Development of a spectral library for minesite rehabilitation assessment

K Pfitzner, A Bollhöfer & A Esparon

Introduction

The aim of this project is to develop a spectral library of land cover components measured in situ in order to make recommendations for appropriate acquisition of remotely sensed data for land cover condition assessment and monitoring of the mine environment and surrounding country. The hypothesis is that with a well designed approach to collecting field spectral measurements and metadata, extraneous factors can be accounted for, accurate processing of spectra can be performed and the first database of Top End spectra relevant to the mine environment can be developed.

To populate the spectral library, reflectance characteristics of weed and native ground covers have been sampled fortnightly from permanent plots at Crocodylus Park, CSIRO and Berrimah Farm near Darwin. Mineral assemblages and soils that represent both mining surfaces and the 'reference' surrounding country will be measured, along with spectra representing the operating mining environment, such as stockpile material.

A field spectrometer that measures reflectance continuously across 350–2500 nm at full-width-half-maximum (FWHM) resolution of 3 nm for the region 350–1000 nm and 10 nm for the region 1000–2500 nm is used to collect the spectra. The spectral data are supported by metadata describing the viewing and illumination geometries, environmental conditions and state of the target measured. SSD has developed standards for collecting field reflectance spectra and these have been reported previously. The Spectral Database will be used to reference, categorise and manage the spectral data and metadata, with the aim to query and analyse suitable spectra only, that are not influenced by extraneous factors that may influence data quality.

Results – vegetation sampling

As part of the spectral database development, dense and homogenous plots of vegetation, particularly those priority species of weeds and native ground covers that are of concern to the revegetation success at minesites, have been established and measured seasonally between 2006 and 2007. Selected examples of these vegetation plots are illustrated in Figure 1.

In 2006 and 2007, around 260 and 200 different sets of spectral measurements of native and weedy vegetation covers were made, respectively. The Research Scientist of this project was on maternity leave March–October 2007, but the collection of spectra and metadata continued with the Remote Sensing Technician. The status of the vegetation plots for the spectral library project was reported in an internal report (IR546), and the collection of spectra ceased in early 2008. The plots at Berrimah Farm and CSIRO were dismantled. Plots remain at Crocodylus Park, but these are not being maintained for homogeneity or density of coverage by the target species.

Digitaria milanjiana (Jarra Grass) _2008_01-23

Brachiaria humidicola (Tully Grass)_2008_01-23

Digitaria eriantha (Pangola Grass)_2008_01-23

Digitaria swynnertonii (Arnhem Grass)_2008_01-23

Stylosanthes humilis _2008_03_19

*Sorghum stipodeum*_2008_03_19

Hyptis suaveolens_2008_03_04

Melinis repens (red natal grass)_2008_03_19

Aeschynomene americana_2008_03_04

Pennisetum pedicellatum_2008_03_04

Figure 1 Examples of vegetation plots used to record the spectral reflectance of selected species over time

To maximise the usefulness of the spectra measured, and account for any extraneous variation in spectral measurement, a system was developed to organise and retrieve spectral and metadata records in SSD's Spectral Database. Metadata entries include SSD's standardised site and target descriptions, environmental and illumination conditions, measurement information and photographic records. SSD required a system to account for and link the spectral and metadata standards and hence, the database structure has been custom designed to maximise cross referencing between spectra, photos and metadata. An SQL server is used as a data warehouse to store all information.

The spectra and photos are stored as binary files within the database. The metadata table contains information about the conditions at the time spectra and photos were taken. Metadata include a unique code (site and date), date of spectral measurement, atmospheric conditions (smoke, haze, temperature, humidity, air pressure, wind direction, wind speed and description), cloud level and cover, probe height (from ground), plant height (from ground level) and ground description (by cover and phenology). Searches can be performed on the fields and individual records displayed. Figure 2 illustrates an example spectrum metadata page with associated photographs. Figure 3 displays the spectrum list for the same metadata and photo page illustrated in Figure 2.

The structure allows the user to easily query information. Selected spectra can be viewed and overlaid to give a visual comparison. Figure 3 provides an example of a solar irradiance, target and white reference spectra. Each spectrum has certain characteristics that can be used to categorise them through an iterative process. As part of the quality control procedure all spectra are processed through an algorithm that categorises the spectrum into a specified group depending on the defined boundary conditions. Spectra that are not found to fit into a known category are marked as undefined ('not defined') by the 'Classify' algorithm. These spectra require further examination and indicate problematic conditions.

Highlighting a detector array issue or atmospheric influence in a white reference spectrum is crucial for data analysis and these anomalies would be very difficult to detect visually with the volume of data that are being stored, processed and analysed. Accurate metadata is required during the data analysis stage to ensure that environmental conditions (such as solar azimuth) are not influencing the spectral response, particularly for time series of spectral measurements. Photographic records help to interpret and determine the quality of time series data by supporting quantitative and qualitative measurements of the hemispheric component.

Future work

Once all 'suspect' spectra have been filtered out, analysis can commence on the high integrity data. There are a number of spectral analysis management systems available online, including SAMS (Rueda & Wrona 2003), SPECCHIO (Hüni 2007, Hüni & Kneubühler 2007), SPECtrum Processing Routines (SPECPR) (Clark 1993, Kokaly 2005) and SpectraProc (Hüni & Tuohy 2006). SSD also has expertise in computing language and interactive environments for algorithm development, data visualisation, data analysis, and numeric computation.

There are a number of toolboxes available including project specific signal processing techniques. These may be tested in parallel to benchmark the performance of any custom methods produced by this project. The data will be analysed for both between and within species similarity and dissimilarity. Feasibility studies will be performed to determine the spectral separability of ground covers for a variety of remotely sensed platforms and recommendations made on the most appropriate datasets required for minesite rehabilitation assessment.

