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Hydrology and suspended sediment of the Ngarradj catchment, Northern Territory: 2003–2004 wet season monitoring

DR Moliere, KG Evans, MJ Saynor & BL Smith

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Contents

Executive summary

Hydrology and suspended sediment data were collected at three gauging stations within the Ngarradj catchment during the 2003–04 wet season as part of a long-term study of the impact of mining at Jabiluka. The two major aims of this report were to:

1 assess the applicability of using turbidimeters to monitor suspended sediment concentration within the catchment compared to the more labour intensive technique of conventional water sample collection and processing, and

2 determine whether earthworks that occurred at Jabiluka during the 2003 dry season had an impact on downstream suspended sediment concentration.

In relation to the first aim, turbidity data measured by *in situ* turbidimeters at the three gauging stations were compared with suspended sediment concentration data determined from water samples collected throughout the annual hydrograph by automatic pump samplers. The relationships between suspended sediment concentration and turbidity at each site showed that there is considerable scatter about the line of best fit. However, the removal of the sand component within the suspended sediment sample reduced the effect of particle size on the sensor calibration process, indicating that the continuous turbidity data could be used to reliably monitor stream mud concentration within the Ngarradj catchment. This result has important implications for the understanding of contaminant movement associated predominantly with mud transport. Analysis of periods of high sediment movement associated with runoff events showed that the use of turbidimeters is considered essential for estimating individual event loads within the Ngarradj catchment, particularly (1) in small streams that exhibit a rapid flushing of mud during the rising stage of the hydrograph, and (2) during relatively minor and/or multi-peaked runoff events.

In relation to the second aim, an event-based mud transport model has been developed for stations upstream and downstream of the mine based on 4 years of 'unimpacted' data (1999–2003). The models provide an understanding of baseline mud movement in the catchment for future mine-related impact assessment. The calibrated mud transport model for the site downstream of the mine was sensitive enough to identify an increase in mud concentration throughout the 2003–04 wet season. It is possible that the increase in event mud loads at this downstream site is a result of erosion on the mine site. However, the 2003–04 event loads were generally not above trigger levels associated with the fitted model.

Water quality trigger values downstream of the mine, derived using upstream percentiles and the before-after-control-impact paired site design (BACIP), were also used to assess mining-related impacts on downstream mud concentration. The BACIP analysis indicated that, similar to the event-based mud model, there was an increase in mud concentration downstream of the mine relative to that measured upstream. However, the analysis showed that (1) the increase in mud concentrations downstream of the mine during the 2003–04 wet season was not significant, and (2) it is not conclusive that the elevated mud concentrations observed downstream was a result of mine disturbance in the Ngarradj catchment.

It is recommended that the catchment be monitored during the 2004–05 wet season to observe if mud concentration, and event mud loads, downstream of the mine return to baseline, unimpacted levels. It is considered that the best monitoring approach is a combination of both the event-based mud model and BACIP techniques.

Acknowledgements

Mr G Fox assisted with data collection and laboratory analysis. Jeff Klein, Klein Electronics Pty Ltd, helped with the installation and the maintenance of the gauging station equipment.

Hydrology and suspended sediment of the Ngarradj catchment, Northern Territory: 2003/2004 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), however, data collected from these stations are not discussed in this report.

This report describes the hydrology and water quality data collected from the three stream gauging stations within the Ngarradj catchment during the 2003–04 wet season. The data were collected as part of the long-term study on the impact of mining at Jabiluka on the Ngarradj catchment. The suspended sediment data were also compared to previous years to assess for any possible impact as a result of earthworks on the mine site which occurred during the 2003 dry season.

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 (Moliere et al 2002).

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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)

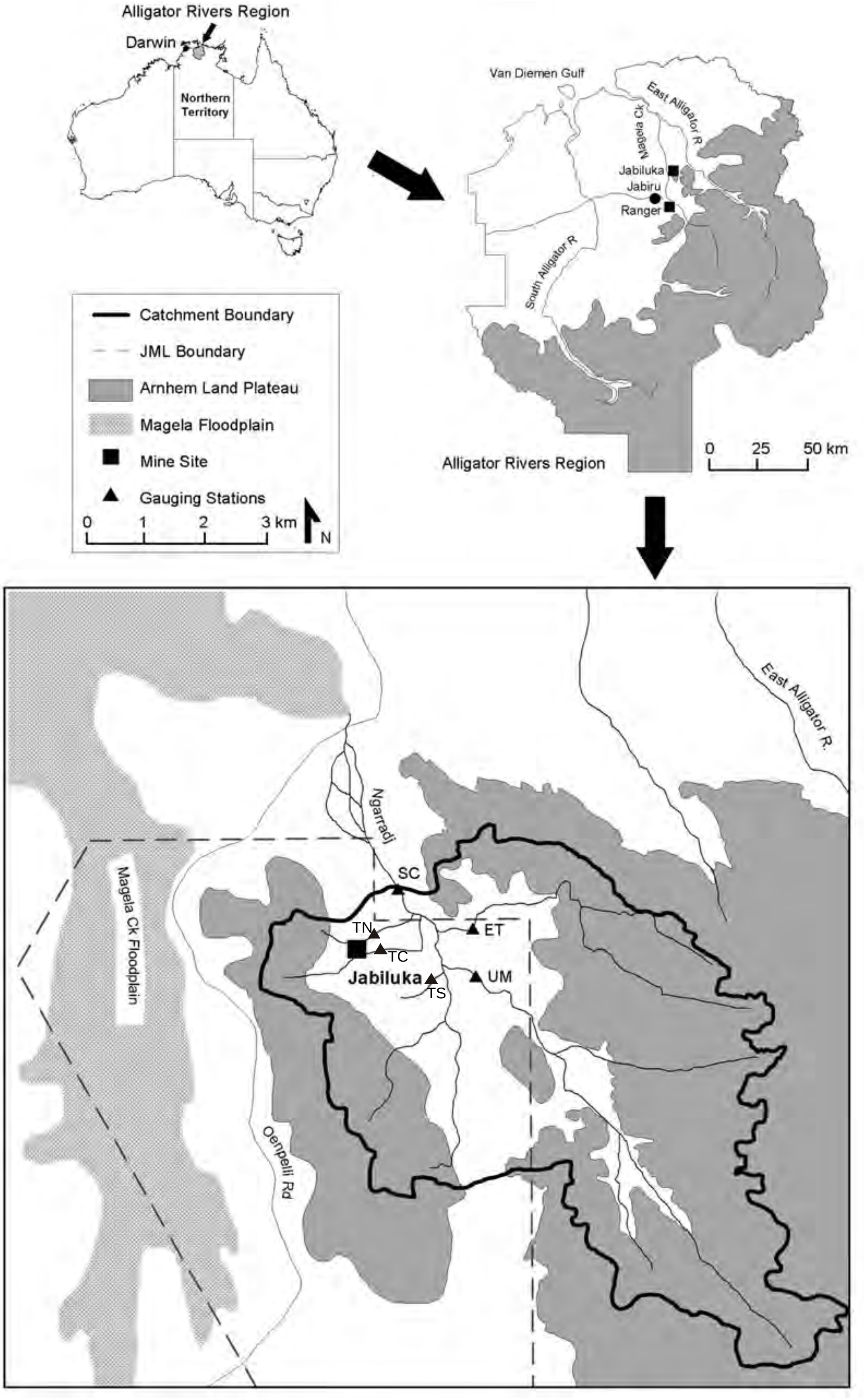

Figure 1.1 The Ngarradj catchment showing the location of the Jabiluka mine and gauging station sites

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.

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 have been collected at Jabiluka mine (fig 1.1) by Energy Resources of Australia since 1998, however, these data were not collected during the 2003–04 wet season. The total annual rainfall at each gauging station (SC, UM and ET) during the 2003–04 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 during the year, was 1330 mm (table 2.1).

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 2003–04, compared to the Oenpelli rainfall distribution, corresponds to a 1:1.6 rainfall year (fig 2.1, table 2.1). Therefore, the annual rainfall for the 2003–04 wet season of 1330 mm is below average for the Ngarradj catchment. The annual rainfall volumes for the previous five years of monitoring are also shown on figure 2.1.

Table 2.1 Total rainfall over the Ngarradj catchment area during 2003–04 derived using the Thiessen Polygon method

Station	Rainfall (mm)	Polygon area (% of total area)
SC	1273	0.385
UM	1353	0.510
ET	1431[1]	0.105
Total [ARI]	1330 [1:1.6]	1.00

1 Rainfall data collection commenced 23 December 2003. Data up to this date were infilled using UM rainfall.

Infilling missing rainfall data

The ET gauging station was destroyed by a fire in late September 2003. The station was reinstalled early December and rainfall data collection at the site recommenced on 23 December 2003. Rainfall data collected at UM, the nearest station to ET, is statistically similar to that collected at ET (Moliere et al 2002). Therefore, the total rainfall figure recorded at UM between 1 September and 23 December 2003 (319.4 mm) was simply transposed to the ET rainfall record.

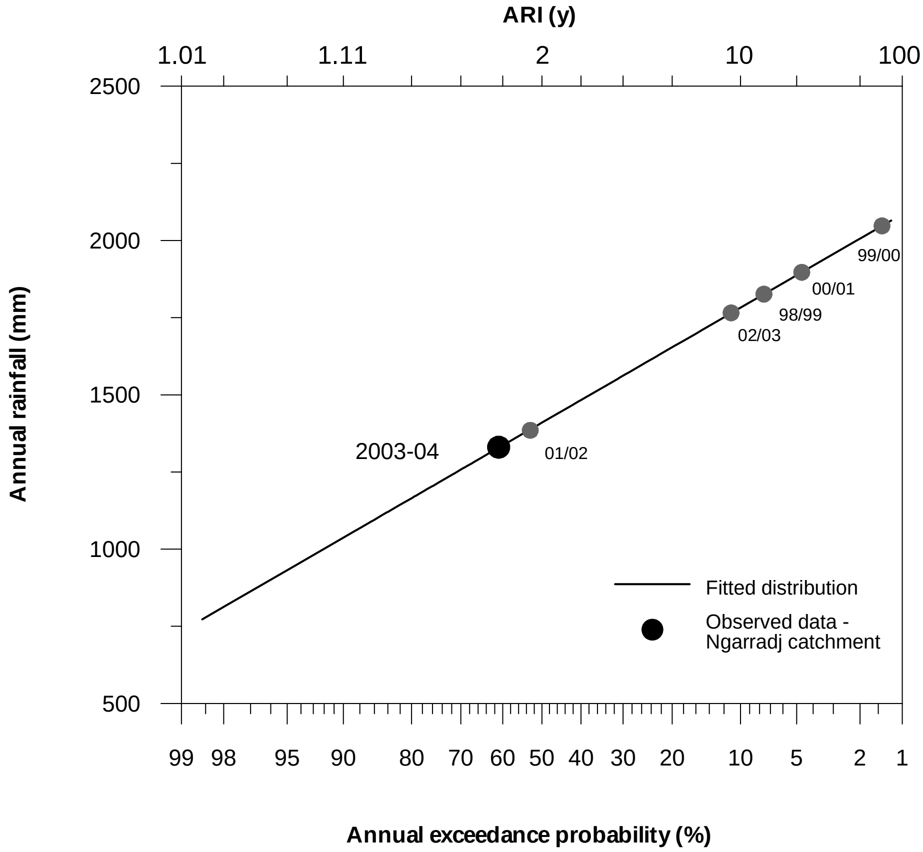

Figure 2.1 Annual rainfall frequency curve for Oenpelli. The 2003–04 rainfall, along with the previous five years of rainfall, for the Ngarradj catchment (table 2.1) are also shown.

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). During the 2003–04 wet season, the shaft encoder was the primary instrument for stage data collection, while the data collected by the pressure transducer were used as back-up.

The stage data measured by either the shaft encoder or the pressure transducer 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 2.2).

A rating table (stage-discharge) was derived for each station from two years of weekly velocity-area gaugings (1998–99 and 1999–2000 wet seasons) (Moliere et al 2001). Velocity-area gaugings taken at each station throughout the 2003–04 wet season fit reasonably well along the rating curves (fig 2.2).

Table 2.2 Stage measured at the gauge board and by the pressure transducer and shaft encoder at each site during 2003–04

		Stage height (m)		
Site	**Date**	**Gauge board**	**Shaft Encoder**	**Pressure transducer**
SC	23-Dec-03	0.29	0.289	0.289
	06-Jan-04	0.545	0.545	0.549
	20-Jan-04	0.88	0.881	0.883
	02-Feb-04	0.56	0.563	0.571
	16-Feb-04	0.94	0.933	0.940
	02-Mar-04	1.36	1.337	1.344
	16-Mar-04	0.97	0.980	0.967
	06-Apr-04	0.495	0.481	0.490
	20-Apr-04	0.30	0.297	0.307
		Average difference	**0.004 m**	**<0.001 m**
UM	06-Jan-04	0.41	0.410	0.410
	20-Jan-04	0.48	0.480	0.489
	28-Jan-04	0.36	0.359	0.366
	02-Feb-04	0.32	0.320	0.326
	16-Feb-04	0.59	0.590	0.594
	02-Mar-04	0.96	0.953	0.957
	16-Mar-04	0.60	0.593	0.597
	30-Mar-04	0.40	0.404	0.413
	06-Apr-04	0.24	0.256	0.264
	20-Apr-04	0.13		0.168
		Average difference	**<0.001 m**	**0.009 m**
ET	23-Dec-03	0.36	0.364	0.372
	06-Jan-04	0.34	0.330	0.331
	20-Jan-04	0.54	0.540	0.542
	02-Feb-04	0.355	0.376	0.373
	16-Feb-04	0.445	0.451	0.448
	02-Mar-04	0.62	0.633	0.625
	16-Mar-04	0.50	0.497	0.498
	30-Mar-04	0.31	0.319	0.317
	06-Apr-04	0.25	0.238	0.238
	20-Apr-04	0.20	0.176	0.173
		Average difference	**<0.001 m**	**<0.001 m**

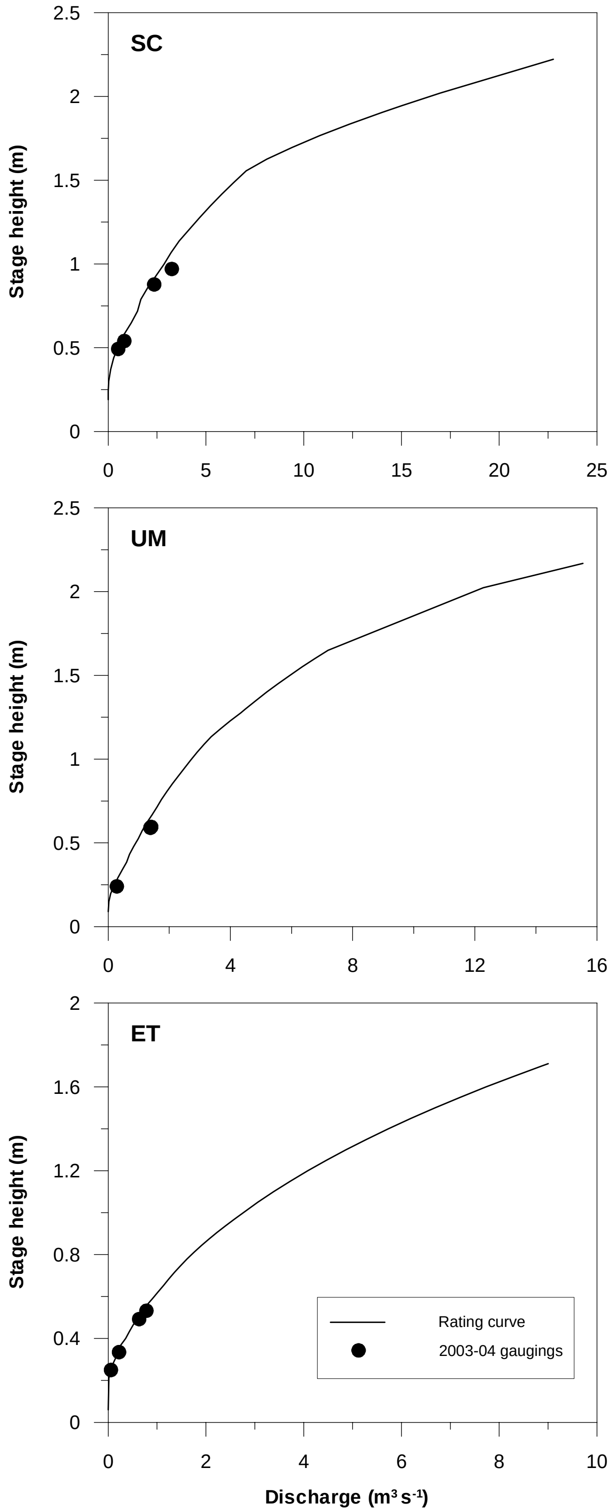

Figure 2.2 Rating curves for SC, UM and ET with the gauging points take during 2003–04 shown

Table 2.2 shows that the data collected by the shaft encoder or the pressure transducer during the 2003/04 wet season at each site were correct. Figure 2.2 shows that, although only a few low velocity-area gaugings were conducted at each site, the rating curves to convert these stage data to discharge data were appropriate for the 2003–04 wet season. The combination of these two results (table 2.2 and fig 2.2) suggest that the hydrograph for each station during 2003–04 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 2003–04 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 2.3. Total rainfall, the runoff period and antecedent rainfall at each gauging station are also given in table 2.3. 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 2.3 Total rainfall and runoff at each gauging station for the 2003–04 wet season

Station	Total rainfall (mm)	Antecedent rainfall (mm)	Runoff period	Total runoff (ML) [Peak discharge (m^3s^{-1})]
SC	1273	278	21 Dec – 10 June	20227.1 [16.7]
UM	1353	303	23 Dec – 10 June	10607.5(2) [12.7]
ET	1431(1)	190	21 Dec – 8 May	5604.5 [7.8]

1 Data infilled using UM rainfall (see Section 2.1); 2 Total runoff volume partly infilled using SC flow data (see below)

Total runoff at each gauging station for 2003–04, compared to previous years, is the second lowest for the 6-year monitoring period. Given the annual rainfall was a 1:1.6 y wet season, this is an expected result.

