Landslide impacts on suspended sediment sources following an extreme event in the Magela Creek catchment, northern Australia

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Abstract Record rainfall of up to 784 mm occurred between 17:00 h 27 February and 17:00 h 2 March 2007 in the Magela Creek catchment, northern Australia. Maximum return periods for 48 and 72 h durations exceeded 1:1000 years. The 24-hour maximum (398.4 mm) is the largest recorded in the region and the 2007 storm exceeded all previous 48 and 72 h recorded rainfall in the Northern Territory but was only one-third of Probable Maximum Precipitation. Sixteen landslides (0.3 km^2) were triggered over a small area where sandstone had been stripped to reveal dolerite. The Munsell® soil colour of the <63 μm fraction of suspended sediment showed that in 2008 a series of "red" flood pulses on Magela Creek at stations up- and downstream of Ranger mine were sourced from the landslides by localised storms. Active fluvial sediment sources were restricted to a very small area for short periods of time during specific hydrological events.

Key words sediment colour; suspended sediment sources; sediment fingerprinting; "red" flood pulses

INTRODUCTION

Suspended sediment fluxes of many rivers around the world are now measured accurately at gauging stations by a combination of continuously recording turbidity meters and automatic pump samplers. In the Magela Creek catchment in northern Australia, sediment yields are low by world standards, except where human disturbance has occurred by mining, roading, burning and housing construction (Duggan, 1994; Erskine & Saynor, 2000). As well as measuring fluxes, it is equally, if not more, important to know precisely where suspended sediment is generated within the upstream catchment. Identification of sediment sources and methods for their determination has been a major research effort over the last 20 years in geomorphology and hydrology.

The purpose of this study is to determine the source of a series of "red" flood pulses that occurred on Magela Creek at Ranger mine (Fig. 1), northern Australia, during the 2007–08 wet season, following the largest flood of record during the previous wet season. The March 2007 extreme event initiated 16 landslides where the underlying geology was olivine dolerite. However, it was not until the following wet season that a number of localised storms generated a series of red flood pulses which originated solely from landslides. In this paper, we evaluate the utility of soil colour as a method of sourcing suspended sediment during the red flood pulses. Lewis and Clark, in their famous expedition across America from Pittsburgh to the Pacific Ocean between 1803 and 1806, used the colour of suspended sediment to follow the Missouri River upstream when similar sized tributaries joined the main stream (Moody *et al.*, 2003). However, it was not until 1980 that Grimshaw & Lewin (1980) first tested the efficacy of soil colour for determining sediment sources. We have corrected the errors in Grimshaw & Lewin's (1980) methods.

METHODS

Rainfall data were obtained for Magela Creek at G8210009, Gulungul Creek at G8210012, Bureau of Meteorology's Jabiru Airport (Station no. 014198) and Energy Resources of Australia's Tailings Dam pluviometer at the Ranger mine (Fig. 1). Discharge data were obtained for Magela Creek at G8210009 and Gulungul Creek at G8210012 river gauging stations. Annual maximum flood series for G8210009 and G8210012 were subjected to flood frequency analysis using the method of Pilgrim (2001) which fits a log Pearson type III distribution by the method of moments.

