

Do suspended sediment and bedload move progressively from the summit to the sea along Magela Creek, northern Australia?

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Abstract Soil erosion rates on plots of waste rock at Ranger uranium mine and basin sediment yields have been measured for over 30 years in Magela Creek in northern Australia. Soil erosion rates on chlorite schist waste rock are higher than for mica schist and weathering is also much faster. Sediment yields are low but are further reduced by sediment trapping effects of flood plains, floodouts, billabongs and extensive wetlands. Suspended sediment yields exceed bedload yields in this deeply weathered, tropical landscape, but the amount of sand transported greatly exceeds that of silt and clay. Nevertheless, sand is totally stored above the topographic base level. Longitudinal continuity of sediment transport is not maintained. As a result, suspended sediment and bedload do not move progressively from the summit to the sea along Magela Creek and lower Magela Creek wetlands trap about 90.5% of the total sediment load input.

Key words turbidity; sediment yields; sediment discontinuities; natural sediment traps; sediment budget

INTRODUCTION

In the Magela Creek basin in tropical northern Australia, sediment yields are low by world standards, except where human disturbance has occurred by mining, burning, and road and house construction (Hart *et al.*, 1982, 1987a; Duggan, 1994; Erskine & Saynor, 2000). However, the influence of scale on sediment yields in this area has only been investigated by Wasson (1992) and Erskine & Saynor (2000), and much more reliable data have now been collected. Saynor & Erskine (2013) mapped ten homogeneous river reaches on Magela Creek from the summit to the sea. Six reaches are located on the highly resistant sandstone of the Arnhem Land Plateau above Magela Falls, and four on the lowlands below Magela Falls. The sand-bedded, island anabranching channel of Nanson *et al.* (1993) corresponds to Reach 8, the extensive lower Magela wetlands of Finlayson *et al.* (1989) and Wasson (1992) to Reach 9, and the current estuary, to Reach 10.

The purpose of this study is to determine how suspended sediment and bedload yields vary from the summit to the sea on Magela Creek. We use plot data (up to 900 m²) combined with sediment yield data collected at river gauging stations (up to 1570 km²) to determine the influence of scale and natural sediment traps (backflow billabongs, channel billabongs, floodplain billabongs, wetlands, floodouts and flood plains) on sediment yields. Magela Creek is located in the World Heritage listed Kakadu National Park which contains Ramsar-listed wetlands of international significance. Furthermore, the Ranger uranium mine and Jabiluka Mineral Lease have been excised from Kakadu National Park to allow mining and processing of uranium ore.

METHODS

We compiled published soil erosion and sediment yield data for the Alligator Rivers Region in the Northern Territory and calculated new suspended sediment and bedload yields for six gauging stations operated by the Supervising Scientist (SS) of the Australian Department of the Environment (Table 1). An automatic pump sampler collected suspended sediment samples at SS gauging stations. A significant relationship between the concentration of silt and clay, and turbidity was

documented for the three gauging stations (East Tributary, Upper Ngarradj and Swift Creek) at Jabiluka (Moliere *et al.*, 2005), for Magela Creek at G8210009 (Moliere *et al.*, 2008) and for the two stations on Gulungul Creek (Erskine *et al.*, 2014). The relationship between suspended sediment concentration for the silt and clay fraction ($>0.45 \mu\text{m}$ and $<63 \mu\text{m}$) and instantaneous turbidity was highly significant at all SSD stations ($p < 0.00001$). Each 5-minute turbidity reading was converted to silt and clay concentration by the relevant regression equation. The concentrations were then converted to loads by multiplying by mean daily discharge for the 5-minute period and integrating the area under the sedigraph. Mean annual suspended silt and clay loads for SS stations are shown in Table 1. Suspended sand ($>63 \mu\text{m}$ and $<2 \text{mm}$) fraction was also measured for suspended sediment samples (Evans *et al.*, 2004a). The suspended sand fraction of the total suspended sediment load was determined and the suspended silt and clay yield was multiplied by the relevant conversion factor to obtain the suspended sand yield (Erskine *et al.*, 2014). The total suspended sediment yield was the sum of the suspended silt and clay and suspended sand yields (Erskine *et al.*, 2014). An independent check on the accuracy of the method was made by comparing our total suspended sediment yield for Gulungul Downstream (2621 t/year) with that measured by Duggan (1994) for 1984-85, 1985-86 and 1986-87 (2156 t/year). Her measurement period was drier than ours (mean annual rainfall of 1289 *versus* 1587 mm/year,) and this accounts for the small difference. Suspended silt and clay is a very small proportion of the total suspended sediment load (Table 1).