Infilling missing runoff volume data

Stage data collected by the shaft encoder at UM were unreliable for a two-week period during January 2004. An internal failure in the datataker at UM also occurred during the same two-week period and as a result, almost 5 days of stage data (15–19 January 2004) were not collected by either the pressure transducer or the shaft encoder (Appendix A).

The volume of flow at SC and ET that occurred during the period of missing flow at UM corresponded to 2 and 1.8 % of the total annual runoff respectively. The observed volume of flow at UM was 10 406 ML which, according to data collected at SC and ET, corresponds to approximately 98.1% of the total annual runoff at UM. Therefore, total annual runoff at UM is assumed to be approximately 10 607.5 ML (table 2.4).

3 Suspended sediment data

During the previous five years of monitoring at Ngarradj, stream suspended sediment concentration has been determined by collecting water samples throughout the annual hydrograph and filtering and drying the samples in the laboratory (Erskine et al 2001, Evans et al 2004). The collection of water samples and the subsequent laboratory process has been very labour intensive and expensive, particularly for monitoring suspended sediment movement over the long term (ie an entire wet season). A common alternative to suspended sediment sample collection is the continuous monitoring of turbidity in streams as an indirect measure of suspended sediment concentration (ie Glysson & Gray 2002, Schoellhamer & Wright 2003). The purpose of this section is to demonstrate that turbidimeters can successfully be used to measure both continuous suspended sediment concentration data and, more importantly, suspended sediment loads associated with individual runoff events within the Ngarradj catchment. In this case, suspended sediment loads for runoff events were determined using turbidity data and compared against loads derived from water samples collected throughout the event hydrograph.

3.1 Data collection

Stage activated pump samplers were installed at each site in 1998 to collect water samples to obtain detailed time series variations in suspended sediment concentration required for accurate load determinations as recommended by Rieger and Olive (1988) and Walling et al (1992). During the 2003–04 wet season, suspended sediment samples collected by the stage activated pump samplers were downloaded fortnightly. Sand (> 63 μm), mud (silt and clay) (< 63 μm & > 0.45 μm) and solute (< 0.45 μm) concentrations in each suspended sediment sample were determined by sieving, filtering and oven drying techniques (Erskine et al 2001). In this study, total suspended sediment concentration was considered to be the sum of the sand and mud component of the sample. Solute concentrations were not considered in this section.

Analite turbidity probes were installed at each site prior to the 2003–04 wet season and were programmed to collect data at 6-minute intervals throughout the annual hydrograph. The probe, contained within a plastic tube which extended from the stream bank to the water channel, was positioned approximately 0.3 m above the bed level at each station. The Analite probes have a self wipe function which was set to wipe the sensor every 3 hours to reduce the build up of algae and other materials on the optical lens. The sensor was only wiped when the water level was above the head of the probe to ensure that the wiper would not scratch the 'dry' optical lens. The probes were calibrated in the laboratory before installation using polymer-based turbidity standards.

3.2 Relationship between turbidity and suspended sediment concentration data

Suspended sediment collected from the water column within the Kakadu region comprises suspended bedload (sand) and suspended mud (silt and clay) (<63 μm & >0.45 μm) (Duggan 1991, Evans et al 2004). The relationships between total suspended sediment concentration (sand and mud) (>0.45 μm) and turbidity for each site were statistically significant although there was considerable scatter about the line of best fit (fig 3.1). This is a similar result to previous studies within the region (Duggan 1991, Riley 1998) and indicates that there are problems with using turbidimeters for the monitoring of total suspended sediment concentration in streams within the catchment.

However, there is a stronger correlation between turbidity and mud concentration – the silt and clay component of suspended sediment – for each station (fig 3.1), which indicates that the continuous turbidity data could be used to monitor stream mud concentration (mud *C*) within the Ngarradj catchment. These relationships were further refined by removing the outliers from the dataset. A test for outliers (using standardised residuals) was performed twice and identified 11, 10 and 12 outliers in the data for SC, UM and ET respectively. These data points were removed and the regression analysis was conducted with the remaining data points (fig 3.1). Clearly, the removal of the sand component within the suspended sediment sample has reduced the effect of particle size on the sensor calibration process. It is well known that nutrients and contaminants, including heavy metals and radionuclides, are transported in association with mud (Walling & Webb 1985, Walling & Owens 2002). Therefore, the use of the turbidimeter in monitoring just the mud component of the suspended sediment within the stream is particularly important for the understanding of the contaminant transport processes within the Ngarradj catchment.

The continuous stream mud *C* at SC, UM and ET for the 2003–04 wet season, collected using turbidimeters and converted to concentration using the regression relationships (fig 3.1), is shown in figure 3.2.

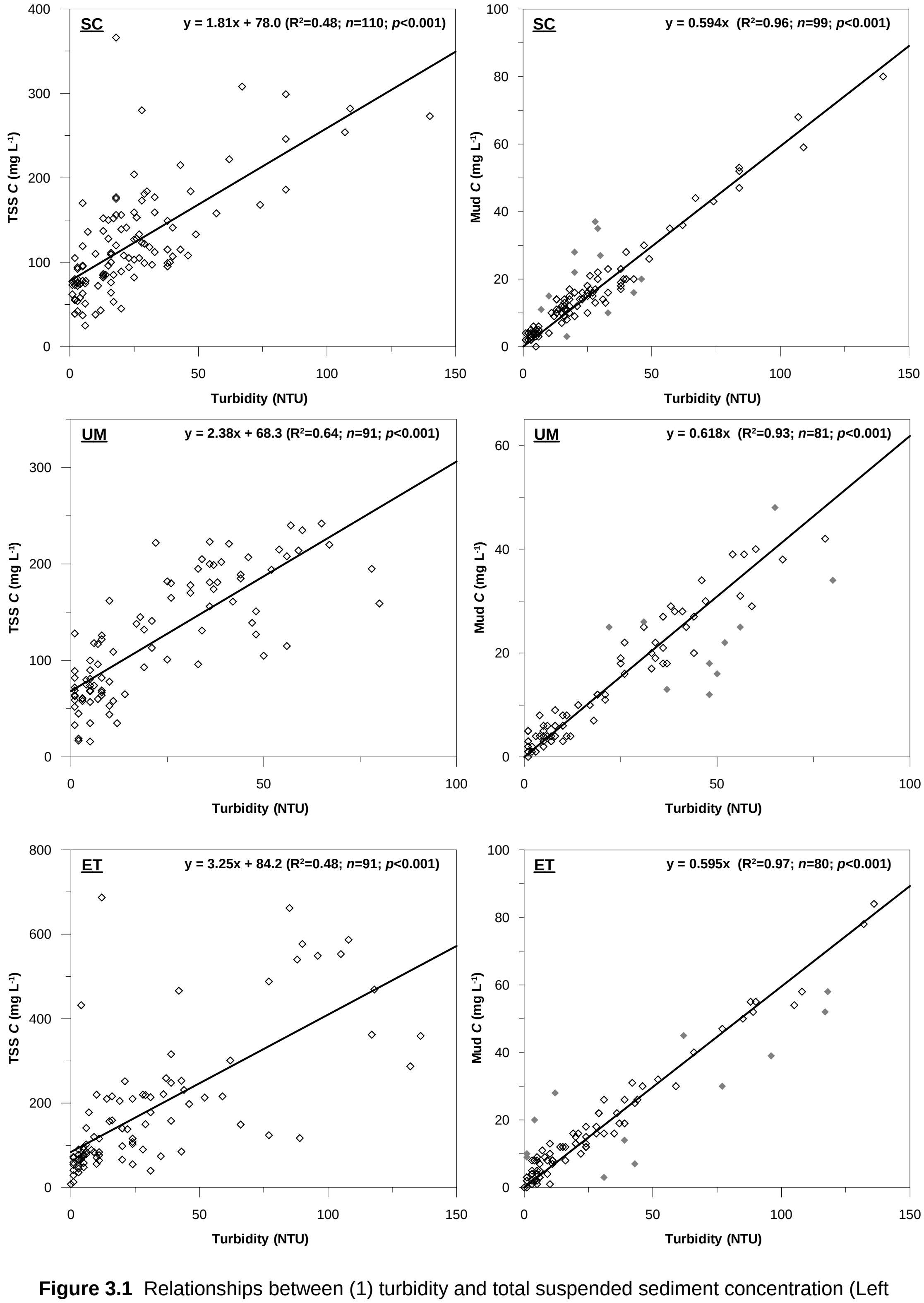

Figure 3.1 Relationships between (1) turbidity and total suspended sediment concentration (Left column) and (2) turbidity and mud concentration (Right column) for each gauging station. (Outliers in the turbidity-mud *C* data are shown as ◆)

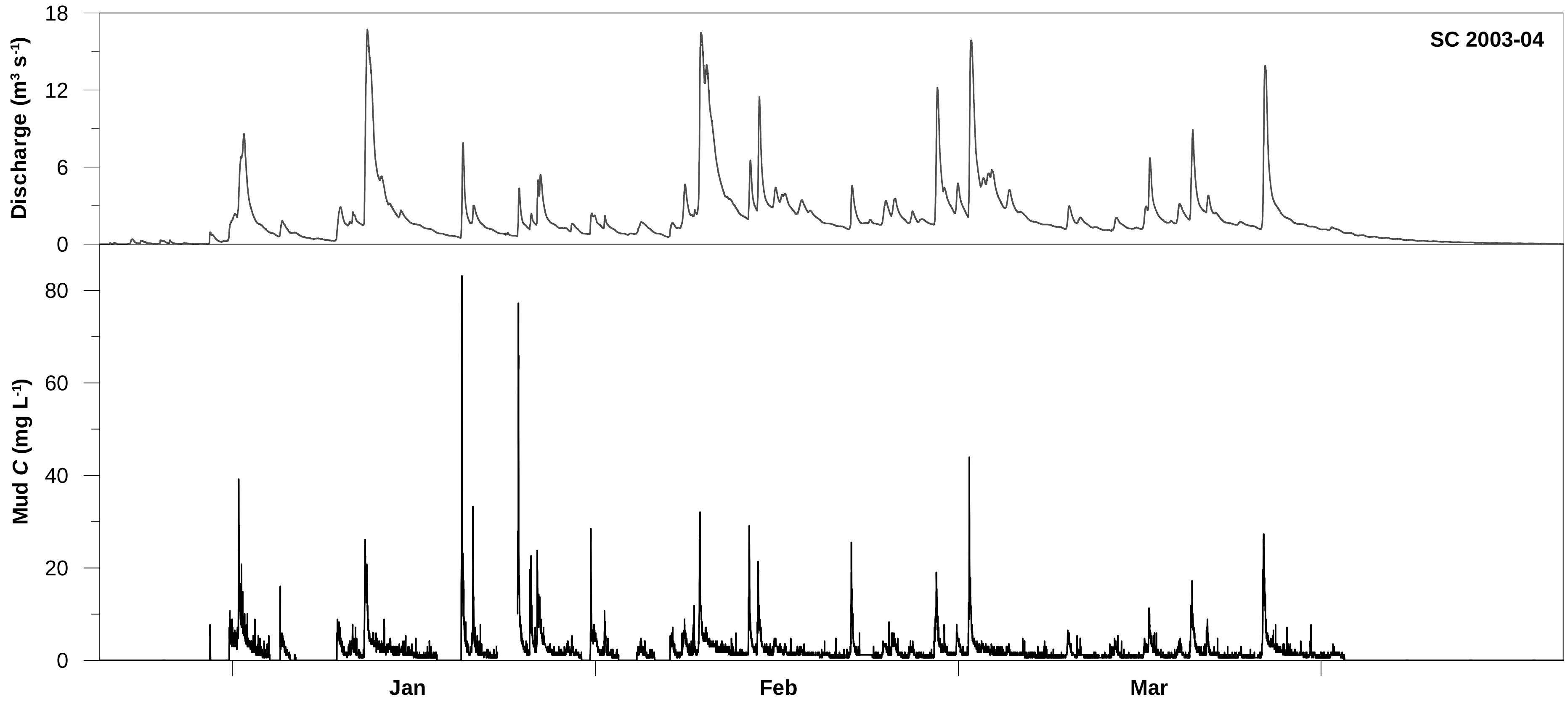

Figure 3.2a Continuous mud *C* data collected by the turbidimeter for the 2003–04 wet season at SC. Discharge data are also shown.

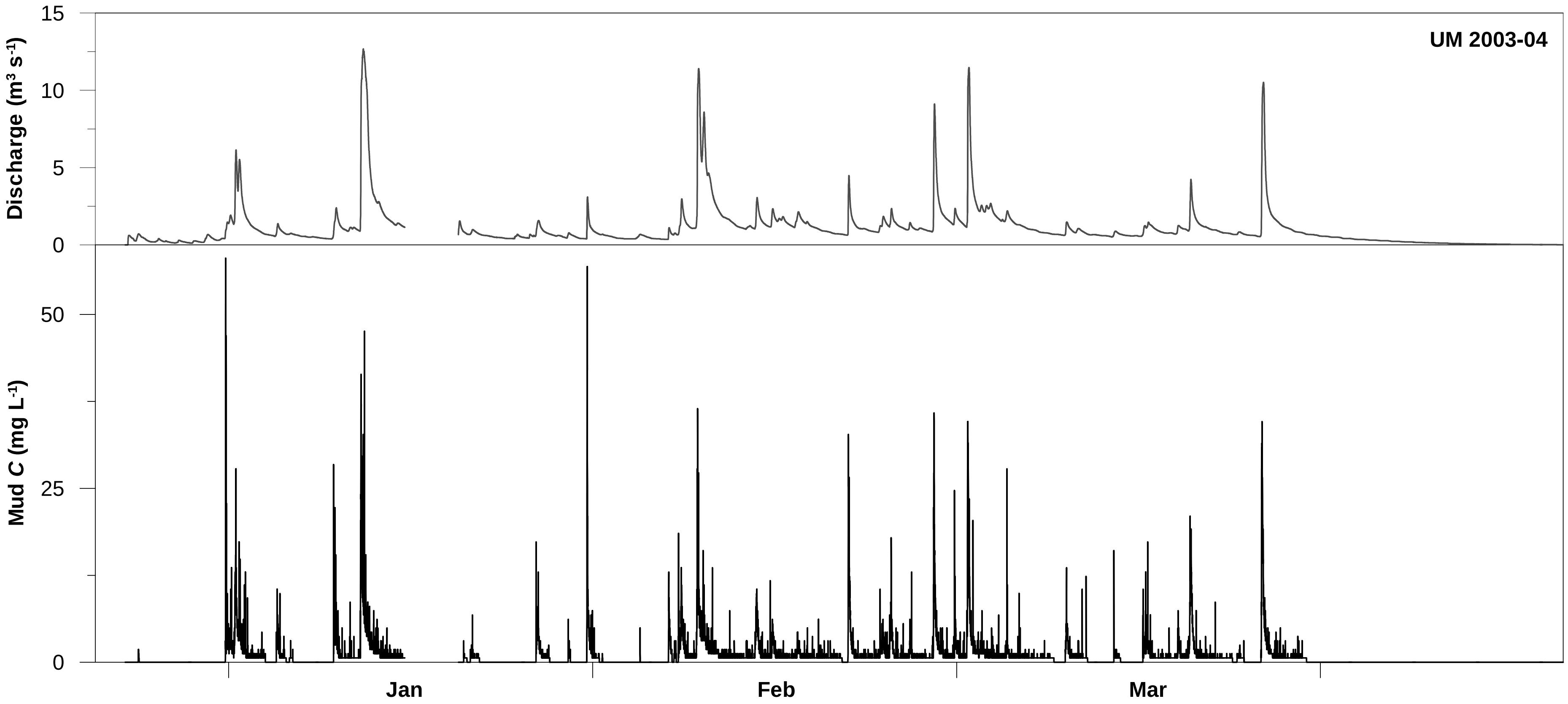

Figure 3.2b Continuous mud *C* data collected by the turbidimeter for the 2003–04 wet season at UM. Discharge data are also shown.

