rainfall for the region is approximately 1410 mm (Bureau of Meteorology pers comm. 2001).

Ngarradj main channel flows in a well-defined valley in a northwesterly direction from the Arnhem Land sandstone plateau to the Magela Creek floodplain with one major right bank tributary (East Tributary) (fig 1.1). Both the upper reaches of the Ngarradj main channel and East Tributary flow in essentially a bedrock confined channel on the plateau (fig 1.1). 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.

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[1] **Ngarradj**: Aboriginal name for the stream system referred to as "Swift Creek" in earlier studies. Ngarradj means sulphur crested cockatoo. The full term is Ngarradj Warde Djobkeng. Ngarradj is one of several dreaming (Djang) sites on or adjacent the Jabiluka mine lease (A Ralph, Gundjehmi Aboriginal Corporation 2000).

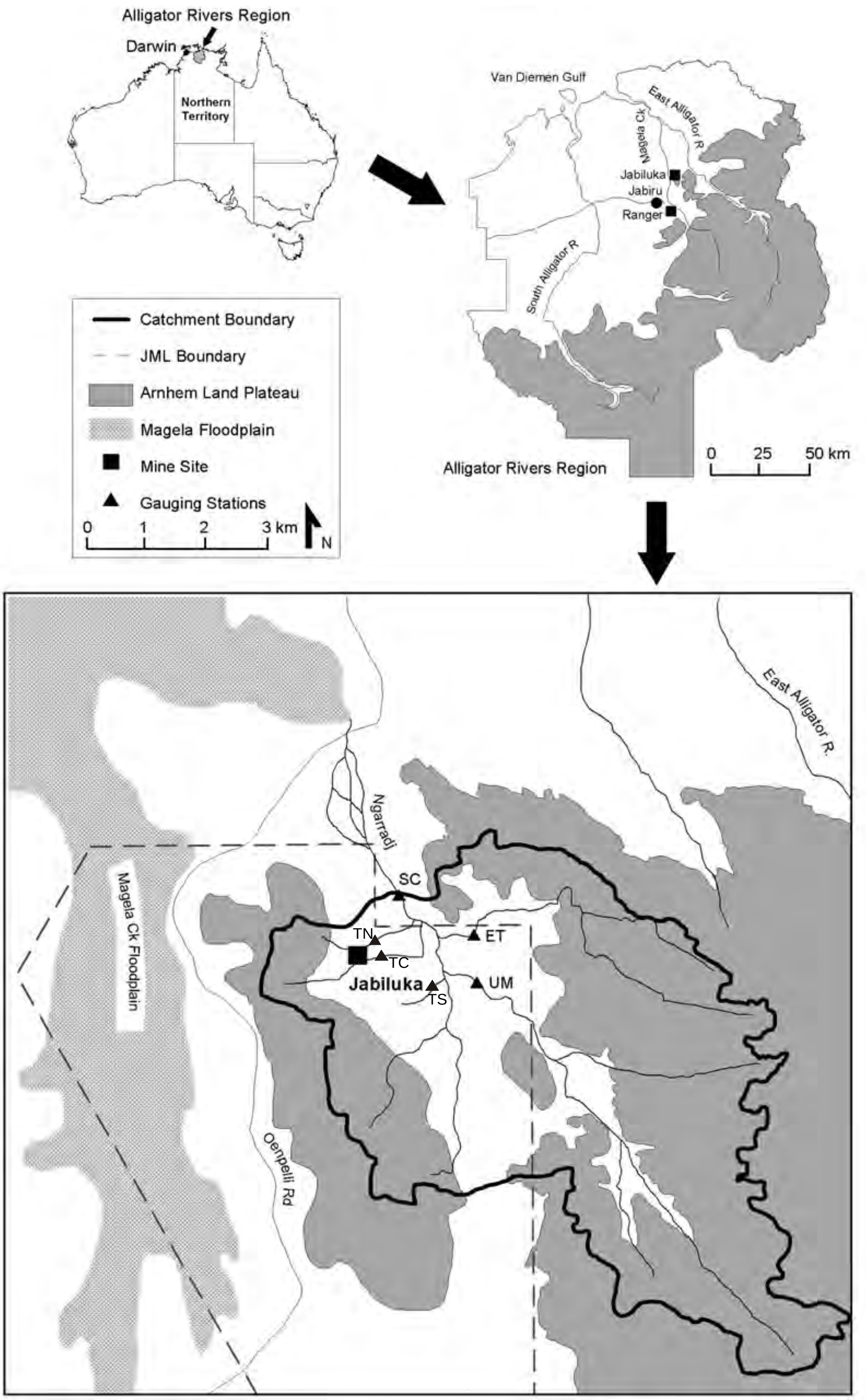

Figure 1.1 The Ngarradj catchment showing the location of the Jabiluka mine and the gauging station sites

2. Hydrology data

2.1 Rainfall data

A 0.2 mm tipping bucket rain gauge was installed at each ***eriss*** gauging station within Ngarradj catchment and readings were taken at 6 minute intervals (Saynor et al 2001). Daily rainfall data were also collected at Jabiluka mine (fig 1.1) by Energy Resources of Australia. The total annual rainfall at each gauging station (SC, UM and ET) and Jabiluka mine during the 2002/03 wet season is shown in table 2.1. The total annual rainfall over the Ngarradj catchment (September to August), determined using the Thiessen Polygon method (Thiessen 1911) to spatially average the total rainfall measured at the three gauging stations and Jabiluka mine during the year, was 1769 mm (table 2.1).

Table 2.1 Total rainfall over the Ngarradj catchment area derived using the Thiessen Polygon method

Station	Rainfall 02/03 (mm)	Polygon area (% of total area)
SC	1759[1]	0.324
UM	1767	0.482
ET	1790	0.105
Jabiluka	1791	0.089
Total [ARI]	1769 [1:9]	1.00

1 Data partly provided by Energy Resources of Australia

To determine an annual recurrence interval (ARI) of the total annual rainfall volume observed at the Ngarradj catchment, it was necessary to compare the observed data to long-term rainfall data collected in the region. Moliere et al (2002) showed that rainfall at the Ngarradj catchment is not significantly different to that at Oenpelli, which has a period of record of approximately 90 years. The annual rainfall at the Ngarradj catchment during 2002/03, compared to the Oenpelli rainfall distribution, corresponds to a 1:9 rainfall year (fig 2.1, table 2.1). The annual rainfall volumes for the previous four years of monitoring are also shown on figure 2.1.

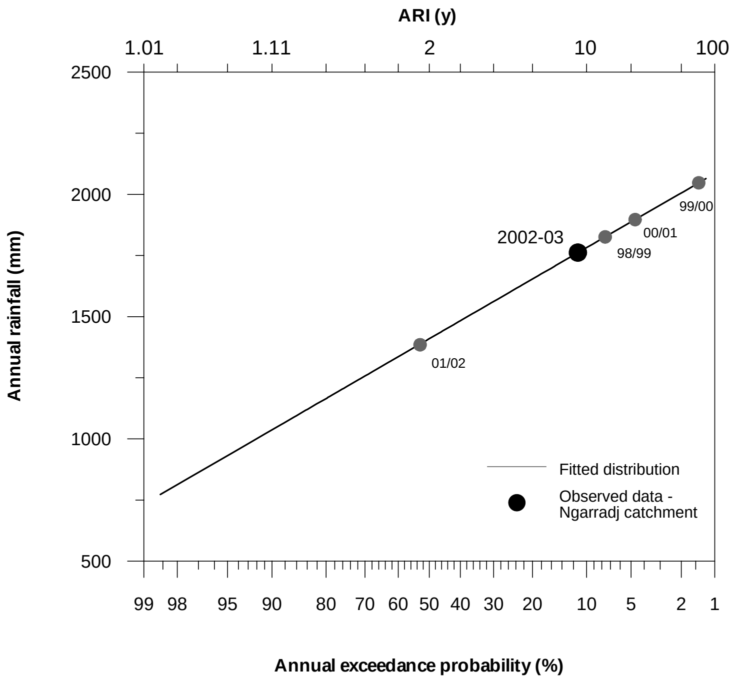

Figure 2.1 Annual rainfall frequency curve for Oenpelli. The 2002/03 rainfall, along with the previous four years of rainfall, for the Ngarradj catchment (table 2.1) are also shown.

2.1.1 Infilling rainfall data

An error occurred during the download process of the datataker at SC on 4 February 2003 and, as a result, rainfall data were not collected at SC for the two-week period from 24 January to 4 February 2003. Moliere et al (2002) showed that rainfall data recorded at Jabiluka mine are very similar to that observed at SC and, therefore, the total rainfall recorded at Jabiluka mine during this two-week period was simply transposed to the SC rainfall record (table 2.2).

Table 2.2 Total rainfall used to infill gaps in the rainfall record at SC, UM and ET during 2002/03.

Station	Gap in the rainfall record	Total infilled rainfall (mm)
SC	24 Jan – 4 Feb 2003	57.4 (1)
UM	1 Sept – 14 Nov 2002	18.0 (2)
	3 Feb – 20 Feb 2003	309.2 (2)
	4 Mar – 18 Mar 2003	216.4 (2)
ET	-	-

(1) Data infilled using Jabiluka mine rainfall

(2) Data infilled using ET rainfall

There were three periods during the 2002/03 Wet season where rainfall data were not recorded at UM (table 2.2). The reasons for these periods of missing data are briefly described as follows:

- The cables connecting the rain gauge to the datataker at UM (which had been faulty since 6 February 2001 and, as a result, no rainfall data were collected since that time) were re-installed on 14 November 2002.
- An internal failure in the datataker at UM occurred during early February 2003 and, as a result, rainfall data collected at UM from 3 February 2003 until 20 February 2003 were unreliable.
- The datataker at UM was removed on 4 March 2003 for repair. Therefore, no rainfall data were collected from 4 March to 18 March 2003, when a new datataker was re-installed.

Rainfall data collected at ET, the nearest gauging station to UM (fig 1.1), were used to estimate the total rainfall during these periods (table 2.2). Similar to above, analysis in Moliere et al (2002) showed that rainfall data recorded at the two stations, ET and UM, are not significantly different.

2.2 Runoff data

Stage height (m) at each gauging station was measured at 6 minute intervals by both a pressure transducer and a shaft encoder (Saynor et al 2001). In previous years, the pressure transducer has been the primary instrument for stage data collection, while the data collected by the shaft encoder have been used simply as a means of checking the pressure transducer readings (Moliere et al 2002).

During the 2002/03 wet season, stage data collected by the shaft encoder at UM and ET were used to infill a two-week period where stage data were not collected by the pressure transducer. At SC, the shaft encoder was selected as the primary instrument for stage data collection throughout the entire wet season as stage data collected by the pressure transducer were either missing or considered unreliable until early February 2003.

The stage data measured by either the pressure transducer or the shaft encoder were checked against the true stage of the stream (gauge board) at regular intervals throughout the period of flow (approximately fortnightly). These checks made during the wet season showed that the instrument readings were similar to that at the gauge board (table 2.3).

