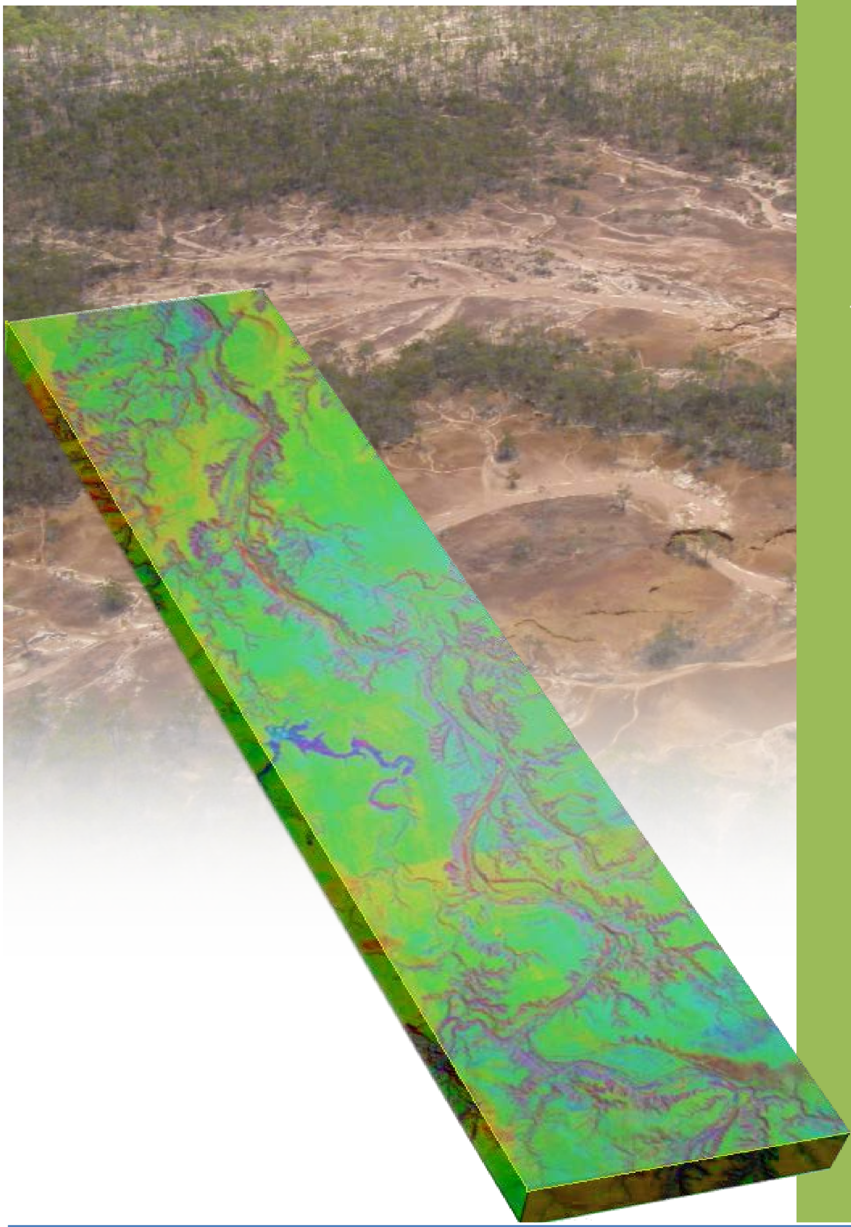

An Empirically-based Sediment Budget for the Normanby Basin

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Appendix 06: Measured hillslope erosion rates in the Normanby Basin

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CARING FOR OUR COUNTRY

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

CAPE YORK WATER QUALITY

Appendix 06: Measured hillslope erosion rates in the Normanby Basin

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DRAFT FOR PUBLICATION

Abstract

Sediment budget models such as SedNet/ANNEX and Source Catchments have become widely used in Australia as a basis for highlighting end of catchment sediment loads and erosion hotspots and hence prioritising catchment and stream management activities. The hillslope erosion component of these models is based on the widely used Revised Universal Soil Loss Equation (RUSLE) which has now been applied over large areas of Australia as a basis for catchment and river management. In this paper we present data from erosion plots in the Normanby catchment, Cape York, Australia, for which extremely high rates of suspended hillslope sediment production have been predicted in models used to predict sediment runoff to the Great Barrier Reef. Using a novel, low budget sediment trap, total sediment yield is measured across the annual wet season (November to April) in 11 plots ranging in size from 0.1 to 1.9ha. Total hillslope erosion rates (i.e. suspended and bed material load) measured within the four main geologies in the Normanby catchment, range between 0.03 – 256 kg/ha/yr across two distinctly different wet seasons. These data are compared with the RUSLE modelled sediment yields determined for the same sites, using five different model formulations; two existing catchment scale models (DNRM, 2012; Brodie et al., 2003) and three plot scale formulations based on measured plot scale parameters in which the RUSLE was applied at the individual plot scale using a 1m DEM, with L and S factors determined for each plot and the erosivity (R factor) determined from local rain gauge data across the study period, C values derived from: 1) timelapse photography for the mean late November (end of dry season) condition and, 2) the season average C factor using the same approach as 1) from fortnightly snap shots; and 3), the DNRM 2012 data. The K factor is the value used in the latest Source Catchments modelling of the Reef Catchments (DNRM, 2012). Modelled sediment yields using the first method range from 730– 9680 kg/ha/yr; the second method, 4290 to 57040 kg/ha/yr, and the plot scale methods, from 1410 – 204700 kg/ha/yr. Depending on which spatial scale is used for the modelled data, this represents an average ratio of over prediction by the RUSLE model of between 12 to 11700 times. We suggest that the over-prediction is due to four key factors: 1) because RUSLE is being applied well outside the bounds for which it was originally designed (i.e. agricultural soils); 2) K factors are wildly inaccurate and because of

high stone content are confounded with C factor; 3) the model assumes unlimited sediment supply, when in fact these savannah hillslopes are likely to be supply limited; 4) the vegetative cover factors applied in previous modeling have used the late dry season C values, when the average cover across the wet season is significantly lower (higher cover). We have derived new K factor values from our data for application in a new catchment model.

Keywords: hillslope erosion, GBR, sediment trap, tropical Australia, sediment yield, RUSLE

1. Introduction

Over the last decade, sediment budget models such as SedNet/ANNEX (Prosser et al., 2001; Lu et al., 2003), and Source Catchments (Source, 2012) have become widely used in Australia as a basis for highlighting end of catchment sediment loads and erosion hotspots and hence prioritising catchment and stream management activities. The method was first applied in an Australian context across large areas by Rosewell et al., (1993a, 1997) and subsequently as part of the National Land and water Resources Audit (NLWRA) for predicting catchments scale sediment yields at a continental scale. A similar situation exists in other parts of the world using a different suite of models, such as SWAT, AGNPS) (insert refs) , where there are similar concerns regarding elevated sediment loads to receiving water bodies following post-European landscape disturbance. Immense credence is being placed on the validity of these models, particularly as a basis for prioritizing government investment in mitigation activities (e.g. Great Barrier Reef catchments (Reef Plan, 2003; 2009); Lake Tahoe, USA (Simon et al., 2003 a, b). In Australia, at the same time that catchment modelling has come to the fore, the systematic collection of high quality data on fluvial sediment loads, bank and gully erosion extent, or detailed soil type and condition, appears to have declined as state government agencies have excised these activities from their core activities. To be believable, sediment budget models must include sufficient high quality empirical data to enable the parameterisation of all budget inputs (i.e. hillslope erosion, hillslope and alluvial gullying, river bank erosion, channel erosion, in-channel storage, floodplain storage and erosion), as well as sufficient data to test the output.

