Erosion, sediment transport and deposition in the Daly River catchment: Implications for catchment management

Technical Report · July 2014

Robert James Wasson
National University of Singapore

Andrew P Brooks
Griffith University

Jon M Olley
Griffith University

Jon Knight
Griffith University

Erosion, sediment transport and deposition in the Daly River catchment: Implications for catchment management

R.J. Wasson[1], A. Brooks[2], J. Olley[2], J. Knight[2] and P. Rustomji[3]

[1]Asia Research Institute, National University of Singapore, Singapore.
[2] Australian Rivers Institute, Griffith University, Nathan, QLD, Australia.
[3] CSIRO Land and Water, Christian Laboratory, Canberra, ACT, Australia.

TRaCK Tropical Rivers and Coastal Knowledge

Acknowledgement:

This project was funded by Charles Darwin University, Griffith University (Australian Rivers Institute), CSIRO and TRaCK's funders as listed below.

Disclaimer

TRaCK has published the information contained in this publication to assist public knowledge and discussion and to help improve the sustainable management of Australia's tropical rivers and coasts. Where technical information has been prepared by or contributed by authors external to TRaCK, readers should contact the author(s), and conduct their own enquiries, before making use of that information. No person should act on the contents of this publication whether as to matters of fact or opinion or other content, without first obtaining specific independent professional advice which confirms the information contained within this publication.

While all reasonable efforts have been made to ensure that the information in this publication is correct, matters covered by the publication are subject to change. Charles Darwin University does not assume and hereby disclaims any express or implied liability whatsoever to any party for any loss or damage caused by errors or omissions, whether these errors or omissions result from negligence, accident or any other cause.

TRaCK brings together leading tropical river researchers and managers from Charles Darwin University, Griffith University, the University of Western Australia, CSIRO, James Cook University, the Australian National University, Geoscience Australia, the Environmental Research Institute of the Supervising Scientist, the Australian Institute of Marine Science, the North Australia Indigenous Land and Sea Management Alliance, and the governments of Queensland, the Northern Territory and Western Australia.

TRaCK received major funding for its first phase of research through the Australian Government's Commonwealth Environment Research Facilities initiative; the Australian Government's Raising National Water Standards Program; Land and Water Australia; the Fisheries Research and Development Corporation and the Queensland Government's Smart State Innovation Fund.

In 2011 TRaCK received funding from the National Water Commission to undertake targeted projects as part of a 'synthesis and adoption' year to ensure research findings are relevant and more widely available.

Front cover – Photo by Prof Michael Douglas

For further information about this publication:
Jon Olley, Australian Rivers Institute, Griffith University,
Email: j.olley@griffith.edu.au
Bob Wosson, Asia Research Institute, National University of Singapore
Email: arirjw@nus.edu.sg

Or to find out more about TRaCK
Visit: http://www.track.org.au/
Email: track@cdu.edu.au
Phone: 08 8946 7619

ISBN 978-1-921576-91-1
Published by: Charles Darwin University

Summary

Further agricultural development in the Daly River catchment is planned. As an input into this planning this report provides the best current understanding of the erosion and sediment transport processes and rates in the catchment, and their drivers. The main sources of sediment and the redistribution of the sediment within the catchment are quantified. The techniques used are: remote sensing of channel change; modelling of erosion, sediment transport in the main river channel, and storage of sediment on floodplains; sediment source tracing using fallout radionuclides; measured rates of riverbank erosion derived from remote sensing and ground measurements; and hydrologic analysis of river flows. The conclusions are that the river does not appear to have filled up with sediment over the last few decades, and that most of the river sediment is coming from river channel widening. This widening is a response to increased river flows and higher groundwater levels. About one quarter of the river sediment is the result of gullying of riverbanks, most of which appears to be the result of grazing pressure by cattle and feral animals. Protection of the river banks where possible is a priority for management, although this may be compromised by continuing widening of the channels in response to increased flows.

1. Introduction

The wet/dry tropics of northern Australia have received relatively little attention with regard to the impact of erosion on the many large river systems that are an important part of Australia's water resource, especially given the potential for erosion when long dry seasons are followed by intense wet-season rain. The Daly River, in the Northern Territory, occupies a mainly uncleared large catchment in the Australian wet–dry tropics. There is a great deal of interest in agricultural development in the Daly River catchment, with competing interest from agriculturalists, conservationists, recreational fishers, and local Indigenous people. Recently there has been increasing concern about possible increased sediment input to the river from clearing and cropping (Wasson *et al.,* 2010).

The Daly Region Community Reference Group (DRCRG, 2004; also see Jackson, 2004) identified sedimentation and habitat degradation of the river as key risks to ecological sustainability. While there appears to be a consensus in the local community that the Daly River is widening by bank erosion and shallowing from sedimentation, the causes of the changes are not clear. As part of a report by the Amateur Fisherman's Association of the Northern Territory the following was noted:

'Erosion and siltation resulting from severe flooding and inappropriate land clearing also pose a threat to the river's fishery. Siltation is already creating navigational challenges at a number of locations in the lower river.... Ironically, it seems likely that the current siltation issues may be the result of natural processes indicating that extreme care needs to be taken to ensure that human activity does not add to the problem'.

Sedimentation in the river is mostly by coarse sediment, but habitat degradation is the result of both coarse and fine sediment. DRCRG (2004) recognised that '… *relative contribution from each sediment source is still unknown…' (p. 103), identifying cleared land, grazed land, river bank erosion, and gully erosion as the possible sources*.

The supply and transport of sediment is one of the defining attributes of both a river and its catchment. It influences the form of the channel, and the type and distribution of the physical habitat (Prosser *et al*., 2001; Olley and Wasson 2003). The flux of sediment depends on both the supply of material and the ability of the river to transport it. Sediment is supplied by a combination of hillslope, gully and channel erosion**.** Where supply exceeds transport capacity, sediment is deposited. These channel deposits can be mobilized at some time in the future if the sediment transport capacity in the reach of river exceeds the supply of material from upstream. The flux of sediment down a river network therefore adjusts in response to changes in sediment transport capacity as well as past and current sediment supply. This dependence on both the past and current sediment supply makes it difficult to predict the effects of changing land-use and climate on the flux of sediment, particularly in areas that have experienced past changes in land-use over many hundreds of years.

Here, we first examine the evidence for changes in the main channel and estuary of the Daly River. Historic aerial photographs and SPOT imagery are used to assess changes in the distribution of sand in the channel and the extent of channel bank erosion since 1948/1949. We then examine erosion sources, sediment transport and deposition and develop a sediment budget for the catchment. The relative effects of land-use change, rainfall variation, and changes in flow are assessed and the implications for catchment management are discussed.

2. The Daly Catchment

The Daly River catchment (53,000 km^2) is situated south of Darwin in the Northern Territory of Australia (Figure 1), and remains relatively uncleared. Elevations range from sea level where the estuary discharges into the Timor Sea to around 400m on the Arnhem Land sandstone plateau in the headwaters of the Katherine River. The Katherine River is the largest tributary, and becomes the Daly River downstream of the Flora River confluence. The Flora, Fergusson and Douglas Rivers are the other major tributaries. Mean annual rainfall grades from about 600 mm in the south to over 1300 mm in northern parts of the catchment, with most of the rain falling during the summer monsoon season from November to March. Dry season flows are maintained by discharge from limestone aquifers in the central part of the basin (Wasson *et al*., 2010).

The native vegetation in the Daly catchment consists of Eucalyptus woodlands and open Forest, with riparian communities of Melaleuca forests, closed monsoon forests and open Eucalyptus forests on levees (Lamontagne *et al*., 2005). Groundcover is highly seasonal, with dense grasses in the wet season and much lower cover during the dry season, especially after fire. About 5% of the catchment has been cleared for cropping and plantation forestry and much of the remainder is used for low density cattle grazing (Townsend and Padovan, 2005).

The main channel is about 15m deep, has low sinuosity, and the banks mostly consist of river sediments consisting of sands and loamy sands. But in many places bedrock crops out in the banks and bed showing that the channel is confined by rock. That is, it has little freedom to either cut downwards or wander across its valley in the way that is available to a meandering river. Tufa dams have also formed across the channel at a number of locations, features that have a stabilising effect on the channel bed similar to bedrock. Elongate billabongs on the floodplain of the main channel show that the channel has been in different positions in the past, moving by a process known as *avulsion* where a channel is blocked by sediment and/or logs and a new channel is carved through the floodplain.