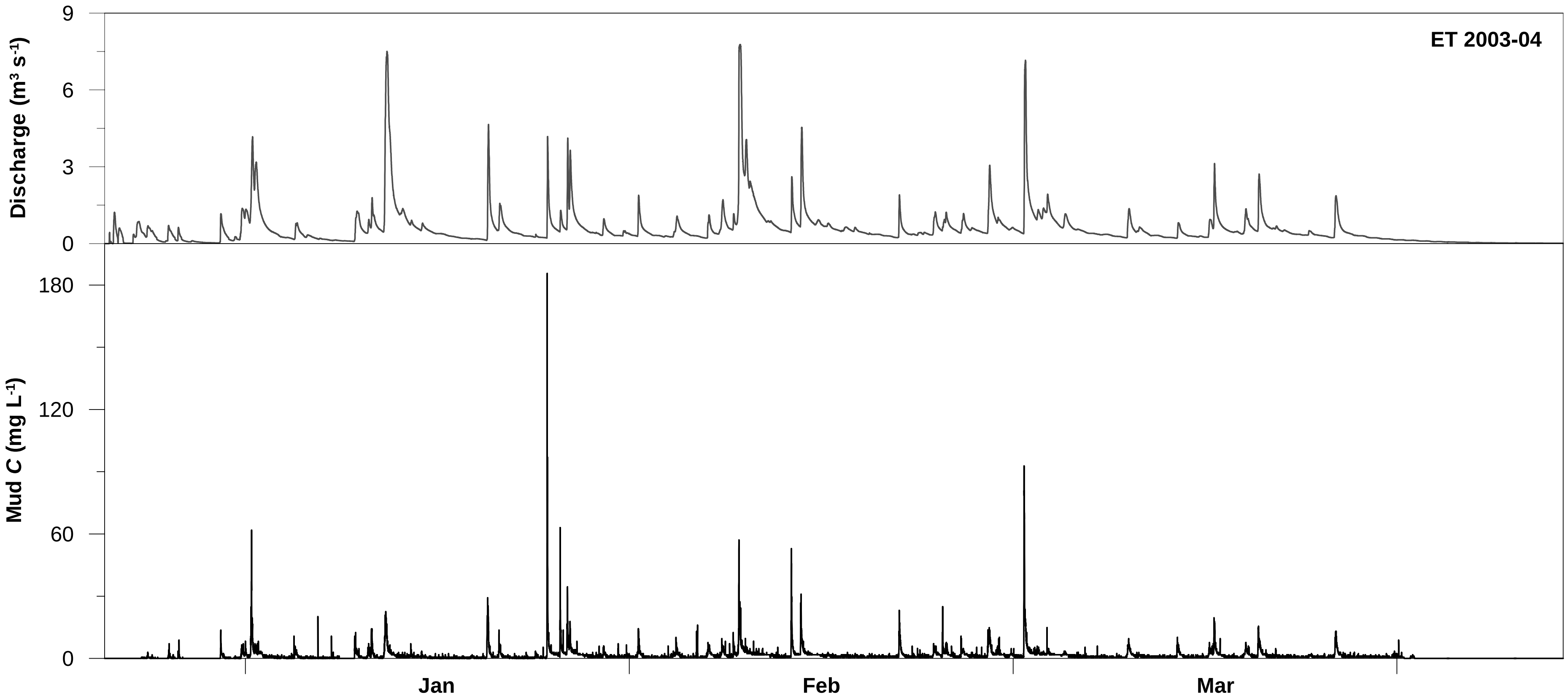

Figure 3.2c Continuous mud *C* data collected by the turbidimeter for the 2003–04 wet season at ET. Discharge data are also shown.

3.3 Estimating event mud loads

Within the Ngarradj catchment mud is transported through the system in pulses associated primarily with a single-peaked event or the first peak of a multi-peaked event (Evans et al 2003) (fig 3.3). Evans et al (2003) describe a monitoring approach that compares total mud load during an event against a calibrated event-based mud load relationship for assessing mine-related mud impact (see Section 4). Therefore, it is important that the measurement of event mud load is reliable.

The following section is an assessment of the reliability of using turbidimeters to derive individual event mud loads for the Ngarradj catchment. Event muds loads were estimated at each site using mud *C* data (1) collected using turbidimeters and applying the calibrated turbidity-mud concentration relationships for each site (fig 3.1) to the continuous turbidity data, and (2) derived from the filtering of water samples collected by the stage-activated pump sampler. Mud loads are defined as the area under the sedigraph for a major mud pulse, where mud *C* begins and ends at approximate baseflow levels (2–5 mg L^{-1}) (fig 3.3). There were 16, 10 and 15 major mud pulses observed during the 2003–04 wet season at SC, UM and ET respectively (Appendix B).

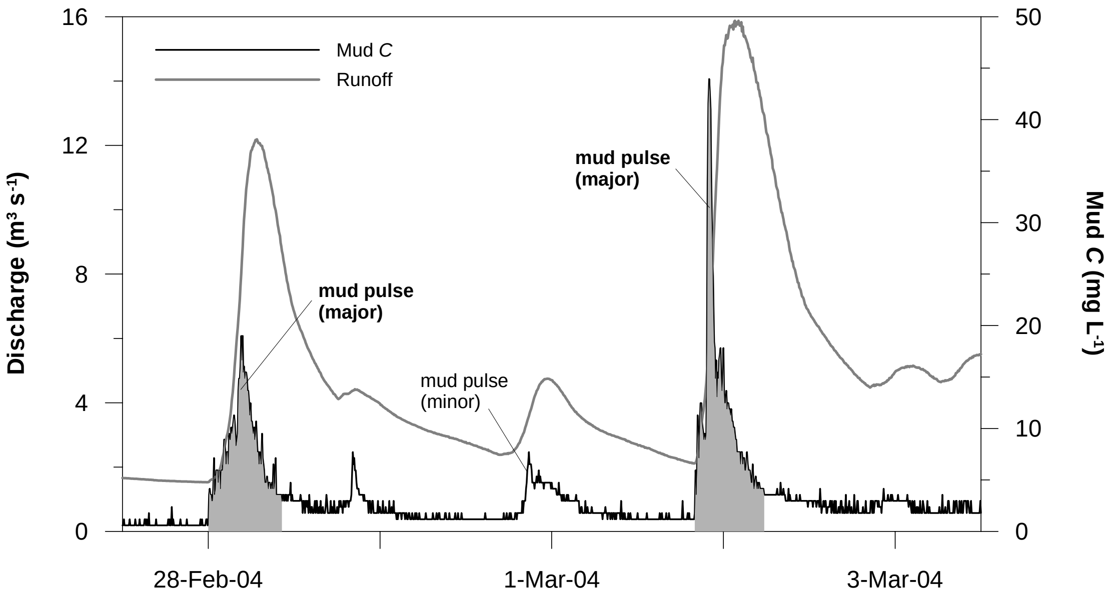

Figure 3.3 Hydrograph and sedigraph at SC during an 8-day period of the wet season. The major mud pulses are indicated as shaded regions of the sedigraph.

3.3.1 Main channel (SC and UM)

Regression analysis showed that there was a significant relationship between event loads derived from the turbidity data and event loads derived from the samples collected by the pump sampler for SC and UM (regression coefficient, $k = 0.89$, $r^2 = 0.81$, $p < 0.001$ at SC; $k = 0.94$, $r^2 = 0.94$, $p < 0.001$ at UM) (Appendix B). The correlation was particularly strong for large runoff events. It is important that event loads for large events are accurately measured as these events can transport most of the total sediment moved during a wet season (Evans et al 2000). Figure 3.4 shows the sedigraphs associated with a runoff event on 19–20 January 2004 at SC and a runoff event on 30 January 2004 at UM which highlights the similarity between mud *C* data (and corresponding mud load) determined using the turbidimeter and that derived from water samples collected by the pump sampler. The peak mud *C* for both of these events corresponded to the highest mud concentration of the 2003–04 wet season at the respective sites.

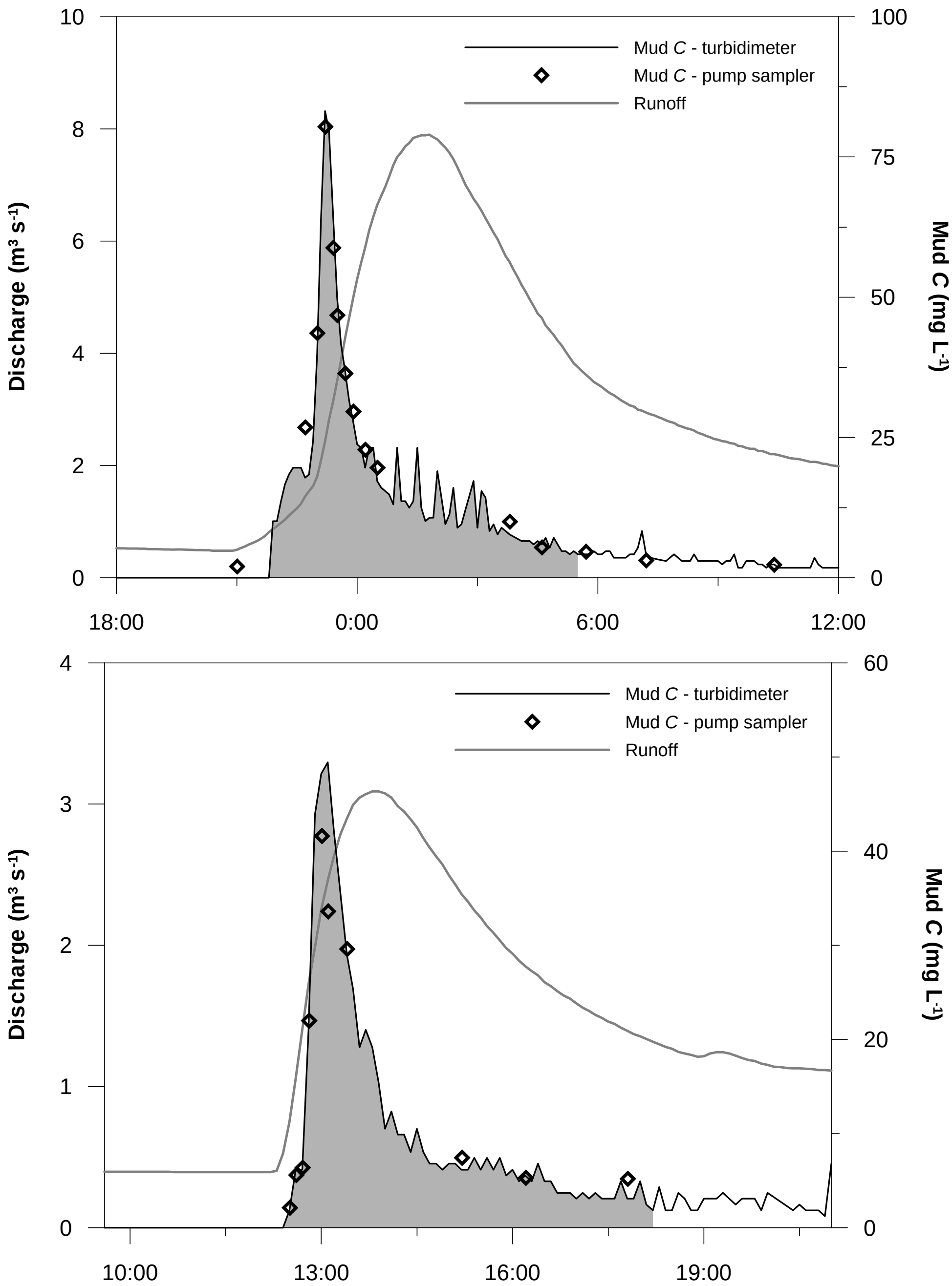

Figure 3.4 Mud *C* during a runoff event at SC on 19 January 2004 (Top) and at UM on 30 January 2004 (Bottom) using (1) turbidimeter data and (2) water samples collected by the stage-activated pump sampler. The mud pulse is indicated as the shaded region of the turbidity-derived sedigraph.

Occasionally, spikes in mud *C* were observed by the turbidimeter at SC and UM which were associated with relatively small runoff events. During these runoff events the stream did not rise enough to obtain a sufficient number of water samples by the stage-activated pump sampler to determine an event load. It was also noted that during some runoff events, water samples collected throughout the hydrograph were not sufficient to accurately characterise the mud movement during the event. For example, figure 3.5 shows a runoff event at SC where the rate of rise of the hydrograph is relatively low and, as a result, samples collected during the rising stage of the hydrograph were not frequent enough to capture the peak of the sedigraph (as observed by the turbidimeter). Furthermore, a second and relatively minor runoff peak occurred during the falling stage of the first hydrograph peak. The stage height of the creek neither dropped or increased enough to activate the pump sampler for water samples to be collected throughout this second peak. As a result, the number of water samples collected by the stage-activated pump sampler were too few to reliably characterise the rapid drop in mud *C* during the falling stage of the sedigraph as observed by the turbidimeter. Therefore, in this case, the mud load estimated from mud *C* data derived from water samples collected by the pump sampler does not compare well to the mud load estimated from turbidity data (fig 3.5).

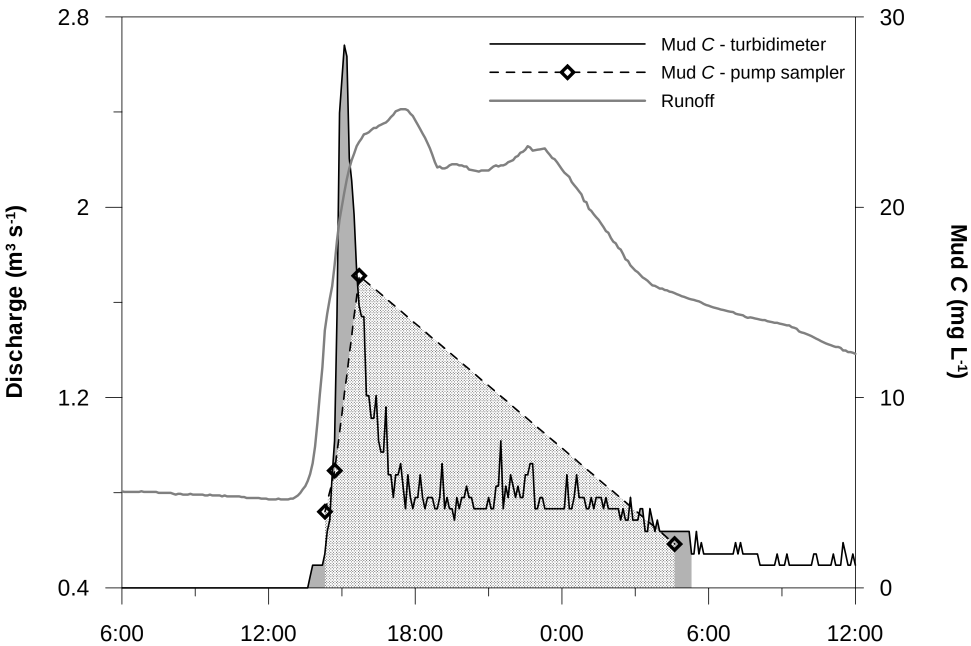

Figure 3.5 Mud *C* during a runoff event at SC on 30–31 January 2004 using (1) turbidimeter data, and (2) water samples collected by the stage-activated pump sampler. The mud pulse is indicated as the shaded region of the sedigraph.

3.3.2 Tributary (ET)

There is a relatively poor correlation between event loads derived from the turbidimeter data and corresponding loads determined from the filtration of water samples collected by the pump sampler at ET (k = 0.54, r^2 = 0.59, p = 0.003) (Appendix B). It is considered that this is attributed to the sampling technique, which may not be adequate to determine an accurate event load at ET. The catchment area upstream of ET is smaller than that of SC and UM and comprises mainly of Arnhem Land Plateau (fig 1.1). The stream at ET is also more sinuous and the runoff response much quicker than SC and UM (Evans et al 2003). This combination of factors may result in a rapid flushing of mud during the rising stage of the hydrograph. Therefore, the first sample of an event is taken after the stream has risen a certain increment above baseflow which, at ET, may often be *after* the peak, or at least after a substantial part, of the mud pulse has already passed. For example, figure 3.6 shows the mud concentration data collected throughout two event hydrographs using the automatic pump sampler. The continuous mud *C* data collected by the turbidimeter for these events indicates that, in general, a significant part of the mud pulse has passed by the time the first water sample is collected. Consequently, event loads determined from water samples collected by the pump sampler at ET may be unreliable.

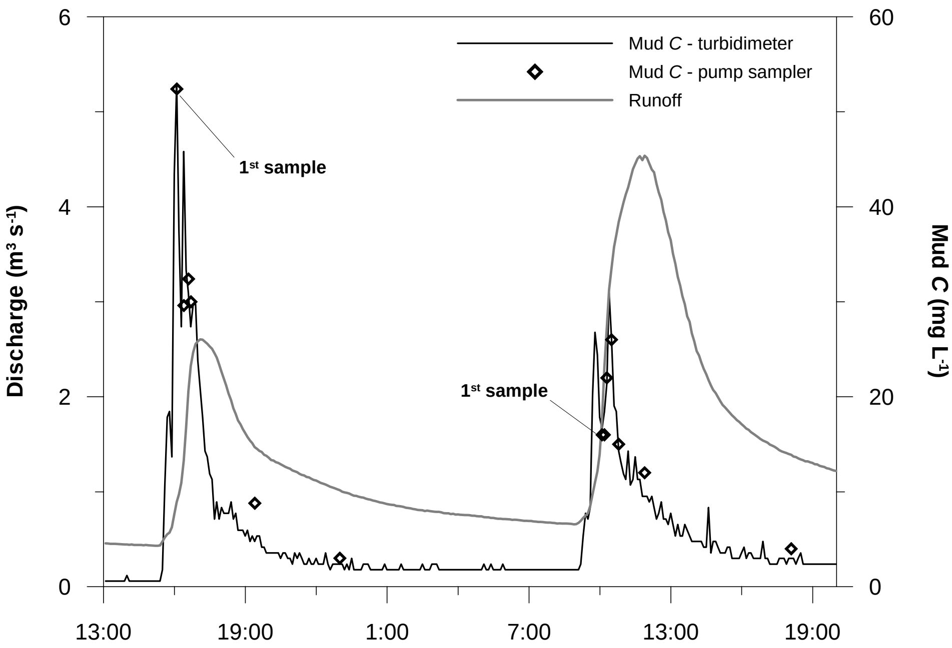

Figure 3.6 Mud C during two events at ET between 12–13 February 2004 using (1) turbidimeter data, and (2) water samples collected by the automatic pump sampler and filtered in the laboratory

3.3.3 Discussion

This analysis has shown that the use of turbidimeters within the Ngarradj catchment is essential for monitoring loads: (1) in small streams that exhibit a rapid flushing of mud during the rising stage of the hydrograph (ie ET), and (2) associated with relatively minor and/or multi-peaked runoff events (Lewis 1996, 2002). To derive a complete sedigraph under these conditions using the stage-activated pump sampler requires samples to be collected at smaller increments throughout both the rising and falling stages of the hydrograph. However, to decrease the current increment at which samples are taken by the sampler on both the rising and the falling stage of the event hydrograph will invariably mean that the pump samplers will be full much sooner. As a result, because of limited access to the sites during the wet season, the storage capacity of the sampler is likely to be exceeded between site visits and therefore not all events will be sampled.