Table 2.3 Stage measured at the gauge board and by the pressure transducer and shaft encoder at each site during 2002/03

SC

	Stage height (m)		
Date	**Gauge board**	**Pressure transducer**	**Shaft encoder**
03-Jan-03	0.73	-	0.734
14-Jan-03	1.28	-	1.292
24-Jan-03	0.82	-	0.818
04-Feb-03	0.67	0.675	0.675
20-Feb-03	2.02	1.996	2.020
04-Mar-03	1.02	1.010	1.020
18-Mar-03	0.84	0.849	0.850
01-Apr-03	0.52	0.518	0.509
14-Apr-03	0.29	0.293	0.286
	Average difference	**0.00 m**	**0.00 m**

UM

	Stage height (m)		
Date	**Gauge board**	**Pressure transducer**	**Shaft encoder**
03-Jan-03	0.51	0.504	-
14-Jan-03	0.72	0.720	-
24-Jan-03	0.48	0.478	-
04-Feb-03	0.44	0.445	-
20-Feb-03	1.19	1.183	1.182
04-Mar-03	0.69	0.692	0.691
18-Mar-03	0.63	0.622	0.623
01-Apr-03	0.38	0.374	0.365
14-Apr-03	0.23	0.233	0.222
	Average difference	**0.00 m**	**0.00 m**

ET

	Stage height (m)		
Date	**Gauge board**	**Pressure transducer**	**Shaft encoder**
03-Jan-03	0.36	0.364	0.371
14-Jan-03	0.59	0.577	0.588
24-Jan-03	0.37	0.393	0.403
20-Feb-03	0.65	0.648	0.650
04-Mar-03	0.50	0.503	0.500
18-Mar-03	0.37	0.388	0.390
01-Apr-03	0.29	0.277	0.271
14-Apr-03	0.24	0.212	0.206
	Average difference	**0.00 m**	**0.00 m**

A rating table (stage-discharge) was derived for each station from two years of weekly velocity-area gaugings (1998/99 and 1999/00 wet seasons) (Moliere et al 2001). Velocity-area gaugings taken at each station throughout the 2002/03 wet season fit reasonably well along the rating curves (fig 2.2).

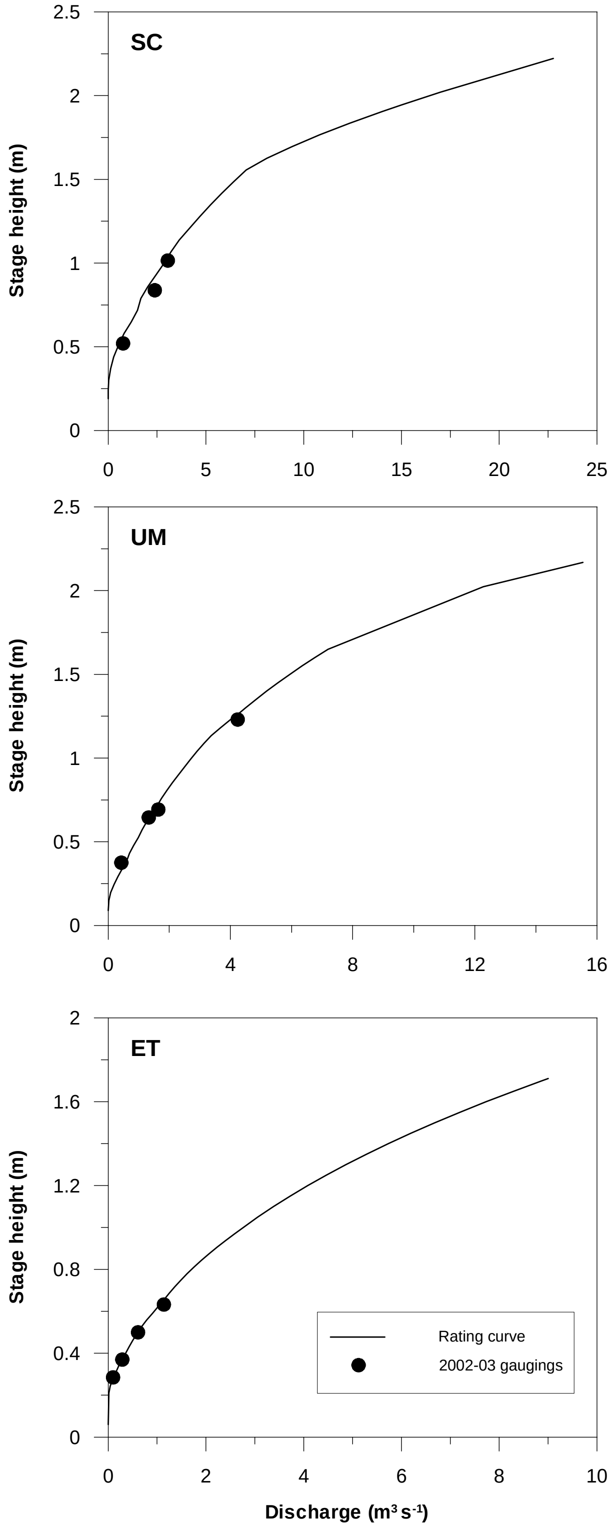

Figure 2.2 Rating curves for SC, UM and ET with the gauging points take during 2002/03 shown

Table 2.3 shows that the data collected by the pressure transducer or the shaft encoder during the 2002/03 wet season at each site were correct. Figure 2.2 shows that the rating curves to convert these stage data to discharge data were appropriate for the 2002/03 wet season. The combination of these two results (table 2.3 and fig 2.2) suggest that the hydrograph for each station during 2002/03 should be considered reliable.

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 complete hydrograph for each gauging station for the 2002/03 wet season is shown in Appendix A.

The total runoff for each wet season at the gauging stations, determined as the area under the hydrograph, is given in table 2.4. Total rainfall, the runoff period and antecedent rainfall at each gauging station are also given in table 2.4. It should be noted that the time that runoff ended was estimated from field observations and is accurate to within 2-3 days, and the antecedent rainfall, in this case, is defined as the amount of rainfall before the start of streamflow.

Table 2.4 Total rainfall and runoff at each gauging station for the 2002/03 wet season

Station	Total rainfall (mm)	Antecedent rainfall (mm)	Runoff period	Total runoff (ML) [Peak discharge (m^3s^{-1})]
SC	1759(1)	226	22 Dec – 7 May	33244.8 [21.2]
UM	1767	250	20 Dec – 1 June	18101.1(2) [12.9]
ET	1790	356	1 Jan – 7 May	7248.5 [8.2]

(1) Data infilled using Jabiluka mine rainfall

(2) Total runoff partly infilled using predicted discharge data generated from the HEC-HMS model (see section 2.2.1)

Total runoff at each gauging station for 2002/03 is above the average runoff volume of 23221, 10841 and 5615 ML at SC, UM and ET respectively. These average annual runoff volumes were determined from the long-term runoff record (22 years) generated from the parameterised HEC-HMS model (Moliere et al 2002). Given the annual rainfall was a 1:9 y wet season, this is an expected result.

2.2.1 Infilling runoff data

As discussed above, an internal failure in the datataker at UM occurred during early February 2003. As a result, both rainfall and runoff data collected at UM from 3 February 2003 until 20 February 2003 were unreliable. During this period there were also no stage data collected by the shaft encoder. Therefore, for the first time throughout the five-year monitoring period of the Ngarradj gauging stations, no stage data were collected at a site for a period of time.

The HEC-HMS hydrology model, parameterised for the UM catchment (Moliere et al 2002) was used to generate a runoff record for the period that was missing. Rainfall data collected at ET, the nearest gauging station to UM (fig 1.1), was used as input into the model and a hydrograph for the period 3 – 20 February at UM was predicted (Appendix A).

The total predicted volume of flow at UM from 3 – 20 February was 3968 ML, 60% of that observed at SC for the same time period. The average percentage volume of runoff at SC contributed by the upstream channel UM throughout the previous four wet seasons (1998-2002) is approximately 50%. Therefore, the predicted volume of flow at UM from 3 – 20 February does not seem unreasonable.

2.2.2 Assessment of impacts on runoff

A flow duration curve can be used to indicate a change in runoff characteristics attributed to a disturbance or impact in an area of a catchment. Flow duration curves were derived for each gauging station for the period of flow during 2002/03 and 1998/99, the first wet season of monitoring (fig 2.3). Figure 2.3 shows that, in general, instantaneous discharge is higher during 2002/03 than 1998/99 at each gauging station.

As the change occurs at all three gauging stations, it is unlikely that the increase in instantaneous discharge at SC is due to mine site construction or activity. The change at SC is likely to be a catchment response, probably due to the fact that although total runoff at each gauging station during 2002/03 (table 2.4) was similar to that recorded during 1998/99 (Moliere et al 2001), it occurred during a shorter period of flow. The runoff period during 2002/03 was approximately 4-5 months (table 2.4) compared to almost 6 months during 1998/99.

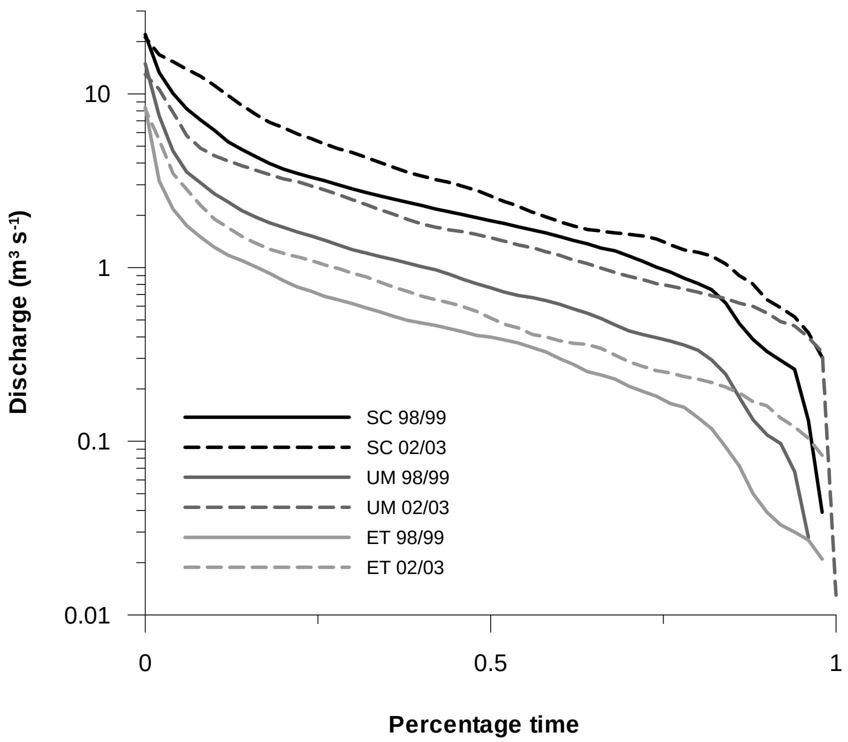

Figure 2.3 Standard flow duration curves for the Ngarradj catchment – 1998/99 and 2002/03

2.2.3 High magnitude events

Two of the largest rainfall-runoff events observed at each gauging station during 2002/03 occurred on 1 and 7 January 2003 (Appendix A). The peak discharge and the corresponding ARI for peak discharge, estimated from frequency curves derived in Moliere et al (2002), for these two events are shown in table 2.5. The total rainfall, duration and maximum rainfall intensity, over several durations, of each rainfall period attributing to the flood peak are also given in table 2.5. Total rainfall and rainfall intensities for the two events (table 2.5) were assumed to occur over the whole Ngarradj catchment and were determined using the Thiessen Polygon method to spatially average the total rainfall and intensities measured at the three gauging stations.

