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Hydrology and suspended sediment transport in the Gulungul Creek catchment, Northern Territory: 2006–2007 wet season monitoring

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Contents

Executive summary

Gulungul Creek is a small left bank tributary of Magela Creek. The Gulungul Creek catchment contains part of the Energy Resources of Australia Ranger mine tailings dam and could potentially receive sediment generated as a result of the removal and rehabilitation of the tailings area. Hence it is important that the hydrology and sediment transport characteristics in the Gulungul Creek catchment are investigated before rehabilitation at the mine site occurs to establish pre-rehabilitation reference conditions. Continuous rainfall, runoff and mud (<63 μm and >0.45 μm fraction) concentration data collected at gauging stations on Gulungul Creek during 2006–07 are presented in this report.

Total annual rainfall and runoff observed during 2006–07 were the highest recorded within the Gulungul Creek catchment since recordings began in 1971. This is largely attributed to a 3-day period of exceptionally high rainfall which occurred between 27 February and 2 March 2007 resulting in the highest flood levels that have been recorded within the catchment.

An assessment was also made of the impact of Cyclone Monica, which occurred on 25 April 2006, on stream suspended sediment concentration within Gulungul Creek during 2006–07. A combination of an event-based Before-After-Control-Impact, paired difference design (BACIP) approach and a relationship between event mud load and corresponding event runoff characteristics showed that the sediment transport characteristics within the catchment were not significantly different to previous years.

Acknowledgments

Grant Staben assisted in the field with several of the velocity-area gaugings and the reinstrumentation of the stations after the March 2007 flood. Richard Houghton assisted in the field with several of the velocity-area gaugings. Elice Crisp conducted suspended sediment analysis in the laboratory and assisted in the field. Bryan Smith assisted with gauging station maintenance prior to the commencement of the wet season and assisted in the laboratory with suspended sediment analysis. Jeff Klein, Klein Electronics Pty Ltd, helped with the maintenance and repairs of some the gauging station equipment. Peter McFadyen, Energy Resources of Australia, supplied rainfall data from the rain gauge at the Tailings Dam. Dr David Jones, Director ***eriss***, constructively and comprehensively reviewed the draft report. Finally, Wendy Murray and the entire Jabiru Field Station are thanked for their help in organising food, clothing and accommodation while we were ‘stranded’ for a week in Jabiru during the March 2007 flood.

Hydrology and suspended sediment transport in the Gulungul Creek catchment, Northern Territory: 2006–2007 wet season monitoring

DR Moliere, KG Evans & MJ Saynor

1 Introduction

As part of the data required to assess the success of rehabilitation of the Energy Resources of Australia (ERA) Ranger mine, baseline suspended sediment loads in relevant streams within the catchment of Magela Creek are being quantified. Gulungul Creek is a small left bank tributary of Magela Creek (Fig 1.1) and is one of the tributaries that will be the first to receive sediment generated from the rehabilitated mine site (Erskine & Saynor 2000). Given the location of Gulungul Creek adjacent to the tailings dam and the potential for erosion and transport of sediment into Magela Creek, the hydrology and sediment transport characteristics in Gulungul Creek are being investigated before rehabilitation at the mine site occurs.

Two gauging stations have been installed within the Gulungul Creek catchment, one station upstream (GCUS) and one downstream (GCDS) of the Ranger mine (Fig 1.1). The upstream station was installed in November 2003 and the downstream station was installed in February/March 2005 (Moliere et al 2005a). Suspended sediment is monitored at the stations using field-calibrated turbidimeters. Mud (fine suspended sediment) concentration data, derived from in situ continuous turbidity measured over several years, will be used to assess mine impact through the derivation of trigger values in accordance with The Australian and New Zealand water quality guidelines (WQG) (ANZECC & ARMCANZ 2000) using a BACIP approach.

This report presents hydrology and mud concentration data collected from the stream gauging stations within the Gulungul Creek catchment during the 2006–07 Wet season. In addition, we have assessed changes to catchment conditions, such as sediment transport characteristics, occurring as a result of Cyclone Monica which moved through the region on 25 April 2006.

1.1 Study area

Gulungul Creek lies within the Alligator Rivers Region and is approximately 220 km east of Darwin. Located in the monsoon tropics climatic zone, the Alligator Rivers Region 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 general flow period for Gulungul Creek is approximately six months (December to May) (Moliere 2005). The average annual rainfall for the region is approximately 1540 mm (Bureau of Meteorology pers comm 2006) based on daily rainfall data collected at the Jabiru airport (Fig 1.1) between 1971 and 2006.

The Ranger mine lies partly within the catchment of Gulungul Creek (Fig 1.1). Current infrastructure in the catchment includes part of the tailings dam, part of the Arnhem Highway, mine access roads and minor tracks (Fig 1.1). Part of the final rehabilitated landform will lie within the catchment (Crossing 2002). The total area of the Gulungul Creek catchment upstream of GCDS is approximately 66 km^2.

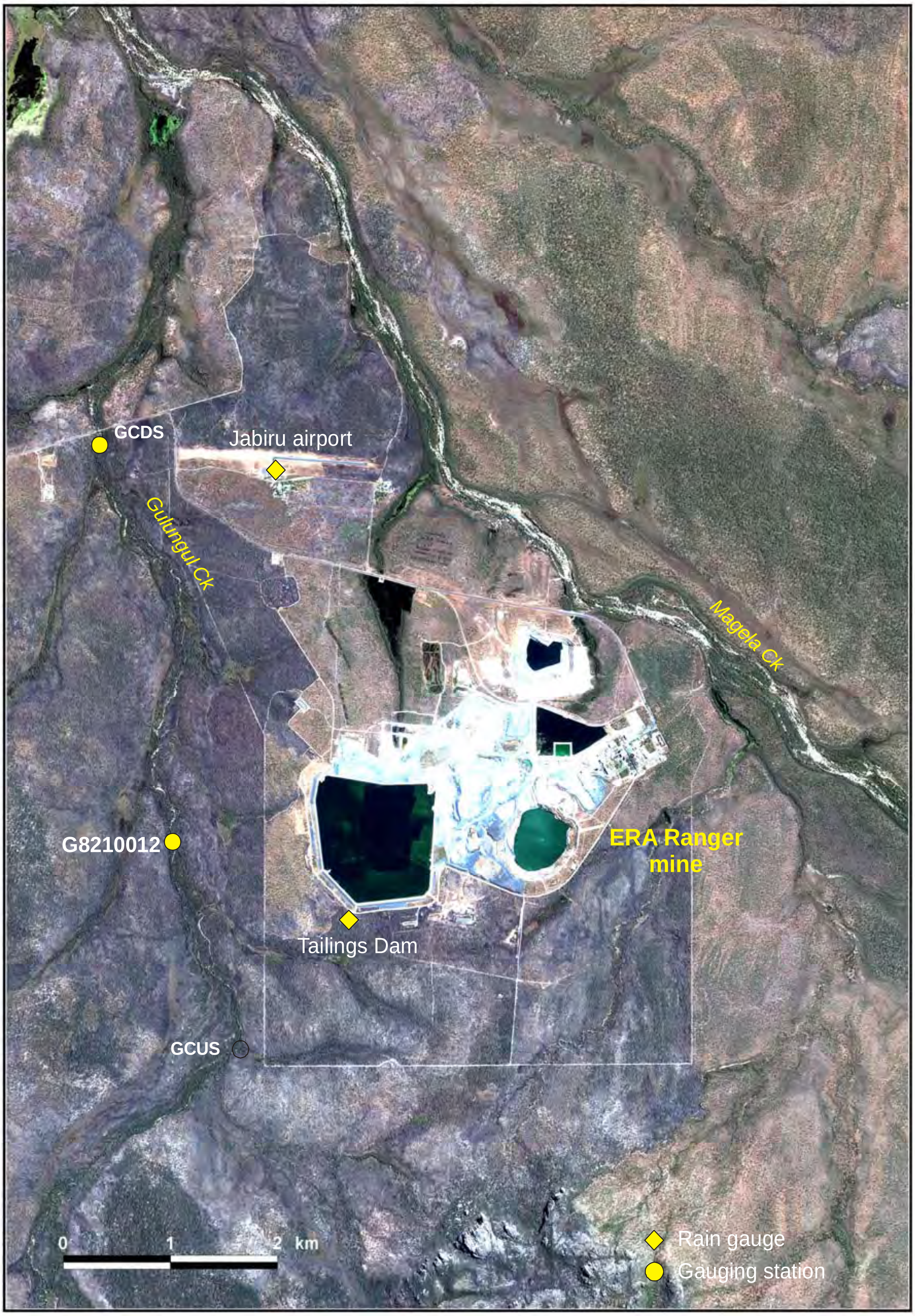


Figure 1.1 Location of Gulungul Creek and the ERA Ranger mine within the Alligator Rivers Region. The gauging stations and rain gauges in the area of interest are also shown. The image is an Ikonos satellite image taken June 2001.

2 Rainfall data

A 0.2 mm tipping bucket rain gauge was installed at each of the three gauging stations along Gulungul Creek (GCUS, GCDS and G8210012) and readings were taken at 6-minute intervals. Daily rainfall and rainfall intensity data were collected at Jabiru Airport (Fig 1.1) by the Bureau of Meteorology, which lies just outside the boundary of the Gulungul Creek catchment (Moliere 2005). Rainfall intensity data were also collected at the Tailings Dam (Fig 1.1) by ERA, which lies within the Gulungul Creek catchment. The total annual rainfall (September to August) at the three gauging stations, the Tailings Dam and Jabiru Airport during 2006-07 are shown in Table 2.1.

Table 2.1 Total annual rainfall over the Gulungul Creek region during 2006–07

Station	Rainfall (mm)
GCUS	2218(1)
G8210012	2204(2)
GCDS	2362(3)
Tailings Dam	2067(1)
Jabiru airport	2528

(1) Data partly infilled using data collected at G8210012 (see Section 2.1)

(2) Data partly infilled using data collected at the Tailings Dam (see Section 2.1)

(3) Data partly infilled using data collected at Jabiru airport (see Section 2.1)

The total annual rainfall at Jabiru airport during 2006–07 of 2528 mm is the highest annual rainfall recorded since rainfall data collection commenced at Jabiru in 1971 (and even more than Darwin Airport’s highest recorded wet season total of 2499 mm (Bureau of Meteorology pers comm 2007)). The previous highest annual rainfall at Jabiru airport was 2222 mm during 1975–76. The annual rainfall at Jabiru airport during 2006–07, compared to the Jabiru airport rainfall distribution (1971–2006), corresponds to a 1:1000 y rainfall year (Fig 2.1). This can be largely attributed to the rainfall which occurred during February and March 2007 (800 mm and 1140 mm respectively), two of the highest monthly rainfall totals ever recorded at Jabiru airport (Fig 2.2) (previous highest monthly rainfall total was 807 mm which occurred in January 1997). Interestingly, Figure 2.2 shows that the January 2007 rainfall at Jabiru airport was the lowest monthly total for January ever recorded.

2.1 Missing rainfall data

Periods where missing data occurred during the 2006–07 wet season at each rain gauge are given in Table 2.2. The reason for a gap, and whether the gap was infilled, is also documented. It should be noted that rainfall data collected at G8210012 were used to infill gaps in the rainfall record at both GCUS and the Tailings Dam as Moliere et al (2005a) showed that rainfall at these stations are statistically similar. An analysis of daily rainfall collected at GCDS and Jabiru airport showed that there is a strong correlation between rainfall collected at the two sites (more significant than the relationship between daily rainfall collected at GCDS and G8210012). Therefore, data collected at Jabiru airport were used to infill gaps in the rainfall record at GCDS.

Table 2.2 shows that the flood event which occurred between approximately 27 February and 3 March 2007 (described in detail in Section 4) effected the collection of rainfall data at all three gauging stations along Gulungul Creek.

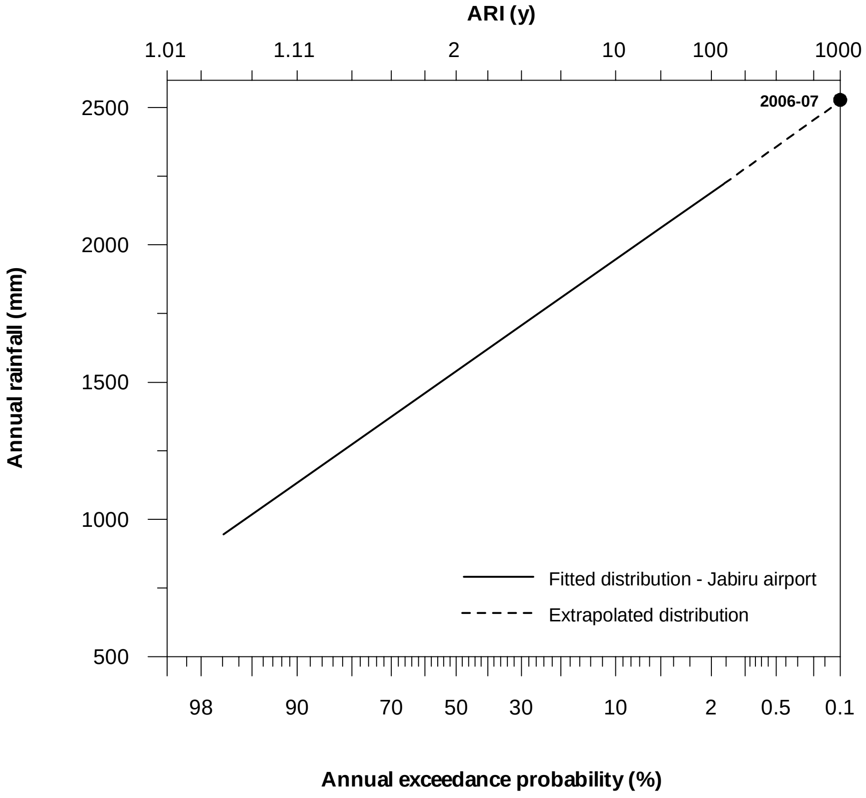


Figure 2.1 Annual rainfall frequency curve for Jabiru airport based on 35 y of record (1971–2006). The 2006–07 rainfall at Jabiru airport is also shown.

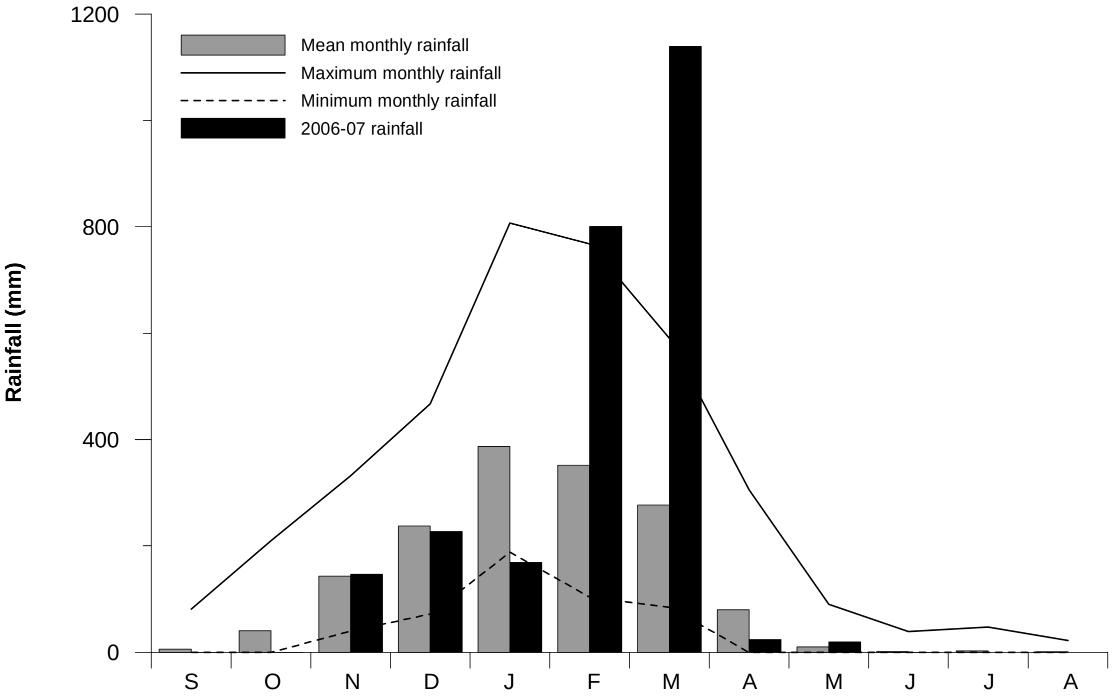


Figure 2.2 Monthly rainfall distribution for Jabiru airport during 2006–07. Mean, maximum and minimum monthly rainfall for Jabiru airport (1971–2006) is also shown.

Table 2.2 Missing data during 2006-07 at Gulungul Creek rain gauges

Station	Missing period	Comments
GCUS	1–22 Mar	Flood damage to Datataker on 1 March. Subsequently no data were recorded until replacement Datataker installed on 22 March. Rainfall record at G8210012 was used to infill the gap (~ 752 mm).
G8210012	1 Mar	Streamflow was above the rain gauge for approximately 1 hour during the flood peak. Unreliable data collected during this period were omitted from the rainfall record and data collected at the Tailings Dam were used to infill the gap (~ 9 mm).
GCDS	16–17 Nov	Problem with the datataker. Rainfall record at Jabiru airport was used to infill the gap (~ 16 mm).
	28 Feb – 1 Mar	Streamflow was above the rain gauge for approximately 8 hours during a flood peak. No data were recorded during this period and therefore the rainfall record at Jabiru airport was used to infill the gap (~ 35 mm).
	1–7 Mar	Flood damage to Datataker on 1 March. Subsequently no data were recorded until replacement Datataker installed on 7 March. Rainfall record at Jabiru airport was used to infill the gap (~ 469 mm).
Tailings Dam	1 Sep – 20 Dec	Rainfall data collection commenced 20 December. Data collected at G8210012 were used to infill the gap (230 mm).
Jabiru airport	na	

GCUS

During the peak of the flood event, the station at GCUS became submerged by floodwaters and consequently all data ceased being collected (except for stage data collected by the shaft encoder, shown in Figure 2.3).