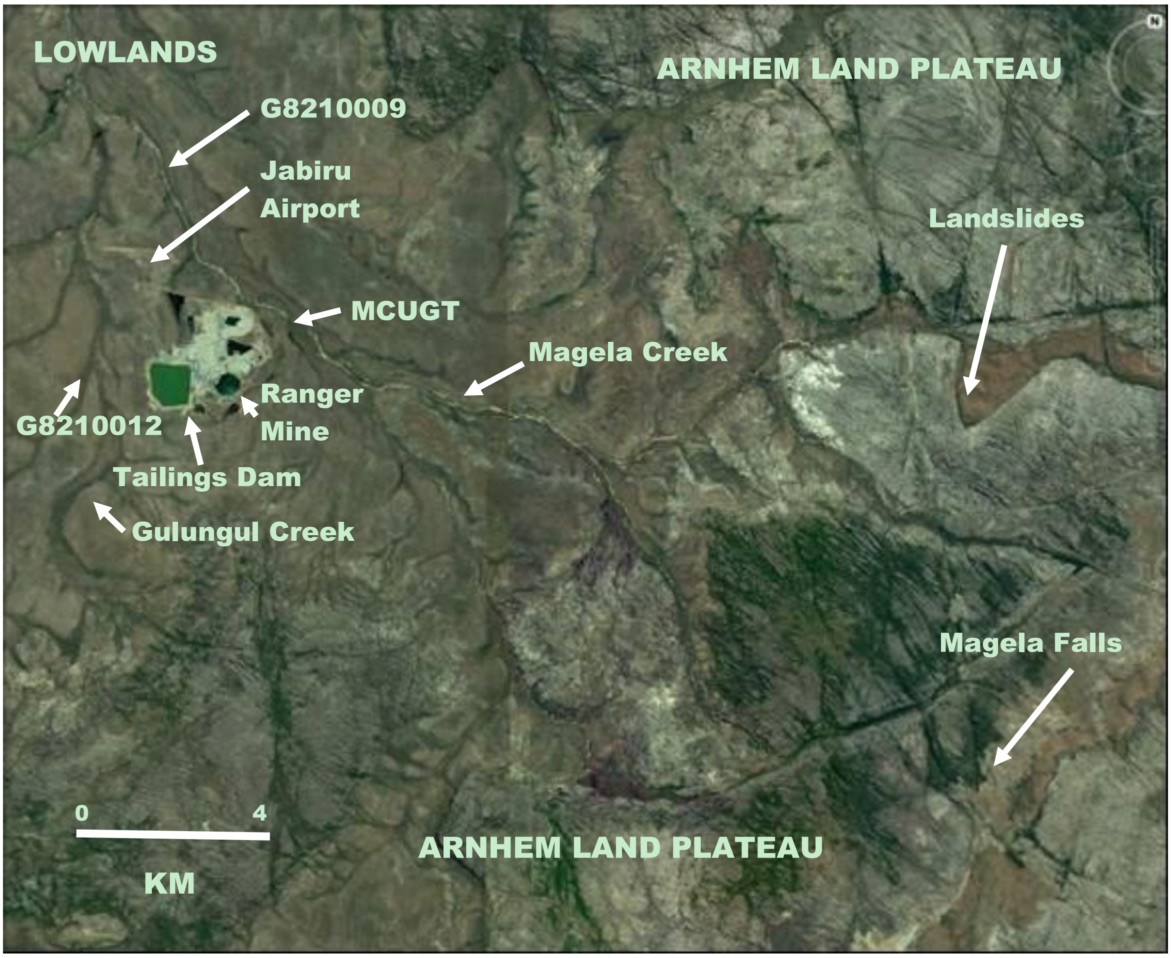

Fig. 1 Location of the landslides, river gauging stations and Ranger Mine in the Magela Creek catchment, northern Australia.

An automatic pump sampler collected suspended sediment samples at two stations on Magela Creek, one upstream of Ranger Mine above the confluence with Georgetown Creek (MCUGT) and one downstream of the mine at gauging station G8210009 (Fig. 1). Selected suspended sediment samples were passed through 2 mm and 63 µm sieves to remove gravel and sand, respectively. The remainder of the sample was filtered through 0.45 µm cellulose nitrate filter, and the silt and clay between 0.45 and 63 µm retained on the filter paper was stored for metals determination. The Munsell® colour (Anon, 2010) of the silt and clay fraction was also determined using methods detailed by Anon (2010) and Melville & Atkinson (1985). In particular, we ensured that:

- assessors had normal colour vision and colour determinations were performed by more than one person;
- moist matrix colour of sediment samples was determined after all gravel had been removed;
- light source was constant and approximated an overcast sky;
- sample and colour chip were viewed in the same plane;
- masks were used (black for dark samples and grey for light and intermediate samples) because only the foveal region of the eye can assess colour; and
- an illuminating angle of 45° to the surface of the chip was used, and the chip was viewed perpendicular to the illuminating angle.

Soil colour was also determined in the same manner for soil samples from the landslides. All sediment samples were assessed in the moist state for consistency and where sediment was aggregated or cemented, the sediment was broken and colour determined on the moistened surface of a fresh face (McDonald & Isbell, 2009).

