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Morphodynamic changes caused by Cyclone Monica in April 2006 on Ngarradj Creek, Northern Territory, Australia

Michael Saynor[1], Wayne Erskine[2,3]
[1](*Environmental Research Institute of The Supervising Scientist, GPO Box 461, Darwin NT 0801 Northern Territory, Australia)*
[2](*School Of Environmental and Life Sciences, The University of Newcastle, PO Box 127, Ourimbah NSW 2258, Australia)*
[3](*Research Institute for The Environment And Livelihoods, Charles Darwin University NT 0909, Australia)*

ABSTRACT: In April 2006, severe tropical Cyclone Monica occurred in western Arnhem Land, northern Australia. The eye of the cyclone passed directly over the Ngarradj Creek catchment which suffered extensive tree fall and trunk and branch damage with estimated wind speeds of 140 km/hour. Tree fall and trunk and branch damage in the Ngarradj Creek catchment was widespread, especially in the riparian monsoon forest along the channel and produced a large increase in large wood loading. The resultant flood had relatively small peak discharges and unit stream powers at all three gauging stations which were used as monitoring reaches. As a result, very little bank erosion was recorded but there were minor changes in bed elevation despite mean bed-material size not changing. The largest historical flood occurred in February/March 2007 and was not associated with a cyclone. This event caused far greater channel change and highlights that not all large tropical floods are associated with cyclones. The morphodynamic impacts of extreme winds are much less than extreme floods in this tropical environment.
Keywords: extreme events, large floods, morphological change, tropical cyclones

I. INTRODUCTION

Wind is a common disturbance agent in forests across the world [1,2] but the significance of tropical cyclones as a supplier of large wood to tropical rivers is still poorly known [3]. While tropical cyclones are often associated with large floods [4,5], this is not always the case [6]. In late April 2006, Tropical Cyclone Monica occurred in western Arnhem Land and Kakadu National Park, northern Australia and was characterised by very strong winds [1,7] but relatively low rainfall and runoff [7].

The morphodynamic significance of tropical cyclones is dependent on the maximum wind speeds which determine the recruitment of large wood from the riparian forest to the bankfull channel and the stability of the riparian vegetation community as well as the peak, duration and frequency of the coinciding flood peak. Tropical Cyclone Monica occurred on 25th April 2006 in the Ngarradj Creek catchment at Jabiluka, northern Australia (Fig. 1). In this paper we investigate the duration and magnitude of the flood associated with Cyclone Monica and its morphological impacts on the river channel.

Ngarradj Creek is a small sand-bed stream (total catchment area of 67 km^2) that has its headwaters in the Arnhem Land Plateau and is a right bank tributary of Magela Creek (Fig. 1). It is located approximately 250 km east of Darwin (Fig. 1) in the Alligator Rivers Region (ARR) and experiences a tropical climate characterised by distinct wet and dry seasons. The channels are forested, laterally stable, sinuous, low energy, sand-bed streams with high large wood loadings [8] and often have an *Allosyncarpia ternata* riparian gallery forest [3]. Three river gauging stations (Fig. 1) were installed in 1998 to collect hydrological data, Swift Creek gauge (catchment area 43.6 km^2), Upper Ngarradj gauge (catchment area 18.8 km^2) and East Tributary gauge (catchment area 8.5 km^2). East Tributary and Upper Ngarradj gauging stations were discontinued in June 2007.

II. CYCLONE MONICA

On 25 April 2006, severe Tropical Cyclone Monica impacted the coast of northern Australia, including Ngarradj catchment. The very destructive core of Monica (category 5) crossed the Northern Territory coastline approximately 35 km west of the township of Maningrida with estimated maximum wind gusts of 360 km h^{-1} [1]. The eye of the cyclone passed almost directly over Ngarradj Catchment and Jabiluka mine, continuing through to Jabiru (Ranger mine)[1]. By the time it arrived in Jabiru, the intensity had reduced to a category 2 level (estimated maximum wind gusts 130 km h^{-1})[1]. Monica then continued to track westerly, weakening to below cyclone intensity 12 hours after first making landfall.

