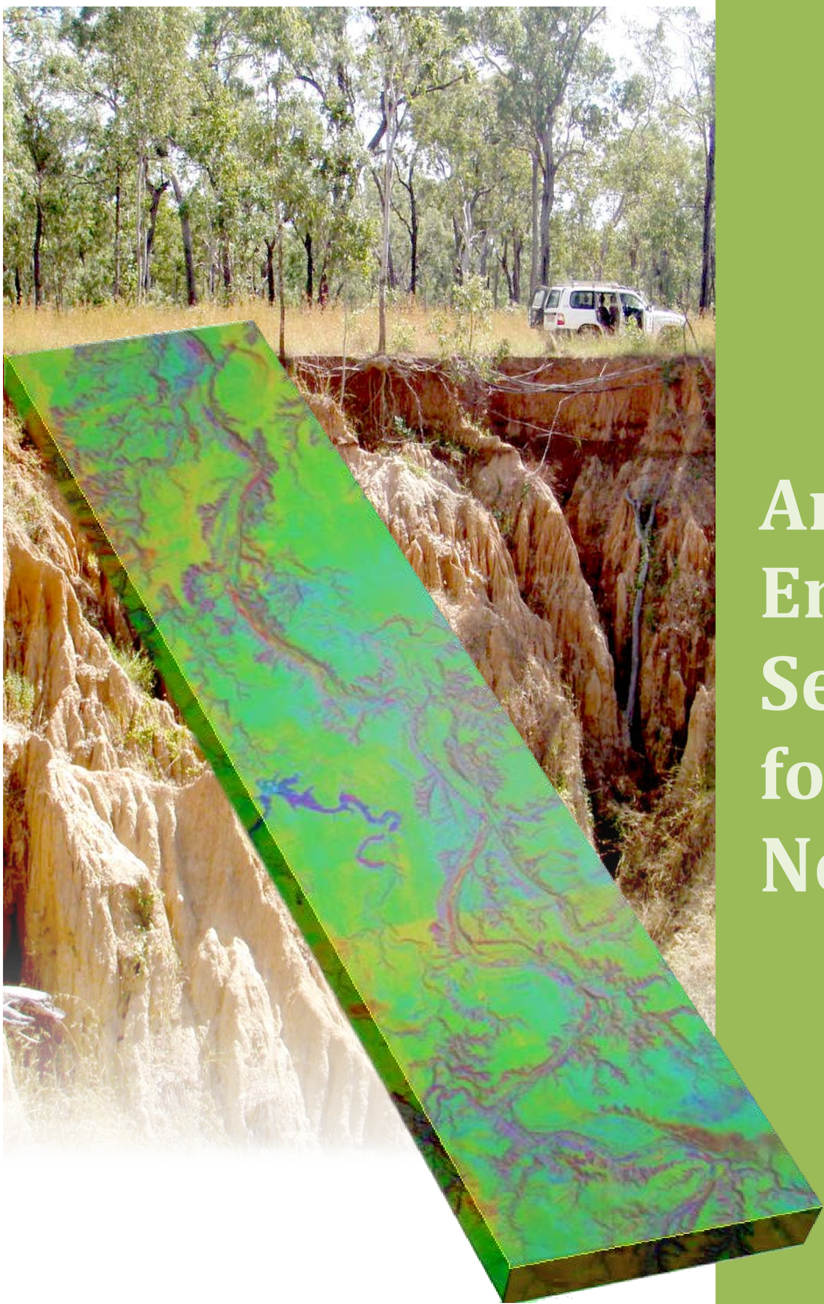
CAPE YORK WATER QUALITY



An Empirically-based Sediment Budget for the Normanby Basin

Sediment Sources, Sinks & Drivers on the Cape York Savannah

Griffith UNIVERSITY

CARING FOR OUR COUNTRY

Final Report prepared for the Australian Government's Caring for our Country - **Reef Rescue initiative**

Andrew Brooks, John Spencer, Jon Olley, Tim Pietsch, Daniel Borombovits, Graeme Curwen, Jeff Shellberg, Christina Howley, Angela Gleeson, Andrew Simon, Natasha Bankhead, Danny Klimetz, Leila Eslami-Endargoli, Anne Bourgeault

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April, 2013

An Empirically-based Sediment Budget for the Normanby Basin:
Sediment Sources, Sinks, and Drivers on the Cape York Savannah

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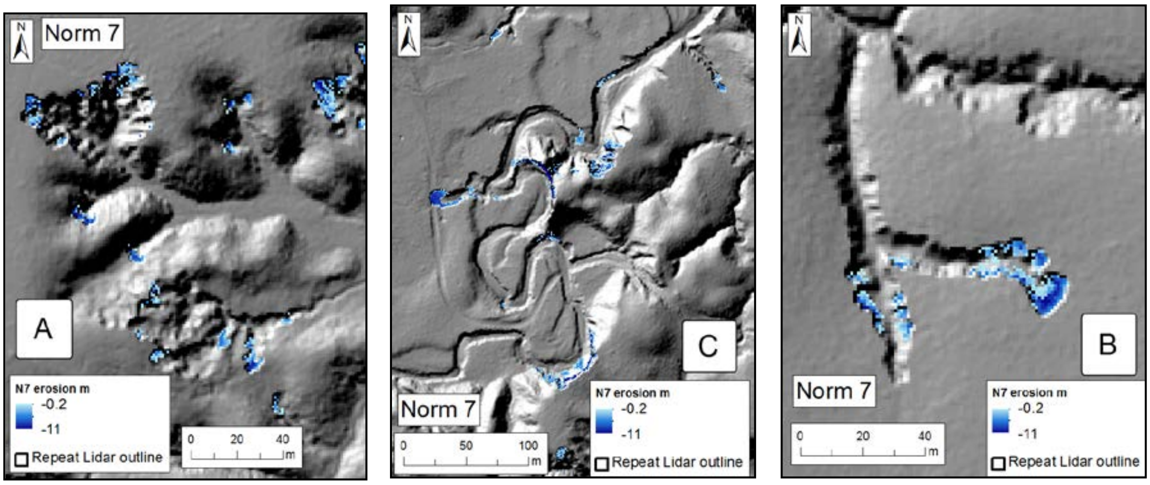
Project components

Water Quality Management | Sediment Budget | Alluvial Gully Prevention & Rehabilitation Options

CAPE YORK WATER QUALITY
http://www.capeyorkwaterquality.info

Oblique aerial of an alluvial gully on Crocodile Station. (Photo: Jeff Shellberg)



Examples of LiDAR change detection between 2009-2011 showing up to 10m of extension in alluvial gullies and secondary channels over 2 year period.

Gully rehabilitation experimental plots at Crocodile Station. (Photo: Jeff Shellberg)

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Time-lapse images of alluvial gully erosion driven by overbank flooding in the Bizant River Nov. 2010 – Feb/March 2011.

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1 Executive Summary

1.1 Normanby Basin in Context

The Normanby Basin in southeast Cape York (AWRC Basin 105) is the fourth largest river system flowing into the Great Barrier Reef (GBR) lagoon (Geosciences Australia, 1997). The Normanby Basin, covering 24,228 km^2, consists of numerous riverine and wetland systems, sacred aboriginal sites, cattle grazing country, one of Queensland's largest conservation areas at Rinyirru (Lakefield) National Park, and the rich agricultural land at Lakeland Downs. The lower catchment includes the largest aggregation of non-maritime wetlands listed on the *Directory of Important Wetlands* on the east coast of Australia – the Marina Plains Lakefield Aggregation (Environment Australia, 2001). The extensive seagrass meadows and estuarine salt flats provide diverse and productive habitat for marine and estuarine plants and animals.

The major population centres within the catchment area are Lakeland Downs and Laura. The resident population for the entire catchment area is less than 500 (ABS, 2006).

Conservation areas occupy a significant proportion of the catchment, with Rinyirru (Lakefield) and Jack River National Parks covering approximately 29%, or 703,000 ha. Both of these areas were formerly cattle stations, and feral and domestic cattle continue to access wetlands and rivers within the National Parks.

Grazing is the most extensive land use, with low density grazing occurring on approximately 75% (18,495 km^2) of the catchment (2011). Some stations have been purchased over the past 5 years by the Queensland government to be designated as National Park/ Aboriginal Land, however grazing still occurs on most of these areas. Average cattle density on grazing lands is estimated at 1 animal per 50 ha (Brodie and Mitchell, 2005), but higher concentrations of animals are typically found along river frontage (~1 beast/10 ha).

Horticulture within the catchment is mainly limited to the rich basaltic soils around Lakeland Downs on the upper reaches of the Laura River. Bananas, passionfruit, pineapples, sorghum, teak, and improved pasture for cattle forage are amongst the dominant crops. The horticultural area is estimated to cover 35 km^2 or 0.1% of the Normanby Catchment (2011), although this area is currently being expanded.

Significant portions of the Normanby River and its tributaries are ephemeral, with late dry season surface water largely stored in a series of waterholes connected via sub-surface flow through river sands. Wet season flood waters feed extensive wetland systems in the alluvial and marine plains of the lower catchment area and connect otherwise isolated wetlands and adjacent river systems.

The delivery of fine-grained sediment and nutrients to the GBR poses a threat to the sustainability of the reef and bay ecosystems.

Various reports have highlighted the Normanby as an erosion hotspot (Brodie et al., 2003; Prosser et al., 2001b) and as such the catchment has been nominated as a priority for erosion mitigation measures (Brodie et al., 2003). Based on these data the Great Barrier Reef Water Quality Protection Plan (2003) identified the Normanby as one of 10 priority river systems exporting significant loads of sediments and nutrients to the GBR.

Due to the small area of horticultural development in the catchment, and discounting the significant impacts of widespread cattle grazing, the Normanby has often been cited as representing "pre-European" water quality conditions compared to other rivers in the Great Barrier Reef catchment area (QDPC, 2003). Furnas (2003) states that "The largely dry Normanby River basin on Cape York Peninsula provides the best example of what sediment exports from dry catchments might have been like prior to 1850" and "Nutrient concentrations in nominally pristine or little-disturbed catchments such as the Normanby River are most likely to represent nutrient levels prior to 1850." Furnas' view is also supported by reef researchers who have suggested that the terrestrial runoff to the northern GBR may represent reference conditions against which other more disturbed rivers should be compared (Fabricius et al., 2005).

Under the Reef Rescue program, land managers are targeted for uptake of best practice recommendations and strategies designed to reduce sediment supply. Competing requirements have to be prioritised. An accurate understanding of sediment dynamics in the catchment is of critical significance to the prioritisation process. We note that the catchment loads derived in Brodie et al. (2003) and subsequent studies (see Table 2-1) have relied heavily on the SedNet sediment budget modelling (and its successor Source Catchments). In the absence of empirical validation such as undertaken in this study, earlier researchers were unable to test the assumptions underpinning the generally accepted models of the day. To obtain a valid budget, previous researchers often used empirical load data from a small number of key sites to calibrate their models. This manual tuning brought the model's predicted outputs in tune with the empirically measured loads. However, this apparent convergence between modelled and measured loads can obscure more than it reveals. An empirically-validated output is produced by the model, but for unknown reasons.

Hence, to ensure that the rehabilitation/restoration investments to reduce anthropogenically enhanced sediment loads are being appropriately targeted, it is essential to revisit and revalidate the assumptions that drive the model outputs.

As part of the process of deriving a new sediment budget model for the Normanby Basin, a key focus of this project has been on questioning all assumptions that underpin the standard SedNet modelling framework, and (where possible) developing multiple lines of evidence to support or refute the assumptions made.

1.2 Core Research Questions: Key Objectives and Approach

This project contributes to the Australian Government's Reef Rescue program. The Australian Government has identified two priorities for targeting under Reef Rescue (QDPC, 2003):

- to increase the number of farmers who have adopted land management practices that will improve the quality of water reaching the reef lagoon; and
- to increase the number of pastoralists who have improved ground cover monitoring and management in areas where run-off from grazing is contributing significantly to sediment loads and a decline in the quality of water reaching the reef lagoon.

The project scope included development of a new empirically driven sediment budget model, incorporating improved understanding of water quality management, and undertaking on-ground rehabilitation research. These activities are combined to address the following core questions:

1. What is the proportional contribution of suspended sediment from eastern Cape York rivers to the GBR lagoon compared with the rest of the GBR catchments?
2. To what extent are the contemporary sediment loads from this area elevated above pre-European levels?
3. Which sub-catchments or stream segments are disproportionately contributing to the total sediment load?
4. Of the current key sediment sources, which ones are elevated as a result of land-use intensification, and can anything be done to practically reduce the supply of sediment from these sources?

Our research approach begins with development of an empirically driven sediment budget for the catchments draining to Princess Charlotte Bay (PCB). This includes the Laura/Normanby/Kennedy Rivers, the North Kennedy, Hann, Annie Rivers, Saltwater Creek and Stewart River. This budget identifies the major sediment sources, erosion processes, sediment stores and transport pathways for the suspended sediment component of the sediment budget at the catchment scale (i.e. end of system loads). The existing Brodie et al. (2003) sediment budget formulation effectively acted as a hypothesis to guide our data collection.

In parallel to development of the sediment budget, the broader project extended a body of existing research on water quality conditions and management in the catchment (Howley, 2010). This work includes a synthesis of the current knowledge regarding environmental values, water quality, and land-use impacts on water quality in the Normanby River catchment. A set of Management Recommendations are being developed into a Water Quality Improvement Plan (published separately: (Howley et al., 2013)), which will be the top-level synthesis.

A third facet to this project was focussed on rehabilitation strategies and land management practice to reduce gully erosion. Due to the unique nature of alluvial gullies in northern Australia compared to colluvial or hillslope gullies in southeast Australia, on-ground trials with new techniques or alternative approaches were needed. We initiated trials of rehabilitation strategies for alluvial gully and road/fence erosion on grazing properties, which will eventually form the basis for deriving best management practices (BMPs) applicable across the alluvial landscape of northern Australia. An extensive report outlining gully rehabilitation literature, on-ground management trials, and the recommendations flowing from them will be reported separately (Shellberg and Brooks, 2013).

This document provides an overview of the new sediment budget, concentrating particularly on development of the sediment budget and implications flowing from its findings. The other two components are reported separately (Howley et al., 2013; Shellberg and Brooks, 2013), and incorporate the outcomes from the sediment budget component.

Due to the multi-faceted nature of this project and the fact that different components of the project have been led by different researchers, we have opted to present the results in the form of a report summary, which draws out the key findings along with implications and recommendations. The detail underpinning all of the key findings, including the methods and results, are presented as a series of Appendices. Some of the Appendices are in the form of manuscripts ready for submission to journals, while others are in more of a report style or as a compendium of data.

Collecting from Y-integrated experimental sampler at Battle Camp gauge, Normanby River in May, following the 2009-2010 wet season. (Photo: Anne Bourgeault)

1.3 Key Findings

A summary of the key sediment inputs, storages and end of system outputs (i.e. the sediment budget) is shown in Table 1-1. Further description of how these data were derived is included in this report, with detail provided in the report appendices.

Table 1-1: Summary table showing the revised suspended sediment budget for the Normanby Basin. Note a full error analysis, along with an analysis of the inter-annual variability for all sources, is still to be completed. It is likely that the standard deviation on the final load estimate will be substantially greater than that reported here. Note that for comparative purposes with the previous modelling, it is the catchment output figures that should be used given that the coastal plain sources are a newly identified source not incorporated into any of the previous sediment budget estimates.

Inputs (t/yr)	**New Budget**	1 StDev	Brodie et al.(2003)*
Hillslope (delivered to stream network)	15,900	n/a	1,567,000
Alluvial Gully	736,400	n/a	n/a
Colluvial Gully	411,800	n/a	173,000
Secondary Channel	1,672,000	n/a	n/a
Main Channel Bank Erosion	249,900	204,900	17,500
Total Inputs	3,086,000	204,900	1,758,000
Storage (t/yr)	**New Budget**	1 StDev	Brodie et al.(2003)*
In-channel Benches	424,000	400	
Floodplain Deposition	1,270,000	17,200	664,000
Total Storage	1,694,000	17,600	664,000
Net Output from Upper Catchment	**1,392,000**	222,500	**1,094,000**
Coastal Plain Sources**	4,000,000	1,880,500	n/a
Total Input to PCB (Annual Load (t/yr))	**5,392,000**	**2,103,000**	**1,094,000**

** Brodie et al. (2003) data is the hillslope yield after application of the 10% HSDR.*
***Estimated average. See discussion at 1.3.6 Sediment source tracing shows significant terrestrial contribution*

1.3.1 SedNet and RUSLE in doubt: correlation and divergence of modelled sediment delivery to the GBR lagoon

The sediment budget model we have developed predicts that the **sediment derived from the upper catchment is contributing around 1.39Mt/yr on average to Princess Charlotte Bay.** The "upper catchment" qualifier is included to enable comparison with previous SedNet modelling given that no previous models included input from coastal plain sources (see Table 1-1).

The new budget's output of 1.39Mt/yr is a similar number to that predicted in earlier SedNet modelling (i.e. 1.1Mt/yr; (Brodie et al., 2003)). However, the fact that the two models have derived similar total loads only serves to highlight the potential dangers of deriving an apparently correct "end of system" load, but from un-validated sources. If the sources are wrong, then it is unlikely that any management strategy devised to mitigate sediment contributions from these sources will achieve their desired result, i.e. reduction of sediment loads to natural background levels.

This study highlights the need for an empirically driven modelling approach that incorporates "multiple lines of evidence", in which different methods are used to identify sediment sources and sediment loads.

1.3.2 Hillslope sediment production is well below predictions of prior models

Previous desktop studies (Brodie et al., 2003; Prosser et al., 2001b) identified **hillslope erosion** as supplying around 90% of the sediment at the basin outlet to PCB. Our findings call this assumption into question.

We take two independent lines of investigation here:

- Hillslope erosion plots were used to better understand how much sediment is actually moving off the hillslopes; and
- Radionuclide tracer analysis of sediment deposits in both the river system and PCB was undertaken to examine the distinctive signatures of material transported toward and reaching PCB.

Hillslope erosion measured at the plot scale (i.e. before any hillslope sediment delivery ratio (HSDR) is applied) indicates that sediment production is 1- 4 orders of magnitude less than previous modelling has suggested (Appendix 6). Based on the empirical results, we show that hillslope erosion could be contributing as little as 1% to the total sediment load delivered to PCB. Radionuclide tracer analysis was used to classify material in PCB core samples and river samples as 'surface' or 'subsurface' in origin. This provides a method for estimating how much of the deposited material in rivers or PCB is sourced from the surface in the upper catchment. Due to technical factors, the data is biased toward over-reporting this surface fraction. Even so, surface soils (from all gradients) appear to represent less than 12% of sediments measured in PCB.

There is clear evidence of significant sediment loads being delivered from the catchment to PCB, and these sediments could be adding undesirable pressure to the coastal and GBR ecosystems. However, our research demonstrates that hillslope erosion is a minor component of the total sediment budget.

1.3.3 Sediment production from small alluvial tributaries and alluvial gullies was found to be far more significant than expected

We investigated the rate and extent of **gully erosion** across the catchment at two spatial scales. First, bare ground gullies were manually mapped from Google Earth imagery to provide a minimum gully distribution across the entire catchment. Second, gullies were mapped at high resolution using Airborne Light Detection and Ranging (LiDAR) data in 45 sample blocks covering around 3% of the catchment. The LiDAR survey includes representative samples of channels at all scales (rivers and creeks) and gullies (colluvial and alluvial) in all parts of the catchment.

This approach enabled us to quantify the contribution of small alluvial tributaries and alluvial gullies, neither of which has been included in previous modelling. The resulting analysis indicates that gully erosion accounts for ~37% of the total suspended sediment load delivered to PCB, with alluvial gullies comprising ~24% and colluvial gullies 13% of the total.

We were also able to determine sediment production from **channel bank erosion in small alluvial tributaries** from the LiDAR datasets. Existing empirical data and model extrapolations indicate that the sediment sourced from the catchment (i.e. excluding the coastal plain) is dominated by channel bank erosion from small alluvial channels (~54%), notwithstanding the error margins with this and other percentage allocations. These channels are at a scale that falls below the channel initiation threshold defined in previous models (Brodie et al., 2003; Prosser et al., 2001b), and thus were previously ignored.

1.3.4 Floodplain and in-channel sediment storage is a significant phenomenon that requires future research

Storage of fine sediment within the mainstem channel network (i.e. within benches) has not been considered in previous sediment budget modelling exercises within the reef catchments. Our conservative estimate of in-channel storage shows that the channel network itself can store >400Kt/yr of suspended sediment, and appears to have been doing so for the last ~150 years. If we assume that gully erosion rates have doubled in the post-European period (a not unreasonable assumption based on evidence presented in this study and others (Shellberg, 2011b)), then, at these rates of in-channel aggradation, the entire increase in sediment supply could have been absorbed within the channel network and would not yet be apparent at the river mouth.

This illustrates the importance of the channel network as a sediment store, and underpins the significance of riparian zone management to ensure that these sediment stores are not continually disturbed and remobilized. Note: the sand bed material fraction of accelerated erosion will have a much greater effect on the channel network in terms of sediment storage, but was not assessed in detail by this study.

Our sediment storage estimates are based on geochronology and stratigraphic data. These data were collected at a range of sites to determine the **depositional rates** within **in-channel bench deposits** and **floodplain aggradations rates.** A total of 85 sediment burial dates were determined using Optically Stimulated Luminescence (OSL). Long term floodplain aggradation data enabled us to firstly test whether there was any evidence for a recent increase in sediment movement across the catchment; and secondly to derive some typical long term sediment aggradation rates that help explain the mechanics of sediment deposition (which represents internal losses within the catchment, reducing sediment throughput).

The results indicate that the total sediment storage represents approximately 55% of the suspended sediment delivered to the stream network. This deposition occurs in two key systems: floodplain storage (41% of inputs); and in-channel storage within benches and inset floodplains (14% of inputs). Floodplain storage in this instance would include the vast wetland systems through Rinyirru (Lakefield) National Park and is not necessarily uniformly distributed.

1.3.5 Land use practices can increase erosion and sediment yields, and degrade water quality

The upper catchment supports the majority of landuse activities that have the potential to degrade (or improve) water quality. Our research identifies a range of land use practices that can degrade water quality and increase sediment sources including:

- **Over grazing cattle** and **cattle pads** along river frontage (floodplains and terraces) can reduce ground cover, disturb fragile soils, enhance water runoff, stimulate rill and gully erosion, and accelerate sediment mobilisation;
- **Poorly designed and maintained roads** and **fence lines** can increase rill and gully erosion and accelerate sediment mobilisation;
- **Intensive agricultural activity** can be a periodic source of intensified water runoff and erosion, especially where cover is reduced at the start of the wet season. Increases in nutrient concentrations from agricultural land use have also been documented in the Laura River (Howley, 2010). Nutrient impacts will be discussed further in the separate report by Howley et al (2013).

Unsealed roads and **road drains** merit special attention as they have not been included in previous models and field observation suggests that they could be a significant sediment source. A rough estimate shows that road-related sediment contributions could be of similar scale to hillslope sourced sediments, particularly when the secondary impact of road induced gullies is factored in. Research and field observations indicate that **primitive roads** and **fence lines** on cattle stations are also significant sediment sources (Shellberg and Brooks, 2013), but are not currently included in past or present models.

These land use impacts--accelerated erosion and elevated sediment loads--are cumulative across the upper catchment. Each impact occurs at relatively small scale, but the result, in sum is hundreds to thousands of kilometres of overgrazed creek and river frontage, roads, and fence lines which cumulatively have become important drivers of water quality at catchment scale.

While there remains uncertainty surrounding precise contributions from each sediment source measured and/or modelled here, we believe that the observation data are robust enough to base management strategies on, especially compared to grossly incorrect assumptions in the past.

1.3.6 Sediment source tracing shows significant terrestrial contribution

The geochemistry data gathered in this study indicate that **Princess Charlotte Bay sediments are comprised of terrestrial sediments (46 ± 5%)**, with the remainder comprised of marine derived carbonates (28 ± 2%), and quartz silt/sand of indeterminate origin (26 ± 3%), a portion of which is likely to be derived from modern catchment inputs. The finding that terrestrially derived sediments dominate the recent sediment supply to PCB is in stark contrast to **previous studies that have estimated a 4% terrestrial contribution** (Chivas et al., 1983; Torgersen et al., 1983).

Of the 46% we suggest to be derived from terrestrial sources, the largest contributions are predicted to come from lower floodplain/channel sediments represented by Bizant River samples (52 ± 1%) and coastal plain sediments (30 ± 1%); with the remaining 18% derived from catchment sources above the coastal plain (9 ± 1% of total).

Research indicates that while 46% of PCB bed material is terrestrial in origin, **riverine delivered sediments from the upper catchment (i.e. sourced from above the coastal plain) only represent about 9% of the sediment present on the bed of Princess Charlotte Bay.**

The interpretation of these measured percentages of sediment origin in PCB bed sediments has been made with caution. These percentages do not necessarily represent the relative proportion or variability of sediment sources in flood plumes delivering sediment to the reefs surrounding PCB. Analysis of the terrestrial contributions from flood plumes over the 2011/12 and 2012/13 wet season is ongoing (Howley et al. unpublished data). It is clear that a great deal more research is required to unravel the interaction between sediment delivered to the near shore zone in PCB by tidal currents, and sediment delivered to reefs in flood plumes; be it sourced from the upper catchment or remobilised from near shore stores and/or the coastal plain.