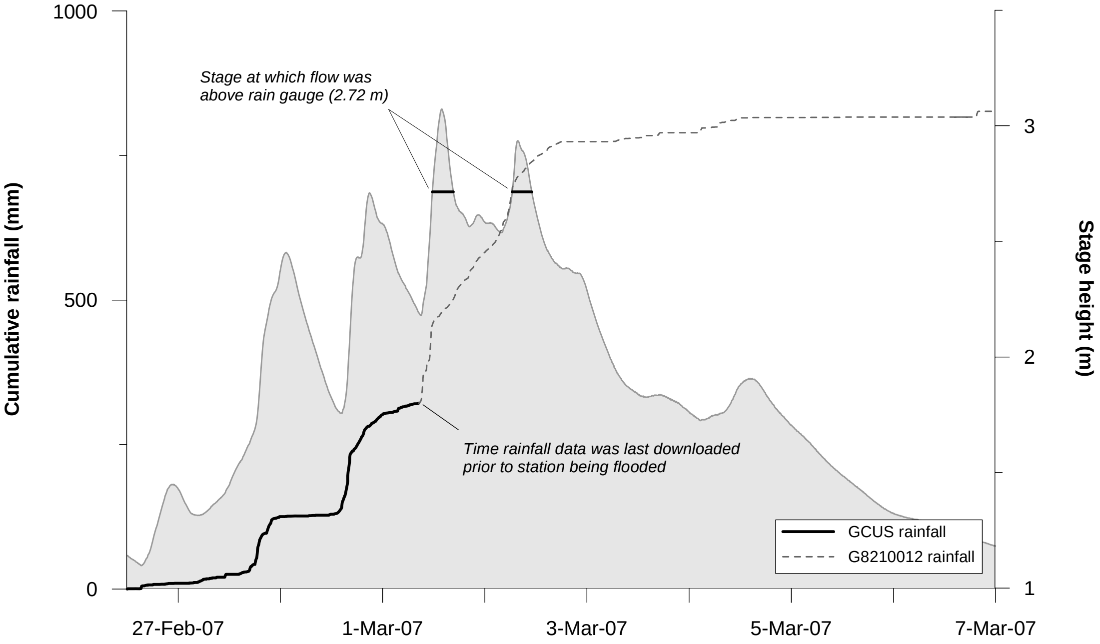


Figure 2.3 Rainfall data recorded at GCUS prior to the peak of the flood occurring (━━). The rainfall data at G8210012 were used to infill the missing rainfall record at GCUS (- - - -). The stage data recorded at GCUS are also shown.

Figure 2.3 shows the rainfall data downloaded hours prior to the station being flooded. Prior to the flood peak, reliable rainfall data were still being collected, which indicates that streamflow associated with the first two peaks of the flood event had not risen above the height of the rain gauge. According to cross sectional survey data, the top of the rain gauge is equivalent to a height of 2.72 m on the gauge board. That is, the rain gauge would have been submerged during the third and fourth peaks of the flood hydrograph for approximately 4.9 h and 4.6 h respectively (Fig 2.3). Streamflow during the peak of the flood would have been approximately 0.35 m above the height of the rain gauge.

It is recommended that, prior to the 2007–08 wet season, the rain gauge at GCUS should be elevated approximately 400 mm above it's current height to ensure that streamflow will not rise above the rain gauge for most flood conditions.

G8210012

At the peak of the flood event, streamflow was above the height of the rain gauge at G8210012 for approximately one hour (Fig 2.4). The poor data collected during this period (Fig 2.4) were subsequently removed from the rainfall record and the gap infilled using data collected at the Tailings Dam (~ 9 mm). The adjusted rainfall for the rainfall period shown in Figure 2.4 (between 26 February and 7 March) at G8210012 is now 834 mm, similar to that observed at Jabiru airport of 880 mm.

The rain gauge at G8210012 was installed in November 2003. During the 2004–05 wet season, streamflow was above the rain gauge for approximately six hours as a result of a flood event which occurred on 3 February 2005 (Moliere et al 2005a). Peak stage height of this event was 3.63 m (approximately 780 mm below the peak stage on 1 March 2007 – Figure 2.4).

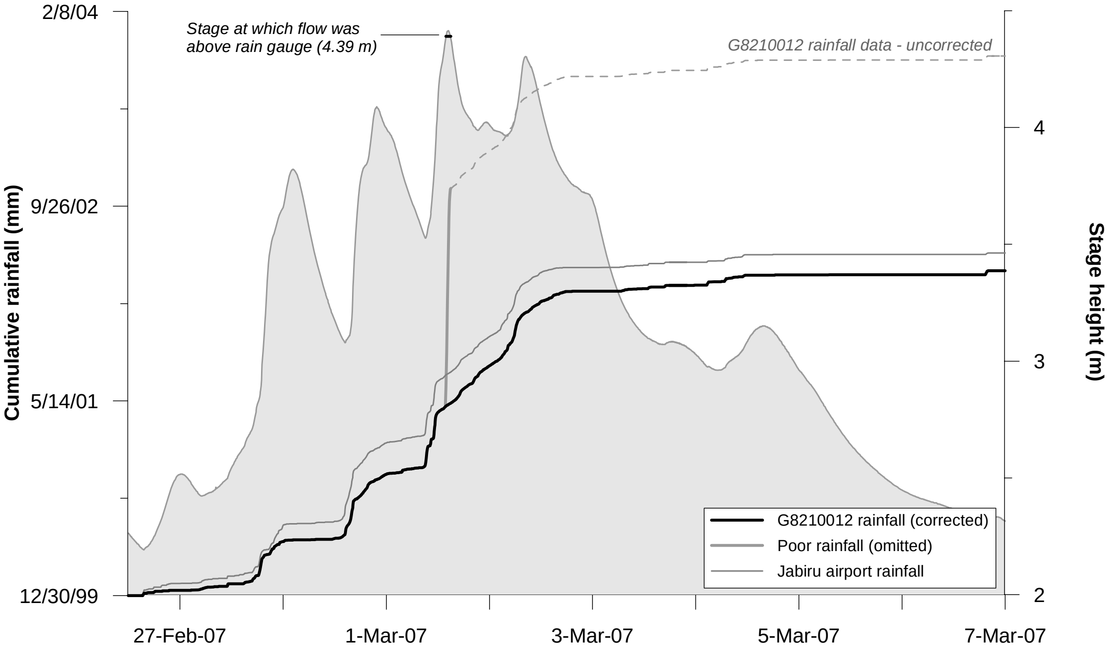


Figure 2.4 Rainfall data recorded at G8210012 and Jabiru airport during the flood event which ocurred between 28 February and 3 March 2007. The stage height at G8210012 is also shown.

As a result, the rain gauge at G8210012 was raised approximately 800 mm prior to the 2005–06 wet season. Despite the fact that streamflow was above the height of the rain gauge during the flood event on 1 March 2007 by about 20 mm (Fig 2.4), it is not recommended that the rain gauge should be further elevated above it's current height. As discussed in Section 4, this flood event is considered to be a statistically rare event and it is unlikely that a flood of this magnitude will occur again in the short or medium term. Furthermore, the associated floodwaters only affected the rain gauge during the flood peak for a short period of time.

GCDS

During the second peak of the multi-peaked flood event, streamflow was above the height of the rain gauge at GCDS for approximately eight hours (Fig 2.5). No rainfall data were collected during this period and, therefore, the rainfall record at Jabiru airport were used to infill this missing period. The stage height at which flow was above the rain gauge was approximately 3.23 m. During the next (and highest) peak of the flood event, the station at GCDS became submerged by floodwaters and consequently all data collection ceased. Rainfall data collected at Jabiru airport were used to infill the missing rainfall record at GCDS for the remainder of the storm event (Fig 2.5).

Assuming the increase in peak stage height at both GCUS and G8210012 from the second peak to the third peak of the flood event of about 0.33 m (Figs 2.3 & 2.4) would be roughly similar to that at GCDS, streamflow during the peak of the flood at GCDS would have been almost 0.5 m above the height of the rain gauge. (Figure 2.6 shows the rain gauge at GCDS submerged by floodwaters on 2 March during the fourth peak of the flood event.) Hence it is recommended that, prior to the 2007–08 wet season, the rain gauge at GCDS should be elevated at least 0.5 m above its current height to ensure that streamflow will not rise above the rain gauge for most flood conditions.

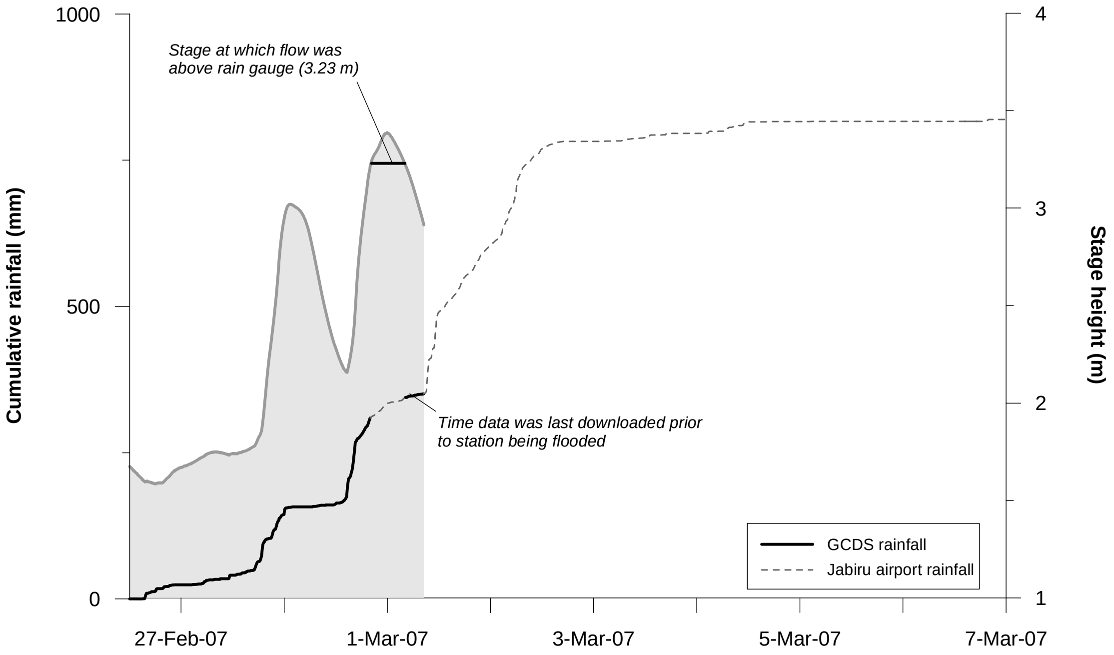


Figure 2.5 Rainfall and stage data recorded at GCDS prior to the peak of the flood occurring. The rainfall data at Jabiru airport used to infill the missing rainfall record at GCDS are also shown.

Figure 2.6 Location of the rain gauge at GCDS. The main creek channel is behind the treeline approximately 20m from the rain gauge. The top photo was taken the week after the major flood, the bottom photo was taken at 1700 h on 2 March 2007 a few hours after the fourth peak of the flood.

3 Runoff data

Stage height (m) at GCUS and GCDS was measured at 6-minute intervals by both a pressure transducer and a shaft encoder. During the 2006–07 wet season, the shaft encoder was the primary instrument for data collection at GCUS, while the data collected by the pressure transducer were used as back-up. At GCDS, the primary instrument for stage data collection was the pressure transducer as there was a major gap in the stage data collected by the shaft encoder during January and February. Stage height at G8210012 was measured at 6-minute intervals by a pressure transducer. At all three gauging stations, the recorded stage data were checked against the stream gauge board at regular intervals throughout the period of flow (Table 3.1). These checks showed that the instrument readings were essentially identical to that at the gauge board for each station.

Table 3.1 Stage measured at the gauge board and by the primary stage recorder at each site (2006–07)

	Stage height (m)					
	GCUS		**G8210012**		**GCDS**	
Date	Gauge board	SE(1)	Gauge board	PT(2)	Gauge board	PT(3)
21 Dec 06	0.45	0.444	1.45	1.435		
04 Jan 07	0.555	0.556	1.595	1.618	0.72	0.711
23 Jan 07					0.94	0.931
30 Jan 07	0.775	0.773	1.83	1.824		
06 Feb 07					1.75	1.747
06 Feb 07					2.14	2.095
13 Feb 07	0.98	0.980	2.0	2.012	1.3	1.314
27 Feb 07	1.54	1.538	2.72	2.704	2.2	2.202
08 Mar 07	1.295	1.293			1.45	1.453
08 Mar 07	1.23	1.230			1.57	1.566
13 Mar 07	1.295	1.297			1.785	1.781
22 Mar 07	1.255	1.254			1.54	1.542
27 Mar 07	1.015	1.019			1.31	1.315
11 Apr 07	0.79	0.789			1.06	1.073
23 Apr 07	0.68	0.679			0.94	0.954
07 May 07	0.605	0.608	1.64	1.643	0.87	0.885
23 May 07	0.575	0.572	1.61	1.608	0.815	0.827
Average difference		<0.01 m		<0.01 m		<0.01 m

(1) Raw stage data collected from 31 January 2007 had 0.37 added to the data to align with gauge board.

(2) Raw stage data had the equation $y = 1.047x + 0.7959$ applied to all data to align with gauge board.

(3) Raw stage data had 0.02 subtracted from all data to align with gauge board.

3.1 Rating curves

A rating curve to convert stage data to discharge data is required for each station. These rating curves are derived using velocity-area gaugings taken along a reasonably stable cross section at each station at various times over a range of flows.

GCUS

Velocity-area gaugings taken at GCUS between 2003 and 2006 were used to derive a rating curve for the site (Moliere et al 2007) (Fig 3.1). However, velocity-area gaugings taken throughout the 2006–07 wet season, and four gaugings taken late in the 2005–06 wet season (post-cyclone Monica), indicate that the rating curve fitted in Moliere et al (2007) is not appropriate for stage data collected after April 2006. This can be attributed to channel changes, particularly infilling of the channel bed, occurring as a result of the rainfall-runoff event associated with Cyclone Monica (which occurred late April 2006). Consequently, a new rating curve was fitted for the 2006–07 wet season using velocity-area gaugings taken post-cyclone Monica.

The highest recorded stage height at GCUS during 2006–07 of 3.07 m, which is 740 mm above the previous highest stage height of 2.33 m on 4 April 2006, is approximately 1.13 m above the highest velocity-area gauging (conducted at 1.94 m) and 2.57 m above cease-to-flow (Fig 3.2). Therefore, GCUS is gauged to approximately 56% of the maximum flow for the 2006–07 wet season, which is a reasonable level of quantitation compared to many gauging stations throughout the tropical rivers region (Moliere 2007).

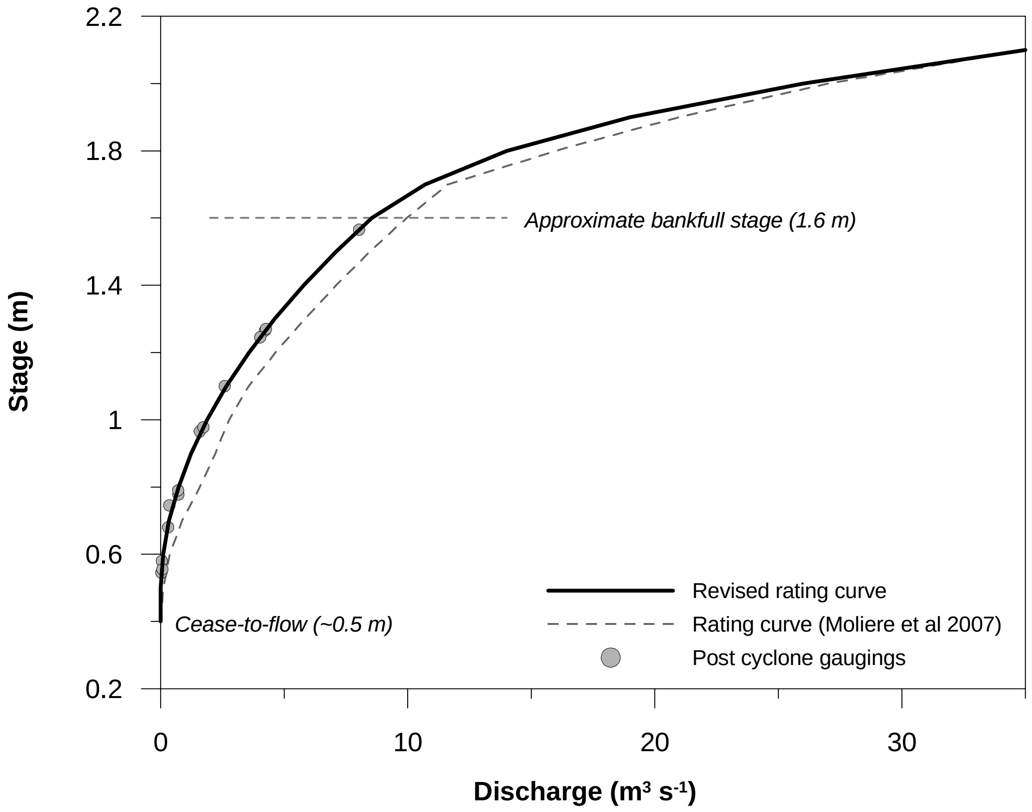


Figure 3.1 Revised rating curve for GCUS with the gauging points shown. Old rating curve for GCUS is also shown.