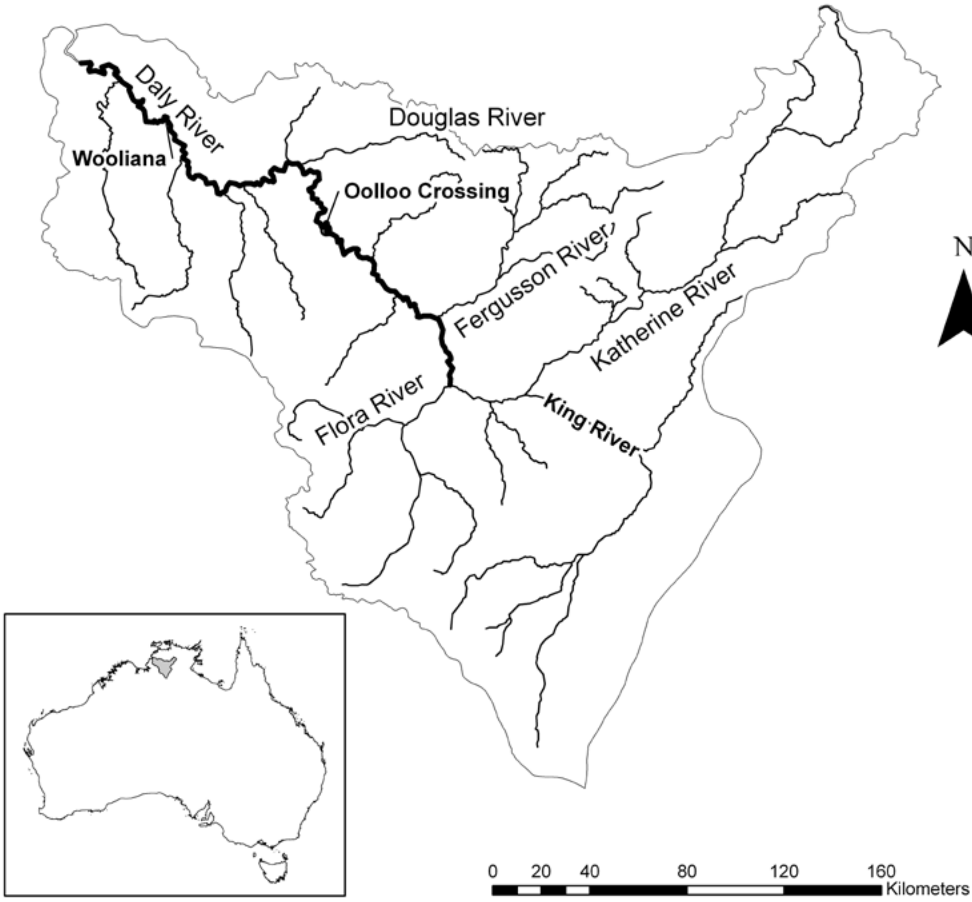

Figure 1: Map of the Daly River catchment showing key locations and tributaries mentioned in the text. The inset map shows the location of the catchment.

3. Evidence for changes in the main channel and the estuary

3.1 The main channel

One of the main concerns amongst the local community is that there has been a significant increase in sand deposits within pools along the Daly River, with concerns for the impact that this is having on in-stream habitat and navigability of the river. The main area of concern is the section of the main channel between Wooliana (around 5km downstream of Daly River Crossing) and Oolloo Crossing (Figure 1). To assess the changes that have occurred in this reach sequences of aerial photographs and 2006 SPOT imagery have been analysed at three locations: Oolloo Crossing, and two bends referred to as "double bend" and "bottom bend". The extent of different geomorphic units (i.e. in-channel sand bars, sand bars below the water, bare eroding banks, bedrock and tufa) have been mapped at each site for four time periods (1948/49, 1963, 1983, 2006) to determine whether there is evidence for a measurable change in the relative distribution of the various units. Tufa and bedrock have been combined as they could not be reliably differentiated; little change would be expected in the extent of both tufa and bedrock given that neither is particularly erodible. Hence variation in the extent of tufa and bedrock are likely to be a function of mapping error associated with image quality and resolution, along with the flow stage at the time the image was acquired (note however, that all images were acquired in the mid dry-season so flow stage is only likely to vary in the order of a few tens of centimetres at most: only the 2006 imagery appears to have a flow stage that is noticeably higher than the others).

The sequential images from the three sites are shown in Figures 2, 3 and 4. So as not to obscure the detail within the channels they are presented without the geomorphic unit map overlays. The quantitative summary of the extents of the in-channel sand bars, sand bars below the water, bare eroding banks, and bedrock and tufa, at the various time periods for each of the three sites are shown in Figure 5. Each site provides a slightly different story of sand accumulation within the main-stem of the Daly River which, when taken together presents a picture that is inconsistent with there being a clear trend towards increasing sand deposition within the channel over the last 60 years. Close analysis shows that mobile sand sheets and sand bars are a ubiquitous feature of the Daly River. These are highly mobile, accumulating some years and then being scoured in others – depending on the sequence of floods from year to year. What is apparent from the images is that there has been a major episode of channel widening at each of the sites between 1983 and 2006.

In addition to the time series site studies of the same geomorphic units were mapped for the entire reach between Oolloo Crossing and Daly River crossing using the 2006 SPOT imagery. Although it is not spatially uniform through the reach there is evidence of channel bank erosion along a significant proportion of the reach (Figure 6). This erosion is present in equal measure on both inner and outer banks on bends, and in straight reaches.

In summary the image analysis is not consistent with there being increasing sand deposition within the channel over the last 60 years. It does however show that there has been a major episode of channel widening between 1983 and 2006; and more evidence of this is provided below. The fact that there is not a concomitant increase in sand deposition with the increased bank erosion, suggests that the bank erosion is either not contributing significant volumes of sand to the river, or that the sand derived from the channel banks is being transported out of the reach.

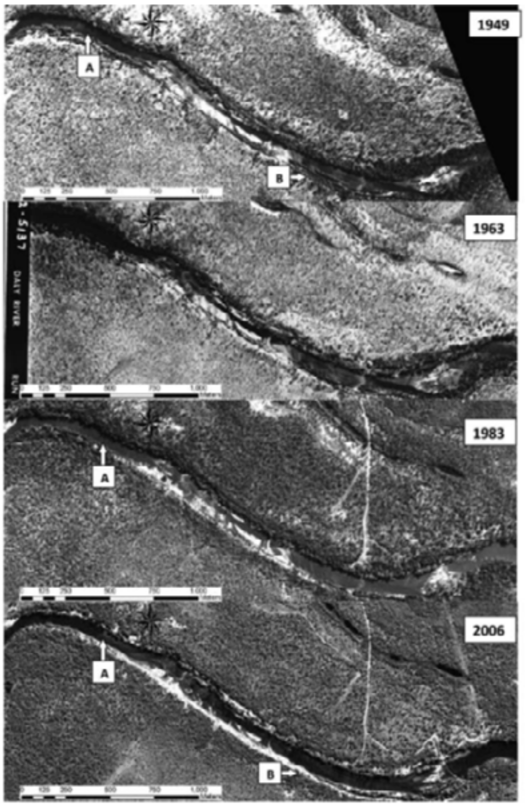

Figure 2: Time series at Oolloo Crossing. Note that in the 1949 image that below-water sand bars are evident in the large pool at the bottom of the reach (pt A). The same bars cannot be distinguished in 1963 (due to poor image quality), but do not appear to be there in 1983. A large sand wedge is however, apparent in 2006. The remainder of the reach, which is dominated by bedrock and tufa, shows little evidence of change in the extent of sand bars. What is evident is a significant increase in the extent of eroding bank (pt B). Note that in 1949 there was extensive vegetation along the toe of the bank (pt B), which appears to have been progressively removed through time, before a major increase in bank erosion between 1983 and 2006.

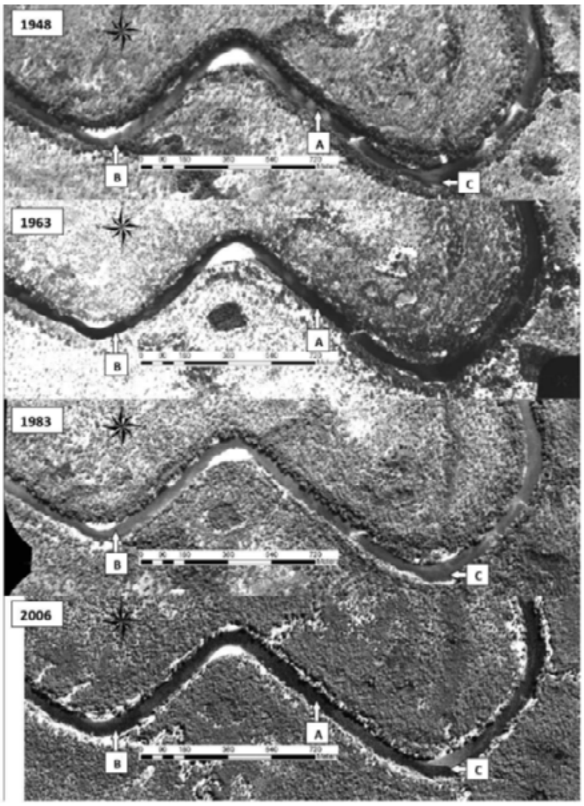

Figure 3: Time series showing "Bottom Bend" reach from 1949-2006. In this sequence fairly extensive below water sand deposits are evident in 1949, but by 1963 seem to have been extensively scoured out (particularly at pts A & B). By 1983 sand deposits are evident again through much of the reach as large sand sheets, whereas by 2006, while there is some evidence for increased sand deposits (pt C), the sand deposits are more discontinuous than they were in 1983, tending to form discrete sand wedges interspersed with large, relatively deep pools. Bank erosion can also be seen to have increased noticeably between 1983 and 2006. Note that the bank erosion is not confined to the outer banks as would be the case if the channel was laterally migrating.