Bedload fluxes were measured with Helley-Smith pressure difference samplers at the six SS gauging stations by Erskine *et al.* (2011; 2014) and by Erskine & Saynor (2014). Roberts (1991) used Helley-Smith samplers to determine bedload ratings for Magela Creek (G8210009) and his suspended sediment and bedload yields are included in Table 1.

EROSION PLOT RESULTS

Most soil erosion research at Ranger mine has been conducted on waste rock (chlorite schist) from pit 1 and relatively little research has been completed on waste rock (mica schist) from pit 3. However, characterisation of waste rock from each pit as a single rock type is an oversimplification. We do not review the extensive rainfall simulation results for Ranger mine in this paper.

East *et al.* (1994) monitored soil erosion under natural rainfall on four unvegetated plots of waste rock from pit 1 for 1987-88 and 1988-89. Two plots had a rectilinear profile on a slope of 1:3, and two plots had a concave profile and slopes of 1:3 above 1:5 above 1:8. One plot in each group was surfaced with 0.3 m of run-of-mine waste rock and one with chlorite schist. Suspended solids concentrations for all plots varied directly with discharge with highest concentrations coinciding with peak discharge. Suspended solids concentrations varied from $<5 \text{mg/L}$ to a maximum of 520mg/L . Concentrations for rectilinear slopes were always higher than for concave slopes because of larger peak discharges. Plots with run-of-mine waste rock had higher suspended solids concentrations than the chlorite schist plots because of more rapid weathering. There was no change in suspended solids concentrations for comparable discharges throughout the wet season because plots were unvegetated. Significant quantities of bedload were discharged from the rectilinear slopes but little bedload was transported from concave slopes. No annual yields were reported.

Riley (1995) used a small flume to compare soil losses from vegetated natural hillslopes with unvegetated batter slopes and cap slopes of waste rock under applied discharges. Maximum sediment concentration recorded was $57\,000 \text{mg/L}$ on batters of the waste rock but the natural site yielded a median concentration of only 20mg/L . Concentrations were commonly high during early stages of a run on waste rock and then decreased as sediment was depleted. Discharge from batter and cap sites had sediment concentrations 10–100 times greater than those from the natural site. Saynor & Evans (2001) measured suspended load and bedload under natural rainfall from two plots (soil and fire sites) during the 1994-95 wet season and one plot (cap site) during the 1993-94 wet season. The soil site had an average slope of 1.2 % and had been ripped, topsoiled and vegetated eight years previously. The fire plot had an average slope of 2.3 % and was topsoiled, surface ripped and vegetated approximately ten years earlier. The cap site had an average slope of 2.8 %, was not surface ripped, had negligible vegetation cover and a fine surface material over a pan. Bedload was

Table 1 Measured sediment yields in the Alligator Rivers Region.