The sediment geochemistry shows that the dominant terrestrial source is the lowland floodplain/coastal plain in the vicinity of the Bizant and North Kennedy Rivers, which if our upper catchment sediment yield is approximately correct, would mean that on average in recent years this area has been contributing around 4Mt/yr of suspended sediment to PCB.

We have mapped an area of ~185km^2 within the PCB coastal plain, with a concentration between the Bizant and North Kennedy River mouths, that appears to have undergone surface stripping to a depth of up to 3m (average ~0.7m) sometime in the past 500 years. Depending on how the surface is reconstructed, and hence how much sediment has been eroded, a conservative estimate of this source is between 175-220 Mt.

Therefore, depending on the timescale over which this material has been eroded, this could represent the source of the material represented as “Bizant” sediments. Furthermore, there are other parts of the coastal plain that appear in satellite imagery to be undergoing similar stripping, particularly in the Marrett River estuary.

The causal process and initiation of this coastal erosion needs to be further investigated. The conceptual model of the development of this coastal plain, first proposed by Chappell (1982), would appear to provide a useful starting point. He described how a combination of episodic variation in alluvial sediment inputs into the bay and a lowering of sea-level by approximately 1m since the mid-Holocene (~6000 yrs BP) produced a prograding chenier plain system. The coastal erosion would appear to be perpetuated by tidal flows once the tidal channel network develops to a certain extent and is occurring concurrently with major erosion of the Bizant River channel as it increasingly becomes the major distributary of the Normanby River.

This coastal erosion is supported by our catchment sediment budget data and preliminary data on PCB aggradation rates, which requires a coastal sediment input to Princess Charlotte Bay of about 4Mt/yr (based on an average of the upper and lower estimates of aggradation) to make the sediment budget balance.

1.4 Summary Response to Research Questions

1.4.1 What is the relative contribution of suspended sediment from eastern Cape York rivers to the northern GBR lagoon?

Our data confirm that the Normanby Catchment is a major contributor of sediment to the Great Barrier Reef Lagoon. Indeed, while our data are in general agreement with the approximate loads that have been previously predicted to be derived from the catchment (albeit from entirely different sources), we have also identified an additional coastal/floodplain source that is in the order of 4 times greater than the upper catchment derived sources to PCB, but perhaps not the GBR during flood. It would seem, however, that the vast majority of the sediment input is retained within PCB, based on the mass balance between the sources we have identified and the estimated aggradation rates. It is perhaps only due to the general physiographic setting of Princess Charlotte Bay (a broad, shallow, north-facing bay) that a lot more of the sediment from this catchment hasn’t been exported to the reef. Hence, understanding the interactions between flood flows, tides, currents, and sediment remobilisation from the in-shore parts of PCB is central to understanding what the potential impacts of suspended sediment are on the reefs surrounding PCB. This is not well understood, and merits further research.

1.4.2 To what extent are the contemporary sediment loads from this area elevated above pre-European levels?

The extent to which the catchment sediment loads estimated in this study are elevated above long term “pre-European” background rates is still not easy to determine. What we can say is that the predicted 5-fold increase in post-European sediment supply rates predicted by Prosser et al., (2001a) and Brodie et.al., (2003) is not supported by our data. These estimates were based on the assumption that hillslope erosion dominates the sediment budget. Hence, the total budget was very sensitive to hillslope cover factor changes. Clearly, the introduction of cattle has resulted in catchment-scale changes to ground cover, weeds, and fire regimes. However our research does not support the dominance of hillslope erosion, and hence the role of catchment-wide cover factor dynamics on hillslope erosion. Thus, it is likely that the pre-European “baseline” sediment loads were substantially higher than previously assumed when the correct sources are taken into account, and therefore the ratio of change is less than predicted.

There is air photo and stratigraphic evidence from our work of a catchment-wide rejuvenation and acceleration of gully erosion within the last 100 years or so, and this can be tied to the introduction of cattle into the catchment. Gully fill geochronology data show that recent aggradation rates are up to an order of magnitude higher than the pre-European rates (Appendix 15). The mechanisms by which this disturbance process can occur has been detailed in Shellberg (2011a) in the adjoining Mitchell catchment, and we have reason to believe a similar process is occurring in the Normanby, albeit with greater complexity, and potentially a more lagged response. The disturbance process is a function of: 1) cattle concentrating along river frontage and hollows on steep banks; 2) overgrazing and reduction of perennial grass cover and erosion resistance; 3) directly disturbing fragile sodic soils reducing infiltration capacity; and 4) cutting cattle pads that concentrate water runoff from floodplains into steep banks, hollows and older channel networks. Weed invasion and change in fire regime likely exacerbated the reduction in perennial grass cover in addition to overgrazing.

Together these factors accelerated gully erosion into older (Pleistocene) floodplain deposits and pre-existing channel networks that were quasi-stable upon arrival of Europeans. Natural factors (climate, relief, soils, earlier drainage forms) primed the floodplain landscape for erosion over long geologic time periods, but recent land-use change pushed the landscape across a stability threshold and triggered accelerated alluvial gully erosion. We have dated several phases of gully activity and channel network development at several sites (see Appendix 15). The recent phase of gully incision is showing greater rates of incision than any of the previous phases of network development, suggesting there is an added land use dimension to the current phase that is not explained by a climatic driver or an autogenic process (i.e. an intrinsic threshold of stability has been exceeded).

1.4.3 Which sub-catchments or stream segments are disproportionately contributing to the total sediment load?

Alluvial and colluvial gully erosion are major sources of sediment and we have evidence that gully erosion has been accelerated by land use since European settlement. We have mapped the major areas of alluvial and colluvial gully erosion across the catchment. Alluvial gully areas coincide with dispersible sodic soils on floodplains and terraces. We have identified several large areas where gully erosion is concentrated, specifically on the Granite Normanby River, near the East and West Normanby River confluence, and the Laura River immediately upstream of Crocodile Gap. These areas could be targeted to reduce sediment yields through passive and active gully rehabilitation measures (Shellberg and Brooks, 2013).

The most surprising result to come from this study was the identification of an additional source of sediment from within the coastal floodplain that has not previously been factored into any of the sediment budgets derived for this (or any) catchment. Geochronology data indicates that erosion of the coastal plain around Princess Charlotte Bay has been initiated sometime over the last 500 years. The sediment sourced from this area contributes an estimated average of 4Mt/yr over and above the 1.39Mt/yr we have identified to be sourced from the "upper catchment" (i.e. the catchment and stream network generally considered in previous catchment models). The most likely mechanism triggering this erosion is the sea level fall of ~1m over the last 5,000 years that has rejuvenated the coastal plain. Erosion associated with this base level drop could have been triggered by a major cyclone or series of cyclones, and the associated storm surge. Such an event is known to have occurred in 1899 (tropical cyclone Mahina), and is regarded as having been accompanied by a large storm surge (Nott and Hayne, 2000).

Small alluvial channels not previously factored into sediment budget models are predicted to be the dominant sediment source from the upper catchment, albeit with some uncertainty of dominance compared to other sub-surface sediment sources (i.e. gullies). These channels fall below the channel initiation threshold used in the earlier models, or else have simply not been mapped. Such alluvial channels are ubiquitous, although the extent to which the erosion of these features represents "natural" background erosion rates or has been elevated by grazing and other land use pressure is difficult to determine (i.e. increased water runoff leading to erosion). It is possible that the channels immediately downstream of alluvial gullies that are contributing elevated sediment supply are more active than other channels that may not have such high sediment supply. This is the subject of ongoing research. It is difficult at this stage to say there is one particular part of the catchment where secondary alluvial channel erosion is greater than elsewhere.

Unsealed roads are likely to be a significant sediment source, about which direct measures can be taken to reduce erosion.

Lakeland horticultural areas are known to periodically produce high sediment yields, particularly when extensive areas of bare ground are exposed at the time of the first wet season storms. Our tracing data (Appendix 7) from time integrated samplers (which show the net contributions from all sources across a wet season), indicates that such sources are overwhelmed by other sub-surface sources (i.e., gully and banks) within around 10 kms of the Lakeland source area. During especially heavy rainfall events, red basalt sediment plumes sourced from Lakeland may be evident more than 10 kms downstream. Under normal conditions, however, it is possible that much of the accelerated sediment yield from farming gets deposited in the numerous dams found in this area, notably Honey Dam. Further analysis of these dams should be undertaken to determine changes in sediment yield over time.

1.4.4 Of the current key sediment sources, which ones are a function of land-use intensification, and can anything be done to practically reduce the supply of sediment from these sources?

The precise extent to which some of the sediment sources are a function of land use or have been accelerated by it is still an open question. Some sources are less ambiguous:

Alluvial gully erosion has been accelerated by land use since European settlement, through cattle overgrazing and soil disturbance on sodic floodplain soils of river frontages. Several large areas of concentrated gully erosion have been identified (Granite and West Normanby, middle Laura River). These areas could be targeted with management actions to reduce sediment yields through passive and active gully rehabilitation measures (Shellberg and Brooks, 2013).

Secondary alluvial channel bank erosion could be driven by land use pressure. There are four potential mechanisms:

1. The direct disturbance of these channels by cattle is increasing the rate at which they erode. Cattle both physically disturb small alluvial banks and reduce the grass vegetative cover, thereby accelerating the erosion of these channels.
2. Increased water runoff associated with catchment-wide changes to ground cover could be increasing the water discharge within these channels, thereby facilitating increased erosion rates. This process could also be exacerbated by altered fire regime and weed invasion.
3. Increased lateral channel migration could also occur in response to a recent increase in upstream sediment supply (e.g. from alluvial gullies). This effect would be especially pronounced with increased bed-material load from gully erosion.
4. Earlier phases of channel incision associated with land use and/or natural disturbance could have destabilized banks. Thus, cut and fill cycles accelerated by land use changes could have initiated a “complex response” to bank erosion in small alluvial channels.

Road erosion is an entirely anthropogenic sediment source, driven by direct water runoff from the surface of unsealed roads and the frequent gullies initiated by road drains. Main dirt roads, secondary dirt roads, cattle station roads, and primitive vehicle tracks are all too commonly associated with accelerating erosion.

Fence lines erosion is associated with the construction and ongoing "maintenance" of fence lines that cause rill and gully erosion. This is also an entirely anthropogenic sediment source. Many fence lines exhibit the characteristics of roads, particularly where they are graded as fire breaks, and similarly produce significant volumes of sediment.

Coastal erosion is seen as a natural process. However, anthropogenic climate change is associated with sea level rise, increased cyclone activity, and associated storm surges, all of which amplify the hydraulic drivers through the vulnerable lower catchment. The net effect of sea level rise on coastal erosion and sediment output to PCB and surrounding reefs is unknown, and requires further investigation.

1.5 Conclusions and Recommendations

1.5.1 Empirical data must provide the foundation to the models

This study highlights the fact that catchment sediment budget modelling should not be undertaken unless there is sufficient empirical data available from the catchment being modelled. As a general principle, a poorly parameterised model that is fundamentally inaccurate can be worse than no model at all. The inaccurate model gives an illusion of progress and insight but ends up being misleading. The effort invested in compiling a model built upon little or no data would be far better used collecting actual empirical data.

1.5.2 RUSLE-based models merit special scrutiny

RUSLE based models that have been used to predict sediment yields from other GBR catchments should be closely evaluated to check whether similar degrees of hillslope erosion over-prediction have occurred.

1.5.3 Invest in gully rehabilitation/restoration research and works

There needs to be continued research on practical and economically viable means of addressing alluvial gully and channel erosion, given that these are the largest sources that we know have been accelerated by land use. The development of "best management practice" (BMPs) guidelines for dealing with alluvial gully and channel erosion in these tropical landscapes will have much wider application than just the Normanby. Initial steps toward identifying gully rehabilitation options through experimental trials have been conducted by Shellberg and Brooks (2013).

1.5.4 Clarify the mechanisms and extent of land use impacts

Further work is required to establish the rates, timing and causes of pre-European channel and gully erosion, so that we can better establish the relationship between elevated erosion post-European settlement and gully erosion from prior eras.

Research is needed to better understand pre- and post-European erosion/deposition rates, particularly within benches. Similar research is needed within some closed tributary catchment sites that have been identified within this project. Sedimentation within dams of the Lakefield area should also be analysed.

1.5.5 Focus on erosion and sedimentation dynamics in the lower catchment

Given that most of the increased erosion from upper catchment land use changes appears to have been delivered to lower catchment sinks, further analysis should be undertaken within Rinyirru/ Lakefield NP to determine whether there is evidence of waterhole and wetland in-filling across this extensive stretch of country.

There is a pressing need to further understand the coastal erosion processes in the lower Normanby, to understand whether this process constitutes a long term threat to the GBR. In particular:

- the chronology of events, and the extent of erosion to the coastal plain, needs to be better constrained than we have been able to achieve in this project; and
- there is a need to better understand the relationship between flood flows re-suspending sediment derived from the coastal zone but stored within the near-shore zone around the various estuaries at the outlets to the rivers draining into PCB. For example, while the source of the sediment to PCB is dominated by the coastal plain sediments, is it the flood plumes that are primarily responsible for transporting this sediment to the reef?

1.5.6 Acquire additional flood plume geochemical tracing

Collecting sufficient samples from flood plumes is needed to enable geochemical tracing. This will enable us to validate the conclusions drawn in this report, and should be a high priority. Some preliminary data have been collected during recent plumes and should highlight the direction of future data needs (Howley et al. unpublished data).

1.5.7 Undertake direct measurement of sedimentation on surrounding reefs

Direct measurement of sedimentation on reefs surrounding PCB will also enable us to better appreciate the extent to which sediments delivered to PCB are being exported to the surrounding reefs.

1.5.8 Develop a better understanding of land use drivers of bank erosion in small alluvial channels

Given the dominance of bank erosion, particularly in the minor alluvial channels, there is a need to continue to understand the processes of bank erosion and whether there is a land use component to their current rates of activity.

1.5.9 Develop a PCB sediment sink mass balance

A more detailed mass balance of sediment stored within PCB over the last 100 years is required to more accurately determine what proportion of sediment entering the bay is exported to the reef.

1.5.10 Analyse gauge flow and sediment bypass around Kalpowar

As a matter of priority further analysis of water flow and sediment bypass around the Kalpowar gauge should be undertaken. The acquisition of LiDAR topographic data across the whole floodplain at and above this site would facilitate this analysis – in addition to on-ground measurement within all distributary channels during large events.

1.5.11 Establish and improve the collection of hydrological data, especially time-series

Hydrological data is integral to this type of sediment budget modelling, without which the modelling could not be undertaken. Catchment scale models have no alternative but to be based on modelled hydrologic data and extrapolation across a stream network, as was done in this study. Large amounts of uncertainty in sediment budget modelling output are a consequence of uncertainty in the underlying hydrologic data.

Hydrologic models require a range of data inputs, but of greatest importance is the time series data, stream gauge and rainfall data, which are used to calibrate these models. Stream gauge data is also part of any sediment load measurement. Four gauges have been discontinued in the Normanby (Jungle Creek 105002A, Kennedy River 105103A, Deighton River 105104A, and West Normanby River 105106A) all in the late 1980's. Currently there are five working gauges (DNRM, 2012).

It is recommended that these empirical data, their ongoing collection, and possible expansion, be considered vital and critical components of resource management infrastructure.

1.5.12 Additional key recommendations with implications beyond the Normanby

1. A state-wide program of measuring RUSLE K values for rangeland soils should be undertaken as a matter of priority, as should a program to map rock outcrops which will deliver minimal suspended sediment on management timeframes.
2. The significance of minor alluvial channels as sediment sources should be investigated in other regions.

3. The potential role of coastal erosion as a source of sediment should be investigated in other reef catchments. Preliminary analysis undertaken by Dr Jon Knight at Griffith University indicates that a similar process may be occurring on the Fitzroy River coastal plain.
4. The potential contribution of unsealed roads, tracks, and fence lines to the suspended sediment budget should be investigated in other regions that are likely to have a much greater density of unsealed roads and fences than the Normanby.

Dramatic example of the power of vegetation cover. The remains of this tree protect the pedestal while the surrounding surface has eroded a further 2-3m (Photo: Jason Carroll)

2 A New Sediment Budget for the Normanby

2.1 Summary Sediment Budget

A summary of the key inputs, storages and end of system outputs (i.e. the sediment budget) is shown in Table 1-1. Further detail of how these data were derived is included in the report appendices, section 3.

2.2 Inventory of New Empirical Data

The Project focused on collecting data on all key erosion processes within the catchment. New data collected included:

- **LiDAR data.** Airborne Light Detection and Ranging (LiDAR) data was collected in a series of sample blocks covering around 3% of the catchment, and included samples of channels at all scales and gullies in all parts of the catchment. The initial acquisition was undertaken in June 2009.
- **Repeat LiDAR** was flown two years after the original LiDAR dataset, to enable geomorphic change to be determined, and hence sediment production from different parts of the landscape to be measured. The repeat LiDAR was acquired in September/October 2011 and covered 0.5% of the total catchment area.
- **Gully mapping** was conducted at two different spatial scales using two datasets. First; bare ground gullies were manually digitised from Google Earth to provide a minimum gully distribution across the entire catchment. Second; gullies were digitised at high resolution from within the LiDAR bare ground DEM. The LiDAR change detection undertaken within these delineated gullies then formed the basis for deriving rates of change across the catchment within the Google Earth derived gully mapping. The Google Earth mapped gully extent is regarded as a minimum because the bare ground LiDAR data shows that--in terms of area--there is at least an order of magnitude more gullies hidden below vegetation than are clearly visible as bare ground gullies. Furthermore, the LiDAR change detection shows that in many instances these vegetated gullies are in fact more active than the bare ground gullies.
- The **short term sediment production rate data** was then coupled with **longer term gully change data derived from historical aerial photography** at 21 sites across the catchment (primarily located within the LiDAR blocks so that the short term rate data could be compared with the multi-decadal data derived from the aerial photography time series data.
- The same change detection data used to derive the short term (2 yr) gully sediment production data were also used to determine **sediment production from channel bank erosion in small alluvial tributaries** as well as from main channel banks.

- **LiDAR change detection analysis of these same data** also highlighted erosion from other parts of the channel zone – particularly open channel bed and bars, which predominantly produce bed material load –but do produce some (<63µm) suspended sediment. In addition, these data also highlight where in-channel deposition is occurring (where deposition exceeds the minimum threshold for detection – which was generally 0.5m in vegetated channels or 0.25m in more open channels).
- **Bank erosion rates** were also derived from a geotechnical analysis of 4 sites in the catchment. This work was undertaken as a pilot for a subsequent, more detailed, analysis of bank erosion in the catchment. These data, coupled with aerial videography of a 110km survey of the channel network in the upper reaches of the East and West Normanby Rivers, provide an independent check of the rates derived from the repeat LiDAR data.
- **Hillslope erosion rates** have been quantified using a new low cost sediment trap designed for the project. Total wet season hillslope sediment production was measured at sites from representative soils on the four major geological units within the upper parts of the Normanby catchment. These data were then used to test the predicted hillslope erosion rates at the same sites using the various iterations of the RUSLE model that have been used to derive the catchment scale sediment budget in previous model runs.
- **Sediment concentration and load data.** At the commencement of the project the existing data on total suspended solid (TSS) concentrations at the active gauges in the catchment were insufficient in quantity and quality across a range of discharges to derive reasonable estimates of the sediment load at any of the gauges except Kalpowar. Hence a component of the study was to collect additional suspended sediment concentration (SSC) data, particularly at high stage, given that much of the existing data was for low to moderate stage conditions. Consequently a series of rising stage samplers (or single stage samplers – *sensu* (Colby, 1961)) were deployed at three operating gauges (Laura @ Coalseam, East Normanby, Normanby at Battle Camp) and one discontinued gauge (West Normanby). Continuous stage recorders were also deployed to correlate to current and past stage and discharge data. In addition to this, a relationship between TSS and turbidity data was derived from the combination of the existing DERM ambient water quality monitoring data and additional data collected as part of the project (Howley, 2010). When combined, these data enable us to convert a considerable amount of existing turbidity data (i.e., CYMAG ambient water quality monitoring data) into sediment concentration data. When coupled with the existing DERM TSS data at 5 gauge sites and the new high stage SSC data, sediment rating curves could then be derived for these gauges to estimate sediment load time series data.

- **Sediment tracing data**. Given the scale of the catchment it is impractical to collect sufficient load and source monitoring data to construct a sediment budget directly. Hence an extensive sediment tracing program was conducted across two wet season (2009/10 and 2010/11) to test the claimed dominance of surface erosion over sub-surface gully and bank erosion sources. Data was collected on hillslope source materials using a new method developed for this project. In this method the mobilised material is used as the source sample rather than the soil grab sample method typically used in the past. In-stream samples were collected using the integrated sampling method (Phillips et al., 2000) and the drape sampling method (Caitcheon et al., 2012). Tracing was continued right through the catchment to sediment cores within PCB.
- **Sediment coring in PCB.** 45 sediment cores were collected from PCB and a source tracing analysis carried out to identify the relative proportions of terrestrial sediments comprising the bay sediments.
- **Geochronology data** was collected at a range of sites to determine: 1) incisional histories within alluvial gullies; 2) depositional rates within in-channel bench deposits; and 3) floodplain aggradations rates. A total of 85 dates were analysed using Optically Stimulated Luminescence (OSL) dating. The gully incisional history data enabled us to test the hypothesis that "gully erosion was a purely post-European phenomenon"; whereas the bench dating enabled us (in combination with sediment particle size analysis data) to determine the importance of these features as sinks or temporary storages of a proportion of the suspended sediment load. Long term floodplain aggradation data enabled us to firstly test whether there was any evidence for a recent increase in sediment supply (as predicted by the previous SedNet modelling); and secondly to derive some typical long term sediment aggradation rates (which represents internal losses within the catchment, reducing the sediment throughput from the catchment).
- **Road erosion.** The data collected over the 2011-12 wet season (Gleeson, 2012) would tend to suggest that this issue should be looked at in more detail. Whilst this should be regarded as a pilot study, it does provide an order of magnitude analysis of the potential contribution to the suspended sediment budget from unsealed roads. This is the first time in the Normanby that road erosion has been incorporated as a distinct sediment source.
- **All of these data were used to parameterize a new sediment budget model.** The model uses the latest DNRM hydrologic modelling (Source Catchments) data for ~300 sub-catchments in the basin. These we have interpolated to the ~9600 Normanby basin stream segments in the Australian Hydrologic Geospatial Fabric (AHGF) (Bureau of Meterology, 2012) stream network (derived from the 9 sec DEM of Australia) as the basis for the catchment model. In each of these segments we have estimated the contribution from

upstream, hillslope, gully and channel erosion, and the storage of sediment in the segment and the downstream transport.

2.3 Previous Understanding of the Normanby Sediment Budget

To date there have been nine published estimates of the sediment loads exported from the Normanby Basin to the northern Great Barrier Reef (Table 2-1), with a tenth in progress at the time of writing. Of the 9 published estimates, only 2 studies undertook independent modelling (2 & 4), while several produced empirical estimates, primarily based on a single gauge at Kalpowar Crossing which has only been in operation since 2005.

Beyond the Kalpowar Gauge data, very few empirical data existed at the outset of this study with which to test the validity of any of the previously published estimates. Of these studies, the estimates from Brodie et al. (2003) form the basis for most of the subsequent published estimates, and have to date been the basis upon which the management priorities for this region have been set. The most recent estimates from the DNRM Source Catchments modelling used the same bank and gully erosion assumptions and estimates as the earlier modelling, but differs in that there are new estimates of the hillslope erosion based on new slope (S) and length (L) factors, based on a higher resolution topographic data, and a new interpolation of the soil erodibility (K) and rainfall R factors as well as an annual C factor time series.

Collecting integrated sampler at Jack River following the 2009-2010 wet season. (Photo: John Spencer)

Table 2-1: Sediment and Nutrient Loads Estimates for the Normanby Basin. * Note the estimates from the DNRM (In preparation) RUSLE model data at the time of writing were not the official data: they are our interpretation of the end of system yield based on input data as supplied.

Source | Estimate Method	Estimate time frame	TSS (kt/yr)	TN (t/yr)	PN (t/yr)	DON (t/yr)	DIN (t/yr)	TP (t/yr)	PP (t/yr)	DOP (t/yr)	DIP (t/yr)
1) (Belperio, 1983)[1]										
Shelf sediment accumulation	Current (80s)	2590								
2) (NLWRA, 2001)[2]										
SedNet/ Annex	Current	1620	4988				920			
	Pre-1850's	540	2625				383			
3) (Furnas, 2003)										
Simple Model based on AIMS data	Current	500	1960	720	394	846	208	158	29	21
4) (Brodie et al., 2003)										
SedNet/ Annex	Current	1093		4544	1175	949		597	61	13
	Natural	184		85	544	517		72	53	10
5) (McKergow et al., 2005)										
SedNet/ Annex (modified)	Current	1093	6668	4544		949	671	597		
	Pre-1850		1146		1175					
6) (Kroon et al., 2010)										
SedNet/ Annex	Current best	1093	6668	4544	1175	949	671	597	61	13
	Pre-1850	184	1146	85	544	517	135	72	53	10
LRE from DERM data w/ correction	Current estimate from limited data	137	1429	440	1081	125	198	81	139	29.7
7) (Brodie et al., 2010a)										
SedNet/ Annex	Current Best estimate	1100[3]		2000[4]	800[4]	900[4]		400[4]	50[4]	20[5]
Flow weighted mean annual load[4]	2006/2007	166				150				57
8) (Kroon et al., 2012) (McKergow et al., 2005) source										
Survey of available estimates	Current	1100[3]	6700	4500	1200	950	670	600	61	13
	Pre-1850	180	1200	85	540	520	140	72	53	10
9) (Joo et al., 2012)[6]										
	2006-2009 DERM data	59 - 211	711 - 1814			54 – 93 (NOx + NH_4)	84 - 168			16 – 30 (FRP)
10) DNRM (In preparation)										
Source Catchments	1983-2009	620*								

1. Reported in Brodie et al., (2010a)
2. NLWRA 2001 Australian Agriculture Assessment 2001 (www.anra.gov.au/topics/water/pubs/national/agriculture_basin_budgets.html)
3. (Brodie et al., 2003): some monitoring data validation
4. Values averaged from Brodie et al., (2003), and Furnas, (2003): little or no monitoring data validation, major assumptions made (Brodie et al., 2010b)
5. Calculated from 2006/2007 DERM monitoring data (Kalpowar Crossing)
6. Unpublished Source Catchments Model data 2012 (based on revised RUSLE values + the same bank and gully erosion data as used in Brodie et al., (2003))

2.3.1 Key sediment sources from Brodie et al. (2003)

Table 2-2 and Figure 1 show the dominant sediment sources and loads determined by the most recent major SedNet modelling exercise (Brodie et al., 2003). These data were used as the initial hypothesis to drive our field sampling program, which in effect became a test of the original modelling.