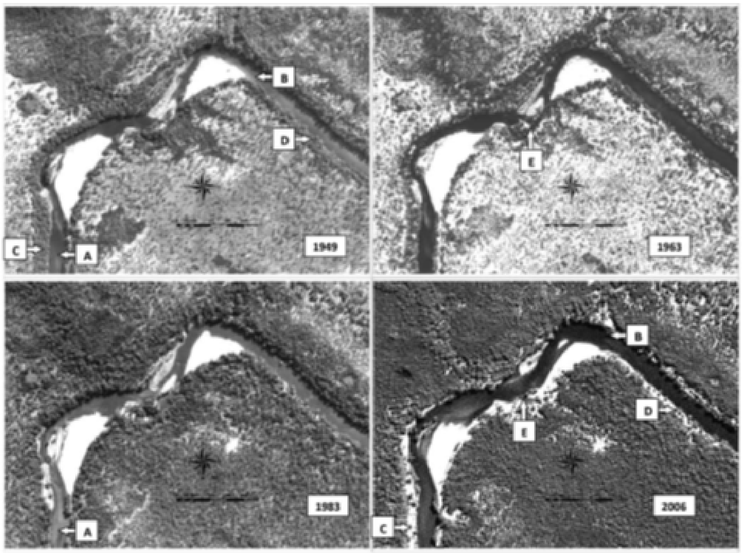

Figure 4: Time series changes at the Double Bend site showing a pattern of change that is similar to that observed at the Bottom Bend site (Figure 3), but with the distinction that there would appear to be more below-water sand deposits at Double Bend in 1983 compared to 1949 (Note pts A & B). Between 1983 and 2006 there has been significant vegetation stripping and channel straightening through the middle of the bend (pt E), and while there is still extensive sand in the channel in 2006 at some locations (pt B), the channel has been scoured to form a large deep pool. As with the other 2 sites (Figures 2 & 3) extensive bank erosion is evident between 1983 and 2006 (pts C & D), and as at the other sites is occurring on both banks - on the inside and outside of bends.

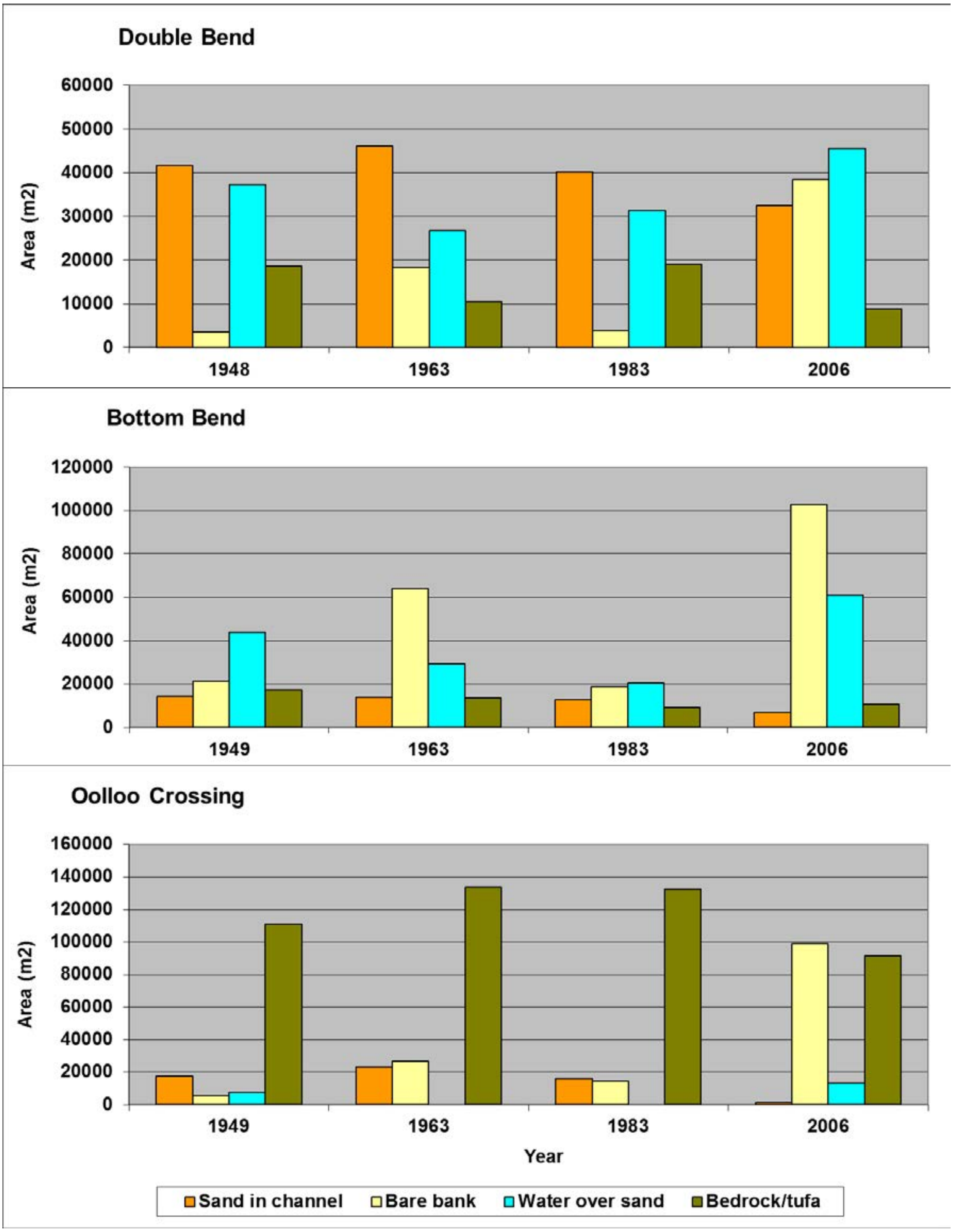

Figure 5: Graphs showing the areas of the various geomorphic units through time at the three sites Double Bend and Bottom Bend and Oolloo Crossing. Note that the only consistent change across all sites is in the extent of bare bank in 2006 compared to all other years. Sand accumulation in the channel - as represented by the categories "sand in channel" and "water over sand" – shows no clear trend towards increased areal extent through time. These two classes indicate that the overall extent of sand in the channel appears generally consistent through time.

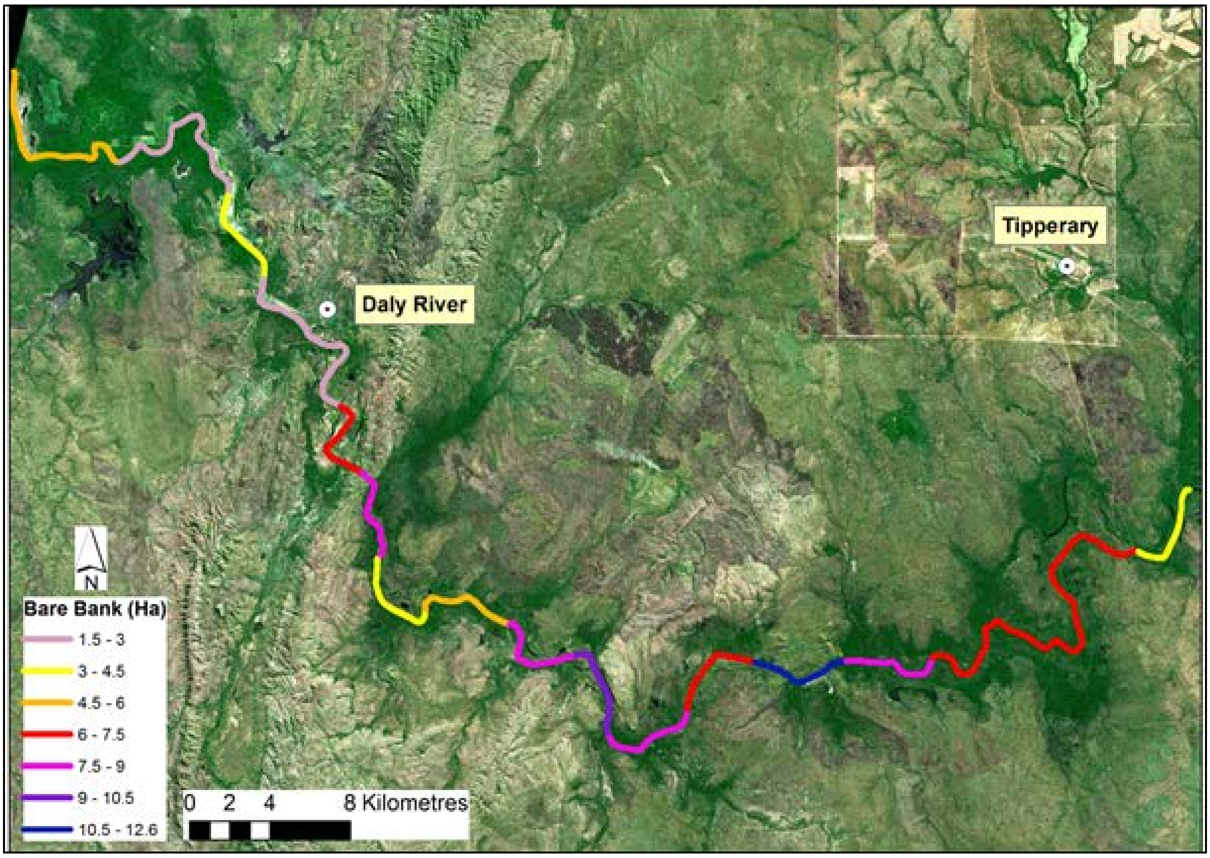

Figure 6: Daly River bank erosion aerial extent between Oolloo Crossing and Daly River Crossing based on 2006 SPOT data. The extent of bare banks is shown in hectares for each 5km river segment. The background image is a Landsat 2006 scene.