Site	Basin area (km ²)	Mean annual rainfall for measurement period (mm/year)	Mean annual suspended silt and clay yield (t/year)	Mean annual suspended sand yield (t/year)	Mean annual total suspended sediment yield (t/year)	Mean annual bedload yield (t/year)	Specific mean annual total sediment load yield (t/km ² /year)
	(A)		(1)	(2)	(1+2)	(3)	(1+2+3)/A
Koongarra Creek - 1	15.4	1329	N/A	N/A	464	N/A	N/A
7J Creek - 1	53.5	1451	N/A	N/A	505	N/A	N/A
Gulungul Creek Downstream - 1	66	1289	N/A	N/A	2156	N/A	N/A
Gulungul Creek Downstream - 2*	66	1587	265	2621	2886	1620	68.3
Gulungul Creek Upstream - 2*	40	1611	469	4639	5108	1318	160.7
Georgetown Creek One - 1	7.8	1781	N/A	N/A	250	N/A	N/A
Georgetown Creek Two - 1	4.8	1044	N/A	N/A	30	N/A	N/A
East Tributary - 3*	8.5	1754	128	486	614	557	137.8
Upper Ngarradj - 3*	18.8	1731	207	912	1119	1062	116.0
Swift Creek - 3*	43.6	1737	148	756	904	1675	59.2
Kawudjulah Creek - 4	63	N/A	N/A	N/A	1197	N/A	N/A
Ranger Tributary - 1	0.22	N/A	N/A	N/A	195.8	N/A	N/A
Jabiru Tributary - 1	0.15	N/A	N/A	N/A	165.2	N/A	N/A
Magela Creek at G8210009 - 5	600	1505.6	N/A	N/A	2940	N/A	N/A
Magela Creek at G8210009 - 6	600	1194.7	N/A	N/A	2330	N/A	N/A
Magela Creek at G8210009 - 7	600	1560.8	N/A	N/A	7080	5100	20.3
Magela Creek at G8210009 – This paper*	600	1812.8	4190	2095	6285	N/A	19.0
Magela Creek at G8210017 - 8	1115	1635	N/A	N/A	3735	N/A	N/A
Magela Creek at G8210019 - 6	1570	1194.7	N/A	N/A	1700	N/A	N/A
Magela Creek at G8210019 - 8	1570	1420	N/A	N/A	3611	N/A	N/A

1 From Duggan (1994); 2 From Erskine *et al.* (2014); 3 From Evans *et al.* (2004a, b), Saynor *et al.* (2006); Erskine *et al.* (2006); Erskine & Saynor (2014); 4 From Duggan (1988); 5 From Hart *et al.* (1982); 6 From Hart *et al.* (1987a,b); 7 From Roberts (1991); 8 From Wasson (1992). * SS

collected after every rainfall event. Bedload was significantly related to total sediment load. Suspended sediment discharge was inversely related to vegetation cover. Bedload declined at a decreasing rate during the wet season for fire and soil sites (vegetated), but increased for cap site (least vegetated) although the slope of the regression line was not significantly different from zero.

Saynor *et al.* (2012) and Lowry *et al.* (2014) reported suspended sediment and bedload yields for four (900 m²) plots on a trial rehabilitated landform at Ranger mine constructed largely of mica schist from pit 3 during the 2009 dry season. The purpose of the trial landform was to assess the effects of two types of potential capping material (waste rock and waste rock mixed with 30% laterite) and two types of planting techniques (direct seeding and tube stock) on suspended sediment and bedload yields. Specific mean annual bedload yield declined exponentially over the first four years since construction (Fig. 1(a)). The highest bedload yield was always generated from plot 2 which had the lowest vegetation cover. Bedload grain size was also dominated by sand then gravel with little silt and clay. Suspended sediment silt and clay yield has only been determined to date for plot 1 for the first four years at 0.0044 ± 0.0002 t/year (4.9 t/km²/year). This is less than those for pit 1.

SEDIMENT YIELD RESULTS

Analyses of data in Table 1 show that there is no relationship between mean annual suspended sediment yield and both basin area and mean annual rainfall for the Alligator Rivers Region (not reproduced here). The envelope curve of mean annual suspended sediment yield and basin area indicates an inverse relationship (not reproduced here), as also found by Wasson (1992) and Erskine & Saynor (2000) for a smaller dataset for the same area. For the SS dataset plus Roberts' (1991) data for gauge G8210009 on Magela Creek, mean annual suspended sediment yield exceeds mean annual bedload yield at six of the seven stations, except for Swift Creek. However, mean annual suspended sand yield exceeds mean annual suspended silt and clay yield at five of the six SS stations (Fig. 1(b)). The sole exception is G8210009 on Magela Creek and further work is being conducted at this station to determine a more accurate result. As first concluded by Saynor *et al.* (2006) for the East Tributary gauge (Table 1) at Jabiluka, sand as suspended sand and bedload is by far the major sediment fraction exported from the Magela Creek catchment upstream of the lower Magela Creek wetlands. All previous results (e.g. Hart *et al.*, 1982, 1987a,b; Wasson, 1992) that exclude bedload, greatly underestimate sediment yields and hence, greatly overemphasise the importance of silt and clay.