Table 2-2: Normanby Sediment Budget Summary (Brodie et al., 2003). Predicted sediment input loads from gully, bank or hillslope erosion sources in the Normanby catchment based on the SedNet/Annex model predictions from Brodie et al. (2003). Note that the gully sources are of the hillslope or colluvial gully form. Note also that the total hillslope erosion value is the amount of sediment predicted by the RUSLE model to be transported off hillslopes before the HSDR is applied; assumed to be 10% in this case.

Source	Suspended Sed Inputs Kt/yr	Bed material Load Inputs Kt/yr
Colluvial gully	173	173
Bank	17.5	17.5
Total hillslope	15,670	
Hillslope delivered	1,567	0
Total inputs	1,758	190.5
Storage	664	115
Export	1,094	76

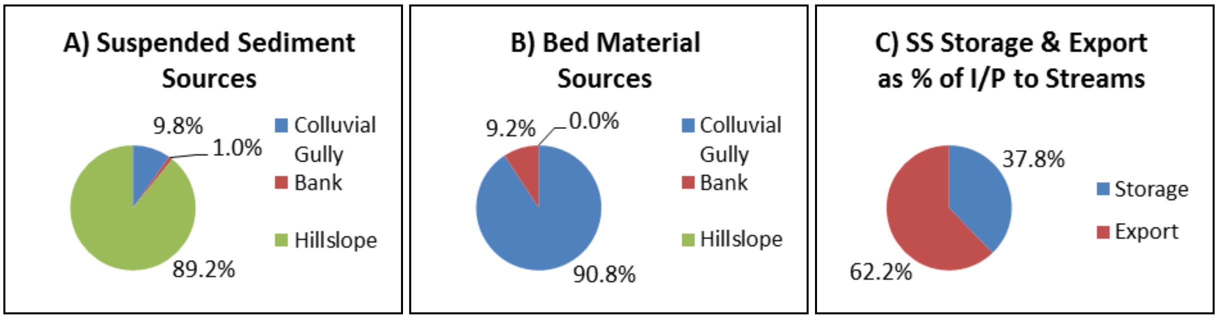


Figure 1: Predicted proportions of suspended and bed material load sediment sources based on the Brodie et al., (2003) SedNet/Annex modelling. Also shown is the predicted proportion of the total suspended load that is stored or exported from the system.

2.4 Hillslope Sediment Yield

Using two independent lines of investigation (hillslope erosion plots and radionuclide tracer analysis) the study has demonstrated that hillslope erosion is only a relatively minor component of the sediment budget in the Normanby (where it was previously thought to dominate). Hillslope plot measurements indicate that hillslope sediment production is 1- 4 orders of magnitude less than previous modelling has suggested (depending on soil type) (Figure 2). Using these measured data, we have back-calculated new K values for the major soil groups in the upper Normanby and run a new RUSLE-based hillslope erosion model for the catchment (Figure 3). A full explanation of the methods used to both measure and model these hillslope sediment production rates is provided in Appendix 5, Appendix 6, and Appendix 7, with the values for all variables provided in Appendix 6, Table 4.

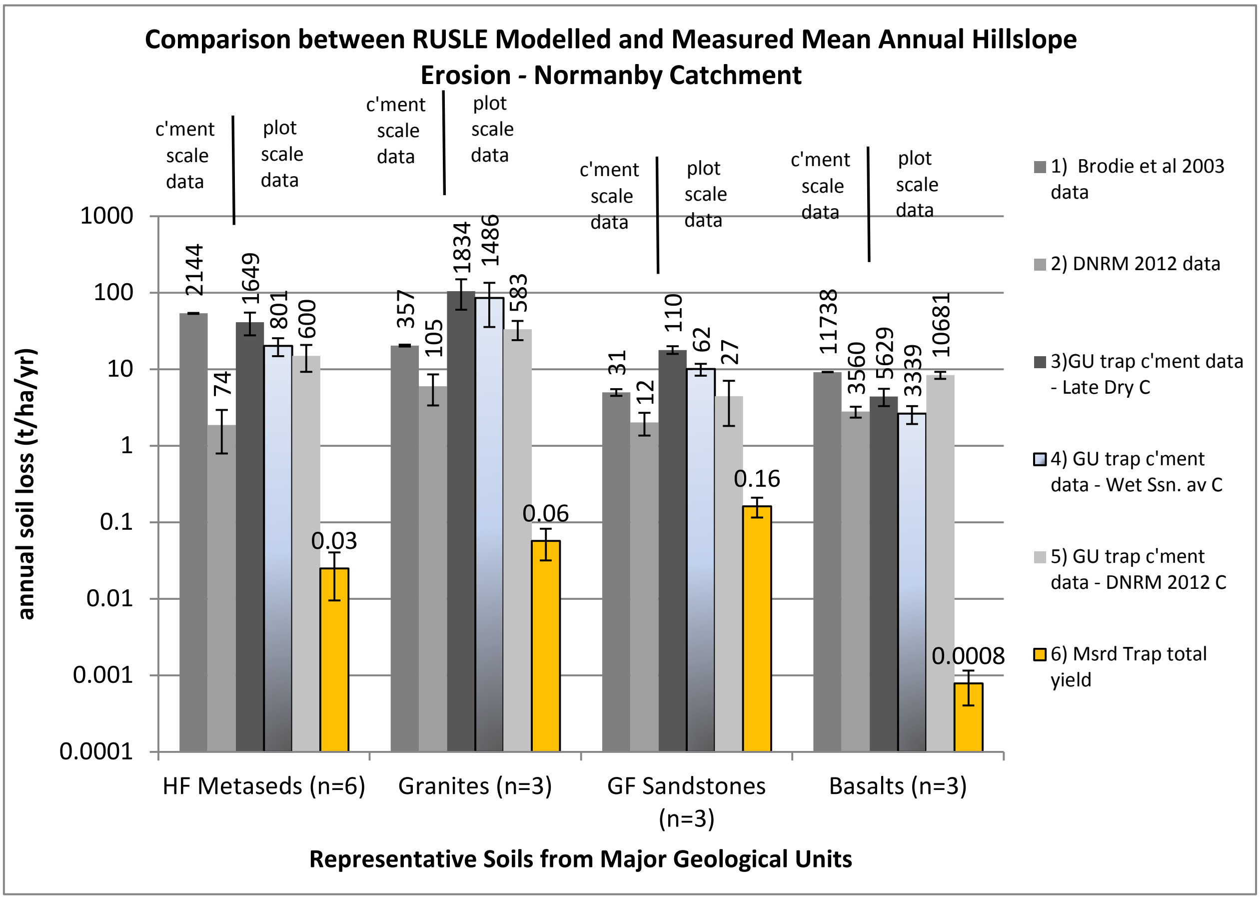


Figure 2: Graph showing the average annual hillslope erosion rates (i.e. total yield) on soils of the four major geologic formations in the upper Normanby catchment. The grey bars show the modelled estimates at the same locations as the measured mean annual loads across the 2009/10 and 10/11 water years (WY). The modelled rates are across the same time period, as reflected in the R & C factor values within the RUSLE modelling. In addition to the Brodie et al., (2003) and the DNRM 2012 models run at the same scale they were originally run (i.e. 270m and 100m pixel resolution respectively), we also ran RUSLE at the plot scale using three different C factor values. The numbers above the yellow bars (i.e. the measured loads) are the mean annual (WY) loads in t/ha), whereas the numbers above the grey bars are the ratio (of over-prediction) of the predicted to measured yields according to the different model formulations.

NOTE LOG SCALE.

Note also that under the DNRM 2012 model formulation these data would not be applied in areas where FPC >20% or in Nature Conservation areas.

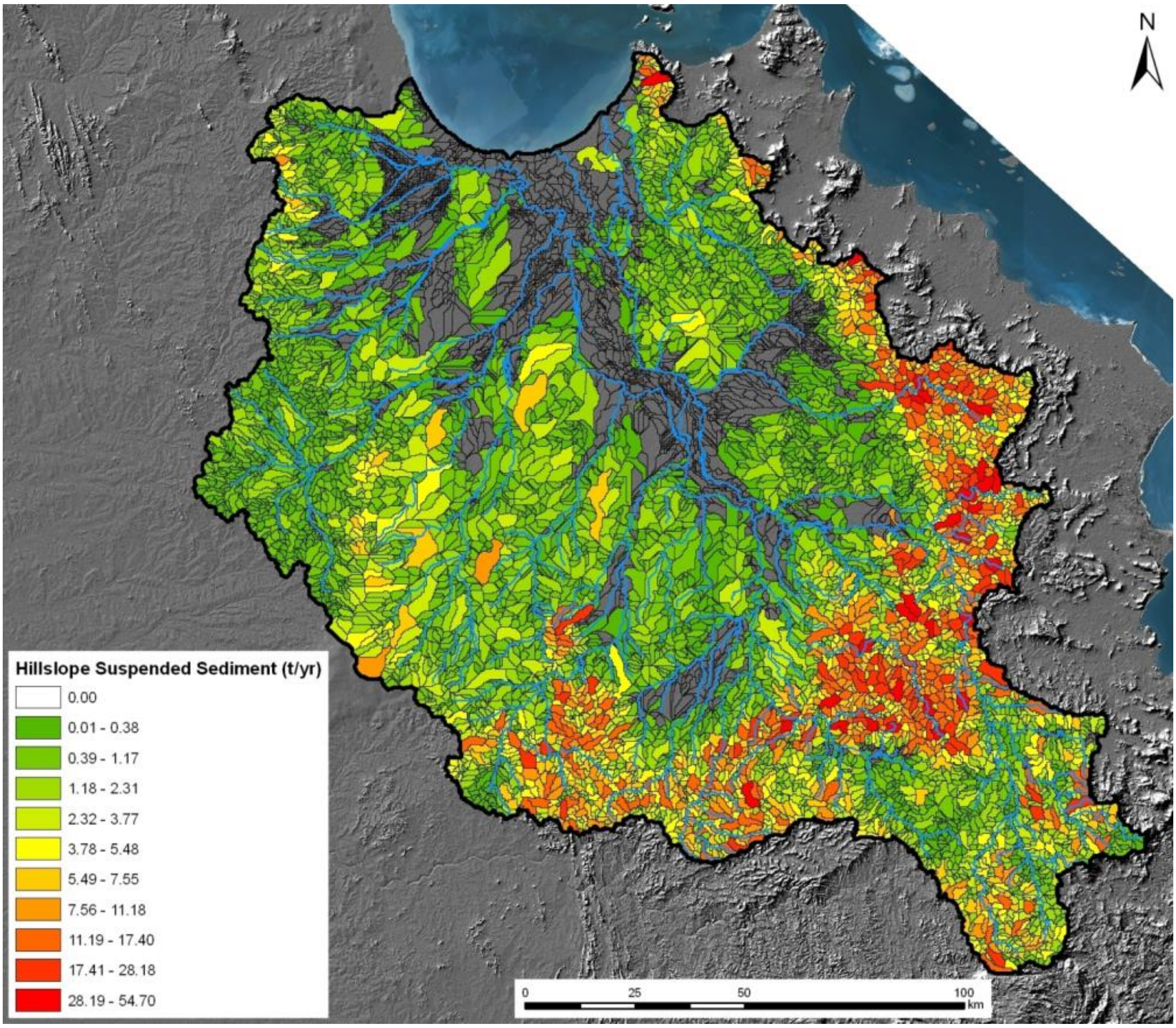


Figure 3: Normanby catchment suspended sediment hillslope erosion (i.e. delivered to the stream network) per sub-catchment area (i.e. not normalized for area).

2.4.1 Supporting a higher value for Hillslope Sediment Delivery Ratio

An important implication of this finding is that, where previous models have assumed there is a relatively low Hillslope Sediment Delivery Ratio (HSDR) in savannah landscapes (10% or less), our data would suggest that hillslopes are more highly connected to the stream network, albeit to varying degrees depending on source area geology. More specifically, the HSDR is a function of the proportion of <63um sediment in the surficial soils, as well as the degree of aggregation and disaggregation during transport, and we believe that this metric provides a more realistic means of quantifying the true HSDR (Figure 4), something which to date has been a major concern amongst modelers undertaking these sorts of analyses. Mitigating against this however, is that the ratio of coarse to fine sediment will vary with cover factor, in that the greater the cover the less likely that the coarser fraction will be delivered from the slope.

An implication of having higher HSDRs than assumed in previous SedNet modelling is that disturbed soils very efficiently find their way into the stream network. Such a finding highlights the importance of sediment derived from sources such as unsealed roads that tend to be even better connected to the drainage network than hillslopes.

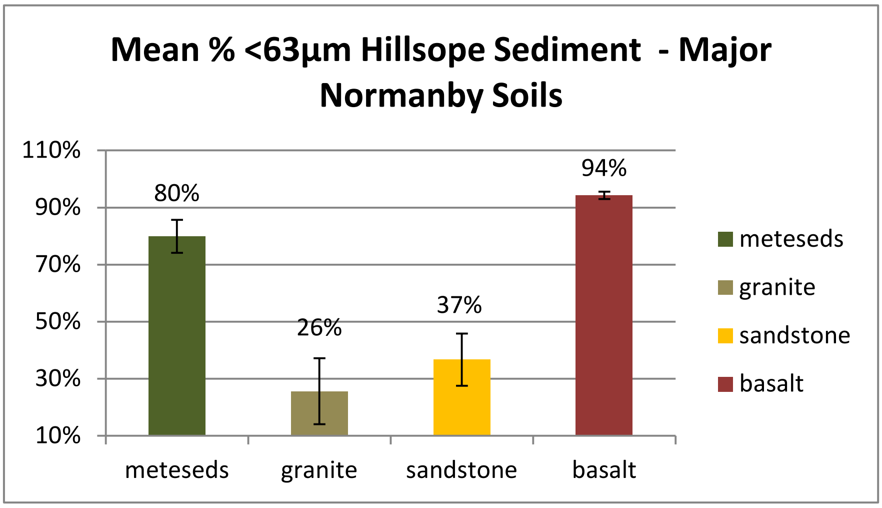


Figure 4: The percentage (%) of fines delivered from hillslope erosion on the four major geologic groups in the upper Normanby catchment. Note that the samples used to derive these data had been mechanically dispersed only.

Fine sediment losses through sediment trap geofabric . (Photo: John Spencer)

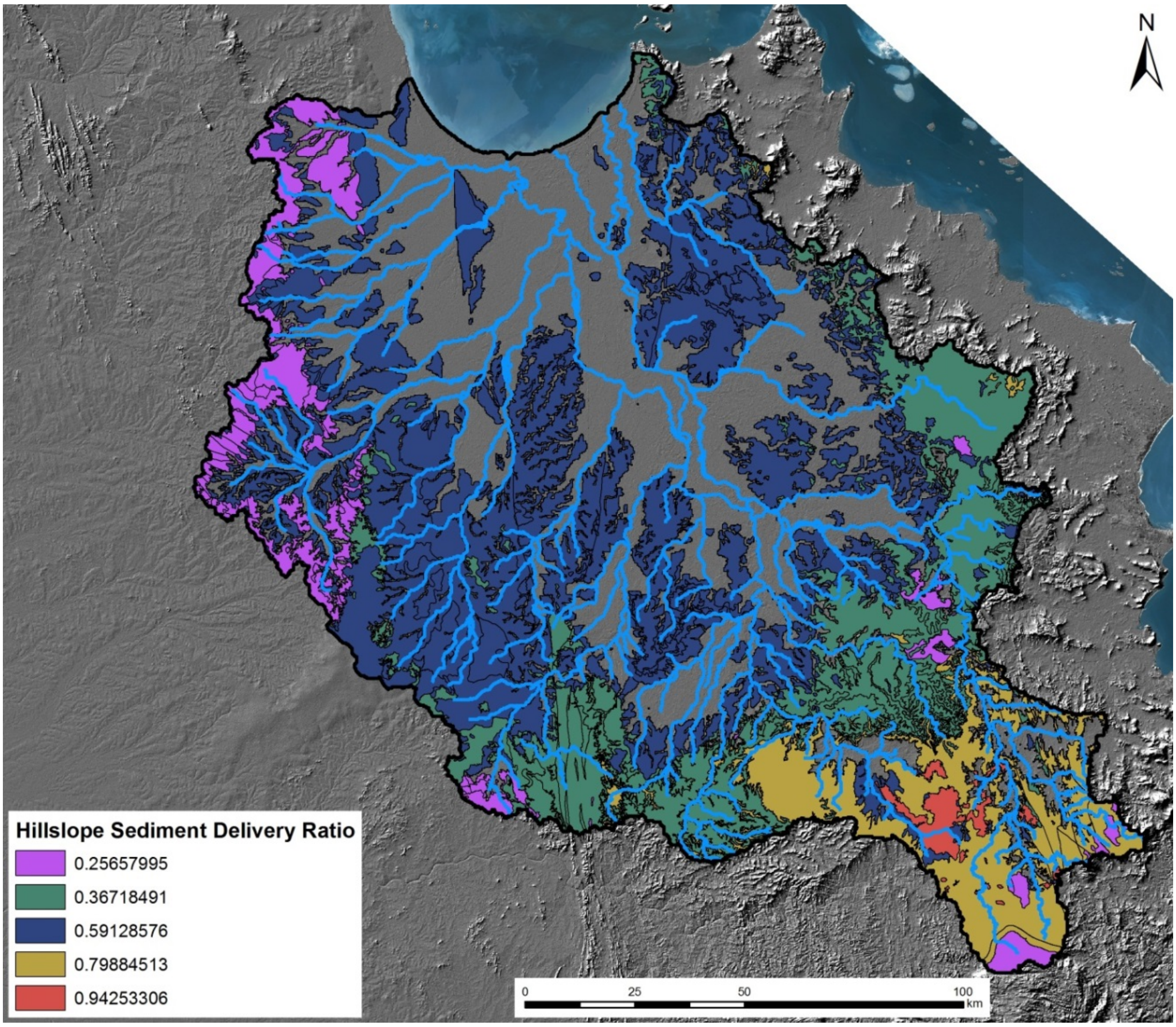


Figure 5: Hillslope Sediment Delivery Ratio, varying according to soil/geologic unit. The HSDR extrapolation is based on values in figure 4 and the catchment geology.

2.4.2 Why is RUSLE over-predicting hillslope erosion?

We believe there are several reasons why the RUSLE-based modelling is grossly over-predicting hillslope erosion rates.

a. Being an empirical model, it would seem that it is being applied beyond the range of conditions for which good empirical data exist in the Australian landscape.
b. RUSLE is a steady state model which does not account for such things as the exhaustion of sediment supply. So if C factor is reduced to negligible levels, sediment will be eroded at the predicted rate as long as there is rainfall to drive the process. This is almost certainly not the case in the very shallow stony soils that abound in the savannah. In the model formulations to date, the annualised erosivity value (R factor) is applied to an annualised C factor. While RUSLE is not a mechanistic model, the effect of this setup is that it assumes that all of the incident

rainfall will result in the same extent of sediment particle detachment and mobilisation irrespective of whether there is sediment available to be mobilised.

c. It seems likely that there are some fundamental problems with the common understanding of K factors for the soils found in these locations. They often have a high stone content, which forms a surface lag, and effectively acts as cover, but also reduces the soil erodibility.
d. Late dry season C Factor has been typically used as an annual proxy of C factor, as it is assumed that most of the soil erosion will occur during the early wet season storms, when grass cover is at a minimum. In reality though, more sustained, intense rainfall tends to occur well into the middle of the wet season, after the grass cover has had an opportunity to increase as a result of the early season storms and rain. Hence by the time the main part of the wet season sets in, grass cover may well have increased markedly. The late dry C factor may well underestimate true average cover (overestimate C) when it is applied across the whole season.
e. Cover factor as derived from Landsat data, is primarily measuring canopy cover with a mixed signature of the ground cover. In savannah landscapes the canopy cover has a minimal influence on C factor (generally < 2%), which instead is largely a function of the ground layer grass cover. So the extent to which the remotely-sensed C Factor is accurately representing "true" ground cover, potentially represents another source of error.

2.4.3 Catchment sediment tracing

As outlined above, previous studies identified surface soil erosion as supplying ~90% of the sediment to Princess Charlotte Bay. We used activity concentrations of the fallout radionuclides ^{137}Cs and $^{210}Pb_{ex}$ to test the hypothesis that surface soil erosion dominates the supply of sediment in the river systems draining into PCB. River sediment samples were collected using both time-integrated samplers and sediment drape deposits. A full outline of the method and results is given in Appendix 7. We show that there is no detectable difference in ^{137}Cs and $^{210}Pb_{ex}$ activity concentrations between samples collected using these two methods. Two methods were also used to collect samples to characterise ^{137}Cs and $^{210}Pb_{ex}$ concentrations in sediment derived from surface soil erosion; sampling of surface deposits after a major rain-events and surface runoff traps which collected samples during rain events. While there was no difference in the ^{137}Cs activity concentrations on samples collected using these two methods, $^{210}Pb_{ex}$ activity concentrations were significantly higher in the samples collected using the runoff traps. The higher $^{210}Pb_{ex}$ concentrations are shown to be correlated with loss-on-ignition (r^2=0.79) and therefore are likely related to higher organic concentrations in the runoff trap samples. As a result of these differences we use a three end member mixing model (channel/gully, hillslope surface lag, and hillslope runoff traps) to determine the relative contribution from surface soil erosion. Probability distributions for ^{137}Cs and $^{210}Pb_{ex}$ concentrations were determined for each of the end members these were then used to estimate the surface soil contribution to each of the river sediment samples collected.

The mean estimate of contribution of surface derived sediment for all of the river samples (n=70) is (16 ± 2%) (Figure 6). For samples collected along the main channel of the Normanby – Laura River system (n = 27) this is (13 ± 3%). When corrected for load, the catchment average surface contribution comes down to 12%, which is reasonable given that the channels contributing the greatest proportion of sediment to PCB have lower proportions of hillslope sediment contributions on average. Our results are consistent with the assertion that sub-surface sources, such as channel and gully erosion, are the dominant source of sediment. The hypothesis that surface soil erosion dominates the supply of sediment in the river systems draining into Princess Charlotte Bay is rejected. This study reinforces the importance of testing model predictions before they are used to target investment in remedial action and adds to the body of evidence that the primary source of sediment delivered to tropical river systems is derived from sub-soil erosion.

It is evident from these tracing data that there is some discrepancy between the estimates of the hillslope contributions at a catchment scale based on the RUSLE modelled loads using our modified, empirically derived K factors (~1% cf 12% wtd). This discrepancy can be partially explained by the limited number of HST data used to derive these K values, and the fact that we have used an average of all measured data for the soils that we did not have data on. Hence, it is possible that rather than being 1% of the total budget (as predicted by our RUSLE modelling), that hillslope derived sediments are somewhat higher (perhaps up to 10%). However, mitigating against the higher tracing derived estimate, is the fact that all sub-surface sediment sourced via the process of bank erosion or gully headwall erosion, will also include surface-labelled material that enters the water column when mass failure of banks and gully head walls occur. Hence, radionuclide tracing methods will always over-estimate hillslope sourced material in situations dominated by gully and bank erosion mass failure. Either way this does not change the overall thrust of the conclusions that the system is dominated by sub-surface sources, but it highlights that there is still some uncertainty regarding the relative contribution of hillslope sheetwash derived runoff (and all other sources) to PCB.