2007 STORM AND FLOOD

Figure 2 shows the discharge hydrograph and rainfall mass curves at G8210009, Jabiru Airport and Ranger Tailings Dam. The rainfall mass curve at G8210009 terminates at 09.00 h on 2 March 2007 because the pluviometer was inundated by overbank flow from Magela Creek. The other pluviometers recorded the whole event. For the 72 h period between 17:00 h on 27 February and 17:00 h on 2 March 2007, 740, 784 and 692 mm were recorded at G8210012, Jabiru Airport and Ranger Tailings Dam, respectively. Between 17:00 h on 27 February and 09:00 h on 2 March 2007, when the pluviometer was overtopped by overbank flow, 736 mm were recorded at G8210009. Probable Maximum Precipitation (PMP) for 72 h duration here is 2200 mm (Bureau of Meteorology, 2011). Three distinct rain bursts occurred, the last being the most intense. Bureau of Meteorology intensity-frequency-duration analyses for G8210012 showed that for durations greater than 6 hours, rainfall intensities exceeded 1:100 year (Fig. 3). However, return periods for durations between 48 and 72 hours exceeded 1:1000 year (Fig. 3). Furthermore, the 24-hour total at G8210012 of 398 mm is the largest recorded in the region (Erskine & Saynor, 2000), although PMP for 24 h duration is 1380 mm (Bureau of Meteorology, 2011).

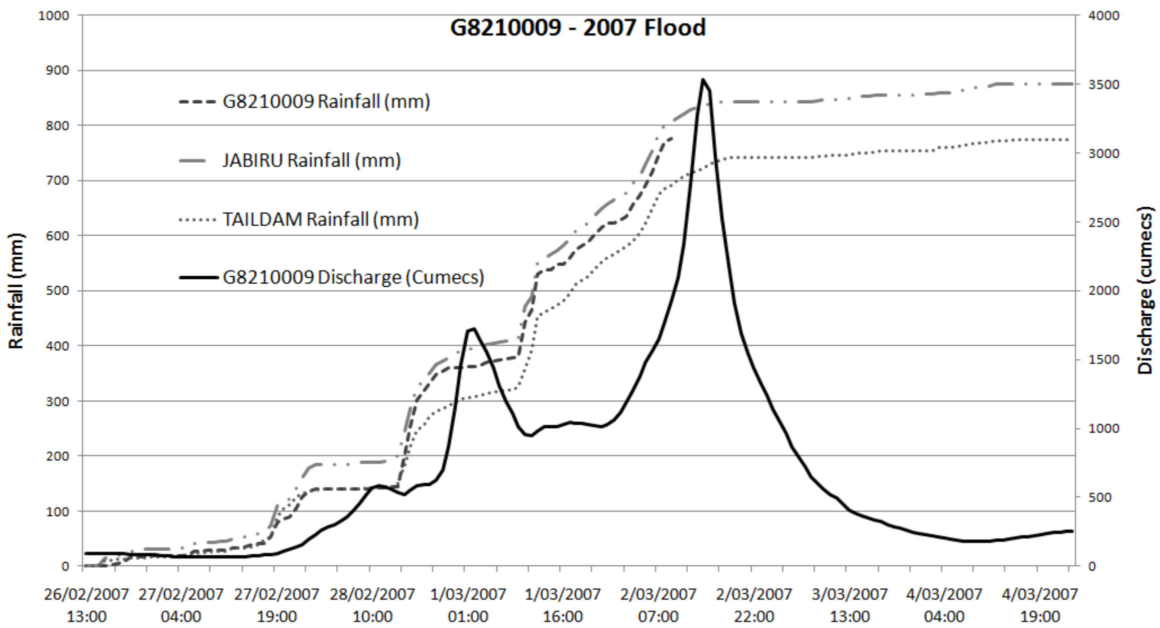

Fig. 2 Mass curves of rainfall at gauge G8210009, Jabiru Airport and Ranger Tailings Dam, and flood hydrograph at Magela Creek at G8210009.

Intense rain between 27 February and 2 March 2007 produced the highest flood since gauging commenced in 1971 on both Magela (G8210009) and Gulungul creeks (G8210012). The 2007 flood on Magela Creek had a flood peak discharge 8.56 times greater than the mean annual flood and on Gulungul Creek had a peak discharge 6.02 times greater, both of which are less than the threshold of 10 proposed by Erskine & Saynor (1996) as the minimum for a catastrophic flood. Return periods of the 2007 flood were 1:450 year and 1:100 year on Magela and Gulungul creeks, respectively. For Magela Creek, the 2007 flood plots on the 5% confidence limit (Fig. 4), but for Gulungul (not shown), plots on the theoretical curve. A longer record is needed to determine the true return period of the 2007 flood on Magela Creek. Nevertheless, it was an extreme event. Moliere & Evans (2010) also demonstrated that the March 2007 flood had higher than expected fine suspended sediment loads downstream of Ranger mine in comparison to the upstream station because of the failure of sediment containment structures on the mine and the activation of erosion on exploration drill pads and tracks.