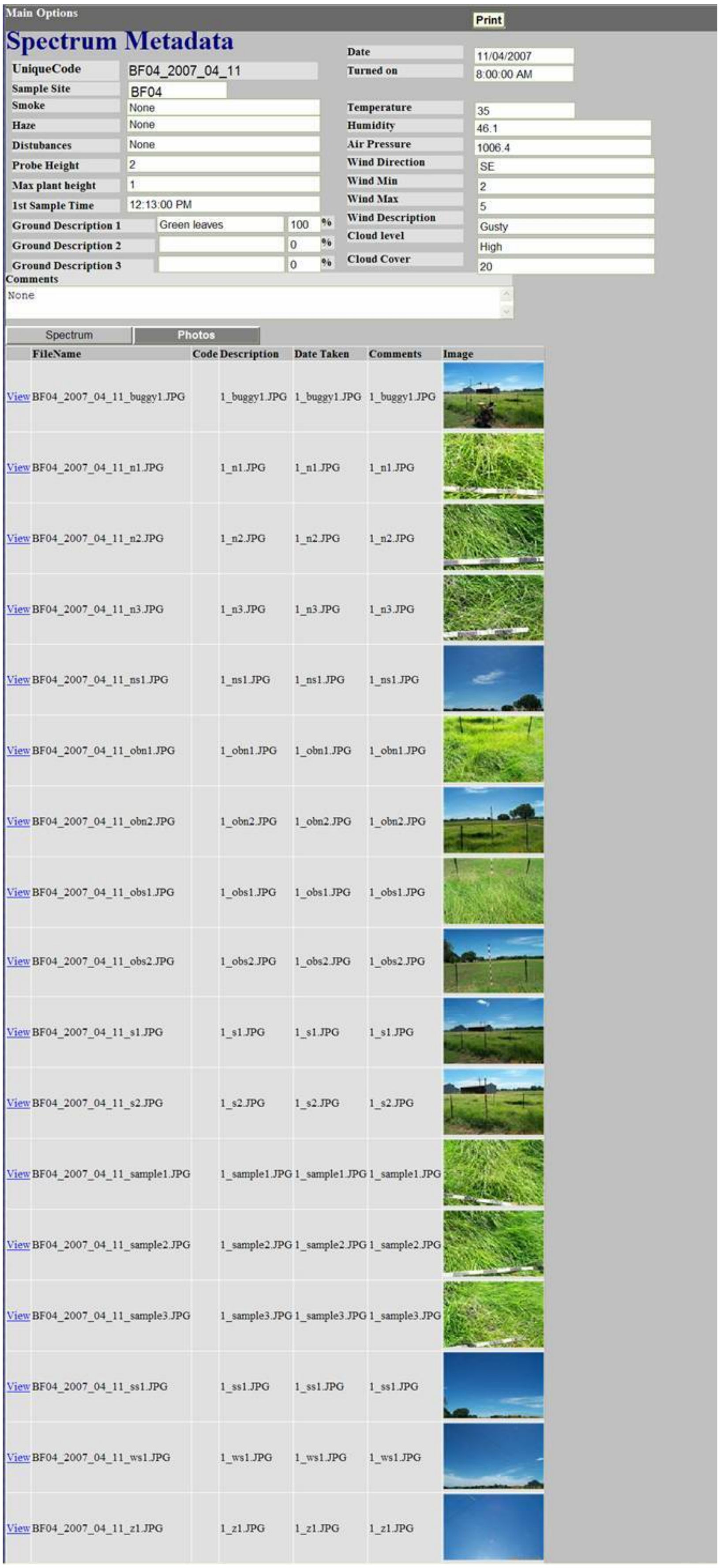

Figure 2 An example metadata page with associated photographs

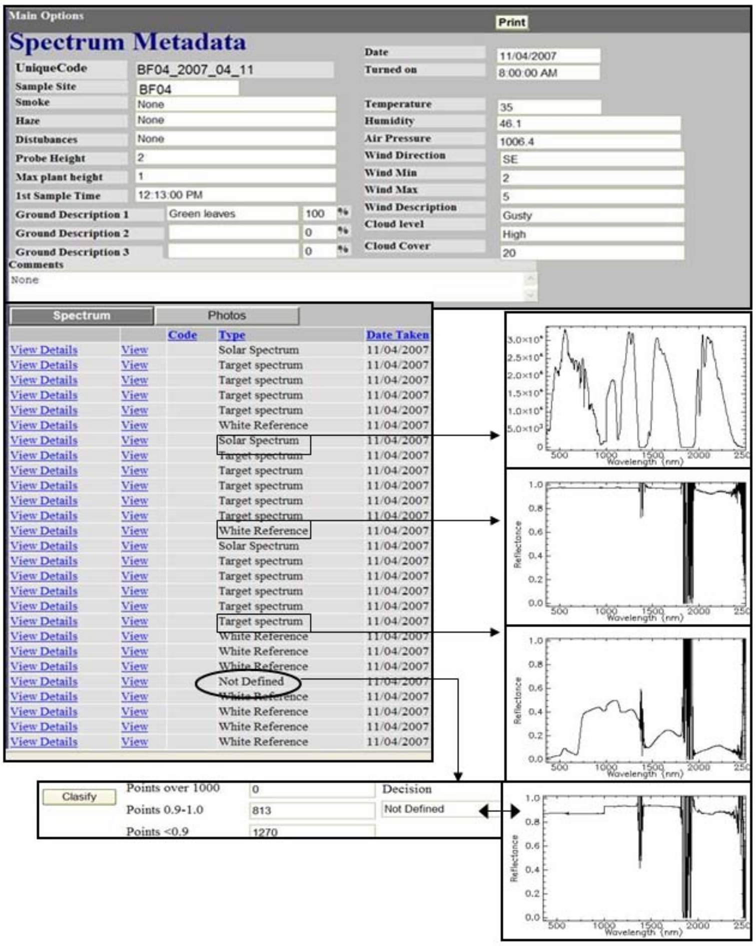

Figure 3 The spectral data associated with Figure 2

Alongside the vegetation spectral analysis will be the extension of the database to incorporate field measurements of mineral and mineral assemblages at minesites. In addition, soil samples taken around the Ranger lease will be prepared and measured in the laboratory, and the field and laboratory measurements of standard panels will be included in the database.

Acknowledgments

Thanks to Geoff Carr for collecting field spectra. Thanks to Dr Grahame Webb, Charlie Manolis and John Pomeroy (Crocodylus Park), Dr Gary Cook and Rob Eager (CSIRO) and Rob Kelley and Arthur Cameron (Berrimah Farm) for continued support and access to vegetation plots suitable for spectral sampling. Thanks also to Peter Bayliss, Mark Gardener, Jane Addison, Sean Bellairs, Bronwyn Bidoli, Dave Walden and James Boyden for initial discussion of the project.

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Development of catchment geomorphic characteristics of Gulungul Creek – monitoring results

DR Moliere, MJ Saynor & KG Evans

Background

The aim of this project is three-fold: (1) to develop reliable impact assessment methods for quantifying the mud loads transported during rainfall/runoff events; (2) to characterise the channel stability of the creek; and (3) to characterise the bedload movement upstream and downstream of Ranger.

In regards to the first aim, event mud load data collected since 2003 from upstream and downstream (GCUS and GCDS) of the Ranger operations footprint along Gulungul Creek have been used to quantify the magnitude of mud loads and assess whether the source is natural or potentially mining related. The locations of the monitoring stations are shown in Figure 1. Trigger levels (which can be used for future impact assessment) for event mud loads have been derived for current pre-rehabilitation conditions using two complementary methods (Moliere & Evans 2008) – BACIP analysis and a relationship between mud load and discharge characteristics.