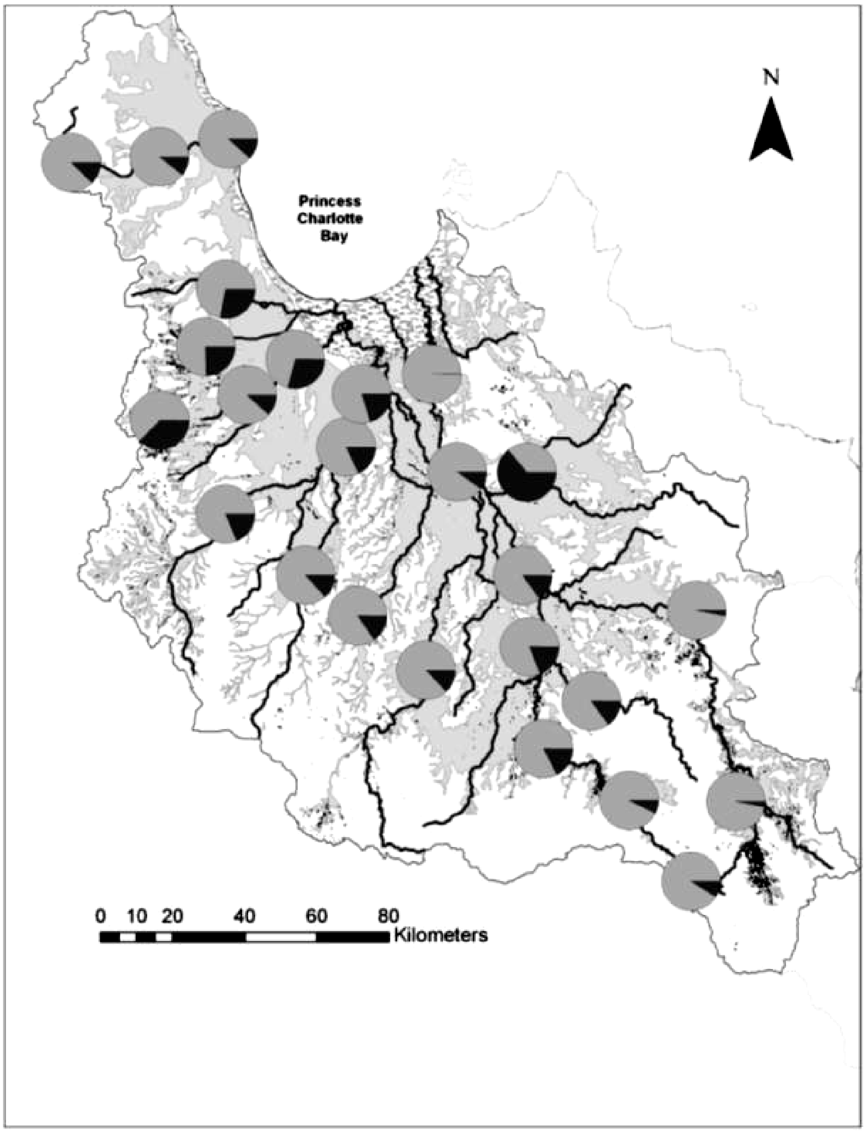


Figure 6: Pie charts showing the average channel (grey) and surface soil contributions (dark grey) to rivers draining into Princess Charlotte Bay. Note that the different samples are not adjusted for the relative sediment load at each site; they are simply the average ratio of sources at each site – irrespective of load.

2.4.4 Hillslope Sediment Traps (HST) measure hillslope yield and HSDR

As part of this project we developed a new low cost hillslope sediment trap (Figure 7) that has proven to be highly effective at measuring hillslope sediment production across a wet season. We believe that these traps could be used to test hillslope erosion rates on a far greater range of hillslope soils, particularly within remote Australian savannahs, than empirical datasets currently encompass. This would greatly improve our empirical understanding of hillslope soil erosion on rangeland slopes, which it would seem are likely to be overestimated in other savannah rangeland areas as well. A full evaluation of the HST is outlined in Appendix 5.

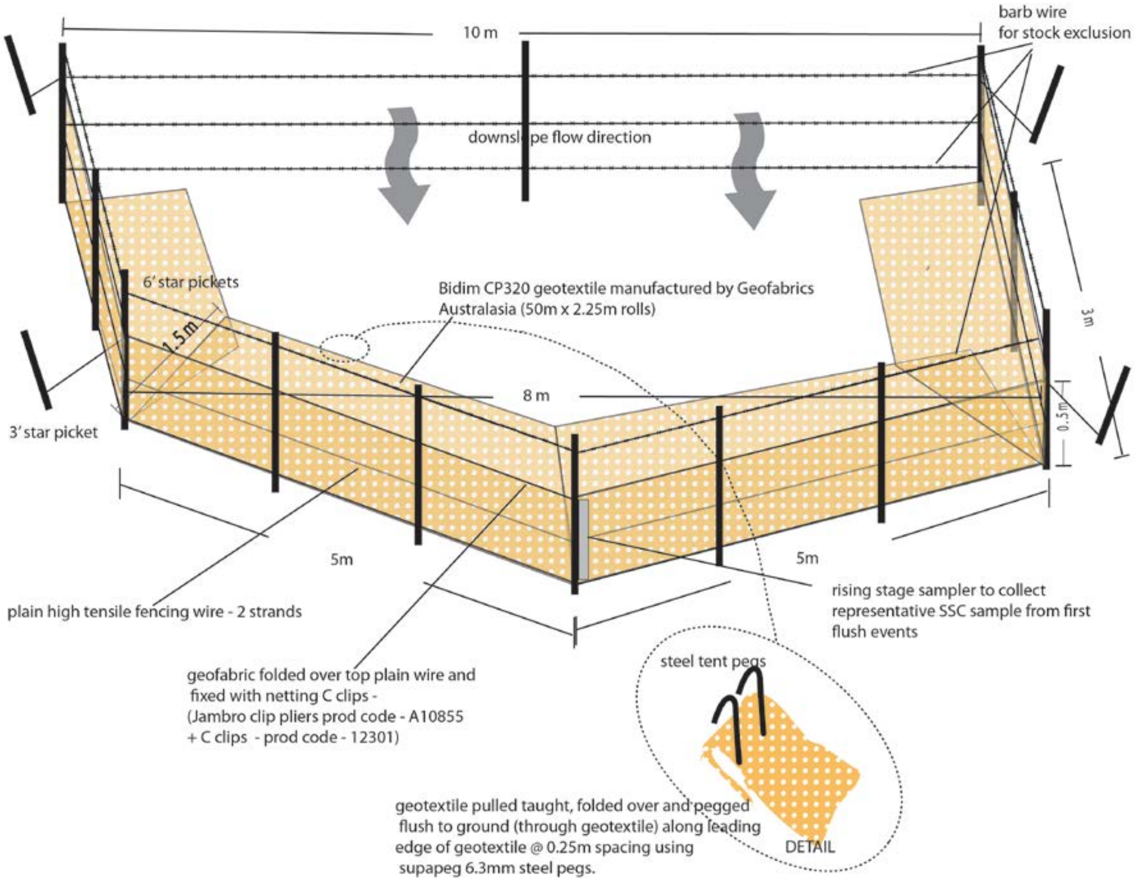


Figure 7: Design specifications for the bent wing variant of the hillslope sediment trap.

Collecting sediment deposition of 2009–2010 wet season sample from hillslope trap. (Photo: Andrew Brooks)

2.5 Bank and Gully Erosion

In the same way that we have used multiple lines of evidence to highlight the lack of contribution from hillslope erosion, we have also drawn on multiple lines of evidence to identify the significant sediment sources to the stream network. Based on a combination of extensive mapping of gullies from Spot & Quickbird imagery in Google Earth, mapping from LiDAR, airphoto interpretation, repeat LiDAR analysis and sediment tracing, the key contributing sub-surface sediment sources have been identified. The erosion processes that most contribute to sediment supply at the catchment outlet are completely dominated by sub-surface sources, principally, bank erosion and gully erosion. The catchment breakdown of key sediment sources is shown in Figure 8.

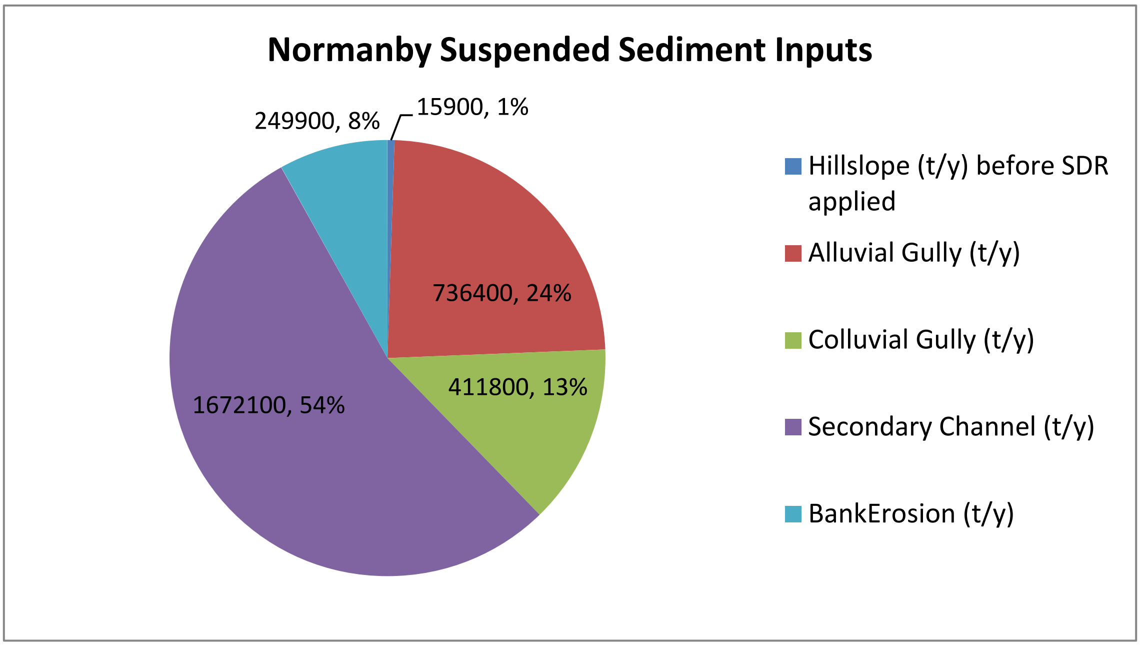


Figure 8: Relative Contributions of Suspended sediment to the Normanby stream network – based on the model output (note the previous discussion on the difference between the model derived hillslope source ratio and the tracing derived ratio). Note secondary channel erosion primarily represents bank erosion within small alluvial tributaries.

2.5.1 Secondary channel erosion

Secondary alluvial channels, here defined as minor tributary channels, most of which have a catchment area of less than 20km^2, have been shown from the repeat LiDAR data to represent the most active source of sediment within the catchment (Figure 9). Given that these channels are small channels that have a catchment area falling below the channel initiation threshold used in previous modelling studies, this source has not been considered in these previous formulations. In instances where observed sediment loads were used to “calibrate” the model, these sources would have been assigned to some other source – probably hillslope erosion. This may be an additional reason why previous model runs have over-estimated hillslope erosion.

The key characteristic of these channels is that, while not large, they are ubiquitous. They form thousands of km of channel length, with the channels often exhibiting some degree of erosion on a high percentage of their length. A full explanation of how the channel erosion rates were derived can be found in Appendix 3, Appendix 11, and Appendix 17.

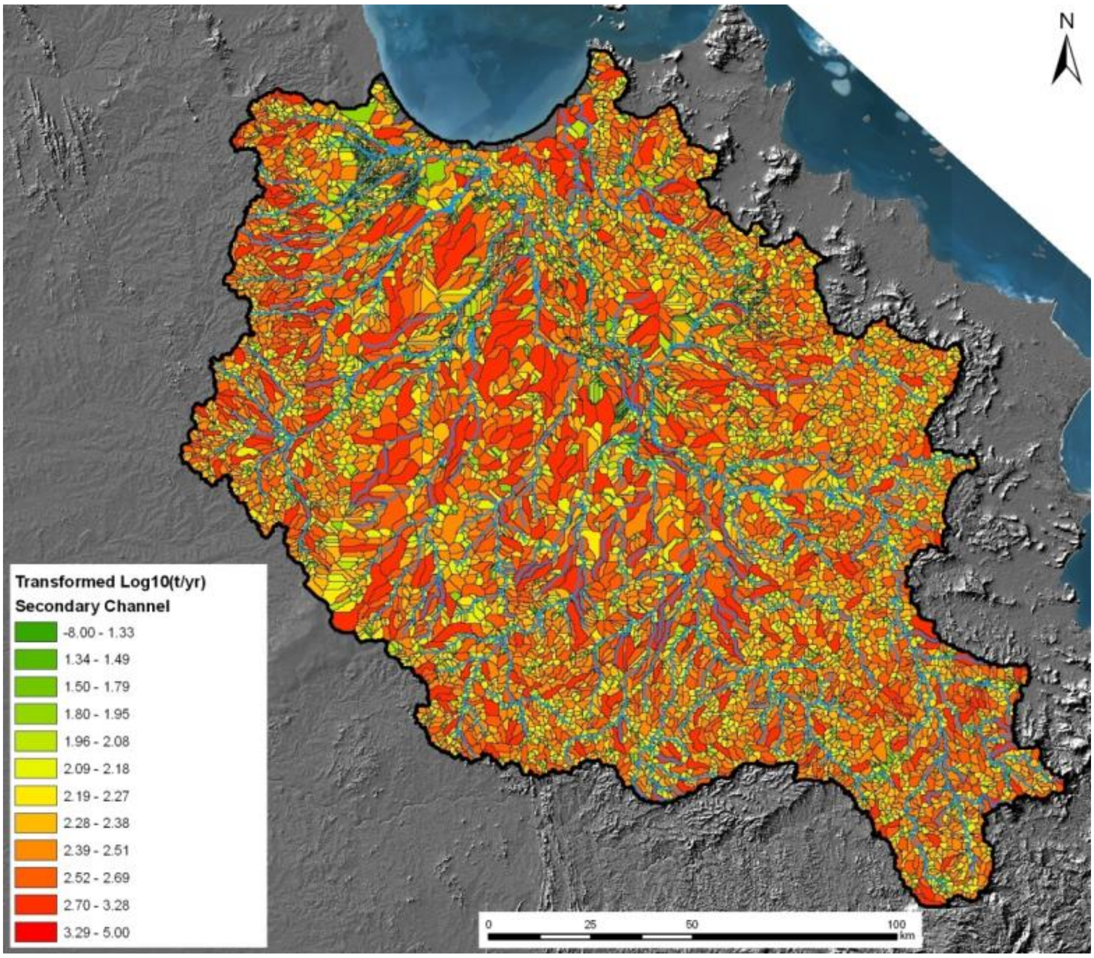


Figure 9: Distribution of inputs from minor/secondary channel erosion.

Figure 10: Examples of the secondary alluvial channels that are the dominant sediment source in the Normanby catchment. (Photos: Andrew Brooks)

2.5.2 Gully erosion

Gully erosion was classified into two components alluvial (Figure 11) and colluvial forms (Figure 12) (Brooks et al., 2009) based on whether they are located in floodplain alluvium or hillslope colluvium. The full explanation of how the gully erosion distribution and rates were derived is contained within Appendix 3, Appendix 4, and Appendix 17).

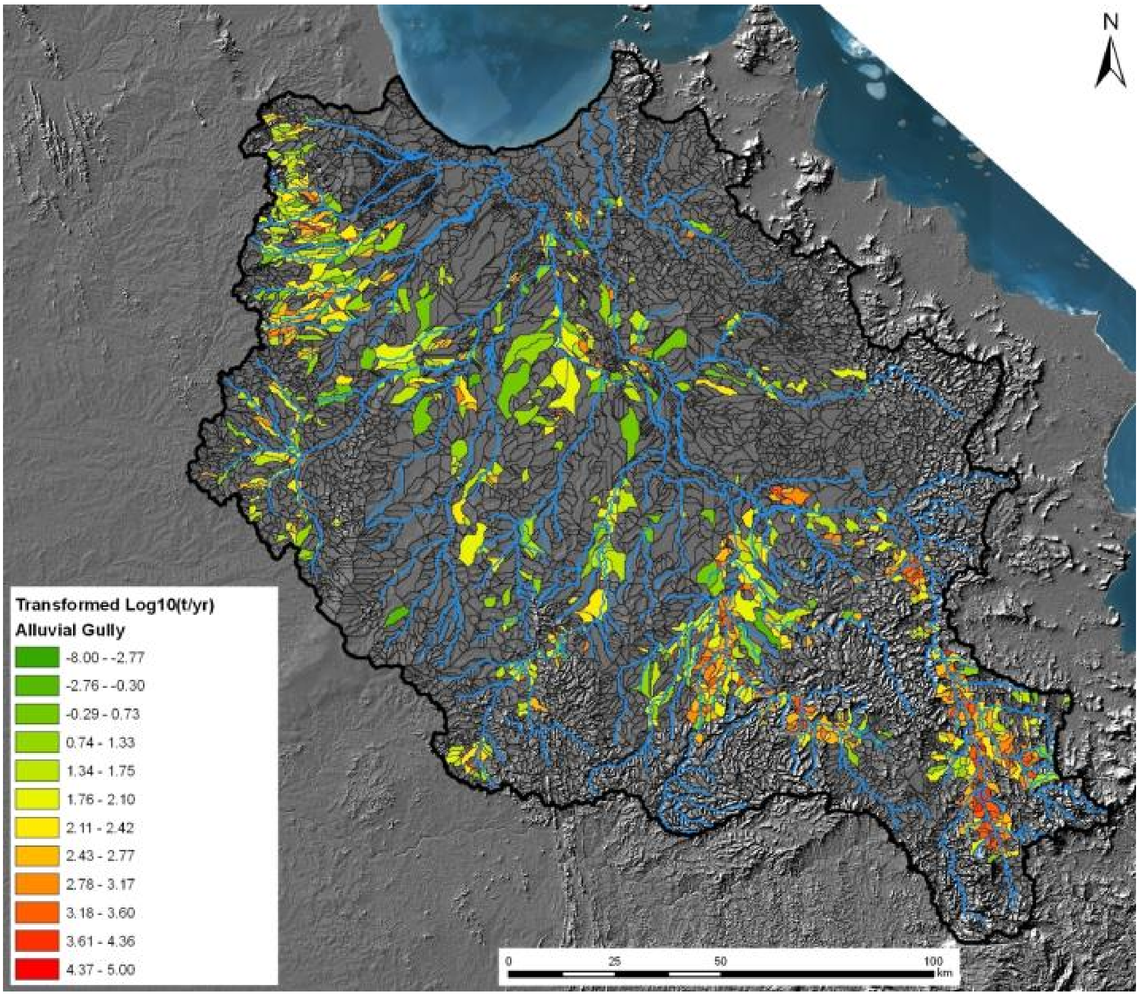


Figure 11: Alluvial gully erosion distribution within the Normanby catchment.

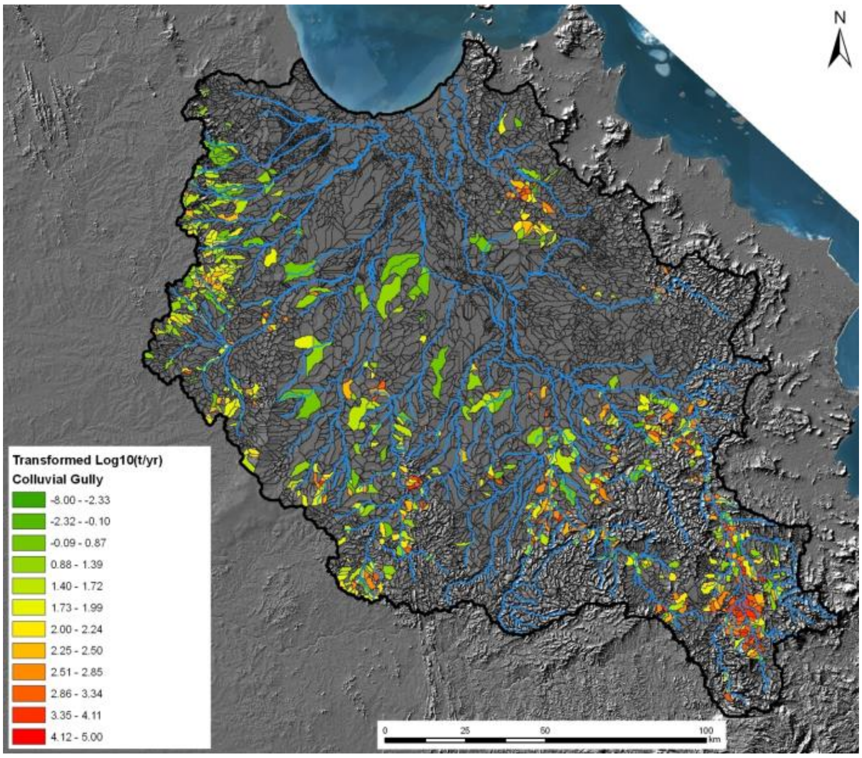


Figure 12: Colluvial gully distribution within the Normanby catchment.

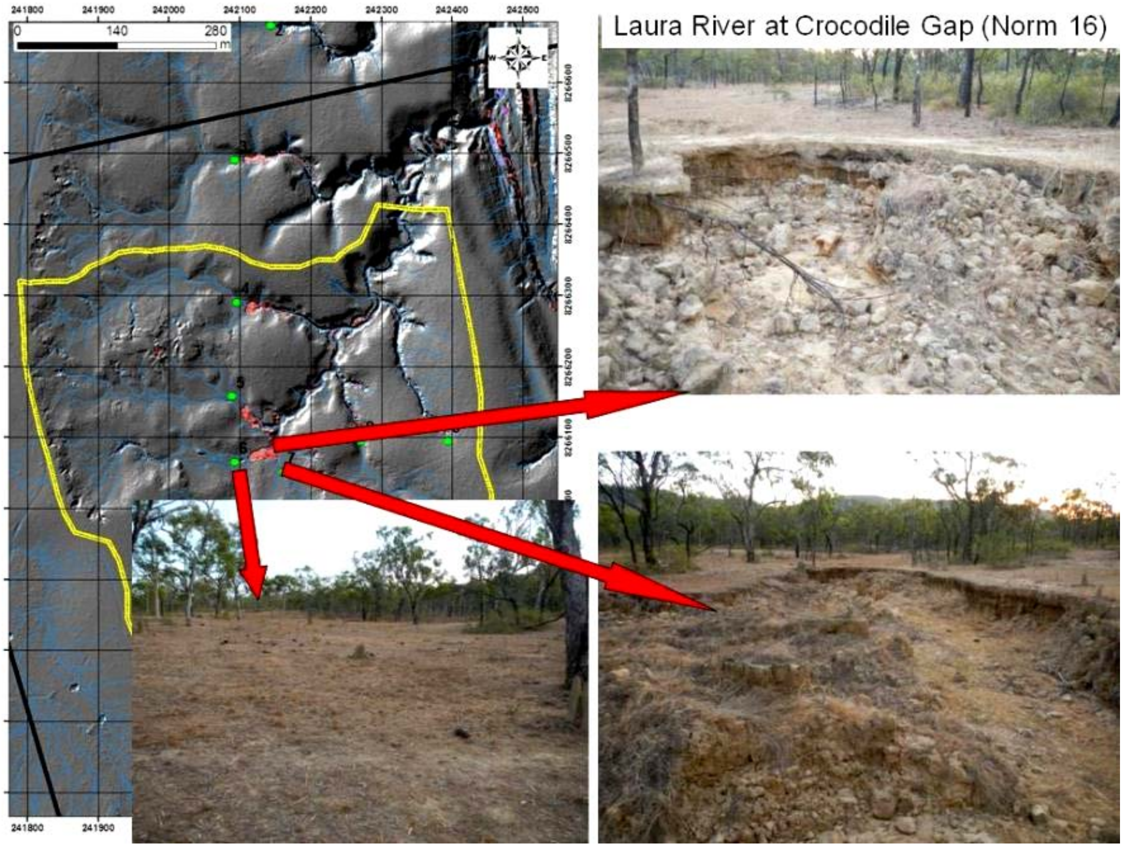


Figure 13: Examples of alluvial gully erosion along the Laura River, near Crocodile Gap showing the extent of change observed in the two year period June 2009 – August 2011 (indicated in red on the LiDAR hillshade). This particular gully has migrated ~40m in 2 years. (Photos: Jeff Shellberg)

2.5.3 Main channel bank erosion

At the time of writing, the contribution to the sediment budget from mainstem channel bank erosion is the most poorly constrained input to the sediment budget. Two approaches have been used within this part of the study to provide an upper and lower estimate of the loads from this source. The lower estimate is the method we have used in this model which is a variation of the standard SedNet calculate of bank erosion rates applied to a spatially distributed modelled bank height and depth. The modelled bank height and depth is based on channel cross sections extracted from the LiDAR data, see Appendix 17. It is our assessment based on considerable field experience, that very few of the main stem channels, particularly in the upper half of the catchment are showing signs of active bank erosion. This is in large part, we believe, due to the influence of the dense riparian vegetation, which often takes the form of gallery rainforest, stabilizing these channels and reducing bank shear stresses.

Developing an improved understanding of bank erosion processes is the subject of ongoing associated research in this, and other catchments, using the Bank Stability and Toe Erosion Modelling (BSTEM) approach developed by Andrew Simon and co-workers at the USDA National Sediment Laboratory in Oxford Mississippi. An overview of this approach, undertaken as a pilot study on the East Normanby River and a small tributary of the Laura River, is provided in Appendix 9. The data used in the catchment model provide a very low overall estimate of the contribution from main channel bank erosion (249Kt/yr) (not to be confused with the small alluvial tributary channels which are estimated to be contributing 1.67Mt/yr). The BSTEM method when applied to a ~105km section of river on the East Normanby, West Normanby and Laura River estimates that this small sub-set of the catchment is producing around 167Kt/yr. We believe this is a significant overestimate, but resolving this is the subject of ongoing work.