The primary advantage of using turbidimeters to monitor mud loads is the significant reduction in labour intensive suspended sediment sample collection and sample processing. Furthermore, the continuous turbidity record can observe mud pulses that are not strongly related to flow, which could be particularly important in terms of monitoring possible mining-related impacts within the catchment. Nevertheless, automated data collection is essential for the validation of the turbidity data (Lewis 1996, 2002). For example, should the turbidity data indicate an unusually large mud pulse that is unrelated to flow (and hence indicating a possible mining-related impact), the water samples collected by a pump sampler are particularly important to validate these spikes. This analysis has shown that the current method of sample collection may not adequately sample across mud pulses associated with the entire range of runoff events and for all streams within the Ngarradj catchment. An alternative method of automated data collection is using changes in turbidity to trigger the collection of water samples rather than changes in stage height (Lewis 1996, 2002, Eads & Lewis 2002). In other words, sample collection occurs throughout the rising and falling stages of a mud pulse. This alternative method of sample collection has important applications for the validation of turbidity data associated with mud pulse events, particularly those unrelated to flow.

3.4 Conclusions

There is a significant relationship between turbidity and mud concentration in streams within the Ngarradj catchment. This has important implications for the understanding of mud and associated contaminant movement within the catchment. The use of turbidimeters is considered essential for estimating individual event loads within the Ngarradj catchment, particularly for monitoring loads: (1) in small streams that exhibit a rapid flushing of mud during the rising stage of the hydrograph (ie ET), and (2) associated with relatively minor and/or multi-peaked runoff events. The primary advantage of using turbidimeters to monitor mud loads is the significant reduction in labour intensive suspended sediment sample collection and sample processing. Furthermore, the continuous turbidity record can observe mud pulses that are not strongly related to flow, which could be particularly important in terms of monitoring possible mining-related impacts within the catchment. However, water samples will still need to be collected to validate the derived relationships and it is recommended that the use of an automatic turbidity-activated pump sampling regime, rather than a stage-activated one, be investigated.

4 Impact assessment using an event-based mud model

As shown above (Section 3, fig 3.3), mud is primarily transported through the system in pulses associated with a single-peaked event or the first peak of a multi-peaked event. It is well documented that mud is an important indicator of stream health because it is associated with contaminant transport and adverse affects on aquatic ecosystems (ie Walling & Webb 1985, Bonta 2000). Evans et al (2003) considered that in order to reliably assess possible future mining impacts, it is important to develop an understanding of the mud transport characteristics during these pulses.

In this section, the calibration of an event-based mud load relationship, where only single peaked events and the first peak of a multi-peaked event were used for analysis, is described. The calibrated model is then used to assess any impacts on event mud loads observed downstream of the mine during the 2003–04 wet season.

4.1 Event-based mud transport model

4.1.1 Original model

The derivation of the event-based mud transport model for SC, UM and ET included regression analysis between event mud load and various discharge characteristics – including total event runoff, total discharge of the rising stage of the hydrograph, maximum periodic rise (6-min, 30-min and 60-min interval) and recovery period preceding the event (ie time taken since previous rainfall-runoff event). Initially, Evans et al (2003) calibrated an event-based mud transport model for the three sites using one year of event data and had the form:

$$\text{Total mud load} = K \int_{Q_0}^{Q_p} Q^m \, dt \qquad (1)$$

where Q is instantaneous discharge ($m^3 s^{-1}$), Q_p is peak event discharge, Q_0 is initial discharge (fig 4.1) and m and K are fitted parameters. Total mud loads were derived through integration of the mud discharge curve associated with the mud pulse.

A sensitivity analysis showed that rising stage discharge was the most significant factor in the mud load relationship. Other variables, such as recovery period and maximum periodic rise, were not significant.

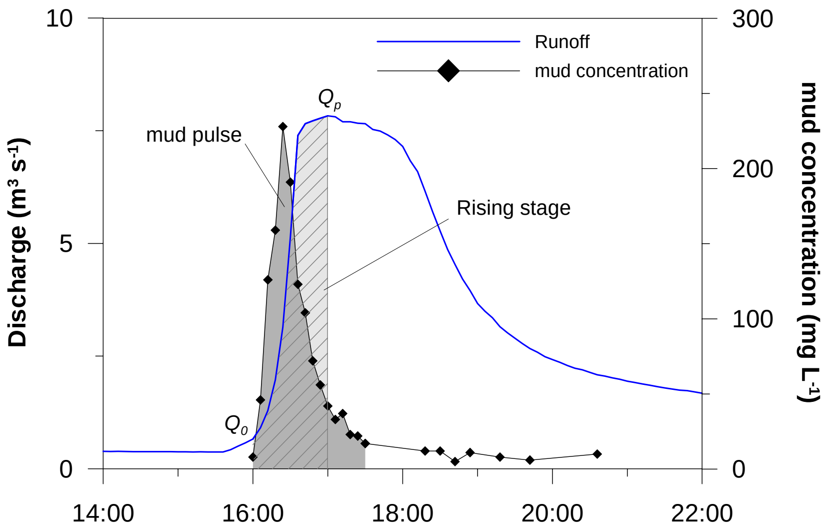

Figure 4.1 Hydrograph and sedigraph for an event at ET on 27 Feb 2002. The mud pulse is indicated as the shaded region of the sedigraph.

To incorporate a wider range of runoff-mud load events within the mud load model, two years of event data were used to calibrate Equation (1) for each site. Mud concentration data collected over two wet seasons (Evans et al 2004), which were considered to be unimpacted by both fire and mining-related activities (1999–00 and 2000–01), were used to estimate individual event mud loads which, in turn, were used to fit the mud load relationship (Eqn 1). The statistically significant event mud transport model derived for SC and UM were:

$$T_{SC} = 0.020\int Q^{0.97}dt \quad (R^2 = 0.57;\ n = 22;\ p<0.001) \qquad (2)$$

$$T_{UM} = 0.042\int Q^{1.07}dt \quad (R^2 = 0.87;\ n = 18;\ p<0.001) \qquad (3)$$

A relationship could not be fitted for ET for the two years of event data. This is attributed to the fact that event loads estimated from mud concentration data collected prior to the 2003–04 wet season may be unreliable (as discussed in Section 3.3.2). Therefore, mud concentration data collected during 2003–04 were used to derive event mud loads for ET. These event loads were used to derive the following relationship:

$$T_{ET} = 0.047\int Q^{0.43}dt \quad (R^2 = 0.39;\ n = 15;\ p=0.013) \qquad (4)$$

The fitted relationship for ET is significant (Eqn 4) at the 95% level (i.e. p>0.05), which indicates that the form of the mud load relationship (Eqn 1) may be adequate for all streams within the Ngarradj catchment. However, the Evans et al (2003) model cannot differentiate between a short-lived, high magnitude runoff event and a long duration, low magnitude runoff event (Moliere et al 2004). The corresponding predicted mud loads for these two types of events will be similar. However, the observed mud load for the high magnitude event is expected to be greater than the low magnitude runoff event. It is therefore considered that a revised model that includes a maximum periodic rise variable (maximum rise in discharge over a period of time) within the mud load model will address the two limitations, particularly the second limitation.

4.1.2 Revised model

The form of the revised event mud model is:

$$\text{Total mud load} = K'(Q_T)^a Ri^b \tag{5}$$

where Q_T is total discharge during the rising stage of the hydrograph, *Ri* is maximum periodic rise in discharge and *a*, *b* and *K′* are fitted parameters.

As mentioned above, the maximum periodic rise (*Ri*) for an individual runoff event is the maximum rise in discharge over a certain period of time. To determine the most significant time interval for the *Ri* variable within Equation (5), the maximum rise in discharge over 6-min, 30-min and 60-min intervals were analysed. Intervals greater than 60-min were not included in the analysis because the entire duration of the rising stage of some runoff events, particularly minor runoff events observed at the smaller catchment areas upstream of UM and ET, were between one and two hours.

Using runoff data collected during events at SC and UM during 1999–2000 and 2000–01 and at ET during 2003–04, there were very strong correlations between the three sets of *Ri* values associated with the three different time intervals (6-min, 30-min and 60-min). This indicates that the *Ri* exponent (*b*) within the mud load model (Eqn 5) would vary little whether the model was calibrated using *Ri* values for either 6-min, 30-min or 60-min time intervals. For all three sites the most significant mud load model was obtained when the *Ri* variable was based on a 6-min interval. However, the correlation coefficient for the regression relationship (using *Ri* based on a 6-min interval) was generally only marginally higher (approximately 1–3%) than that associated with the regression relationships derived using *Ri* for a 30-min or 60-min interval for all three sites.

The revised event-based mud load models for SC and UM, derived using mud concentration data collected over two wet seasons (1999–2000 and 2000–01) (Evans et al 2004) and *Ri* based on a 6-min interval, are as follows:

$$T_{SC} = 27.55 Q_T^{0.416} Ri^{0.66} \quad (R^2 = 0.69;\ n = 22;\ p<0.001) \tag{6}$$

$$T_{UM} = 0.82 Q_T^{0.755} Ri^{0.498} \quad (R^2 = 0.90;\ n = 18;\ p<0.001) \tag{7}$$

The revised model for ET, used mud concentration collected during the 2003–04 wet season (and *Ri* based on a 6-min interval), is as follows:

$$T_{ET} = 4.97 Q_T^{0.591} Ri^{0.81} \quad (R^2 = 0.90;\ n = 15;\ p<0.001) \tag{8}$$

Figure 4.2 shows that the observed event mud loads compare reasonably well with the predicted event mud loads derived using equations 6, 7 and 8 for SC, UM and ET respectively. The correlation coefficients for the revised models (Eqns 6 to 8) have improved from the previous event mud load models (Eqns 2 to 4), particularly for ET. Overall, the mud load relationship described by Equation (5) is a more robust relationship than that described by Equation (1), with its ability to (1) adequately describe different catchment areas within the Ngarradj catchment, and (2) differentiate between various types of runoff events (ie a short-lived, high magnitude runoff event and a long duration, low magnitude runoff event).

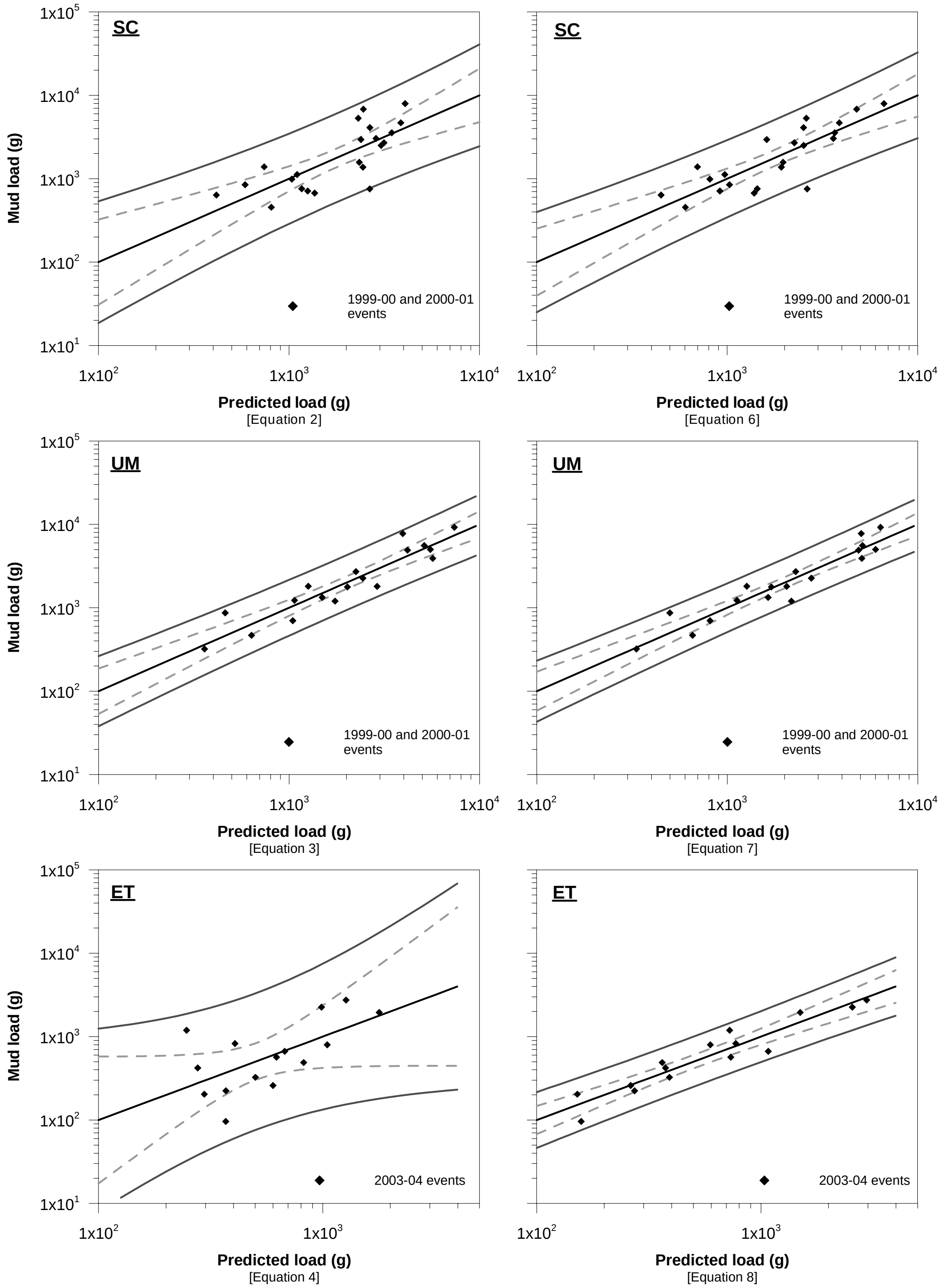

Figure 4.2 Event-based mud load models for each gauging station. Mud load relationships of the form described by Equations (2) to (4) (Left column) and Equations (6) to (8) (Right column) are shown.

Walling and Webb (1982) discuss the importance of the length of recovery period on peak suspended sediment concentration (and hence mud loads). However, storm activity in this study area is generally frequent during the wet season and the length of time between rainfall-runoff events is relatively short (average rate of recovery at Ngarradj is approximately 3–4 days during the wet months of January to March). As a result, regression analysis showed that recovery time was not a significant variable in the mud load relationship and the inclusion of this variable within the model resulted in only a very minor improvement in the correlation coefficient for each site (<1%).

4.1.3 Model validation

Mud load data were also collected during the 2001–02 and 2002–03 wet seasons at both SC and UM. These data were used to validate the calibrated mud load models for these two sites. (As discussed in Section 3.3.2, mud loads determined at ET from mud concentration data collected prior to the 2003/04 wet season may be unreliable. Therefore, the model fitted for ET (Eqn 8), cannot be tested.) Only seven mud pulses were observed at both SC and UM during these two wet seasons. Figure 4.3 shows that all but one of these events fit within the prediction limits associated with the fitted models for both sites.