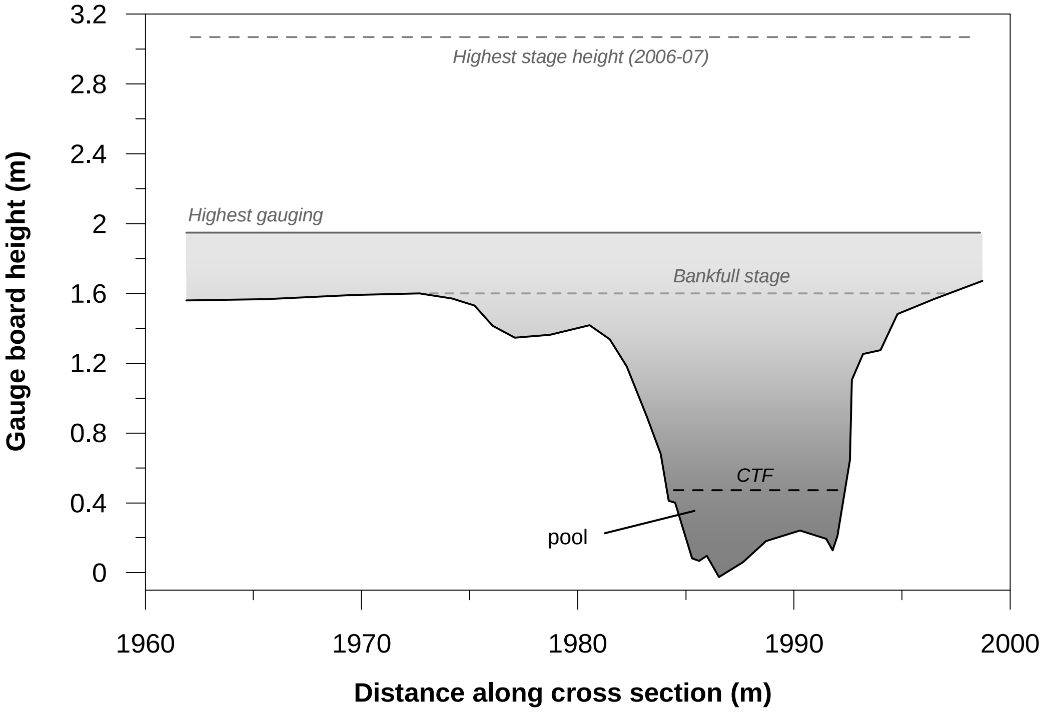


Figure 3.2 Cross section at GCUS taken during August 2005. CTF = cease-to-flow.

G8210012

As discussed in Moliere et al (2007), a series of rating curves were previously fitted for G8210012 by NRETA using 107 velocity-area gaugings taken between 1971 and 1993. Velocity-area gaugings taken by ***eriss*** between 2003 and 2006 indicated that the latest of these rating curves fitted by NRETA was not entirely appropriate for the low to medium flow range for the stage data collected by ***eriss*** since 2003 (Moliere et al 2007). Consequently, the rating curve was revised between cease-to-flow and approximately 2.3 m on the gauge board to better fit the velocity gaugings taken since 2003.

Five velocity-gaugings were taken post-cyclone Monica – two late in the 2005–06 wet season and three during the 2006–07 wet season. The two medium flow gaugings fit reasonably well along the rating curve (Fig 3.3). However, the three low flow gaugings indicate that the cease-to-flow value at G8210012 has changed to that prior to cyclone Monica (previously 1.6 m). This could be attributed to the scouring of the channel bed occurring as a result of the rainfall-runoff event associated with Cyclone Monica. The bottom end of the rating curve was slightly adjusted to accommodate this change in cease-to-flow (Fig 3.3). The rating curve fitted by Moliere et al (2007), with the minor adjustment of the curve at very low flows, is considered appropriate for the 2006–07 wet season.

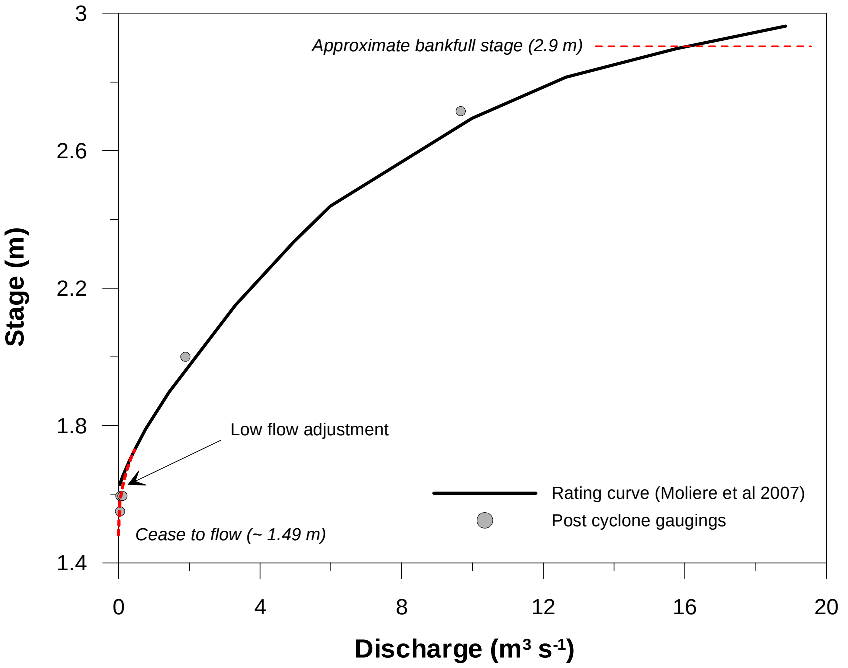


Figure 3.3 Rating curve for G8210012 with the gauging points shown. The minor adjustment to the rating curve as a result of the change in cease to flow is also shown.

The highest recorded stage height at G8210012 during 2006–07 of 4.414 m is approximately 1.11 m above the highest velocity-area gauging (conducted at 3.3 m by NRETA in March 1976) and 2.92 m above cease-to-flow (Fig 3.4). Therefore, G8210012 is gauged to approximately 62% of the maximum flow for the 2006–07 wet season, which, similar to GCUS, is a reasonable level of quantitation compared to many gauging stations throughout the tropical rivers region (Moliere 2007).

The highest stage height at G8210012 during 2006–07 is also the highest stage height ever recorded at the station. Prior to this flood event, the previous highest stage height was

4.322 m, which occurred on 4 February 1980. The event on 4 February 1980 was considered to be a statistically rare event (Moliere 2005).

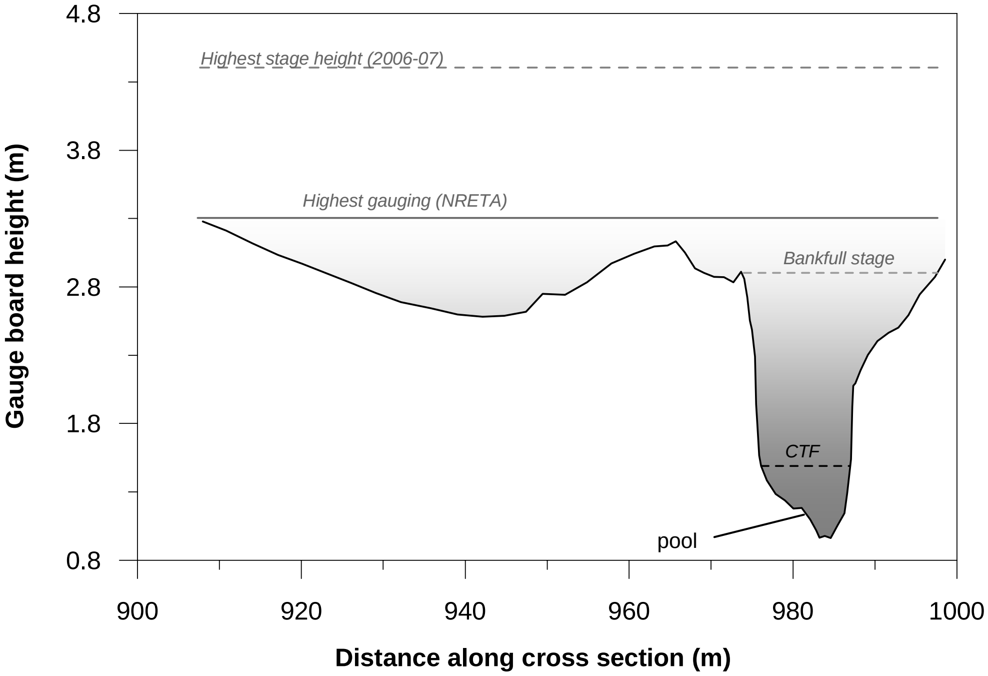


Figure 3.4 Cross section at G8210012 taken during August 2005. CTF = cease-to-flow.

GCDS

Velocity-area gaugings taken at GCDS between 2005 and 2006 were used to derive a rating curve for the site (Moliere et al 2007) (Fig 3.5). However, similar to GCUS, velocity-area gaugings taken at GCDS throughout the 2006–07 wet season, and three gaugings taken late in the 2005–06 wet season (post-cyclone Monica), are all above the previously fitted rating curve, indicating that the rating curve fitted in Moliere et al (2007) is not appropriate for stage data collected after April 2006. Again, this can be attributed to channel changes occurring as a result of the rainfall-runoff event associated with Cyclone Monica. Consequently, a new rating curve was fitted for the 2006–07 wet season using velocity-area gaugings taken post-cyclone Monica.

The highest recorded stage height at GCDS during 2006–07 of 3.39 m was observed during the second peak of the multi-peaked flood event which occurred between 27 February and 3 March 2007 (refer to Figure 2.5). During the next (and highest) peak of the flood event, the station at GCDS became submerged by floodwaters and consequently all data ceased being collected. Based on stage data collected upstream at GCUS and G8210012, it is estimated that the peak stage during the flood event may have reached approximately 3.72 m. The estimated peak stage height is 1.15 m above the previous highest stage height of 2.57 m on 5 April 2006. It is also approximately 1.39 m above the highest velocity-area gauging (conducted at 2.33 m) and 2.96 m above cease-to-flow (Fig 3.6). Therefore, GCDS is gauged to approximately 53% of the maximum flow for the 2006–07 wet season, which is a reasonable level of quantitation compared to many gauging stations throughout the tropical rivers region (Moliere 2007), although less than the upstream stations GCUS and G8210012.

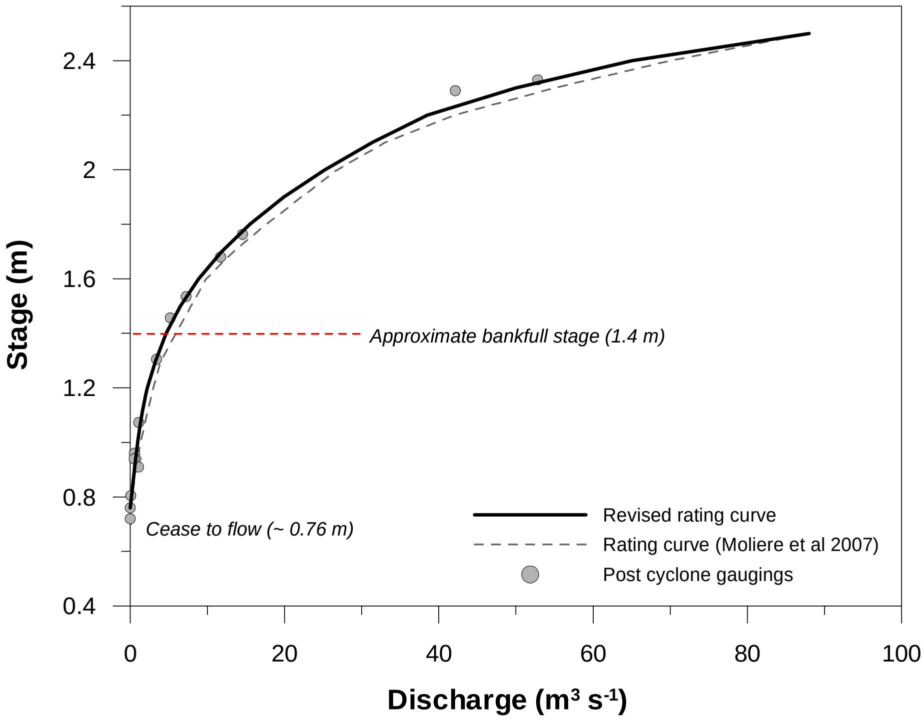


Figure 3.5 Rating curve for GCDS with the gauging points shown

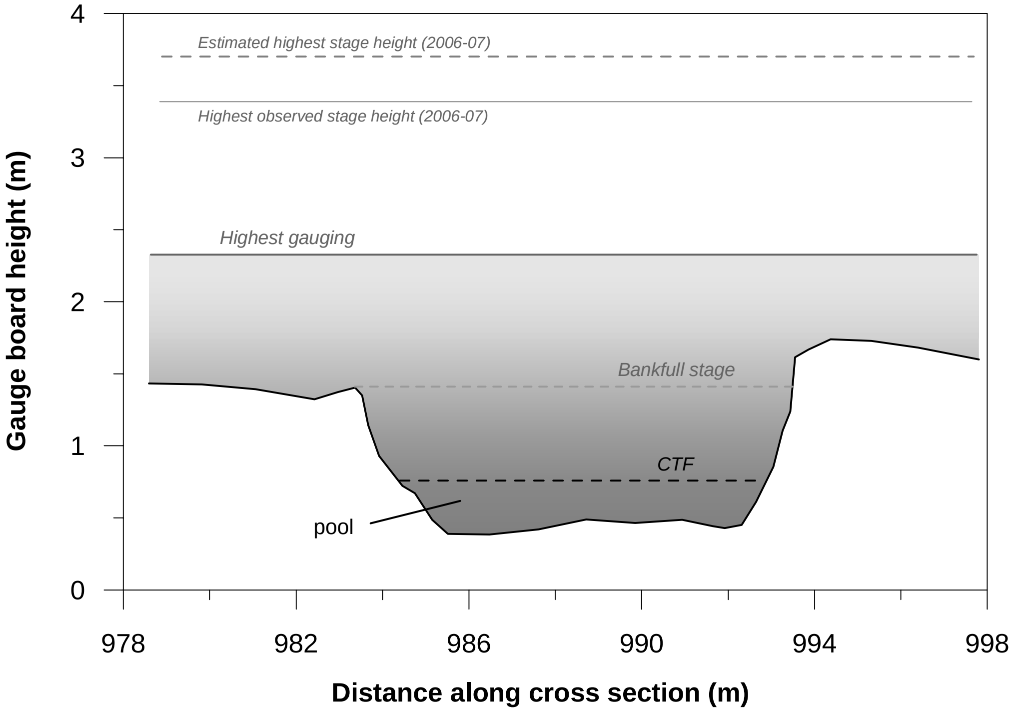


Figure 3.6 Cross section at GCDS taken during September 2005. CTF = cease-to-flow. The highest observed stage corresponds to the second peak of the multi-peaked flood event which occurred between 27 February and 3 March 2007 (see Fig 2.5). The estimated highest stage occurred during the third and highest peak of the flood event when stage data ceased collection at GCDS and was derived using stage data collected at GCUS and G8210012.

3.2 Annual hydrograph

The annual hydrographs for GCUS, G8210012 and GCDS for the 2006-07 wet season are shown in Figures 3.7a–c. The total runoff at each station, determined by the area under the hydrograph, is given in Table 3.2. The total annual runoff at G8210012 during 2006–07 (Table 3.2) is more than three times the average annual runoff volume of 25 548 ML (derived by Moliere (2005) using the historical runoff record between 1971 and 1993) and is the highest annual runoff recorded at the station. This result can be largely attributed to the extraordinary flood event which occurred between 27 February and 3 March 2007 (Fig 3.7).

The runoff record at GCDS is incomplete (Fig 3.7). Between 1 and 6 February 2007 stage data were not collected by either the pressure transducer (due to a problem with the sensor) or the shaft encoder (due to a battery problem with the shaft encoder logger). Both the pressure transducer sensor and the shaft encoder battery were replaced on 6 February 2007. According to the flow data collected at GCUS and G8210012, only two relatively minor runoff events occurred during this gap in the record.

Stage data at GCDS are also missing between 1 and 7 March 2007 (Fig 3.7). As discussed above, data were only collected at GCDS during the first two peaks of the multi-peaked flood event that occurred between 27 February and 3 March 2007 (refer to Figure 2.5). During the next (and highest) peak of the flood event, the station at GCDS became submerged by floodwaters and consequently all data collection ceased, including stage data collected by both the pressure transducer and the shaft encoder. The station was repaired and reinstrumented on 7 March.

Figure 3.7 also shows the discharge at which the highest velocity-area gauging was conducted at each station. Above this maximum gauged discharge the rating curve fitted for each station has been extrapolated. Therefore, flow data collected above this maximum gauged discharge is not considered to be as reliable compared to the flow data collected below the maximum gauged discharge. At GCUS and G8210012 flow exceeded the maximum gauged discharge during 2006–07 for approximately 4.4 days and 3.7 days respectively, including a period of 3.2 days at both stations during the flood event which occurred between 27 February and 3 March 2007 (Fig 3.7). It is estimated, based on flow data collected at GCUS and G8210012, that flow exceeded the maximum gauged discharge at GCDS during 2006–07 for approximately 3.6 days, including a period of 3.2 days during the major flood event.