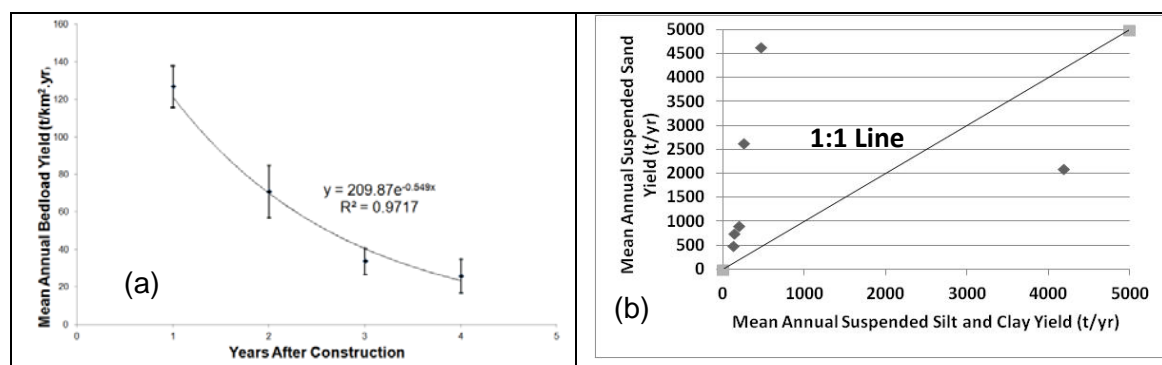


Fig. 1 (a) Changes in mean annual specific bedload yield \pm SE over time from the four plots on the trial rehabilitated landform. Vertical bars represent SE for four plots for each year. (b) Mean annual suspended sand yield greatly exceeds mean annual suspended silt and clay yield at all SSD stations, except G8210009. Data in Fig. 1(b) taken from Table 1.

LOWER MAGELA CREEK WETLANDS: VEGETATION COMMUNITIES

Reaches 9 and 10 of Magela Creek (Saynor & Erskine, 2013) have long been considered a significant sediment trap because of their low elevation, low slope, extensive inundation, dense macrophytes and resultant reduction in flow velocity (Hart *et al.*, 1987b; Wasson, 1992). The distribution and composition of the vegetation communities on the lower Magela Creek wetlands were mapped for 11 May 2010 from multispectral high spatial resolution (2-m pixels) satellite imagery (WorldView-2) and a canopy height model derived from an airborne laser scanning survey (Fig. 2). The resultant map (Fig. 2) has 12 vegetation classes consistent with Finlayson *et al.* (1989). *Hymenachne* grassland (3639 ha) also occurs with *Oryza meridionalis*, *Nymphaea spp.* and *Pseudoraphis spinescens* (Finlayson *et al.*, 1989). The *Melaleuca* woodland and *Melaleuca* open forest typically contain *M. cajuputi* and *M. viridiflora* in the northern region and at the edges of the wetland, and *M. leucadendra* in the backswamps (Finlayson *et al.*, 1989). Woodland communities have 10–50% woody cover (5039 ha), whereas open forest communities have 50–70% cover (822 ha). *Oryza meridionalis* grassland occupied 4040 ha, *P. spinescens* grassland, 943 ha, *Pseudoraphis/Hymenachne*, 375 ha and *Eleocharis dulcis* sedgeland, 1054 ha. The invasive weed, *Urochloa mutica* (Para grass) occupied 2181 ha, and *Nelumbo* herbland, 243 ha. *Salvinia molesta* occupied 108 ha and *L. hexandra* grassland, 967 ha. Mangrove communities (249 ha) are located on Magela Creek estuary (Reach 10).