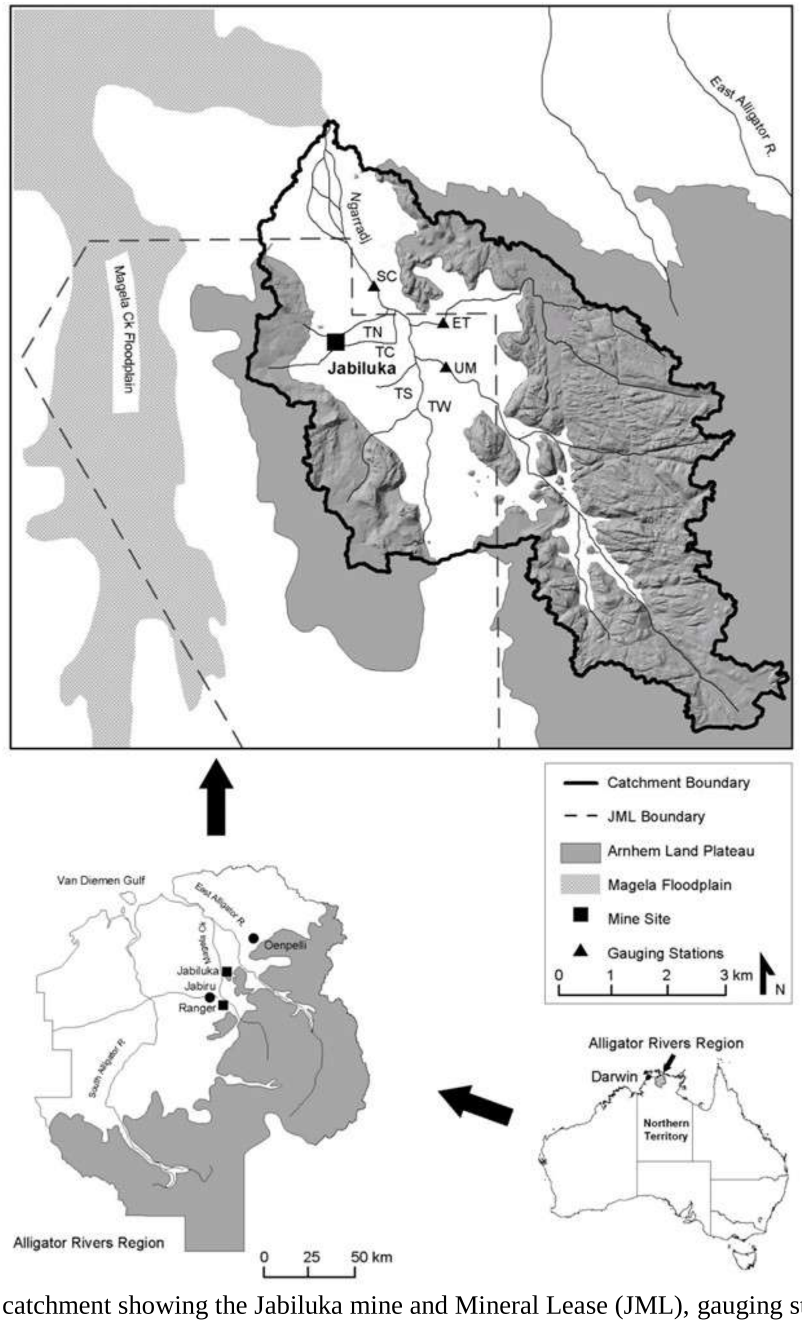

Figure 1 The Ngarradj catchment showing the Jabiluka mine and Mineral Lease (JML), gauging stations and local drainage names. SC refers to Swift Creek gauging station, ET East Tributary gauging station and UM Upper Ngarradj gauging station. Other tributaries shown, TN Tributary North, TC Tributary Central, TS Tributary South and TW Tributary West are not discussed in this paper.

Cyclone Monica was considered to be a small cyclone in spatial extent, however, at its core, the winds were extremely destructive [1]. There was a large amount of tree throw and damage in the Ngarradj Creek catchment [7]. Cyclone Monica was an example of an extreme wind event in the Ngarradj Creek catchment although it did not have the accompanying prolonged heavy rainfall and subsequent runoff that is often associated with a cyclone [7]. Most of the immediate damage was caused by high wind velocities knocking over and damaging trees. Closure is currently being planned for the Ranger uranium mine and one issue that needs to be understood is the impact of extreme wind events on revegetated areas of the mine [7].

At the East Tributary gauging station (Fig. 1) the peak height of the Cyclone Monica flood was 1.626 m at 05:54 hours on 25 April 2006. The corresponding peak discharge was 8.21 m^3s^{-1} and the duration of overbank flow was 4.5 hours. At Ngarradj Creek at Upper Ngarradj gauging station (Fig. 1) the peak height of the Cyclone Monica flood was 2.029 m at 09:36 hours on 25 April 2006. The corresponding peak discharge was 12.40 m^3s^{-1} and the duration of overbank flow was 4.9 hours. At Ngarradj Creek at the Swift Creek gauging station (Fig. 1) the peak height of the Cyclone Monica flood was 2.078 m at 11:36 hours on 25 April 2006. The corresponding peak discharge was 18.76 m^3s^{-1} and the duration of overbank flow was 12.1 hours.