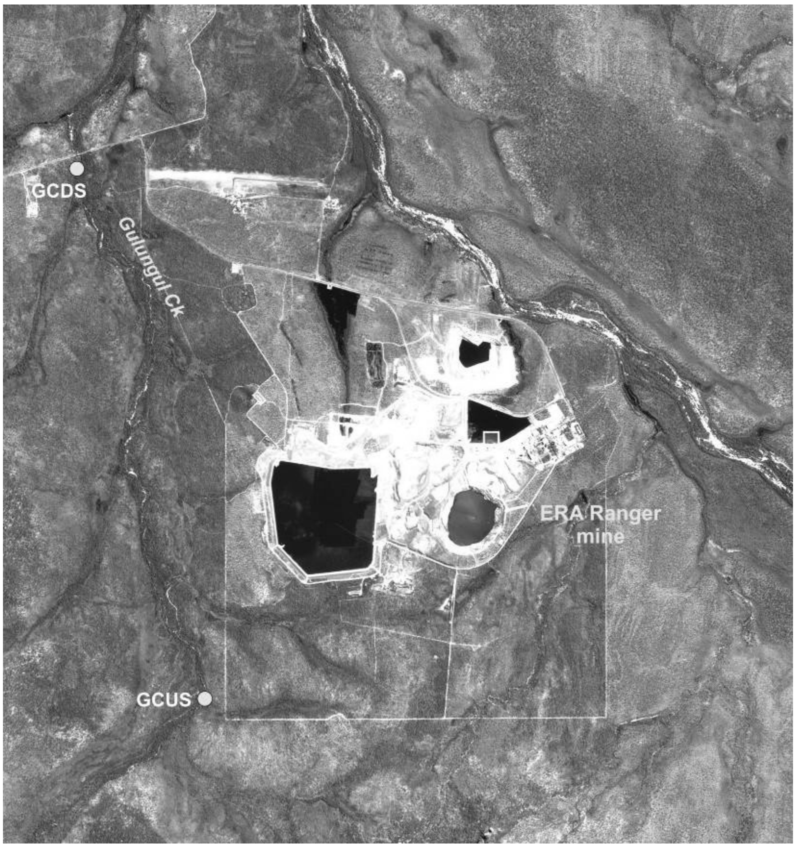

Figure 1 Location of the monitoring stations along Gulungul Creek

Bed material sediment sampling was initiated during the 2007–2008 wet season using a pressure difference Helley-Smith bed load sampler to determine baseline sediment loads for the derivation of a complete sediment budget. The sediment budget will be used to (1) provide data inputs into and validation of the predictions of, landform evolution models, and (2) baseline for monitoring the performance of the rehabilitated landform.

Cross sections, scour and fill and bed particle size are measured at numerous locations along the main channel on an annual basis to determine the stability of the stream channel along Gulungul Creek. These data will be used to develop knowledge of the geomorphic behaviour of the creek under current conditions (which can be used for future impact assessment). At this time the collected bedload samples have yet to be processed and analysed.

Results

Impact assessment methods for quantifying the mud loads (Aim 1)

Event mud load data collected since 2003 at GCUS and GCDS have been used to establish preliminary trigger values for both the event-based BACIP analysis and the relationship between mud load and discharge approaches to analysing event loads. Details of the methods used for deriving trigger values for both assessment techniques are described in detail in the companion paper 'Turbidity and Suspended Sediment Management Guidelines and Trigger Values for Magela Creek' under this KKN and in Moliere and Evans (2008).

Using the BACIP approach, events that lie above the 95th percentile ('action' trigger) are considered to have an elevated mud load measured downstream relative to the load upstream. Using the regression model approach, a potentially impacted event is identified if the mud load measured downstream is significantly elevated compared to the corresponding event discharge characteristics (ie lies above the + 2 SD line) for that location. An impact is confirmed if the corresponding event mud load measured upstream of Ranger is not significantly elevated compared to the flow discharge characteristics (ie lies within + 2 SD of the fitted relationship) for that location.

Events where mud loads measured downstream have exceeded the 'action' trigger levels associated with both assessment techniques are highlighted by specific date labels in Figures 2 and 3.

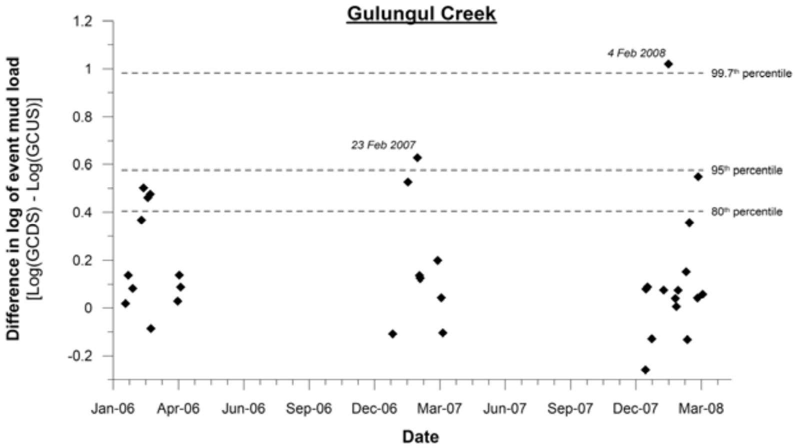

Figure 2 Temporal variation of the difference in the logarithms of the discrete event mud loads (indicated as ♦) measured in Gulungul Creek during the 2005–06, 2006–07 and 2007–08 wet seasons. The 80th, 95th and 99.7th percentiles of the difference in the logarithms of the event mud loads are marked so that potentially impacted events (indicated by date) can be identified.

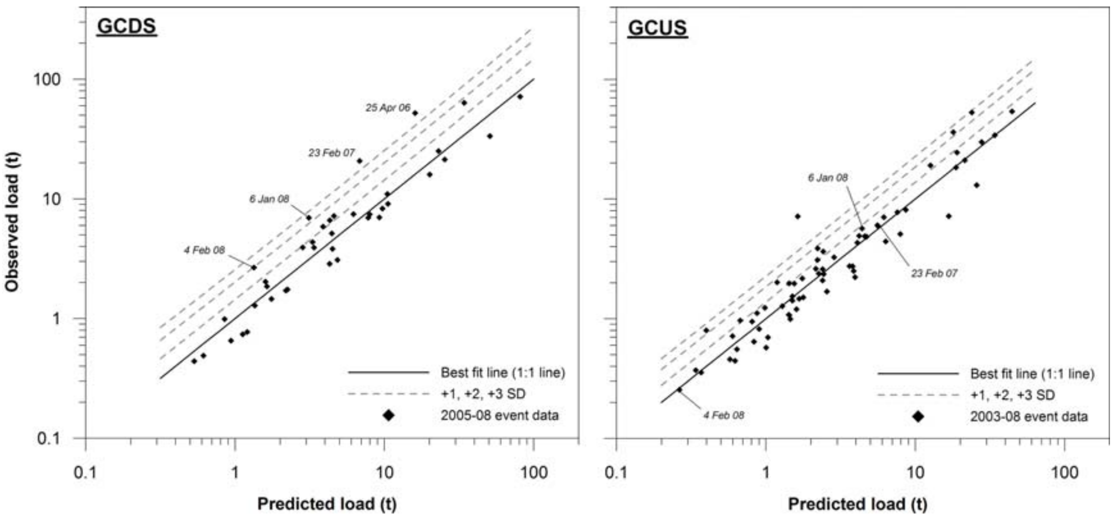

Figure 3 Event-based mud load relationships and associated +1, +2, and +3 standard deviation lines for GCDS (Left) and GCUS (Right). Discrete event data collected during the monitoring period are marked as dots, with potentially impacted events shown with event description and date. (Note: no mud load data were collected at GCUS during the event on 25 April 06.)

As discussed in the companion paper 'Turbidity and suspended sediment management guidelines and trigger values for Magela Creek', it is considered that an impacted event is one with a significantly elevated mud load compared to both the mud load measured upstream and the corresponding event discharge characteristics observed at the downstream site. Data collected within the Gulungul Creek catchment since 2003 show that there have been two events that would be classified as 'impacted' (23 February 2007 and 4 February 2008). These events are identified as elevated by both BACIP and the mud load-discharge relationship impact assessment techniques (Figs 2 & 3). Prior to the 2006–07 wet season, construction works commenced to elevate the tailings dam wall for increased storage capacity (Jacobsen 2007). It is possible that mud was washed into the main Gulungul Creek channel downstream of GCUS as a result of relatively intense rainfall over the exposed soil associated with earthworks around the perimeter of the tailings dam (Moliere & Evans 2008).