Although the amount of time that flow exceeded the maximum gauged discharge throughout the entire wet season at GCUS and G8210012 is relatively low (< 3%), the total *volume* of flow during this small period is more than 50% of the total annual flow in both cases. Therefore, it is likely that the errors associated with both the total annual runoff and the annual peak discharge values for each station (Table 3.2) are relatively large. This result highlights the importance of conducting velocity-area gaugings at high flows to refine the top end of the rating curve.

Table 3.2 Total annual rainfall and runoff at each gauging station for the 2006–07 wet season

Station	**Total rainfall (mm) (from Table 2.1)**	**Antecedent rainfall (mm)**	**Runoff period**	**Total runoff (ML) [Peak discharge (m^3s^{-1})]**
GCUS	2218	266	16 Dec – 01 July	51822 [284]
G8210012	2204	229	17 Dec – 01 July	77303 [319]
GCDS	2362	301	30 Dec – 01 July	- [334](1)

(1) This is the observed peak discharge before data collection ceased at GCDS. Estimated peak discharge during the height of the flood is 460 m^3 s^{-1}.

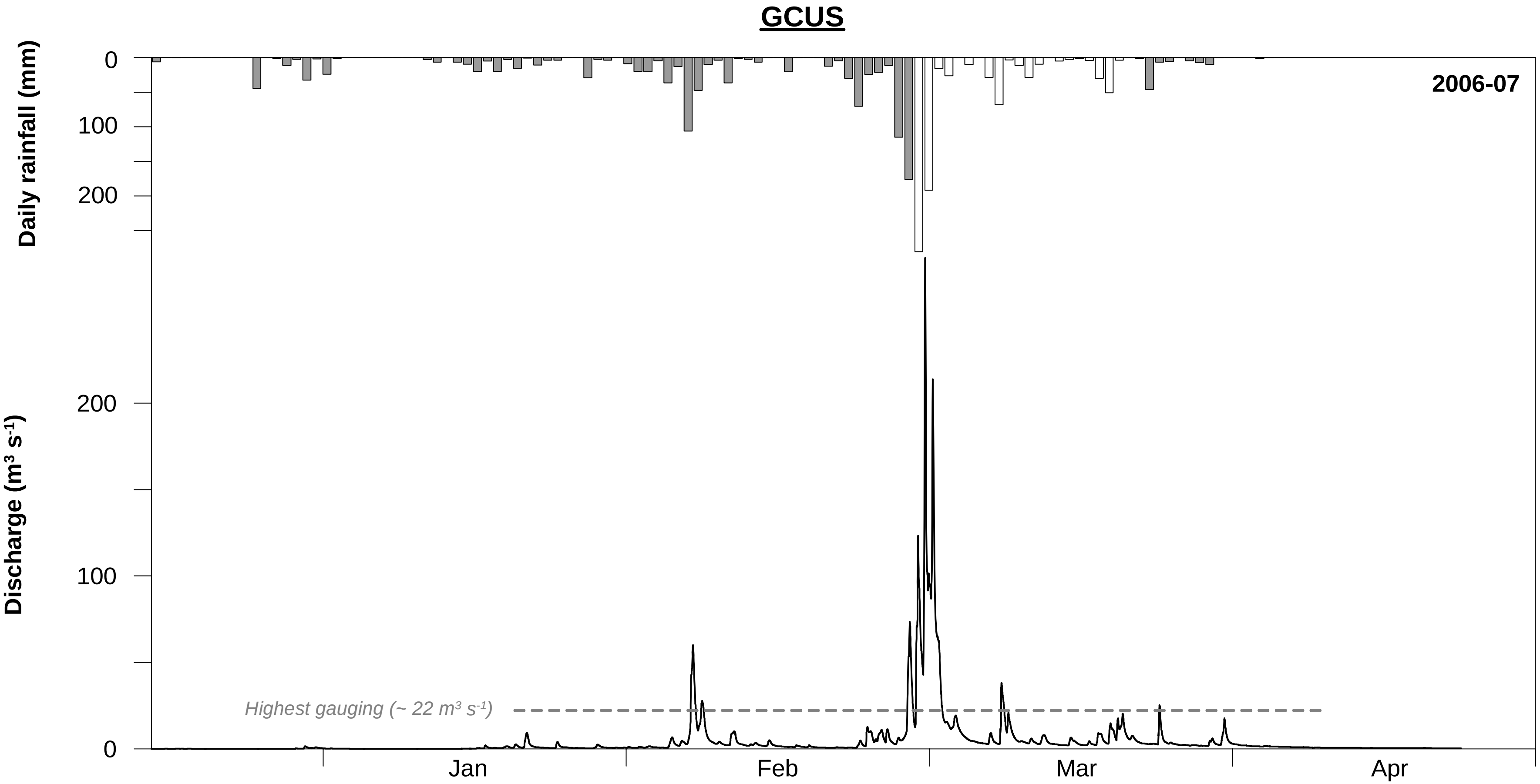


Figure 3.7a Daily rainfall and the hydrograph for GCUS during the 2006–07 wet season. Rainfall data used to infill the rainfall record (using data from G8210012) are shown as white bars.

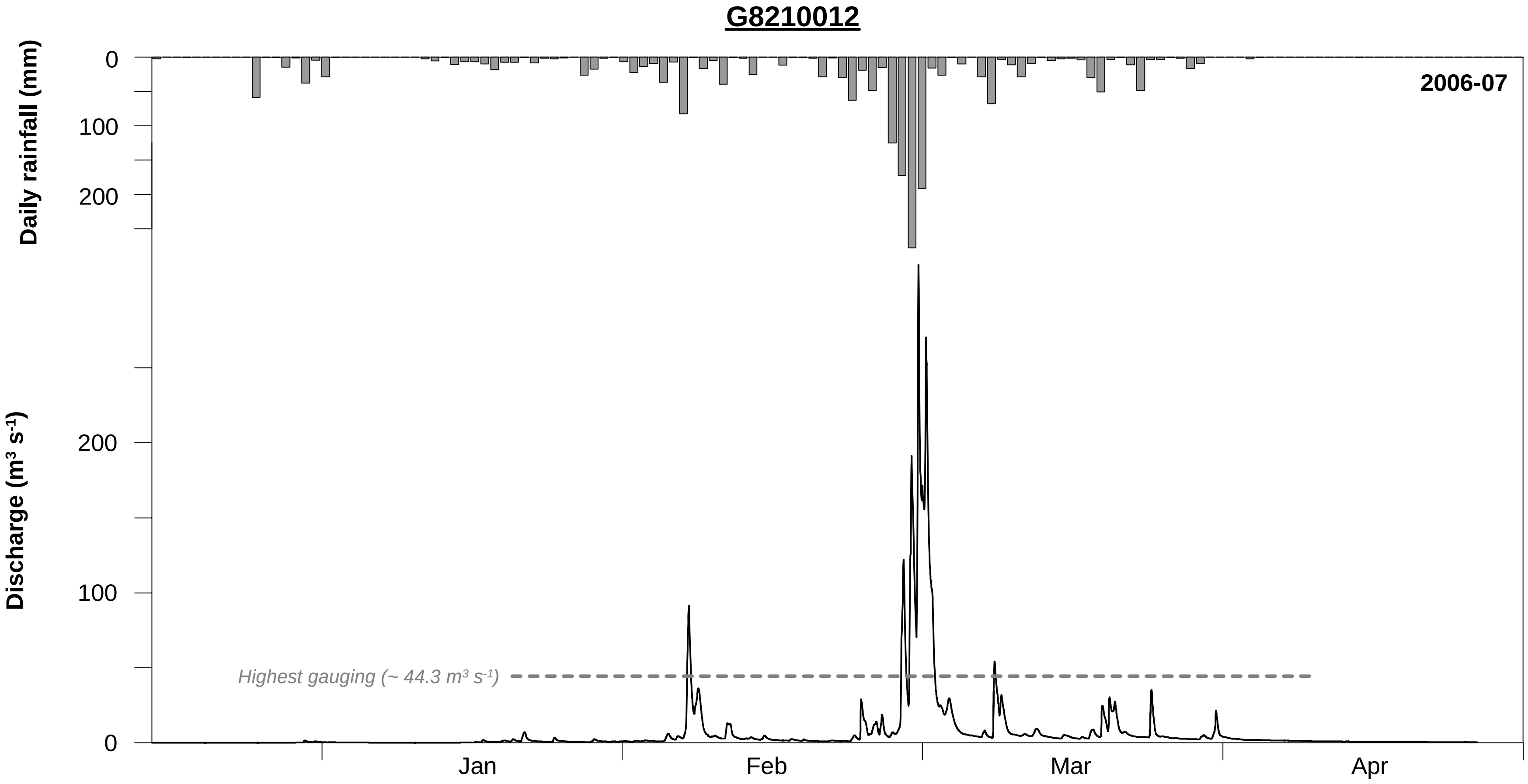


Figure 3.7b Daily rainfall and the hydrograph for G8210012 during the 2006–07 wet season

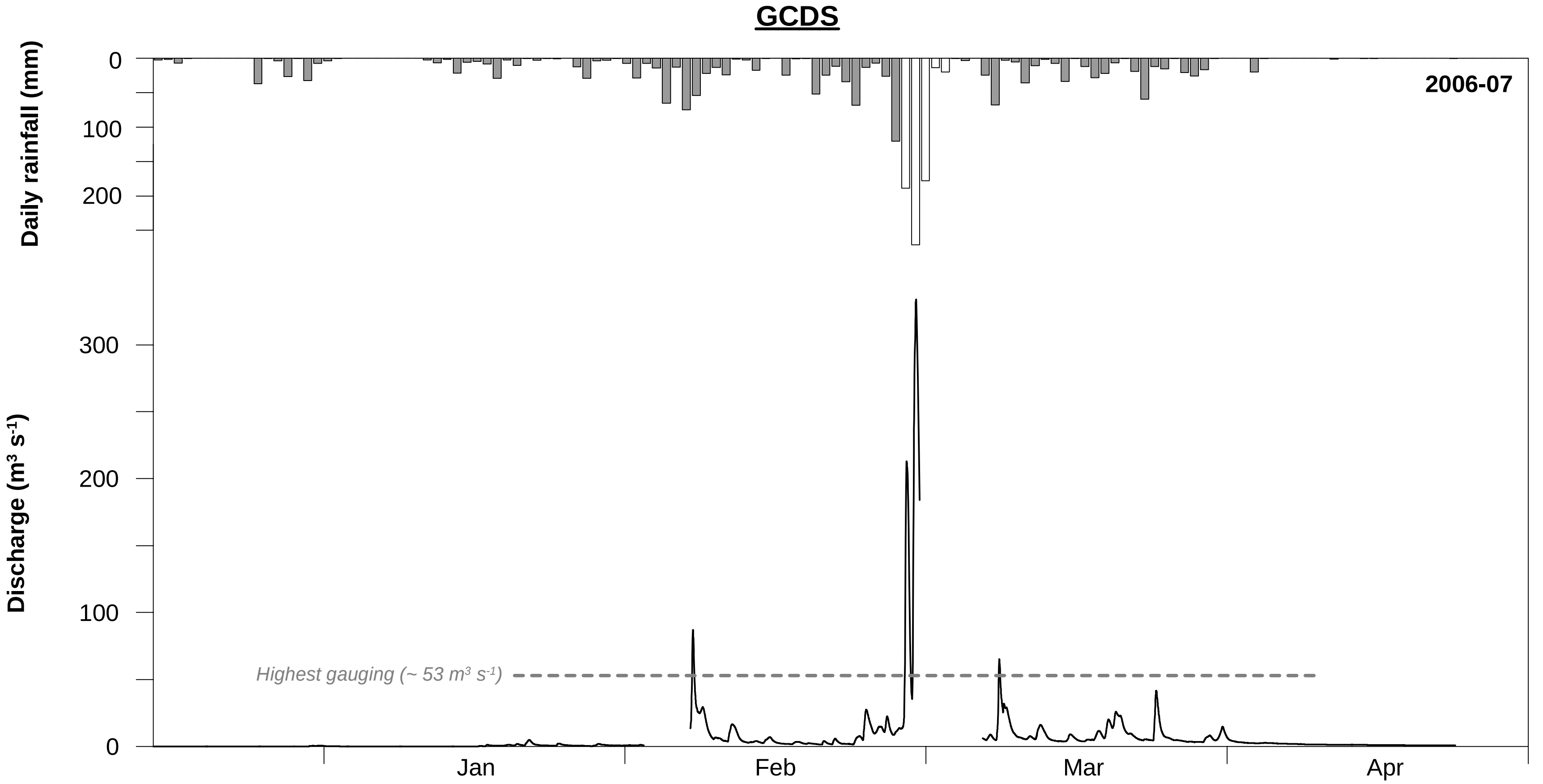


Figure 3.7c Daily rainfall and the hydrograph for GCDS during the 2006–07 wet season. Rainfall data used to infill the rainfall record (using data from Jabiru airport) are shown as white bars.

Antecedent rainfall

The antecedent rainfall, which is defined as the amount of rainfall between the start of rainfall and the start of streamflow, during 2006–07 at all three stations (Table 3.2) is similar to the mean antecedent rainfall derived for the Gulungul Creek catchment of 295 mm (Moliere 2005).

4 Flood

During late February to early March 2007 exceptionally large rainfall occurred throughout the entire Magela Creek system, including Gulungul Creek catchment. During a one-week period between 16:30 23 February and 16:30 2 March, 908 mm and 945 mm of rain was recorded at G8210012 and Jabiru airport respectively. Within this 7-day period of rainfall, 740 mm and 784 mm of rain fell at G8210012 and Jabiru airport, respectively, within a 3-day period between 17:00 27 February and 17:00 2 March. As a result of this intense 3-day rainfall period, the highest flood levels were recorded at both Gulungul Creek and Magela Creek since recording began in 1971.

4.1 The storm event

As discussed above in Section 2.1 – Missing rainfall data, rainfall data collection ceased at both GCUS and GCDS during the peak of the flood hydrograph as a result of the stations being submerged by floodwaters. Rainfall data at G8210012, the Tailings Dam and Jabiru airport were collected during the entire flood event and, therefore, were used for rainfall intensity analysis within the Gulungul Creek catchment. (As discussed in Section 2.1, the rain gauge at G8210012 was effected by floodwaters for approximately one hour at the peak of the flood event. The poor data collected during this period were subsequently removed from the rainfall record and the gap infilled using data collected at the Tailings Dam.)

Figure 4.1 shows that rainfall was almost continuous during the 3-day period between 17:00 27 February and 17:00 2 March and that within this period there were four relatively intense rainfall periods that contributed to the four peaks of the flood hydrograph. The most intense period of rainfall occurred during the morning of 1 March 2007 and this contributed to the peak of the flood event (Fig 4.1).

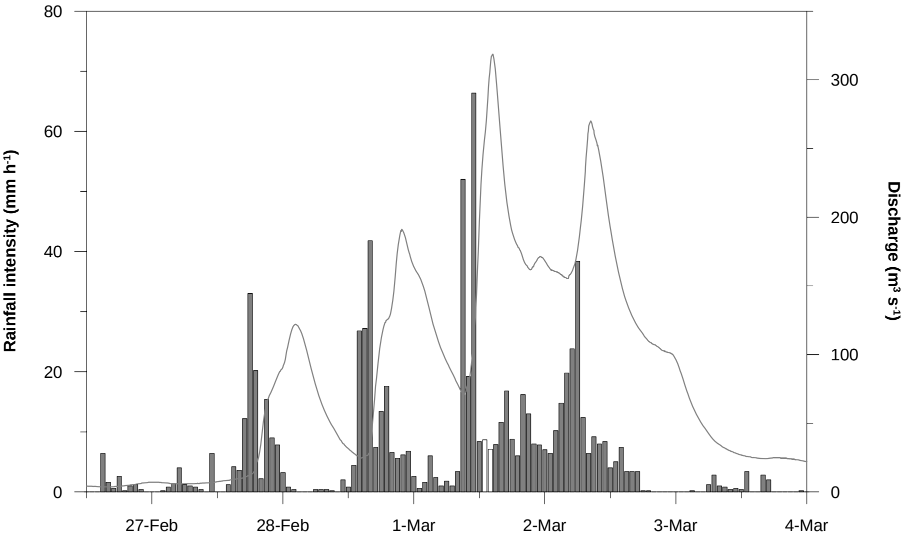


Figure 4.1 One hour hyetograph of rainfall collected at G8210012 during the flood event. Rainfall data used to infill the rainfall record (using data from the Tailings Dam) are shown as white bars. The flood hydrograph at G8210012 is also shown.

The rainfall event was plotted on a series of intensity-frequency-duration curves established for the Gulungul Creek catchment (Bureau of Meteorology pers comm 2007) to illustrate the severity of the storm during the 3-day period (Fig 4.2).