Continued research into sediment sources and their spatial variability within GBR catchments (e.g. Bartley et al., 2007; 2010; Wilkinson., et al. 2008, Wilkinson et al., 2012) has cast doubt on some of the earlier predictions for sediment production to the GBR using the earlier SedNet formulations. Furthermore, evidence from research in adjacent western Cape Rivers (e.g. the adjacent Mitchell Catchment) has highlighted some shortcomings of the assumptions underpinning SedNet modelling in savannah catchments (Rustomji et al., 2010), particularly with regard to dominance of hillslope erosion, and the source of unmeasured residuals (*sensu* Kondolf XX) notably bank erosion from small tributary streams. Brooks et al. (2008; 2009 with erratum) and Shellberg et al., (2011) have shown that a previously unrecognised form of alluvial gully erosion is a dominant sediment source in many savannah catchments on the western Cape/Gulf of Carpentaria. Shellberg (2011) has demonstrated that grazing was the initiator of the current phase of this now widespread erosion process. Tracing data (Caitcheon & Olley, 2012) from the Mitchell suggests that > 90% of the contemporary suspended sediment load is derived from either gully or bank erosion sources (i.e. sub-surface sources), with the majority predicted to be from gully sources (e.g. Brooks et al., 2008, 2009 with eratum, Rustomji et al., 2010). Previous modelling of tropical savannah landscapes was predicated on the dominance of hillslope erosion processes (Prosser et al., 2001; Brodie et al., 2003). This was largely based on the preconception that the open woodland vegetation that dominates the savannah, coupled with the intense tropical rainfall and seasonal burning regimes, would result in high hillslope sediment yields, particularly on steeper slopes – as predicted by the Revised Universal Soil Loss Equation (RUSLE). Detailed work within experimental catchments in the Burdekin has, however, cast doubt on the dominance of hillslope erosion in savannah landscapes (Bartley et al., 2007; 2010; Hawdon et al., 2008). Recent tracing work in the Bowen River suggests that > 80% of the sediment load in this catchment is sourced from gully and bank erosion (Wilkinson et al., 2012). Neglected in the original assumptions regarding the dominance of hillslope erosion in savannah landscapes, was that for the same reasons high sediment production rates were predicted in these areas, long term slope evolution has led to a situation where many of the steeper slopes are sediment starved, and either mantled by a stone lag or stripped to bedrock. Hence these stripped hillslopes commonly found throughout these high intensity rainfall zones may contribute very little sediment supply under contemporary conditions, irrespective of high erosivity or low apparent cover on steep slopes. Much of the stored sediment that can potentially be remobilised in these landscapes is instead found in colluvial toe slope deposits or in alluvial deposits, where erosion by colluvial gullying (Hancock & Evans, 2010) or alluvial gullying (Brooks et al., 2009 with erratum) is more likely to be the dominant process leading to the remobilisation of the sediment. Hence, the processes that rework these sediments are likely to be the critical controls on contemporary sediment yields.

2. Background

Catchments draining the eastern portion of Cape York contribute continental runoff to a stretch of the northern section of the Great Barrier Reef (GBR), approximately 750 km in length. The Normanby River is the largest eastward draining river on Cape York, and is the fourth largest of the catchments draining to the GBR. The Great Barrier Reef Water Quality Protection Plan (Reef Plan, 2003, 2009) identified the Normanby River as one of 10 priority rivers exporting significant loads of sediments and nutrients to the Great Barrier Reef due to predictions from the SedNet modeling (Prosser et al., 2001; Brodie et. al., 2003; Brodie., et. al., 2010; Kroon et al., 2010). These models have predicted that the Normanby catchment is the third largest contributor of sediment to the GBR (of the 35 AWRC basins draining to the reef). The Normanby River has also been cited as representing "pre-European" water quality conditions due to the lack of development in the catchment compared to other rivers in the Great Barrier Reef catchment area (Reef Plan, 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". On the face of it these two views of the Normanby would appear to be at odds. Determining whether the Normanby River is a major exporter of contaminants to the GBR or a near pristine reference river is challenging due to the lack of long-term monitoring data and the reliance to date on modeled data.

To date there have been nine published estimates of the mean annual sediment load delivered from the Normanby catchment to the GBR, based on, or calibrated against, very scant empirical data (Table 1). From these studies it can be seen that all of the modelled loads, which are derived from the SedNet/Annex model, are essentially the same, and they are persistently around an order of magnitude greater than the estimates derived from empirical data. It should be pointed out that some of the empirical load estimates are for the Kalpowar gauge site, which, based purely on the catchment area gauged, only captures around 50% of the drainage in the Normanby Basin. Furthermore, given the location of the gauge on a distributary dominated floodplain, it is suggested to that at least 43% of the discharge is bypassing the gauge (Wallace et al., in press). Hence, it is apparent that there are potentially many additional sediment sources that are not captured by the Kalpowar gauge, and hence it is not surprising that there is a considerable disparity between the modelled and measured loads. Referring back to the original Brodie et al., (2003) SedNet data, which is only slightly modified from the original NLWRA modelling (Prosser et al., 2001), and which is replicated in all of the subsequent reports, the predicted source breakdown indicates that hillslope erosion accounts for around 89% of the predicted suspended sediment input, gully erosion 10% and bank erosion 1% (table 2).

Given the lack of empirical data on any of the erosion processes in this catchment and the apparent disparity between the modelled and measured sediment loads in the catchment, there is a pressing need to test some of the assumptions that underpin the existing models and to validate the relative inputs of sediment from different sources. Given the predicted dominance of hillslope erosion in these savannah landscapes, this paper focuses on quantifying hillslope erosion rates on soils within the key geological formations predicted to be contributing the bulk of the hillslope sediment input within the Normanby catchment.

Table 1 Published Sediment Load Estimates for the Normanby River

Source	Estimate Method	Estimate time frame	TSS (K tonnes/yr)
1 Belperio 1983[1]	Shelf sed accumulation	**Current (80s)**	**2590**
2 NLWRA 2001[2]	Sednet/ Annex	**Current**	**1620**
		Pre-1850's	540
3 Furnas 2003	Simple Model based on AIMS data from Kalpowar Gauge	Current	500
4 Brodie et al., 2003	Sednet/ Annex	**Current**	**1093**
		Natural	184
5 McKergow et al., 2005	Sednet/ Annex (modified)	**Current**	**1093**
		Pre-1850	
6 Kroon et al., 2010	Sednet/ Annex	**Current best**	**1093**
		Pre-1850	184
	LRE from DERM data w/ correction	Current estimate from limited data	137
7 Brodie et al., 2010 (ACTFR Report)	SedNet/ Annex	**Current Best estimate**	**1100[3]**
	Flow weighted mean annual load[4]	2006/2007	166
8 Kroon et al., 2011) (McKergow et al., 2005 source)	Survey of available estimates	**Current**	**1100[3]**
		Pre-1850	180
9 Joo et al., (2012)	Load estimated from 3 yrs data at Kalpowar gauge	2006-2009 DERM data	59 to 211
10 DNRM 2) 2012	Source C'ments[4]	1983-2009	620

1 Reported in Brodie et al., 2003, 2010

2 N*ational Land and Water Resources Audit 2001* (www.anra.gov.au/topics/water/pubs/national/agriculture_basin_budgets.html

3 Based on Brodie et al., 2003/McKergow et al., 2005: some monitoring data validation

4 Note these are not official DNRM data – but our interpretation of the model output based on supplied input layers

Table 2 Breakdown of sediment budget inputs by source from SedNet modelling as originally published by Brodie et al (2003) and subsequently by various authors

Sed Budget Inputs (Kt/yr) – Normanby Basin (Brodie et al., 2003)			**% of Susp. Sed. I/P**
gully	Fines (<63um)	173	9.8%
	bedload (> 63um)	173	
Bank	Fines (<63um)	17.5	1.0%
	bedload (> 63um)	17.5	
Hillslope (RUSLE)	total erosion	15,670	
	fines to stream network (post HSDR)	1,567	89.2%
total SS I/P		1,758	
total Bedload I/P		191	
	Total sediment I/P	**1,948**	
Storage (Kt/yr)			
	SS export to F/P	664	37.8%
	b/load export to F/P	115	
Export (Kt/yr)			
	Fines (<63um)	1,094	
	bedload (> 63um)	76	
	total	**1,169**	

2.1 Study Aims

The aim of this study is to determine empirically whether the hillslope erosion rates predicted by the RUSLE in the previous model runs that have been undertaken in the Normanby catchment (table 1) are of an appropriate order of magnitude. By direct measurement of all the RUSLE parameters at 11 plot sites, except K, which we back calculate from the observed load, we will then compare the various model formulations that have been run in the past with our observed data. We will then provide some explanation for the variation between our empirical data and the various model runs. Finally, as outlined in the companion paper to this (Brooks et al., this vol., it is apparent there is some confusion as to what the hillslope sediment delivery ratio (HSDR) actually is, and greater uncertainty as to how it should be quantified (Wilkinson et al., 2008). Hence, we investigate an alternative method of empirically deriving the HSDR that has a more robust physical basis.

2.2 Study Area

The Laura-Normanby Catchment area covers approximately 24,353 km^2 and lies between Latitude 14° 15' to the north and 16° 15' in the south, and Longitude 143° 45' and 145° 20' (Figure 1). The catchments are located in the dry tropics where climate is characterised by extreme wet (summer) and dry (winter) seasons with 95% of its annual rainfall occurring between the months of November and April. Mean annual rainfall varies from 800 mm to 1600mm across the catchments with higher rainfall occurring in the mountains along the eastern and southern borders of the catchment. Mean maximum monthly temperatures in the region range from approximately 29°C in June to 36°C in November. Mean minimum monthly temperatures ranging from approximately 17°C in August to 24°C in February.