Tabulated intensity-frequency-duration (IFD) data for the Ngarradj catchment region for these durations (Bureau of Meteorology pers comm 2000) were used to estimate the average recurrence interval (ARI) for each of the rainfall events (table 2.5).

The peak discharge for the event on 7 January 2003, had an average ARI of approximately 1:2.8 y at all three gauging stations (table 2.5). This event was a long duration, low intensity rainfall event (table 2.5) that resulted in one of the largest flood events observed within the catchment. In terms of total rainfall over the entire Ngarradj catchment, this was the largest rainfall event observed during the five-year monitoring period. Rainfall intensity across both a 12 h (table 2.5) and 24 h duration corresponded to a 1:4 y event.

The peak discharge for the event on 1 January 2003, had an average ARI of approximately 1:2.4 y at all three gauging stations (table 2.5). This storm event was relatively intense across many durations, particularly over a 3-h duration where rainfall intensity corresponded to a 1:25 y storm event (table 2.5). The intensity of the rainfall was not reflected in terms of the resultant peak discharge, and two possible explanations for this are that:

1 This storm resulted in the first significant runoff event for the 2002/03 wet season at Ngarradj (Appendix A), and therefore it may be assumed that this event occurred when the catchment was relatively dry and infiltration rates were high.

2 Total rainfall and rainfall intensity may have been less on the upper reaches of the catchment than that recorded at the gauging stations.

There were only two other rainfall events during the 2002/03 wet season with a rainfall intensity which corresponded to a greater than 1:1 y event (across various durations) at the Ngarradj catchment: (1) 26 December 2002 – 1:3 y and 1:2 y event over 30 minute and 1 h durations respectively; (2) 4 January 2003 – 1:1 y event over a 30 minute duration. As a result of the relatively intense rainfall event on 26 December 2002, no significant runoff occurred at the gauging stations (Appendix A). Similar to the event on 1 January 2003, this storm occurred when flow had only just commenced at SC and UM (and not yet at ET) and therefore it is likely that this storm occurred when the catchment area was still relatively dry.

2.3 Hydrology data summary – 1998–2003

The total annual rainfall over the Ngarradj catchment (September to August), determined using the Thiessen Polygon method to spatially average the total rainfall measured at the three gauging stations and Jabiluka mine, for the 5-year monitoring period is given in table 2.6. It is assumed that these figures reflect the annual rainfall that occurred over the whole Ngarradj catchment, despite the fact that the rain gauges are all located in the wooded lowland areas of the catchment (fig 1.1) (Moliere et al 2002). The ARI of the total annual rainfall volume observed at the Ngarradj catchment, compared to the long-term rainfall data collected at Oenpelli, is also given in table 2.6.

The runoff period (estimated from field observations and accurate to within 2-3 days), total annual runoff and antecedent rainfall (defined as the amount of rainfall before the start of streamflow) at each gauging station for the 5-year monitoring period are also given in table 2.6.

Table 2.5 Two flood events at each gauging station during 2002/03. Approximate ARIs for peak discharge and maximum rainfall intensity are also shown.

				Intense rainfall period		Duration				
						60 min	120 min	180 min	360 min	12 h
Date	**SC – Peak Q ($m^3 s^{-1}$) [ARI (y)]**	**UM – Peak Q ($m^3 s^{-1}$) [ARI (y)]**	**ET – Peak Q ($m^3 s^{-1}$) [ARI (y)]**	**Rainfall (mm)**	**Duration (h)**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**
1 Jan 2003	17.0 [2.1]	11.6 [2.1]	7.9 [2.9]	129	4	63.8 [4]	48.7 [12]	39.8 [25]	21.9 [20]	11.0 [6]
7 Jan 2003	21.2 [2.9]	12.6 [2.4]	8.2 [3.1]	147	18	22.3 [0.2]	19.6 [0.4]	16.5 [0.5]	14.1 [2]	10.2 [4]

Table 2.6 Total rainfall over the Ngarradj catchment and runoff at each gauging station for the 5-year monitoring period (1998 to 2003)

Year	Total rainfall (mm) [ARI (y)]	Rainfall period	Station	Antecedent rainfall (mm)	Runoff period	Total runoff (ML) [Peak discharge (m^3s^{-1})]
1998/99	1826 [1:13]	20 Sep – 28 Apr	SC	430(1)	9 Dec – 27 May	33665 [22.3]
			UM	440(1)	12 Dec – 10 Jun	15666 [15.0]
			ET	415(1)	9 Dec – 27 May	7621 [8.5]
1999/00	2047 [1:71]	14 Oct – 24 May	SC	260	20 Nov – 14 Jul	34899 [18.1]
			UM	305	20 Nov – 20 Jul	17426 [12.2]
			ET	280	20 Nov(2) – 25 Jun	8532 [8.1]
2000/01	1897 [1:21]	14 Oct – 27 Apr	SC	250	29 Nov – 14 Jun	34781 [20.6]
			UM	250	3 Dec – 14 Jun	17052 [13.0]
			ET	245	28 Nov – 21 May	8275 [8.2]
2001/02	1390 [1:2]	17 Oct – 14 Apr	SC	420	31 Dec – 15 Apr	14382 [22.0]
			UM	370	31 Dec – 1 May	7495 [13.6]
			ET	330	28 Dec – 25 Apr	3963 [8.3]
2002/03	1769 [1:9]	13 Sep – 1 May	SC	225	22 Dec – 7 May	33245 [21.2]
			UM	250	20 Dec – 1 Jun	18101 (3) [12.9]
			ET	355	1 Jan – 7 May	7249 [8.2]

(1) Data partly provided by Energy Resources of Australia

(2) A small surge of runoff occurred on 8 Nov, 1900 – 2300 h (Moliere et al 2002 - Appendix A)

(3) Total runoff partly infilled using predicted discharge data generated from the HEC-HMS model (see section 2.2.1)

3 Water quality data

During the 2002/03 wet season, water samples were collected throughout the hydrograph by a stage activated pump sampler. These samples were downloaded approximately fortnightly in the field and taken back to the laboratory for water quality analysis. A maximum of 48 samples were collected from each gauging station per download. The water samples were analysed in the laboratory using standard sediment filtering and water chemistry techniques. The water quality parameters measured were turbidity, pH, electrical conductivity and sediment concentration (sand (>63 µm Ø), mud (<63 µm >0.45 µm Ø) and solute fractions(<0.45 µm Ø)).

3.1 Turbidity and mud concentration data

During the previous four years of monitoring, the mud concentration (mud *C*) of every water sample collected by the pump sampler at each gauging station was determined by filtering techniques. Due to the large number of samples collected during each wet season and the time spent in the laboratory filtering each sample, the determination of mud *C* throughout a wet season proved to be a very labour-intensive task. As a result, it was decided that a less resource-intensive method for determining stream mud *C* within the Ngarradj catchment was required.

Water samples collected by the pump sampler during the 2002/03 wet season were used to develop a relationship between turbidity and mud *C* for each gauging station. Using a calibrated turbidity-mud *C* relationship, the mud *C* of each collected water sample can be established by simply measuring the turbidity of the water sample and applying the calibrated relationship to the turbidity reading. The amount of time taken to measure the turbidity of a water sample in the laboratory is much less than that taken to process the sample using filtering techniques. This technique of using turbidimeters to determine suspended sediment concentration in streams has been successfully used in many other studies (ie Walling 1977, Whyte and Kirchner 2000).

3.1.1 Calibrating the turbidity-mud *C* relationship

Water samples collected at each gauging station during 2002/03 within the catchment were used to derive turbidity-mud *C* relationships for each station. For the water samples collected during the first month of flow, the turbidity of the sample was measured and then the corresponding mud *C* was determined using filtering techniques. The analysis of this first month of samples indicated that a high percentage of samples collected over the hydrograph were relatively “clear” (turbidity < 10 NTU). In order to obtain a more even spread of data over a large range of turbidity values, it was decided that for the remainder of the wet season only one in four samples, plus those with a turbidity reading above 10 NTU, would be then filtered for the corresponding measurement of mud *C*.

It should be noted, turbidity was measured for a sample after the sand fraction of the suspended sediment was removed. The sample was poured through a 63 µm sieve, and the resultant filtrate was then analysed. (Previously, turbidity measurements in the laboratory were made on the water sample before the sand fraction of the suspended sediment was removed.)

Regression analysis was conducted between corresponding turbidity and mud *C* data for each gauging station (fig 3.1).

The water sample collected at ET with a turbidity reading of 100 NTU was identified as a possible outlier (fig 3.1). All other samples collected during the wet season at ET had a turbidity reading less than 60 NTU (fig 3.1). As a result, this point was removed from the regression analysis and the revised calibrated equation for ET is shown in figure 3.2.

The establishment of a single turbidity-mud *C* relationship for the Ngarradj catchment, rather than three station-specific relationships, would be more convenient for future monitoring/sampling in the region. To validate the process of combining the data collected at all three sites, an Analysis of Covariance test was conducted to determine if the three derived regression equations were not significantly different. The STATISTICA™ software package, which was used for this test, showed that the regression equation fitted for SC was significantly different to that fitted for UM and ET. Therefore, the data cannot be combined to derive one turbidity-mud *C* relationship for the Ngarradj catchment.

A further test was conducted to compare just the two regression equations fitted for UM and ET to confirm that the data collected at these two sites are not significantly different and can therefore be combined. The method used for this test was the Student’s *t*, as outlined in Zar (1974). The test showed that both slope and y-intercept of the two regression equations were not significantly different, and hence a common regression equation for the two sites was derived (fig 3.3).

Outliers were identified as samples with mud *C* values greater than 2 standard deviations away from the mean for the corresponding turbidity value (ie outside the prediction limits in fig 3.3). These were removed from the combined dataset and the regression equation was refitted. This was performed twice, before all data fit within the prediction limits (fig 3.4).