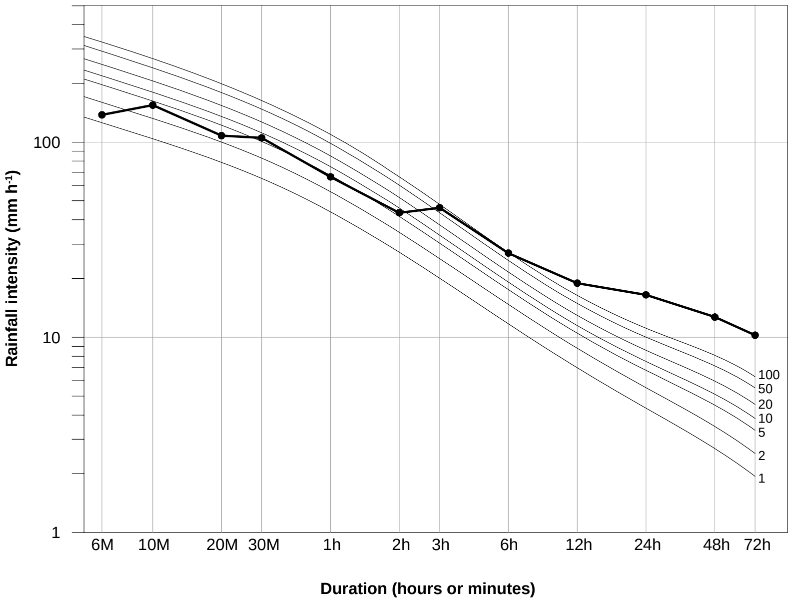


Figure 4.2 Intensity-frequency-duration curves for Gulungul Creek for various recurrence intervals. The maximum rainfall intensity associated with the storm event between 27 February and 2 March recorded at G8210012 is shown in **bold**.

Figure 4.2 shows that for durations greater than 6 hours the storm intensity recorded at G8210012 exceeded the 1:100 year event. The maximum return period was achieved for a duration of 48 and 72 hours, however, any estimate of the return period for these durations would be unreliable given that the intensity exceeded the 100 year event by such a large margin (Fig 4.2). Nevertheless, given the logarithmic scale in Figure 4.2, the rainfall over the 48 h and 72 h durations may correspond to a greater than 1:1000 y event. Table 4.1 summarises the maximum amount of rainfall recorded at G8210012 during various durations within the 3-day storm event. It should be noted that the maximum rainfall intensities recorded at the Tailings Dam and Jabiru airport are very similar to that recorded at G8210012 for the various durations. Only the rainfall recorded for the 48 h and 72 h durations at Jabiru airport (of 642 mm and 784 mm respectively) are larger than that recorded at G8210012 (Table 4.1).

The 24-hour rainfall total at G8210012 of 398.4 mm is the largest recorded in the Alligator Rivers Region. The previous highest 24-hour rainfall recorded at Jabiru airport (1971–2006) and Oenpelli (1910–2006) was 293.5 mm on 4 February 1980 and 245 mm on 10 January 1919, respectively. The highest 24-hour rainfall total at Darwin, which has a higher average annual rainfall than the Alligator Rivers Region, was 380 mm on 2 January 1997. McGill (1983) tabulated extreme daily rainfalls recorded in the Top End. Only eight events were listed with higher daily rainfall than at G8210012 and Jabiru airport during the event on 1 March 2007. The largest daily rainfall event was 544 mm recorded at Roper Valley Station on 15 April 1963.

McGill (1983) also listed extreme rainfalls for periods of 48 h and 72 h recorded in the Top End. No events were listed that exceeded the 48 h and 72 h rainfall totals recorded at G8210012 and Jabiru airport. The previous highest 48 h and 72 h rainfalls were 599 mm and 731 mm respectively, recorded at Maningrida during March 1981. Therefore, it is likely that the rainfall that occurred on the Gulungul Creek catchment over the three-day period between 27 February and 2 March is the largest recorded in the Top End.

Table 4.1 Summary of rainfall intensities and recurrence intervals for the storm event recorded at G8210012 between 27 February and 2 March 2007

Duration (h)	Period start	Rainfall (mm)	ARI
0.1	11:24 01 March	13.8	>1
0.167	11:20 01 March	25.8	>2
0.333	11:16 01 March	36.0	>2
0.5	11:00 01 March	52.6	>5
1	11:00 01 March	66.4	>2
2	09:30 01 March	87.0	>5
3	09:00 01 March	138.4	>50
6	08:30 01 March	162.8	>50
12	09:00 01 March	229.6	>100
24	09:00 01 March	398.4	>100
48	13:30 28 February	611.4	>100
72	17:00 27 February	740.0	>100

4.2 The flood event

As mentioned above, the extraordinary rainfall which occurred over the Gulungul Creek catchment during the 3-day period between 27 February and 2 March 2007 contributed to the highest flood levels recorded at Gulungul Creek since recording began in 1971. The flood peak at each station occurred on the afternoon of 1 March during the third peak of the multi-peaked runoff event (Fig 4.3). The previous highest flood event observed within the Gulungul Creek catchment occurred on 4 February 1980 as a result of an intense 5-h duration storm event (Water Division 1982). The peak discharge at G8210012 during this event of 278 $m^3 s^{-1}$ corresponded to a greater than 1:50 y flood event (Moliere 2005).

Peak stage (and corresponding discharge) observed at each station during each of the four peaks of the flood hydrograph are given in Table 4.2. At G8210012 the four peaks of the flood hydrograph occurred between 30 and 60 minutes after the flow peaked at GCUS, which corresponds well to the lagtime between the two stations of 1 h predicted by Moliere (2005).

As discussed above, data were only collected at GCDS during the first two peaks of the multi-peaked flood (Figure 4.3). During the third (and highest) peak of the flood event, the station at GCDS became submerged by floodwaters and consequently all data collection ceased. Stage data collected upstream at GCUS and G8210012 increased by approximately 0.33 m from the second and third peak at both stations (Table 4.2) and, therefore, it is estimated that the peak stage during the flood event at GCDS may have reached approximately 3.72 m. This corresponds to a peak discharge of 460 $m^3 s^{-1}$.

Based on 11 high flow events observed at both GCUS and GCDS between 2005 (when data collection commenced at GCDS) and 2007, mean lagtime in peak discharge between the two stations is approximately 4.2 h (SD – 1 h). That is, event peak discharge at GCDS generally occurs 4.2 h after event flow peaks at GCUS. This corresponds well to the lagtime of 4.1 h between the two stations predicted by Moliere (2005) using catchment characteristics. Therefore, it is estimated that the peak of the flood event at GCDS may have occurred at approximately 18:00 on 1 March 2007.

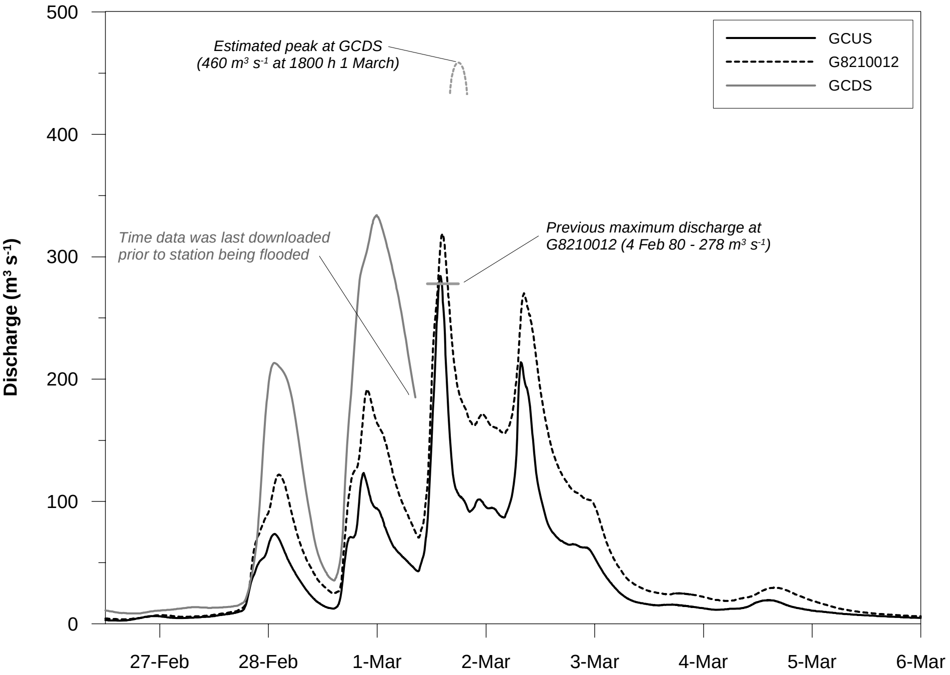


Figure 4.3 Flood hydrographs at each station along Gulungul Creek. Estimated peak discharge at GCDS is also shown.

Table 4.2 Time and flow at each of the four peaks during the flood event between 28 February and 2 March at each station along Gulungul Creek. Predicted time and discharge for the flood peak at GCDS is highlighted in grey.

	GCUS		G8210012		GCDS	
	Peak flow (m^3 s^{-1}) [Peak stage (m)]	Time of peak	Peak flow (m^3 s^{-1}) [Peak stage (m)]	Time of peak	Peak flow (m^3 s^{-1}) [Peak stage (m)]	Time of peak
1st peak	73.6 [2.45]	01:24 28 Feb	122 [3.82]	02:18 28 Feb	213 [3.02]	01:30 28 Feb
2nd peak	123 [2.71]	21:00 28 Feb	191 [4.09]	21:48 28 Feb	334 [3.39]	23:54 28 Feb
3rd peak	284 [3.07]	13:54 01 Mar	319 [4.41]	14:24 01 Mar	460 [3.72]	18:00 01 Mar
4th peak	214 [2.94]	07:42 02 Mar	270 [4.30]	08:24 02 Mar		

4.2.1 Flood duration

Floods occur when flow fills an alluvial channel and begins to overflow onto the floodplain (Leopold et al 1964, Grayson et al 1996). The bankfull stage at GCUS and G8210012 is 1.6 m and 2.91 m respectively (Fig 4.4).

Based on discharge data collected over three wet seasons between 2003 and 2006, the mean flood duration (ie mean time that flow is overbank during a flood event) at GCUS is approximately 11 hours (SD – 8 h). During the major flood event of 2006–07, flow was overbank for 5.6 days (between 1600 h 27 February and 0545 h 5 March 2007 – see Fig 4.4), well above the previous maximum flood duration recorded at GCUS of 1.6 days that occurred between 22 and 24 January 2006.

Based on historical discharge data collected between 1971 and 1993 by NRETA and data collected between 2003 and 2006 by ***eriss***, the mean flood duration at G8210012 is approximately 10 hours (SD – 11 h). During the major flood event of 2006–07, flow was overbank for 5.3 days (between 1900 h 27 February and 0200 h 5 March 2007 – see Fig 4.4).

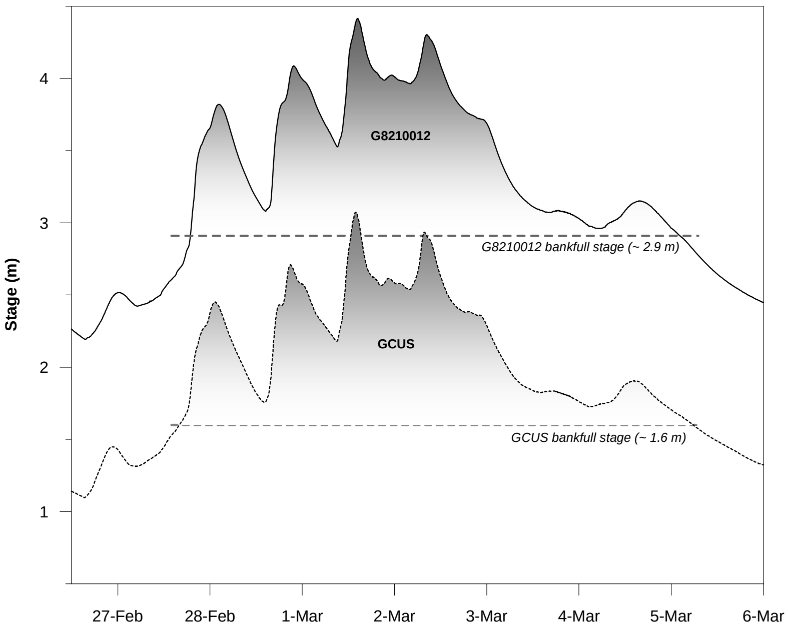


Figure 4.4 Period of overbank flow at GCUS and G8210012 during the 2006–07 flood event

This was the longest period of overbank flow observed at the station. The previous maximum flood duration was 4.8 days, which occurred 14–19 March 1976. However, runoff during this multi-peaked event was significantly less (peak stage of 3.57 m) than that recorded between 27 February and 5 March 2007. It is worth noting that the March 1976 and 2006–07 floods are the only periods of overbank flow at the station (out of more than 170 flood events) which exceed 2 days in duration.

4.2.2 Flood extent

As discussed above, the peak stage at G8210012 during the 2006–07 flood event was 4.414 m. Therefore, according to the cross section data at G8210012, it is likely that the width of the creek during the peak of the flood was greater than 1 km at the station (Fig 4.5), more than 40 times the bankfull channel width of 24 m.

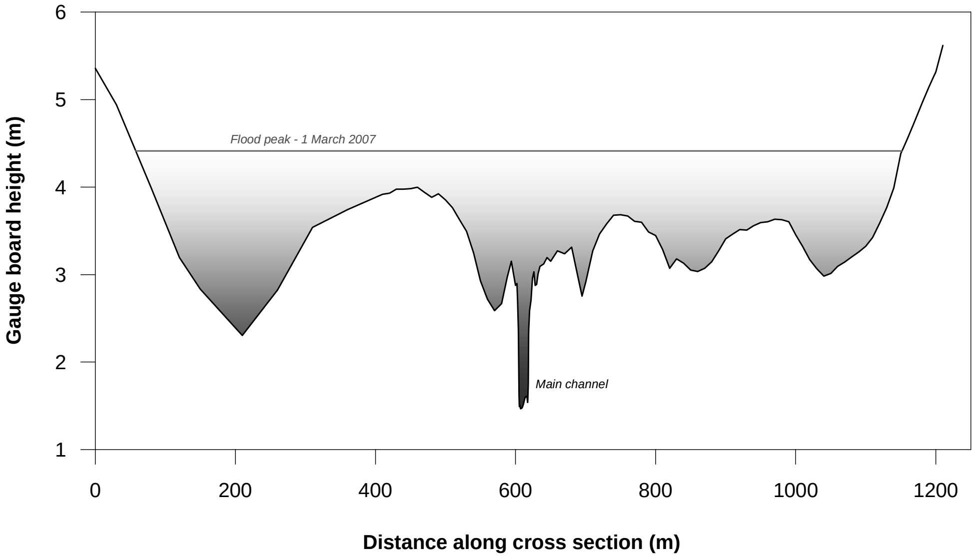


Figure 4.5 Extent of flow at G8210012 during the peak of the 2006-07 flood event

4.2.3 Flood recurrence interval

Moliere et al (2007) established flood frequency curves for GCUS and GCDS based on observed discharge data collected between 2003 and 2006 combined with predicted discharge data between 1971 and 1993 (using fitted relationships between annual peak discharges observed at the two stations (GCUS and GCDS) and G8210012). Using these flood frequency curves, the flood peak discharge at GCUS and the estimated flood peak discharge at GCDS on 1 March 2007 corresponded to a greater than 1:100 y flood event at both stations.

A flood frequency curve fitted for G8210012 by Moliere (2005) based on historical discharge data collected by NRETA between 1971 and 1993 was revised to incorporate discharge data collected by ***eriss*** between 2003 and 2006. Using the method outlined in Pilgrim (2001), a log Pearson III distribution was fitted for the annual peak discharges for G8210012 using annual peak discharges for 23 years of record.

Initially, while the frequency curve gave an adequate fit to most of the plotted annual floods (ie most of the data fits within the 5% and 95% confidence limits), it diverged from the highest flood event which occurred on 4 February 1980. It appears that the log Pearson III distribution is unable to fit both the lower and higher annual floods and, as a result, the frequency curve is distorted at both ends of the observed range. Therefore, similar to the flood frequency analysis conducted for G8210012 (Moliere 2005), a test for outliers indicated that the lowest annual flood was an outlier. The outlier was deleted from the dataset and a revised log Pearson III distribution for the station was fitted to the remaining data (Fig 4.6). Using the flood frequency curve, the annual peak discharge at G8210012 for 2006–07 of 319 $m^3 s^{-1}$ that occurred on 1 March 2007 corresponds to a 1:100 y flood event (Fig 4.6). The peak discharge during the flood event on 1 March 2007 is approximately six times the mean annual flood (53 $m^3 s^{-1}$, which corresponds to an annual exceedance probability of 50% in Figure 4.6).

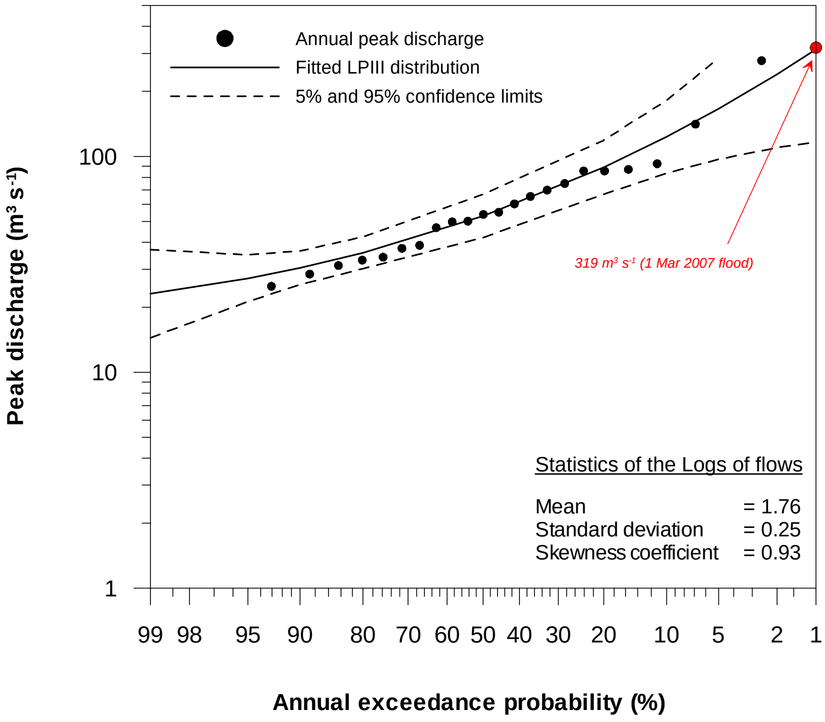


Figure 4.6 Frequency curve of annual peak discharge (1971–2006) at G8210012. The annual peak discharge during 2006–07 is plotted against the curve.