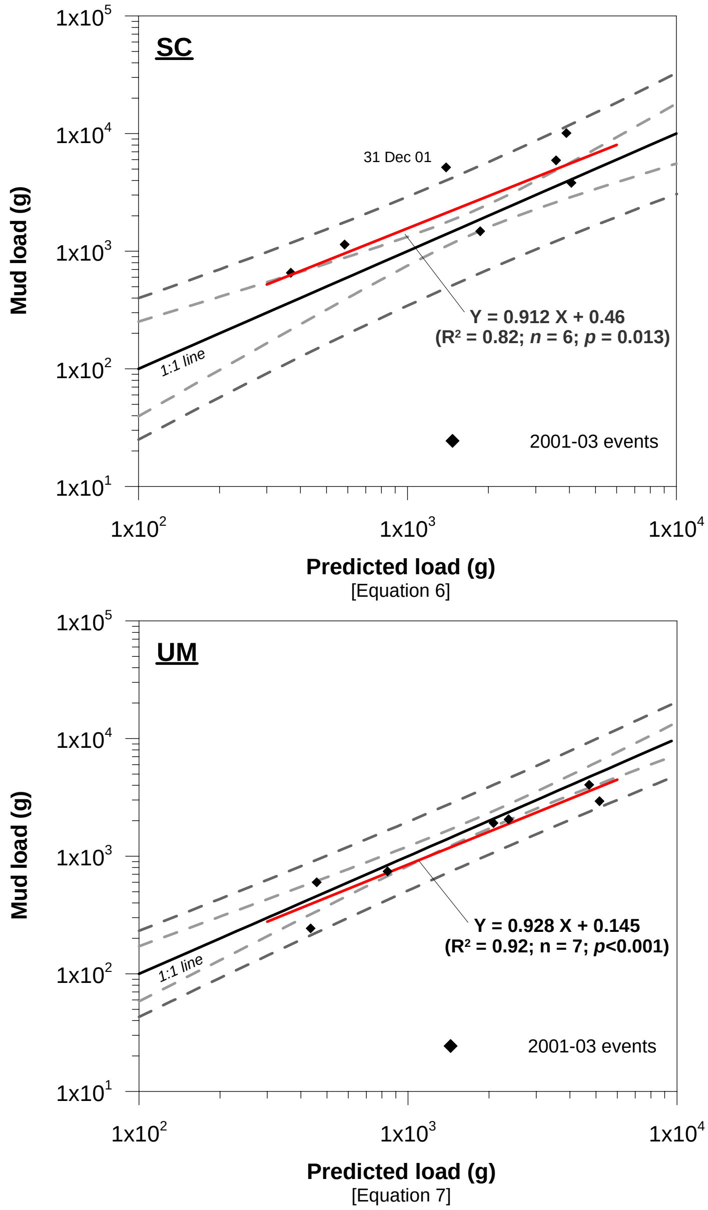

Figure 4.3 Event-based mud load models for SC and UM (Eqns 6 and 7 respectively) and associated confidence and prediction limits (indicated as dashed lines). Observed mud loads for 2001–02 and 2002–03 at SC and UM, and the line of best fit through these data, are also shown.

The event on 31 December 2001 at SC was the first flush of the season and was also fire-impacted. A fire which occurred within the Ngarradj catchment late in the 2001 dry season had an impact on the southern part of the SC catchment area, but no impact on the catchment area upstream of UM (Evans et al 2004). Therefore, the observed mud load for this same event at UM was not elevated above the prediction limits. Figure 4.3 indicates that the general trend in event load data collected during these two wet seasons at SC and UM, excluding the fire-impacted event at SC on 31 December 2001, is not significantly different from that of previous years.

A wide range of runoff-mud load events collected over a four-year monitoring period were used to calibrate and validate the models. Therefore, it is considered that the models are valid for most wet season conditions.

4.2 Impact assessment

Mud load models provide us with a means of assessing impacts (mine-related or natural) on stream mud concentration within the Ngarradj catchment on an event basis. The Australian Guidelines for Water Quality Monitoring and Reporting (ANZECC & ARMCANZ 2000) recommend establishing trigger values representing different levels of interventions by supervising authorities and industry. The guidelines recommend that if the population distribution is normal then standard deviations should be used to set trigger values, otherwise the trigger values were set as percentiles. Since the distribution of the population of predicted event mud loads about the 1:1 line is normal (fig 4.4), trigger values were set as +1σ, +2σ and +3σ respectively. As mentioned above, earthworks occurred at Jabiluka mine during the 2003 dry season and, therefore, it is important to assess any subsequent impact on event mud loads, and hence stream mud concentration at SC.

For a more reliable impact assessment of mud loads during 2003–04 at the downstream station, it was considered that the mud model should be refitted using all four years of mud load data collected between 1999 and 2003. As shown in Section 4.1.3, there is no significant difference between event load data collected during 1999–2001 and 2001–03. The revised models for SC and UM are:

$$T_{SC} = 236.2 Q_T^{0.246} Ri^{0.83} \quad (R^2 = 0.71;\ n = 28;\ p<0.001) \qquad (9)$$

$$T_{UM} = 0.625 Q_T^{0.774} Ri^{0.459} \quad (R^2 = 0.90;\ n = 25;\ p<0.001) \qquad (10)$$

Using mud concentration data collected during the 2003–04 wet season at each station, the mud load associated with every event driven mud pulse was determined. There were 16, 10 and 15 mud pulses observed during 2003–04 at SC, UM and ET respectively (Appendix B).

Figure 4.4 shows the event loads at SC at UM observed during 2003–04, plotted against the calibrated models (Eqns 9 and 10 respectively). The trigger values associated with the mud transport models are +1σ, +2σ and +3σ from the 1:1 line. At SC, there were two events that were above the second trigger level – 1 January and 11 January 2004 (fig 4.4). These were the first two events for the year and were likely to have been fire-impacted events. A fire which occurred within the Ngarradj catchment during November 2003 prior to the commencement of flow will have had only a minor impact on the catchment areas upstream of UM and ET, but a relatively large impact on the southern part of the SC catchment area (fig 4.5). According to Townsend and Douglas (2000), late dry season fires can increase stream sediment concentration by up to a factor of 10 compared to early dry season fires. However, a dry season fire within a catchment area will only impact stream mud concentration during the early period of flow, after which it is expected that mud concentration will return to baseline, unimpacted levels (Evans et al 2004).

A line of best fit through the 2003–04 event data (excluding the two fire-impacted events) lies above that fitted for the model, but below that of the first trigger level (fig 4.4). In other words, the mean difference between observed and predicted mud loads for 2003–04 events is within +1σ of the fitted mud load model (Eqn 9). A *F*-test showed that the line of best fit through the 2003–04 event data (fig 4.4) is not significantly different to the event mud transport model curve (the 1:1 line on figure 4.4). Furthermore, a second mud transport model of the form described by Equation (5) was fitted for the 2003–04 event data at SC and this relationship was not significantly different to that fitted for the previous four years of data collected between 1999 and 2003 (Eqn 9).

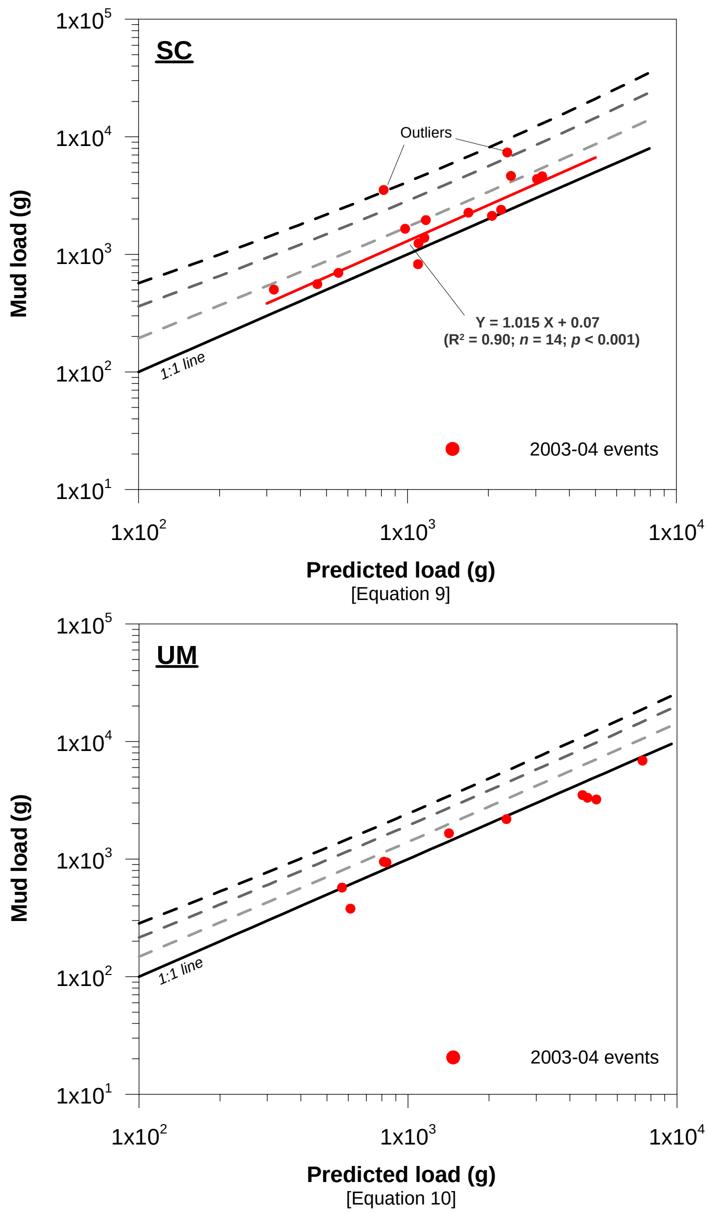

Figure 4.4 Event-based mud load models for SC and UM and associated trigger levels (indicated as dashed lines) derived using event data collected between 1999 and 2003. Observed mud loads for 2003–04 at SC and UM, and the line of best fit through these data at SC, are also shown.

Therefore, statistical analysis suggests that there has not been a significant increase in mud loads at SC during the 2003–04 wet season. However, event loads for almost all of the events that occurred during 2003–04 at SC were observed to be higher than the 1:1 line (fig 4.4). The elevated mud concentration at SC during these events cannot be attributed to an elevation in mud concentration at the upstream UM site. The events at UM all fall well within trigger levels associated with the calibrated model and lie around the 1:1 line (fig 4.4). The evidence supports the inference that the increase in mud loads at SC is a result of erosion on the mine site. While it is considered that this increase in mud loads at SC during 2003–04 is not of major concern, given the majority of these events do not plot above the first trigger level associated with the model and the general trend is not significantly different to previous years', a change has been detected even though the mine disturbance was relatively minor. This supports the hypothesis that the monitoring technique is sensitive enough to detect event related change in the system.

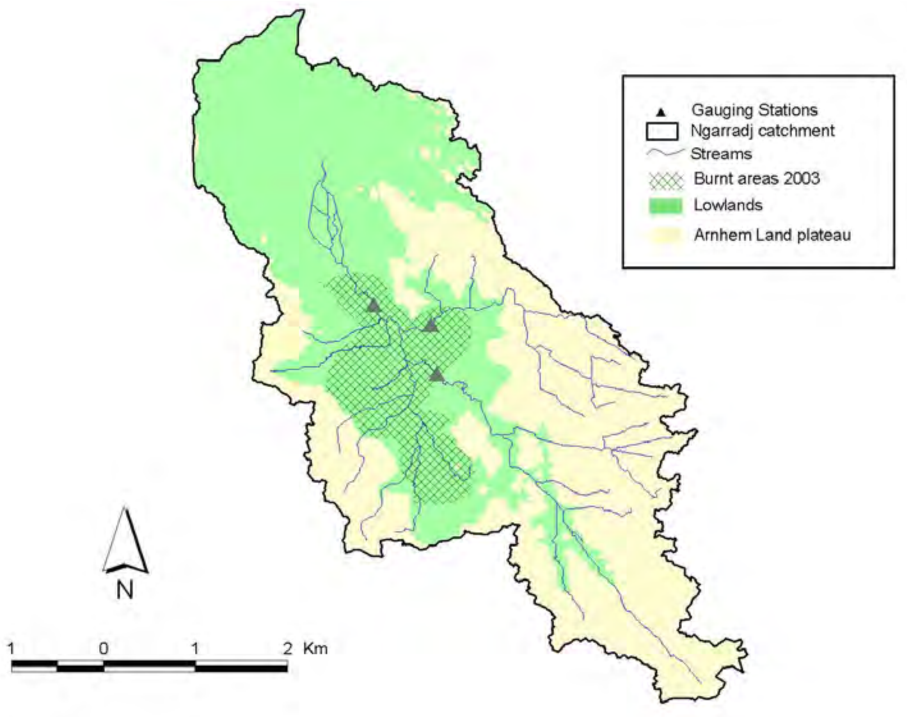

Figure 4.5 Extent of the 2003 dry season fire within the Ngarradj catchment

4.3 Conclusions

This study has illustrated two important findings:

1 The total runoff to peak discharge (Q_T) and the maximum periodic rise in discharge (*Ri*) are significant discharge characteristics within the mud load relationship. The calibrated event-based mud transport model, which includes these two factors, has the ability to adequately describe different catchment areas within the Ngarradj catchment and differentiate between various types of runoff events. The recovery period between events is not a significant factor within the mud load model for the Ngarradj catchment, which is probably a result of the frequent storm activity for the region.

2 The calibrated mud load model for SC was sensitive enough to identify an increase in mud concentration throughout the 2003–04 wet season. It is likely that the increase in

event mud loads at SC is a result of erosion on the mine site attributed to earthworks which occurred during the 2003 dry season. However, the 2003–04 event loads were generally not above trigger levels associated with the fitted model.

The catchment should be monitored during the 2004–05 wet season to observe if event mud loads at SC return to baseline, unimpacted levels. This would validate the hypothesis proposed by Evans et al (2003) in terms of applying the event-based mud modelling approach to impact assessment.

5 Impact assessment using mud concentration trigger values

Evans et al (2004) derived mud (defined in their report as 'fine suspended-sediment') concentration values for the Ngarradj catchment, which when exceeded, should trigger a management response. These concentration values were derived in accordance with The Australian and New Zealand water quality guidelines (WQG) (ANZECC & ARMCANZ 2000). Evans et al (2004) used two methods to derive these numerical values. The first method is comparison of the downstream SC site with limits at the upstream UM site. The second method is a Before-After-Control-Impact, paired difference design (BACIP) where the upstream site UM is before impact in a spatial sense and the downstream site SC is after impact in a spatial sense. In both cases the ET site can be used to confirm whether an observed elevated measurement at SC, not observed at UM, is (1) from the mine-site catchment, or (2) from ET and therefore a natural occurrence. If elevated values are not observed at ET it is assumed that the source is from the mine-site catchment and investigations are required to identify the source.

In this section, mud concentration data collected by the automatic water sampler at sites within the Ngarradj catchment during the 2003–04 wet season were assessed against the mud concentration limits derived in Evans et al (2004).

5.1 Upstream limits

In this case the reference site of the downstream site, SC, is the upstream site UM. This means that values measured at SC should be lower than the 80th percentile at UM. Trigger values for SC were determined using the complete data set from four years monitoring (Evans et al 2004) (table 5.1). These values are 80th, 95th and 99.7th percentiles representing different levels of interventions by supervising authorities and the mining company. The percentage of SC water samples that had mud concentration values above the trigger values, given in table 5.1, indicate that mud concentration at SC during the 2003–04 wet season is not significantly elevated compared to UM.

Table 5.1 Percentage of SC water samples collected during 2003–04 with mud concentration values exceeding trigger values

Trigger percentile	Mud concentration value (mg L^{-1}) (Evans et al 2004)	No. of samples at SC above trigger value [% of total samples]
80	16	35 [15.9]
95	36	9 [4.1]
99.7	70	1 [0.5]

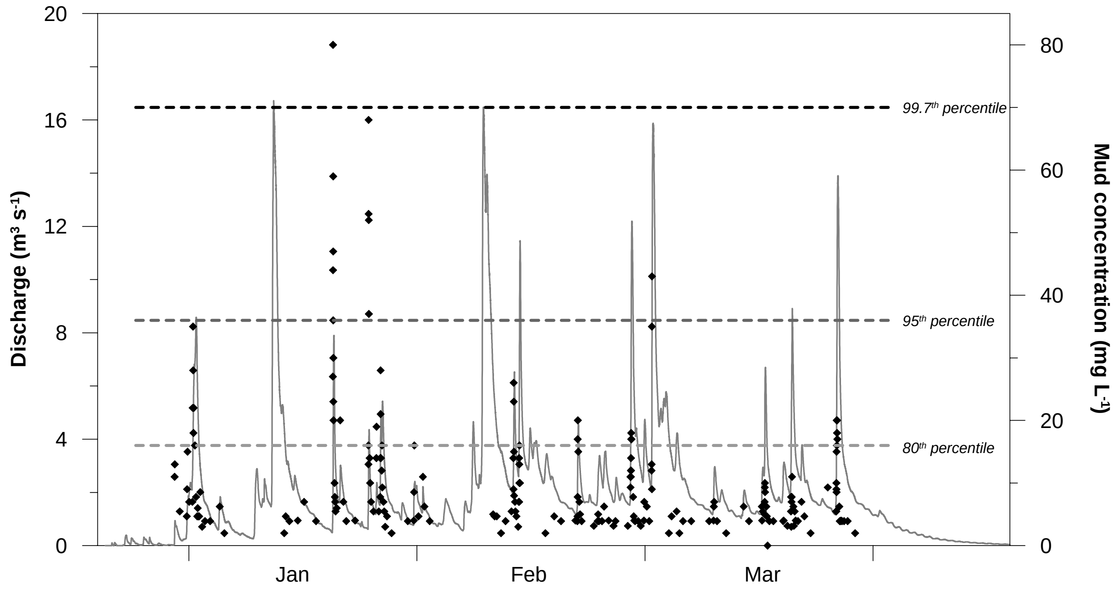

Figure 5.1 Mud concentration data at SC collected during 2003–04 from the automatic pump sampler (◆). Streamflow and trigger levels (relative to mud concentration) derived in Evans et al (2004) are also shown.