3.2 Daly Estuary

While it is clear that there have been some changes to the freshwater reaches of the Daly main-stem channel over the last few decades, primarily associated with bank erosion, the changes to the estuary have been far more dramatic and extensive as shown in Figure 7. To date little research has been published on the extent to which changes to the estuary may be contributing to sedimentation within the upper estuary. This is process is important because of the potential for the macro-tides in the Daly to transport sediments upstream towards the head of the estuary, as has been documented elsewhere (Bryce *et al*., 1998). The summary map in Figure 7 shows how the Daly River estuary has experienced major channel expansion over the three and a half decades between 1972 and 2006. There has been an increase of around 8 km^2 in the total area of estuary over this period. Put another way, if we assume that the average bank height throughout the estuary is 5m (a conservative estimate) then floodplain erosion within the estuarine reach has contributed a total of 60 Mt of sediment to the estuary (assuming a sediment density of 1.5 g cm^{-3}), or 1.75 Mt per year between 1972 and 2006. If 10% of the sediment contained within these floodplain deposits was sand, this represents a source of 175 Kt per year to the estuary.

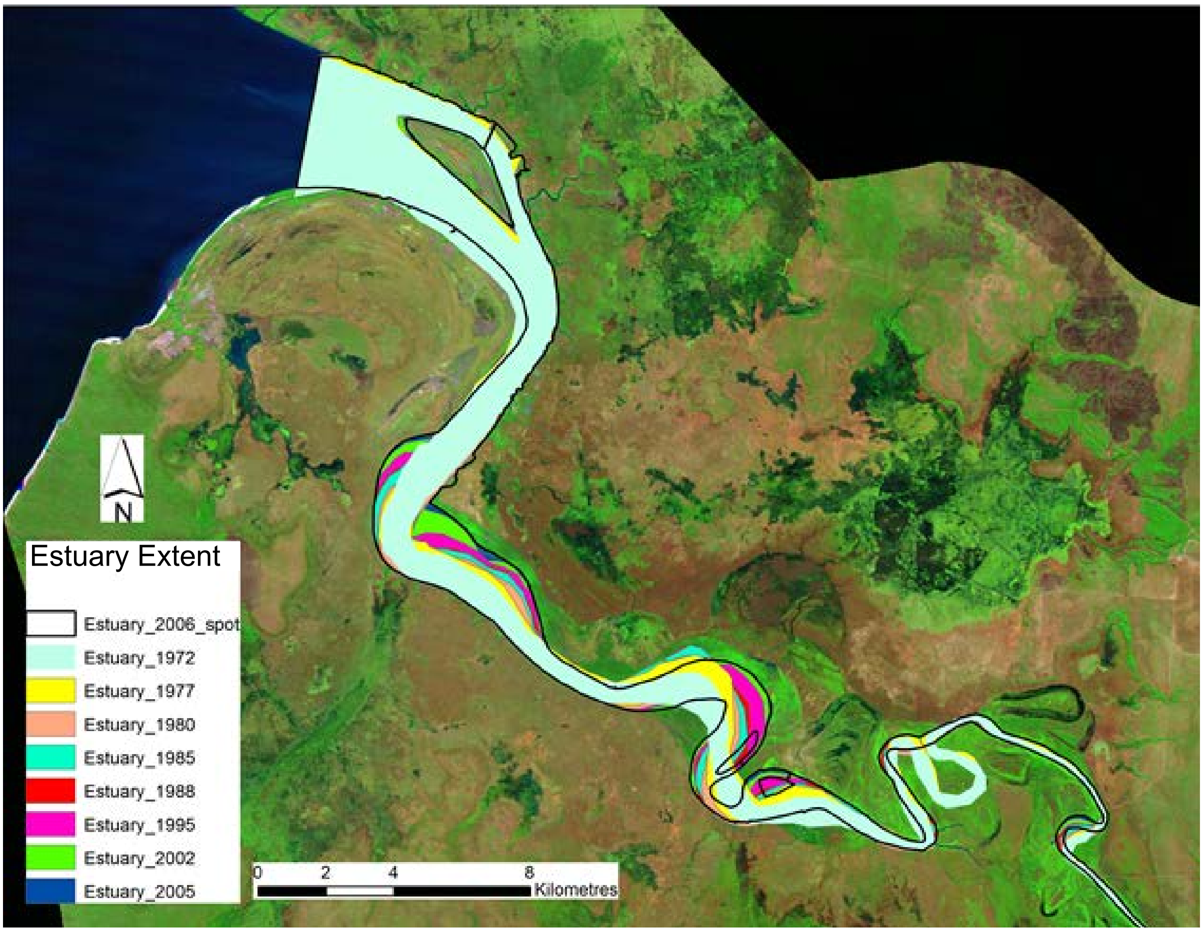

Figure 7: Changes in the channel form of the Daly River estuary between 1972 and 2006 based on analysis of Landsat (1972-2002) and SPOT imagery (2006, shown as the black outline).

4. Sediment budget

In this section we quantify what we can of the various components of the sources of sediment to the Daly River and its estuary by developing a sediment budget. The sediment budget concept has been a central organising principle within the discipline of geomorphology since at least the 1970s (Dietrich and Dunne, 1978; Dunne and Leopold, 1978), with the concept increasingly refined in subsequent decades. In essence a sediment budget provides a method of accounting for the amount of sediment derived from different sources, the amount stored within a catchment, and the amount that leaves a catchment in a river at its outlet, usually expressed as an amount per year.

In the Daly River catchment the processes of erosion and sources of sediment are: surface erosion - erosion of hillslope soils by sheet and rill processes; erosion dominantly of sub-surface soils and sediments - gullying of hillslopes, floodplains, and riverbanks; slumping of riverbanks; and abrasion of riverbanks by the flow of river water. Storage of sediment occurs at the base of hillslopes, on floodplains, and in river channels. Downstream of the freshwater section, sediment storage also occurs in the estuary.

In the following we first assess the total sediment yield from the Daly River. For the present purposes, sediment loss from the catchment is estimated at the Daly River Crossing, the head of the estuary. We then examine the relative contribution of surface versus sub-surface dominated erosion. Each of the source components is then quantified and estimates are made of sediment storage in the catchment.

4.1 Catchment Sediment Yield

The sediment yield from a catchment varies from year to year depending on both the supply of sediment and the ability of the river to transport the sediment. Sediment transport capacity (Q_s) is given by:

$$\frac{Q_s}{w} = k\left(\frac{Q}{w}\right)^{\beta} S^{\gamma}$$

Equation 1

where the constant *k* reflects the sediment characteristics (e.g. size and density) and the hydraulic roughness, and γ and β are empirically derived exponents, Q is discharge, w is channel width and S is channel slope (to approximate the hydraulic gradient). Using exponent values from Prosser and Rustomji (2000), the sediment transport capacity of a river reach is given by

$$Q_s = kw^{-0.4}Q^{1.4}S^{1.4}$$

Equation 2

It should also be noted that changes in sediment transport capacity mainly relate to a river's ability to transport bed sediments; suspended sediment transport is usually supply limited. Relative variations in sediment transport capacity in the Daly River in relation to changes in discharge are shown in Figure 8.