Channel stability (Aim 2)

To investigate the channel stability on Gulungul Creek, 12 cross-sections were installed in 2002 between GCUS and GCDS. These cross-sections have been surveyed annually and generally exhibit scour of the bed sediments over time indicating naturally driven net export of bed sediments along the creek (Saynor et al 2005, Saynor & Smith 2006). Figure 4 shows the cross-section where the most scour has occurred . This trend has been more pronounced during the last two survey's (2006 and 2007), which were conducted after Cyclone Monica passed through the region late in April 2006 and after the largest recorded flood occurred early March 2007, respectively. Subsequent surveys of the channel cross-sections will show if these events had any long-term impacts on the channel stability.

To further investigate scour and fill of the bed sediments, scour chains were first installed in 2002 at 6 of the 12 cross sections. Late in each dry season (when the watertable has dropped to its lowest level) the scour chains are located, measured and re-installed to current bed level (resetting the datum). In some cases, the scour chains could not be located as the water table had not dropped sufficiently to enable their recovery. Bed material sediments were also collected from the cross sections during each survey. These sediments have been characterised by particle size analysis to allow comparisons between the years. The samples collected late in 2007 are currently being analysed in the laboratory with the results to be incorporated into an internal report.

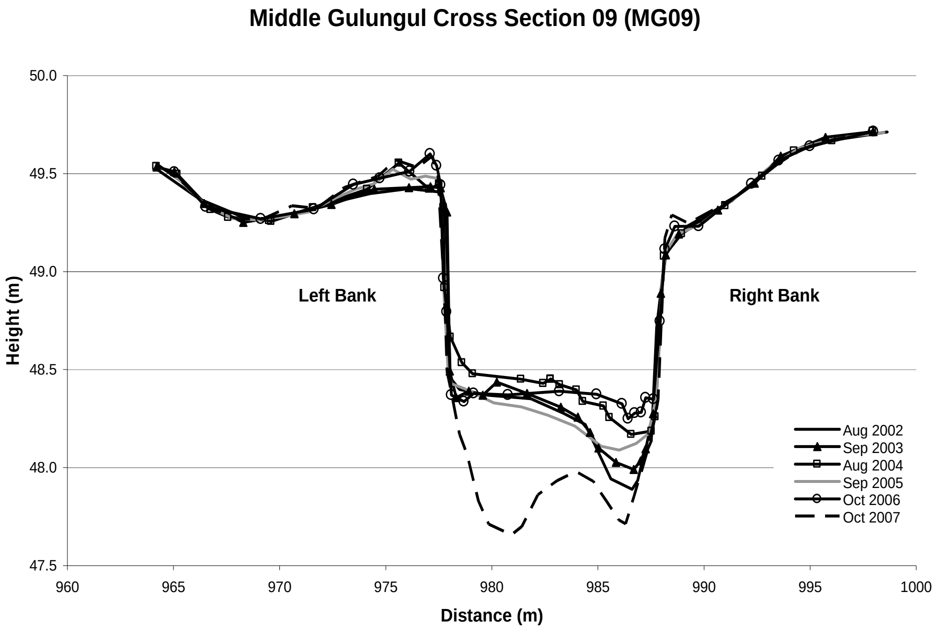

Figure 4 Cross section survey data collected since 2002 at middle Gulungul cross-section 09 (MG09)

Conclusions and future work

The combination of BACIP and regression model techniques has identified two possible mine-related impacts on event mud loads measured downstream of Ranger in Gulungul Creek since 2003. Future measured event load data which plot above the 'action' trigger levels derived from these methods of sediment load analysis should prompt further investigation and management action, if required.

Scour of the bed sediments was generally more pronounced in 2006 and 2007 after Cyclone Monica and an extraordinary flood event occurred, respectively. Subsequent surveys of the channel cross-sections will show if these events had any long-term impacts on the channel stability. Particle size analysis of the bed materials still needs to be completed.

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Development of catchment geomorphic characteristics of Gulungul Creek – gauging station upgrades

D Moliere, G Staben, M Saynor & R Houghton

Background

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, resulting in the highest flood levels in the Gulungul Creek catchment since recording began in 1971 (Moliere et al 2007). Temporary gauging stations located in the catchment upstream (GCUS) and downstream (GCDS) of the Ranger mine (see previous paper 'Development of catchment geomorphic characteristics of Gulungul Creek – monitoring results' for locations) were submerged by floodwaters (Fig 1), resulting in damage to equipment and data loss during the peak and subsequent recession of the flood. Given the substantial extension to the life of the Ranger mine, and the potential for increased impact in the Gulungul catchment, a strategic decision was made to replace these stations with structurally engineered, permanent stations.

Figure 1 Gauging station at GCDS submerged by floodwaters during the March 2007 flood. This photo was taken several hours after the flood peak when waters were at least 0.5 m higher than that shown here.

Station upgrade

The new stations, designed in-house with external engineering review and approval, were built late in the 2007 Dry season (Fig 2). The instrument platforms were elevated at least 1 m above the peak water level height recorded during the March 2007 flood. Both the design and the construction of these stations constituted a large part of the HGP 2007–08 work effort to have the stations in place and the new instrumentation operational for the 2007–08 wet season. In addition to this, the gauging station in Ngarradj Creek downstream of the Jabiluka Mineral Lease also required rebuilding as a result of flood damage.

The stations were equipped with a new generation of dataloggers (selected after considerable market research) to provide the capability of being able to remotely access the outputs of all connected sensors and also being able to trigger the automatic water samplers installed at the stations by predetermined output levels from the water quality or flow sensors. Prior to the upgrade, not all of the flow and water quality sensors could be connected to the original dataloggers, which meant some of the data had to be manually downloaded in the field. Therefore, the upgrade of both the stations and the logging equipment represents a significant improvement to the reliability and efficiency of data collection from our remote sites. The new generation loggers were installed at all SSD stations along Gulungul Creek, Magela Creek and Ngarradj to provide uniformity across the sites.

Figure 2 Original station at GCUS (left) and the new permanent gauging station constructed late in the 2007 dry season (right)

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Assessment of the significance of extreme events in the Alligator Rivers Region – impact of Cyclone Monica on Gulungul Creek catchment, Ranger minesite and Nabarlek area

G Staben, MJ Saynor, DR Moliere, GR Hancock[1] & KG Evans

Introduction

The title of this project in the 2007-2008 workplan is ‘Assessment of the significance of extreme events in the Alligator Rivers Region – impact of Cyclone Monica on stream sediment loads resulting from tree fall in the Gulungul Creek catchment’. However in addition to the Gulungul creek catchment this paper is also reporting on data collected from the Ranger mine site and Nabarlek area.