The mud concentration data, determined from the filtration of water samples collected by the pump sampler at SC during 2003–04, were plotted against the derived upstream trigger levels (fig 5.1). Figure 5.1 shows that high event-related mud *C* were observed at SC during two events – 20 January and 24 January 2004. High mud *C* was not observed during these two events at UM and ET (Appendix A) which, in this case, does not necessarily suggest that the source of the elevated mud *C* at SC is from the mine-site catchment for the following reasons:

- An internal failure in the datataker at UM occurred during January 2004 (see Section 2.2) and, as a result, mud *C* data were not collected during the event on 20 January (ie both the stage-activated pump sampler and the *in situ* turbidimeter were not operating during this storm event (Appendix A and fig 5.2 respectively)). Without mud *C* data for UM during this event, it cannot be said with any degree of certainty that the source of the elevated mud *C* at SC is from the mine-site catchment.
- No mud *C* data were collected at UM during the event on 24 January 2004. This runoff event at UM was only minor (fig 5.2) and as a result, the stream did not rise enough to collect any water samples by the stage-activated pump sampler. Furthermore, *in situ* turbidity data were not collected throughout this event at UM as the water level during this event was below the head of the turbidity probe (fig 5.2). However, mud *C* data collected at ET (by the *in situ* turbidimeter) show elevated mud *C* at ET (fig 5.2) indicating that this tributary is the likely source of elevated mud *C* at SC. This mud pulse at ET was not 'captured' by water samples collected by the automatic sampler (Appendix A).

This analysis highlights the importance of continuous mud *C* data collected by the *in situ* turbidimeters at each site for impact assessment. For various reasons, as discussed above, water samples are sometimes not collected at each site for the same storm event. If elevated mud *C* is observed at SC, missing data at the two upstream sites can make it impossible to identify the source of the elevated mud *C* downstream. In general, the *in situ* turbidimeters will collect mud *C* data for most runoff events.

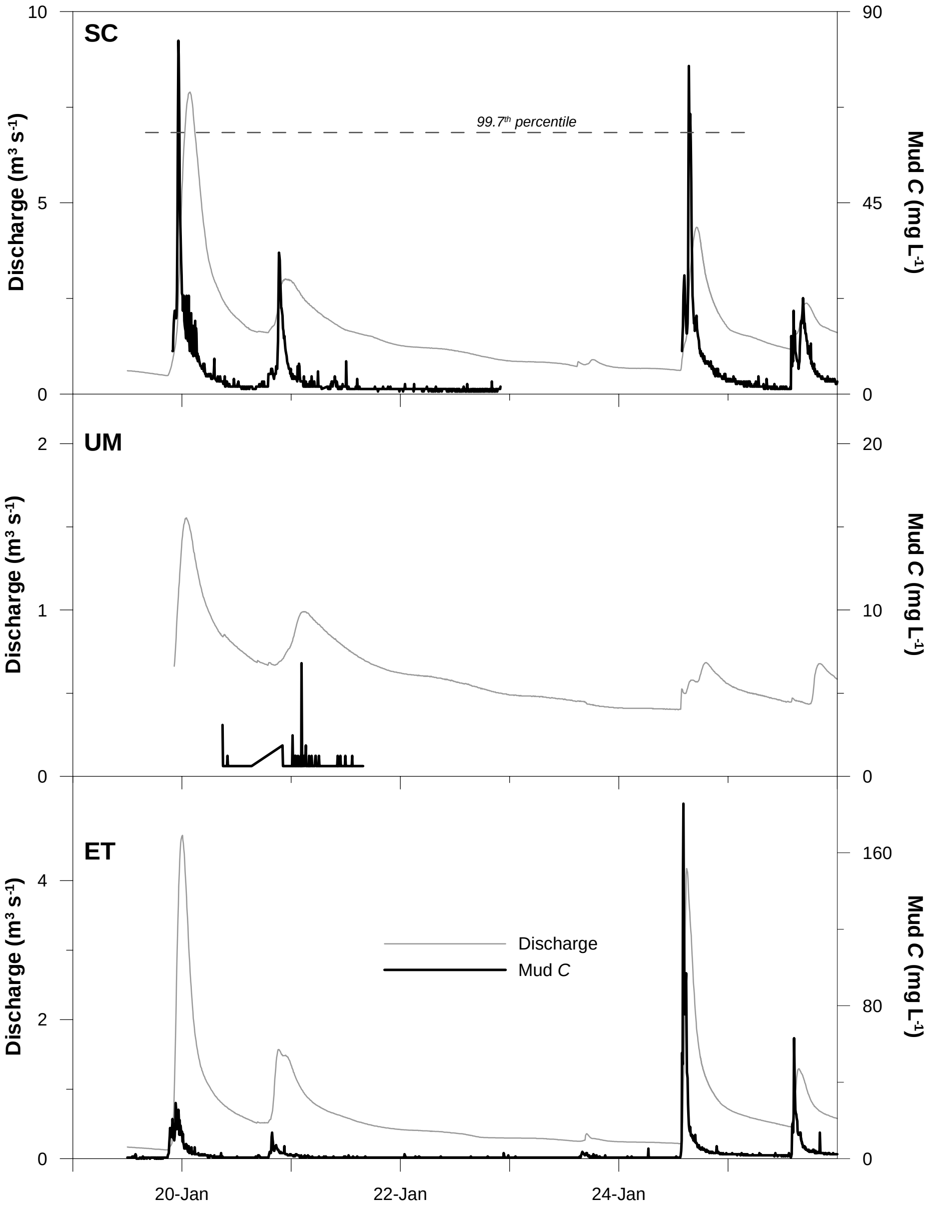

Figure 5.2 Extract of mud *C* data collected from the turbidimeters during late January 2004. Streamflow and the third trigger level for SC are also shown.

5.2 BACIP

This assessment uses a BACIP design (Stewart-Oaten et al 1986, 1992, Humphrey et al 1995) where UM and SC (and ET and SC) are treated as paired sites and the comparison of differences is used to assess impact. Using four years of mud concentration data (1998–2002), Evans et al (2004) determined the mean difference, and associated trigger levels, in monthly median mud concentration (μ) values between SC and UM (and between SC and ET). The difference in μ at SC and UM (and SC and ET) during the 2003–04 wet season were plotted against these trigger levels for impact assessment (fig 5.3).

Figure 5.3 shows that the mean difference in μ between SC and UM and SC and ET during 2003–04 is not significantly different to that of previous years. That is, the mean difference during 2003–04 is not above the 1st trigger level associated with previous years' data. However, the difference in μ between SC and UM during 2003–04 is above that of previous years in all months.

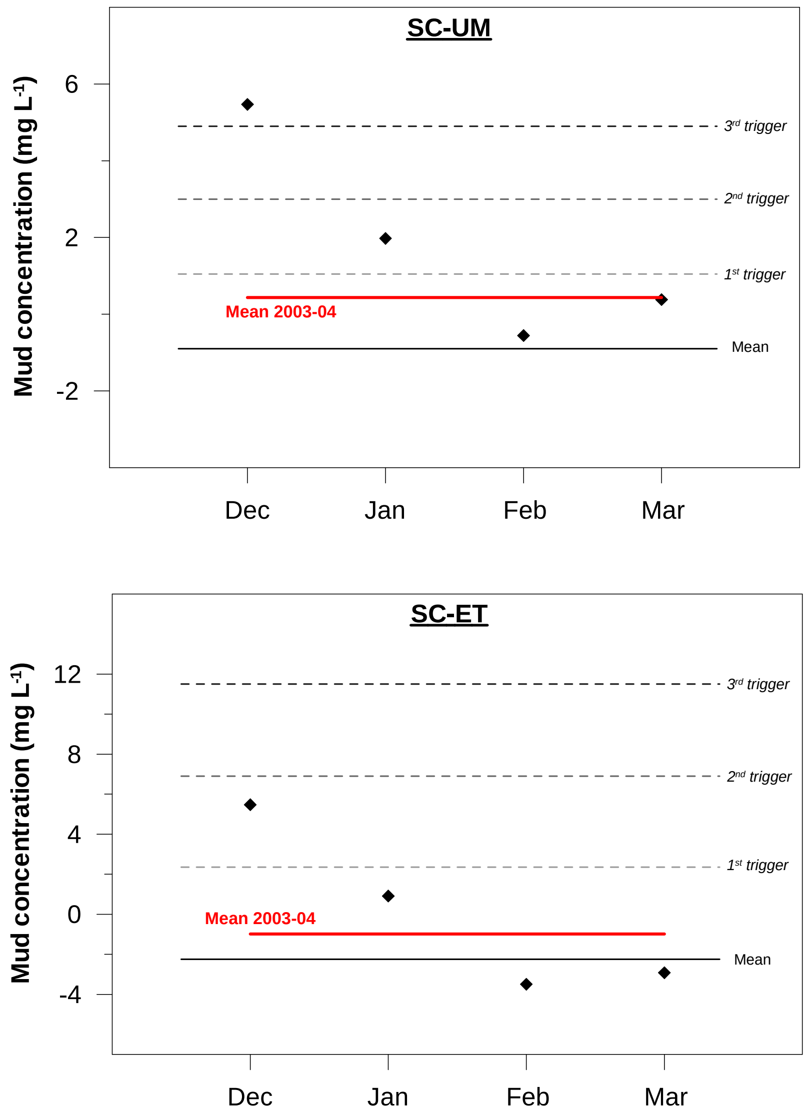

Figure 5.3 Temporal variation of the difference in monthly median mud concentration at SC and UM (Top) and SC and ET (Bottom) during 2003–04 (indicated as◆). The mean difference and associated trigger levels, derived from previous years (Evans et al 2004), are also shown.

During December 2003 the difference in μ between SC and UM is above the 3rd trigger level associated with previous years' data (fig 5.3). However, this could be attributed to the small dataset – only 6 water samples were collected during December at the two sites. The difference in μ between SC and UM during January 2004 lies above the first trigger level (fig 5.3). As discussed above (Section 4.2), it is considered that mud concentration at SC was elevated during the first two runoff events in January 2004 as a result of a fire which occurred within the Ngarradj catchment during November 2003 prior to the commencement of flow. This fire had only a minor impact on the catchment areas upstream of UM and ET, but a relatively large impact on the southern part of the SC catchment area (fig 4.5).

The difference in μ between SC and UM during February and March 2004 is elevated above that of previous years, although not above the 1st trigger level (fig 5.3). The direct comparison of μ between SC and UM indicates that, similar to the event-based model (Section 4), an increase in mud concentration was observed at SC during 2003–04 compared to previous years, that was not observed upstream at UM. Therefore, the elevated mud concentration at

SC during 2003–04, particularly during February and March 2004, could indicate that an impact on mud concentration has occurred at SC as a result of mine disturbance.

However, the difference in μ between SC and ET during February and March 2004 suggests that this may not necessarily be the case. Figure 5.3 shows that the difference in μ between SC and ET during February and March 2004 is below the mean difference for previous years. A possible explanation is that during these months, storm events occurred over the catchment area upstream of ET that were of intensities greater than that over the catchment area upstream of UM. As a result, mud concentrations at ET during these storm events may have been high relative to mud concentrations observed at UM for the same events. The relatively high mud concentrations at ET during these storm events may have contributed to the elevated mud concentrations observed at SC compared to UM during February and March 2004. A second possible explanation is that there has been a natural disturbance within the catchment area upstream of ET which has contributed to the elevated mud concentrations observed at ET, and in turn at SC, compared to that observed at UM. In other words, multiple-BACIP analysis indicates that it is not conclusive that the elevated mud concentrations observed at SC, compared to UM, during 2003–04 is a result of mine disturbance in the Ngarradj catchment.

6 Sand and solute concentration data

As discussed above, stream suspended sediment concentration within the Ngarradj catchment is determined by automatically collecting water samples using a stage-activated pump sampler throughout the annual hydrograph (Erskine et al 2001, Evans et al 2004). The suspended sediment samples collected by the pump samplers were downloaded fortnightly during the 2003–04 wet season. Sand (> 63 μm), mud (silt and clay) (< 63 μm & > 0.45 μm) and solute (< 0.45 μm) concentrations in each suspended sediment sample were determined by sieving, filtering and oven drying techniques (Erskine et al 2001).

Sand concentration was determined for every water sample. However, solute concentration was determined for approximately one in four water samples. Solute concentration data collected between 2000 and 2002 (no solute concentration data were collected during the 1998–99 and 1999–2000 wet seasons), 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 (Moliere et al 2003). This is typical of streams in the region (Duggan 1991). It was decided that analysing one in four samples would require much less laboratory time for no loss in the quality of data.

6.1 Impact assessment

Sand or solute transport models which, similar to the mud transport model derived in Section 4, can be used to assess mining-related impacts on sand or solute concentration within the Ngarradj catchment have not been established. Therefore, for impact assessment the sand and solute concentration data collected during 2003–04 were compared to the sand and solute concentration trigger values derived by Evans et al (2004). As described in Section 5 for the impact assessment on mud concentration, Evans et al (2004) used two methods to derive the trigger values – (1) the comparison of the downstream SC site with limits at the upstream UM site, and (2) a Before-After-Control-Impact, paired difference design (BACIP) where the downstream site SC is after impact and the upstream sites UM and ET are before impact in a spatial sense.

6.1.1 Upstream limits

The percentage of SC water samples collected during 2003–04 that had sand and solute concentration values above the trigger values are given in table 6.1. The sand and solute concentration data are plotted against the derived upstream trigger levels in figures 6.1 and 6.2 respectively.

Table 6.1 Percentage of SC water samples collected during 2003–04 with sand and solute concentration values exceeding trigger values

	Sand		Solute	
Trigger percentile	**Concentration value (mg L^{-1}) (Evans et al 2004)**	**No. of samples at SC above trigger value [% of total samples]**	**Concentration value (mg L^{-1}) (Evans et al 2004)**	**No. of samples at SC above trigger value [% of total samples]**
80	78	111 [50.5]	28	60 [60]
95	151	27 [12.3]	41	6 [6]
99.7	325	2 [0.91]	71	1 [1]

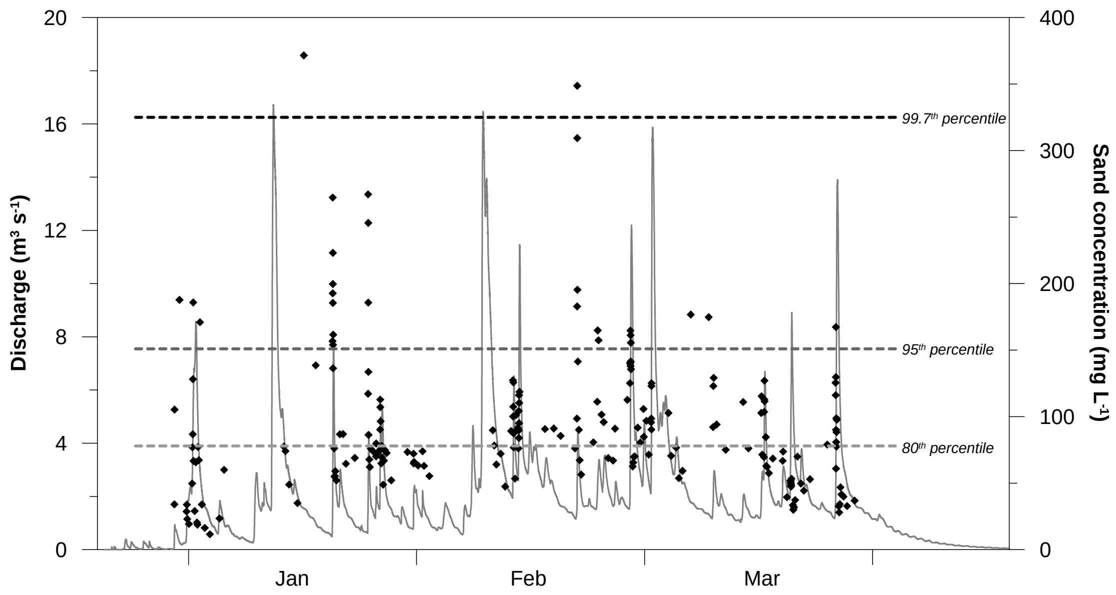

Figure 6.1 Sand concentration data collected during 2003–04 from the automatic pump sampler (◆). Streamflow and trigger levels (relative to sand concentration) derived in Evans et al (2004) are also shown.

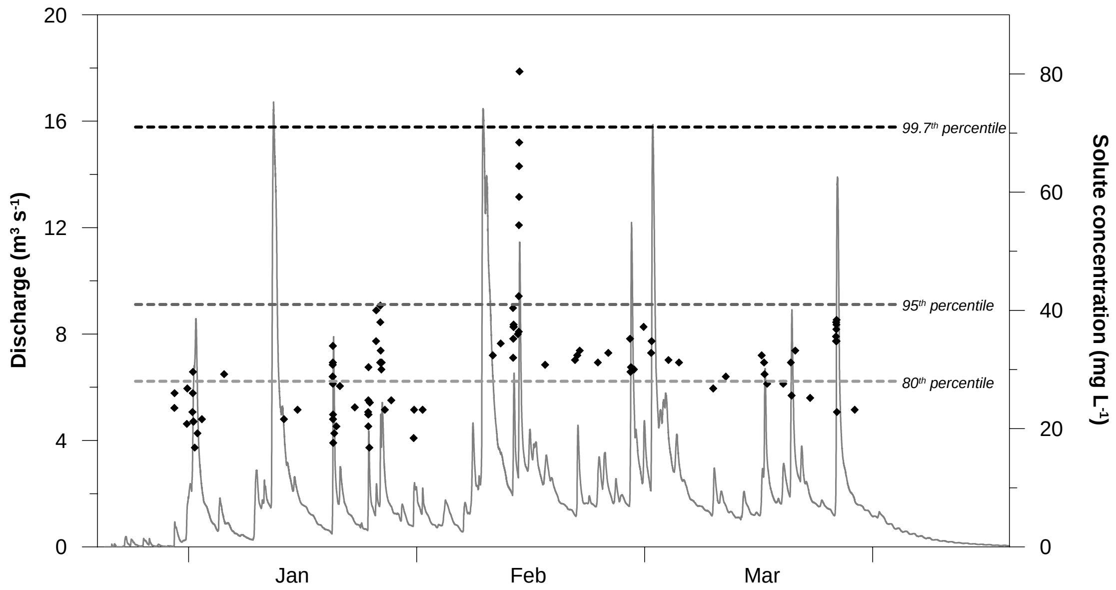

Figure 6.2 Solute concentration data collected during 2003–04 from the automatic pump sampler (◆). Streamflow and trigger levels (relative to solute concentration) derived in Evans et al (2004) are also shown.