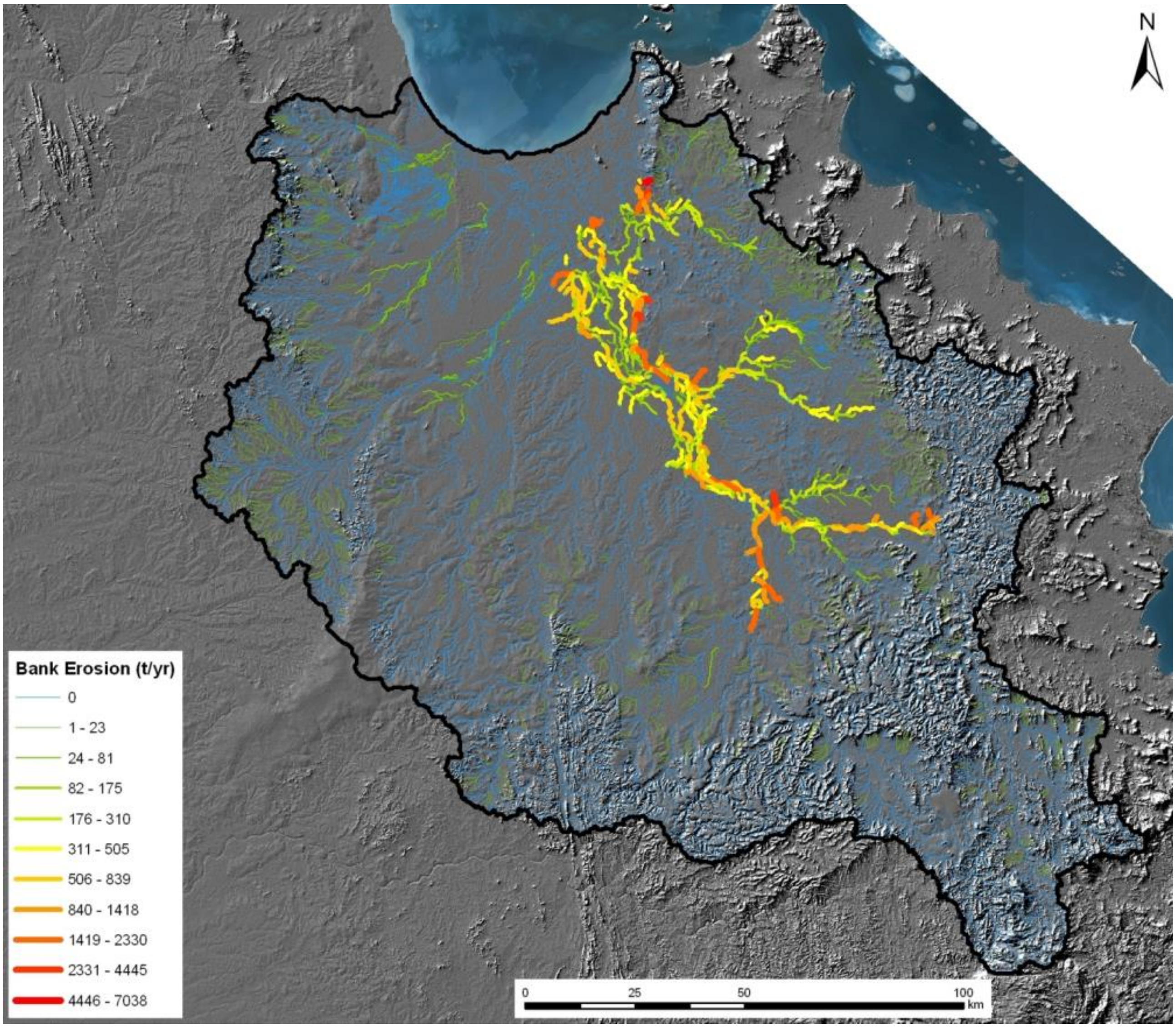


Figure 14: Distribution of mainstem channel bank erosion sources using a slightly modified version of the standard SedNet approach.

2.5.4 Main channel bank erosion rate has been derived, but is poorly constrained

Bank erosion rates were also derived from a geotechnical analysis of 4 sites in the basin, however this was a preliminary effort undertaken as a pilot for a subsequent, more detailed, analysis. These data, coupled with aerial videography of a 110km survey of the channel network in the upper reaches of the East and West Normanby Rivers, provide an independent check of the rates derived from the repeat LiDAR data. Main Channel bank erosion is estimated to contribute around 8% of the total load. However, this is the most poorly constrained source and is the subject of further research (i.e. QSFF Bank Erosion Project).

2.6 Sediment Sinks and Storage

Total sediment storage represents 54.9% of the suspended sediment input to the system. This is broken into two key components; floodplain storage and in-channel storage within benches and inset floodplains. Storage of fine sediment within the mainstem channel network has not been considered in previous sediment budget modelling exercises within the reef catchments. Clearly failure to include such a significant sink represents a significant source of model error, which could have a major influence on monitoring strategies employed to detect end of system sediment loads as a function of management strategies employed in the upper catchment that aim to reduce sediment inputs. These data highlight the fact that there are potentially huge temporal lags between sediment source inputs and catchment outputs within these catchments.

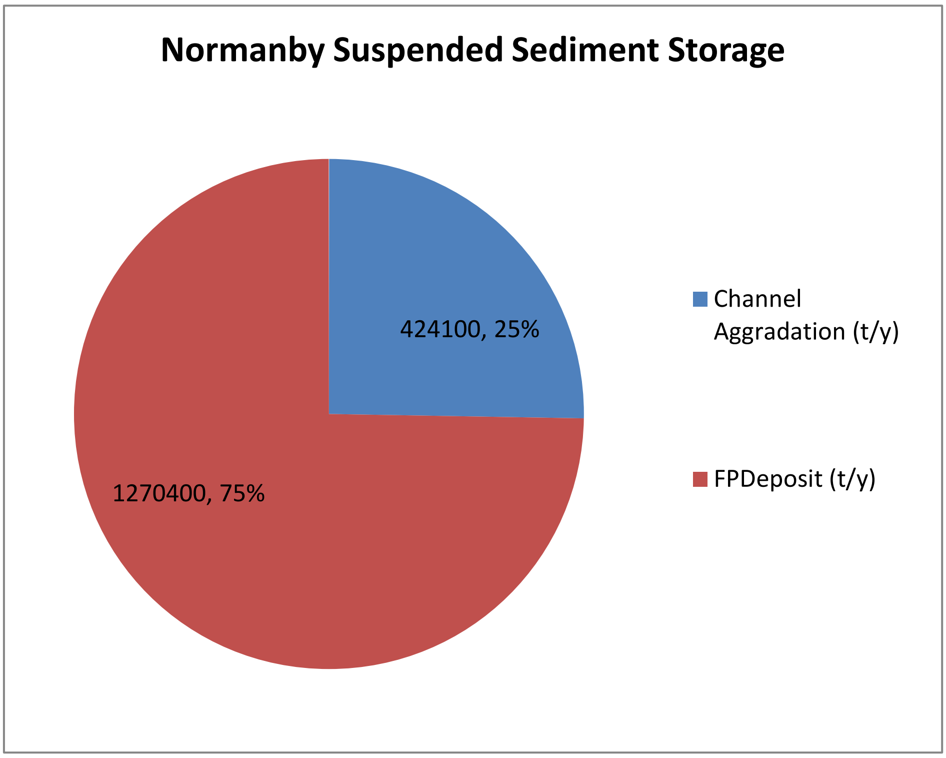


Figure 15: Key sediment sinks within the Normanby Basin. The residence time of sediment in each zone obviously differs considerably for each of these sinks/storages (from decades to centuries in benches, and centuries to millennia in floodplains).

2.6.1 Floodplain deposition

Floodplain deposition represents the major sediment store within the Normanby catchment, given the significant extent of very low relief floodplain and extensive wetland systems. Floodplain deposition rates were determined using optical dating and stratigraphy at a five sites on the lowland floodplain and the modelled deposition rates from overbank flow adjusted accordingly. In total we have estimated that floodplain deposition accounts for around 75% of within catchment storage (1.27 Mt/yr).

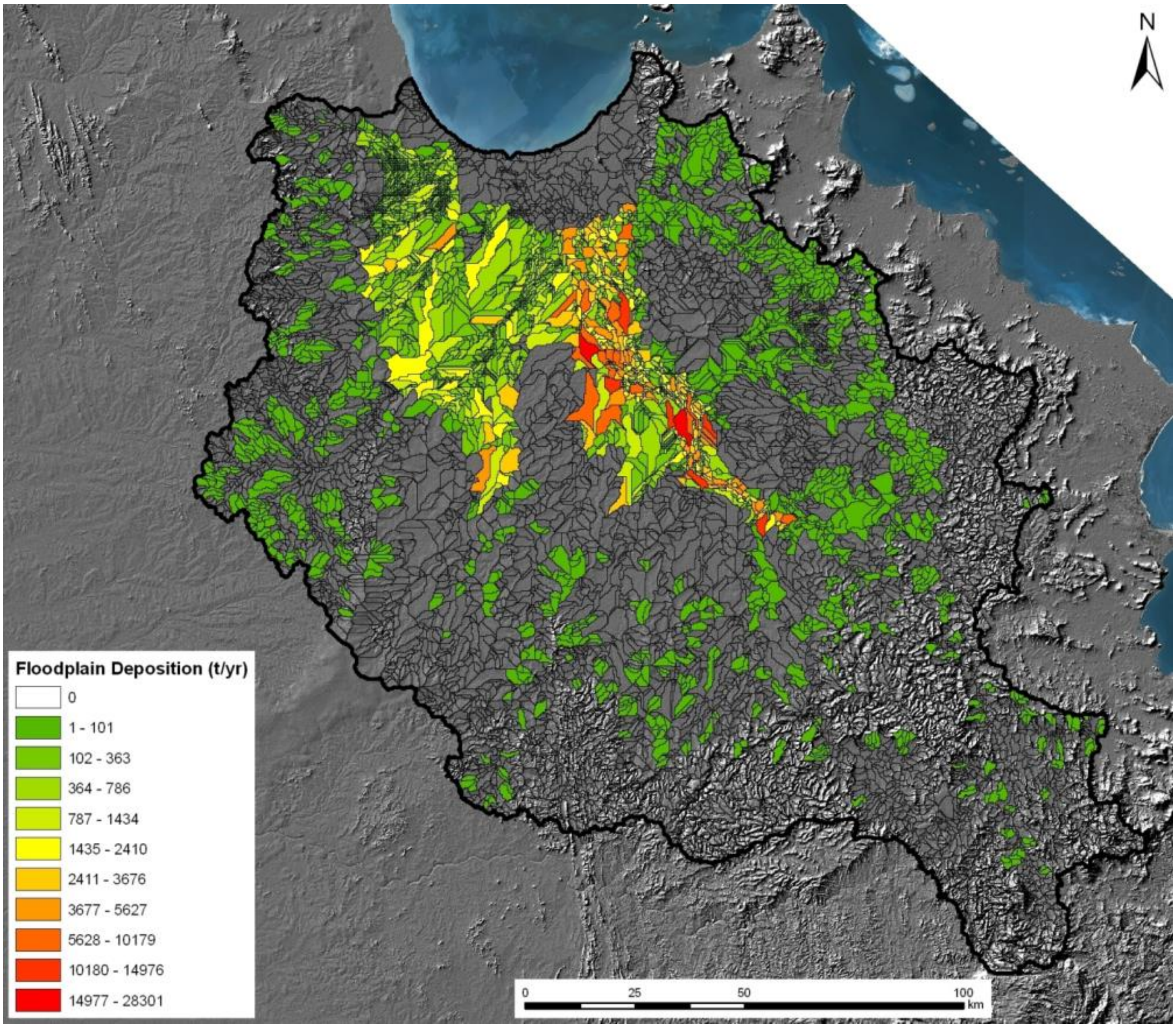


Figure 16: Floodplain deposition within the Normanby Basin. A detailed explanation of how the floodplain aggradation rates were derived is shown in Appendix 15 and Appendix 17.

2.6.2 In-channel deposition

A key new finding from this project is that a significant proportion of the suspended sediment load is deposited within benches and inset floodplains that are located within the macro-channel of the major trunk streams throughout the catchment. This sediment is stored on timescales of 10s to 100s of years, and potentially longer. Given that many of the apparent "floodplain" features are in fact terrace deposits, into which the modern channel has incised, and which are no longer active depositional surfaces, the role of benches and inset floodplain features potentially becomes extremely important as a storage mechanism for any increased sediment loads. For a full description of the methods used to derive the bench and inset floodplain sediment storage estimates, refer to Appendix 10. The extent of benches was accurately determined (+/- 0.5m) within the LiDAR blocks, and the unit volumes of bench per km of channel interpolated between consecutive LiDAR blocks (Figure 18 and Figure 19). We have only measured bench area and volume within the mainstem channels and major tributaries, so the load estimates are considered to be conservative. Based on an empirical estimate of deposition rate with elevation of the surface above the channel thalweg, coupled with data on the particle size distribution of the bench deposits, we have estimated the total annual suspended sediment storage within benches and inset floodplains at 424,000 tonnes per annum. The distribution of the sediment storage in benches is shown in Figure 17. Previous SedNet modelling did not account for this type of storage, and hence the models are likely to be significantly underestimating within catchment storage, particularly in circumstances where the modern channel is disconnected from the high floodplain/terrace.

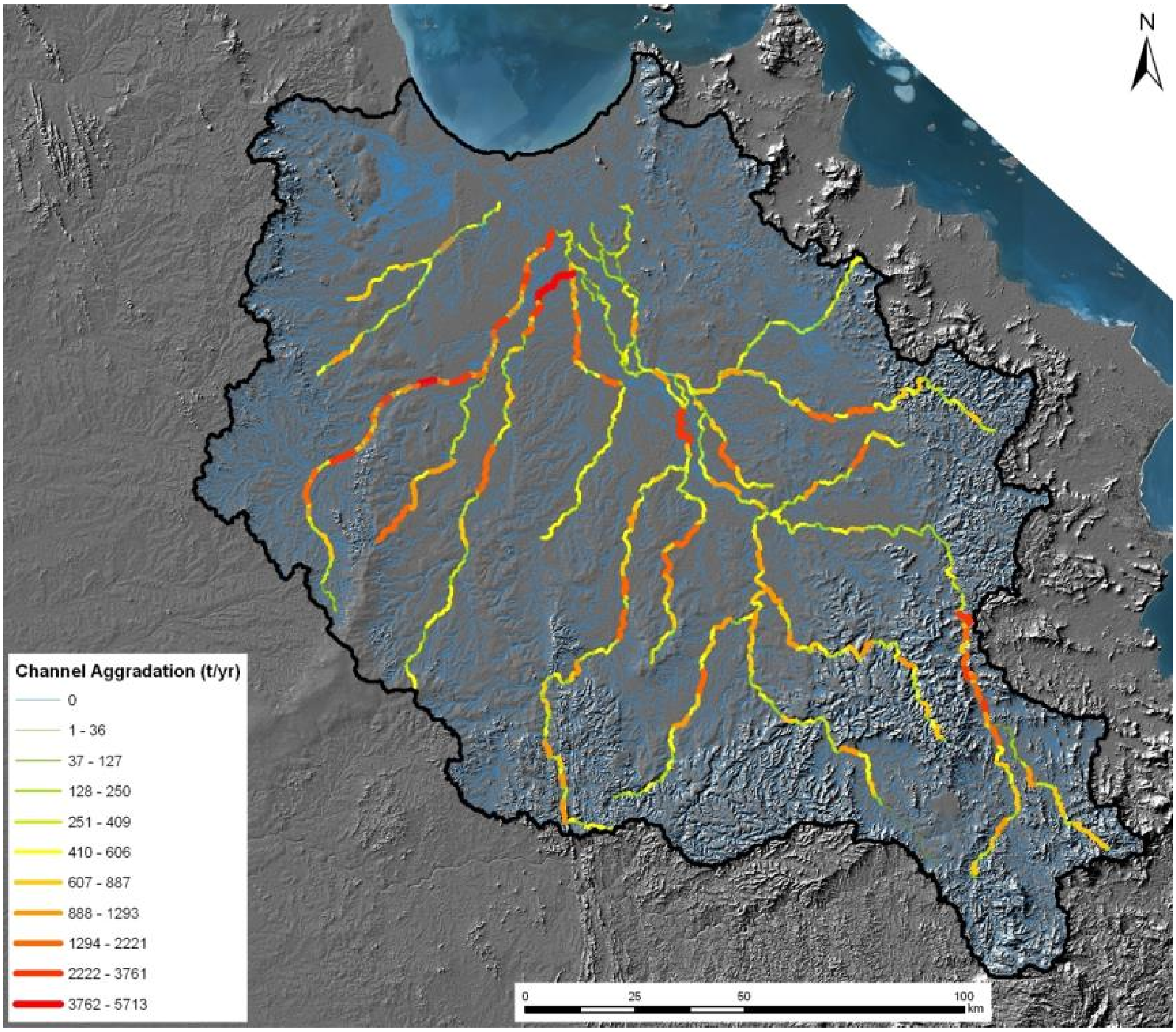


Figure 17: In-channel fine sediment storage within the mainstem channel network.

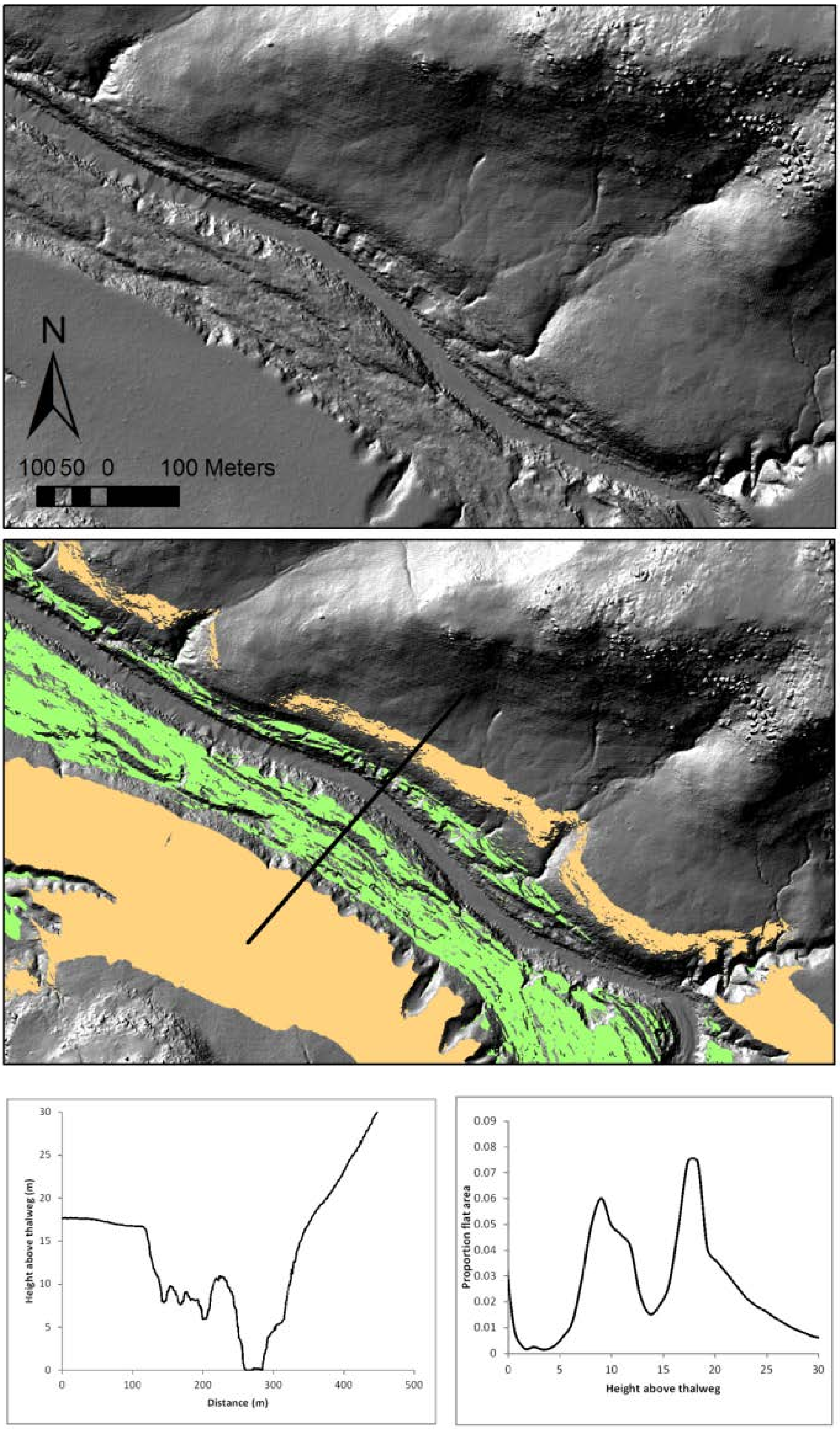
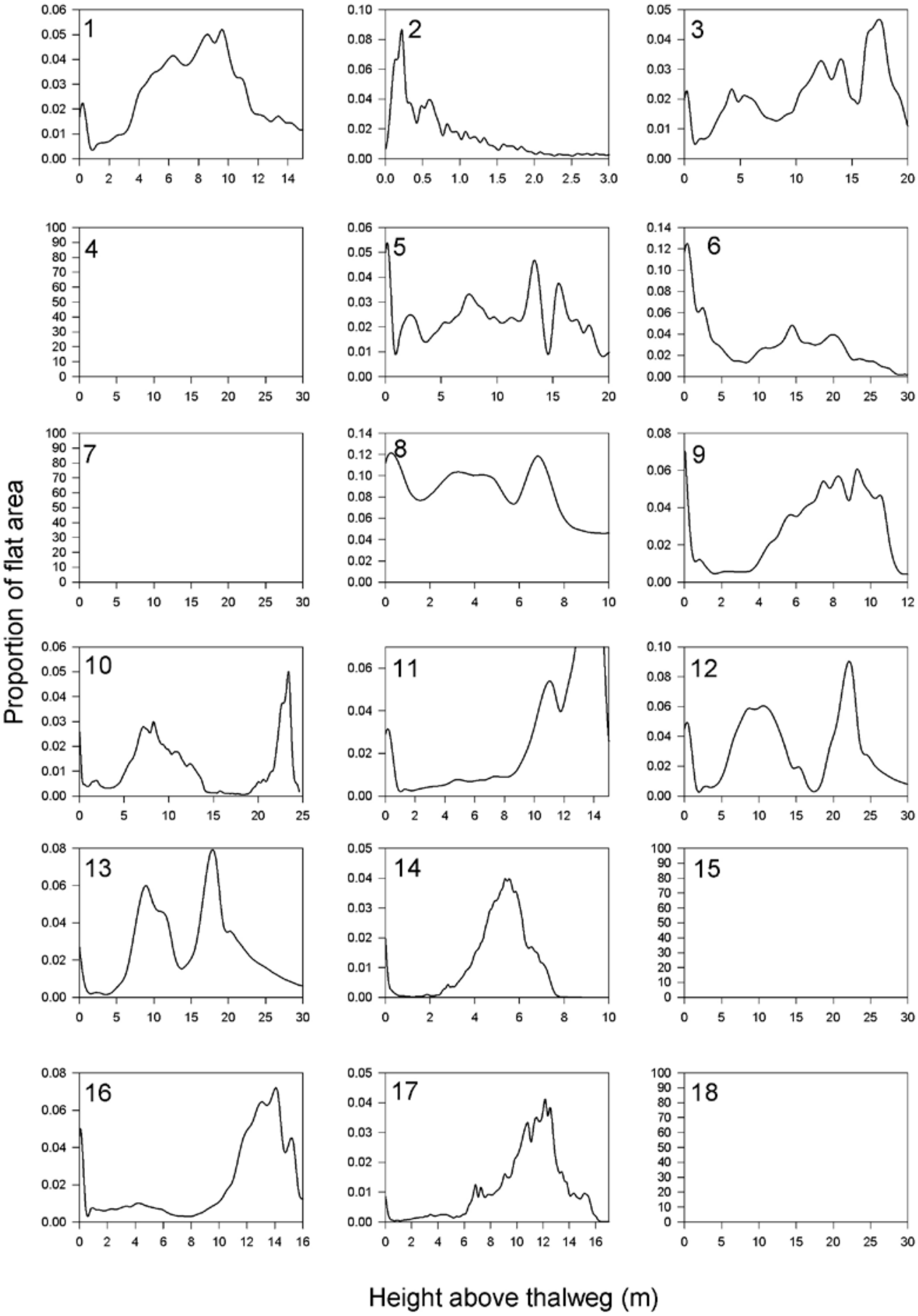


Figure 18: Example of the method used for delineating in-channel benches using a frequency distribution of flat surfaces identified within the channel cross section. The image shows how the "floodplain" (yellow) and the inset benches (green) have been defined.