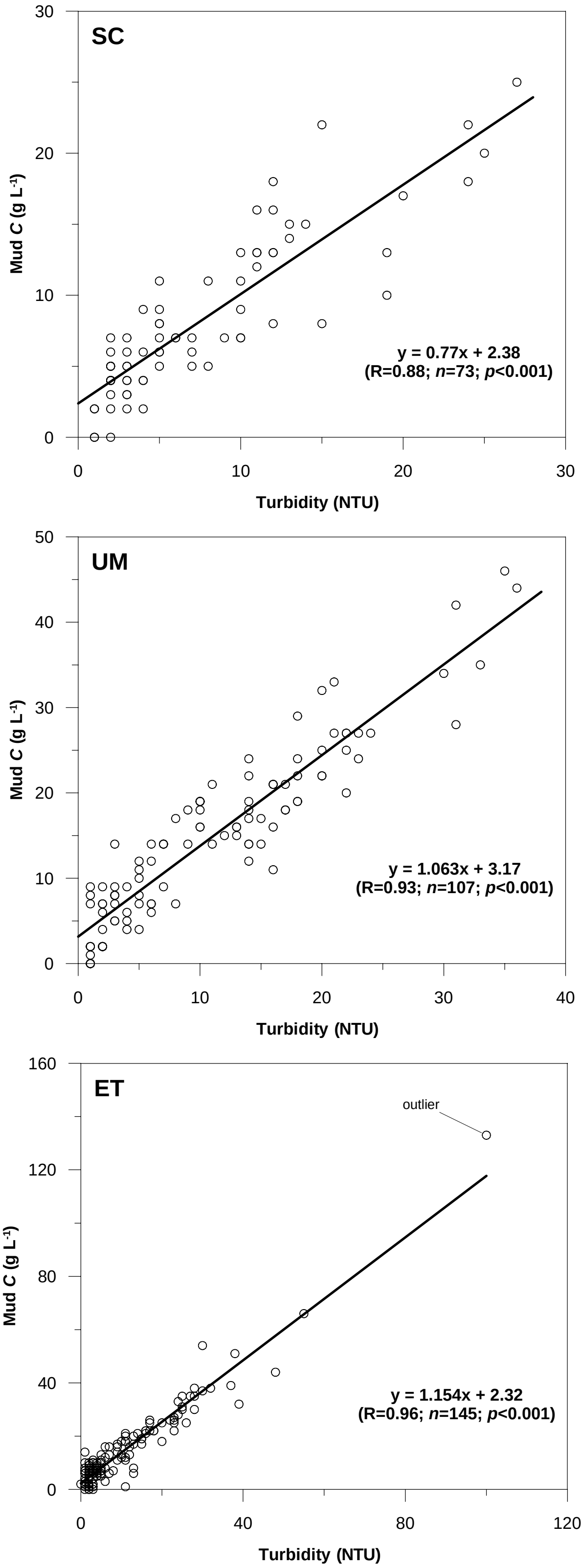

Figure 3.1 Calibrated turbidity-mud *C* relationships for each gauging station

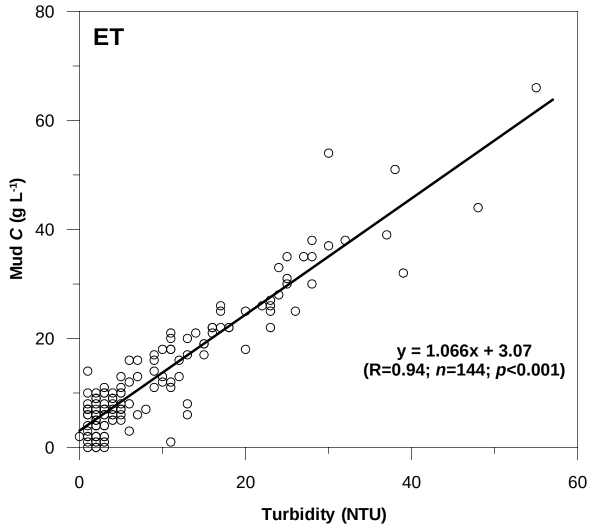

Figure 3.2 Revised calibrated turbidity-mud C relationship for ET with outlier removed

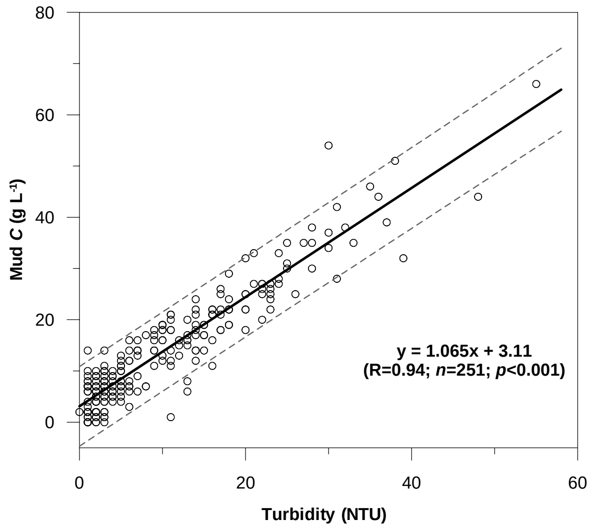

Figure 3.3 Calibrated turbidity-mud C relationship for the combined data collected at UM and ET. 95% prediction limits for the regression equation are shown as dashed lines.

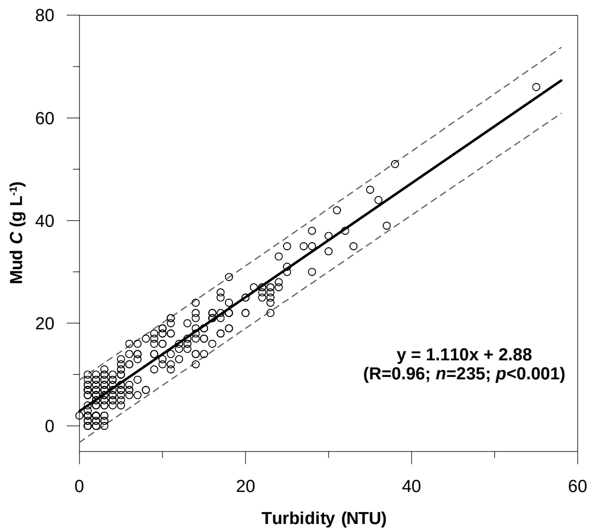

Figure 3.4 Revised calibrated turbidity-mud C relationship for the combined data collected at UM and ET (outliers removed). 95% prediction limits for the regression equation are shown as dashed lines.

As discussed above, the data collected at SC was statistically different to that collected at UM and ET. A plot of the regression line fitted for data collected at SC compared to that fitted for the combined dataset for UM and ET highlights this difference (fig 3.5). While the y-intercepts of the two equations are relatively similar, the slopes of the two equations are significantly different.

Figure 3.5 also shows that the range of turbidity data collected at SC is much smaller than that collected at UM and ET. This is probably due to the fact that, unlike at UM and ET, samples were not collected by the pump sampler at SC until a few weeks after flow had commenced. (The pump sampler is automatically activated by the rise and fall of stage measured by the pressure transducer, however, stage data collected by the pressure transducer at SC were either missing or considered unreliable during the first few weeks of flow.) In general, stream mud *C* associated with a particular storm which occurs at the beginning of the flow period is often much higher than mud *C* associated with a similar size storm which occurs later in the wet season. Therefore, the small range of turbidity-mud *C* data at SC may be a result of the first flush events not being sampled.

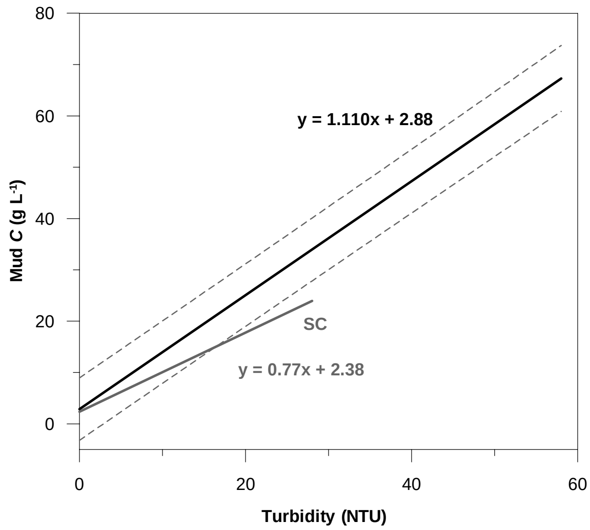

Figure 3.5 Turbidity-mud *C* relationships fitted for data collected at SC and the combined data collected at UM and ET

It is possible that if more turbidity-mud *C* data were collected at SC, in particular during the first few weeks of flow of a wet season when stream mud *C* is relatively high, a revised regression equation could be fitted for SC that is not significantly different to UM and ET. However, from the current analysis, there is a need for two turbidity-mud *C* relationships for data collected at Ngarradj - one for SC and one for UM-ET.

3.1.2 Mud *C* data – sedigraph and descriptive statistics

Using the calibrated turbidity-mud *C* relationships fitted above, the mud *C* of every water sample collected at each gauging station was determined. As mentioned above, turbidity readings were made on all samples collected at the gauging stations, but not all samples were filtered for a corresponding direct measurement of mud *C*. The mud *C* of every sample was determined in two ways: (1) using the calibrated turbidity-mud *C* relationships above (fig 3.5) to convert all the turbidity readings to a mud *C* value; and (2) combining the measured mud *C* values (ie samples filtered in the laboratory) with predicted mud *C* values (ie turbidity readings were converted to mud *C* values using the calibrated relationships for samples that were not filtered).

A *t*-test showed that there was no significant difference between the two techniques for each gauging station. Therefore, in this study, we used the combination of measured and predicted mud *C* data (method 2 above) to establish sedigraphs and mud *C* statistics for each gauging station for 2002/03.

The stream mud *C* throughout the hydrograph at each station is shown in Appendix A. As discussed in Evans et al (2003), the majority of the mud transport occurs during the single or first peak of a multi-peaked event.

The largest event in terms of peak mud *C* occurred at ET during the first flush on 1 January 2003 (133 mg L^{-1}) (Appendix A). However, samples were not collected during this event at SC and UM. The high peak mud *C* during this event was attributed to a combination of two probable causes: (1) this storm event was relatively intense, particularly over a 3-h duration (table 2.5); and (2) this was a first flush event and hence sediment availability in the catchment was high (Walling & Webb 1982). For these reasons, it is very likely that should samples have been collected at SC and UM, elevated mud *C* data would have been observed at these sites as well.

Aside from the event on 1 January 2003 at ET, there were very few significant "spikes" of mud transport throughout the 2002/03 wet season (Appendix A). Rainfall intensity (and corresponding rate of rise in discharge) is a factor in predicting the total event mud load (Evans et al 2003). Therefore, given there were no intense events observed after the first period of flow during the wet season (as discussed in section 2.2.2), the relatively small mud spikes that occurred throughout the wet season was not an unexpected result.

The annual and monthly statistics for these data are shown in tables 3.1 and 3.2 respectively.

Mud *C* data determined using filtering techniques were recorded and stored in HYDSYS® in units of g L^{-1} to three decimal places (equivalent of zero decimal places in units of mg L^{-1}). Therefore, values of 0 in tables 3.1 and 3.2 indicate a data point <0.5 mg L^{-1}. The actual lower limit of detection for mud *C* using the standard laboratory techniques is 3 mg L^{-1} (Evans pers comm. 2002). However, in this study, data less then the lower limit of detection of 3 mg L^{-1} have not been changed.