The Laura and Normanby Rivers originate in the mountains in the east and south of the catchment area and flow to the north, discharging into the Coral Sea at Princess Charlotte Bay. Major tributaries include the East and West Normanby Rivers and the Jack River to the southeast and east, and the Hann and Kennedy Rivers in the south and southwest (Figure 1). The majority of the catchment area is of relatively low relief with a gentle slope towards Princess Charlotte Bay. Topography in the upland areas ranges from undulating rises to steep mountain ranges, with deeply dissected sandstone plateaus and intervening plains. Mean Annual Runoff between 1986 – 2009 is estimated from this study at 4,600 GL/year (± 3400 GL – 1 stdev).

2.3 Geology and soils

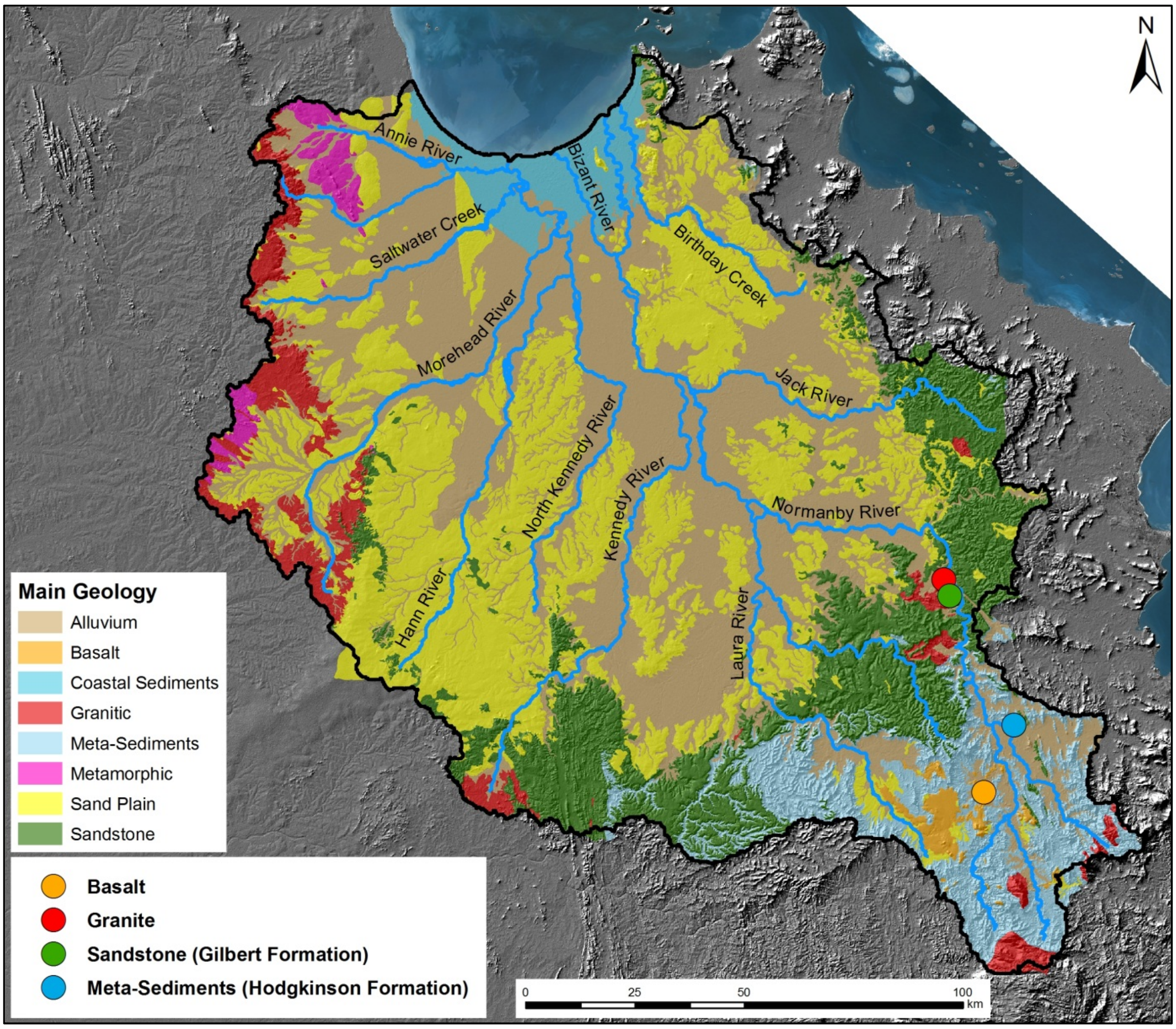

Figure 1 Geologic map showing the locations of the Hillslope Sediment Traps within the four main geological formations in the upper Normanby catchment.

3. **Study Methods**

3.1 Hillslope Sediment Traps

A series of Hillslope Sediment Traps (HSTs) were deployed at 11 sites on the four main geological formations in the upper slopes of the Normanby catchment, in areas predicted by previous modelling to have high hillslope sediment yields (ranging from 1 – 100t/ha/yr) (Brodie et al., 2003). A full description of the HSTs, and their performance characteristics is presented in the companion paper (Brooks et al., this vol.), however, they are designed to sample total sediment production from a given hillslope across an entire wet season. As outlined in the companion paper, the reason for utilising these low budget, low maintenance sediment traps was that access was restricted (or impossible) during the northern monsoonal wet season when any more complex flume type trap would need to be accessed to collect samples or perform maintenance tasks. Furthermore, we wanted to sample runoff from a number of soil types under different conditions, and to do this requires sampling equipment that is low cost and easy to operate so that they can be easily replicated. Detailed specifications for the trap set up and their performance under laboratory conditions are outlined in the companion paper.

In the first year of the study (water year 2009/10) four traps were deployed as a “proof of concept”, then once the traps were demonstrated to have performed as expected, a further seven traps were deployed for the following wet season (water year 2010/11), making a total of 11 traps (Figure 2). For the second year of the study, replicate traps were established on each soil type, and at one site (Kings Plains Meta-sediments) five traps were established on the same soil type and in the same vicinity, allowing us to assume equivalent rainfall, grazing pressure and hence cover dynamics, but with slightly different trap catchment areas and slopes, to test the intra-site variability in sediment production.

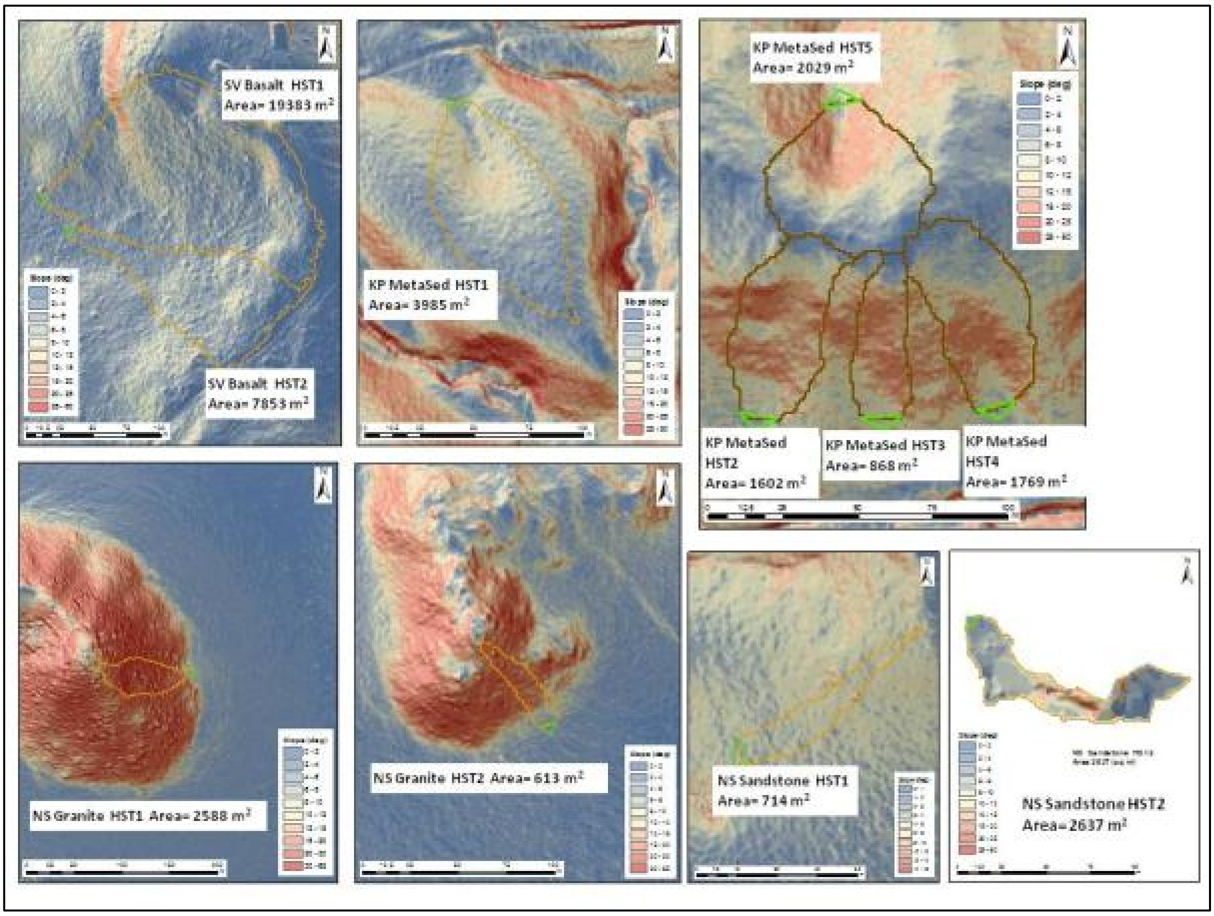

Figure 2 Hillshape relief maps of the 11 HST sites showing the delineated catchments for each trap on the 1m LiDAR DEM. Colours represent slope classes. Note that NS Sandstone HST2 was the only trap without LiDAR data. In this case the catchment area was surveyed with a total station and a DEM of the catchment area constructed.