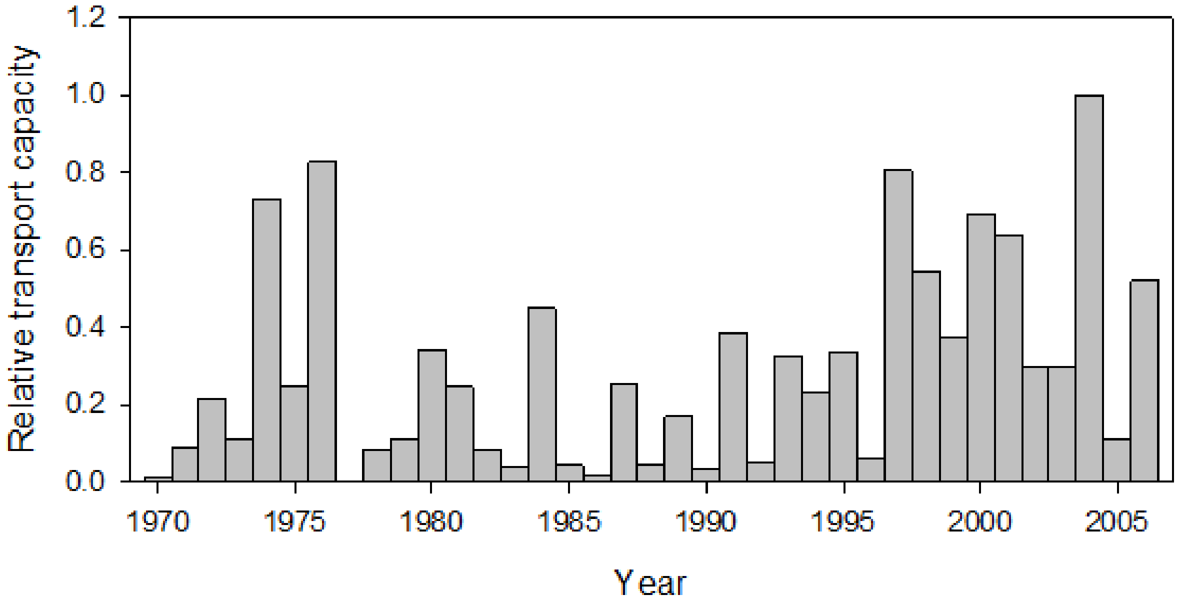

Figure 8: Relative variations in sediment transport capacity in Daly River in relation to changes in discharge. It is scaled so that the year with the greatest transport capacity = 1. Note the data for 1977 are missing.

From this figure it can be seen that sediment transport capacity varies significantly year to year. Sediment load, which is a product of both the sediment transport capacity and the sediment supply, would be expected to show even greater annual variation. Given this level of variation, estimates of the long-term average annual load in the Daly River would require at least 30 years of annual load estimates, and any estimates based on single years are unlikely to provide good estimates of the long-term average annual loads.

Three methods have been used to estimate the sediment yield of (or loss from) the catchment. The first is the measurement of the suspended load of the Daly for the 2007-08 wet-season and the following dry-season reported by Rustomji and Caitcheon (2010), while the other two methods provide average long term rates that at best can be applied over timescales of thousands of years. Consequently, none of these methods can be relied on in their own right to provide an estimate of the sediment dynamics in the Daly catchment at the management timescale we are interested in (multi-decadal), particularly in light of the inter-annual variability highlighted above. As such, these estimates provide only the broad context against which estimates of decadal to century scale variability can be assessed using other methods.

The estimate of the annual suspended sediment yield (i.e. < 63 µm) for the 2007-08 wet-season from Rustomji and Caitcheon (2010) is 503,000 tonnes/year (t/yr). Using the data compiled by Turowski *et al.,* (2010) the bedload fraction (sand and gravel) is estimated to be 10% giving a total load of 553,300 t/yr. The estimate reported by Rustomji and Caitcheon came from an incomplete analysis of the data later reported by Robson *et al.,* (2010) in which they estimated the load of the Daly River at 420,000 t/yr, or 462,000 t/yr if bedload is included.

The second method uses a model that compares measured sediment yields in rivers (globally) with the average slopes of their catchments (Nawaz and Wasson, unpublished). From the model the calculated amount of sediment passing the Daly River Crossing each year, applicable for the last few decades, is 789,000 $\pm$ 120,000 t/yr, of which ~10% is bedload. The remaining 90% consists of silt and clay, the suspended load of the river. Nawaz and Wasson (unpublished data) have also used a model of catchment erosion, based on long-term (millennial) rates derived from measured concentrations of ^{10}Be (see below for more details), giving an average yield of 761,000 $\pm$ 115,000 t/yr.

The third method also uses the concentration of ^{10}Be in river sediments that accumulates from rainfall in soils and is released into rivers by erosion. This approach can provide catchment-wide erosion rates averaged over time scales of 10^3 to 10^6 years, given that the half life of Be is 1.39 M yrs (Bierman and Nichols, 2004). The long-term estimated sediment yield for the Daly River from this method is 765,000 $\pm$ 115,000 t/yr based on measured ^{10}Be in the Daly River sediments (J.M.A. Chappell, personal communication). This rate is the average over 30,000 years.

All of the estimates based on the Nawaz and Wasson model and on ^{10}Be are statistically equivalent, given the large uncertainties of each estimate. Both approaches provide averages of sediment load over millennial timescales, and are therefore of little value for telling us about potential land use driven changes to the sediment loads over recent decades. So we can state that the average of these estimates is 772,000 $\pm$ 116,000 t/yr, of which 695,000 t/yr is estimated to be suspended sediment (using a bedload component of 10%). This is 1.4 times higher than the estimate by Rustomji and Caitcheon and 1.7 times higher than the estimate by Robson *et al*., however, both were based on one year's data. At best all of these estimates form a starting point for future research on sediment load fluctuations over timescales that are more applicable to understanding land management induced changes in sediment supply.

What also must be stressed is that these estimates are end of catchment averages at varying timescales (years to millions of years), and there are considerable time lags between sediment yields measured in small upstream tributaries and sediment yields measured at the bottom of catchments. Furthermore, there are a range of transmission losses at play as sediment is transmitted down a catchment. As such, these end-of-system estimates cannot tell us whether there are local-scale impacts in smaller tributaries that are a function of land-use accelerated erosion. That is, while there may not be a detectable increase in sediment yield at the Mt Nancar gauge that can be directly tied to land-use change (if we had a good long term sediment load time series at this site upon which such an assessment could be made), the small tributaries that are directly impacted by some of the recent land clearing for forestry may be heavily impacted by increased erosion. Measuring these changes would require an entirely different approach focused in the tributaries directly impacted by the land-use change.

4.2 The relative contribution of surface versus sub-surface dominated erosion.

Fallout radionuclides (^{137}Cs and $^{210}Pb_{ex}$) have been widely used to determine the relative contributions of surface soil and channel erosion (gully and stream banks) to stream sediments (Walling and Woodward, 1992; Olley *et al*., 1993; Wallbrink *et al*., 1998; Everett *et al*., 2008; Caitcheon *et al*., 2011; Olley *et al*., 2013).

Fallout ^{210}Pb is a naturally occurring radionuclide, formed through the radioactive decay of ^{222}Rn gas. The parent of ^{222}Rn is ^{226}Ra, part of the ^{238}U decay series. These radionuclides are present in all soils. Some ^{222}Rn gas escapes from the soil into the atmosphere where it decays to ^{210}Pb. This ^{210}Pb is then deposited on the soil surface, primarily by rain. The maximum concentrations of fallout ^{210}Pb (also known as 'unsupported' or 'excess', i.e. $^{210}Pb_{ex}$) in soils are found at the surface. Concentrations then generally decrease with depth to detection limits at about 100 mm.

^{137}Cs, as found in the Australian environment, is a product of atmospheric nuclear weapons testing that occurred during the 1950-70s. Initially the distribution of this nuclide in the soil decreased exponentially with depth, with the maximum concentration at the surface. However, due to processes of diffusion the maximum concentration is now generally found just below the surface in undisturbed soils. The bulk of the activity of this nuclide is retained within the top 100 mm of the soil profile. In subsoils recently exposed by erosion ^{137}Cs is virtually absent (Wallbrink and Murray 1993).

As both fallout radionuclides are concentrated in the surface soil, sediments derived from sheet and rill erosion will have high concentrations of both nuclides, while sediment eroded from gullies or channels have little or no fallout nuclides present. By measuring the concentration in suspended sediments moving down the river, and comparing them with concentrations in sediments produced by the different erosion processes, the erosion process generating the sediment can be determined.

Two studies, Wasson *et al*., (2010) and Caitcheon *et al*., (2012) have examined fallout radionuclide concentrations in the Daly River; both demonstrated the dominance of sub-soil sources. Figure 9 shows the relative surface soil contributions with distance upstream of the catchment outlet (after Caitcheon *et al*., 2012). The graph shows that surface soil contributions are highest in the upper catchment but still dominated by subsoil sources, and they decrease rapidly to less than 5% along most of the main channel. The most likely explanation for this trend is that channel-bank erosion dominates the supply of sediment in the lower reaches of the major tributaries and along the main channel.