Proportion of flat area
Height above thalweg (m)
1
2
3
4
5
6
7
8
9
10
11
12
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15
16
17
18

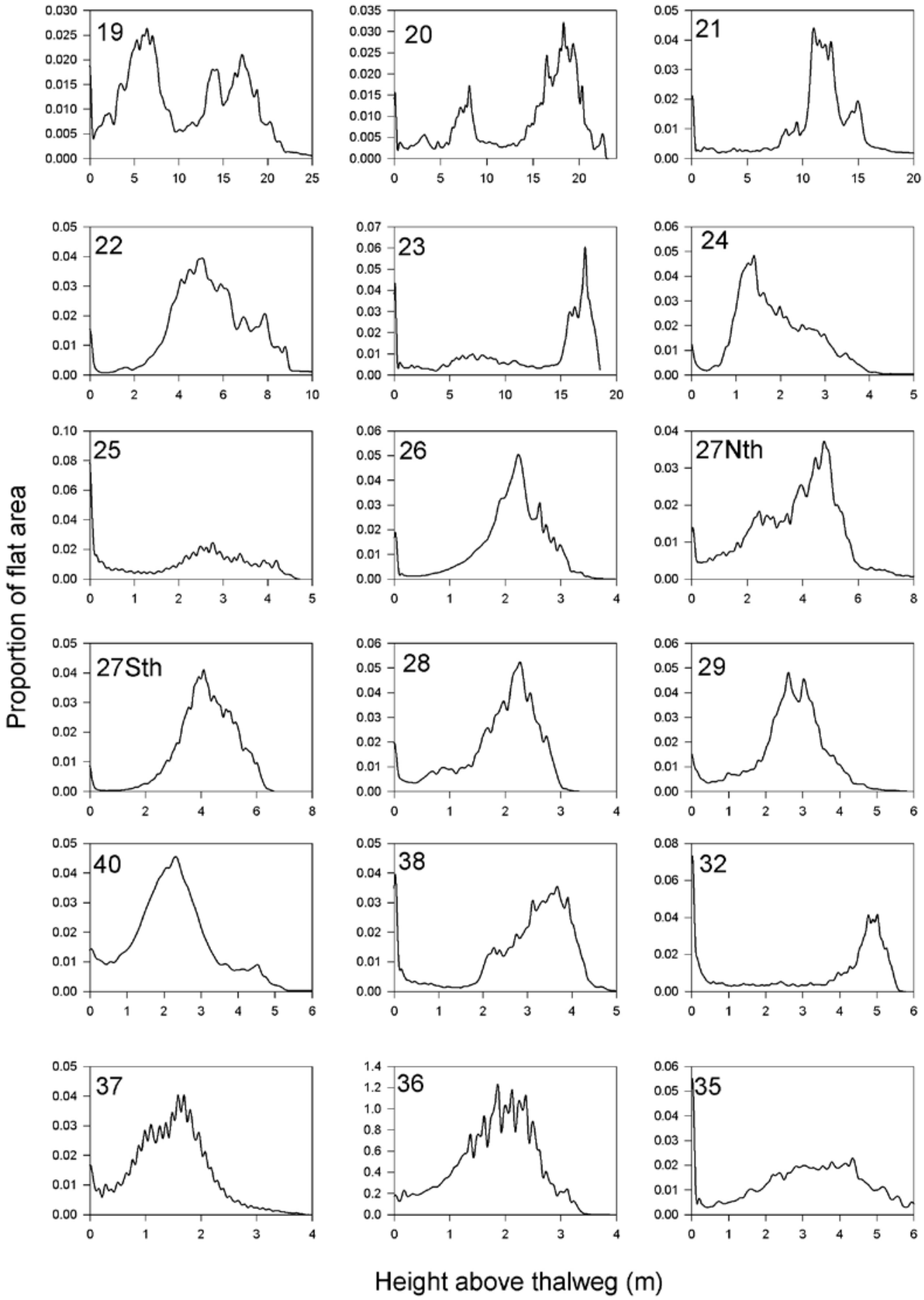

Figure 19: Bench frequency distributions were derived for each of the 45 LiDAR blocks within the Normanby catchment. These data were then used to interpolate between consecutive blocks (where no LiDAR existed).

2.7 Model Predictions of Sediment Delivery to Princess Charlotte Bay

The net model output is shown in Figure 20 and highlights how the high loads within the mid-catchment channels decline downstream with increasing fine sediment deposition on floodplains and benches. It must be stressed that this model represents the net sediment supply from the basin's sources and sinks, but excludes processes occurring within the coastal plain and delta. As outlined below there is a substantial additional contribution from this area. In total, the mean annual contribution to PCB from the catchment derived sediments is 1.39Mt/yr, which is similar to the estimate from Brodie et al., (2003), albeit from entirely different sources. These results highlight the fact that, for catchment management purposes, identifying the correct sediment sources is far more important than identifying the "apparently correct" load at the end of the system.

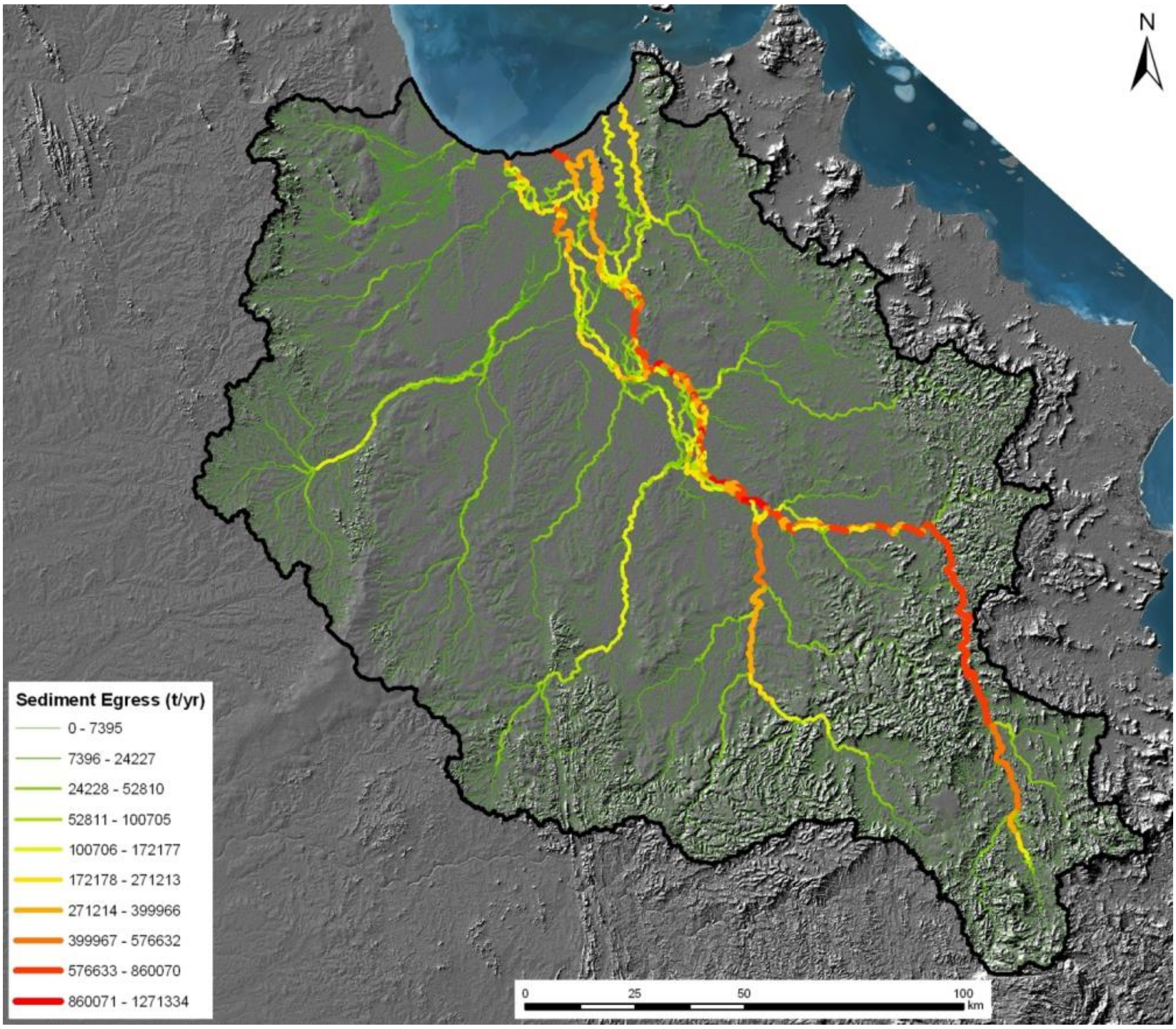

Figure 20: Overall sediment budget for the Normanby Basin. Sediment Egress represents the net sediment output from each stream segment, accounting for upstream inputs, new inputs to the segment and sediment storage.

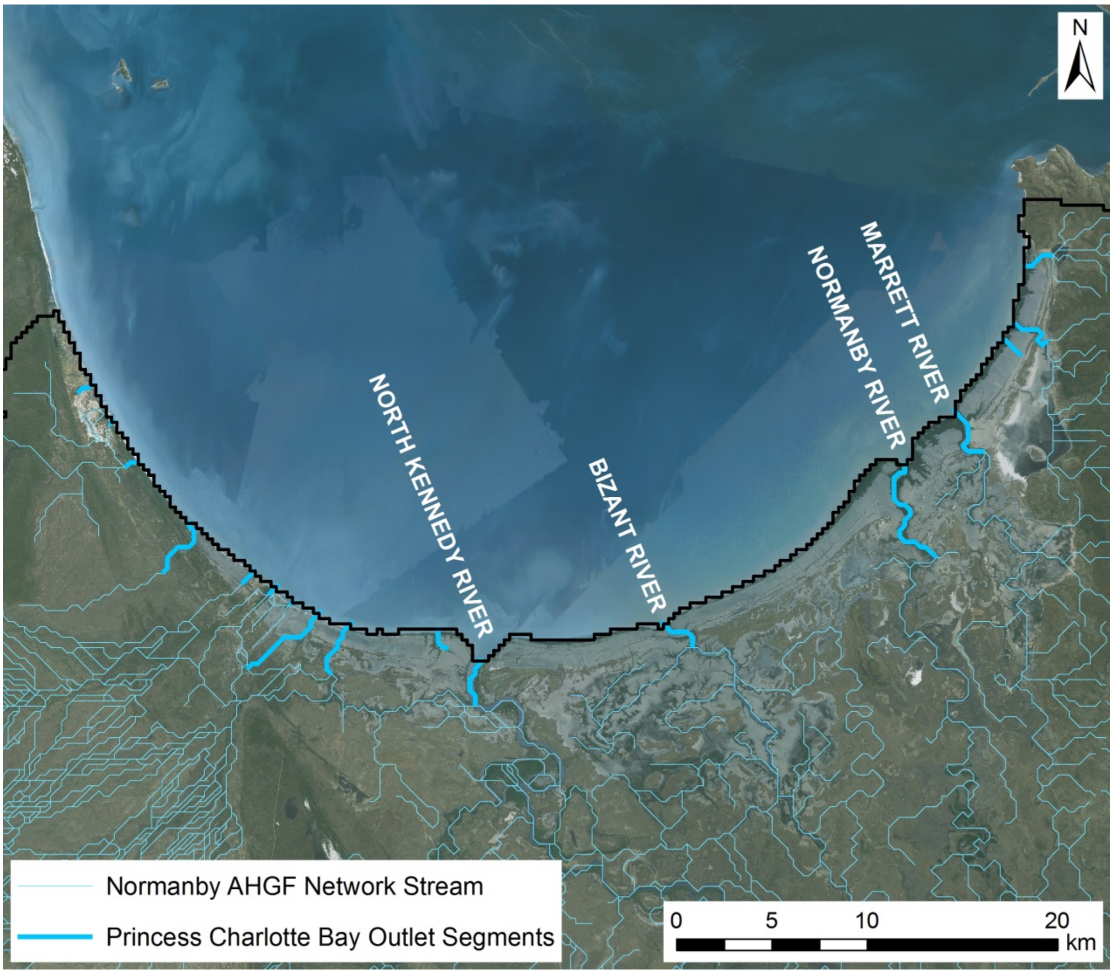

Figure 21: Map showing the four main outlets to PCB, the other 13 smaller outlets have been grouped as "other" for the purpose of comparison with the main outlets.

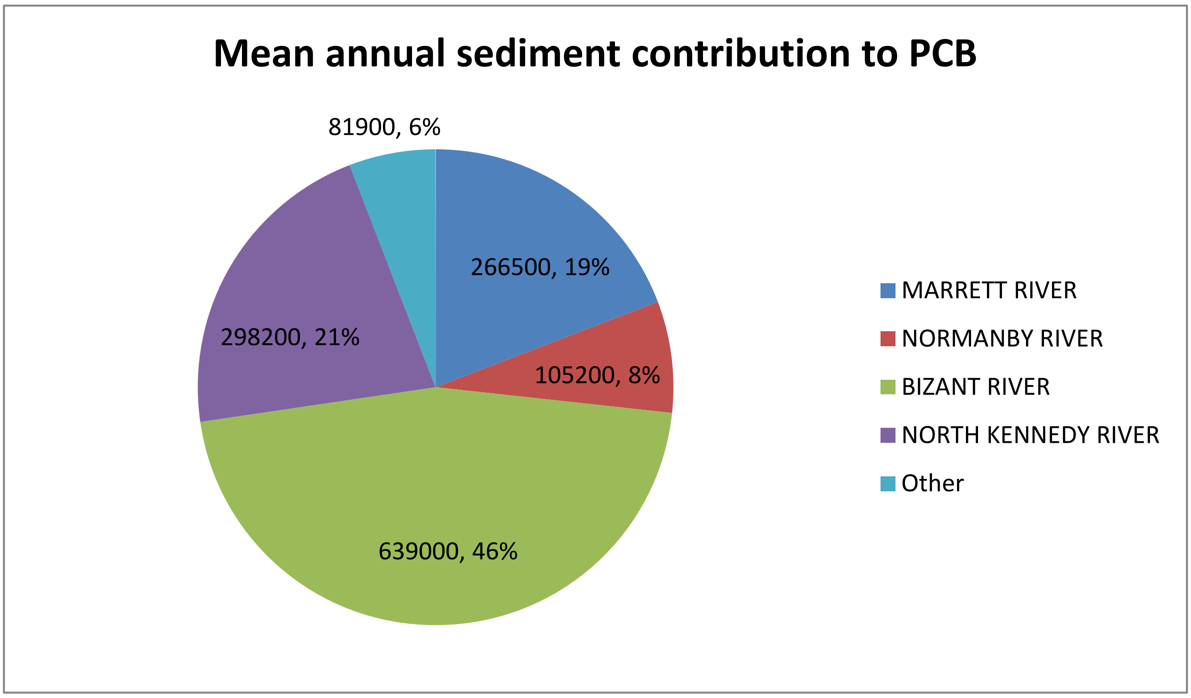

Figure 22: Breakdown of the relative contributions in each of the main channel outlets to PCB.

2.8 Model Comparison with Tracing Data

The following data provides some comparison between relative tributary contributions as predicted by our sediment budget model and the tracing data. We have opted not to attempt to calibrate the model to the tracing data or the gauge load data, as there are errors associated with each method: calibrating one approach to the other gives an illusion of precision. We acknowledge that there is considerable uncertainty surrounding each method, and we have opted to present each data set as independent data. Reducing the variance between the different approaches requires ongoing research.

Table 2-3: Tributary Contributions from In-stream Geochemistry (**model contribution in bold – t/yr**). Note that for the modelled loads we have not differentiated between the additional alluvial sources between the upstream and downstream sample points, so the alluvial component would be distributed between the two tributary inputs. This could explain some of the discrepancy between the model and tracing data. The underestimation of the Kennedy signal in the tracing data supports the notion that there is significant bypass of Kalpowar gauge.

Laura-Deighton		Laura-Normanby		Jack-Kennedy-Normanby	
Laura	0.90+/-0.02 (369,000) =0.88	Laura	0.54+/-0.03 (440,000) = (0.37)	Kennedy	0.01+/-0.01 (147,000) =0.1
Deighton	0.10+/-0.02 (51,500) = 0.12	Normanby	0.25 +/-0.03 (742,000) = (0.63)	Normanby	0.83 +/-0.02 (1,230,000) =0.83
		Alluvium	0.25 +/-0.03	Alluvium	0.10 +/-0.01
				Jack	0.07 +/-0.01 (101,000) = 0.07
Goodness of fit 73%		Goodness of fit 88%		Goodness of fit 94%	

2.9 Model Comparison with Observed Gauge Load Data

2.9.1 Gauge load estimates

A significant contribution to our empirical understanding of sediment loads at flow gauging stations has been made through this project with the development of sediment rating curves at a number of the other gauges within the catchment (see also Appendix 10). Previously the only empirical load data that was available for estimating sediment loads was from a single gauge at Kalpowar Crossing (stn.105107A) based on the TSS data collected by DERM/DNRM over the past 5-6 yrs. To augment these data we have developed a relationship between TSS and SSC and observed turbidity (Figure 23). Turbidity data has been collected as part of the standard monitoring regime undertaken by DNRM hydrographers over several decades, and a fairly extensive data set from CYMAG (Howley, 2010) plus some additional unpublished data collected since 2010. When coupled with SSC data collected with rising stage samplers as part of this project, this SSC/turbidity relationship enabled the reconstruction of sediment rating curves for an additional four gauging stations within the catchment (Figure 24, Figure 25).

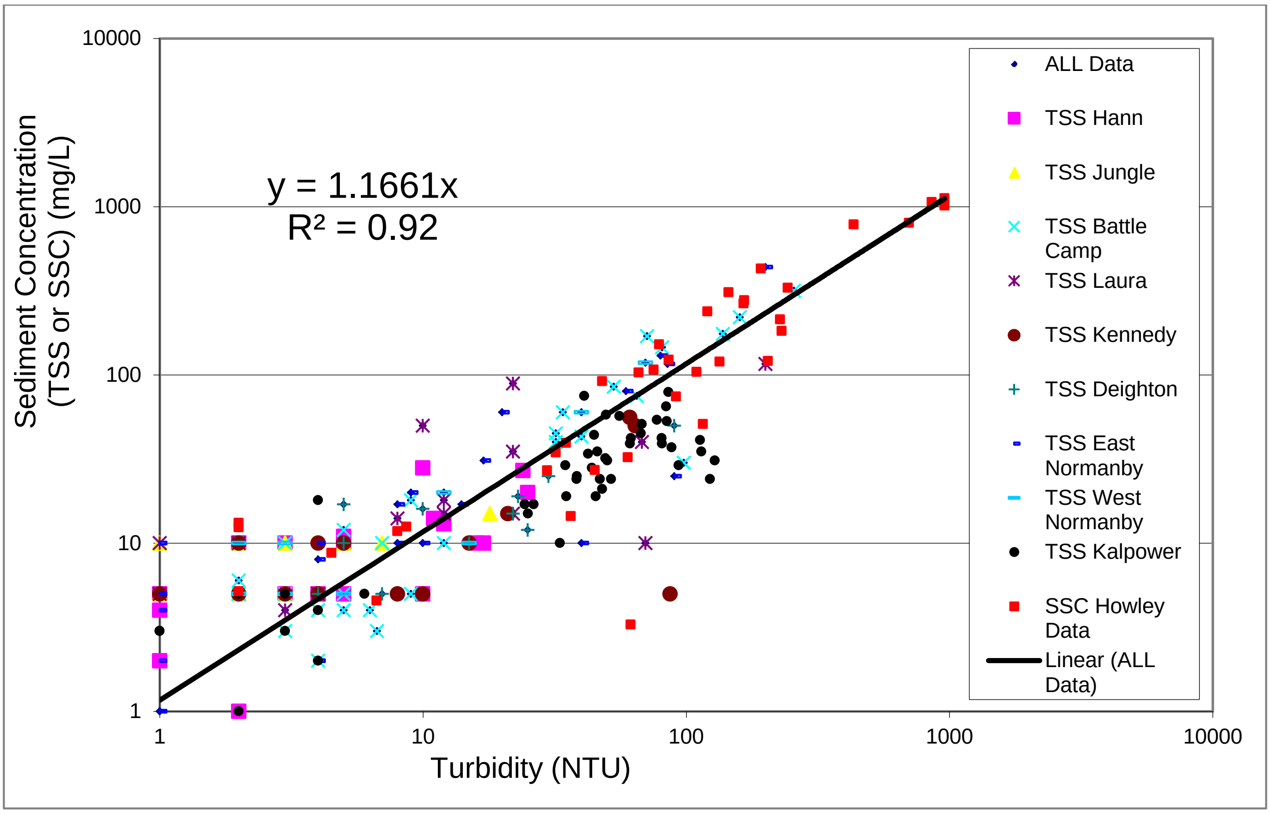

Figure 23: Catchment wide relationship between surface water turbidity (NTU) and either total suspended solid (TSS) or suspended sediment concentration (SSC) data from either DERM or Howley (2010).

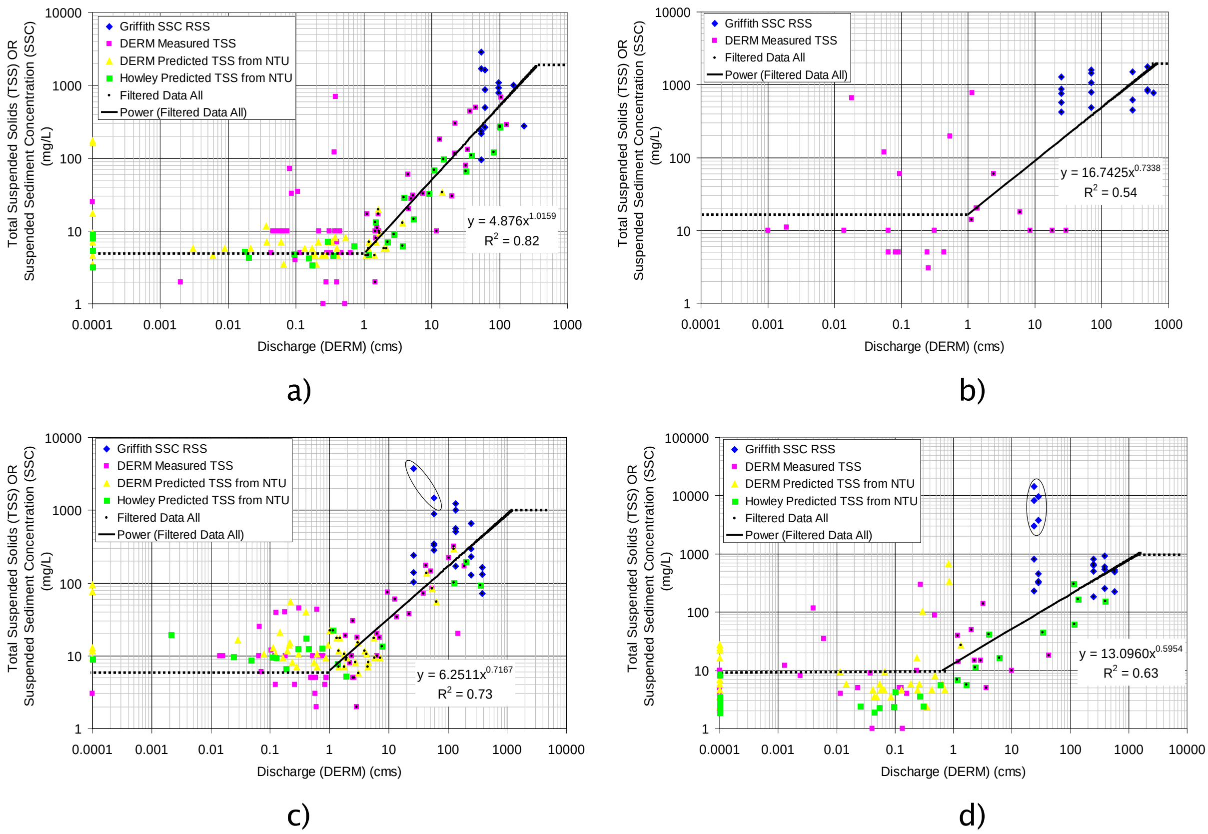

Figure 24: Suspended sediment rating curve for a) the East Normanby River gauge (105105A), b) West Normanby River gauge (105106A), c) Normanby River at Battle Camp gauge (105101A), and d) Laura River at Coalseam gauge (105102A). Note circled GU RSS data points have been excluded from the load calculations due to the fact that we cannot rule out contamination due to recirculation of the instruments during subsequent events.

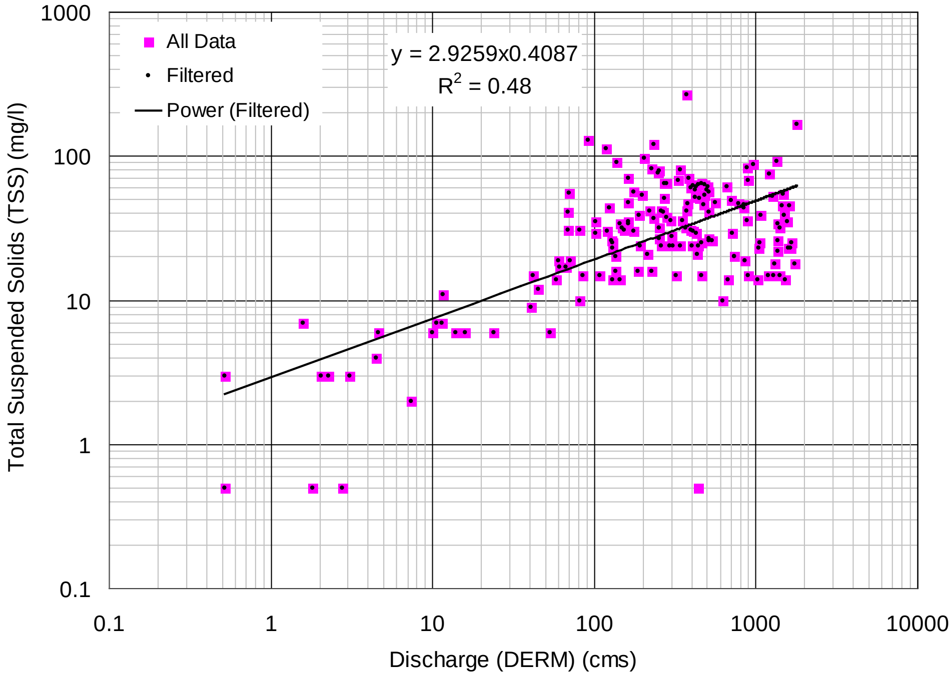

Figure 25: Suspended sediment rating curve for the Normanby River at Kalpowar gauge (105107A) using pooled TSS data from WY 2006 to 2011.