Table 3.1 Annual mud *C* descriptive statistics

Site	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
SC	172	6.6	4.1	5.5	25.0	0.0
UM	189	11.2	8.7	8.0	46.0	0.0
ET	258	10.8	12.3	7.0	133.0	0.0

3.2 Event-based mud loads

Four years of mud C data collected at each gauging station (1998-2002) have been used to derive, and validate, mud load models for each site (Evans et al 2003). These models are event-based, and were derived by regression analysis between event mud loads and the cumulative function of runoff during the rising stage of the hydrograph ($\int Q^m\ dt$) (Eqn 3.1):

$$\text{Total mud load} = K \int_{Q_0}^{Q_p} Q^m dt \qquad (3.1)$$

where Q is instantaneous discharge ($m^3\ s^{-1}$), Q_p is peak event discharge, Q_0 is initial discharge and m and K are fitted parameters.

Table 3.2 Monthly mud *C* descriptive statistics

SC

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Jan	12	10.0	5.9	7.5	22.0	5.0
Feb	86	6.9	4.4	5.5	25.0	2.0
Mar	73	5.9	2.9	5.5	16.0	0.0
Apr	1	0.0				

UM

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Dec	1	7	-			
Jan	72	15.8	10.2	14.0	46.0	2.0
Feb	94	9.6	6.2	7.3	29.0	0.0
Mar	19	3.7	2.0	4.0	8.4	0.0
Apr	3	3.0	1.7	4.0	4.0	1

ET

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Jan	132	15.3	15.7	9.8	133	1
Feb	27	7.6	4.0	6.2	16	0
Mar	69	6.3	3.0	6.0	18	0
Apr	30	4.0	2.4	4.0	13	0

The fitted models provide us with a means of assessing impacts (mine-related or natural) on stream mud C within the Ngarradj catchment on an event basis. Event loads that fall above trigger values, derived in accordance with the Australian Guidelines for Water Quality Monitoring and Reporting (ANZECC & ARMCANZ 2000), for the model require further investigation.

Mud loads were determined for events that occurred during 2002/03 at each gauging station, and were then plotted against the derived event-based mud load models (fig 3.6). The event-based mud load models for SC and UM (fig 3.6) were derived using mud *C* data collected over two wet seasons (1999/00 and 2000/01). This differs from the relationships fitted by Evans et al (2003), where only one year of data were used to derive the relationships for each gauging station. The event-based mud load model for ET (fig 3.6) is from Evans et al (2003).

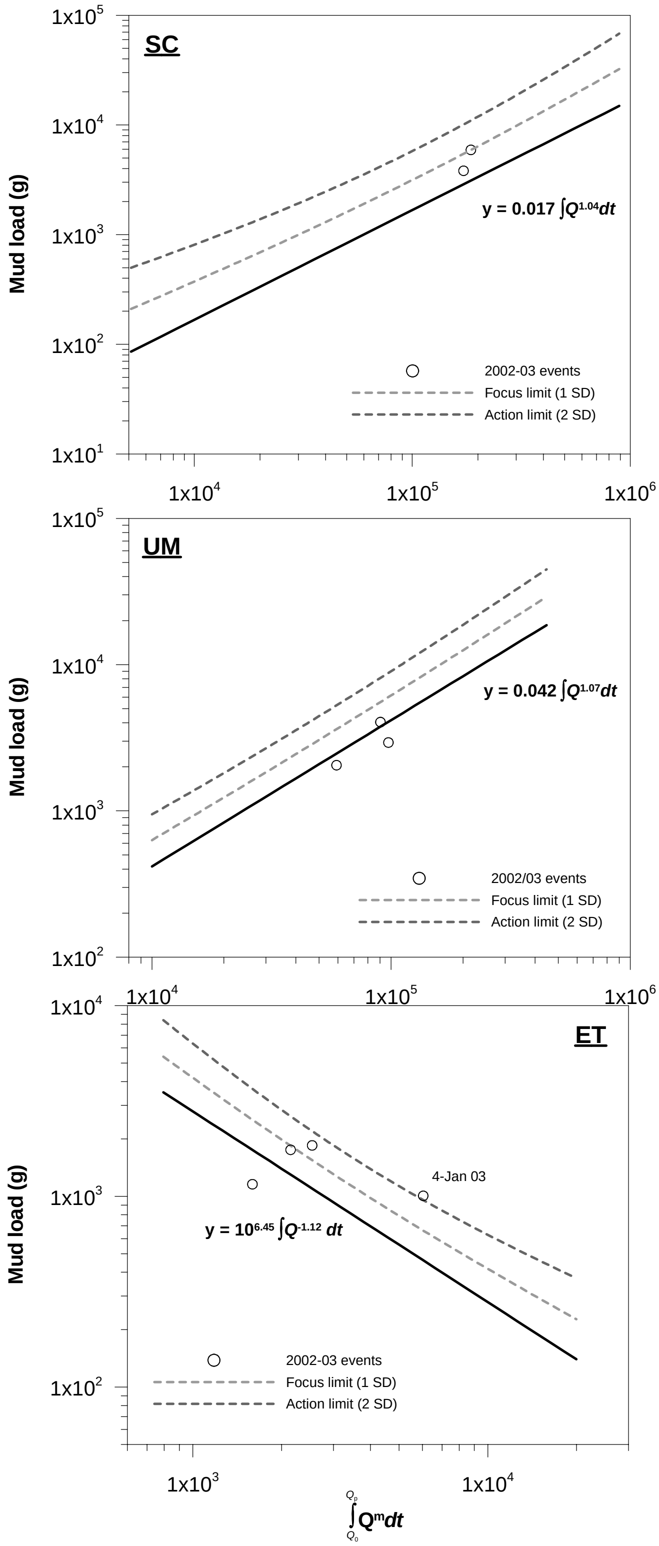

Figure 3.6 Event-based mud load models for each gauging station. Observed event mud loads for 2002/03 are also shown.

Mud loads were derived for:

- Two events at SC – 18-January and 9 February 2003
- Three events at UM – 4, 18 and 31 January 2003
- Four events at ET – 1, 4 and 18 January and 20 February 2003.

These events appear as distinct mud spikes on the hydrograph (Appendix A). The mud load for the event occurring at UM on 9 February 2003 was not derived as the predicted runoff data for this event did not match the mud *C* data (Appendix A).

Figure 3.6 shows that no observed event mud loads are above derived action limits (ie two standard deviations from the mean) except for the event on 4 January 2003 at ET, which is only slightly above the action limit. This event at ET was only the second rainfall-runoff event since flow commenced, so it is likely that the elevated mud load was due to first flush effects. In general, figure 3.6 indicates that it was unlikely any disturbances occurred within the Ngarradj catchment during 2002/03.

3.3 Conductivity and pH data

In the laboratory, conductivity and pH readings were taken for approximately one in every four water samples collected during 2002/03. During the previous four wet seasons, conductivity and pH readings were taken for every water sample. Using these four years of data, it was established that annual and monthly trends in data would not be significantly different if only one in four samples (rather than every sample) were analysed for these water quality parameters.

The annual and monthly descriptive statistics for conductivity and pH data for 2002/03 at each gauging station is shown in Appendix B. A plot of conductivity throughout the wet season at each station is shown in figure 3.7.

Figure 3.7 indicates that stream conductivity within the Ngarradj catchment follows a general basin-shaped profile, which is typical of the region (Iles & leGras pers comm 2003 (www.ea.gov.au/ssd/monitoring/index.html)). The high conductivity during the first flush of flow in the catchment (early January 2003) is due to flushing of the soil profile and resuspending of creek bed sediments (Iles & leGras pers comm 2003). After the first flush effects the conductivity decreases steadily throughout the wet season (fig 3.7). Towards the end of the wet season, conductivity begins to increase again as a result of groundwater intrusion (Iles & leGras pers comm. 2003). As surface flow decreases, the groundwater entering the creek system contributes a higher proportion of the flow which impacts on the stream water quality.

Figure 3.7 also highlights the change in conductivity during an individual event. During a rainfall-runoff event, conductivity decreases rapidly as the percentage of surface water flow within the total flow increases, diluting the stream salts. After the storm event, as runoff approaches baseflow, conductivity returns to pre-event conditions. This change in conductivity on an event-basis also changes throughout the wet season. The drop in conductivity as a result of a storm event is relatively large at the beginning of the wet season compared to that which occurs as a result of a storm during the latter stages of the wet season (fig 3.7). By February-March, the surface water contribution to total stream flow during baseflow conditions is higher than that during the initial period of flow. Therefore, during a rainfall event, further dilution of the salts within the stream will only be relatively small compared to the first flush period of the wet season.

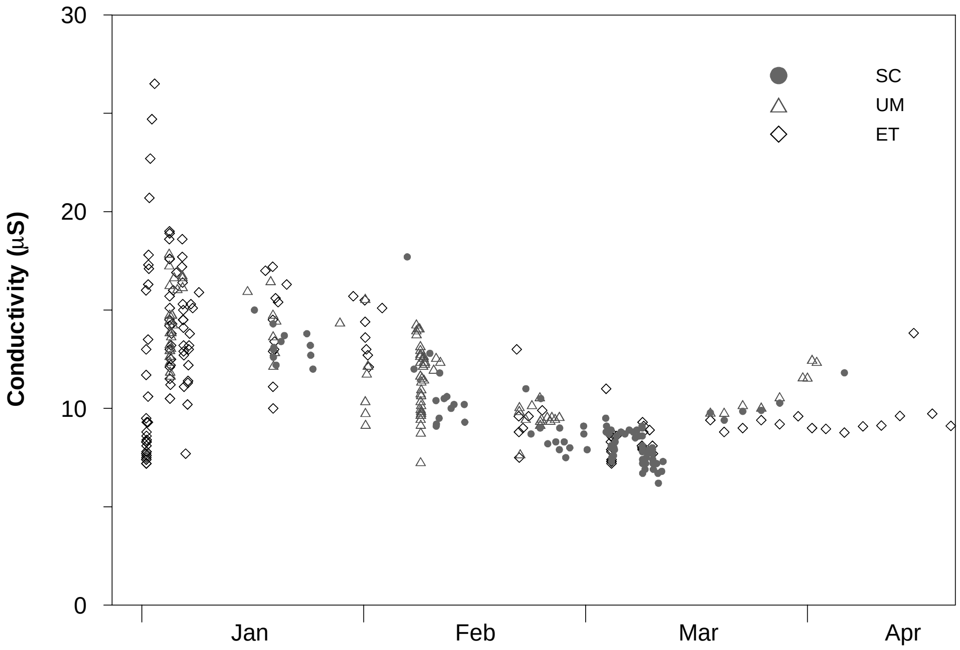

Figure 3.7 Conductivity at each gauging station throughout 2002/03.

A plot of pH throughout the wet season at each station (fig 3.8) indicates that, unlike conductivity, there is no general trend in this parameter throughout the wet season. However, both figure 3.8 and table B.3 (Appendix B), suggest that the value of pH in the stream is influenced by catchment area. The pH at SC is generally higher than that at UM, which in turn, is higher than that at ET. This is possibly due to the fact that the effect of leaf litter (which contribute organic acids to the stream) on the water chemistry decreases with catchment size (C McCulloch pers comm. 2003).