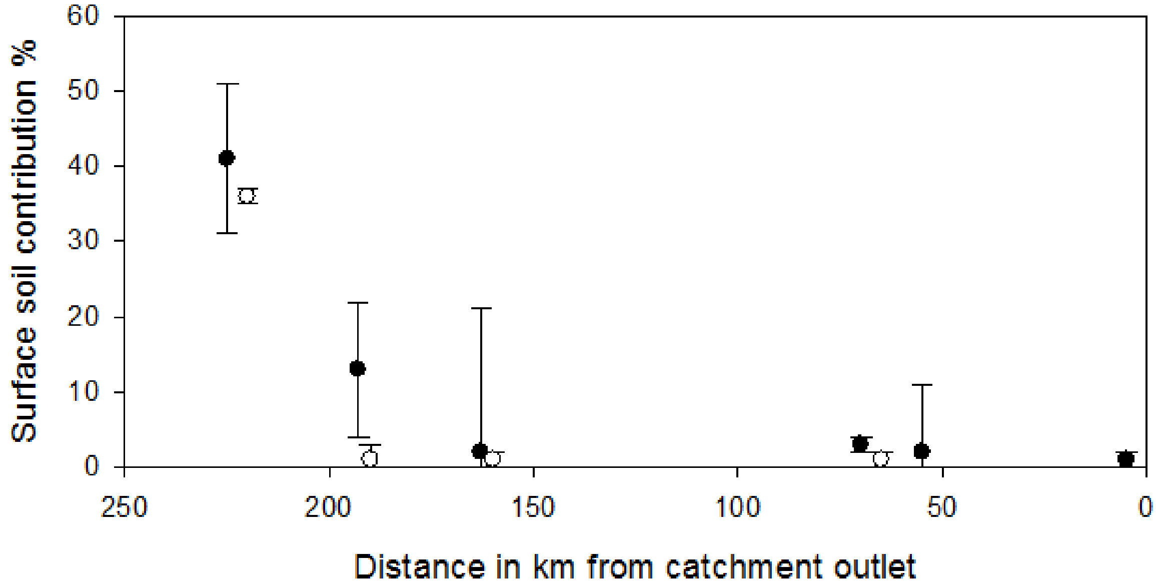

Figure. 9. Surface soil contributions along the main channels of the Daly and Mitchell Rivers. Relative surface soil contributions on the Daly-Katherine River (closed circles) and from its tributaries (open circles) against distance from the catchment outlet. The error bars are equivalent to one standard deviation on the mean and are derived from the mixing model.

4.3 Surface erosion

Using our best estimate of the long-term average annual load of 772,000 ± 116,000 t/yr, of which 695,000 ± 116,000 t/yr is suspended sediment, and the relative contribution from hillslope erosion of 5%, we estimate that 38,600 ± 6,000 t/yr comes from sheet and rill erosion of hillslopes. The catchment-wide average sheet and rill erosion rate modelled using the Revised Universal Soil Loss Equation is 7,000,000 t/yr (M. Nawaz, personal communication). Therefore on average only ~0.6% of soil eroded on hillslopes reaches the river or the soils erode at much lower rates than predicted by the model. It should be pointed out that studies in similar tropical savannah landscapes in Cape York have shown that the RUSLE can overestimate surface erosion rates by 4 orders of magnitude (10000 times) (Brooks *et al*., submitted a and b). Hence it is more likely that the total contribution from sheet and rill erosion on hillslopes is substantially less than has been previously estimated.

4.4 Gully erosion

Estimates of the amounts of sediment coming separately from gullies, slumps on riverbanks, and from abrasion of riverbanks are still being made. But some preliminary estimates are available. There are very few gullies away from the rivers, and there are no reliable estimates of their sediment yields. Gullies are however common on floodplains (alluvial gullies – Brooks *et al*., 2009) and on riverbanks. One large group of gullies has been examined in considerable detail along the Fergusson River. These gullies are connected to the Fergusson River and have produced 92,000 ± 9,000 t/yr between 1948 and 2008 (F. Sattar, personal communication). There are other alluvial gullies in the Daly catchment developed on the hydrosol and tenosol soil types, although none has been examined to estimate sediment yields. These alluvial gullies are the result of surface flow and groundwater seepage. Their initiation is almost certainly a result of grazing pressure by domestic stock and feral animals in the riparian zone (*sensu* Shellberg *et al*., 2010), and has spread upslope from natural channels that take floodwater from floodplains to the river channels. They are therefore the only tangible evidence of a land use impact on erosion and sediment delivery to the rivers in the catchment. Other gullies begin in the slumps on the river banks, and are a secondary feature of channel widening that is described below.

By far the largest numbers of gullies occur in the riparian zone (also known as alluvial gullies) of the Daly River. S. Karki (personal communication) has estimated the annual sediment yield to the river from a 15km reach at Oolloo between 1963 and 2010 at 2200 ± 580 t/km/yr. By assuming that this rate applies to the full 335km of the Daly River where riparian gullies occur, the maximum annual input may be 737,000 t/yr. We note that alluvial gullies are sometimes absent from the Daly River and therefore, the estimate of 737,000 t/yr is likely to be an over estimate. Further surveys are needed to more accurately determine gully distribution and contribution to the sediment load of the river. To this end, Karki (unpublished data) has shown that the area of gully erosion on the Oolloo reach has increased between 1963 and 2010 by ~35% and yield has increased proportionally.

4.5 Channel Bank erosion

Bank slumps are very common along the Daly River, and Karki (unpublished data) has calculated an annual rate of slumping of 1700 t/km/yr for the Oolloo reach. For the entire length of river where slumps occur the rate is 570,000 t/yr. But about 20% of this slump material does not immediately reach the river after slumping, and is retained on the riverbanks until washed off by a flow in the river. Also, as in the case alluvial gullies, the area of slumps has also increased (the current estimate by Karki is by ~70%) between 1963 and 2010 in the Oolloo reach with an accompanying increase in yield. The slumps are the result of groundwater pressure in the banks, and the slumps occur as the level of flowing water in the river falls and the weight of the saturated banks leads to failure. That the rate of slumping has been increasing is consistent with observations that groundwater levels have been rising as a result of increasing rainfall since the mid-1970s (L. Hutley, personal communication).

In addition to alluvial gullies and slumps, the riverbanks are abraded by river flow; that is, scouring and hydraulic lifting of the most coherent sediments. The rate of this set of processes is very difficult to estimate, and reliable estimates are not yet available.

By combining the estimates of alluvial gullying and slumping given above, ignoring abrasion, and assuming that 80% of slump debris reaches the river each year, total sediment delivery to the Daly River from bank erosion is 1,307,000 t/yr.

But it is the combined effects of abrasion, slumping, and alluvial gullying that produces erosion of riverbanks. If this occurs on both banks without compensating deposition, the channel widens. This is the case for most of the Daly River. Karki has measured widening of the Oolloo reach. To convert her measured widening at bank tops into volumetric and mass changes, the channel is considered to be trapezoidal in cross section with a constant bank angle of 20° and an unchanging bed elevation. The difference between the volume of the channel in 1963 and 2010 is 153,000 t/yr on the Oolloo reach.

About half of the 335km stretch of the Daly River considered above has the approximate dimensions of the Oolloo reach, and the remainder of the channel is about half the width of the Oolloo reach and rectangular in cross section rather than trapezoidal. From this it is estimated that in total 3,020,000 t/yr has been eroded by channel widening. Even though these calculations are preliminary, it appears that the bank erosion calculated from estimates of slumping and alluvial gullying underestimate the total by about 1,713,000 t/yr. This difference is presumably the result of removal of whole sections of bank, particularly on outer bends of the river, by flow in the river which will remove all evidence of then existing slumps and riparian gullies. These erosion features will of course not be included in any estimates of bank erosion.

4.6 Storage in the catchment

Storage of sediment within the catchment is poorly known. Quantitative estimates of storage in the channels are not available, although the evidence provided by the analysis of satellite imagery suggests no net change over recent decades. Storage by deposition at the bases of hillslopes of the products of sheet erosion from hillslopes is estimated to about 6,945,000 t/yr, the difference between the estimated catchment-wide sheet erosion rate (7,000,000 t/yr) and the proportion of this sediment in the Daly River (average of the estimated range is 34,500 t/yr). But we will see later that this is an overestimate.

Storage by deposition on floodplains has been estimated by Rustomji and Caitcheon (2010) by modelling the location and area of floodplains (10,466 km^2) and by using the model SedNet to estimate deposition rates (0.6 to 2.5mm/yr). These authors estimate an annual storage on floodplains of 2,138,000 t/yr.

4.7 Balancing the Budget

The best estimates of the various components of the sediment budget so far are as follows:

- Catchment sediment yield at the Daly River crossing: 772,000 $\pm$ 116,000 t/yr.
- Sheet and rill erosion input to the river 38,600 t/yr (based on geochemical tracers).
- Erosion of subsoils by gullying, slumping and abrasion of river banks: 733,400 t/yr (based on the difference between the sediment yield and the input from sheet and rill erosion).
- Erosion by widening of the main channel: 3,020,000 t/yr (by measurement and estimation of channel change).
- Storage on the floodplains: 2,138,000 t/yr (by modelling).

From these figures the total sediment input to the river equals the sum of sheet/rill erosion (38,600 t/yr) and net channel widening (3,058,000 t/yr); that is 3,058,000 t/yr. Of this 2,138,000 t/yr (70%) is stored on floodplains and 30% (772,000 t/yr) leaves the catchment. So the input≈storage+yield, which is a balanced budget.