A total census of large wood in the bankfull channel at the East Tributary and Upper Ngarradj gauges was completed in 2002 and in 2006 [9]. Large wood was defined as living and dead trees and branches of any length that were at least 0.1 m in diameter. At Upper Ngarradj, large wood loading increased after Cyclone Monica from 184 to 315 m^3/ha [9]. At East Tributary, large wood loading increased after Cyclone Monica from 302 to 560 m^3/ha [9]. In 2002 there were 272 individual pieces of large wood at Upper Ngarradj at an average spacing of 1.07 m which had increased to 697 pieces in 2006 at an average spacing of 0.41 m [9]. In 2002 there were 230 individual pieces of large wood at East Tributary at an average spacing of 0.57 m which had increased to 541 pieces in 2006 at an average spacing of 0.32 m [9]. Clearly Cyclone Monica was an important event for the recruitment of large wood [9], as shown at the East Tributary and Upper Ngarradj gauging stations in Fig. 2.

III. FEBRUARY AND MARCH 2007 FLOOD

Extreme rainfall between 27 February and 2 March 2007 occurred in the East Alligator River catchment and produced the highest flood since gauging commenced in 1998 on Ngarradj Creek. This 2007 flood was not associated with cyclonic activity. Floods caused by the same rain event also occurred on the neighbouring Magela and Gulungul Creeks [10] and the East Alligator River [6,11]. At the East Tributary gauge the 2007 flood had a peak discharge of 20.74 m^3s^{-1} and a duration of overbank flow of 48 hours. At the Upper Ngarradj gauging station the 2007 flood had a peak discharge of 31.80 m^3s^{-1} and a duration of overbank flow of 60.1 hours. The 2007 flood at Swift Creek had a peak discharge of 213 m^3s^{-1} and a duration of overbank flow of 65 hours. The recorder at the Swift Creek gauge was inundated by the flood peak which was estimated from a debris mark and converted to peak discharge by extrapolation of the rating curve.

The extreme rainfall that caused the 2007 flood was not caused by a cyclone but generated the largest flood on record at each of the three gauging stations in the Ngarradj catchment. At the Swift Creek gauge the peak discharge was an order of magnitude greater for the 2007 flood than for the flood generated by Cyclone Monica.

Figure 2 Photos before and after Cyclone Monica at East Tributary (A & B) and Upper Ngarradj (C & D). The before photos(A&C) should be compared with the after photos (B&D).A and C were taken on 10 Jan 2006, and B and D were taken on 3 May 2006.

IV. GAUGING STATION CROSS SECTIONS

In each gauging station reach, permanently marked cross sections were installed in the 1998 dry season and were resurveyed almost annually using a Topcon Total Station until 2007, with an additional survey in 2010. The cross sections were marked using a star picket driven into the ground with the top 0.3 m encased in concrete at each end of the cross-section. At each gauging station, cross sections were located upstream and downstream of the gauging station recorder. There was a total of 24 cross-sections installed, eight at each gauging station. Saynor et al. [12] found the following for the gauging reaches for the period 1998 to 2003:

- The East Tributary reach was stable due to the protective effects of the *Allosyncarpia ternata* riparian gallery forest,
- The upper Ngarradj gauge reach was also stable due to the protective effects of the *Allosyncarpia ternata* riparian gallery forest, with the channel bed aggrading slightly (as determined from scour chains [12]) due to supply of sand from the upstream catchment, probably from a combination of channel erosion and soil erosion from episodically burnt areas,
- The Swift Creek gauge reach was also stable, with minor bed aggradation.

In addition to the surveys discussed above [12], the cross sections were surveyed before Cyclone Monica in the 2004 dry season, after Cyclone Monica in the 2006 dry season and after the 2007 flood in the 2007 dry season. They were re-surveyed in 2010. The complete results are presented here for the first time. An example of each gauging station reach is shown in figs 3, 4 and 5. Each of the surveys from 1998 to 2004 is shown as a black line, as the banks are stable and the channel bed varied little over time, thus there is little difference between the surveys. On some of these cross sections erosion pins were installed for the period 1998 to 2002. Saynor and Erskine [13] found, using these erosion pins, that the banks at all three gauging stations were very stable, with bank erosion rates being non-significantly from zero. The post-Monica, post-2007 flood and the 2010 surveys are shown with different line markers to enable differentiation between the surveys.