Additional monitoring equipment was installed at each site to quantify total rainfall and rainfall intensity, from which total erosivity during the sampling period was then calculated. We used Onset tipping bucket rain gauges (0.2mm/tip with Hobo data logger) at each site, along with a Moultrie i60 game camera set to take 3 photographs of the trap site per day. The camera images were used for observing runoff conditions during some of the recorded events, and for monitoring ground cover change across the monitoring period, and hence estimating C factor variation through the season. A single rising stage sampler (*sensu* IAWCR, 1961, Graczyk et al., 1993) was also incorporated in each trap as a single sample validation for the event concentration of an early wet season runoff event.

The sediment traps were deployed in late November of each year, before the onset of the first wet-season rains, and collected in May, well after the end of the conclusion of the annual monsoon. Given that the traps are designed to sample total hillslope sediment production, the sediment retained on and within the geofabric apron is then collected and measured in the laboratory. All of the material captured on the geofabric apron and face was then swept up and placed in samples bags for transport to the lab, with the remaining fines collected with a Miele S2120 1600W vacuum. The vacuum bags were taken with the swept samples to the laboratory for processing for total load; differentiated between fines (<63um); silt/sand, sand/gravel and organics. Sub-samples of the fine fraction were analysed in a Malvern Mastersizer 2000 at the Department of Science, Information Technology, Innovation and the Arts (DSITIA) Laboratories, EcoSciences Precinct, Dutton Park, Queensland, to derive a complete particle size distribution. Representative samples of the geofabric after cleaning were also collected to determine the mass and particle size distribution of the sediment retained within the fabric. These data were used to correct for the suspended fraction of the sediment load retained in the trap. These data were coupled with the trapping efficiency data derived from laboratory flume experiments (see Brooks et al., this vol.), to derive the corrected annual sediment production from each site.

Figure 3 Sediment trap from Normanby sandstone 1, at the completion of the post wet season sediment collection, showing the samples of geofabric taken for analysis of the residual material retained within the geofabric.

3.2 RUSLE Parameter Determination at the Plot Scale

To enable the measured hillslope erosion to be compared with predicted erosion using the RUSLE model, as has been previously applied across this region, we also parameterised each of the inputs to the RUSLE model (except K, which has been back calculated from the total load data). The widely used empirically derived RUSLE (Renard, et al.,1997) is defined by the equation :

$$A = R \times K \times L \times S \times C \times P \quad \text{(Eqtn 1)}$$

Where:

A = mean annual total hillslope sediment production (t/ha/yr)

R = is erosivity (MJmm/(ha.h.yr)

K = soil erodibility

L = is the slope length factor

S = slope factor

C = cover factor

P = farming management practice (which for the purposes of the application of the model in this study is set to 1 given that the model is almost entirely being applied to rangeland grazing country)

The full numerical definitions of each of these parameters is outlined in Renard, et al.,1997.

All sites were located within areas where we had acquired LiDAR data, so that we could accurately determine the trap catchment areas, as well as the RUSLE slope factor (S), using the method of Renard (1996) and the slope length factor (L) using the approach of Desmet and Govers (1996) with the LiDAR data. Woodland canopy cover was determined directly from the LiDAR derived projected foliage cover data. Tree canopy was defined as representing all points >5m above the ground. Erosivity was determined from tipping bucket rain gauge data at each site and determined according to the method of Yu (1998). Cover factor trends across the wet season were determined from daily time lapse photography, sub-sampled at fortnightly intervals. Pasture yields (in kg/ha) were visually estimated from the photographs against the established regional pasture grass yield standards (*sensu* Rolfe et al., 2004) and converted to a projected foliage cover using an empirical relationship developed from 103 x 4m² square plots collected within the Normanby catchment over the 2011 dry season and 2011/12 wet season (Shellberg unpublished data). The relationship between pasture yield and ground cover projected foliage cover, while fairly weak ($R^2 = 0.315$), is similar to the relationship that Rolfe et al. (2004) found in the adjoining Northern Gulf region, and conforms to the following relationship:

$$GC = 126.68ln(Py) - 53.042 \qquad \text{(Eqtn.) 2}$$

Where Py= pasture yield in kg/ha, and GC = ground cover (%)

As an independent test, ground cover % foliage cover was also visually estimated directly from the time lapse photography. The C factor was then calculated according to the methods of Rosewell (1997), in which it is a product of the canopy and ground layer sub-factors:

$$C = CC \times SC \qquad \text{(Eqtn.) 3}$$

The canopy cover sub-factor CC is defined as a function of the projected foliage cover and canopy height.

$$CC = 1 - \left(\frac{Cpfc}{100}\right) exp^{(-0.328 \times CH)} \qquad \text{(Eqtn.) 4}$$

Where $Cpfc$ = canopy projected foliage cover in % and CH= canopy height in metres

The surface cover sub-factor is a function of the ground cover (%) with various empirically based coefficients depending on whether the ground cover is dominated by grasses or herbaceous vegetation.

$$SC = exp^{(a+b \times GC + c \times GC^2 + d \times GC^3)} \qquad \text{(Eqtn.) 5}$$

Where for Grass (G) cover type:

a = −0.7986
b = −0.047384
c = 0.0004488
d = −0.0000052035

For Herbaceous (H) cover type:

a = −0.7982
b = −0.040083
c = 0.0005212
d = −0.0000049749

3.3 Catchment Scale RUSLE Parameters

For comparison with previous RUSLE erosion modelling, two broad scale RUSLE datasets were also used. These are the data layers used in the National Land and Water Resources Audit (NLWRA, 2001 - downloadable from http://adl.brs.gov.au/anrdl/metadata_files/pa). These are the same data used by Brodie et al., (2003) with the exception of the C factor, which was set at 0.05 for all grazing land in Cape York, and which is the land use type on which all the experimental sites are located. A more recent data set developed by the Queensland Department of Natural Resources and Mines (DNRM, 2012), has also been used for comparison, along with Brodie et al., 2003) dataset. The DNRM (2012) dataset differs from the Brodie et al., (2003) dataset in that the K factors have been remodeled at a higher resolution (100m), a new C factor derived from 25m resolution Landsat data, while the S and L factors have been calculated from a 100m resolution DEM, rather than the 270m DEM (9 arcsec) used to determine these parameters in the Brodie et al., (2003) model.

3.4 Trap Sediment Preparation and Analysis

The material captured by the HSTs was processed for total suspended load, particle size distribution and separation of sediment into various size classes for further processing. A continuous-flow filtration unit (CFFU) was constructed specifically to aid in the removal of all organics from the raw trap material, and the separation of fine and coarse sediment. This unit consists of two nested 30 l square polypropylene tubs, with the top section containing a fixed plastic hose for input of de-ionised water and a 240mm X 140mm mesh sieve with a 1.0mm aperture fixed over a hole in the bottom of the tub. This mesh plate allowed suspended fine sediment and micro-organics (small leaves, grasses, chaff etc) to be washed into the base section, which was then continuously gravity-fed as a slurry into a large commercial centrifuge (Interfil IC-45), and the retention of macro-organics (large leaves, sticks etc) for further processing.

The base section contains a tap assembly which allowed the flow rate to be equalised between the incoming de-ionised water and the outgoing suspended fines slurry, thereby maintaining a constant water level in the CFFU facilitating the agitation and washing process. Specific steps involved in the processing of the material captured by the HSTs for total suspended load are detailed in Figure 4.