But this sediment budget is incomplete. The estimated input from channel widening of 3,020,000 t/yr ignores widening in any of the tributaries of the Daly River and gully erosion of the kind analysed by Sattar (pers. comm.). If the actual input of sediment is larger than 3,058,000 t/yr then there must be more than 772,000 t/yr in transport in the Daly River. The figure of 772,000 t/yr is an average over many decades, but Karki's results show that there has been a large increase in slumping and alluvial gullying, probably since the early 1990s. Any recent increase in the sediment load of the Daly River will not be detected by the methods used here for estimating its load, and the only solution is to establish a sediment monitoring system for the river. If such an increase has occurred, it is likely to be reflected in the suspended load given that the bedload is only about 10% of the total load. Also the remote sensing analysis suggests that there has been no net change in the riverbed, although a higher transport rate of bedload may have occurred as flows have increased without changing the bed. At this stage we remain uncertain about how to explain the observations of Indigenous inhabitants and recreational fishers that there is more sediment in the bed of the Daly River.

The Daly River catchment is large and much of it not easily accessible. The amount of information therefore available is generally only sufficient for the construction of an approximate catchment-wide sediment budget, although the reports of Rustomji and Caitcheon (2010) and Robson *et al*., (2010) contain some information about sediment transport rates in a few tributaries of the Daly River. Also, some major sources of sediment (riverbank slumping and alluvial gullying) are still being quantified, and currently available data are preliminary. Rates of sediment accumulation on floodplains need further investigation, particularly because this storage could be as much as 70% of all inputs to the river-floodplain system.

Given that there has been an increased sediment input from channel widening, there may also have been a recent increase in the amount of sediment transported by the Daly River, seeing as the amount of sediment in transport is limited by sediment supply rather than transport capacity (Wasson *et al.,* 2010). Modelling of the channel suggests however that widening is accompanied by deposition in the channel (Miloshis and Valentine, 2010), a conclusion not supported by the remote sensing. This disagreement needs to be resolved.

Despite the considerable uncertainties described above, it is clear that erosion by gullying, abrasion, slumping and wholesale removal of riverbanks dominates the sources of sediment in the Daly River over recent decades.

5. Key drivers of change in sediment and flow regimes

The key drivers of change in the catchment are land use and climate, and possibly fire. Land use impacts to date are relatively minor at the catchment scale, with less than 5% of the catchment having been cleared for cultivation. Large areas across the rest of the catchment are grazed relatively lightly. Where clearing has occurred, it is likely that there are significant local scale impacts on water courses, which do then feed into the main channels of the Daly River. The dominant erosion process in grazed parts of the catchment is gully erosion, particularly within riparian zones which often delivers sediment directly into the main channels. Fire as an agent of change has not been analysed here because of a lack of resources. But it can be considered another impact on native vegetation along with grazing, and therefore the comment about the buffers between the grazed land away from the riparian zones and the river applies. The exception to this maybe fire in the riparian zone, but this must await further analysis.

The impact of climate is here analysed as it affects river flows. The following graph shows observed flood peaks and fitted flood frequency curves for the Daly River at Mt Nancar (G8140040). A flood frequency curve (Figure 10) shows the peak flow rate (in units of cubic metres per second) for a flood of a given return period, such as the one in ten year flood. The daily maximum streamflow record for this site has been divided into two periods (1967/68 water year to 1995/96 water year, and 1995/96 water year to 2009/10 water year). A peaks-over-threshold analysis was performed to extract statistically independent flood peaks using a 30 day separation period between floods. The threshold was determined by progressively lowering a flow threshold from the maximum flow until at least 1.1 flood peaks per year were identified.

Figure 10 shows that, post-1995/96, floods along the Daly River at Mt Nancar have been substantially larger for all return periods than was the case in the pre-1995/96 period. For example, the 1 in 2, 1 in 5 and 1 in 10 year average return period floods are on average 1.5 times the size of a flood with comparable return period in the pre-1995/96 period. In the 1967/68 to 1995/96 period, the most recent largest flood of note was back in the 1983/84 water year when a flood peak of approximately 3450 cubic metres per second was observed. Flood peaks exceeding 3450 cubic metres per second were observed eight times in the post-1995/96 period. These results confirm the conclusions reached by Wasson *et al*., (2010).

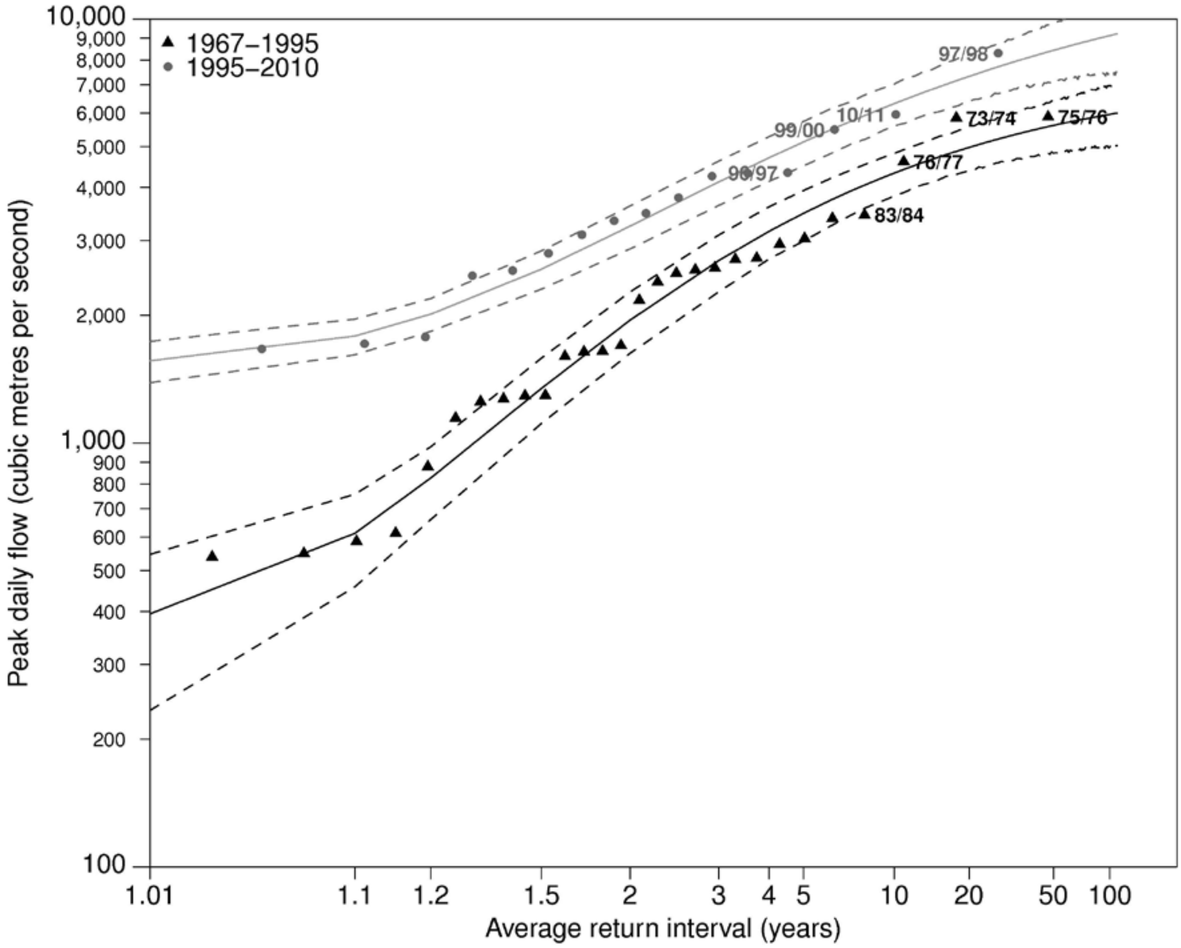

Figure 10: Peak daily flow versus average return interval for periods 1967 – 1995 and 1995 -2010. The flood frequency curve is a Generalised Pareto Distribution fitted using L-moments. 95% confidence intervals are shown in dashed lines around each fitted curve. Observed flood peaks are shown along with the water year in which they occurred (for the four largest floods in each period). Note that the graph has a logarithmic y-axis.

6. Putting it all together

This analysis must be considered provisional because there are too many uncertainties to be definitive. But despite these uncertainties a number of conclusions can be reached, as follows:

1. There is no evidence of a net change in the bed of the main channel in recent decades, a conclusion inconsistent with the observations of the local people and inferences from hydraulic modelling. In part this inconsistency might be explained by the different scales of observation (i.e. at a specific location compared with the whole of the Daly River main channel) as it is apparent from the remote sensing that sand bars have built up in some areas over recent years. However, when the average (or net) change is considered across the whole river, accumulations at one location are balanced out by decreases in other areas.
2. River discharge has increased along with rainfall, and this has increased groundwater levels in the floodplains adjacent to the river. One consequence of these changes is widening of the channel by river flow and mass failure of the banks due to elevated groundwater levels in the floodplain, and a sequence of large floods.
3. There is some evidence for impact of land use on the amount of sediment in the river and the major processes generating the sediment. Alluvial gully erosion rates are likely to have been accelerated due to grazing pressure by cattle and feral animals. The alluvial gullies produce about 24% of the sediment input to the main channel, and this along with the small amount of sediment from sheet and rill erosion (about 2%) gives a total of about 26% which is the total amount potentially generated by land-use change. Of course it is possible that the increased rainfall, and the climate shift that it represents, is also the result of human actions.