6.1.2 BACIP

Evans et al (2004) determined the mean difference, and associated trigger levels, in monthly median sand and solute concentration (μ_{sand} and μ_{sol} respectively) values between SC and UM (and between SC and ET). The difference in μ_{sand} and μ_{sol} at SC and UM (and SC and ET) during the 2003–04 wet season were plotted against these trigger levels for impact assessment (figs 6.3 and 6.4 respectively).

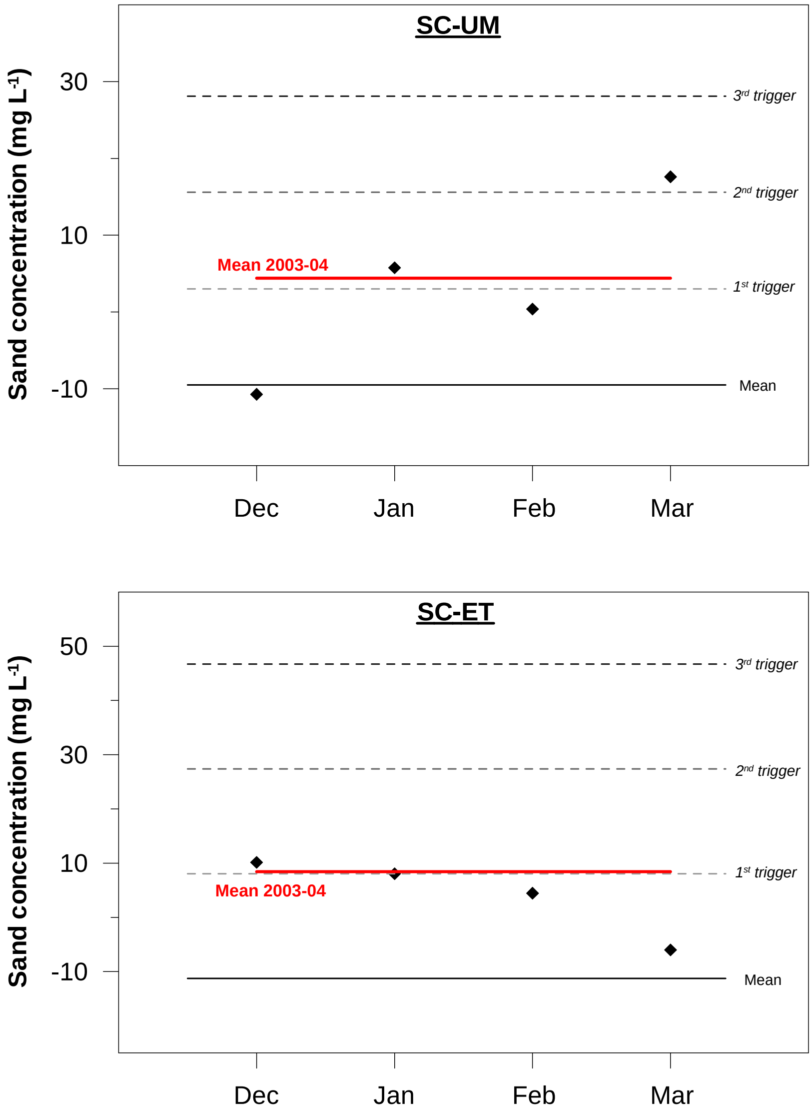

Figure 6.3 Temporal variation of the difference in monthly median sand concentration at SC and UM (Top) and SC and ET (Bottom) during 2003–04 (indicated as◆). The mean difference and associated trigger levels, derived from previous years (Evans et al 2004), are also shown.

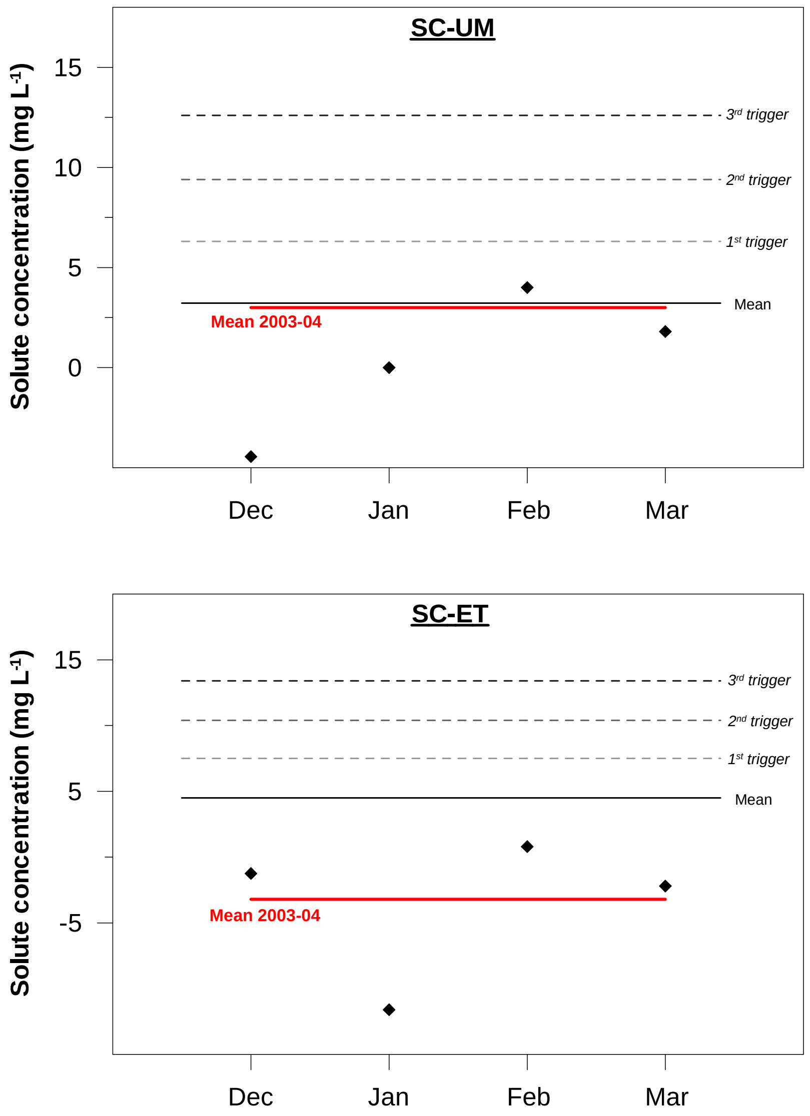

Figure 6.4 Temporal variation of the difference in monthly median solute concentration at SC and UM (Top) and SC and ET (Bottom) during 2003–04 (indicated as◆). The mean difference and associated trigger levels, derived from previous years (Evans et al 2004), are also shown.

6.2 Discussion

More than 50% of the sand concentration data collected during the 2003–04 wet season at SC is above the 80th percentile trigger level (table 6.1 and fig 6.1). The mean difference in μ_{sand} between SC and UM and SC and ET during 2003–04 is significantly different to that of previous years. That is, the mean difference during 2003–04 is above the focus level associated with previous years' data. Therefore, this analyis indicates that sand concentration at SC is elevated compared to previous years, and that this increase has not been observed at upstream sites UM and ET. It is considered unlikely that such a significant increase in sand concentration at SC is a result of a mining-related impact (ie earthworks at Jabiluka during the 2003 dry season). It is more likely that aggradation has occurred in the stream bed at SC during the previous few years of monitoring at a much faster rate relative to that at UM and ET (Evans et al 2004). Aggradation of the bed at SC means that the bed is closer to the inlet pipe of the automatic pump sampler, which would result in an increase in sand entering the inlet compared to previous years. For a reliable impact assessment, Evans et al (2004) recommended that the location of the inlet to the sampler needs to be reassessed on an annual basis dependent on aggradation rate.

More than 60% of solute concentration data collected during the 2003–04 wet season is above the 80^{th} percentile trigger level (table 6.1 and fig 6.2) which suggests that solute concentration is also elevated compared to previous years. However, the mean difference in μ_{sol} between SC and UM and SC and ET during 2003–04 is not significantly different to that of previous years. Therefore, this analyis indicates that there has been an increase in solute concentration at SC compared to previous years, but this increase has also been observed at UM and ET. In other words, there is no evidence to suggest that there has been a mining-related impact on solute concentration during the 2003–04 wet season.

7 Conclusions and further work

Turbidimeters were installed at all three gauging stations within the Ngarradj catchment during the 2003–04 wet season. This study has shown that there is a significant relationship between *in situ* turbidity and mud concentration in streams within the catchment. The use of turbidimeters has important implications for the future monitoring of mud concentration and mud loads within the catchment for the following reasons:

- it is associated with a significant reduction in labour intensive suspended sediment sample collection and sample processing;
- it is considered essential for estimating individual event loads within the catchment, particularly in small streams that exhibit a rapid flushing of mud and during relatively minor and/or multi-peaked runoff events; and
- the continuous turbidity record can observe mud pulses that are not strongly related to flow, which could be particularly important in terms of monitoring possible mining-related impacts within the catchment.

Water samples will still need to be collected by the automatic pump samplers to validate the derived relationships. For the 2004–05 wet season, it is recommended that (1) only one gamet sampler is operated at each site, and (2) the sampler should be set to collect water samples only during the rising stage of the event hydrograph.

Mud concentration data collected during 2003–04 were compared to previous years' data for impact assessment. Both the event-based mud model (Section 4) and the before-after-control-impact paired site design (BACIP) (Section 5) techniques were sensitive enough to indicate a general increase in mud concentration downstream of the mine relative to that measured upstream during the 2003–04 wet season. It is likely that the general increase in mud concentration at SC, although not above associated trigger levels, is a result of erosion on the mine site. It will be important to monitor mud concentration and event mud loads during the 2004–05 wet season to observe if mud concentration at SC return to baseline, unimpacted levels. It is recommended that a combination of both the event-based mud model and BACIP techniques should be used for future impact assessment.

Finally, it is recommended that sand and solute concentrations need not be monitored within the Ngarradj catchment during 2004–05, given that (1) there was no evidence to suggest that there has been a mining-related impact on sand or solute concentration during the 2003–04 wet season; and (2) there is an increased focus on monitoring stream mud concentration within the Ngarradj catchment.

8 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.

Bonta JV 2000. Impact of coal surface mining and reclamation on suspended sediment in three Ohio watersheds, *Journal of the American Water Resources Association* 36(4), 869–887.

Duggan K 1991. Mining and erosion in the Alligator Rivers Region of Northern Australia. Open file record 81, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.

Eads RE & Lewis J 2002. Continuous turbidity monitoring in streams of northwestern California. In: *Turbidity and Other Sediment Surrogates Workshop* (Proceedings. Reno, Nevada, USA, April/May 2002). US Geological Survey Circular 1250. (http://water.usgs.gov/osw/techniques/TSS/eads.pdf)

Erskine WD, Saynor MJ, Evans KG & Boggs GS 2001. *Geomorphic research to determine the off-site impacts of the Jabiluka Mine on Swift (Ngarradj) Creek, Northern Territory*. Supervising Scientist Report 158, Supervising Scientist, Darwin.

Evans KG, Moliere DR, Saynor MJ, Erskine WD & Bellio MG 2003. Assessing impacts of impact disturbance on mud transport in a seasonal stream. In *Environment, ethics, economics and engineering in our sustainable future,* Proceedings. Brisbane symposium, June 2003, 38, 231–247.

Evans KG, Moliere DR, Saynor MJ, Erskine WD & Bellio MG 2004. *Baseline suspended sediment solute, pH, EC and turbidity characteristics for the Ngarradj catchment, Northern Territory*. Supervising Scientist Report 179, Supervising Scientist, Darwin.

Evans KG, Saynor MJ, Willgoose GR & Riley SJ 2000. Post-mining landform evolution modelling: 1. Derivation of sediment transport model and rainfall-runoff parameters. *Earth Surface Process Landforms* 25, 743–763.

Glysson GD & Gray JR 2002. Turbidity and Other Sediment Surrogates Workshop, Proceedings, Reno, Nevada, USA, April/May 2002, US Geological Survey Circular 1250. (http://water.usgs.gov/osw/techniques/turbidity.html)

Humphrey CL, Faith DP & Dostine PL 1995. Baseline requirements for assessment of mining impact using biological monitoring. *Australian Journal of Ecology* 20, 150–166.

Lewis J 2002. Turbidity-controlled sampling for suspended sediment load estimation. In: *Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances*, Proceedings. Oslo Workshop, June 2002, IAHS Publ. 283, 13–20.

Lewis J 1996. Turbidity-controlled suspended sediment sampling for runoff-event load estimation. *Water Resources Research* 32(7), 2299–2310

Moliere DR, Boggs GS, Evans KG, Saynor MJ & Erskine WD 2002. *Baseline hydrology characteristics of the Ngarradj catchment, Northern Territory*. Supervising Scientist Report 172, Supervising Scientist, Darwin NT.

Moliere DR, Evans KG & Saynor MJ 2003. Hydrology of the Ngarradj catchment, Northern Territory: 2002/2003 Wet season monitoring. Internal Report 448, August, Supervising Scientist, Darwin. Unpublished paper.

Moliere DR, Evans KG, Saynor MJ & Boggs GS 2001. Hydrology of the Ngarradj catchment, Northern Territory – 1998–1999 and 1999–2000 Wet season monitoring: Interim Report. Internal Report 366, Supervising Scientist, Darwin. Unpublished paper.

Moliere DR, Evans KG, Saynor MJ & Erskine WD 2004. Estimation of suspended sediment loads in a seasonal stream in the wet-dry tropics, Northern Territory, Australia. *Hydrological Processes* 18, 531–544.

Rieger WA & Olive LJ 1988. Channel sediment loads: comparisons and estimation. In: *Fluvial geomorphology of Australia*, Warner RF (ed), Academic Press, Sydney, 69–85.

Riley SJ 1998. The sediment concentration-turbidity relation: its value in monitoring at Ranger Uranium Mine, Northern Territory, Australia. *Catena* 32, 1–14.

Saynor MJ, Dawson JC, Smith BL, Crisp E & Moliere DR 2001. Installation, maintenance and running of gauging stations in the Swift (Ngarradj) Creek catchment, Northern Territory. Internal Report 384, Supervising Scientist, Darwin. Unpublished paper.

Schoellhamer DH & Wright SA 2003. Continuous monitoring of suspended sediment in rivers by use of optical backscatter sensors. In *Erosion and sediment transport measurement: Technological and methodological advances*, Proceedings Oslo Symposium, June 2002, IAHS Publ. 283, 28–36.

Stewart-Oaten A, Murdoch WW & Parker KR 1986. Environmental impact assessment: 'Pseusoreplication' in time? *Ecology* 67, 929–940.

Stewart-Oaten A, Bence, JR & Osenberg CW 1992. Assessing effects of unreplicated perturbations: No simple solutions. *Ecology* 73, 1396–1404.

Thiessen AH 1911. Precipitation averages for large areas. *Monthly Weather Review* 39, 1082–1084.

Townsend SA & Douglas MM 2000. Effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savanna (northern Australia). *Journal of Hydrology* 229, 118–137.

Walling DE & Webb 1982. Sediment availability and the prediction of storm-period sediment yields. In *Recent developments in the explanation and prediction of erosion and sediment yield*, Proceedings, Exeter Symposium, July 1982, IAHS Publ. 137, 327–337.

Walling DE & Webb BW 1985. Estimating the discharge of contaminants to coastal waters by rivers: some cautionary comments. *Marine Pollution Bulletin* 16(12), 488–492.

Walling DE, Webb BW & Woodward JC 1992. Some sampling considerations in the design of effective strategies for monitoring sediment-associated transport. In *Erosion and sediment transport monitoring programmes in river basins*, Proceedings, Oslo Symposium., August 1992, IAHS Publ. 210, 279–288.

Walling DE & Owens PN 2002. The role of floodplain sedimentation in catchment sediment and contaminant budgets. In *The structure, function and management implications of fluvial sedimentary systems*, Proceedings, Alice Springs symposium, Australia, September 2002, IAHS Publ. 276, 407–416.