Given that the flood frequency curve fitted for G8210012 is based on observed annual peak discharge data, it is considered that this curve is reliable for estimating the exceedance probabilities of floods compared to the curves fitted for GCUS and GCDS. Therefore, it is considered that the peak flow observed along Gulungul Creek during the flood event on 1 March 2007 corresponds to a 1:100 y flood event.

4.3 Summary

An extraordinary rainfall event occurred over a 3-day period between 27 February and 2 March 2007, which resulted in the highest flood levels recorded within the Gulungul Creek catchment since recording began in 1971. The most intense rainfall period occurred on 1 March 2007, where maximum rainfall intensity at G8210012 exceeded a 1:100 y storm event for durations greater than 6 hours. In the 72 hour period from 17:00 27 February, 784 mm of rain was recorded at Jabiru airport, the highest 3-day rainfall ever recorded in the Top End.

The peak of the flood occurred at all three stations during the afternoon of 1 March 2007. Peak stage at G8210012 was 4.414 m, corresponding to a discharge of 319 m^3 s^{-1}. The previous highest flood event at G8210012 was 278 m^3 s^{-1}, which occurred as a result of an intense 5-h storm event on 4 February 1980. The fitted flood frequency curve for G8210012 indicates that the peak discharge during the flood event on 1 March 2007 corresponds to a 1:100 y event.

It is clear that both the rainfall over the Gulungul Creek catchment during the 3-day period between 27 February and 2 March 2007 and the resulting streamflow at all three stations were statistically rare events.

5 Suspended sediment

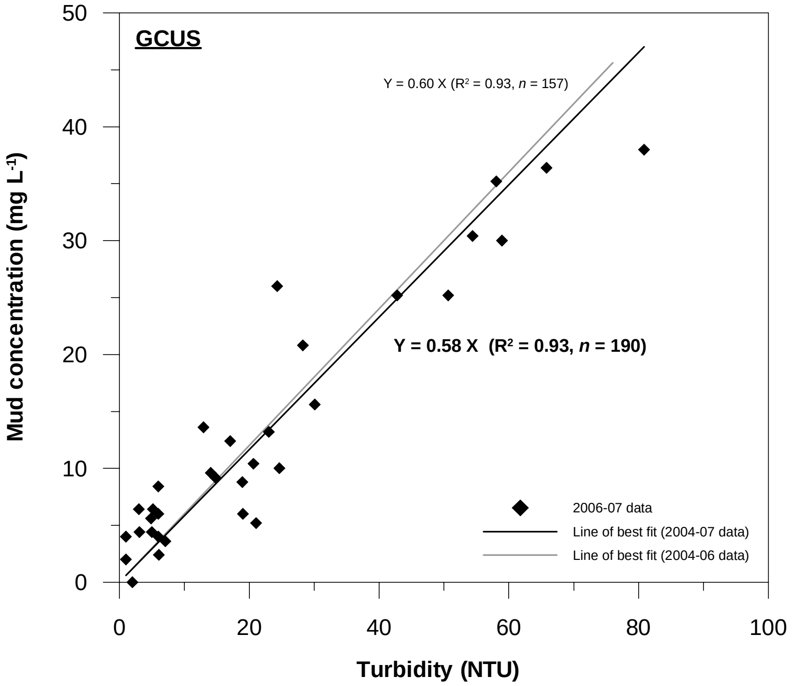
5.1 Methods

During the 2006–07 wet season, turbidity data were collected at GCUS and GCDS at 6-minute intervals using Analite turbidity probes. The probes were calibrated in the laboratory prior to the wet season using polymer-based turbidity standards. Statistically significant relationships between turbidity and mud concentration (mud *C*) had previously been found for GCUS and GCDS by Moliere et al (2007) using data collected during 2004–06.

To further validate the turbidity-mud *C* relationship for the two stations, water samples were collected by a stage-activated pump sampler during the 2006–07 wet season. As discussed in Moliere et al (2007), the pump samplers (which have a 24 bottle capacity) were programmed to collect water samples only during the rising stage of the event hydrograph as it has been shown that most of the mud movement in the region generally occurs before the peak of the hydrograph (Hart et al 1982, Duggan 1991, Moliere et al 2002). The water samples were collected from the pump sampler at fortnightly intervals and mud *C* in each sample was determined by filtering and oven drying techniques (Erskine et al 2001).

It should be noted that water samples were collected by the pump samplers only until the end of February 2007. The samplers at both stations were submerged by floodwaters during the peak of the March flood event. As a result, no samples were obtained throughout the flood event (samples which had been collected on the rising stage of the flood hydrograph were lost when the samplers were flooded). Repairs to the sampling equipment were not able to be completed until the end of March, at which time no more runoff events occurred for the remainder of the wet season (Fig 3.7).

The 2006–07 turbidity-mud *C* data are consistent with the line of best fit established by Moliere et al (2007) for both stations, particularly for GCUS (Fig 5.1). Revised turbidity-mud *C* relationships were derived by combining the 2006–07 turbidity-mud *C* data with that collected between 2004 and 2006 (Fig 5.1). These revised relationships, which were almost identical to that fitted using 2004–06 data, were used to convert the continuous turbidity data to mud concentration for the 2006–07 wet season. The continuous stream mud *C* at GCUS and GCDS for the 2006–07 wet season, collected using turbidimeters and converted to concentration using the regression relationships (Fig 5.1), is shown in Figure 5.2.



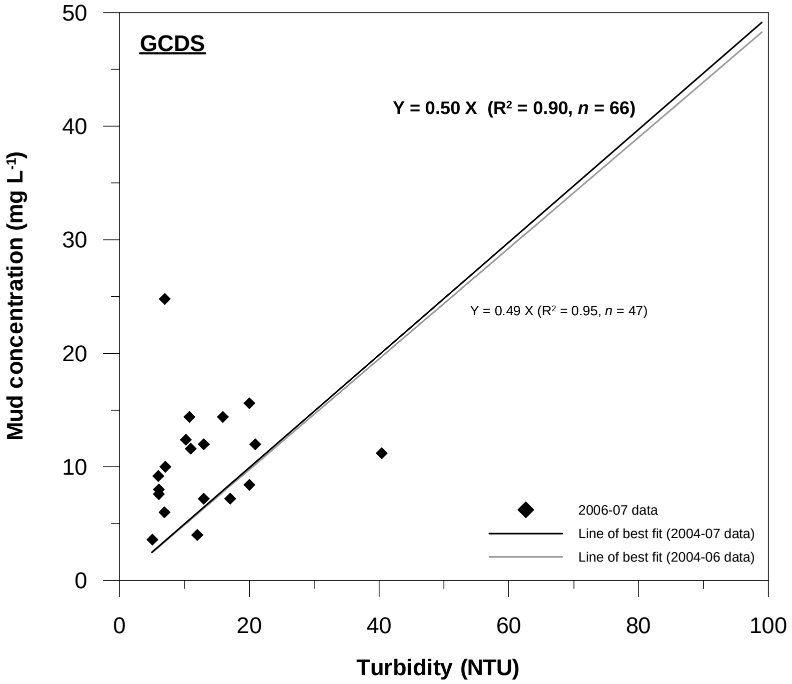


Figure 5.1 Relationship between turbidity and mud concentration for GCUS (Top) and GCDS (Bottom)

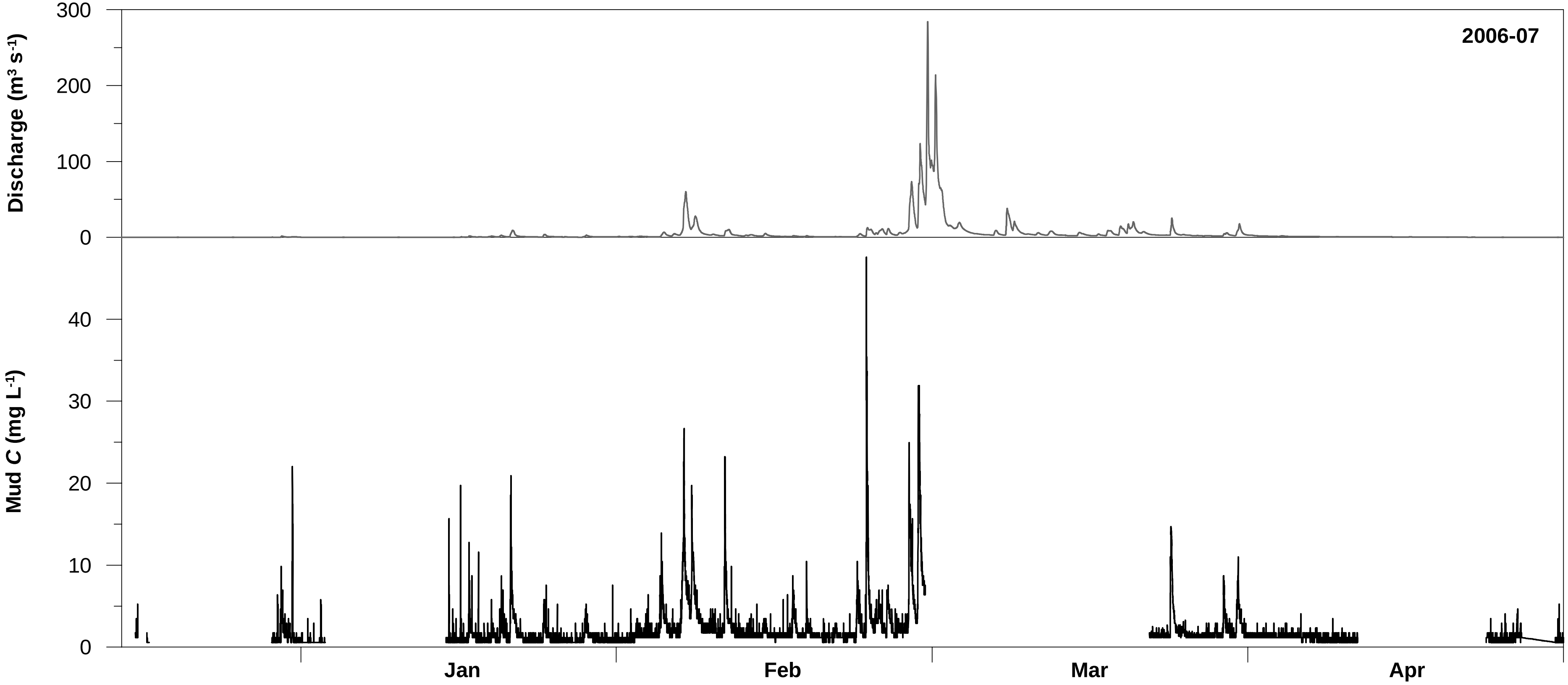


Figure 5.2a Continuous mud *C* data derived from the turbidimeter record for the 2006–07 wet season at GCUS. Discharge data are also shown.

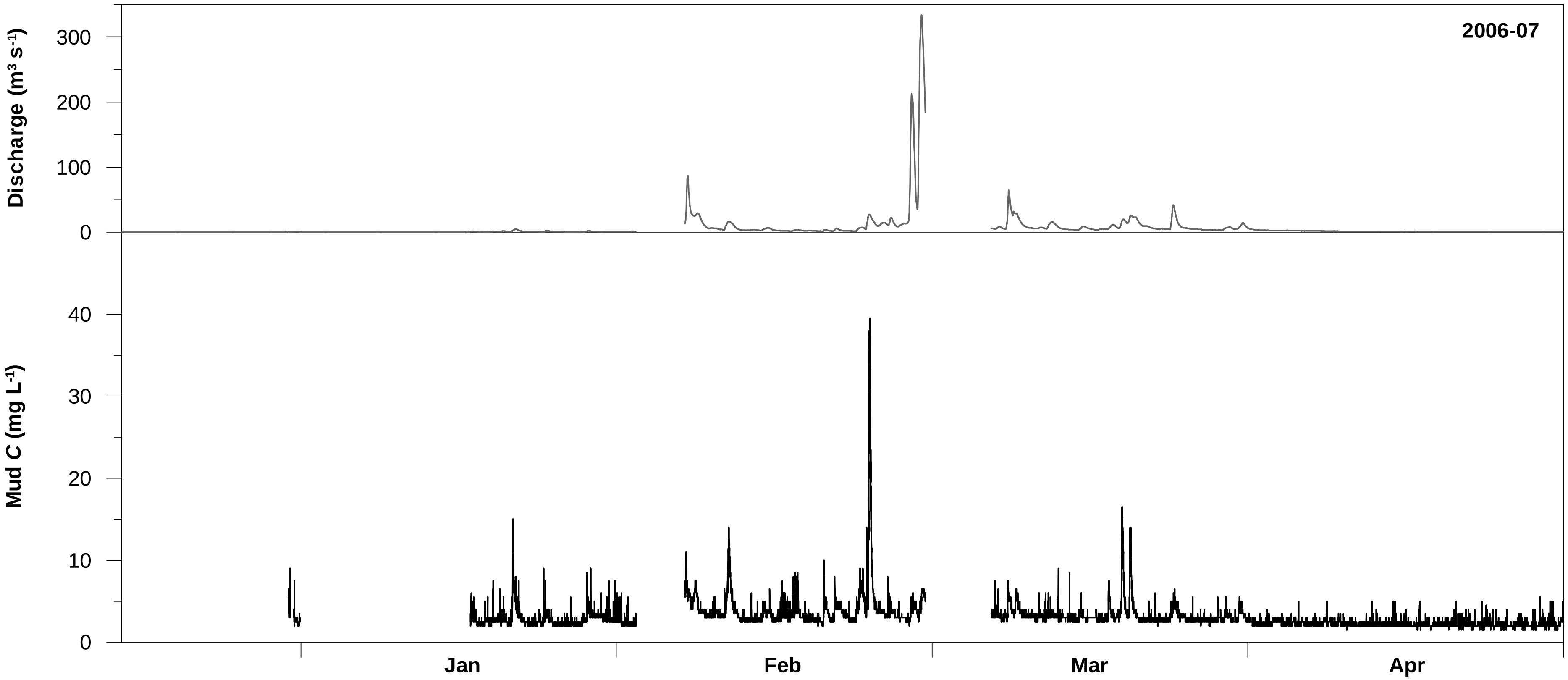


Figure 5.2b Continuous mud *C* data derived from the turbidimeter record for the 2006–07 wet season at GCDS. Discharge data are also shown.

5.2 Missing data

During the 2006–07 wet season there were periods where no turbidity data were recorded at both GCUS and GCDS, which means that the annual sedigraphs are incomplete. The reason for each gap is documented in Table 5.1.

Table 5.1 Missing turbidity data during 2006–07 at Gulungul Creek

Station	Missing period	Comments
GCUS	Dec & Jan	Stage height was below the level of the turbidimeter and hence no turbidity data were recorded. During these low flow periods, mud *C* was at baseflow concentrations of approximately 1 mg L^{-1}.
	1–22 Mar	Flood damage to Datataker on 1 March. Subsequently, no data were recorded until replacement Datataker was installed on 22 March.
	11–23 Apr	Data were lost due to a download error. The gap occurred during a period when no rainfall or runoff events occurred and, therefore, mud *C* was likely to be at baseflow concentrations of approximately 1 mg L^{-1}.
GCDS	Dec & Jan	Stage height was below the level of the turbidimeter and hence no turbidity data were recorded. During these low flow periods, mud *C* was at baseflow concentrations of approximately 2-3 mg L^{-1}.
	1–6 Feb	Problem with pressure transducer sensor. As a result, no stage data were collected until a replacement sensor was installed on 6 February. Turbidity data collection is triggered by the pressure transducer, therefore, no turbidity data were collected during this period.
	1–7 Mar	Flood damage to Datataker on 1 March. Subsequently no data were recorded until replacement Datataker installed on 7 March.

6 Impact assessment

Fine suspended sediment moves through stream systems in pulses or waves generated by discharge events. Reliable impact assessment requires an understanding of the mud loads transported during these pulses. Mud load during a pulse is defined as the area under the event sedigraph, where mud *C* begins and ends at approximate baseflow levels (2–5 mg L^{-1}) (Fig 6.1).