Fig. 3 shows the surveys for East Tributary gauge at cross section 4. The other seven cross sections at this site showed similar channel changes. The survey in 2006 following Cyclone Monica shows minor bed degradation on the left bank side of the channel but aggradation against the right bank. There was minor bank erosion on the right bank. The 2007 survey shows scour across the whole channel and was up to 0.4 m deeper next to the left bank. The channel bed had aggraded by the 2010 survey, being similar to the pre-Cyclone Monica levels, except for a small section near the middle of the channel.

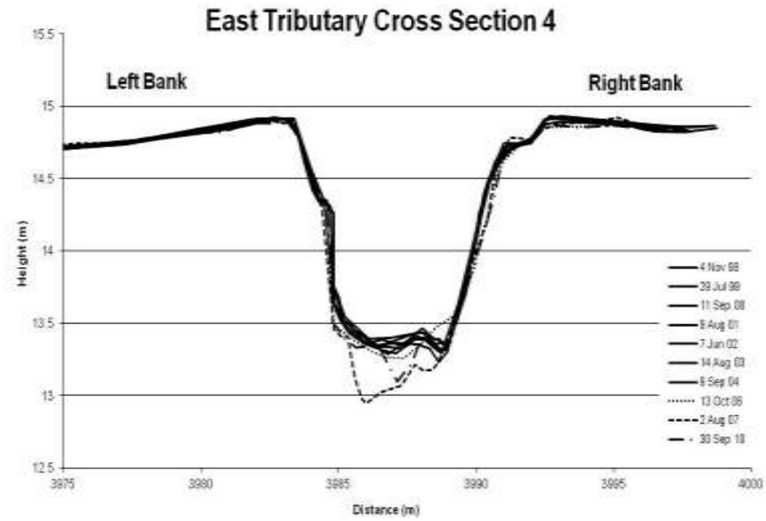

Figure 3 Cross section surveys at East Tributary cross section 4.

Fig. 4 shows the surveys for Upper Ngarradj gauge at cross section 5. The other seven cross sections at this site showed similar channel changes. There was minor bank erosion on the left bank following Cyclone Monica and some scour of the bed near the right bank. There was also scour of the bed near the right bank following the 2007 flood. The 2010 survey mostly overlaps with the pre-2004 surveys although there is some aggradation in the centre of the channel and near the right bank. At these cross sections, Cyclone Monica produced minor scour, the 2007 flood produced more scour, which had essentially been filled by the 2010 survey.

Fig. 5 shows the surveys for Swift Creek gauge at cross section 4. . The other seven cross sections at this site showed similar channel changes. The surveys prior to Cyclone Monica depict a stable cross section. The survey following Cyclone Monica shows up to 0.3 m of scour against both the left and the right banks.

Following the 2007 flood the channel was substantially scoured up to a maximum depth of 0.7 m across the whole bed. The channel had scoured further against the left bank by the 2010 survey, indicating that the channel at this time did not aggrade to the pre-2004 levels. The cross sections in figs 3, 4 and 5 show that the impact of Cyclone Monica on the channel geometry at Ngarradj Creek was less than the impacts of the 2007 flood.

V. CHANGES IN BED-MATERIAL PARTICLE SIZE

Bulk bed-material samples were collected with a trowel or small spade from at least three equally spaced points across the stream bed at each cross section [14]. These samples were oven dried at 105°C for 24 hours before being subjected to particle size analysis by sieving [14]. Graphic grain size statistics were calculated using the equations of Folk [15] and the phi scale for grain size. Phi (Φ) equals:

$$\text{Phi } (\Phi) = -\log_2 d \qquad (1)$$

where d is the grain size in mm.

Saynor et al [14] found, for the period 1998 to 2003, that a statistically significant increase in graphic mean size occurred between 1998 and 1999 at all three gauging stations. After 1999, graphic mean size remained constant [14].

The particle size statistics have been averaged for the 8 cross sections at each gauging station and are shown in Table 1 for the period 2003 to 2010.