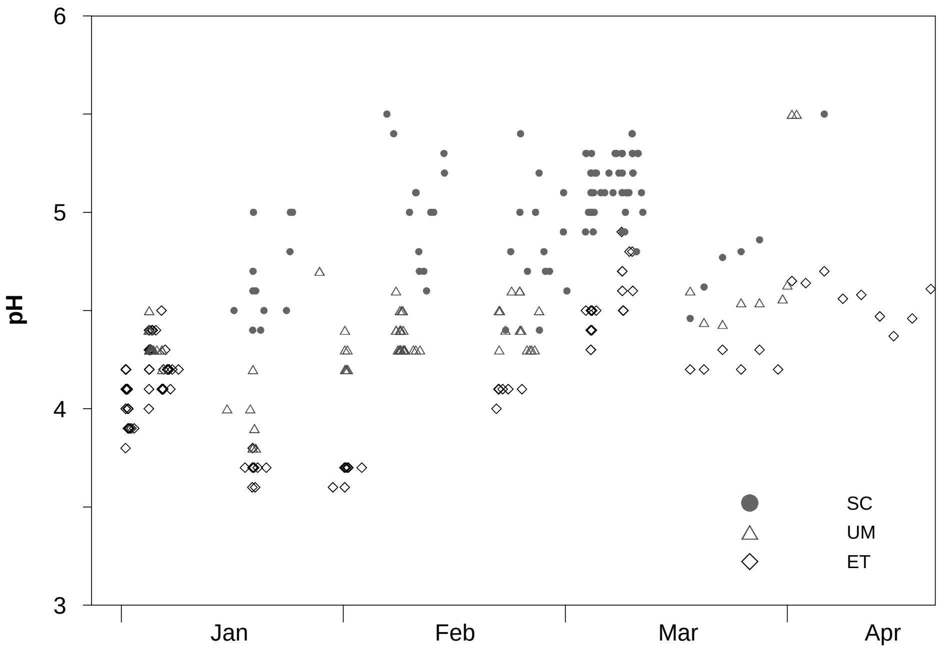

Figure 3.8 pH at each gauging station throughout 2002/03

Overall, Appendix B and figures 3.7 and 3.8 indicate that it is unlikely that there has been any measurable impact as a result of the mine during the 2002/03 wet season.

3.4 Sand and solute concentration data

Sand concentration was determined for every water sample using standard filtering techniques. As mentioned above, turbidity readings were required for every water sample as part of the derivation of the turbidity-mud C relationships (fig 3.5). As a result, the removal of the sand fraction of the suspended sediment was necessary before the turbidity of the sample was measured.

Similar to conductivity and pH, solute concentration was determined for approximately one in four water samples. The previous four years of solute concentration data, derived for every collected water sample, indicated that very little variation occurred in solute concentration throughout the wet season hydrograph – both on an event basis and on a long-term annual basis. It was decided that only analysing one in four samples would require much less laboratory time for no loss in the quality of data.

Solute concentrations were determined for the same water samples that conductivity was measured. Other studies have described a relationship between conductivity and stream solute concentration. Although not in the scope of this study, the conductivity-solute concentration data collected during 2002/03 could still be used to derive such a relationship in the future.

Similar to conductivity, there is very little difference in mean annual solute concentration between the sites (Appendix B). Mean annual solute concentration for 2002/03 at each site is also similar to that observed during the previous four-year monitoring period. The trends in conductivity shown in figure 3.7 are not observed within the solute concentration data. It is difficult to determine whether this is a due to the fact that (1) there is not a strong correlation between solute concentration and conductivity data for the Ngarradj catchment, or (2) the filtering technique for the direct measurement of solute concentration is not suitable for the Ngarradj catchment conditions (ie stream solutes are too low – the filtering technique cannot reliably measure the small changes in stream salt concentration that a conductivity meter can detect).

For both the sand and solute concentration data, there is little change in mean annual concentration values between the upstream and downstream sites (Appendix B). Similar to water quality parameters pH and conductivity, the sand and solute concentration data suggest that it is unlikely that there has been any measurable impact as a result of the mine.

4 Conclusions

The hydrology and water quality data collected within the Ngarradj catchment during the 2002/03 wet season indicate that there has been no measurable impact on the catchment as a result of the mine.

5 References

ANZECC (Australian and New Zealand Environment and Conservation Council) & ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand) 2000. *Australian Guidelines for Water Quality Monitoring and Reporting*. National Water Quality Management Strategy, No. 7, Canberra. 6-17 to 6-21.

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Appendix A – Observed hydrographs and daily rainfall

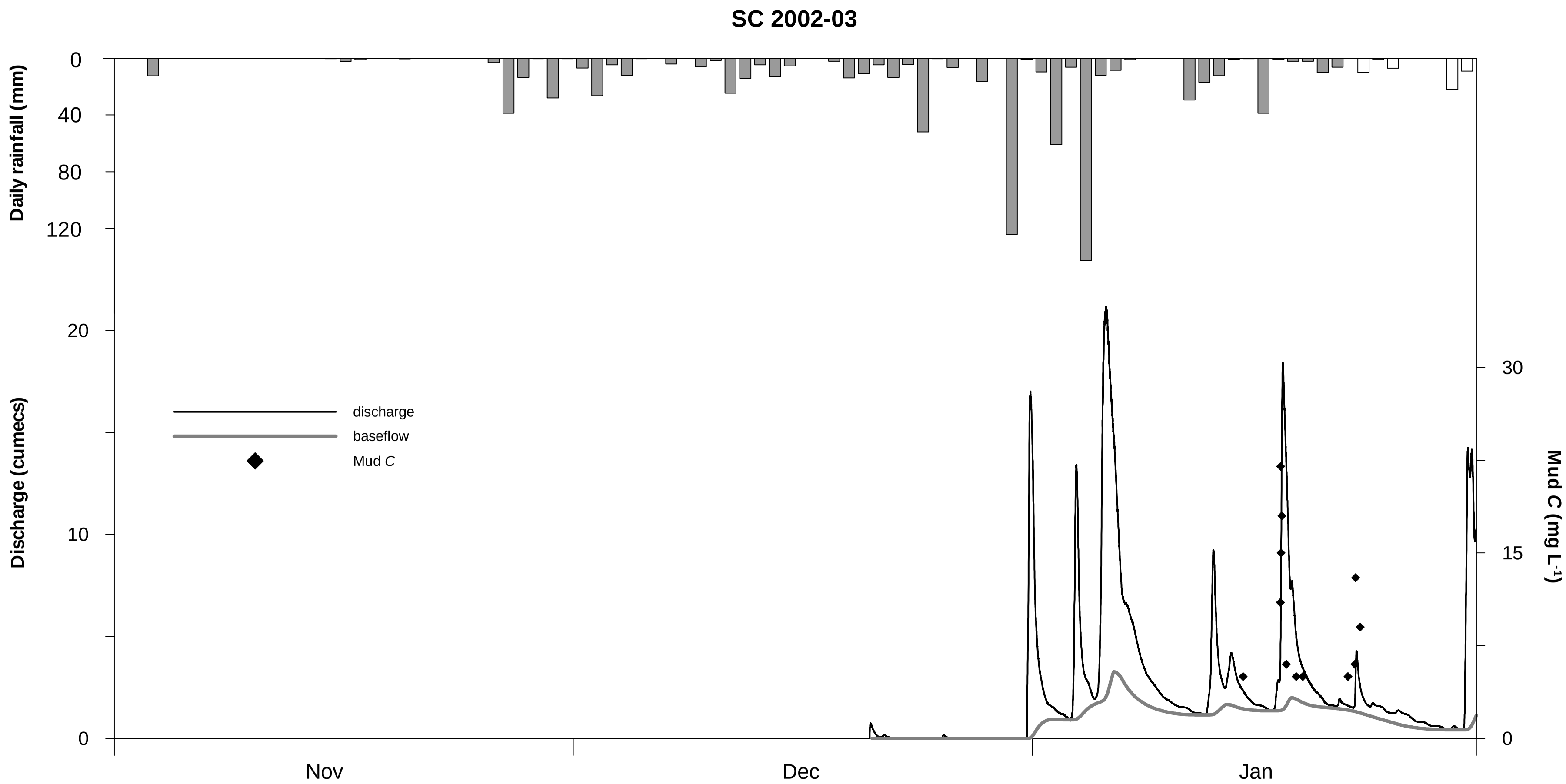

Figure A.1 Daily rainfall and the hydrograph for SC during the 2002/03 wet season. Daily rainfall at Jabiluka mine site used to infill the rainfall record at SC are shown as white bars. Baseflow and mud *C* data are also shown.

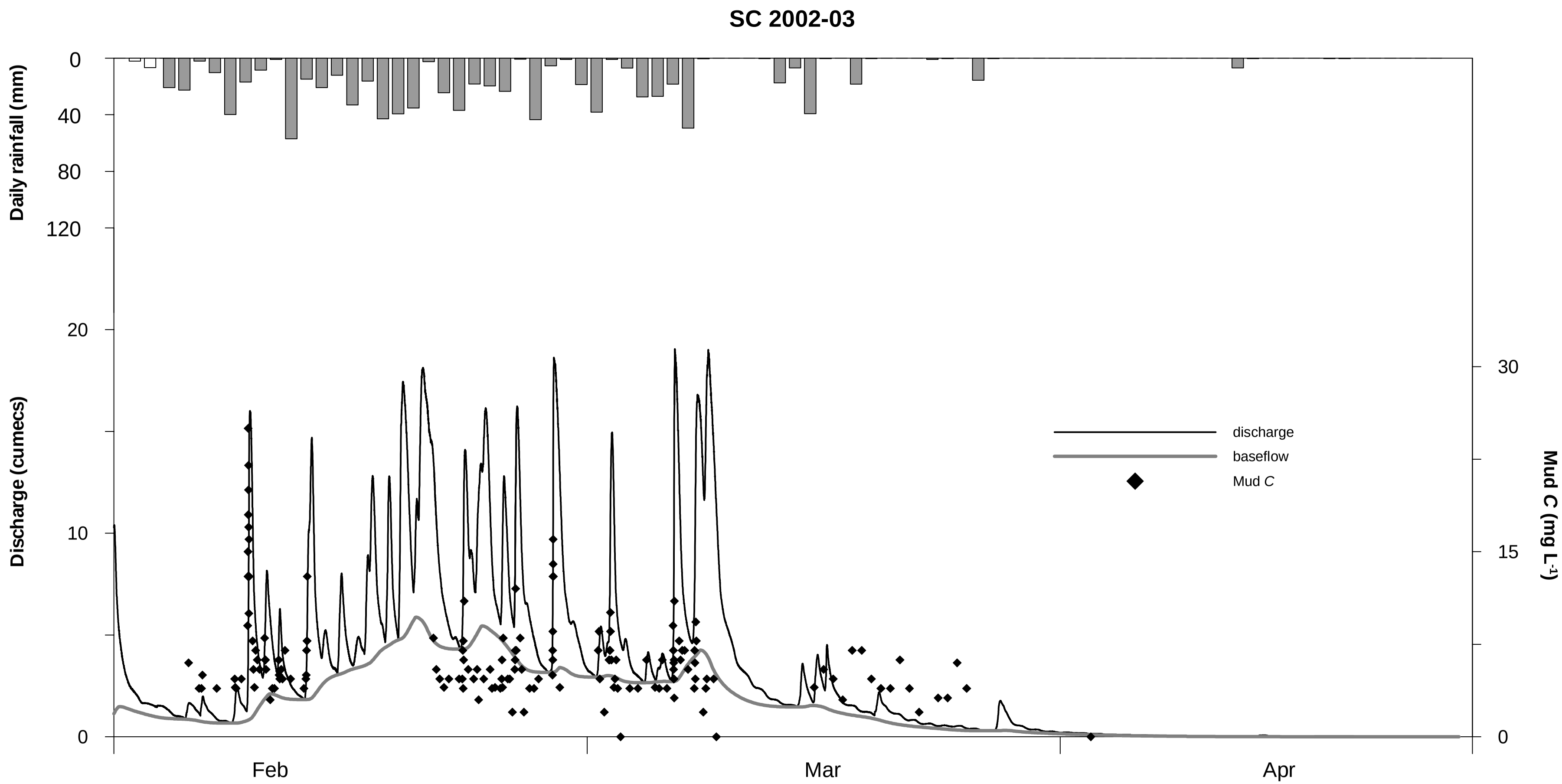

Figure A.1 (continued) Daily rainfall and the hydrograph for SC during the 2002/03 wet season. Daily rainfall at Jabiluka mine site used to infill the rainfall record at SC are shown as white bars. Baseflow and mud *C* data are also shown.