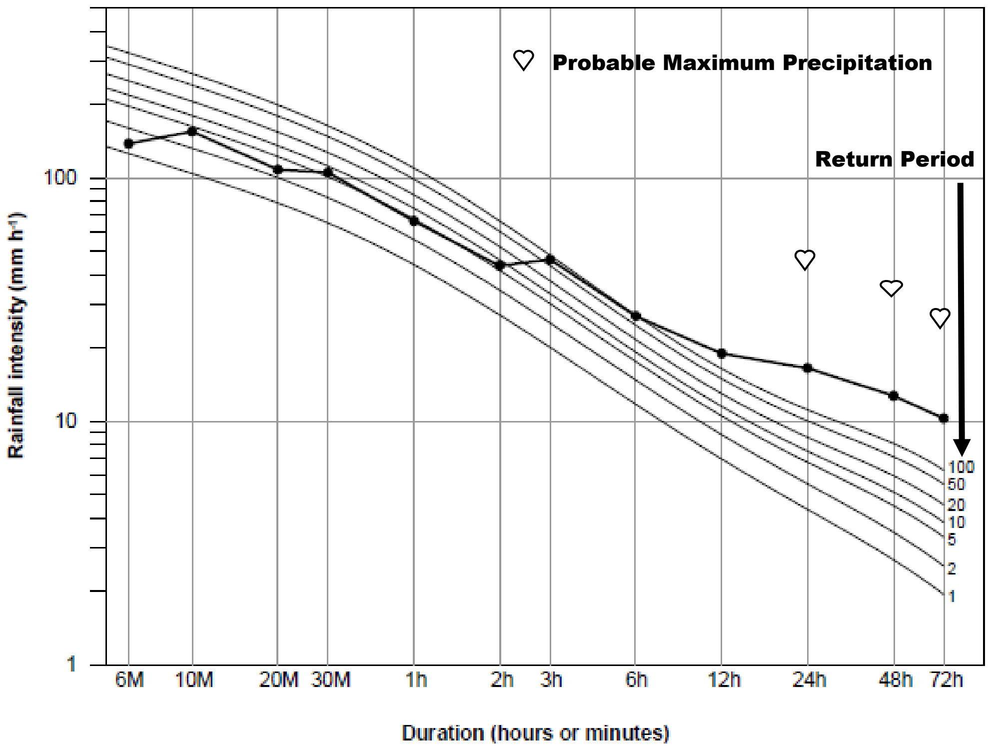

Fig. 3 Rainfall intensity-frequency-duration curves for G8210012 derived by the Bureau of Meteorology with the recorded rainfall for G8210012 shown in bold and PMP shown by hearts.

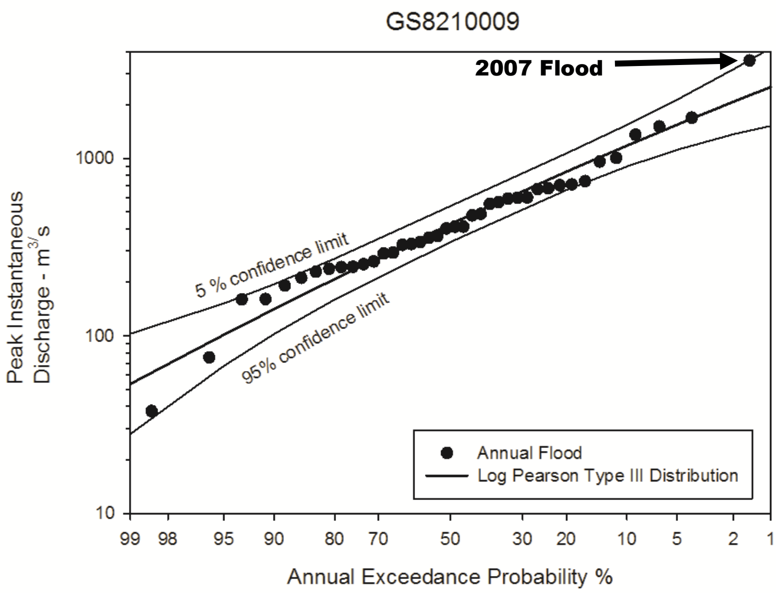

Fig. 4 Annual maximum series flood frequency curve for Magela Creek at G8210009.