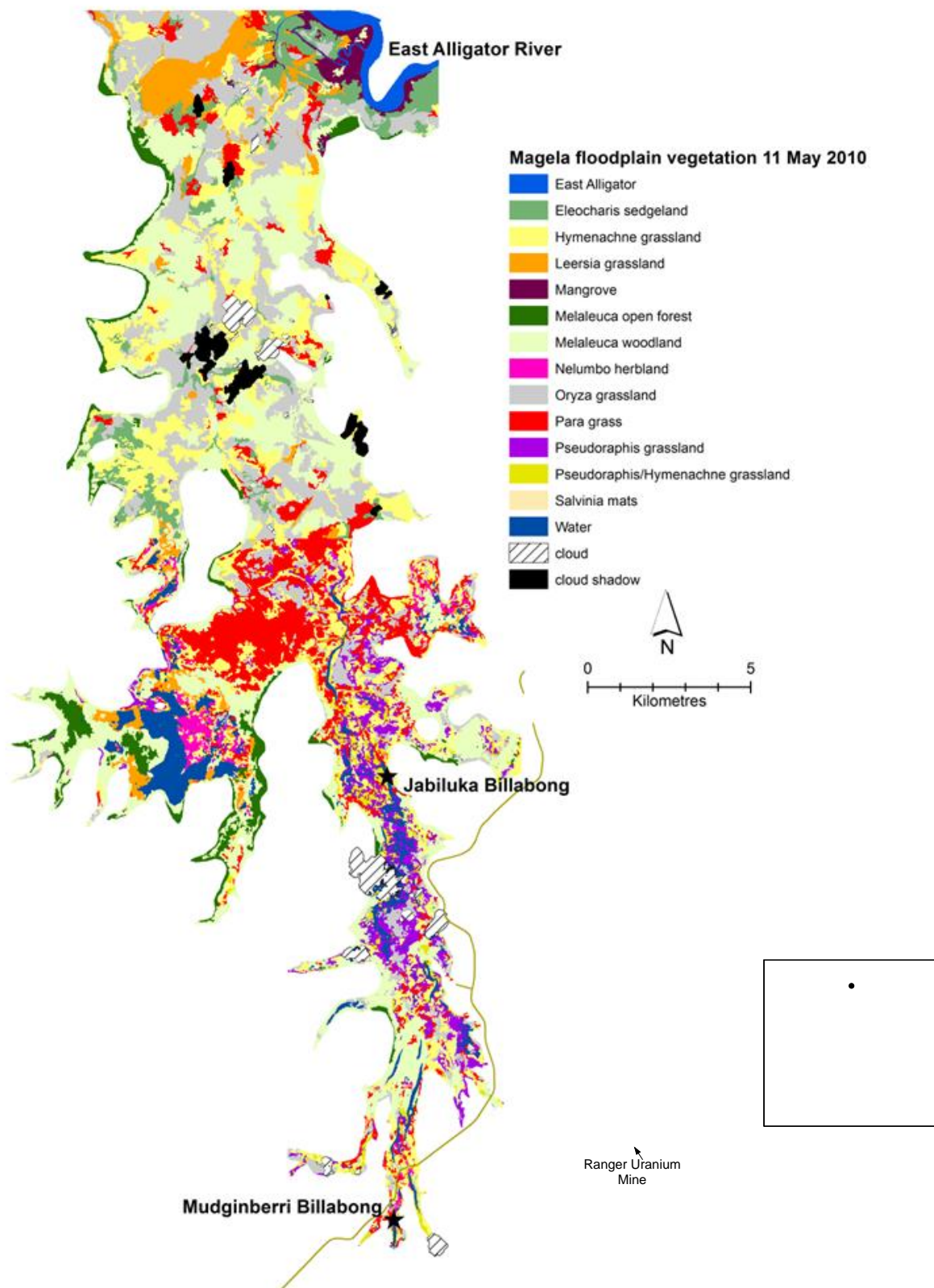


Fig. 2 Vegetation communities of lower Magela Creek wetlands.