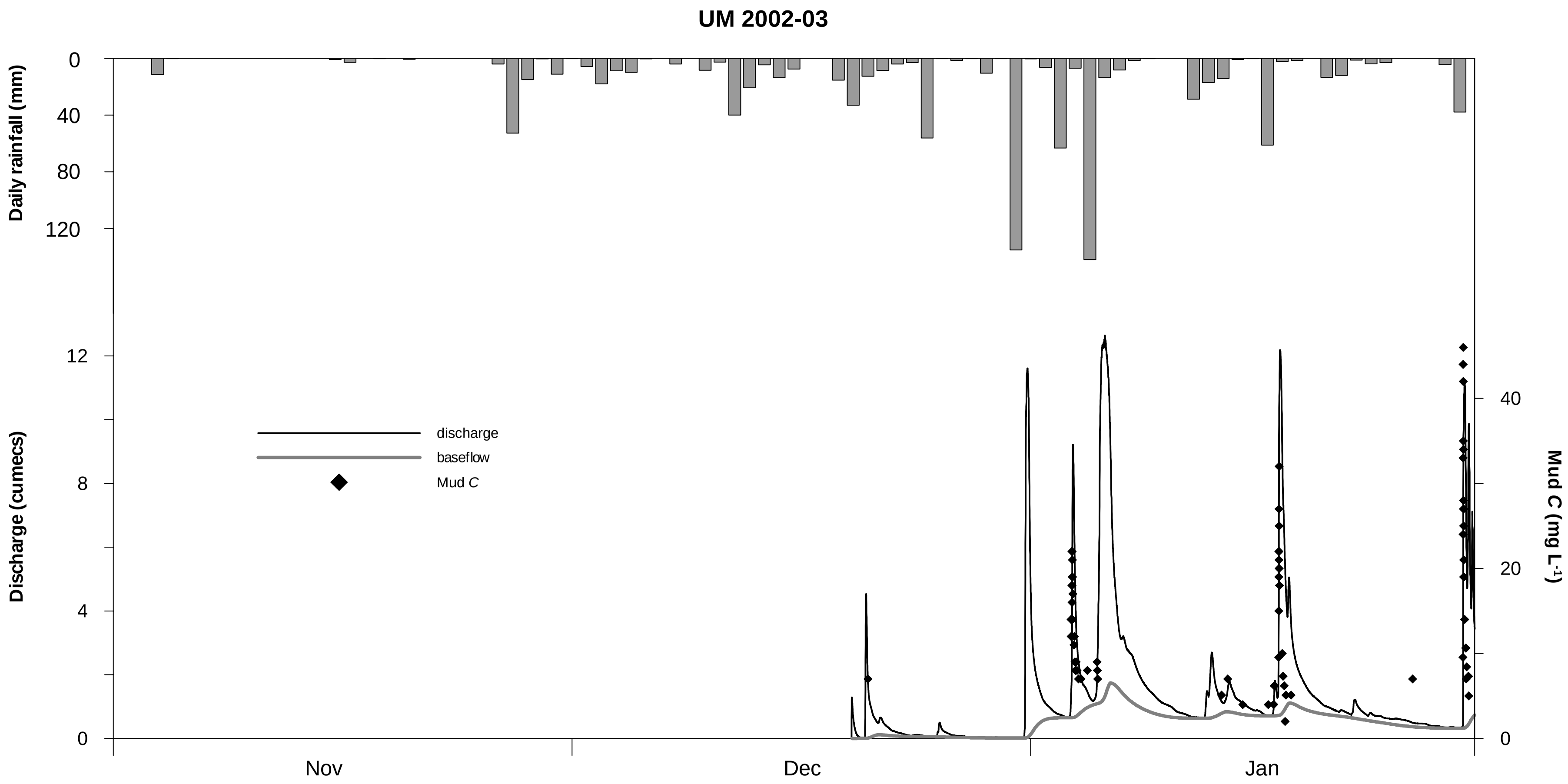

Figure A.2 Daily rainfall and the hydrograph for UM during the 2002/03 wet season. Baseflow and mud *C* data are also shown.

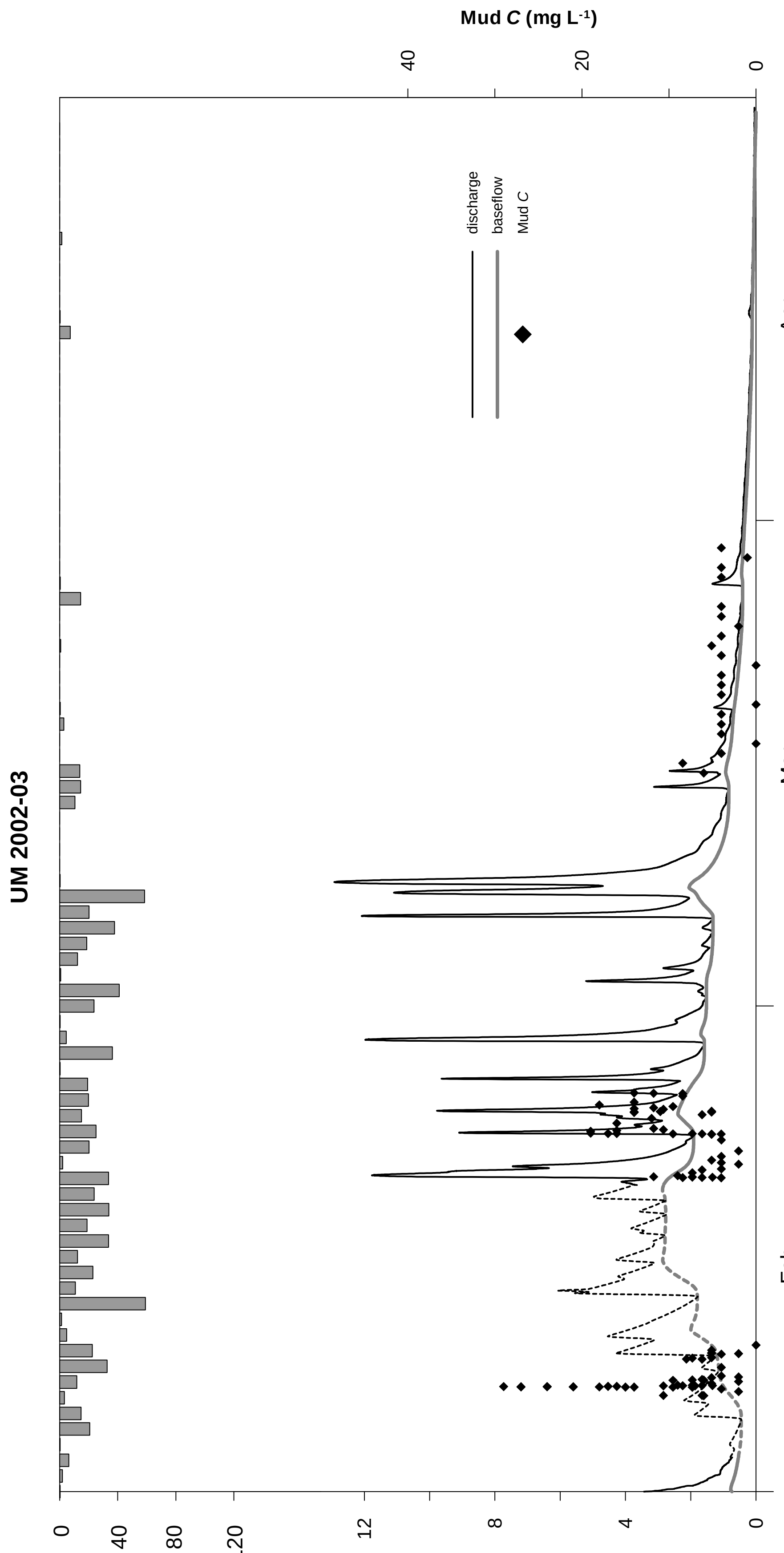

Figure A.2 (continued) Daily rainfall and the hydrograph for UM during the 2002/03 wet season. Predicted discharge generated from the calibrated HEC-HMS hydrology model is shown as a dashed line. Baseflow and mud *C* data are also shown.