During April 2006, severe tropical Cyclone Monica impacted the coast of northern Australia, including the Alligator Rivers Region (ARR). The very destructive core of Monica (category 5) crossed the Northern Territory coastline approximately 35 km west of the township of Maningrida with maximum gust speeds estimated to be 360 km h^{-1} (Australian Bureau of Meteorology 2008). It continued to move inland in a south-westerly direction, rapidly weakening in intensity. Based on the track map produced by the Bureau of Meteorology, and satellite imagery, the eye of the cyclone passed over the rehabilitated Nabarlek minesite, with estimated maximum wind gusts of 180 km h^{-1}. It then passed directly over the Ngarradj sub-catchment (maximum wind gusts of 140 km h^{-1}) in Kakadu National Park (KNP), continuing through the Gulungul Creek sub-catchment and the town of Jabiru (Figure 1). Wind speed estimates for Nabarlek and Ngarradj were derived from a logistic decay curve equation in Cook and Goyens (2008).

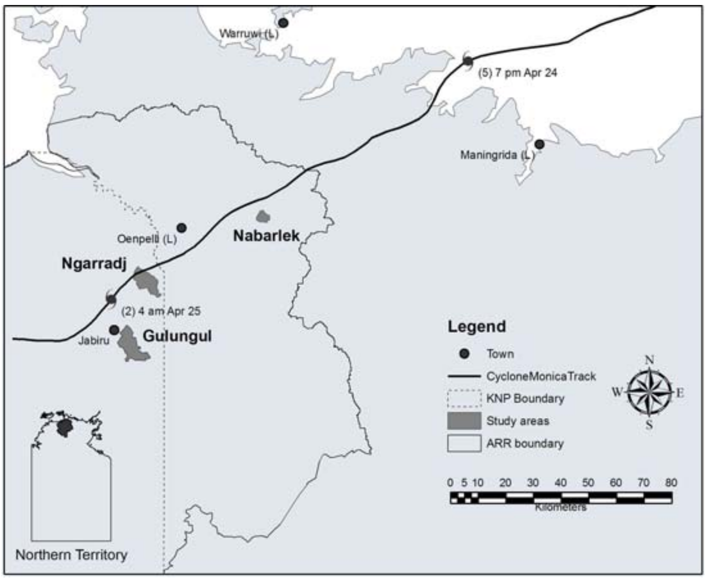

Figure 1 Estimated track of Cyclone Monica across the Alligator Rivers Region

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By the time winds gusts affected the Gulungul catchment, wind speed had reduced to a category 2 level with maximum destructive wind gusts of 135 km h^{-1}. Monica then continued to track westerly, weakening to below cyclone intensity 12 h after first making landfall.

Remote sensing and fieldwork were undertaken to assess the impact the cyclone had on the catchments within the Ranger and Jabiluka leases. The findings from the remote sensing study were reported in the 2006–07 SSD annual report and recently in Staben and Evans (2008) The initial results from the extensive on-ground field data collected in the months after cyclone Monica in the Nabarlek lease area, Gulungul Creek catchment, and rehabilitated sites located at the Ranger minesite are provided here.

Field data

A total of fifty-five 30 x 30 m plots were sampled, 31 in the Gulungul Creek Catchment, 15 at Nabarlek, and 9 on the Ranger minesite. Selection of the sites in the Gulungul catchment was undertaken using a stratified random sampling approach. Five broad vegetation communities were derived from a Landsat TM5 satellite image (acquired on 15 April 2005) using an unsupervised Isodata classification. Six survey sites were then randomly selected within each of the vegetation classes using the Hawths Tools extension in ArcMap v.9. The escarpment region within the catchment was excluded from fieldwork due to sacred site access restrictions.

Slightly different methods were used to select sites on both Nabarlek and Ranger. The selection of the 15 sites on Nabarlek mine lease were based on seven land units taken from the Land Units of the Nabarlek Mine Area, Northern Territory 1:5 k dataset created by the Northern Territory Government (Day & Czachorowski 1982). Three plots were located in rehabilitated areas and the remainder in natural vegetation communities. Plot sites at Ranger were located on experimental rehabilitation areas with three different soil treatments. The 31 plots in the Gulungul catchment were located within natural vegetation communities while the 9 plots on the Ranger minesite were located on revegetated areas of waste rock.

A number of parameters were measured for trees within each plot including: identification to species level of all trees ≥ 2 m in height (fallen and standing), diameter at breast height (DBH), tree orientation, living or dead and amount of damage. In addition, each tree was assigned one of eleven status codes (Table 1) describing the level of physical impact of the cyclone.

Table 1 Eleven status codes used to describe the level of impact of cyclone Monica on each tree ≥ 2 m in height

Status code	Status explanation	Status code	Status explanation
AS	Alive standing undamaged	DU	Dead uprooted
ASS	Alive standing snapped trunk	DL	Dead leaning
ASB	Alive standing broken limbs	DSN	Dead standing snapped
AU	Alive uprooted	DSC	Main trunk dead standing coppicing at base
AL	Alive leaning	DUC	Main trunk dead uprooted coppicing at base
DS	Dead standing		

The dimensions of the crater and the volume of material uplifted, termed pit and mound in the literature (Putz 1983, Norman et al 1995), caused by tree throw and potentially available for future erosion, were also measured. This was done to assess whether it was likely that the displaced material would be washed back into the depression by rainfall or be moved to the surrounding surface and be transported by overland flow. Particle size analysis (PSA) of soil samples collected from uplifted soil and nearby undisturbed surface soil was done to provide estimates of erosion potential. The potential for movement of soil will be influenced by the surface grade (slope) in the plot area where the trees have fallen. Slope angle of the plots sampled was usually less than 5%.

Results

A total area of 4.95 ha containing a combined total of 3049 trees was surveyed in the three study areas. For the initial analysis, the 11 status codes describing the impact of Cyclone Monica on each of the trees measured were pooled into three broad categories;

- undamaged (AS)
- damaged (AL, ASB, ASS, AU)
- dead (DS, DU, DL, DSN, DSC, DUC)

The results show that 13.8% of the trees in the 31 plots located in the Gulungul catchment had died, with a further 25.5% suffering some form of damage. The remaining 60.7% were undamaged. Of the 765 trees impacted by Cyclone Monica at Nabarlek, 36.5% died, 21.8% were recorded as suffering some form of damage, and 41.7% were undamaged (Table 2).

Table 2 Summary of the impact of Cyclone Monica on trees for each study area

Status post Cyclone Monica	Gulungul (Cat 2)*	Ranger minesite (Cat 2)*	Nabarlek (Cat 3)*
N trees	1579	705	765
Alive undamaged **	958 (60.7%)	321 (45.5%)	319 (41.7%)
Alive damaged	403 (25.5%)	10 (1.4%)	167 (21.8%)
Dead	218 (13.8%)	374 (53 %)	279 (36.5%)

* Cyclone category. ** percentage of total in parenthesis

On the rehabilitated Ranger sites 53% of trees were recorded as dead, 1.4% were alive with damage and 45.5% were not impacted by the cyclone (Table 2). Results of the three rehabilitated plots located at Nabarlek appear to show a similar trend to the Ranger sites. It appears that trees, on rehabilitated areas, which have been significantly impacted by a cyclone are more likely to suffer mortality (Table 3). It must be noted that it is possible that the occurance of fire at both the Ranger and Nabarlek plots may be contributing to the results observed, this requires further research.