Appendix A – Daily rainfall, hydrographs and sedigraphs

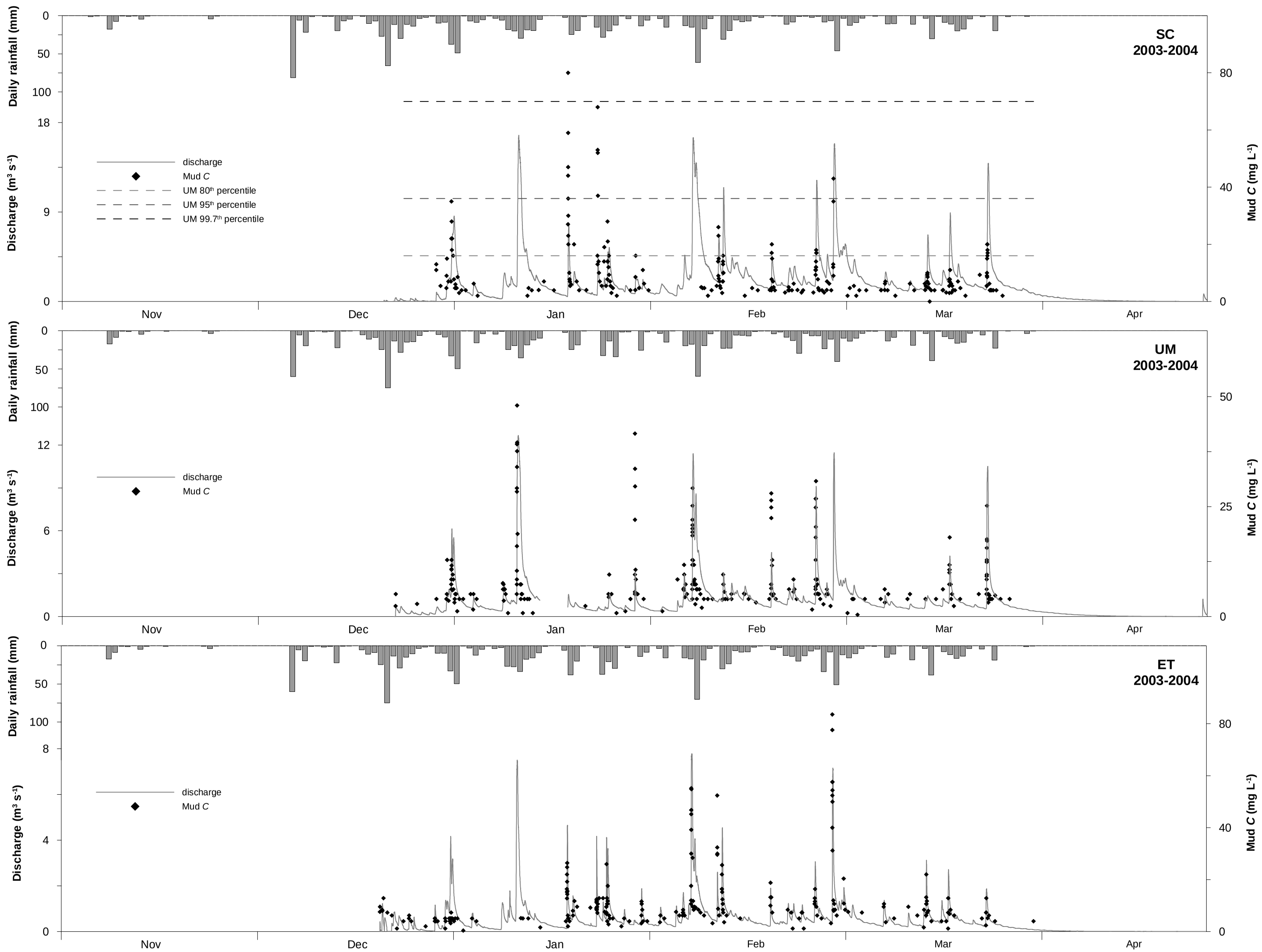

Figure A.1 Daily rainfall, hydrograph and mud concentration (mud *C*) during 2003–04

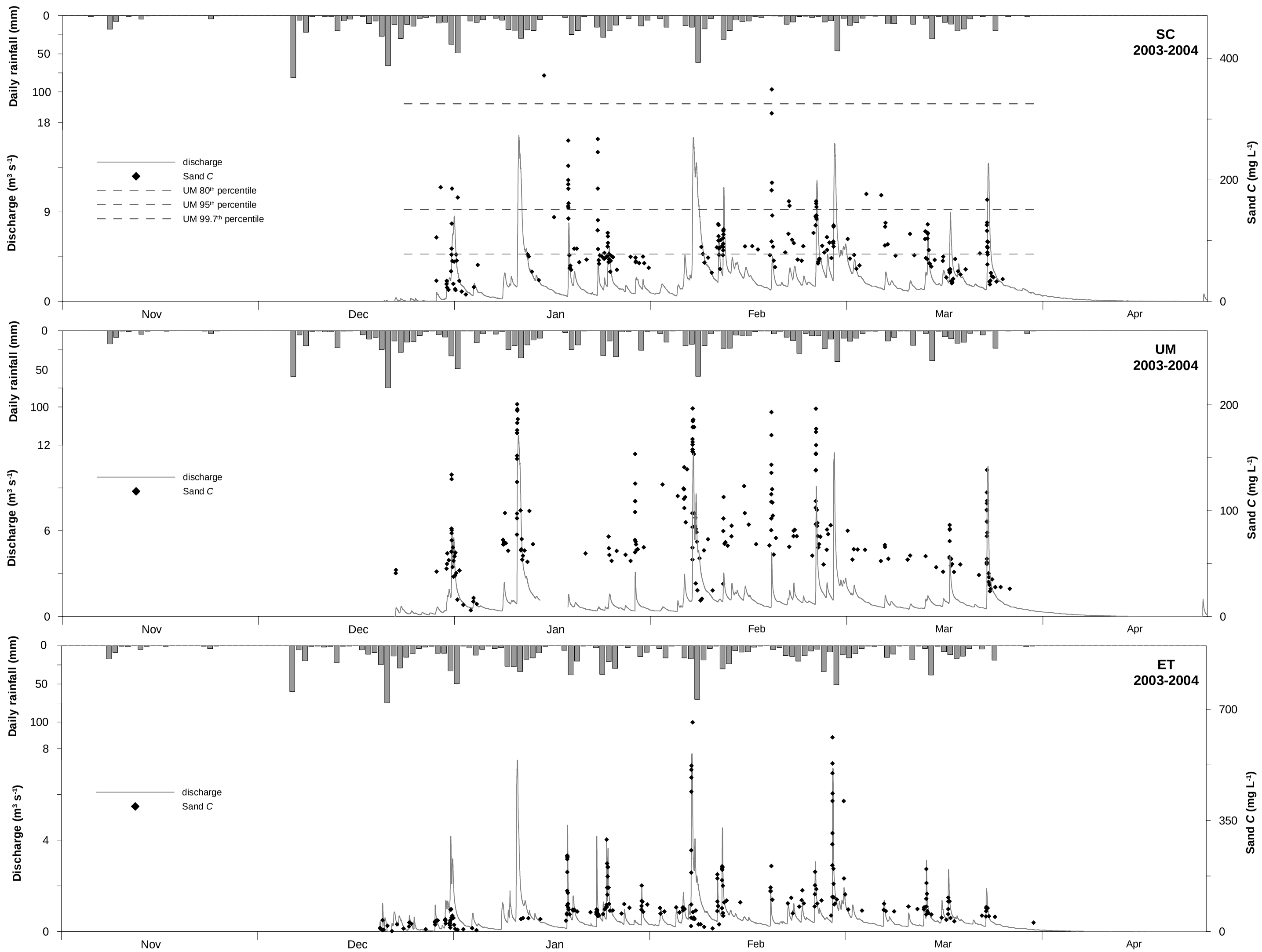

Figure A.2 Daily rainfall, hydrograph and sand concentration (sand *C*) during 2003–04

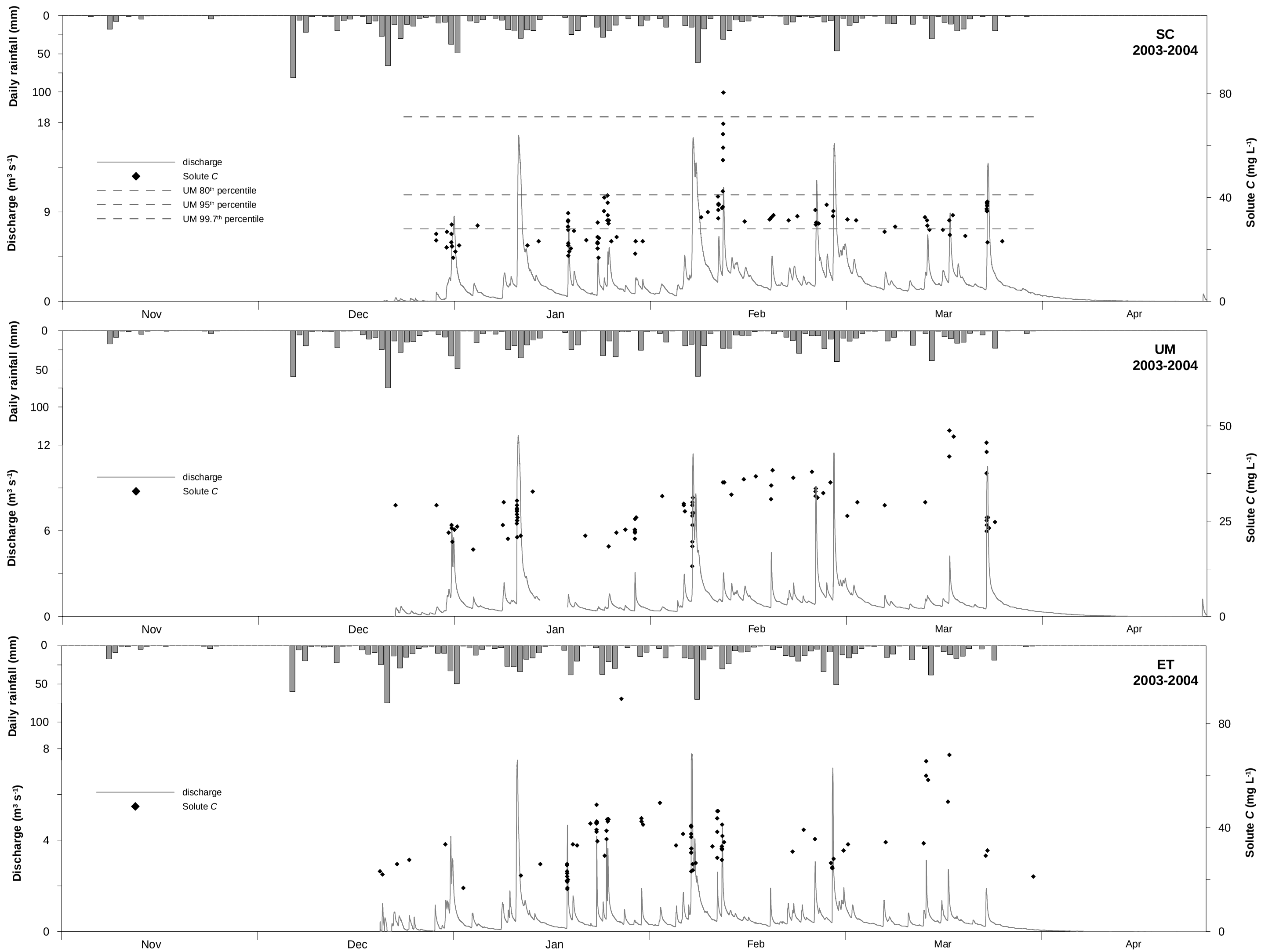

Figure A.3 Daily rainfall, hydrograph and solute concentration (solute *C*) during 2003–04

Appendix B – Mud pulse characteristics

Table B.1 Rainfall, discharge and mud characteristics for each mud pulse event observed at SC during 2003–04

Date	Rain		Discharge		Mud pulse				
	Total rainfall (mm)	Start of rainfall	Peak discharge (m^3)	Time of Q_p	Peak mud C (mg L^{-1})	Time of mud C_p	Duration	Mud load – Turbidimeter (g)	Mud load - water samples (g)
01 Jan	47	09:54	6.83	17:12	39.2	12:42	01-Jan 09:54 – 02-Jan 04:00	3531	4577
11 Jan	42	19:36	16.67	03:48	26.1	23:36	11-Jan 21:24 – 12-Jan 16:24	7359	-
19 Jan	24	20:54	7.99	01:42	83.2	23:12	19-Jan 21:00 – 20-Jan 05:30	2265	2379
20 Jan	19	18:54	3.04	22:42	33.3	21:18	20-Jan 18:54 – 21-Jan 01:18	559	-
24 Jan	66	13:30	4.38	17:00	77.2	15:24	24-Jan 13:36 – 24-Jan 21:12	1384	2089
25 Jan	20	13:48	2.42	17:00	22.6	16:30	25-Jan 13:48 – 25-Jan 21:24	502	-
26 Jan	12	02:48	5.02	06:30	23.8	05:06	26-Jan 03:00 – 26-Jan 15:30	1652	1810
30 Jan	-	-	2.45	17:24	28.5	15:06	30-Jan 12:54 – 31-Jan 05:18	697	1052
08 Feb	48	11:12	16.51	17:48	32.1	16:00	08-Feb 11:24 – 08-Feb 22:12	4619	-
12 Feb	31	15:12	6.58	19:30	29.1	17:18	12-Feb 15:18 – 12-Feb 23:24	1244	1194
13 Feb	19	08:48	11.56	13:18	21.4	10:54	13-Feb 09:06 – 13-Feb 19:12	2128	-
20 Feb	1	23:54	4.63	05:24	25.5	04:00	20-Feb 23:06 – 21-Feb 08:42	826	1089
28 Feb	8	00:48	12.28	06:42	19.0	04:36	28-Feb 00:00 – 28-Feb 10:18	2397	3366
01 Mar	47	20:00	15.88	01:30	44.0	22:00	01-Mar 20:00 – 02-Mar 05:42	4380	-
20 Mar	20	02:48	9.03	09:06	11.9	05:06	20-Mar 02:54 – 20-Mar 16:48	1960	1357
26 Mar	20	03:24	14.01	08:48	27.3	05:42	26-Mar 02:24 – 26-Mar 14:00	4651	4048

Table B.2 Rainfall, discharge and mud characteristics for each mud pulse event observed at UM during 2003–04

Date	**Rain**		**Discharge**		**Mud pulse**				
	Total rainfall (mm)	Start of rainfall	Peak discharge (m^3)	Time of Q_p	Peak mud C (mg L^{-1})	Time of mud C_p	Duration	Mud load – Turbidimeter (g)	Mud load - water samples (g)
01 Jan	44	09:48	6.08	14:18	27.8	14:12	01-Jan 11:00 – 02-Jan 03:18	1657	1256
11 Jan	49	19:24	12.38	02:18	41.4	21:42	11-Jan 20:30 – 12-Jan 15:30	6877	7852
30 Jan	-	-	3.11	13:54	49.4	13:18	30-Jan 12:24 – 30-Jan 18:12	573	616
08 Feb	49	11:24	11.32	17:54	36.5	15:42	08-Feb 12:36 – 08-Feb 22:48	3218	3157
13 Feb	22	08:54	3.09	13:12	10.5	12:36	13-Feb 09:06 – 13-Feb 20:42	379	310
20 Feb	5	23:00	4.51	02:54	32.8	02:00	21-Feb 00:48 – 21-Feb 09:36	936	1129
27 Feb	21	23:48	9.10	04:18	35.8	03:24	28-Feb 01:30 – 28-Feb 10:54	2189	2528
01 Mar	43	20:00	11.43	00:12	34.6	22:12	01-Mar 20:06 – 02-Mar 08:18	3503	-
20 Mar	16	02:54	4.27	07:30	21.0	06:00	20-Mar 04:06 – 20-Mar 18:42	949	793
26 Mar	11	03:24	10.47	07:00	34.6	04:18	26-Mar 02:12 – 26-Mar 13:42	3325	2300

Table B.3 Rainfall, discharge and mud characteristics for each mud pulse event observed at ET during 2003–04

Date	Rain		Discharge		Mud pulse				
	Total rainfall (mm)	Start of rainfall	Peak discharge (m^3)	Time of Q_p	Peak mud C (mg L^{-1})	Time of mud C_p	Duration	Mud load – Turbidimeter (g)	Mud load - water samples (g)
01 Jan	27	09:54	4.09	13:18	61.9	11:36	01-Jan 08:42 – 01-Jan 16:30	797	189
11 Jan	47	19:42	7.29	01:48	22.6	23:24	11-Jan 19:48 – 12-Jan 09:54	1944	-
19 Jan	38	20:30	4.37	00:06	29.2	22:36	19-Jan 20:48 – 20-Jan 05:42	566	567
20 Jan	20	18:54	1.50	21:18	13.7	19:48	20-Jan 19:00 – 21-Jan 01:54	96	-
24 Jan	37	13:30	3.92	14:54	185.6	14:12	24-Jan 13:30 – 24-Jan 19:54	1189	342
25 Jan	21	13:54	1.26	15:42	63.1	14:30	25-Jan 13:48 – 25-Jan 19:06	204	-
26 Jan	17	02:42	3.94	04:42	34.5	04:06	26-Jan 02:42 – 26-Jan 12:30	827	908
08 Feb	58	11:18	7.52	15:30	57.1	13:54	08-Feb 10:42 – 08-Feb 22:42	2744	6186
12 Feb	30	15:18	2.46	17:00	53.0	16:06	12-Feb 15:24 – 12-Feb 22:36	422	676
13 Feb	23	08:54	4.26	11:54	30.9	10:24	13-Feb 09:06 – 13-Feb 17:12	667	806
20 Feb	6	22:54	1.72	02:54	23.2	02:30	21-Feb 00:00 – 21-Feb 08:36	224	385
28 Feb	27	23:48	2.90	04:12	13.7	00:54	27-Feb 23:42 – 28-Feb 10:00	488	638
01 Mar	51	20:00	6.73	23:24	92.8	20:42	01-Mar 20:06 – 02-Mar 04:30	2258	2559
20 Mar	16	03:00	2.48	05:42	15.5	04:36	20-Mar 03:00 – 20-Mar 12:00	325	188
26 Mar	19	03:24	1.70	06:06	13.1	05:24	26-Mar 02:30 – 26-Mar 11:30	260	313