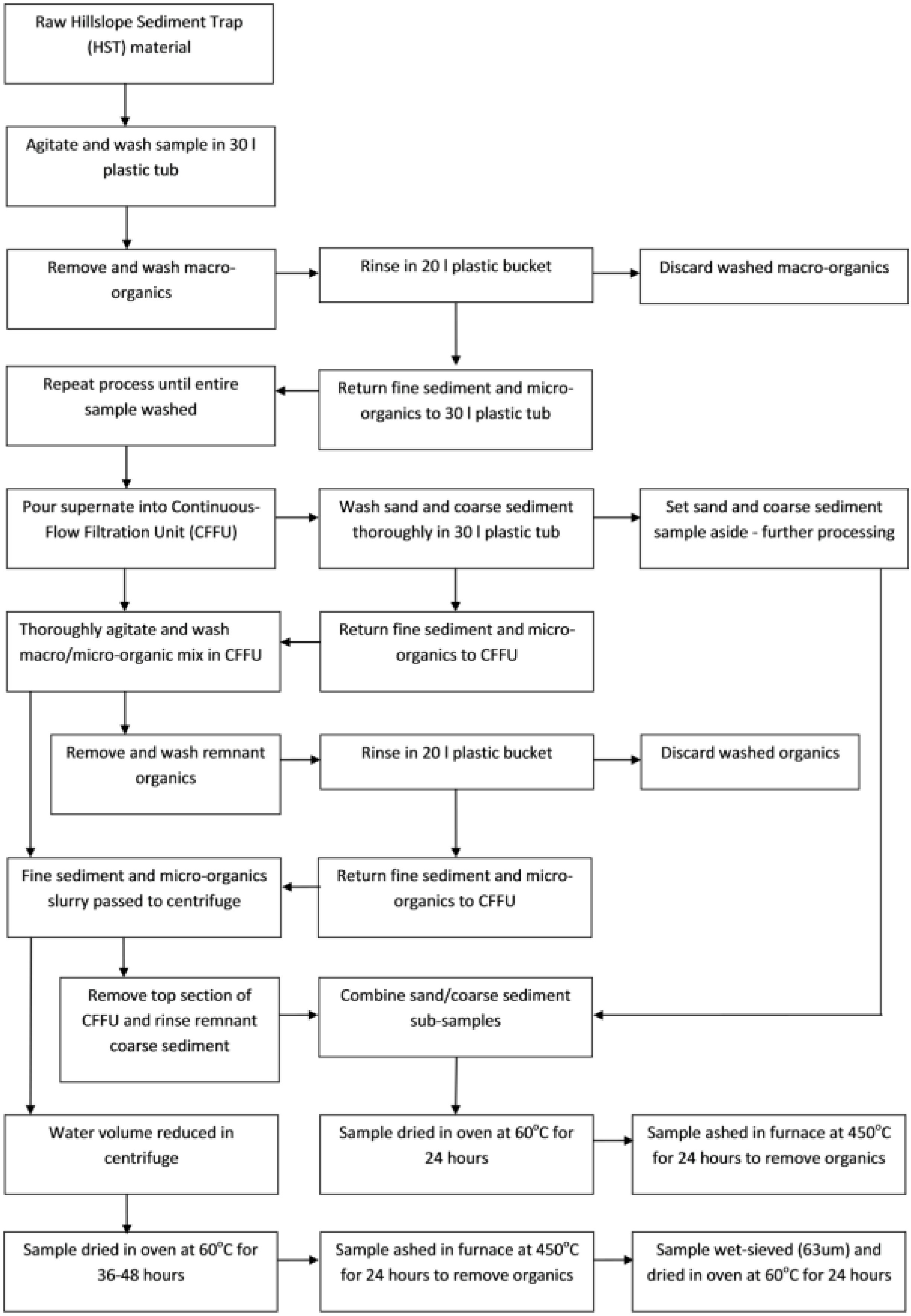

Figure 4 Flow chart detailing the removal of organics from the HST raw material

3.5 Particle Size Analysis

Once the mineral sediment fraction from the traps had been separated, sub samples were then taken and further processed for particle size analysis, according to the following procedure. All particle size distribution analysis was carried out at the Department of Science, Information Technology, Innovation and the Arts (DSITIA) Laboratories, EcoSciences Precinct, Dutton Park, Queensland. A representative 200g sub-sample was taken from each HST size class <63μm fines, >63μm fines and the sand/coarse sediment for each (where total sample size was <200g the entire sample was used) and sent to the laboratory for processing. A 0.5g sub-sample was taken and wet-sieved using a 1.0mm mesh sieve, then mixed with approximately 1000ml of de-ionised water to provide a suspended sample for analysis by the Malvern Mastersizer 2000 particle size analyser. The wet-sieved samples were then mechanically dispersed in a cut-bottle using a screw propeller attached to the Mastersizer.

The dispersed sample was left to soak in the bottle for a minimum of 12 hours. The soaked sample was once again mechanically dispersed by the screw propeller, which also served to homogenise the suspended sample as it is pumped through the measurement cell in the Mastersizer. With the laser obscuration level on the Mastersizer set to 5-15%, the suspended sample was continuously pumped through the measurement cell, and particle size measurements taken for 15 seconds providing 15000 measurement snaps per cycle, with a total of 15 measurement cycles per sample. Initial measurements were taken for each sample, with results reported for pre-dispersion (W_PSD_PRED) and mechanical dispersion (W_PSD_MECD). A subsequent set of measurements were taken following further dispersion of the sample by immersion in an ultrasonic bath (processed internally within the Mastersizer), and the results reported (W_PSD_ULTD).

4. Results

4.1 Trap Hydrological Characteristics

The hydrological characteristics derived from the tipping bucket rain gauge data at the 11 HSTs are shown in Table 3. The number of runoff generating events across the wet season has been calculated from these data, based on a minimum event threshold of around 11mm. This represents the mean event magnitude (i.e. of all events) across the wet season. A rate of around 11mm/hr has been identified in a number of forestry road erosion studies as a threshold for initiating sediment producing runoff events (Reid & Dunne, 1984; Croke et al., 2006; Thompson et al., 2009). The definition of an event follows the method of Yu (1998), in which an event must be preceded by 6hrs without rainfall. From these data it can be seen that there are typically between 30 – 40 events across the wet season exceeding this threshold, and that typically >85% of the total rainfall falls in these 30 – 40 events.

These data have been used for two primary purposes: 1) to determine the number of events across the wet season that are likely to have filled the sediment traps, and based on the infiltration characteristics of the geofabric determined in the laboratory, (see the companion paper – Brooks et al., subm.), to estimate the likely number of times the traps may have overtopped. 2). These data also enable us to derive the "event mean concentration" (EMC) of runoff from these hillslopes, based on the corrected sediment production data for each trap site. The measured sediment retained in each trap has been corrected upwards by a factor of 2 for the <63μm sediment fraction not retained within the trap, as outlined in the companion paper (Brooks et al., subm.). An additional correction for the material retained within the geofabric has also been applied as shown in Table 5. The EMC data were used to determine the sediment loads run in the laboratory flume experiments, albeit increased by a factor of 20 to ensure that we are replicating the "worst case" conditions likely to have been experienced during the field sampling period (see Brooks et al., subm.).

To determine the actual runoff volumes, and hence the discharge into each trap, assumptions as to the runoff coefficients (ROCs) at each site had to be made. As a guide to estimating the ROCs, only a few of the traps provided any physical evidence that they had been overtopped (via "high tide" marks KP2, KP3 & KP5), and these sites were used as a guide to calibrate the ROCs. In addition to the trap storage capacity (line 9 Table 3) the geofabric infiltration rate provides the other critical component for determining the overtopping frequency. As outlined in Brooks et al (subm.) the infiltration rates determined in the laboratory are conservative, given that they are at lower depths than experienced in the field traps, and given that the apron sealing phenomenon seen in the laboratory flume experiments is unlikely to occur to the same extent in the field traps. Consequently, a slightly higher average infiltration rate of 2 l/sec/m^2 has been adopted. From these data, it can be seen that most traps would appear to have overtopped 1 or 2 times each wet season. Hence, this could represent an additional error in the measured sediment loads, but at this stage this cannot be fully quantified. Suffice to say, the correction factors applied for both the incomplete retention of fine sediments and the material retained within the geofabric are both conservative corrections, which are likely to have overcompensated for "unrecorded" sediment. Hence it is unlikely that the sediment yields will vary markedly from the corrected values shown in both Table 3 and Table 4.

Also shown in Table 3 (lines 13-19) is a breakdown of how the EMC values have been determined at each trap site, based on the >11mm events. These data show that the EMCs for all sites across the two water years sampled have a mean of 19.5mg/l for total load (stdev 28 mg/l), or an average of 6.9 mg/l for suspended load (i.e. <63μm) (stdev 10.8 mg/l). The Gilbert Formation sandstone soils have the highest loadings for both the bed material load and the suspended load. These EMCs are, however, extremely low when compared with data from other sediment sources in Australia. A dataset compiled by Bartley et al (in press) for similar landuse (grazing on native pasture and forested land) indicated a median EMC of 229 mg/l (stdev 1220 mg/l), whereas our data has a median EMC of 3.76 mg/l (stdev 27.8 mg/l).