Table 3 Summary of the impact of Cyclone Monica on trees in rehabilitated mine sites

Status post Cyclone Monica	Ranger minesite (Cat 2)* 9 sites	Nabarlek (Cat 3)* 3 sites
Number of trees	705 (27 species)	151 (15 Species)
Alive undamaged	321 (45.5%)	80(53%)
Alive damaged	10 (1.4%)	10 (6.6%)
Dead	374 (53%)	61 (40.4%)

* Cyclone category

The eleven status codes were then pooled into six broad categories to provide capacity for more detailed assessment of the data:

- undamaged (status code AS)
- broken limbs (status code ASB)
- leaning (status code AL, DL)
- trunk snapped (status code ASS, DSN)
- uprooted (Status codes, AU, DU, DUC)
- dead standing (status codes DS, DSC)

Of the total number of trees affected by Cyclone Monica in the 31 plots in Gulungul catchment 15.6% (246) had some form of limb damage, 3.2% (41) were leaning as a result of the cyclonic winds, 2.6% (51) were snapped at the main trunk, 10.9% (173) were uprooted and 6.9% (110) were dead standing. While the number of trees unaffected by the cyclone represented just over 60% of the total trees, the percentage of tree basal area[2] impacted was far greater with. Just over 65% of the total stand basal area (8.15 m^2 ha^{-1}) in the 31 plots occurring in the 5 categories represented cyclone damage. Trees with broken limbs represent 34% of the total basal area, uprooted 21.5%, snapped 4.4%, dead standing 3.1% and leaning 2% (Figure 2 (a) & (b)).

Just over 58% (446) of the total trees surveyed at the Nabarlek rehabilitated mine site were impacted by the cyclone. A total of 26.2% (201) of the trees were uprooted, 15.3% (117) had snapped main trunks, 13.1% (100) were dead standing, 2% (15) had broken limbs and 1.7% (13) were leaning. The total basal area for the 15 plots in Nabarlek was 6.2 m^2 ha^{-1} with trees in the uprooted status representing 37.4% of the total basal area. Undamaged trees represented 26.2%, trees with snapped trunks represented 19.7%, broken limbs 9.9%, dead standing 5.5% and trees leaning 1.3% (Figure 2 (a) & (b)).

Assessment of the impact of the cyclonic winds on trees within the 9 plots on the Ranger mine site found that of the majority of the 705 individuals were either recorded as undamaged 45.5% (321) or dead standing 41.4% (292). Of the remaining trees 7.5% (53) were uprooted, 4.3% (30) had snapped trunks and 1.3% were leaning. Again trees in the undamaged and dead standing categories represented the majority of the total basal area (3.5 m^2 ha^{-1}) with 45.5% and 36.6% respectively. Uprooted trees represented 11% of the total basal area, snapped trunks 7.1% and trees leaning 1.2% (Figure 2 (a) & (b)).

This initial analysis of the field data collected at the three study areas shows that the level of impact of cyclone Monica on trees was greatest at the Nabarlek site. The maximum distance between any one of the survey plots located in the Gulungul creek catchment and the Ranger mine is ~ 10 km. It could be expected due to the geographic location of the survey plots in Gulungul creek catchment and Ranger mine that the level of impact may have been similar. However, the results clearly show that the trees on the Ranger mine site suffered similar levels of damage to Nabarlek, which experienced greater wind speeds than both Gulungul and Ranger. The results observed in the analysis to date may be due to the differences in soil types/structure, morphological differences between tree species or the occurance of fire. Further analysis of these data is being undertaken to investigate these possibilities.

[2] Tree basal area is the cross-sectional area (over the bark) measured at breast height (1.3 metres above the ground) measured in metres squared (m). Tree basal area is a measure of tree volumes and stand competition.

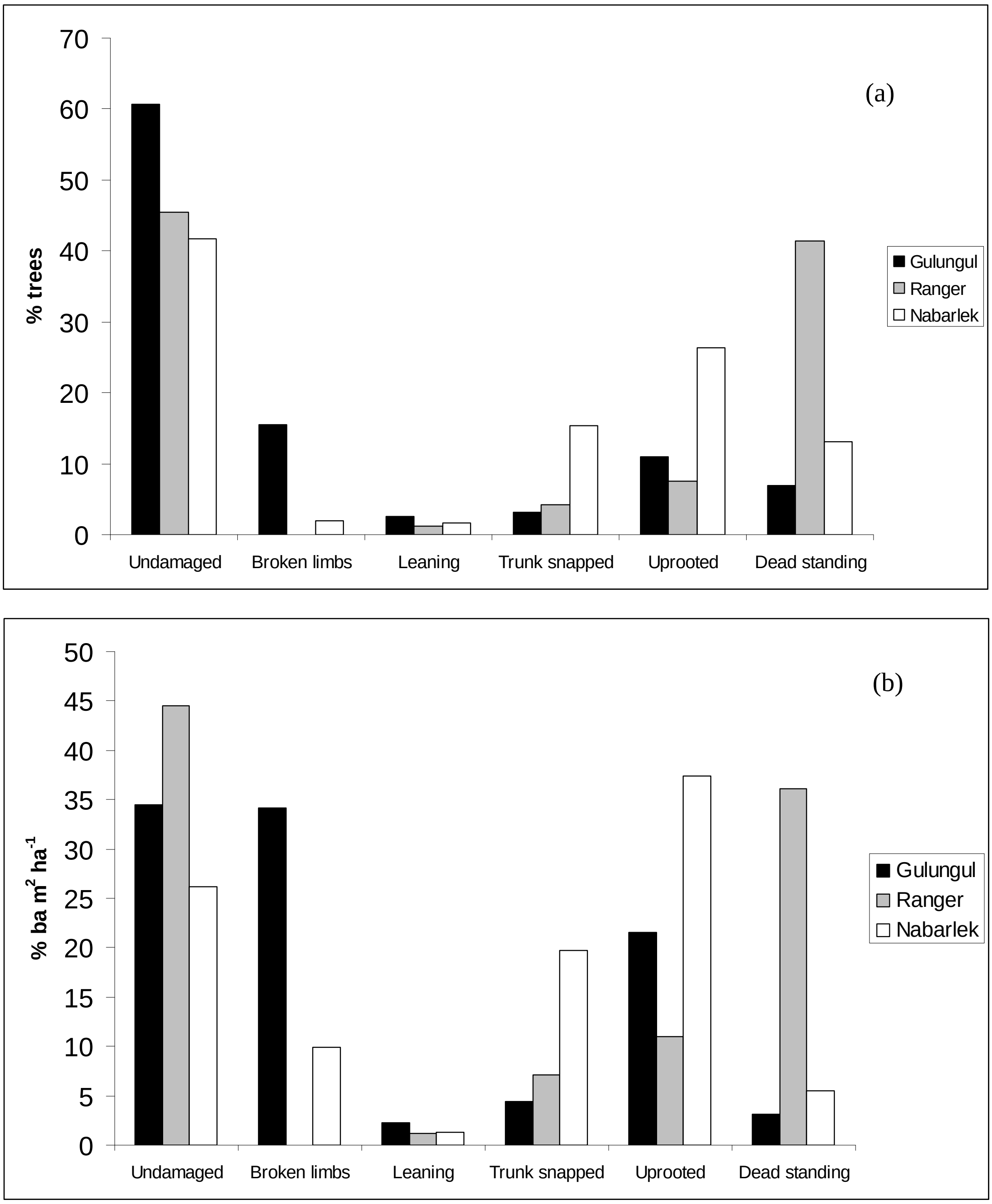

Figure 2 Number of trees (a) and total basal area (b) represented as a percentage for each of the pooled status codes describing cyclone impact in the three study areas

Sediment transport

The total volume of sediment that was contained within root balls in the uprooted trees in the three catchments is shown in Table 4. It was expected that the sediment contained within the rootballs would fall mainly back into the crater or onto the ground surrounding the crater hole. Observations at some of the sites that were visited during the 2007 dry season suggest that the little sediment that had been displaced from the rootball had fallen back into the craters although this is not quantifiable.