The changes documented here are therefore largely the result of a changed climate, river flow and groundwater levels. While there is some impact from land use, it is hoped that any future agricultural developments will not increase this impact, and may even reduce it. A key priority is to protect river banks from further erosion, although this will be difficult if the river continues to widen.

7. Future research

There is an urgent need to monitor the sediment transport rate in the main river to test the estimates provided here and to determine if they have increased as a result of increased bank erosion. Further to this, there is a need to monitor sediment loads in small tributaries that are directly influenced by clearing and land-use intensification. Where clearing has already taken place, this could take the form of a paired catchment monitoring program, in cleared and uncleared catchment s of equivalent size and land type. However, it should be recognised that the major increase in sediment yield will often be in the first wet season post-clearance, so this may not represent the “worst case” scenario in terms of quantifying increased sediment yield if the monitoring only commences some years after the initial clearing. In areas where new clearing is mooted, it would be a good idea to collect some “before clearance” baseline data, as well as establishing control sites, so that full Before After Control Impact BACI designed analysis can be undertaken.

Given the apparent dominance of bank erosion as a sediment source in the Daly River, there is a need to undertake a geotechnical analysis of the banks and the floodplain groundwater to determine the relative importance of bank mass failure compared with fluvial scour (or bank abrasion) and to what extent vegetation loss through grazing is contributing to this process.

Further analysis is also required about the causes of the alluvial gullies that have grown headward from the natural floodwater return channels on the floodplain and floodplain levees, and also the potential for further growth. Also we need to understand the potential for gullies that have been initiated on slump headwalls to grow headward into the floodplain and floodplain levees.

Sedimentation rates in the riverbed sediments are also needed to test the idea that there has been no net change in the bed. Further research is required to determine the exact quantum of sediment sourced from this phase of channel expansion, be it sand or mud, and the amounts coming from tributary streams. We also need to know the fate of the sediment once it is supplied to the estuary. Significant transfers of carbon and nutrients will also have occurred as part of this channel expansion, which is also worthy of further investigation. We also need to gain a better understanding of the processes driving bank erosion within the estuary, in particular the relative contributions to bank erosion of flood and tidal flows.

References

1) Bierman, P.R., Nichols, K.K., 2004. *Rock to sediment – slope to sea with* ^{10}Be – rates of landscape change Annual Review of Earth and Planetary Sciences, 32, 215-255.

2) Brooks P.A., Shellberg G.J., Knight J., Spencer J., 2009. *Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia*. Earth Surface Processes and Landforms, 34, 1951-1969.

3) Brooks, A., Borombovits, D.K., Spencer, J.S., Pietsch, T., and Olley, J.M., under review. *Measured hillslope erosion rates in the wet-dry tropics of Cape York, northern Australia Part 1: A low cost sediment trap for measuring hillslope erosion in remote areas - trap design and evaluation*. Catena.

4) Brooks, A., Borombovits, D.K., Spencer, J.S., Pietsch, T., Olley, J.M., under review. *Measured hillslope erosion rates in the wet-dry tropics of Cape York, northern Australia: Part 2, RUSLE-based modeling significantly over-predicts hillslope sediment production*. Catena.

5) Bryce, S., Larcombe, P., Ridd, P. V., 1998. *The relative importance of landward-directed tidal sediment transport versus freshwater flood events in the Normanby River estuary, Cape York Peninsula, Australia*. Marine Geology. 149:55-78.

6) Caitcheon, G., Olley, J., Pantus, F., Hancock, G., Leslie, C., 2012. *The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) Rivers*. Geomorphology 151 , 188-195.

7) DRCRG (Daly Region Community Reference Group), 2004. *Draft Report*. 131 pp.

8) Dietrich, W., Dunne, T., 1978. *Sediment budget for a small catchment in mountainous terrain*. Zeitschrift F Geomorphologie, Suppl. Bnd. 29, pp 191-206.

9) Dunne, T., Leopold, L.B., 1978. *Water in Environmental Planning*. W.H. Freeman, San Francisco.

10) Jackson, S., 2004. *Preliminary report on Aboriginal perspectives on land-use and water management in the Daly River region, Northern Territory*. A Report to the Northern Land Council. CSIRO. 53 pp.

11) Everett, S.E., Tims, S.G., Hancock, G.J., Bartley, R., Fifield, L.K., 2008. *Comparison of Pu and* ^{137}*Cs as tracers of sediment transport in terrestrial environments*. Journal of Environmental Radioactivity 99, 383-393.

12) Lamontagne, S., Cook, P.G., O'Grady, A., Eamus, D., 2005. *Groundwater use by vegetation in a tropical savanna riparian zone (Daly River, Australia)*. Journal of Hydrology 310, 280–293.

13) Miloshis, M., Valentine, E.M., 2011. *Sediment Transport Modelling in a Tropical River System* In: Proceedings of the 34th IAHR World Congress, Brisbane, Australia.

14) Nanson, G., Jones, B.G., Price, D.M., Pietsch, T. J., 2005. *Rivers Turned to Rock: Late Quaternary Alluvial Induration Influencing the Behaviour and Morphology of an Anabranching River in the Australian Monsoon Tropics*. Geomorphology, 70, 398-420.

15) Prosser, I. P., Rutherfurd I.D., Olley, J.M., Young, W.J., Wallbrink, P.J. Moran, C.J., 2001. *Large-scale patterns of erosion and sediment transport in rivers networks, with examples from Australia*. Freshwater and Marine Research, 52, 81-99.

16) Prosser, I.P., Rustomji, P., 2000. *Sediment transport capacity relations for overland flow*. Progress in Physical Geography, 24(2), 179-193.

17) Olley, J.M., Murray, A.S., Mackenzie, D.H., Edwards, K., 1993. *Identifying sediment sources in a gullied catchment using natural and anthropogenic radioactivity*. Water Resources Research, 29, 1037-1043.

18) Olley, J.M., Wasson R.J., 2003. *Changes in the flux of sediment in the Upper Murrumbidgee catchment, SE Australia, since European settlement*. Hydrological processes, 17, 3307-3320.

19) Olley, J.M., Burton, J., Smolders, K., Pantus, F., Pietsch, T., 2013. *The application of fallout radionuclides to determine the dominant erosion process in water supply catchments of subtropical South-East Queensland, Australia*. Hydrological Processes, 27/6, 885-895.

20) Rustomji, P., Caitcheon, G., 2010. *A catchment sediment and nutrient budget for the Daly River, Northern Territory*. Report to Tropical Rivers and Coastal Knowledge Research Program. CSIRO: Water for a Healthy Country National Research Flagship. http://www.clw.csiro.au/publications/waterforahealthycountry/2010/wfhc-Daly-River-sediment-nutrient-budget.pdf

21) Robson, B.J., Schult, J., Smith, J., Webster, I., Burford, M., Revill, A., Townsend, S., Haese, R., Holdsworth, D., 2010. *Towards understanding the impacts of land management on productivity in the Daly River*. Tropical Rivers and Coastal Knowledge (TRaCK) report. Charles Darwin University, Darwin. 166 pp. ISBN: 978-1-921576-29-4

22) Townsend, S. A., Padovan, A., 2005. *“The seasonal accrual and loss of benthic algae (Spirogyra) in the Daly River, and oligotrophic river in tropical Australia.”* Marine and Freshwater Research 56: 317-327.

23) Turowski, J.M., Rickenmann, D., Dadson, S.J., 2010. *The partitioning of the total sediment load of a river into suspended load and bedload: a review of empirical data.* Sedimentology, 57, 1126–1146.

24) Shellberg, J., Brooks, A., Spencer, J., 2010. *Landuse-change from indigenous management to cattle grazing initiates the gullying of alluvial soils in northern Australia*. Soil Solutions for a changing world, 19th World Congress of Soil Science, August 2010, published on CDROM.

25) Walling, D.E., Woodward, J.C., 1992. *Use of radiometric fingerprints to derive information on suspended sediment sources*. In Erosion and Sediment Transport Monitoring Programmes in River Basins, J. Bogen, D.E. Walling and T.Day (eds.) IAHS Publ. 210, 153-164.

26) Wallbrink, P.J., Murray, A.S., 1993. *Use of fallout radionuclides as indicators of erosion processes*. Hydrological Processes, 7, 297-304.

27) Wallbrink, P.J., Murray, A.S., Olley, J.M., Olive, L., 1998. *Determining sources and transit times of suspended sediment within the Murrumbidgee tributaries, NSW, Australia, using fallout* ^{137}*Cs and* ^{210}*Pb*. Water Resources Research, 34, 879-887.

28) Wasson, R. J., Furlonger, L., Parry, D., Pietsch, T., Valentine, E., Willams, D., 2010. *Sediment sources and channel dynamics, Daly River, Northern Australia*. Geomorphology 114, 161–174.

Personal communication

F. Sattar, Charles Darwin University, Farha.Sattar@cdu.edu.au, ph 08 8946 7636

L. Hutley, Charles Darwin University, Lindsay.Hutley@cdu.edu.au, ph 08 8946 7103

Nawaz and Wasson, unpublished

J.M.A. Chappell, Australian National University, John.Chappell@anu.edu.au