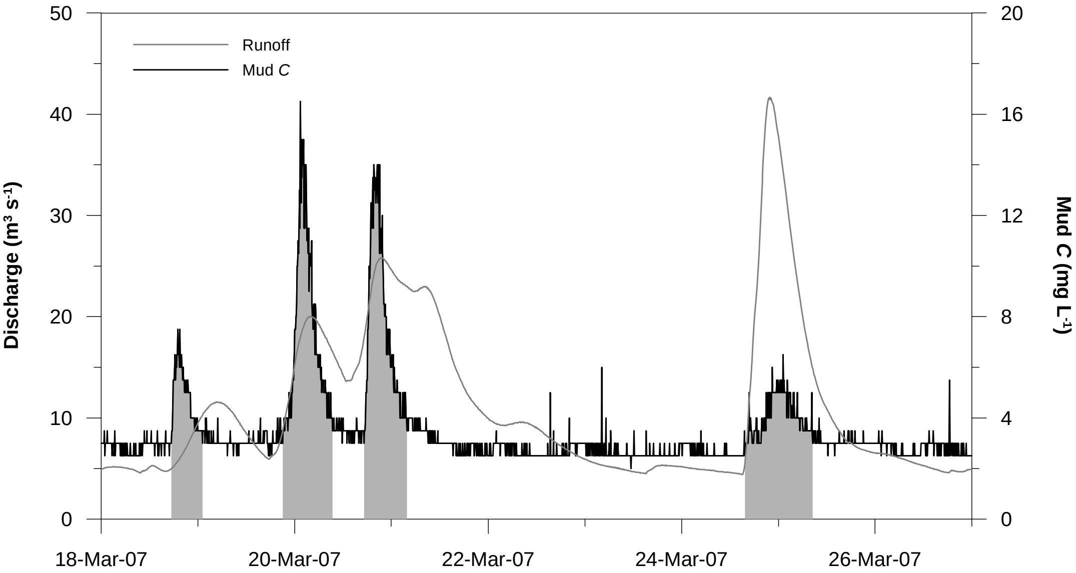


Figure 6.1 Hydrograph and sedigraph at GCUS during a 9-day period of the wet season. The mud pulses are indicated as shaded regions of the sedigraph.

Trigger levels for event mud loads based on current, pre-rehabilitation conditions (which can be used for future impact assessment) were derived using two techniques:

1. Before-After-Control-Impact, paired difference design (BACIP) (Stewart-Oaten et al 1986, 1992), and
2. A relationship between event mud load and corresponding event discharge characteristics

6.1 BACIP

Previous studies by Evans et al (2004) and Moliere et al (2005b) used a Before-After-Control-Impact, paired difference design (BACIP) (Stewart-Oaten et al 1986, 1992, Humphrey et al 1995) to establish trigger levels for mud concentration and mud load respectively for the nearby Ngarradj catchment. These trigger levels were derived in accordance with The Australian and New Zealand water quality guidelines (WQG) (ANZECC & ARMCANZ 2000) and, when exceeded, should inititate a management response.

Using a similar approach to the Ngarradj catchment, GCUS and GCDS were treated as paired sites. Event mud load data collected during 2005–06 and 2006–07 were used to establish preliminary trigger values for the event-based BACIP analysis. During the two year monitoring period there were 19 events with complete event load data collected at the two stations. (Event load data for events observed at GCUS and GCDS during 2005–06 are given in Moliere et al (2007). Event load data for events observed at each station during 2006–07 are given in Appendix A.)

In this report, we investigate two methods for BACIP analysis – (1) simple comparison of differences in event mud loads measured at GCDS and GCUS (Fig 6.2), and (2) comparison of differences of log-transformed event mud loads at the two stations (Fig 6.3). The log-transformation is effectively an assessment of the ratio between GCDS and GCUS as shown in Equation (1).

$$\log(GCDS) - \log(GCUS) = \log\left(\frac{GCDS}{GCUS}\right) \tag{1}$$

The trigger levels associated with both types of analysis are based on the 80th, 95th and 99.7th percentiles of the data. These trigger levels can potentially be used to specifiy increasing levels of interventions by supervising authorities and the mining company to control impact. This is analgous to the focus, action, and limit framework establish for management of water quality in Magela Creek.

The events of ‘interest’ are those that lie above the 95th percentile because these are events where significantly elevated mud loads are measured at GCDS relative to the load at GCUS. Using a comparison of differences in event mud loads, the analysis indicated that one event lies above the 95th percentile line (28 February 2007) (Fig 6.2). Using a comparison of differences of log-transformed event mud loads, the analysis indicated that an event that occurred on 23 February 2007 lies above the 95th percentile line (Fig 6.3).

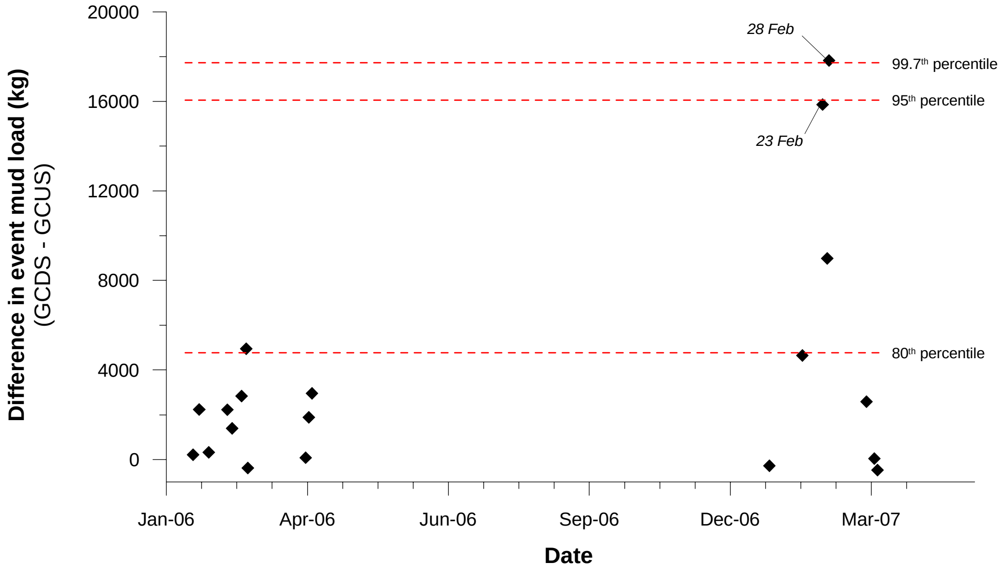


Figure 6.2 Temporal variation of the difference in event mud loads measured at GCDS and GCUS during 2005–06 and 2006–07 (indicated as ◆). The 80th, 95th and 99.7th percentiles of the difference in event mud loads are also shown.

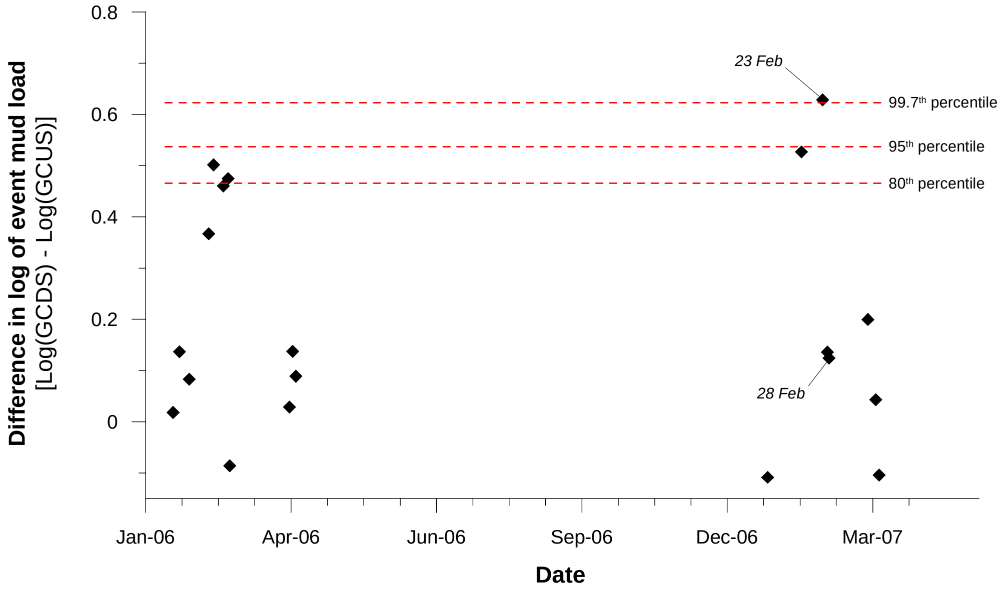


Figure 6.3 Temporal variation of the difference in the logarithms of the event mud loads measured at GCDS and GCUS during 2005–06 and 2006–07 (indicated as ◆). The 80th, 95th and 99.7th percentiles of the difference in the logarithms of the event mud loads are also shown.

6.2 Relationship between mud load and discharge characteristics

An alternative to the BACIP approach is the use of a relationship between event mud load and corresponding event discharge characteristics – including total event runoff, total discharge of the rising stage of the hydrograph, maximum periodic rise and recovery period preceding the event (ie time taken since previous rainfall-runoff event). Moliere et al (2005c) found significant relationships between event mud load and corresponding event discharge characteristics for stations within the Ngarradj catchment of the form:

$$\text{Total mud load} = K'(Q_T)^a\, Ri^b \qquad (2)$$

where Q_T is total discharge during the rising stage of the hydrograph, *Ri* is maximum periodic rise in discharge over 6-minutes and *a*, *b* and *K′* are fitted parameters.

This relationship was shown to be valid for different subcatchment areas within the Ngarradj catchment and was able to differentiate between various types of runoff events (ie a short-lived, high magnitude runoff event and a long duration, low magnitude runoff event).

Significant relationships were fitted for both stations (Eqns 3 & 4) using all event data collected at the site i.e. a four-year monitoring period at GCUS (2003-07) and a two-year monitoring period at GCDS (2005–07).

$$T_{GCUS} = 59.0 Q_T^{0.37} Ri^{0.78} \quad (R^2 = 0.92;\ n = 52;\ p<0.001) \qquad (3)$$

$$T_{GCDS} = 269 Q_T^{0.27} Ri^{0.71} \quad (R^2 = 0.81;\ n = 24;\ p<0.001) \qquad (4)$$

Outliers were identified as events outside two standard residuals from the line of best fit. These were removed from the analysis and the relationships were refitted as follows:

$$T_{GCUS} = 88.7 Q_T^{0.37} Ri^{0.82} \quad (R^2 = 0.93;\ n = 50;\ p<0.001) \qquad (5)$$

$$T_{GCDS} = 56.6 Q_T^{0.38} Ri^{0.60} \quad (R^2 = 0.87;\ n = 22;\ p<0.001) \qquad (6)$$

Figure 6.4 shows the event mud loads at GCUS and GCDS observed during the monitoring period plotted against the fitted relationships (Eqns 5 & 6 respectively). Observed loads are normally distributed around the best-fit line (predicted loads) so +1 SD, +2 SD and +3 SD from the 1:1 line were used to derive trigger levels. The events of ‘interest’ are those that lie above the +2 SD line as these are events that have a relatively high mud load compared to the corresponding runoff characteristics. This analysis indicates that one event with an elevated mud load was recorded at GCUS (31 December 2004) (Fig 6.4a) and two events with elevated loads were recorded at GCDS (25 April 2006 & 23 February 2007) (Fig 6.4b).

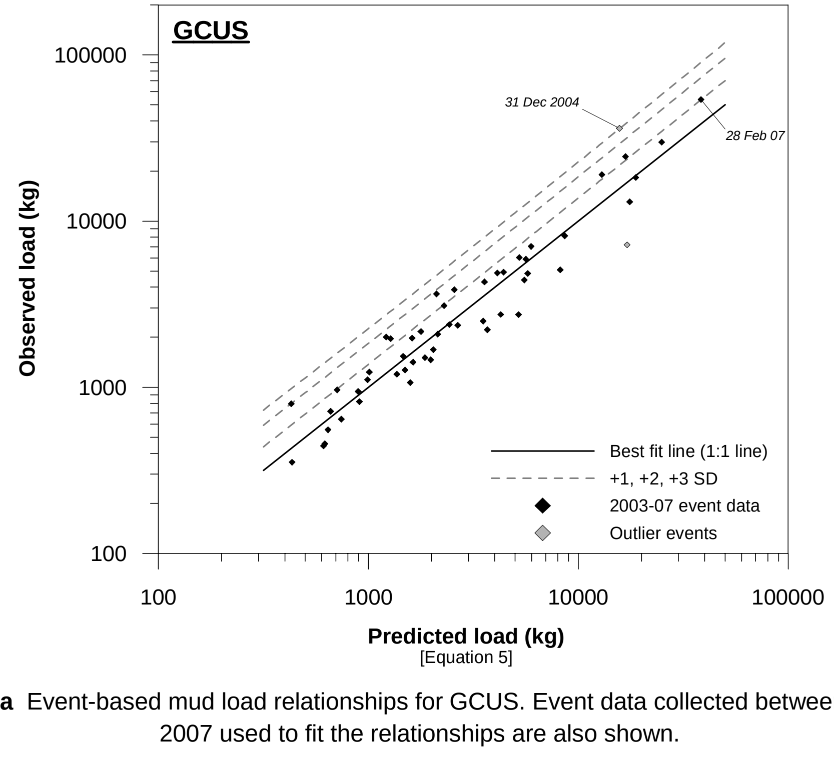


Figure 6.4a Event-based mud load relationships for GCUS. Event data collected between 2003 and 2007 used to fit the relationships are also shown.

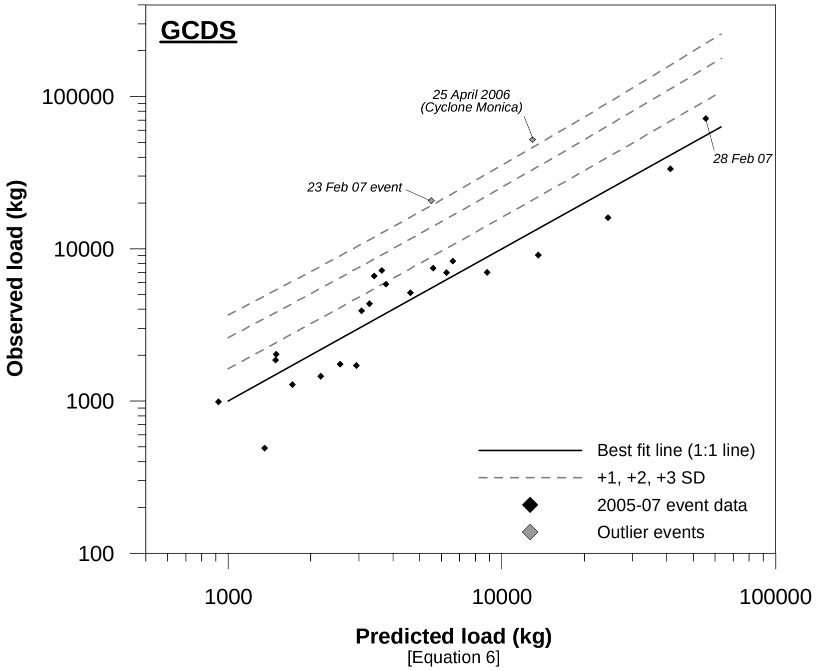


Figure 6.4b Event-based mud load relationships for GCDS. Event data collected between 2005 and 2007 used to fit the relationships are also shown.

6.3 Discussion

The BACIP analysis using simple comparison indicated that the event on 28 February 2007 (the largest monitored event) had a significantly elevated mud load at GCDS compared to that measured at GCUS (Fig 6.2). However, the log-transformed difference method indicates that the 28 February 2007 event plots well below the 80th percentile line (Fig 6.3). The mud load–discharge relationship fitted for GCDS (and GCUS) also indicated that the mud load on 28 February 2007 was not significantly elevated compared to the load predicted using the event discharge (ie the event plots within +2 SD of the 1:1 line) (Fig 6.4).

This analysis indicates that the BACIP approach using a direct difference comparison between event loads at the two sites is biased towards events with large mud loads. For example, the mud load at GCDS and GCUS during the event on 28 February 2007 was 72 t and 54 t respectively. This corresponds to a difference of 18 t, the largest difference in mud load between the two stations for the two-year monitoring period. However, the mud load at GCDS during this event is only 1.3 times that measured at GCUS and the log-transformed difference value plots well below the 80th percentile for this method of data analysis.

Consider the event on 23 February 2007 where the mud load measured at GCDS of 21 t is more than four times the 5 t measured at GCUS, but the difference is 16 t. This event exceeds the 99.7th percentile for the log-transformed difference method (Fig 6.3) but is within the 95th percentile for the simple difference analysis (Fig 6.2). Using the log-transformed difference method, a number of events exceed trigger levels where GCDS loads are relatively much greater than GCUS loads. These same events are below triggers levels using simple differences because they may be relatively small discharge events where total loads are less and subsequently the difference in loads between sites will be small. Alternatively, a large mud load event associated with a high magnitude flood may plot above the simple difference 95th percentile line despite it being a natural, non-impacted event.

Both the log-transformed difference method (Fig 6.3) and the mud load-discharge relationship fitted for GCDS (Fig 6.4b) identified the event on 23 February 2007 as an outlier. That is, this event had a significantly elevated mud load at GCDS relative to (1) the mud load measured at GCUS, and (2) the predicted load using event discharge characteristics at GCDS, respectively. The mud pulse for this event at GCDS peaked at about the same time as the hydrograph (Fig 6.5). The sedigraph generally peaks before the hydrograph (as shown in Figure 6.5 at GCUS). As a result of this 'shift' in the timing of the mud *C* peak at GCDS, the observed mud load is elevated compared to that at GCUS, and to the predicted load for that event discharge at GCDS.