The gently sloping land surface (<5% grade) of the plots suggested a priori that displaced soil was unlikely to be transported any great distance from the area of immediate disturbance. Suspended sediment studies in Gulungul Creek catchment have found that despite a large rainfall and runoff event during the cyclone giving elevated stream mud loads at the time, the sediment transport characteristics within the catchment during 2006–07 and 2007–08 were not significantly different to previous years (Moliere & Evans 2008). This finding implies that the disturbance of the soil profile by tree throw has not had a significant impact on the net export of fine suspended sediment in Gulungul Creek. Thus the effect of a cyclone (at least to Category 3) on export of fine soil material appears to be relatively minor.

Table 4 Volume of sediment in the rootballs of fallen trees in each study area

Study site	Fallen trees with rootball	Total volume of rootball (m^3)	Total hectares sampled (ha)	Total volume per hectare (m^3ha^{-1})
Gulungul catchment	121	23.60	2.79	8.46
Nabarlek minesite	154	10.03	1.35	7.43
Ranger minesite	45	0.75	0.68	1.10

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Turbidity and suspended sediment management guidelines and trigger values for Magela Creek

D Moliere & K Evans

Background

Fine suspended sediment (the mud or < 63 μm fraction) moves through stream systems in pulses or waves generated by rainfall/runoff events. Reliable impact assessment requires a method for quantifying the mud loads transported by these pulses, such that inputs coming from the subcatchments adjacent to the mine can be clearly distinguished from inputs from the natural catchment upstream of the mine.

Mud load event data, using turbidity as a surrogate, collected during the past three wet seasons from upstream and downstream of Ranger along Magela Creek (MCUS and MCDS) have been used to quantify the magnitude of mud loads and assess whether the source is natural or potentially mining related. The locations of the monitoring stations are shown in Figure 1.

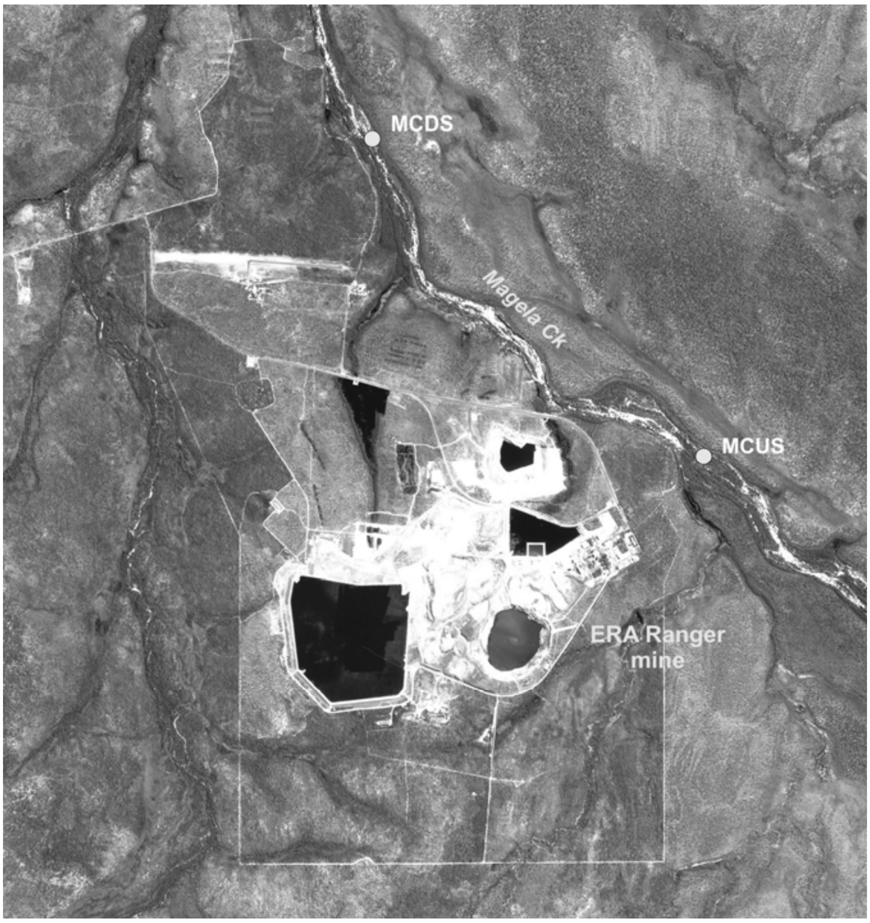

Figure 1 Location of the monitoring stations along Magela Creek

Trigger levels (which can be used for future impact assessment) for event mud loads have been derived for current pre-rehabilitation conditions using two complementary methods (Moliere & Evans 2008).

Impact assessment methods

BACIP Analysis (Method 1)

The basis of BACIP analysis (Stewart-Oaten et al 1986, 1992) is to produce a set of paired-site (P) 'difference' values by subtracting mud load data from the upstream (Control (C)) site from those at the downstream (Impact (I)) site. The mud load measured downstream of the disturbance is thus compared to that measured upstream on an event basis to assess impact.

'Trigger' values derived from statistical percentiles of the difference data distributions provide the basis for assessing the significance of the event mud load data for a particular event. For this work the BACIP analysis uses the differences between log-transformed event mud loads at the upstream and downstream stations along Magela Creek.

Event mud load data collected during 2005–06, 2006–07 and 2007–08 for Magela Creek were used to establish preliminary trigger values for the event-based BACIP analysis. Given that the log-transformed difference data are non-normally distributed, water quality management trigger levels are assigned to the 80th, 95th and 99.7th percentiles of the data. These trigger values represent 'focus', 'action' and 'limit' triggers, respectively (Supervising Scientist 2002), and define an escalating hierarchy of management response. Figure 2 is essentially a control chart plot that enables the significance of events to be assessed.