The SSC data derived from the rising stage samplers in 8 of the traps (line 20, Table 3) shows that on average these values are an order of magnitude higher than the derived EMC data, with a mean concentration of 178 mg/l (stdev 154 mg/l). These results seem quite reasonable given that these samples would most likely represent the "worst case scenario" given that they will most likely have been collected in the first storms at the start of the wet season. The backwater conditions in the trap will also likely increase the sediment concentrations as the sediment is progressively retained in the trap. The difference between the EMC data and these peak stage values is also simply explained by the dilution effect from the more numerous smaller events that contribute to the EMC data, but not the peak instantaneous data associated with the RSS samples.

4.2 Inter-annual Variability of Trap Yields

Whilst there are insufficient data from this study to say anything definitive about the variability of sediment yields between years, there are some interesting observations that can be made from these data that highlight some of the issues that arise when attempting to predict erosion rates in the real world. Only three sites have replicate data from the same sites over the two different wet seasons: Kings Plains HST1; Normanby Station Granite HST1, Normanby Station Sandstone HST1; a fourth (Springvale HST1) was collected but was rendered unusable due to a sample processing error.

Of the three sites with replicated data, in each case the sediment yield from the 2010/11 wet season was appreciably less than that from the previous year, 1.137kg vs 0.677 kg; 26.77kg vs 0.868 kg; 18.821 vs 4.895 kg for Kings Plains 1; Normanby Station Granite1, Normanby Station Sandstone 1respectively. In the case of the Normanby granite site, it can be seen that the yields vary by more than an order of magnitude, when the total wet season rainfall is about the same.

Such anomalies probably have multiple contributing factors, and highlight the fact that a single event could account for a large proportion of the annual yield, depending on when the event occurs. Such events are not well captured by the annualized data. However, it is also likely that much of the variation is explained by the distinctly different patterns of rainfall across the two wet seasons (see Figure 5), where it can be seen that the wet season was very late commencing in 2009/10 and then hit fairly intensively when it did arrive. The 2010/11 wet season, apart from a single early storm, had a more gradual build up, which enabled cover to build up before the most intense rains began. In this instance the 2010/11 wet season had a significantly higher annual aggregate rainfall than did the previous year, with only half the sediment production. Similar patterns are evident at the other sites but are not included here due to space constraints. In addition to this, and not reflected in these data, is the fact that the 2009 dry season was a particularly harsh one, with much of the catchment having been burnt, leaving very little cover at the end of the dry. The 2010 dry season on the other hand was unusually wet, receiving scattered rain throughout the year, which while not producing any runoff, enabled a much higher grass cover to be maintained right through to the later dry season, and thereby significantly limiting the amount of runoff that did occur. The variation in C factor between the two years can be seen in Figure 6 where it is evident that the C factor values in 2009/10 don't peak until mid-late December, whereas in 2010/11, they decline consistently from the start of the monitoring period in early November.

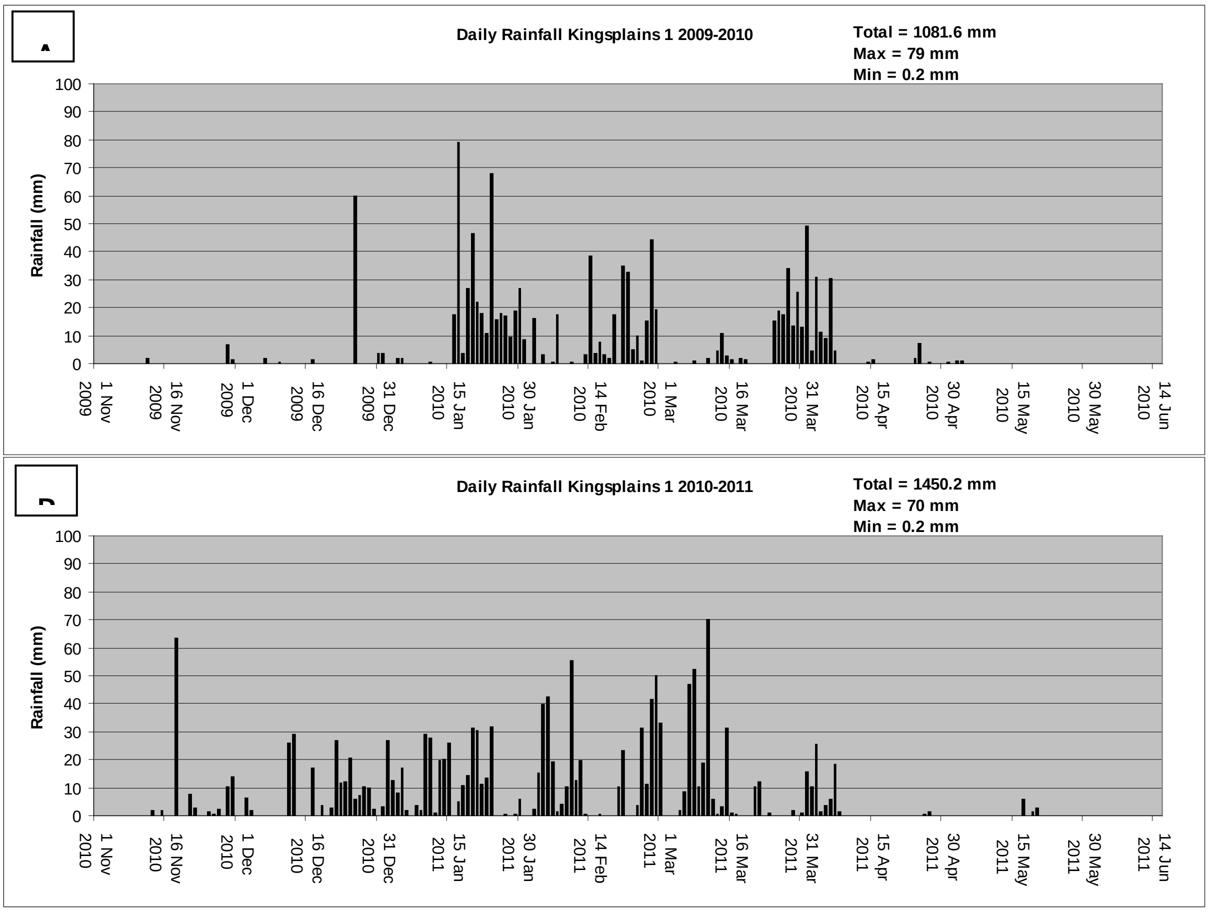

Figure 5 Daily rainfall at the Kings Plains Metasediments site 1, showing the distinctly different pattern of rainfall across the wet season for the two years of the study. Note how the 2009/10 wet season was late to start, while the 2010/11 wet season started with an intense storm in mid November, but then gradually built up through the season. Similar patterns were observed at all sites where data was collected across both water years.

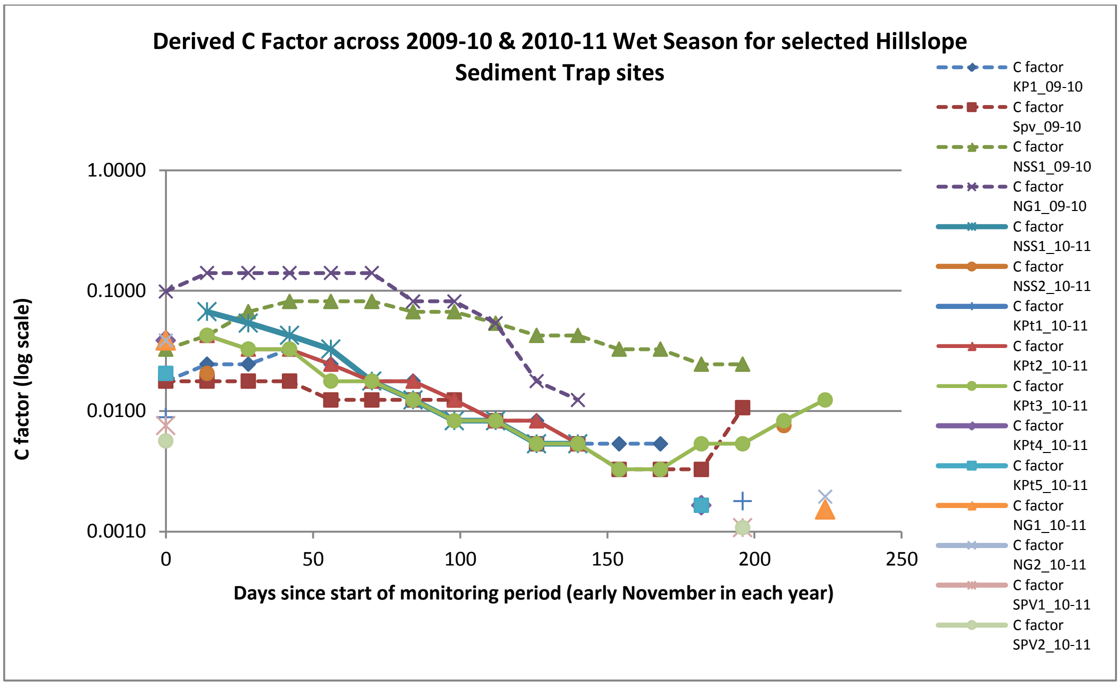

Figure 6 Graph of the cover factor trends across the 2009/10 and 2010/11 wet seasons, showing fortnightly trends at 6 sites and the start and end points for a further 9 sites.