LOWER MAGELA CREEK WETLANDS: SEDIMENT BUDGET

Hart *et al.* (1987b) first constructed an approximate sediment budget for lower Magela Creek wetlands which indicated that they were a net sink for suspended solids. They used two approximate methods to determine sediment inflows for just one wet season (1982-83), both of which overestimated sediment inflows because they erroneously assumed that the whole upstream basin uniformly contributed sediment. This assumption is incorrect because upstream flood plains trap sediment, terminal sand floodouts (Tooth, 1999) trap sand bedload (Erskine *et al.*, 2014), and backflow billabongs or terminal wetlands trap and store fine sediment in essentially every tributary valley (Erskine & Saynor, 2000). Furthermore, Magela Creek derived sediment is completely stored in the upper wetlands (Wasson, 1992).

For the 1982-83 wet season, Hart *et al.* (1987b) calculated that of the 5400 ± 5800 t of suspended solids supplied to the wetlands, 1700 ± 540 t were discharged into the East Alligator River estuary and that 3700 ± 5900 t were deposited in the wetlands. Based on the mean values, 68.5% of the supplied sediment would be deposited in the wetlands but based on the maximum values, 85.7% would be deposited. The exclusion of bedload from these calculations greatly underestimates the sediment trap efficiency of lower Magela wetlands, because no bedload is transported through both reaches 9 and 10 to the East Alligator River. Furthermore, a single water year should not be used for such sediment budget analysis.

Wasson (1992) found that 90% of Magela Creek sediment load is deposited upstream of Jabiluka Billabong (Fig. 3) in an area of only 30 km² or 15% of the wetlands. Channel billabongs are only located in the upper wetlands where there is still a remnant channel, and have well vegetated steep banks, deep (6 m) water and sandy bed (Hart & McGregor, 1980). Sand is not transported beyond the channel billabongs. Further downstream there are only flood plain billabongs which are reasonably deep (up to 5.3 m) with shelving banks and fine-grained bed (Hart & McGregor, 1980). Wasson (1992) also measured suspended sediment loads at the most downstream station, G8210019, for three years instead of the one by Hart *et al.* (1987a,b).

The difference in mean annual total sediment load between the two stations on Gulungul Creek in Table 1 for SS data is 2524 t/year. Assuming a soil bulk density of 1.6 t/m³ yields an annual sediment volume addition to the flood plain surface of 4038 m³/year. This converts to an annual depth of overbank deposition of 4 mm/year when divided by the flood-plain area between the two gauging stations. The flood-plain area was determined by interpretation of a WorldView-2 image captured on 11 May 2010. Erskine *et al.* (2014) found that the surface of the Gulungul flood plain was veneered by a variable layer, 5–10 cm thick, of recent overbank deposits of fine-medium sand. This surficial overbank deposit represents the deposition of sediment transported past the Upstream gauge but which is deposited before reaching the Downstream gauge, during the last 34 years since uranium mining commenced at Ranger. This highlights the large potential error of simply measuring a sediment yield at a point on a flood plain river and then uniformly allocating it to the whole basin, as practised by Hart *et al.* (1987b). Flood plains must be treated as sediment stores in any sediment budget, even in areas of globally low sediment yields.

Erskine *et al.* (2014) also mapped a terminal floodout (Tooth, 1999) on Gulungul Creek where all the sandy bedload is deposited upstream of the junction with Magela Creek. Gulungul Creek has not supplied sand to Magela Creek, the main stream, for the last 8000 years. In addition, there is a backflow billabong on lower Gulungul at the junction with Magela Creek (Hart & McGregor, 1980) which exhibits a reverse sandy delta from Magela Creek (Erskine & Saynor, 2000). Gulungul billabong is flooded by deep fine silt and clay with a high organic matter content (Thomas & Hart, 1984) which indicates that the backflow billabong also has a high sediment trap efficiency for fine suspended sediment (Erskine & Saynor, 2000). Backflow billabongs were present on all mine site tributaries before mining, and are still present on Gulungul, Coonjimba and Georgetown creeks (Hart & McGregor, 1980).