RAINFALL-GENERATED LANDSLIDES IN 2007

Saynor *et al.* (2012) discuss these landslides in detail. The area in which landslides occurred is confined to small surface outcrops of dolerite. Elsewhere, the dolerite is unconformably overlain by sandstone. Using the classification of Cruden & Varnes (1996), the landslides were mudslides, multiple mudslides, debris slides and multiple debris slides. There were 16 mudslides and debris slides (total area of 0.3 km^2) in a 2.5 km^2 area of dolerite. One extra debris slide occurred on sandstone and is not considered further. Detailed grain size analysis on multiple mudslide and debris slide sediment samples showed that soil textures (McDonald & Isbell, 2009) varied from clay loam to silty clay to clay. Therefore, our investigation of suspended sediment was restricted to the silt and clay fraction.

RED FLOOD PULSES IN 2008

What were locally called "red" flood pulses were observed by Supervising Scientist staff on Magela Creek on 24, 25 and 30 January and 5 February 2008 during helicopter trips to routine monitoring sites around the Ranger mine. Examples of these red pulses are shown in Fig. 5. When first observed on 24 January 2008, the red water was followed upstream by helicopter directly to the landslides. Tributaries that drained catchments without landslides produced "clear" water. Dissolved organic carbon concentrations in Magela Creek have been measured weekly at the two sites over two years and exhibited mean concentrations of 2.23 ± 0.20 (SE) and 3.61 ± 0.20 (SE) mg/L, and do not produce "blackwater" in this stream (Dr M. Trenfield, 2012, pers. comm.). The red flood pulses were, therefore, highly visible to staff familiar with Magela Creek. Subsequent work also revealed that these events produced a different turbidity–fine suspended sediment concentration relationship to that before and after the red pulses (Moliere & Evans, 2010).

The occurrence of red flood pulses did not coincide with large storms. At Jabiru Airport, daily rainfall during red pulses varied from 0 to 55.2 mm. However, there are no raingauges within 21 km of the mudslides and the size of intense rain cells in the Magela Creek catchment is typically 100 km^2, except during tropical cyclones and well developed monsoonal troughs. We believe that red flood pulses were generated by localised storms concentrated on the mudslides.

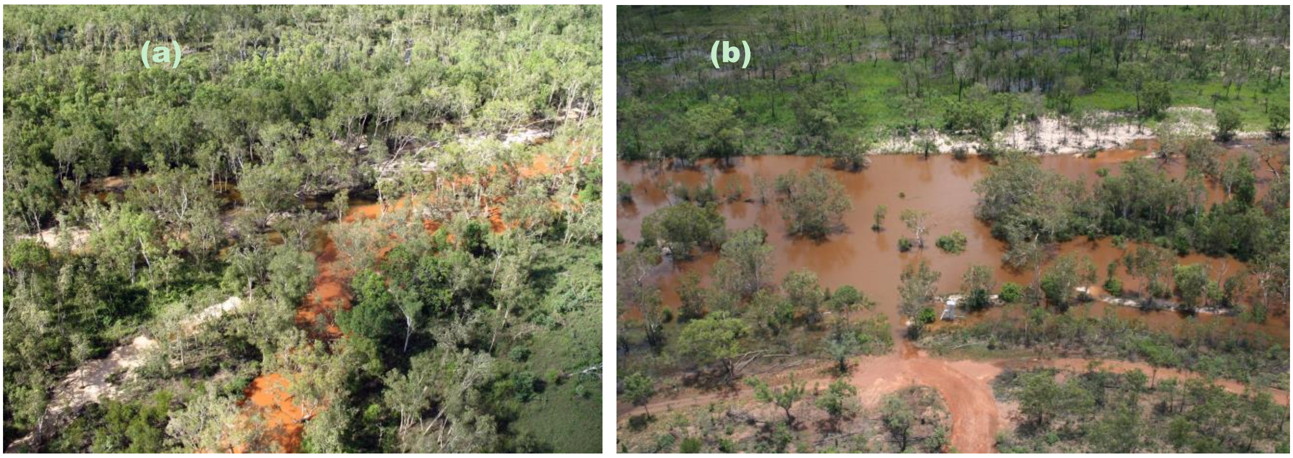

Fig. 5 (a) Red flood pulse on Magela Creek upstream of the Ranger Mine on 24 January 2008 (photo: R. Thorn), and (b) red flood pulse on Magela Creek at gauging station G8210009 on 5 February 2008 (photo: M. Saynor).