Comparison Between Modeled and Measured Hillslope Yield Data

The full set of input parameters for the various RUSLE model formulations used to compare with the observed hillslope sediment yields from the 11 sites (14 sampling events) are shown in Table 4. The first two blocks of data provide the estimates that have been developed at a fairly course resolution at the catchment scale (100m & 270m pixel resolution respectively), whereas the next three model runs are all applied at the plot scale derived from our measured plot scale parameters (R, L, S) with the C factor varying according to the three scenarios outlined in the Methods. The K factor used in these scenarios is the most recent value used in the Source Catchments modeling (Source, 2012). A summary of the sediment yields derived from each model scenario, for each of the four main soil groups, as well as the measured (corrected) sediment yields for the same sites, can be seen in Figure 7.

From the first two catchment scale model runs, it is apparent that the most recent DNRM yields are around an order of magnitude less than the earlier model runs. Most of the difference between these two scenarios can be accounted for by variations in the S and C factors for the two different model runs. All other parameters are much the same. Another important observation from these data is that the RUSLE predicted yields at the plot scale (i.e. based on high resolution topographic data) are of the same order of magnitude as those derived from the coarse resolution catchment scale data. The comparison between run 5 and run 1 effectively shows the effect of scale of observation, in which it can be seen that there is on average a 4.5 fold variance between observed and modeled data at the different model resolutions. The majority of this variation is accounted for in the L factor. Hence, scale of observation can explain part of the mismatch between the predicted and observed sediment yields.

4.3 Cover Factor

The use of the late dry season cover factor, which to date has been the standard measure used in SedNet and Source catchments in the tropical savannah particularly, is another potential source of error in the modeling. There are cogent reasons as to why the late dry season C factors have been used, the most important of which is that the C factors are derived from ground cover assessment using Landsat time series image analysis. In this tropical savannah, the ground is often obscured by cloud cover during the northern Monsoon, making it very difficult to obtain consistent images that capture the ground cover time series across the whole wet season. It is also assumed that most erosion is going to occur in the late dry/early wet season while ground cover is still relatively low, and hence it has been thought reasonable to use the late dry season cover factor to simulate these conditions.

The results from this analysis, however, would suggest that this approach can potentially over predict hillslope sediment yield typically by a factor of 2 – 3 times than if the wet season average C factor is used. As can be seen in Figure 8 and Figure 6, grass cover changes fairly dramatically over the wet season, which has the effect of varying the C factor by as much as an order of magnitude, between the start and end of the season.

4.4 K Factor

The vast majority of the variance between the observed and modeled data appears to be explained by the K factor. Recalculation of the K factor, based on the observed sediment yield data and all other measured variables, indicates a 330 fold variance between the most recent K factor data (Source, 2012) and the back calculated version, using the plot scale data and the season average C factor value. It is recognized that this approach does lump all other errors into this one factor, but it would seem reasonable that this is where most of the error lies, given that it is unlikely that any comparable, rocky, sediment-starved hillslope soil types were used to drive the empirical based model that has been used to derive the national scale K factor distribution maps. A characteristic stony hillslope surface can be seen in Figure 8. It is acknowledged that the effect of surface stone lags could, at least partially, be included in the C factor, rather than all being absorbed by the K factor. The original formulation of the USLE (Wischmeir & Smith, 1978) and the RUSLE (Renard et al., 1993) makes some accommodation for the effect of things like stone lags as part of the cover factor, however, in the context of catchment modeling, C factor has tended to become regarded as being all about the vegetative cover factor. Hence, for this reason, we have opted to adopt the same framework, incorporating the effect of stone lags into the K factor. This way the C factor can be determined simply from measures of the above ground vegetative biomass, and associated cover.

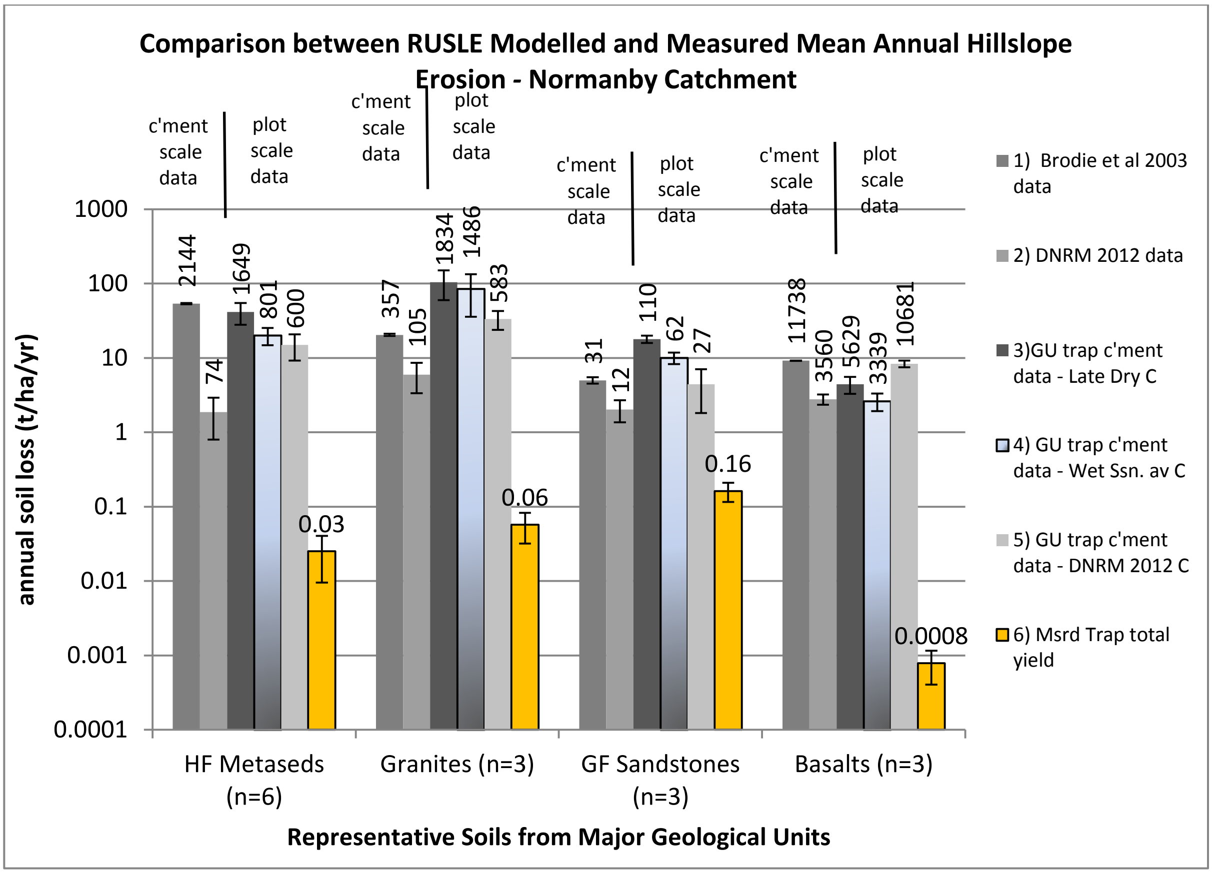

Figure 7 Graph showing the average annual hillslope erosion rates (i.e. total yield) on soils of the four major geologic formations in the upper Normanby catchment. The grey bars show the modeled estimates at the same locations as the measured mean annual loads across the 2009/10 and 10/11 water years. The modeled rates are across the same time period – as reflected in the R & C factor values within the RUSLE modeling. In addition to the Brodie et al., (2003) and the DNRM 2012 (Source, 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 modeled to measured yields according to the different model formulations. NOTE LOG SCALE