Figure 3 shows our sediment budget in terms of total sediment load for lower Magela Creek wetlands for 2003-04 to 2012-13. Wasson's (1992) suspended sediment budget is also shown for comparison. The total sediment load input to the lower Magela Creek wetland is 42000 t/year and

the output to the East Alligator River is 4000 t/year. This means that the output is only 9.5% of the input and that 90.5% is trapped and stored in the wetland. Our error terms are standard errors and reflect the total supply of clastic sediment, not just suspended sediment as previously reported by Hart *et al.* (1987a,b) and Wasson (1992). As suspended silt and clay constitute a minor component of total sediment load, suspended sediment only should not be used for such a budget. Sand is not transported very far into the wetlands, changing the character of billabongs from channel billabongs upstream to flood plain billabongs downstream.

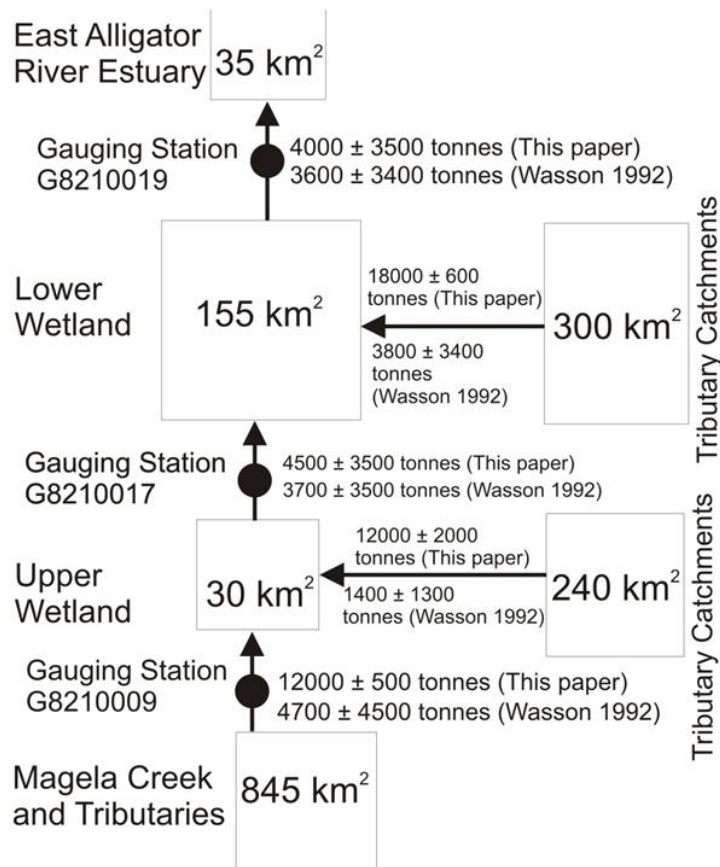


Fig. 3 Mean annual sediment fluxes for lower Magela Creek wetlands. Wasson (1992) only cites suspended sediment load and this paper uses total sediment load for the period 2003-04 to 2012-13.

CONCLUSIONS

The short answer to the question posed in the title of this paper is no for both suspended sediment and bedload. Very little silt and clay is generated from the tropical Magela Creek drainage basin. While sand production is much greater than silt and clay, sand is not transported by many tributaries into Magela Creek (Nanson *et al.* 1993; Erskine *et al.* 2014). However, soil erosion rates on the rehabilitated Ranger mine, where waste rock from pit 1 is used for a surface cover, may greatly increase sediment yields. In addition to the low natural sediment generation rates, many efficient sediment traps store sediment throughout the channel network. These sediment traps comprise extensive backswamps on meandering channels, flood plains on anabranching channels, floodouts, backflow billabongs on tributaries immediately upstream of the junction with higher order channels and the 220 km² lower Magela Creek wetlands. Lower Magela Creek wetlands trapped about 90.5% of the inflowing total sediment load for the period 2003-04 to 2012-13.

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