SEDIMENT COLOUR AS A FINGERPRINT

There are two fundamental requirements in using fingerprinting for tracing fine particulate sediments, such as silt and clay:

1. the selection of a property or a suite of properties which uniquely characterises sediment from a specific source; and
2. comparison of this property or properties with actively transported or deposited sediments (Foster & Lees, 2000).

Due to the description of the flood pulses originating from the landslides in 2008 as "red", soil colour was chosen as the fingerprinting property. We believed that if soil colour did not accurately identify the landslides as a significant sediment source on Magela Creek for the series of small floods in 2008, then soil colour was unlikely to be a successful fingerprint elsewhere. Soil colour is described in terms of three characteristics: Hue, Value and Chroma (Melville & Atkinson, 1985; Anon, 2010). Hue is the dominant spectral colour and is denoted by a letter abbreviation for the colour of the rainbow (for example, R: red, YR: yellow-red, Y: yellow). The letter(s) is preceded by a number which ranges from 0 to 10. For each letter range, hue becomes more yellow and less red as the numbers increase. Value is the relative lightness or intensity of colour and ranges from 0 (black) to 10 (white). Chroma is the relative purity, strength or saturation of a colour and ranges from 0 to 20 and is separated from the value by a virgule. Verbal colour descriptions are also included for various colour chips in Anon (2010).

Colours of 45 landslide samples are summarised in Table 1 and range from dark reddish brown (2.5YR 2.5/3, 2.5/4, 3/4, 5YR 3/4) to dark red (2.5YR 3/6) to very dark brown (7.5YR 2.5/2) to strong brown (7.5YR 4/6). Silt and clay fraction of the suspended sediment transported in Magela Creek at MCUGT and G8210009 in 2006-07 before the red flood pulses ranged from white (2.5Y 8/1, 5Y 8/1) to pale brown (2.5Y 8/2, 2.5Y 7/4, 5Y 8/2, 8/3, 7/3) to light grey (2.5Y 7/2, 5Y 7/2) to light yellowish brown (2.5Y 6/4) (Table 1). Silt and clay suspended sediment in 2006–07 at the two stations on Magela Creek was much yellower than landslide sediments.

Chartres *et al.* (1991) mapped two areas of lowland soils near Ranger mine and found that there were four major soil types. Three of these (yellow earths, siliceous sands, and grey clays) dominated and had surface soils with hues of 10YR or yellower. The minor red earths had surface soils with redder hues. Wells' (1979) extensive soil and land unit mapping of part of the Magela Creek catchment demonstrated the wider applicability of Chartres *et al.*'s (1991) results. Wells (1979) found that shallow yellow or reddish brown earths, earthy sands and siliceous sands with gravels throughout dominated upslope areas and deep yellowish brown gravel free earths dominated on lowlands. Saynor *et al.* (2009) found that 84% of surface soils on the lowlands near Ranger mine exhibited hues of 10YR or yellower, and Erskine & Saynor (2012) found that essentially all surface soils on floodplains near Ranger mine exhibited hues of 10YR or yellower. All the above indicates that the suspended sediment in Magela Creek in 2006–07 originated from the "yellow" soils of the lowlands, floodplains and quartz sandstones of the Arnhem Land Plateau.

There were a few red flood pulses in 2008 and the hues of the silt and clay suspended sediment of these pulses at the two stations on Magela Creek ranged from 5YR to 7.5YR to 10YR. These hues are produced by mixing landslide sediments (hues of 2.5YR, 5YR and 7.5YR) with suspended sediment from the floodplains, lowlands and sandstones (hues of 10YR, 2.5Y and 5Y). The Munsell colour names for the measured soil colours of the silt and clay fraction of the suspended sediment of the red flood pulses were yellowish red, reddish yellow, very pale brown, yellow, brownish yellow and strong brown. Clearly, none were "red", although 51.1% of the landslide sediment samples were "dark red" or 2.5YR 3/6 (Table 1).

During 2008 when red flood pulses did not occur, the colour of silt and clay suspended sediment at both Magela Creek stations was essentially the same as the previous wet season (Table 1). For 2008–09 and 2009–10 wet seasons, the colour of silt and clay suspended sediment at both stations was similar to 2006–07, except for four samples with hues of 10YR at MCUGT and one sample with a hue of 10YR at G8210009. These five samples were suspended sediment mixed from the mudslides and the rest of the catchment. Mudslides have ceased being a significant sediment source.