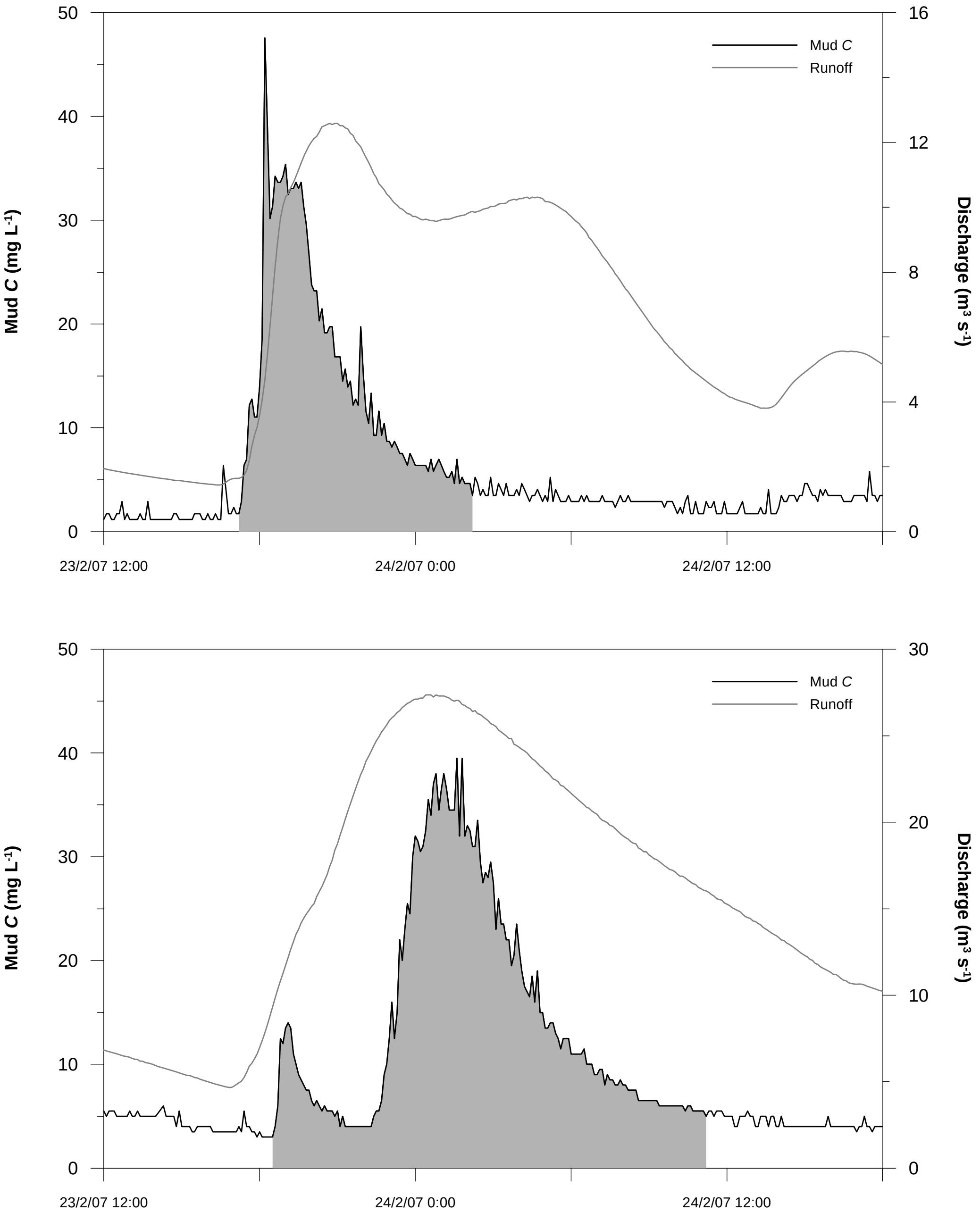


Figure 6.5 Hydrograph and sedigraph at GCUS (Top) and GCDS (Bottom) during 23–24 February 2007. The mud pulses associated with the storm events are indicated as shaded regions of the sedigraph.

Intense rainfall associated with this event was recorded for approximately one hour at all five rain gauges (see Fig 1.1 for locations). Rainfall data observed at both GCUS and GCDS during this event are almost identical (Appendix A). However, maximum rainfall intensities at both Jabiru airport and the Tailings Dam during this event are higher than that recorded at GCUS and GCDS. Maximum rainfall intensity for durations of 10-min and 20-min were the highest at Jabiru airport for the 2006–07 wet season. The rainfall data indicates that the storm centre may have been over the mine-site tributaries between GCUS and GCDS. Therefore, it is possible that the contribution of mud load at GCDS from the ungauged, mine-impacted tributaries downstream of GCUS may have been relatively high during this runoff event and subsequently affected the timing of the sedigraph peak. However, this is difficult to clarify given the fact that flow and mud *C* are not monitored in these tributaries. It is recommended that turbidity data be collected at G8210012 to better assess inputs from small streams draining the western side of the footprint of the tailings dam.

The mud load recorded at GCDS on 25 April 2006 during runoff associated with Cyclone Monica plots as an outlier using Equation 6 (Fig 6.4b). Treefall along the channel banks was a differentiating physical factor (compared with the ‘normal’ riparian conditions) that would have been expected to have resulted in increased stream mud concentrations during the event. Unfortunately, turbidity/mud concentration data were not recorded at GCUS during this event owing to damage to the gauging station (Moliere et al 2007). Since cyclonic treefall was catchment-wide, the mud load at GCUS *may* also have been elevated relative to event discharge characteristics. This shows the value of assessment using the mud load-discharge relationships for a given gauging station. Once a pre-impact relationship is developed for a site, upstream data are not required to assess post-impact conditions. This is a ‘before-after’ assessment in a temporal rather than a spatial sense. Such an approach is predicated on having obtained a sufficient record of downstream data before the impacting activity is established in the catchment. It is recommended that upstream data are collected during the period of establishing the relationship to ensure that catchment characteristics are fully understood. This approach also does not replace the need for monitoring of water quality upstream and downstream as part of an ongoing water quality compliance monitoring program.

Streams are highly variable systems where the magnitude of event mud loads is driven by hydrology. This analysis indicates the log-transformed difference method (Fig 6.3) and the mud load-discharge relationship fitted for GCDS (Fig 6.4) may be more robust for assessing impact than using event-mud-load simple differences between GCDS and GCUS.

6.4 Cyclone Monica impact assessment

Cyclone Monica (Category 3 cyclone) moved through the Gulungul Creek catchment early on 25 April 2006. Substantial tree fall occurred throughout the catchment as a result high wind velocities at a time when the soil was saturated towards the end of the wet season. It is important to assess the changes to the sediment transport characteristics as a result of catchment-wide treefall associated with this event. To determine whether a change in sediment transport characteristics has occurred or not, mud load data collected during 2006–07 were compared to mud load data collected prior to the cyclone using: (1) BACIP analysis based on differences of the log-transformed event mud loads, and (2) relationship between event mud load and corresponding event discharge characteristics (described in Sections 6.1 and 6.2 respectively).

A *t*-test showed that the differences in the log-transformed event mud loads for 2006–07 events were not significantly different to those for events observed prior to the cyclone

(2005–06 data). In other words, the BACIP analysis indicates that Cyclone Monica did not have a significant impact on sediment transport characteristics within the catchment.

A fitted relationship was derived between event mud load and corresponding discharge characteristics for each station (of the form shown in Equation 2) based on data collected prior to the cyclone (2003–2006) (Eqns 7 and 8). (Similar to above (Section 6.2), outliers that were identified as events outside two standard residuals from the line of best fit were removed from the analysis and the relationships refitted.)

$$T_{GCUS} = 97.0 Q_T^{0.32} Ri^{0.78} \qquad (R^2 = 0.91;\ n = 40;\ p<0.001) \qquad (7)$$

$$T_{GCDS} = 56.7 Q_T^{0.37} Ri^{0.52} \qquad (R^2 = 0.86;\ n = 11;\ p<0.001) \qquad (8)$$

Event mud load data observed during 2006–07 at each station were plotted against these fitted relationships derived for the previous years (Fig 6.6). There were 10 and 12 mud load events observed during 2006–07 at GCUS and GCDS respectively (Appendix A). All 10 events at GCUS fell within +2 SD of the fitted relationship and lie around the 1:1 line (Fig 6.6a). All but one of the 11 events at GCDS fell within +2 SD of the fitted relationship and generally lie around the 1:1 line (Fig 6.6b). The event that lies above the +2 SD level of the fitted relationship at GCDS occurred on 23 February 2007, which was identified as an outlier in the previous analysis (refer to the description of this event in Section 6.2). Therefore, in general, event mud loads for the 2006–07 wet season relative to the event discharge characteristics are not significantly different to previous years. This analysis indicates that, similar to BACIP, treefall associated with Cyclone Monica did not have a significant impact on sediment transport characteristics within the Gulungul Creek catchment.

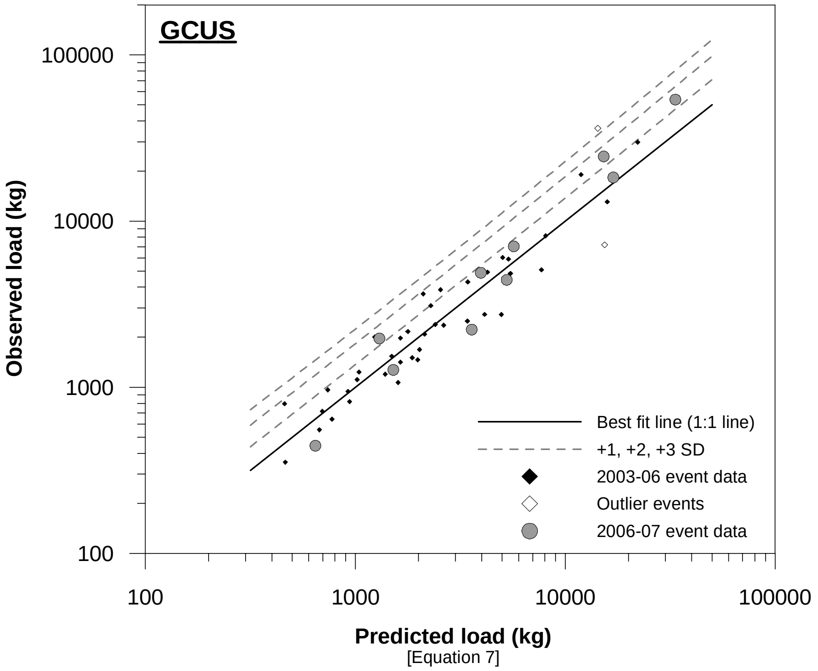


Figure 6.6a Event-based mud load relationships for GCUS. Event data collected between 2003 and 2006 used to fit the relationships and the 2006–07 data are also shown.

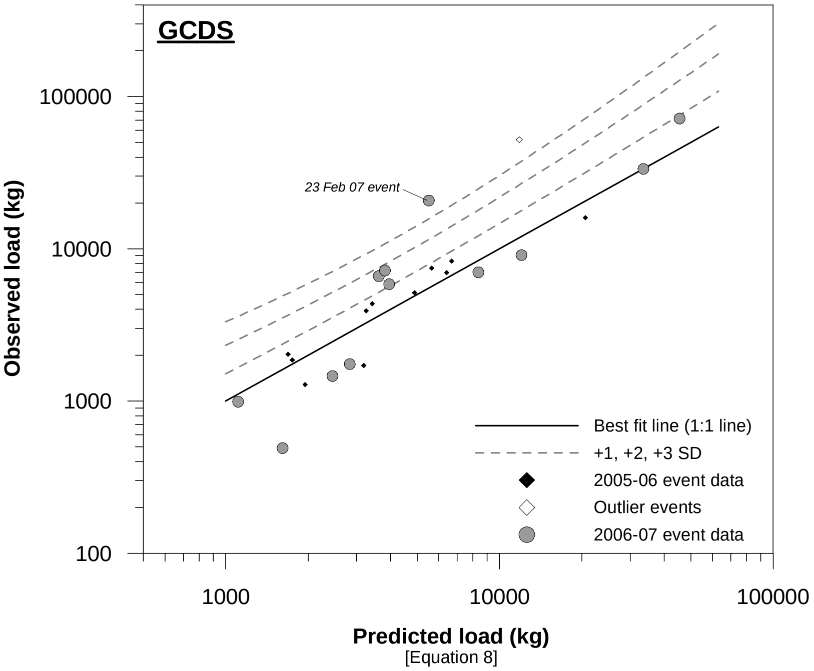


Figure 6.6b Event-based mud load relationships for GCDS. Event data collected between 2005 and 2006 used to fit the relationships and the 2006–07 data are also shown.

7 Conclusions

Continuous rainfall, runoff and mud concentration data collected within the Gulungul Creek catchment during 2006-07 are presented in this report. Annual rainfall across the catchment was well above average, with annual rainfall recorded at Jabiru airport corresponding to a 1:1000 y rainfall year. This is largely attributed to the record rainfall which occurred during February and March 2007. Annual flow in the catchment was also above average. Total annual runoff at G8210012 was more than three times the mean annual runoff volume based on historical data collected by NRETA between 1971 and 1993.

The rainfall-runoff event associated with Cyclone Monica, which moved through the catchment on 25 April 2006, contributed to channel form changes along Gulungul Creek, particularly infilling of the channel bed at GCUS and GCDS. As a result, velocity-area gaugings conducted during 2006-07 were used to fit new rating curves for the two stations. An assessment was also made on the impact of Cyclone Monica on stream suspended sediment transport within Gulungul Creek. A combination of an event-based Before-After-Control-Impact, paired difference design (BACIP) approach and a relationship between event mud load and corresponding event runoff characteristics showed that the sediment transport characteristics within the catchment during 2006–07 were not significantly different to previous years.

During the 2006–07 wet season, an extraordinary rainfall event occurred across the region over a 3-day period between 27 February and 2 March 2007, which resulted in the highest flood levels recorded within the Gulungul Creek catchment since recording began in 1971. Equipment at GCUS and GCDS were submerged by floodwaters, resulting in data loss during the peak and subsequent recession of the flood. Rainfall data collected at G8210012 indicated that maximum rainfall intensity within the catchment exceeded a 1:100 y storm event for durations between 6 and 72 hours. The peak of the flood occurred at all three stations during the afternoon of 1 March 2007. The fitted flood frequency curve for G8210012 indicates that the peak discharge during the flood event on 1 March 2007 corresponds to a 1:100 y event.

Prior to the 2007–08 wet season it is recommended that rain gauges and dataloggers at GCUS and GCDS are elevated above their current positions to ensure that streamflow will not rise above the equipment for most flood conditions. It is also recommended that a turbidimeter is installed at G8210012 to better assess elevated mud loads downstream of ERA Ranger Mine tailings dam compared to loads measured upstream.

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Appendix A
Mud pulse characteristics

Table A.1 Rainfall, discharge and mud characteristics for each mud pulse event observed at GCUS and GCDS during 2006–07

Station	Date	Rain		Discharge		Mud pulse			
		Total rainfall (mm)	Start of rainfall(1)	Peak discharge (m^3)	Time of Q_p	Peak mud C ($mg\ L^{-1}$)	Time of mud C_p	Duration	Mud load (kg)
GCUS	20 Jan	15	16:54	9.2	03:48	20.9	23:24	20 Jan 21:24 – 21 Jan 04:42	1271
	06 Feb(2)	106	00:42	60.1	14:18	26.7	10:12	06 Feb 03:00 – 06 Feb 17:24	18302
	07 Feb(2)	48	02:00	27.7	12:00	19.7	03:54	07 Feb 02:06 – 07 Feb 15:30	7039
	10 Feb	37	05:54	8.7	09:48	23.2	07:30	10 Feb 06:06 – 10 Feb 14:42	1966
	23 Feb	70	16:24	12.6	20:42	47.6	18:12	23 Feb 17:12 – 24 Feb 02:12	4879
	27 Feb	100	16:42	73.6	01:24	24.9	19:42	27 Feb 18:00 – 28 Feb 07:06	24472
	28 Feb	178	14:24	123	21:00	31.9	16:36	28 Feb 14:30 – 01 Mar 02:30	53855
	24 Mar	45	14:54	25.2	18:54	14.7	16:48	24 Mar 15:00 – 25 Mar 01:30	4427
	29 Mar	7	14:30	4.8	18:36	8.7	16:42	29 Mar 15:36 – 29 Mar 21:30	445
	30 Mar	10	19:12	17.6	04:48	11.0	01:48	30 Mar 21:42 – 31 Mar 10:36	2221
GCDS	21 Jan	11	17:06	4.9	11:12	15.0	04:18	21 Jan 02:06 – 21 Jan 15:30	990
	10 Feb	24	06:00	16.5	15:54	14.0	16:30	10 Feb 07:42 – 11 Feb 01:00	6612
	23 Feb	68	16:54	27.4	00:24	39.5	01:36	23 Feb 18:30 – 24 Feb 11:12	20736
	27 Feb	117	17:06	213	01:12	6.0	00:36	27 Feb 22:00 – 28 Feb 15:12	33459
	28 Feb	182	14:36	334	23:54	6.5	00:42	28 Feb 19:06 – 01 Mar 08:18	71685
	09 Mar(2)	52	22:18	65.0	06:54	7.5	05:18	09 Mar 04:18 – 09 Mar 14:24	9088
	18 Mar	11	09:42	11.6	04:42	7.5	19:30	18 Mar 17:24 – 19 Mar 05:00	1460
	19 Mar(2)	28	17:42	20.0	03:42	16.5	01:24	19 Mar 21:00 – 20 Mar 09:24	5856
	20 Mar(2)	12	12:42	25.9	21:30	14.0	19:36	20 Mar 17:12 – 21 Mar 03:48	7199
	24 Mar	59	15:12	41.7	21:54	6.5	01:12	24 Mar 15:42 – 25 Mar 08:30	7008
	29 Mar	25	14:06	8.1	06:00	5.5	21:30	29 Mar 19:30 – 30 Mar 00:54	491
	31 Mar	10	19:12	14.7	12:42	5.5	04:54	31 Mar 01:54 – 31 Mar 14:06	1748

(1) Start of effective rainfall (ie rainfall that produces runoff)

(2) Event not used in BACIP analysis because either data were not collected at both sites or a mud pulse was not observed at one of the sites.