2.9.2 Empirical vs. modelled load estimates

The comparison between the modelled and measured loads at the five gauging stations is shown in Table 2-4. **No attempt has been made to adjust or calibrate the model to the gauge load estimates, as this would introduce unknown error while making the model appear more accurate.** It is our view that it is better to keep both datasets completely independent and continue to improve our understanding of the errors that account for the variance, rather than "tweak" the model to match the observed data.

From these data it can be seen that the East and West Normanby and the Laura River are all within a standard deviation of the modelled mean annual sediment discharge. Modelled loads at the Normanby River, Battle Camp gauge, appear to be an over estimate, as do the loads at the Kalpowar gauge. There are good reasons to believe, however, that the observed loads at Kalpowar are a significant under-estimate of total load passing this point in the catchment.

2.9.3 Suspended sediment loss around or above Normanby at Kalpowar

The Kalpowar gauge (105107A) is located in the centre of the large Normanby River floodplain along the main channel of the Normanby River. This gauge is located downstream of several major distributaries, notably Two-Mile Creek located 1.5 km upstream of the gauge and Catfish Creek and associated distributary channels originating from the Kennedy River 20-25 km above the gauge (Figure 26). These distributary channels route water and sediment onto and through the floodplain and into the North Kennedy River, bypassing the Kalpowar gauge (Figure 26). The water and sediment discharged through these distributaries and across the floodplain are unmeasured. There are no gauges on the North Kennedy River near Kalpowar. Therefore, water and sediment measurement at Kalpowar are an absolute minimum estimate of discharges onward toward Princess Charlotte Bay.

Tracing data (Table 2-3) shows that the contribution from the Kennedy River is barely detectable at the Kalpowar gauge, which supports the hypothesis that a significant volume of water is bypassing the gauge.

Locally, the Kalpowar gauge only estimates water and sediment discharge within the bankfull channel at the gauge site. Once water reaches initial flood levels and eventually the height of the banks (bankfull), water will begin flowing onto the floodplain and into local distributaries on both sides of the river (i.e., Two-Mile Creek; Figure 26) and further upstream. This overbank floodwater is not measured locally or upstream during standard water gauging procedures. In a preliminary analysis for the Normanby at Kalpowar gauge, Wallace et al., (2012) estimated that 43% of the mean annual water discharge is bypassed around the Kalpowar gauge during floods. This estimate was based on the duration of time that floodwaters were above minor flood stages at the gauge site. This estimate does not necessarily include the water lost into distributaries or the floodplain many kilometres upstream (i.e., Catfish Creek; Figure 26), and is therefore likely to be a minimum estimate of bypass. Future analysis of the floodplain topography via LiDAR, along with floodplain hydraulics and water conveyance measurement and modelling, will be needed to assess the full potential for water and sediment bypassing the Kalpowar gauge.

In summary from an empirical viewpoint, the amount of water and suspended sediment actually being discharged into Princess Charlotte Bay from the Normanby catchment remains unknown due to insufficient measurement locations and gauging efforts in a complex floodplain environment. The Normanby at Kalpowar gauge only measures a fraction of this discharge.

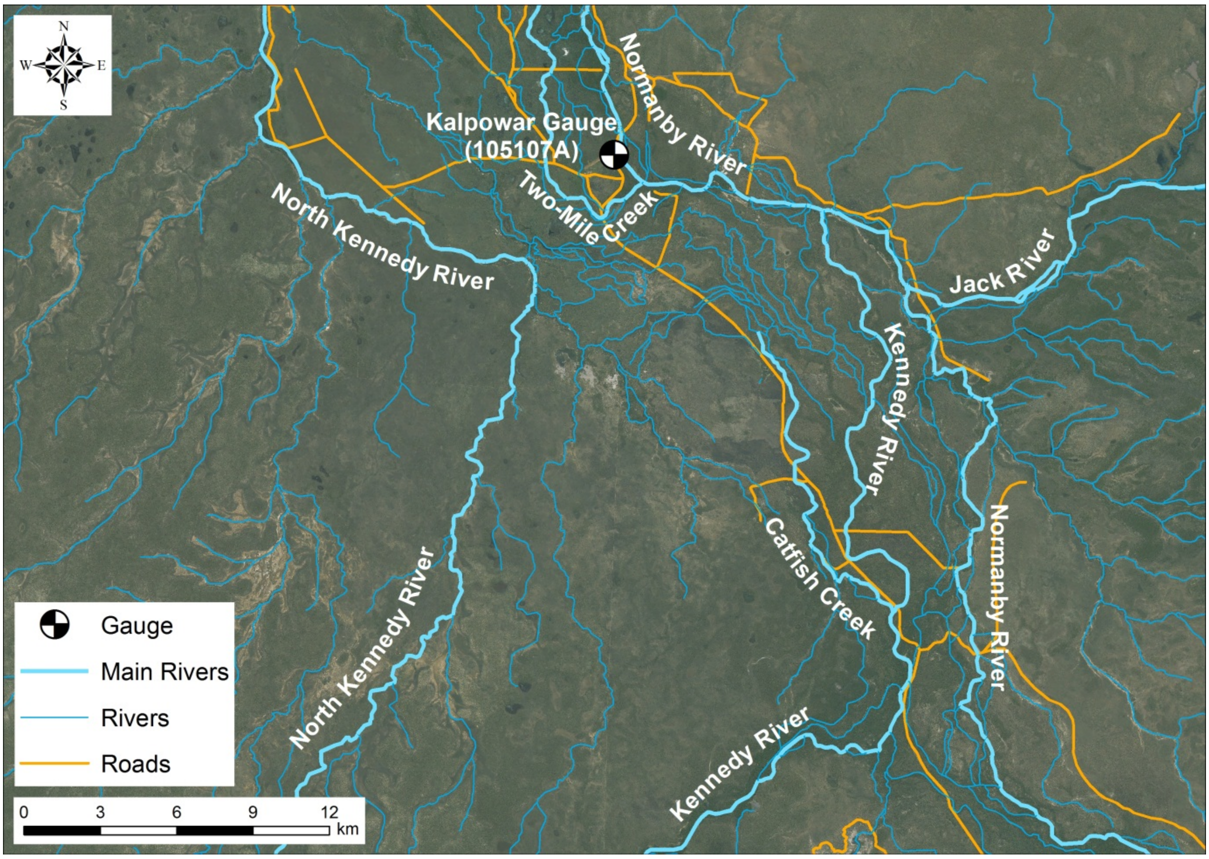

Figure 26: Map of main river channels and floodplain distributaries upstream of the Kalpowar gauge (105107A) indicating the potential flow paths of water and sediment bypassing the Kalpowar gauge. Note the orange lines indicate roads.

2.9.4 Multi-decadal empirical estimates of sediment loads

Irrespective of the discharge and sediment load bypass issues at Kalpowar gauge, the empirical load estimates derived from this study match the estimates from Joo et al., (2012) reasonably well (Table 2-5), and highlight the significant inter-annual variability of loads at the site. Longer term sediment load estimates, interpolated from the full flow records at the other four gauges highlight the profound inter-annual variability of flow and sediment discharge over multiple decades (Figure 27).

Also apparent from these data (Figure 27, Figure 28, and Table 2-4) is the downstream decline in specific sediment yield within increasing catchment area. A significant proportion of this decline is likely explained by floodplain and in-channel deposition, but gauge bypass would also explain a portion of it.

Table 2-4: Estimate annual suspended sediment loads at selected gauges in the Normanby.

River **Gauge Site #**	**Site**	**C'ment Area** (km^2)	**Total Record** Annual Suspended Sediment Load (tonnes)	**Total Record** Average Specific (LHS) **Common Record** (WY 2006-2012) (RHS) (t/yr/km^2)		**Common Record** (WY 2006-2012) Annual Suspended Sediment Load (tonnes)	**Model**
East Normanby 105105A	Mulligan Highway	297	**Ave: 65,732** Median: 46,545 StDev: 67,115	221.3	230.6	**Ave: 68,483** Median: 63,068 StDev: 51,788	**46,000**
West Normanby 105106A	Mulligan Highway	839	**Ave: 247,070** Median: 90,004 StDev: 314,478	294.5	N/A	N/A	**468,000**
Normanby 105101A	Battle Camp	2302	**Ave: 261,751** Median: 240,807 StDev: 238,737	113.7	140.0	**Ave: 322,325** Median: 270,380 StDev: 192,636	**688,000**
Laura 105102A	Coalseam Creek	1316	**Ave: 135,482** Medium: 88,468 StDev: 154,118	102.9	128.8	**Ave: 169,485** Median: 222,754 StDev: 100,990	**190,000**
Normanby 105107A	Kalpowar Crossing	12,934	**Ave: 126,015** Median: 109,165 StDev: 77,465	9.7	9.7	**Ave: 126,015** Median: 109,165 StDev: 77,465	**650,000**

Table 2-5: Estimates of annual suspended sediment loads at the Kalpowar gauge between 2006 and 2012 using DERM TSS data different analytical methods (This study; (Joo et al., 2012)).

Water Year (WY, July-June)	**Annual Total Suspended Sediment Load (tonnes/yr)** This Study, Pooled DERM TSS Data, One Rating Curve	**Annual Total Suspended Sediment Load (tonnes/yr)** Joo et al. (2012), DERM TSS Data, Loads Interpolated and Calculated at Event Scale
2006	145,270	N/A
2007	70,355	59,000
2008	175,037	211,000
2009	89,184	104,000
2010	109,165	N/A
2011	264,125	N/A
2012	28,967	N/A

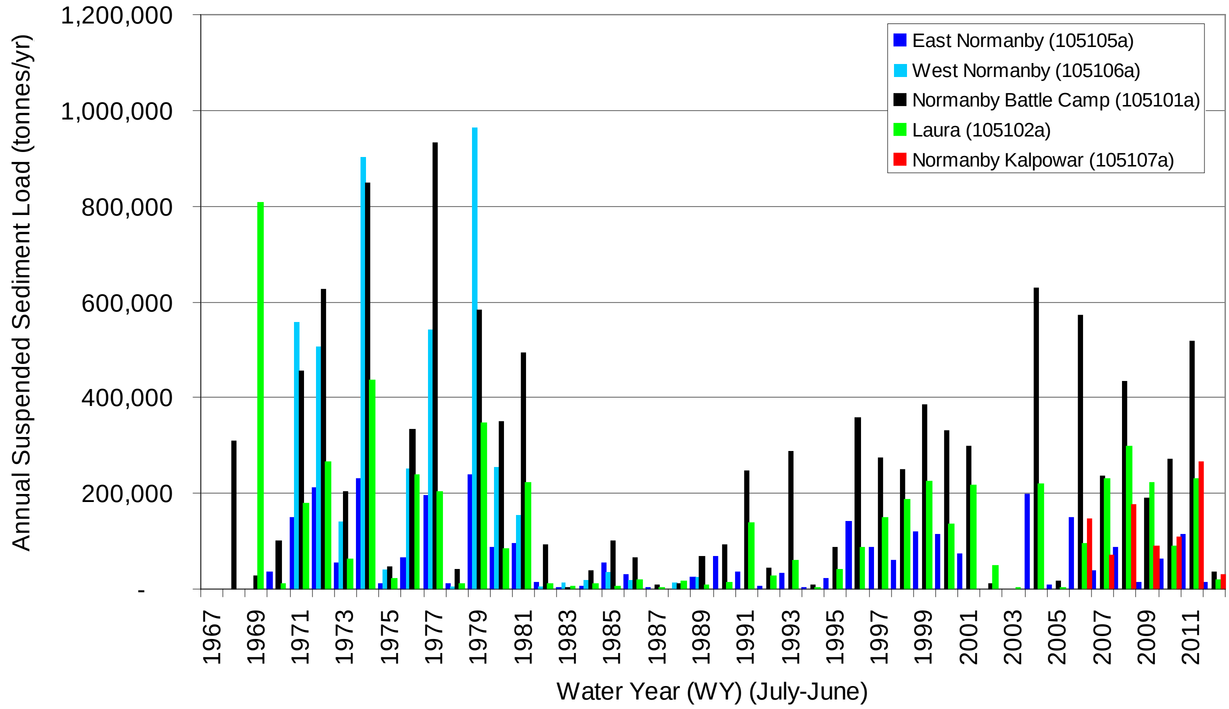

Figure 27: Estimated annual suspended sediment loads (tonnes/year) for each water year (WY, July–June) for 5 DERM gauge sites in the Normanby catchment.

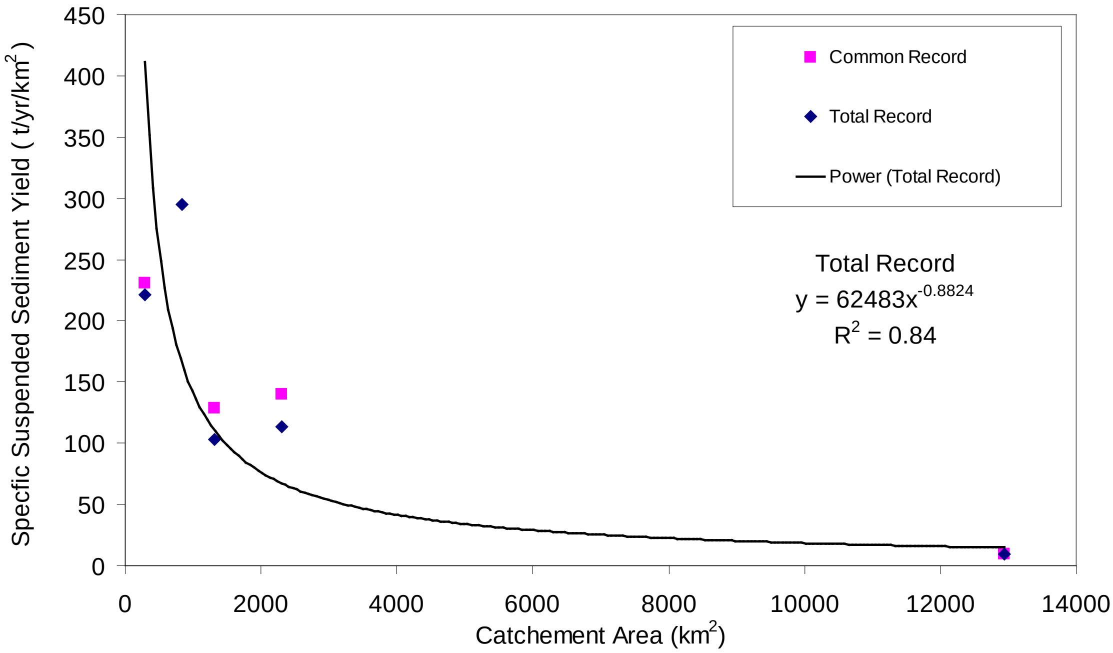

Figure 28: Decline in specific suspended sediment yield (t/yr/km^2) with increasing catchment area in the Normanby, which is a combined function of 1) a reduction in the effective contributing catchment area of suspended sediment from low gradient lands, 2) actual sediment deposition onto channel beds, benches, floodplains, and wetlands, and 3) unmeasured water and sediment discharge due to floodwater bypassing the lowest Kalpowar gauge.

2.9.5 Evidence for post-European increase in sediment supply

The results from this study render the previous estimates of a five-fold increase in sediment yield from the Normanby catchment as invalid, given that they are predicated on an incorrect assumption as to the dominant sediment source (i.e. assumed to be ~90% from hillslope erosion). The predicted change in yield is erroneously ascribed to a change in ground cover (C Factor) leading to increased hillslope erosion.

This is not to say that there has been no increase in sediment supply from the sources identified in this study (notably gully erosion and secondary channel erosion) and a range of other sources such as road and rill erosion, particularly associated with cattle tracks and fence lines. The precise extent to which the sediment supply has increased cannot be conclusively determined from current data. We have, however, identified several largely closed depositional zones where changes in deposition rates could be determined.

The evidence from gully sites where we have undertaken a detailed analysis of the geochronology and sedimentology indicates there is evidence of several pre-European phases of gully erosion activity within the last 30,000 years, with the most recent (pre-European phase) occurring in the late Holocene (i.e. last thousand years), and an earlier phase that would seem to coincide with the last glacial maximum (~20Ka) (see Figure 29, and Appendix 15). This has produced a landscape template upon which the current active phase is overwritten. As yet, it is unclear what the drivers for the earlier phases were, or what the rates of development were. For example, it is not clear whether these phases of activity were short lived, followed by a long period of stability, or whether they have been gradually developing across this entire period. More likely it is a combination of some periods of elevated activity, with gradual development over the period between the active phases. As shown in the example in Figure 29, the current phase has incised into surfaces not previously incised over the last 30,000 years, indicating that the current phase of activity is more extreme than the previous phases.

Figure 29: Photos of profile at site 1 at N9GC, showing orange mottled Pleistocene sands at base, 900-200 year old infill mid profile, and overlying stratified sands dating to 17±7a and later. Note that the current phase of incision must by definition be more developed than the incision phase <32Ka and >0.9Ka, given that is currently incising into material that has not previously been incised for 32000 years. Note also the most recent aggradation phase prior to incision is more than an order of magnitude greater than the phase just prior to European settlement. (Photos: Jon Olley)

The airphoto analysis presented in Appendix 4, suggests that many of these currently active phases have been initiated in the post-European period.

These earlier phases highlight that this is a sensitive landscape that is highly prone to this form of erosion given the appropriate conditions. It would appear that in general we are currently only in the very early stage of a new phase of gully reactivation. Hence the landscape needs to be managed extremely carefully to ensure that the extent of reactivation does not increase further.

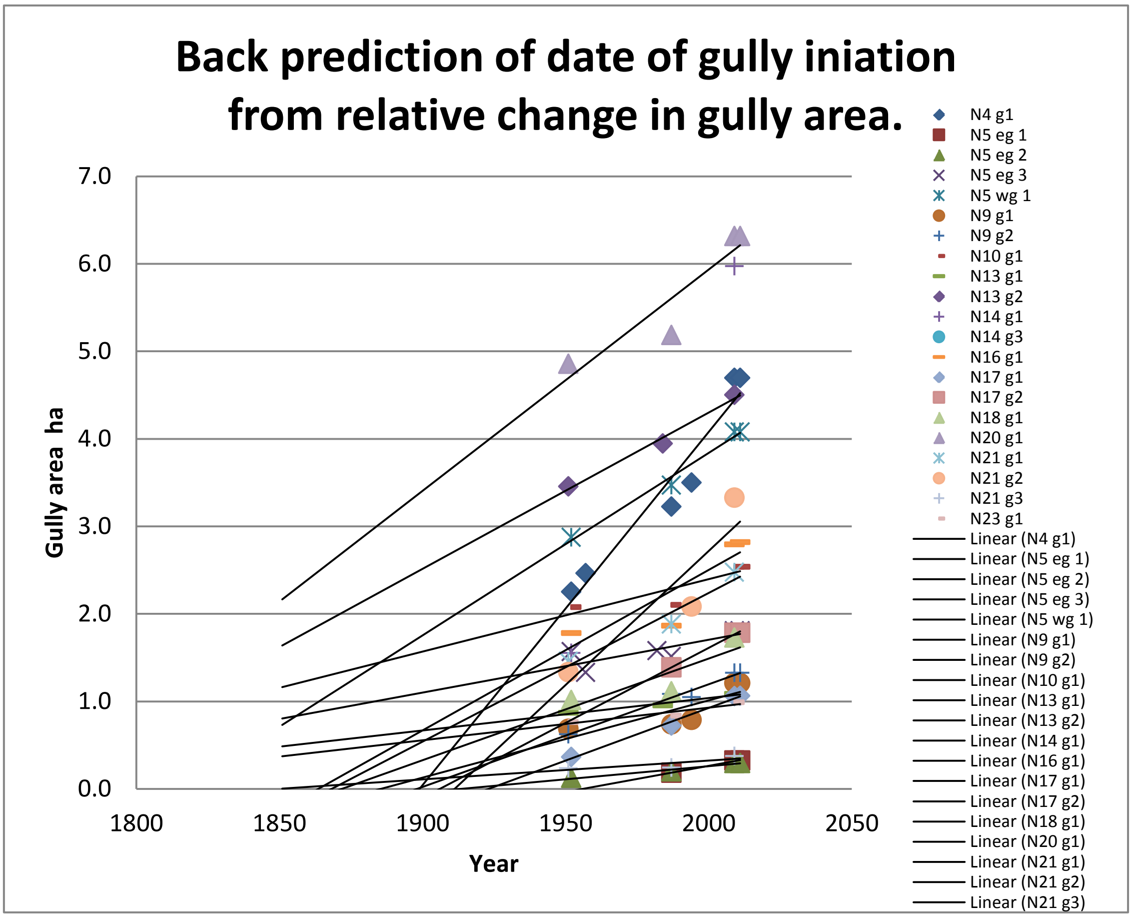

Figure 30: Change in relative gully area of 21 gullies. Each gully was covered by repeat LiDAR. Two phases of initiation are suggested by this data. A phase between 1850 and 1950, and a phase prior to 1800 that cannot be accurately predicted due to limitations of the data set.

2.9.6 The role of benches and inset floodplains

The geochronology data from benches (Appendix 10) indicates that, with one exception, all benches can be dated to the post-European period. From the data presented above regarding the significance of in-channel benches as depositional zones, which have been shown to conservatively absorb on average of 430Kt/yr, it is quite possible that the majority of any elevated post-European sediment supply has been deposited within these benches. For example, if gully erosion rates have doubled in the last 100 – 150 years; a not unreasonable assumption, representing an increased sediment supply of around 360Kt/yr of suspended sediment, this could all have be absorbed within the channel network, and have worked its way through the river network to the coast.

This highlights both the importance of these riparian buffers in filtering catchment sediment sources, but it also highlights the importance of appropriate riparian management to ensure that these sediment stores are not rapidly remobilized. By their very nature, benches are not long term sediment sinks, and it is unlikely that they will continue to absorb sediment at the same rate for over the next 100 years as they have for the past 100 years. Appropriate management of these zones will be critical for the foreseeable future.

2.9.7 Sediment source: road erosion

An initial study into the impacts of unsealed main and secondary roads on sediment supply to the stream network (Gleeson, 2012) has highlighted the importance of this sediment source (Appendix 12). Roads are a sediment source not considered in previous models.

The study showed that main and secondary roads represented the single largest intensive land use category within the catchment, with a total surface area of 5676 ha, which is 2.5 times greater than the area of intensive agriculture (2185 ha) for the Cook Shire Local Government area (which encompasses the whole Normanby catchment and much of Cape York) (ABS, 2006). These road data to not include the large distribution of tertiary dirt roads, tracks and fences on cattle station, which if included would greatly increase this land use category.

The main and secondary road network was shown, based on a conservative estimate, to intersect the stream network 1190 times (Figure 31). Event mean suspended sediment concentrations measured at road drains over the 2011/12 wet season ranged from 113mg L^{-1} to 13,509 mg L^{-1}, with a mean of 1029 mg L^{-1} (STDV 1961 mg L^{-1}).

The comparison between these data and other land use in the tropics is shown in Figure 32. Using these data, based on a number of assumptions about the contributing area of road to each stream intersection point, a minimum potential contribution from road surface runoff to the stream network is around 3000 t/yr (STDV 5690 t/yr). This is of the same order of magnitude as hillslope erosion at the catchment scale. This is an absolute minimum estimate as it only accounts for the surface runoff, whereas the larger impact of roads is likely to be on their propensity to initiate gully erosion through accelerated water runoff (Figure 33).

From the limited survey undertaken (Gleeson, 2012), 40 % of road drains were found to have initiated gully erosion, which created a direct hydrologic connection between the road drain and the stream network. Hence, the contributions of roads to the total sediment budget are likely to be significantly greater than 3000 t/yr. Further research is required to fully quantify this source, as well as erosion from cattle station roads, tracks and fences.