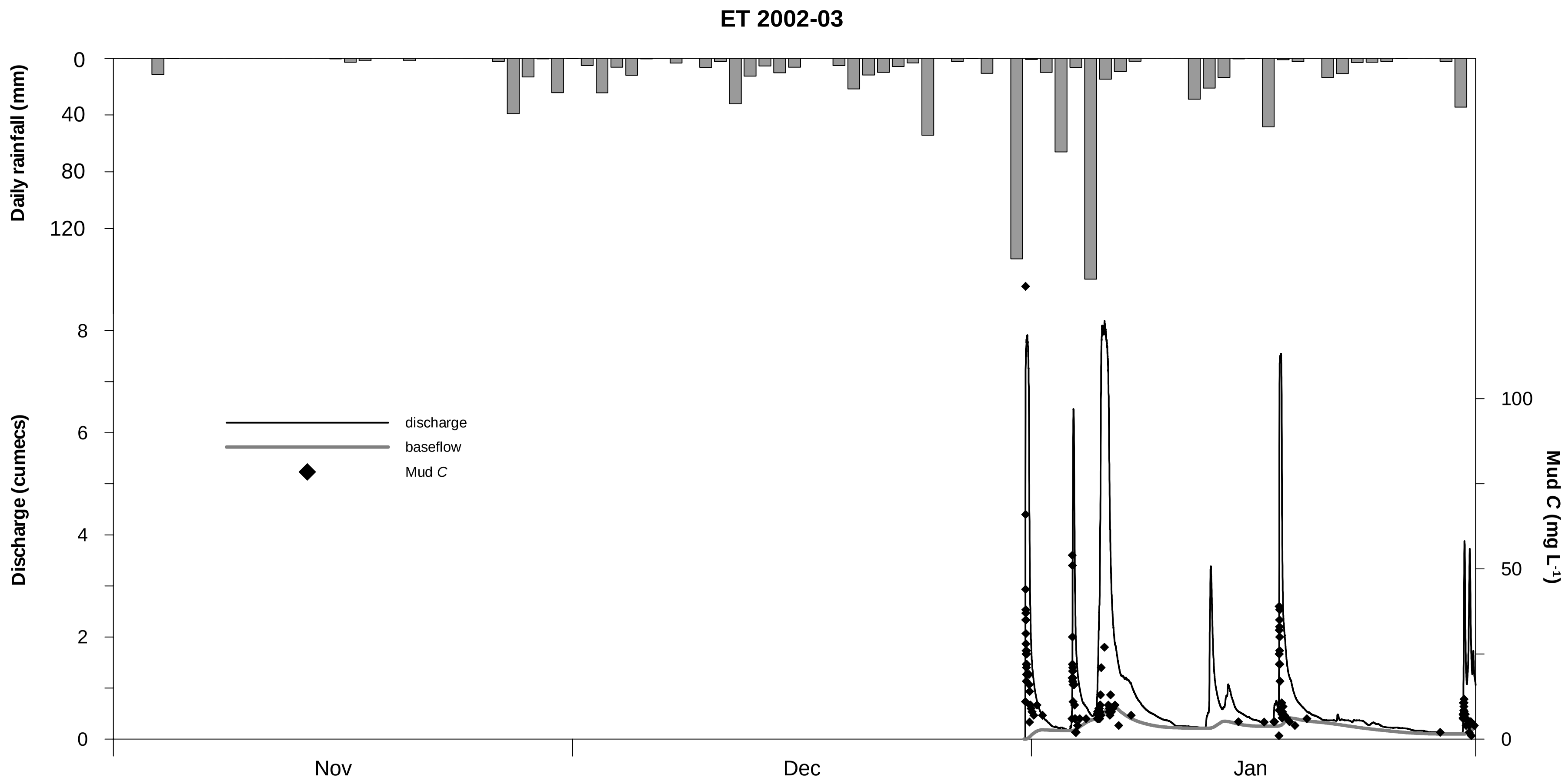

Figure A.3 Daily rainfall and the hydrograph for ET during the 2002/03 wet season. Baseflow and mud *C* data are also shown.

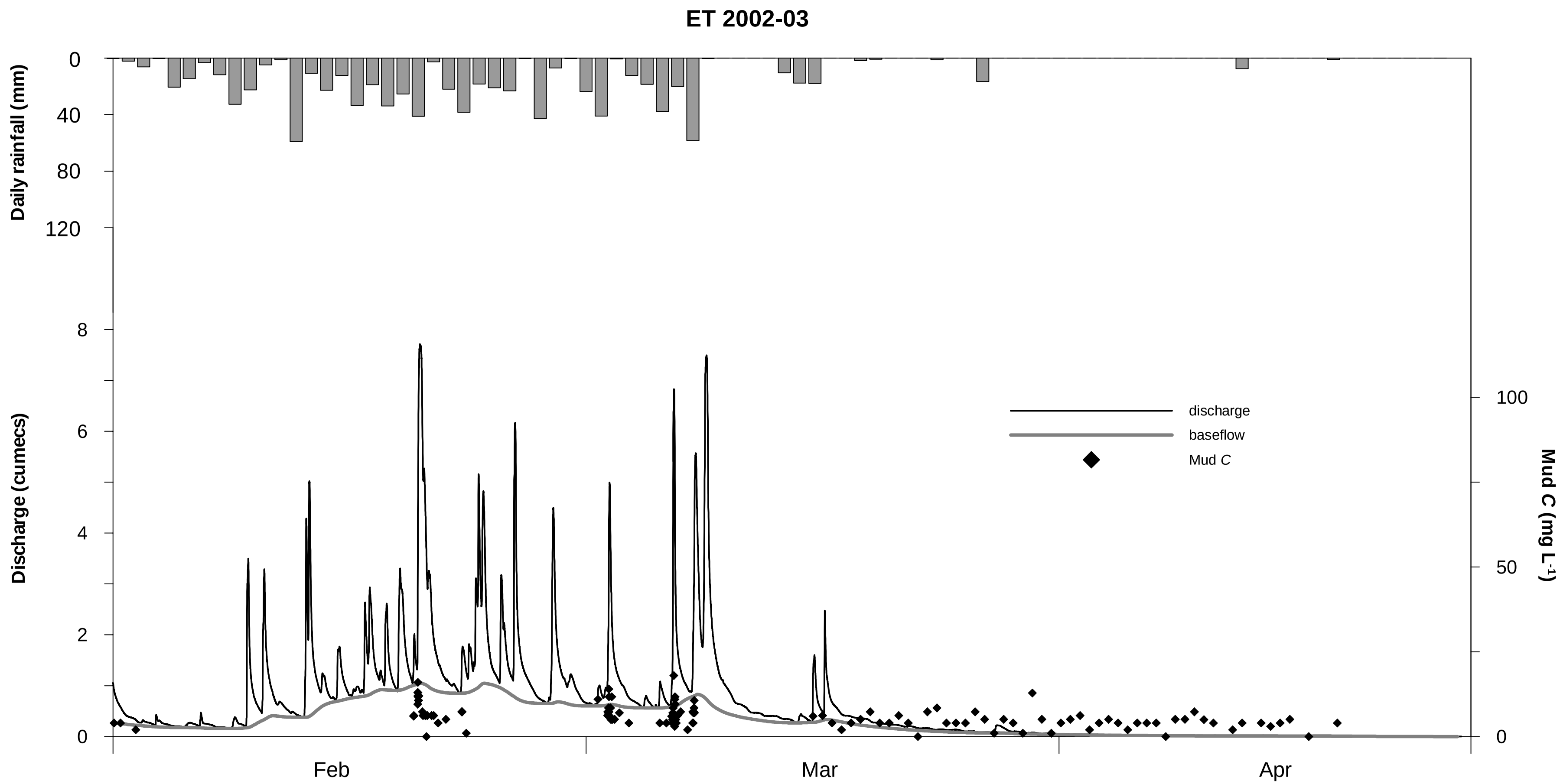

Figure A.3 (continued) Daily rainfall and the hydrograph for ET during the 2002/03 wet season. Baseflow and mud *C* data are also shown.

Appendix B – Water quality parameter descriptive statistics

Table B.1 Annual electrical conductivity (EC) descriptive statistics.

Site	No. of samples	Mean (uS)	Standard Deviation	Median (uS)	Maximum (uS)	Minimum (uS)
SC	94	9.3	2.2	8.8	17.7	6.2
UM	101	12.2	2.3	12.3	17.9	7.3
ET	142	12.1	3.9	11.5	26.5	7.2

Table B.2 Monthly electrical conductivity (EC) descriptive statistics.

SC

Month	No. of samples	Mean (uS)	Standard Deviation	Median (uS)	Maximum (uS)	Minimum (uS)
Jan	12	13.2	0.8	13.2	14.5	12.0
Feb	25	10.0	2.1	9.5	17.7	7.5
Mar	56	8.2	0.9	8.0	10.3	6.2
Apr	1	11.8				

UM

Month	No. of samples	Mean (uS)	Standard Deviation	Median (uS)	Maximum (uS)	Minimum (uS)
Dec	1	15.8				
Jan	40	14.0	2.1	13.9	17.9	9.2
Feb	51	11.0	1.7	10.7	14.3	7.3
Mar	6	10.4	0.7	10.1	11.6	9.8
Apr	3	12.2	0.5	12.4	12.5	11.6

ET

Month	No. of samples	Mean (uS)	Standard Deviation	Median (uS)	Maximum (uS)	Minimum (uS)
Jan	97	13.5	3.9	13.2	26.5	7.2
Feb	8	10.3	2.5	9.6	15.1	7.5
Mar	28	8.5	0.9	8.6	11.0	7.2
Apr	9	9.7	1.6	9.1	13.8	8.8

Table B.3 Annual pH descriptive statistics.

Site	No. of samples	Mean	Standard Deviation	Median	Maximum	Minimum
SC	94	5.0	0.3	5.1	5.5	4.4
UM	101	4.4	0.2	4.3	5.5	3.8
ET	142	4.2	0.3	4.2	4.9	3.6

Table B.4 Monthly pH descriptive statistics.

SC

Month	No. of samples	Mean	Standard Deviation	Median	Maximum	Minimum
Jan	12	4.7	0.2	4.6	5.0	4.4
Feb	25	4.9	0.3	5.0	5.5	4.4
Mar	56	5.1	0.2	5.1	5.4	4.5
Apr	1	5.5				

UM

Month	No. of samples	Mean	Standard Deviation	Median	Maximum	Minimum
Dec	1	4.1				
Jan	40	4.3	0.2	4.3	4.7	3.8
Feb	51	4.4	0.1	4.4	4.6	4.3
Mar	6	4.5	0.1	4.5	4.6	4.4
Apr	3	5.2	0.5	5.5	5.5	4.6

ET

Month	No. of samples	Mean	Standard Deviation	Median	Maximum	Minimum
Jan	97	4.1	0.2	4.1	4.5	3.6
Feb	8	4.0	0.1	4.1	4.1	3.7
Mar	28	4.5	0.2	4.5	4.9	4.2
Apr	9	4.6	0.1	4.6	4.7	4.4

Table B.5 Annual sand concentration descriptive statistics.

Site	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
SC	174	73.4	30.7	67	218	2
UM	187	89.8	52.9	78	304	13
ET	259	74.2	55.7	65	484	5

Table B.6 Monthly sand concentration descriptive statistics.

SC

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Jan	12	100.4	30.6	103	175	65
Feb	87	75.9	29.4	70	134	5
Mar	74	66.3	29.9	64	218	2
Apr	1	65.0				

UM

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Dec	1	27.0				
Jan	72	110.5	65.6	99	304	13
Feb	92	86.6	35.8	83	183	28
Mar	19	37.4	12.8	40	66	14
Apr	3	41.3	13.9	45	53	26

ET

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Jan	133	91.8	66.8	79	484	14
Feb	27	75.1	19.3	79	103	26
Mar	69	56.0	36.0	48	153	9
Apr	30	37.2	17.4	43	69	5

Table B.7 Annual solute concentration descriptive statistics.

Site	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
SC	53	25.4	13.2	24	61	0
UM	56	23.2	12.0	24	58	1
ET	81	26.6	12.6	26	69	8

Table B.8 Monthly solute concentration descriptive statistics.

SC

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Jan	4	16.8	19.6	15	37	0
Feb	25	32.4	13.5	30	61	11
Mar	23	19.3	7.2	22	30	4
Apr	1	24.0				

UM

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Dec	1	28.0				
Jan	22	33.6	8.3	32	58	22
Feb	28	16.6	9.1	16	35	1
Mar	4	10.8	2.6	11	13	8
Apr	1	24.0				

ET

Month	No. of samples	Mean (mg L^{-1})	Standard Deviation	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})
Jan	42	34.0	12.2	30	69	14
Feb	8	24.6	6.3	27	33	13
Mar	22	14.6	4.3	14	25	8
Apr	9	23.2	6.1	22	32	14