CONCLUSIONS

Although the largest storm on record initiated 16 mudslides and debris slides on olivine dolerite in the Magela Creek catchment, NT, it was not until the following wet season that a series of minor local storms generated red flood pulses from just 0.3 km^2 of a 605 km^2 catchment. These red flood pulses were characterised by Munsell® soil colours with hues of 5YR, 7.5YR and 10YR,

Table 1 Sediment colour determinations for red flood pulses, landslide deposits and silt and clay suspended sediment in the Magela Creek catchment, Northern Territory, Australia. The moist colour for the red flood pulses refers to the colour of the silt and clay suspended sediment at each gauging station. The moist colour of the silt and clay suspended sediment at each gauging station for 2007/08 refers to non-red flood pulses. Locations of MCUGT, G8210009 and mudslides shown in Fig. 1.

Sediment type	Moist soil colour using the Munsell® notation						
Red flood pulses at MCUGT in 2008 (n = 27)	5YR 5/8 n = 4	7.5YR 7/8 n = 4	7.5YR 6/8 n = 6	10YR 8/4 n = 3	10YR 7/6 n = 5	10YR 6/6 n = 5	
Red flood pulses at G8210009 in 2008 (n = 10)	7.5YR 6/8 n = 4	7.5YR 5/8 n = 1	10YR 7/6 n = 3	10YR 6/6 n = 2			
Landslide deposits (n = 45)	2.5YR 2.5/3 n = 1	2.5YR 2.5/4 n = 9	2.5YR 3/4 n = 4	2.5YR 3/6 n = 23	5YR 3/4 n = 4	7.5YR 2.5/2 n = 1	7.5YR 4/6 n = 3
Silt and clay suspended	**<u>2006/07</u>**	2.5Y 8/1 n = 1	2.5Y 8/2 n = 1	2.5Y 7/2 n = 2	2.5Y 7/4 n = 1	2.5Y 6/4 n = 1	5Y 8/1 n = 19
Sediment at MCUGT (n = 54)		5Y 8/2 n = 23	5Y 8/3 n = 2	5Y 7/2 n = 3	5Y 7/3 n = 1		
Silt and clay suspended sediment at MCUGT (n = 50)	**<u>2007/08</u>**	2.5Y 8.5/2 n = 3	2.5Y 8/2 n = 24	2.5Y 8/3 n = 9	2.5Y 8/4 n = 2	2.5Y 7/4 n = 4	5Y 8/2 n = 8
Silt and clay suspended	**<u>2008/09 & 2009/10</u>**	10YR 7/6 n = 2	10YR 6/6 n = 1	10YR 3/4 n = 1	2.5Y 9.5/2 n = 1	2.5Y 9/2 n = 4	2.5Y 8.5/2 n = 1
Sediment at MCUGT (n = 49)		2.5Y 8/2 n = 1	2.5Y 8/3 n = 5	2.5Y 8/4 n = 3	2.5Y 7/2 n = 1	2.5Y 7/3 n = 1	2.5Y 7/4 n = 12
		2.5Y 6/3 n = 3	2.5Y 6/4 n = 5	2.5Y 6/6 n = 1	2.5Y 5/4 n = 1	5Y 8/2 n = 1	5Y 8/3 n = 2
		5Y 7/2 n = 2	5Y 6/3 n = 1				
Silt and clay suspended	**<u>2006/07</u>**	2.5Y 8/2 n = 3	2.5Y 7/2 n = 1	2.5Y 7/4 n = 1	2.5Y 6/3 n = 3	5Y 8/1 n = 11	5Y 8/2 n = 29
sediment at G8210090 (n = 50)		5Y 8/3 n = 1	5Y 7/2 n = 1				
Silt and clay suspended	**<u>2007/08</u>**	2.5Y 8.5/1 n = 1	2.5Y 8/2 n = 1	2.5Y 8/3 n = 4	2.5Y 8/4 n = 4	2.5Y 7/4 n = 6	5Y 8/1 n = 3
Sediment at G8210090 (n = 38)		5Y 8/2 n = 18	5Y 5/8 n = 1				
Silt and clay suspended	**<u>2008/09 & 2009/10</u>**	10YR 4/4 n = 1	2.5Y 8/3 n = 14	2.5Y 8/4 n = 21	2.5Y 7/4 n = 12	2.5Y 6/4 n = 3	5Y 8/2 n = 3
sediment at G8210009 (n = 57)		5Y 8/4 n = 1	5Y 7/2 n =1	5Y 7/3 n = 1			

and were progressively mixed and diluted downstream because the upstream station (MCUGT) recorded more and redder silt and clay suspended sediment samples than the downstream station (G8210009) (Table 1). Traditional owners were concerned about the mine's contribution to the coloured water, and the combination of sediment fingerprinting using soil colour and up- and downstream of mine measurement of suspended sediment was capable of demonstrating that a mudslide source was responsible for the short term "red" flood pulses on Magela Creek. Munsell®soil colour deserves further investigation as a reliable sediment fingerprint.