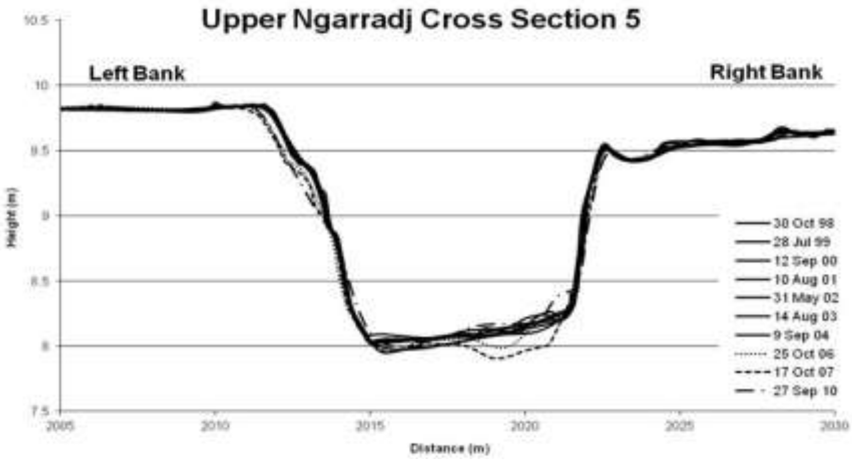

Figure 4 Cross section surveys at Upper Ngarradj cross section 5.

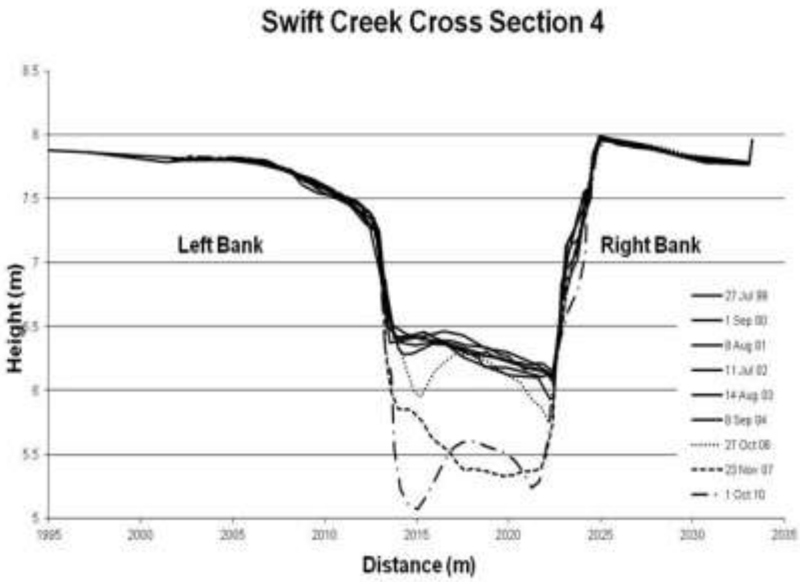

Figure 5 Cross section surveys for Swift Creek Gauge at cross section 4.

There has been no statistically significant change in graphic mean size of bed material at all three gauging stations between 2003 and 2010, as determined by the non-parametric Mann-Whitney U test. At East Tributary gauging station there was no difference between 2003 and 2006 with only a slight but non-significant fining in 2007 (from coarse to medium sand). Bed material had coarsened by 2010. Clearly Cyclone Monica and the largest historical flood have not altered bed material grain size and sand supply in the Ngarradj catchment.

Table 1 Average graphic mean values for the three gauging station reaches on Swift Creek

	East Tributary		Upper Ngarradj		Swift Creek	
	Average Graphic Mean (Φ)	Standard Error of Estimate (Φ)	Average Graphic Mean (Φ)	Standard Error of Estimate (Φ)	Average Graphic Mean (Φ)	Standard Error of Estimate (Φ)
2003	0.85	0.07	0.90	0.07	0.97	0.08
2004	0.79	0.11	0.95	0.06	0.98	0.25
2006[1]	0.85	0.14	1.00	0.06	0.83	0.57
2007[2]	1.27	0.14	0.87	0.07	0.99	0.19
2010	1.02	0.11	0.92	0.13	1.02	0.06

[1] – after Cyclone Monica
[2] – after Feb/Mar 2007 flood

VI. CONCLUSION

The take home message from our work is that Cyclone Monica damaged many riparian trees in the *Allosyncarpia ternata* riparian forest, both within the channel and on the floodplain but that the flood associated with the cyclone was relatively small. Greater morphodynamic change was affected by the largest historical flood of February/March 2007. No change in bank stability and little change in bed level were noted. Very high wind speeds and associated tree damage were not morphologically significant in the Ngarradj catchment. Although there was a significant increase in large wood loading due to Cyclone Monica [9], it did not cause bank erosion, outflanking of debris dams and avulsions. Our work suggests that these low energy, well vegetated, sinuous, sand-bed channels have the capacity to store very high large wood loadings without changing their morphodynamic state and behaviour.

The 2007 flood, which was not associated with a cyclone, had much larger peak discharges than the 2006 Cyclone Monica flood. Peak stream power was a better indicator of potential morphological change than maximum wind speed. Although there was more scour of the bed during the 2007 flood, partial recovery had occurred by the 2010 surveys.

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