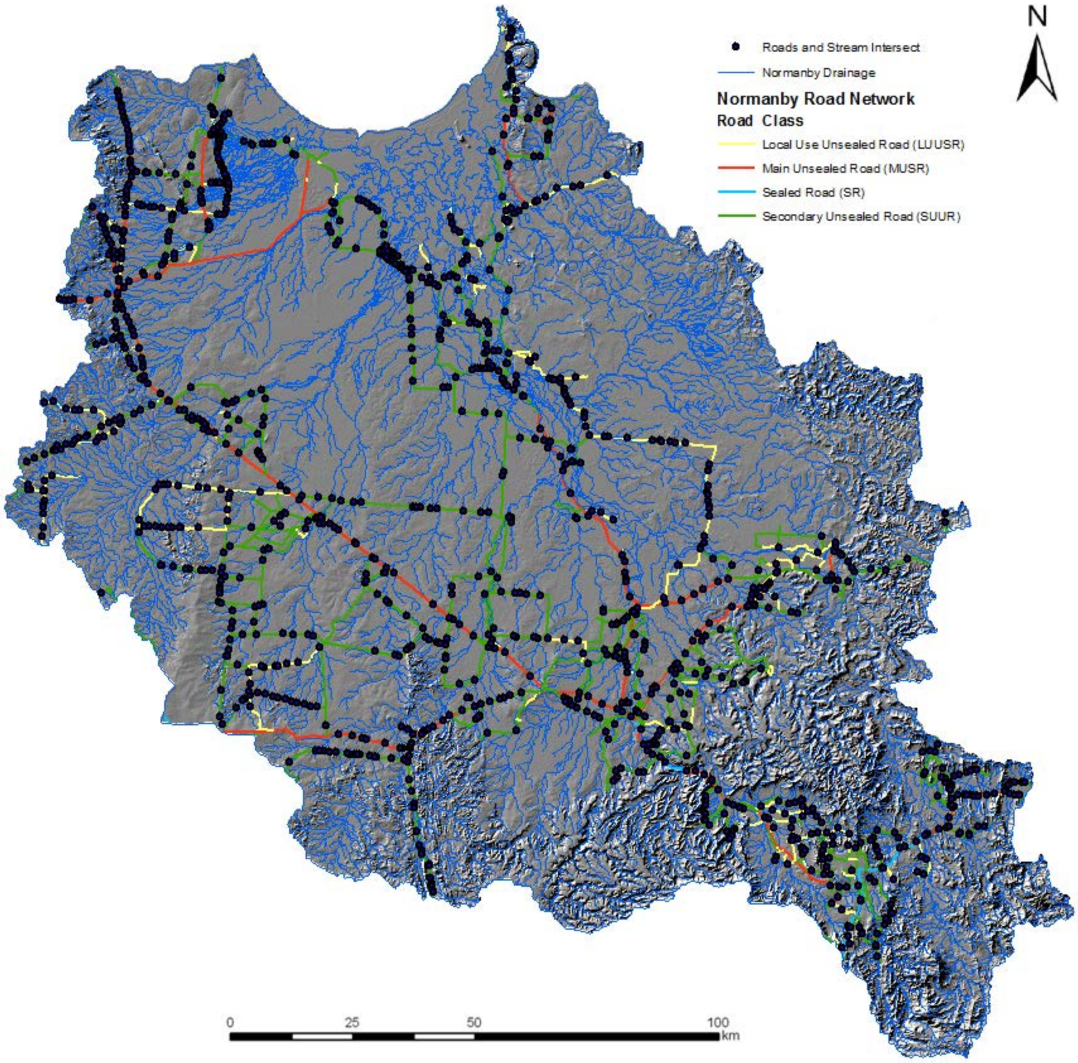

Figure 31: Map of the Normanby catchment showing the points of intersection between the main and secondary unsealed road network and the stream network. Note that most cattle station roads, tracks and fences are not included in this map or analysis.

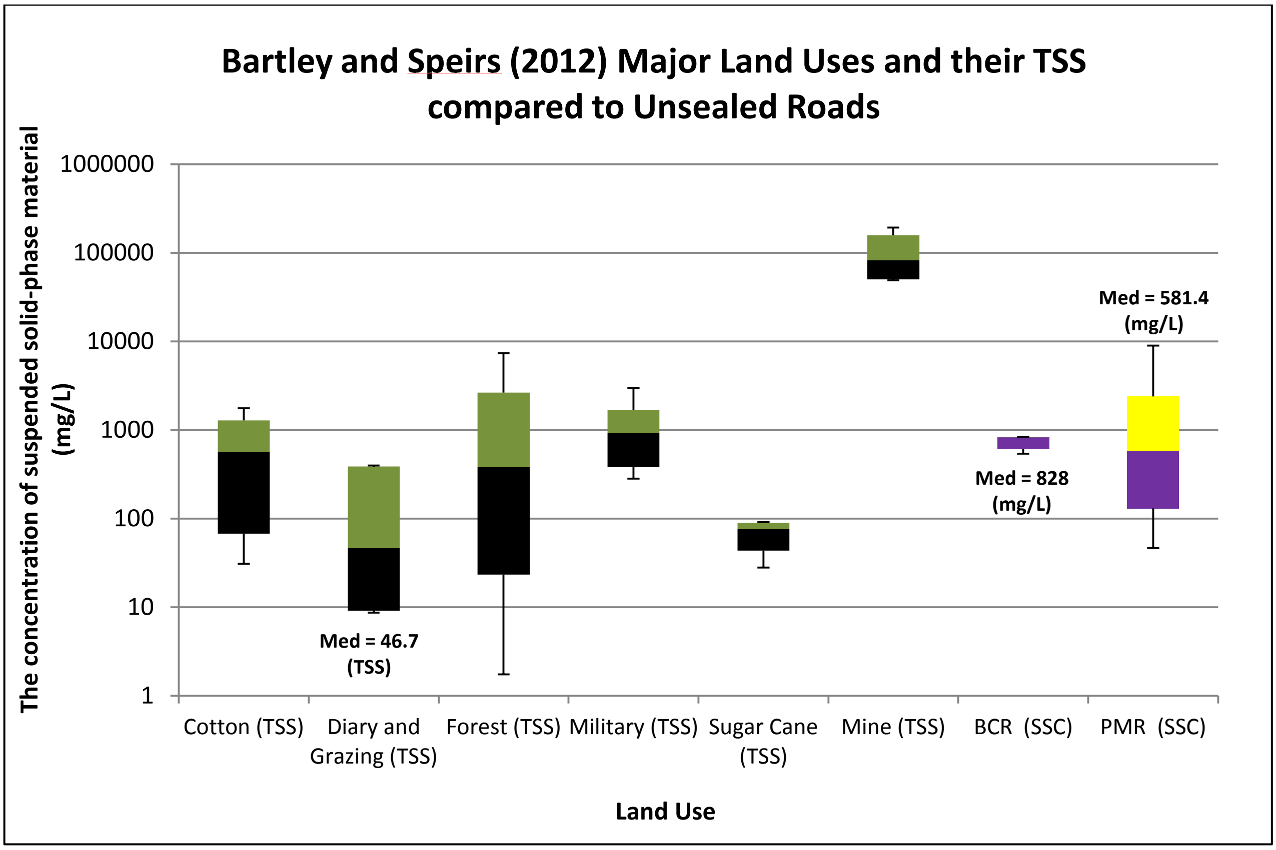

Figure 32: Comparison of SSC data (<63um fraction) for unsealed roads in the Normanby Catchment compared to TSS data from other land-uses in similar wet-dry savannah catchments, as summarised by Bartley (2012) BCR =Battle Camp Rd; PMR = Palmerville Road.

Table 2-6: Unsealed road dimensions and event mean SSC values for road runoff in the Normanby catchment (Gleeson, 2012), with estimates of the total road surface erosion contributed to the stream network from road surface erosion. The actual road contribution will also include the contribution from gullies initiated by road drains - which as yet unquantified.

	Average	1 StDev
Average Contributing Length (m)	182.8	180.2
Average Width (m)	12.8	
Total Stream Crossings	1190	
Average Contributing Area per Crossing(m^2)	2344	
Total Contributing Area (m^2)	2789830	
Total Road Area Draining to Road Crossings (ha)	279.0	
Average Runoff Concentration (mg/l)	1029	1961
avg Events >11mm/yr	35	
avg RF/Event (mm)	29.7	
avg RF/Event/Crossing (l)	69629	
avg Sed/Event/Crossing (kg)	71.6	
Mean Annual Road Surface Erosion t/yr	**2984**	**5687**

Figure 33: Examples of road drain initiated gullies. These have the dual effect of contributing large amounts of sediment to the stream network, and at the same time increasing the connectivity between road drains and the stream network. (Photos: Angela Gleeson).

2.9.8 Provenance of surficial sediments in PCB

In this component of the project we used sediment geochemistry to identify the primary sources of sediment to PCB (Appendix 12). Principle component analysis of the chemistry (34 major, trace and rare earth elements) of surficial sediments (n=64) collected from the bay and its estuaries (Figure 34) indicate that the sediments consist primarily of three components; marine derived carbonates, quartz silt-sand and terrestrially derived silt-clays. A geochemical mixing model, incorporating all of the major sources, indicates that these components respectively constitute on average 28 ± 2, 26 ± 3, and 46 ± 5% of the bay sediment sampled (Figure 35). The model also demonstrates that the terrestrial silt-clay component is dominated (82 ± 2%) by sediment derived from the coastal plain and the Bizant River. The Bizant River derives its sediment primarily from erosion into the lowland floodplain and coastal plain. Erosion from the upper catchments makes a relatively small contribution to the sediment present in the bay (< 10% of the total and ~ 18% of the silt-clay fraction). Coastal plain erosion has not previously been identified as a significant contributor to sediment delivered to the Great Barrier Reef Lagoon. Our study shows that in Princess Charlotte Bay it is the dominant source of terrestrially derived sediment to PCB. Tidal transport of suspended sediments from the coastal plain and the estuaries into the bay occurs twice daily. This potentially is the dominant mechanism by which terrestrial sediments are delivered to the bay. However, there also appears to be a relationship between the increased development of the Bizant River channel as the major distributary for discharge from the Normanby channel system to PCB. A new channel is in the process of being incised across the lowland floodplain from the Normanby to the Bizant Estuary, and it would appear as this channel develops there is a positive feedback with the development of tidal channels that are continuing to erode coastal plain sediments that have been accumulating during the mid-late Holocene (~5000 - 1000 years BP; Figure

36) i.e. the more the fluvially driven channel incises and develops, the more the tidally driven channels develop further. Our data shows that remnant pedestals of the former coastal plain material were aggrading until sometime after 500 years BP, and have then started eroding at some time since. The precise date at which this transition occurred has not been determined, and requires further research, but based on our dates it could be as recent as the last few hundred years.

The sediment had been stored as an extensive coastal plain that had been prograding and accreting for several thousand years as a complex system of supra-tidal mud flats interspersed with chenier (shell) ridges as described in Chappell (1982). But it would appear that something has changed the sediment dynamics at the coast. The cause of this change is unknown at this time, but could involve variation of sediment inputs to the coast (marine or terrestrial), changing currents in PCB, the perturbation of a high magnitude cyclone or cyclones, variation in the strength of the monsoon over hundreds of years, the development of the Bizant distributary channel, variation in the degree of dry season aeolian deflation of the coastal floodplain, etc. These and other possible influences on the coastal sediment dynamics probably have interdependent relationships.

We have identified a ~ 185km^2 area within the PCB coastal plain, with a concentration between the Bizant and North Kennedy River mouths (Figure 37) that appears to have undergone surface stripping to a depth of 2 – 3m in some areas within this coastal plain. We have used the LiDAR data to estimate the average elevation of the basal and remnant surfaces; these are 1.61 $\pm$ 0.02 m (n=44) and 2.32 $\pm$ 0.08 m (n=45), respectively (Figure 8). The difference between these is 0.71$\pm$ 0.08 m. Given that the remnant surfaces captured in the LiDAR have some areas with an elevation greater than 5m above the surrounding mud flat, we consider this estimate to be conservative. If we assume that these remnant areas represent the pre-erosion surface then (using a sediment density for the coastal plain material of 1.5t/m^3; note this is likely to be an underestimate) then between 175Mt and 220Mt has been eroded from this area.

Example of the erosion into an older, higher surface on the coastal plain. (Photo: Andrew Brooks)

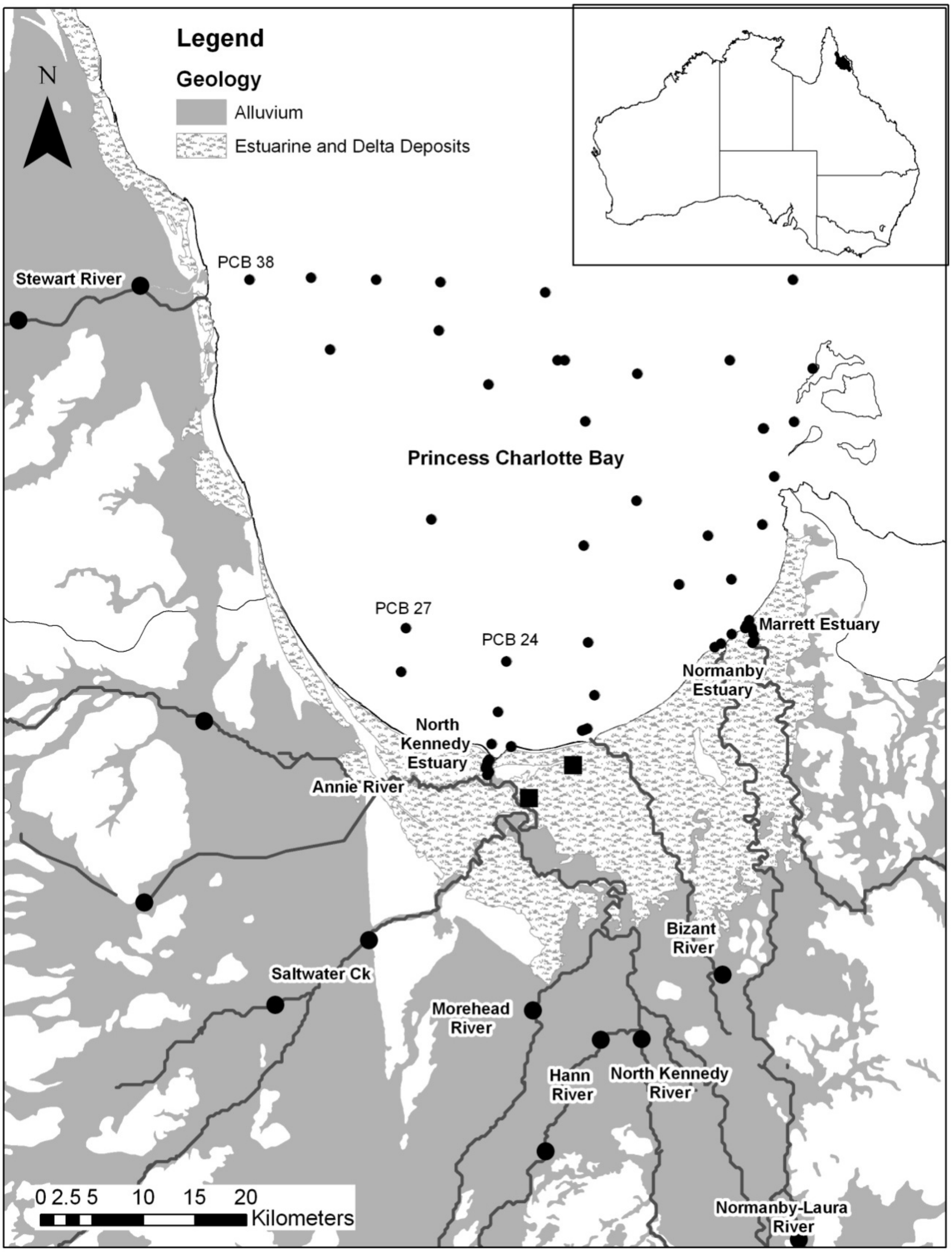

Figure 34: Map of the Princess Charlotte Bay showing the location of the river (large circles) and Bay (small circles) sampling sites. The map also shows the major areas of alluvium, coastal deltaic and estuarine deposits, the major rivers (thick dark grey lines).

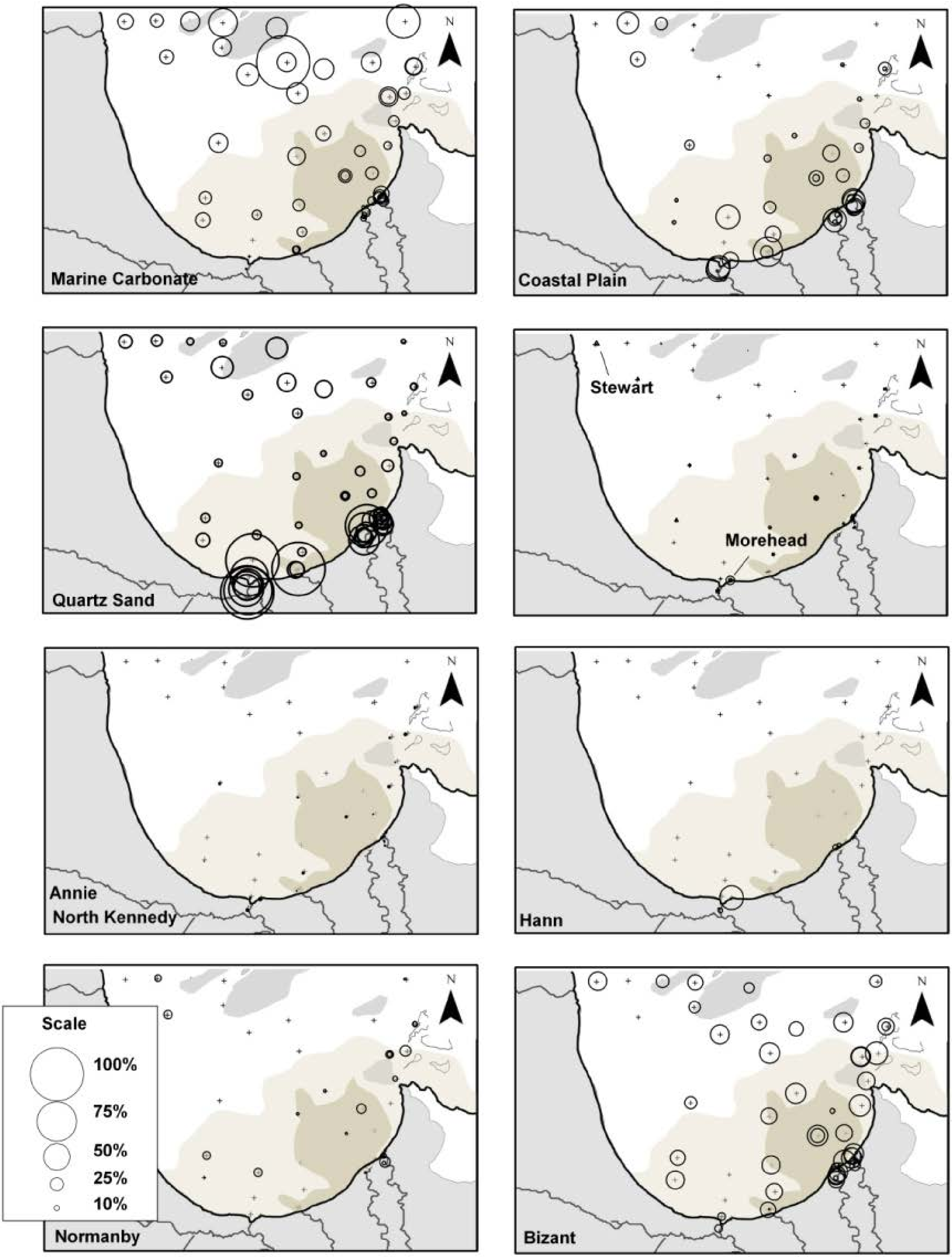

Figure 35: The relative contribution of each of the source end members to the surface sediment samples collected from Princess Charlotte Bay and its estuaries. The shading in the bay indicates the mud distribution (dark grey -100-80% mud, and light grey - 80-60% mud) as reported by Mathews et al., (2007).

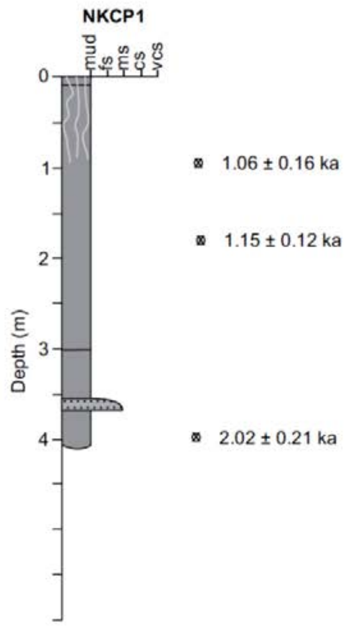

Figure 36: Coastal plain sediment pedestal, indicating that this area shifted from being a depositional to an erosional site about 500 years BP. (Photo: Jon Olley)

Seaward edge of the coastal plain around PCB showing active erosion of the mangrove fringe. (Photo: Andrew Brooks)

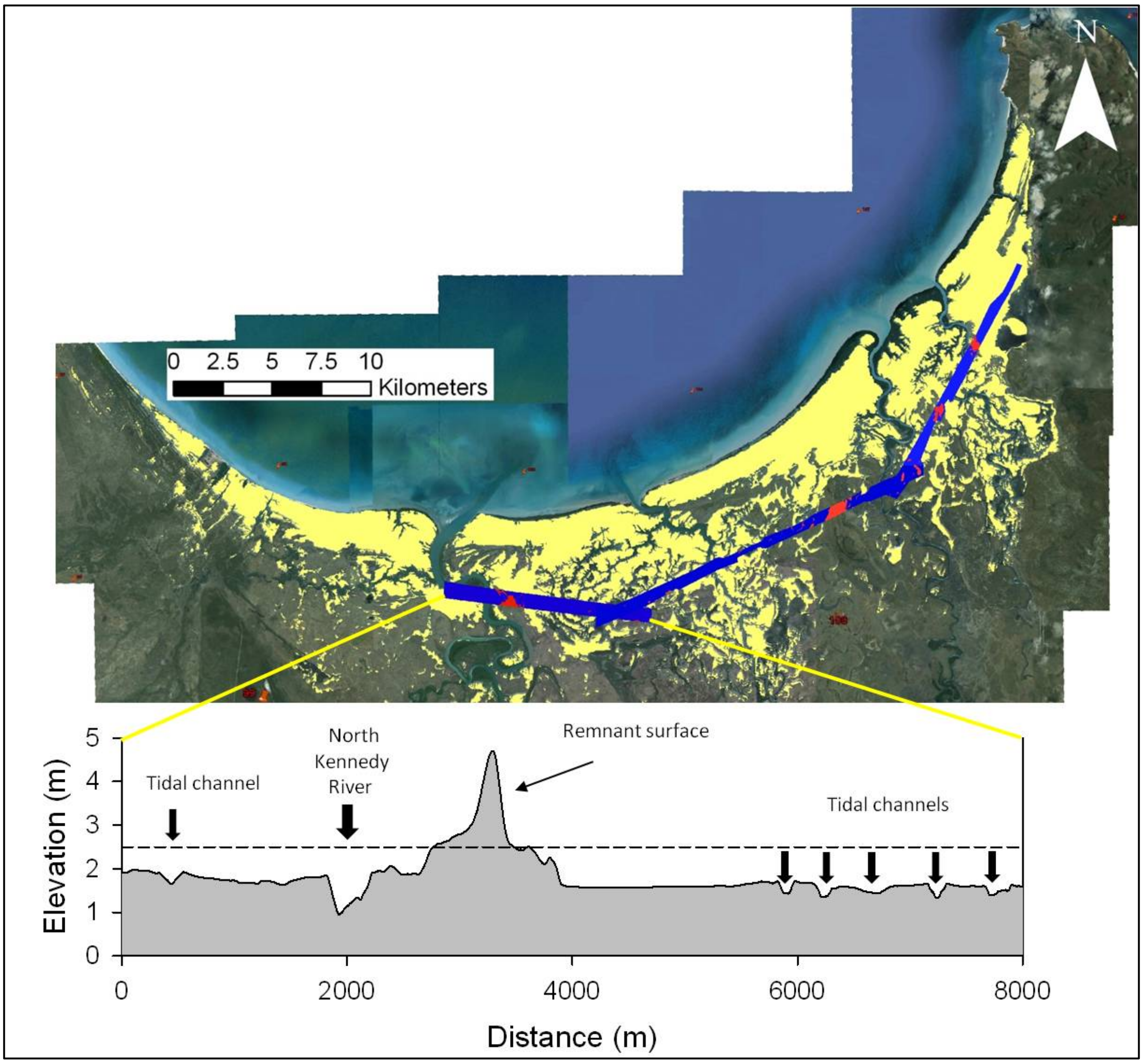

Figure 37: Map of the Normanby coastal plain showing the 185 km² area that has potentially been transformed to a major sediment source over the last 500 years or less. The remnant pedestal indicated in the cross section is similar to the one we dated in Figure 36.

2.9.9 Sediment contributions to PCB from geochemical data

From the estimates of sediment aggradation rates in PCB derived by Torgersen et al., (1983) we have been able to derive upper and lower estimates of the relative contributions by volume when reconciled with our source geochemistry data (above) (Table 2-7). These data would suggest that the relative contributions from the various entry points to PCB are of an appropriate order of magnitude, as is net contribution, when taking into account the fact that an additional volume of sediment approximately four times the volume of sediment is required to close the budget.

Clearly much more research is required in the coastal plain to identify precise areas and rates, but the multi-lines of evidence approach that we have taken in this study would tend to support the finding the coastal plain is a major, previously unrecognized, sediment source to PCB.

Table 2-7: The mean contribution, standard deviation and standard error of each source end member to surficial sediment samples collected from PCB and the associated Ktonnes per year based on Torgersen et al., (1983) minimum and maximum sedimentation rates of 2.3 to 6.1 mm year.

	Annie	Bizant	North Kennedy	Hann	Morehead	Normanby	Saltwater	Stewart	Coastal plain	Sand	Marine
Mean	0.012	0.239	0.002	0.012	0.009	0.039	0.002	0.011	0.138	0.260	0.276
Std Deviation	0.019	0.141	0.007	0.069	0.031	0.062	0.009	0.022	0.150	0.222	0.171
Std error	0.003	0.021	0.001	0.010	0.005	0.009	0.001	0.003	0.022	0.033	0.026
Deposition rates	Ktonnes per year derived from each source										
6.1 mm/yr	189	3839	27	195	143	633	27	185	2207	4172	4432
2.3 mm/yr	71	1448	10	74	54	239	10	70	832	1573	1671

Bank gully in an ephemeral channel on Normanby Station showing erosion into the highly weathered Pleistocene surface (>20 K yrs old) (Photo: Andrew Brooks)

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