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REFERENCES

Anonymous (2010) *Munsell Soil Color Charts* (with genuine Munsell® soil color chips). Munsell Color, Grand Rapids, USA.

Bureau of Meteorology (2011) *Generalised Probable Maximum Precipitation Estimates for the Ranger Tailings Dam*. Hydrometeorological Advisory Service HAS Report no. GTSMR/47.

Chartres, C. J., Walker, P. H., Willett, I. R., East, T. J., Cull, R. F., Talsma, T. & Bond, W. J. (1991) *Soils and hydrology of Ranger Uranium Mine sites in relation to application of retention pond water.* Technical Memorandum 34, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra.

Cruden, D. M. & Varnes, D. J. (1996) Landslide types and processes. In: *Landslides – Investigation and Mitigation* (ed. by A. Turner and R.L. Schuster), 36–75, Transportation Research Board Special Report 247, National Academy of Science, Washington, USA.

Duggan, K. (1994) Erosion and sediment yields in the Kakadu region of northern Australia. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby), 373-–83, IAHS Publ. 224, IAHS Press, Wallingford, UK.

Erskine, W. D. & Saynor, M. J. (1996). Effects of catastrophic floods on sediment yields in southeastern Australia. In: *Erosion and Sediment Yield: Global Perspectives* (ed. by D. E. Walling & B. W. Webb), 381–388, IAHS Publ. 236, IAHS Press,Wallingford, UK.

Erskine, W. D. & Saynor, M. J. (2000). *Assessment of the off-site geomorphic impacts of uranium mining on Magela Creek, Northern Territory, Australia*. Supervising Scientist Report 156, Supervising Scientist, Darwin NT.

Erskine, W. D. & Saynor, M. J. (2012) *Lithostratigraphy of Gulungul Creek alluvial landscapes*. Internal Report, Supervising Scientist, Darwin (in press)

Foster, I. D. L. & Lees, J. A. (2000) Tracers in geomorphology: Theory and applications in tracing fine particulate sediments. In: *Tracers in Geomorphology* (ed. by I. D. L. Foster), 3–20. Wiley, Chichester, UK.

Grimshaw, D. L. & Lewin, J. (1980) Source identification for suspended sediment. *J. Hydrol.* 47, 151–162.

McDonald, R. C. & Isbell, R. F. (2009) Soil profile. In: *Australian Soil and Land Survey Field Handbook* (ed. by The National Committee on Soil and Terrain), 147–204, CSIRO Publishing, Collingwood, Australia.

Melville, M. D. & Atkinson, G. (1985) Soil colour and its designation in models of uniform colour space. *J. Soil Sci.* 36, 495–512.

Moliere, D. R. & Evans, K. G. (2010) Development of trigger levels to assess catchment disturbance on stream suspended sediment loads in the Magela Creek catchment, Northern Territory, Australia. *Geogr. Res.* 48(4), 370–385.

Moody, J. A., Meade, R.H. & Jones, D. R. (2003) Lewis and Clark's Observations and Measurements of Geomorphology and Hydrology, and Changes with Time. *US Geol. Survey Circular 1246*.

Pilgrim, D. H. (2001) *Australian Rainfall and Runoff*. Institution of Engineers Australia, Barton, ACT.

Saynor, M. D., Erskine. W. D., Staben, G. & Lowry, J. (2012) A rare occurrence of landslides initiated by an extreme event in March 2007 in the Alligator Rivers Region, Australia. In: *Erosion and Sediments Yields in the Changing Environment* (this volume).

Saynor, M. J., Houghton, R., Hancock, G., Staben, G., Smith, B. & Lee, N. (2009) *Soil sample descriptions – Gulungul Creek, Ranger mine site and Nabarlek: Cyclone Monica fieldwork*. Internal Report 558, Supervising Scientist, Darwin.

Wells, M. R. (1979) *Soil Studies in the Magela Creek Catchment 1978 Part 1.* Land Conservation Unit, Territory Parks and Wildlife Commission, Darwin.