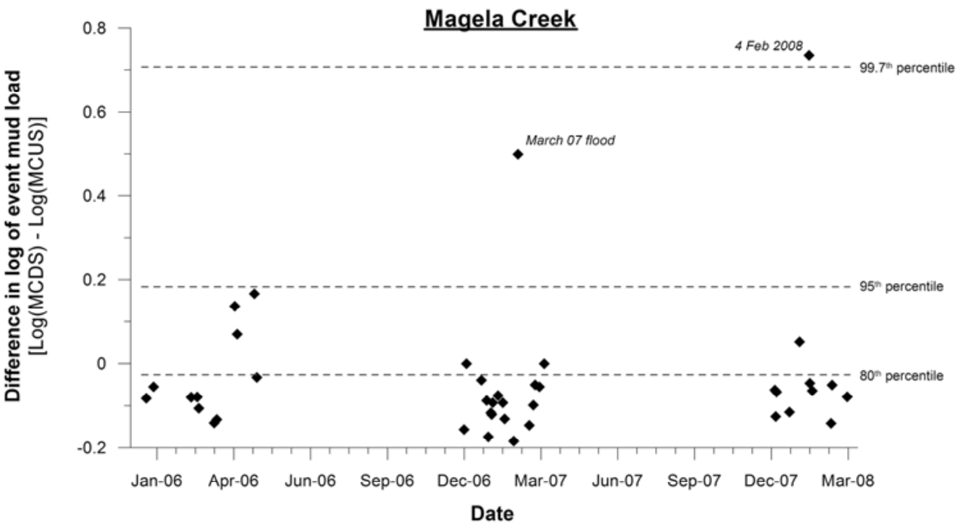

Figure 2 Temporal variation of the difference in the logarithms of the discrete event mud loads (indicated as ♦) measured in Magela Creek during the 2005–06, 2006–07 and 2007–08 wet seasons. The 80th, 95th and 99.7th percentiles of the difference in the logarithms of the event mud loads are marked so that potentially impacted events (indicated by date) can be identified.

Events that lie above the 95th percentile ('action' trigger) should be specifically investigated to determine the cause of the elevated mud load measured downstream relative to the load upstream. Events where mud loads measured downstream have exceeded the 'action' trigger level are highlighted by specific date labels in Figure 2.

Relationship between mud load and discharge characteristics (Method 2)

This approach uses a site-specific regression relationship between event mud load and corresponding event discharge characteristics.

Stepwise multivariate regression analysis between event mud load and a selection of discharge characteristics (such as total effective rainfall, maximum periodic rainfall intensity, total event runoff, total discharge of the rising stage of the hydrograph, maximum periodic rise and recovery period preceding the event) showed that the most significant discharge characteristics for predicting event mud load within the region are total event runoff and maximum periodic rise in discharge (Moliere & Evans 2008).

The form of the regression equation is as follows:

$$\text{Total mud load} = K\left(Q_T\right)^a Ri^b \qquad (1)$$

where Q_T is total discharge during the mud pulse, Ri is maximum periodic rise in discharge over 10 minutes and a, b and K are fitted parameters.

Event data collected between 2005 and 2008 were used to fit statistically significant regression relationships (Equation 1) between event mud load and corresponding event discharge characteristics for each site (Figure 3). Given that observed loads are normally distributed around the best-fit line (predicted loads), 'focus', 'action' and 'limit' trigger levels correspond to +1 standard deviation (SD), +2 SD and +3 SD from the 1:1 line, respectively (Supervising Scientist 2002). Events that plot above the +2 SD line ('action') have a significantly higher mud load than would be predicted using the corresponding event runoff characteristics for a non-impacted condition. Using the regression model approach, a potentially impacted event is one in which the mud load measured downstream of Ranger is significantly elevated compared to the corresponding event discharge characteristics (ie lies above the + 2 SD line). An impact is confirmed if the corresponding event mud load measured upstream of Ranger is not significantly elevated compared to the flow discharge characteristics (ie lies within + 2 SD of the fitted relationship).

Mud loads for discrete turbidity events observed in Magela Creek are shown plotted as dots against the predicted event mud loads in Figure 3. Possible minesite related events are identified by specific date labels.

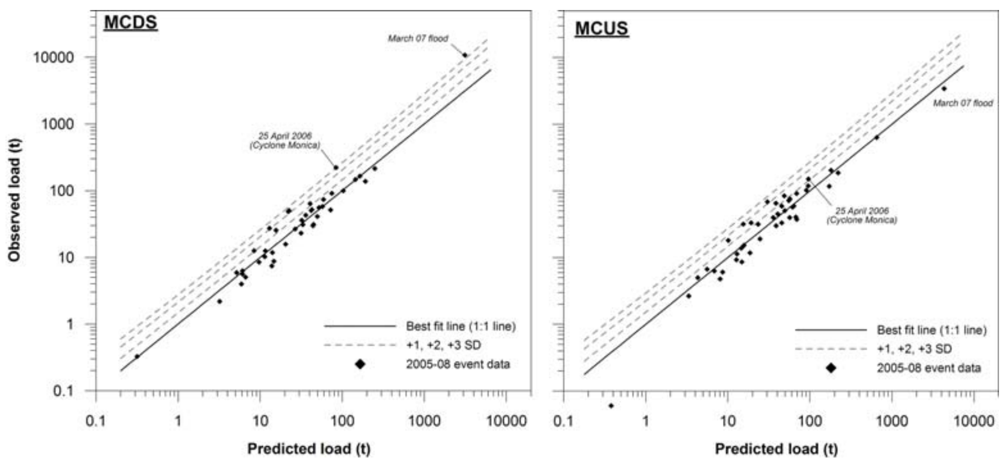

Figure 3 Event-based mud load relationships and associated +1, +2, and +3 standard deviation lines for MCDS (Left) and MCUS (Right). Discrete event data collected during the monitoring period are marked as dots, with potentially impacted events shown with event description and date.

Discussion

There is generally good correlation between the BACIP and regression model approaches to assess impact on mud loads. However, the results have shown that the impact assessment methods (treated separately) may not be reliable for all flow and storm conditions. For example, the event on 4 February 2008 at Magela Creek was associated with an isolated storm that occurred over a subcatchment between the upstream and downstream stations. BACIP analysis indicated that the mud load measured at the downstream station was elevated compared to that measured upstream (Fig 2) and, as such, warrants further assessment. However, the measured mud load during this event at the downstream station was well within the trigger levels derived from the regression model. That is, the mud load was reasonable for the flow conditions (Fig 3) and as such would not be considered impacted.

Therefore, it is recommended that a combination of BACIP and regression model techniques be used for impact assessment on mud load within the Magela Creek catchment. Using such an approach, an impacted event is one with a significantly elevated mud load compared to both the mud load measured upstream and the corresponding event discharge characteristics observed at the downstream site. Data collected along Magela Creek since 2005 show that there has been one event that would be classified as 'impacted' (ie identified as elevated by both BACIP and the mud load-discharge relationship impact assessment techniques). During the March 2007 flood, which was a record rainfall–runoff event for the region, the sediment management controls on the minesite area were simply overwhelmed (Moliere et al 2008). The subsequent input of turbid water from the site, including exploration drill pad areas to the east of Pit 3, into minesite tributaries and hence into Magela Creek, contributed to the elevated mud concentrations recorded downstream of Ranger (Figures 2 & 3).

Conclusions and future work

The combination of BACIP and regression model techniques has identified one possible mine-related impact on event mud loads measured downstream of Ranger since 2005. It is recommended that impact assessment of mud loads continue to use both approaches, given their complementary strengths and weaknesses.

Future measured event load data which plot above the 'action' trigger levels derived from these methods of sediment load analysis should prompt further investigation and management action, if required. The investigation should include analysis of the suspended sediment to ascertain if it has come primarily from the minesite or from adjacent un-impacted subcatchment areas. This distinction needs to be made since elevated sediment loads could result from the impact of an intense local storm event on land that is not impacted by mining activity, yet lies within the lease boundary. Water samples for this analysis will be provided by the event triggered autosamplers located at the downstream sites in Magela Creek.

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