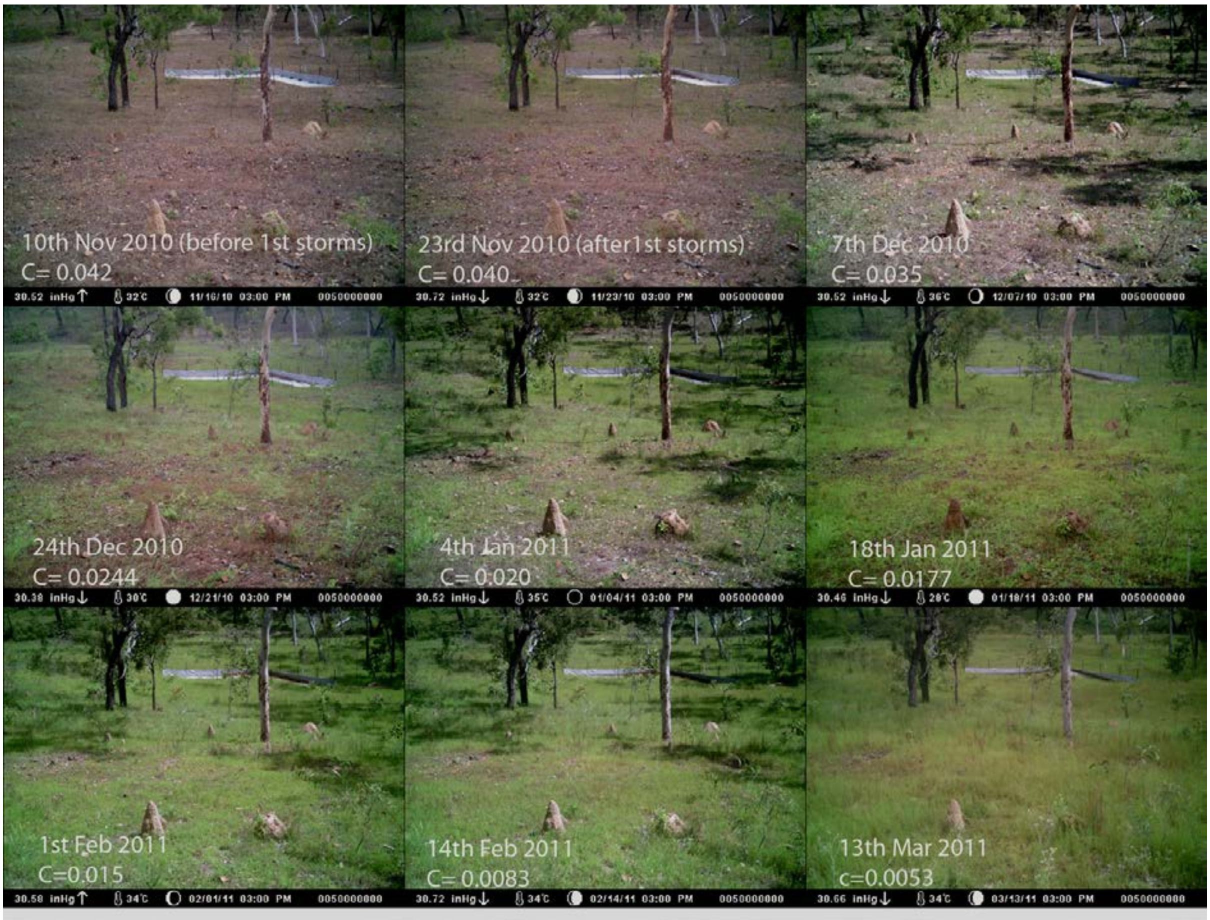

Figure 8 Photo time series showing the changing ground cover at approximately two weekly intervals across the 2010/11 wet season (with calculated C factors indicated on each image).

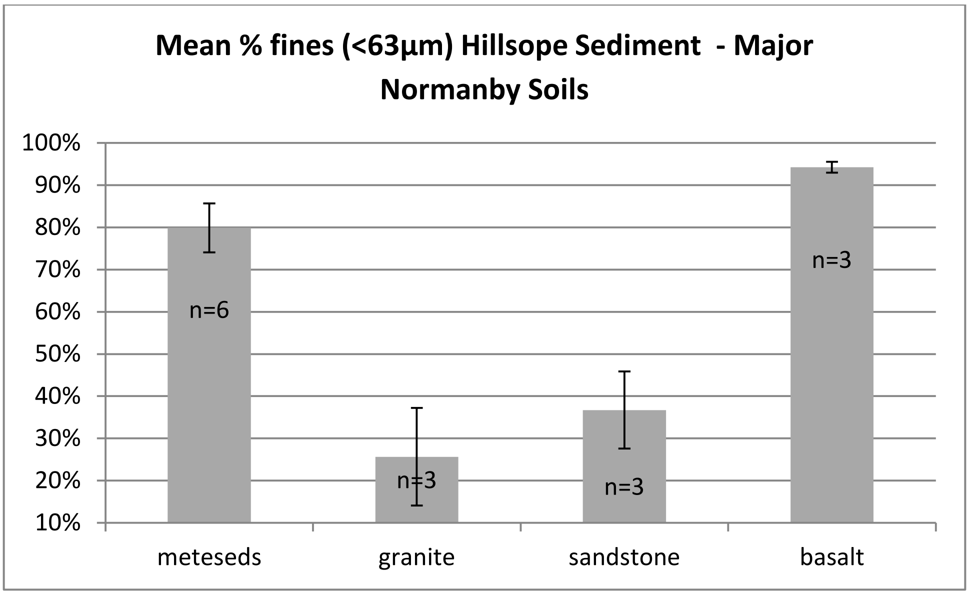

Figure 9 The proportion of fine sediment (<63µm) for each of the main soil groups in the Normanby catchment source zone. These ratios provide a more realistic measure of the likely "Hillslope Delivery Ratio (HSDR)", than any other measure previously proposed (error bars represent ± 1 stdev).

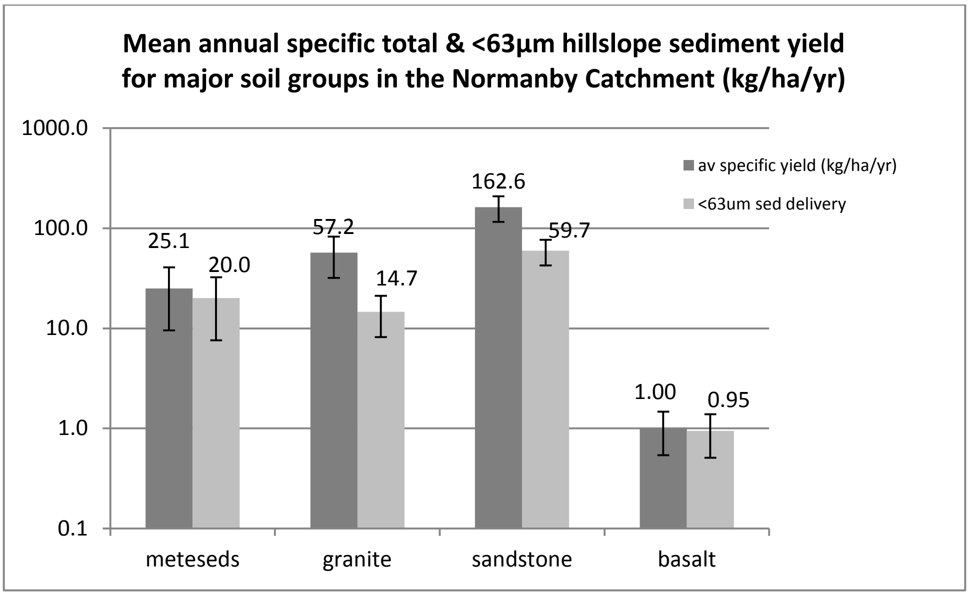

Figure 10 Specific hillslope sediment yields for each soil group, showing the comparison between total yield and fines only yield (error bars represent ± 1 stdev).

4.5 Particle Size Distribution of Mobilised Hillslope Sediment

The particle size distribution (PSD) plots of the sediment collected in each trap are shown in Figure 11. From these data it can be seen that there is considerable variation in the composition of the mobilized sediments, which is largely a function of the hillslope soil's parent geology. As shown previously, the three sites that had data across two years, which varied markedly in terms of total load between the respective years, show only minor variation in the gross PSD, despite the load variation. When the data are aggregated by soil type (Figure 9), it is clear that there is a stark difference in the % fine fraction of the delivered sediment according to parent geology. The extent to which this matters, depends on how the data are ultimately being used. For comparison with RUSLE data at the hillslope scale, it is the total load that is being predicted, so to some extent the PSD is irrelevant. However, when the data is being used to predict catchment scale hillslope sediment contribution, the PSD of the delivered sediment makes a significant variation to the overall predicted sediment yield. For this purpose, we need to know the suspended sediment load (i.e. <63µm fraction) being delivered to the stream network, rather than just applying a uniform hillslope sediment delivery ratio (HSDR), as is currently done with SedNet and Source Catchments modeling. As shown in Figure 10 the relative contributions from different sources can vary markedly when the PSD is taken into account, and hence, the sediment delivery ratio will vary proportionally.

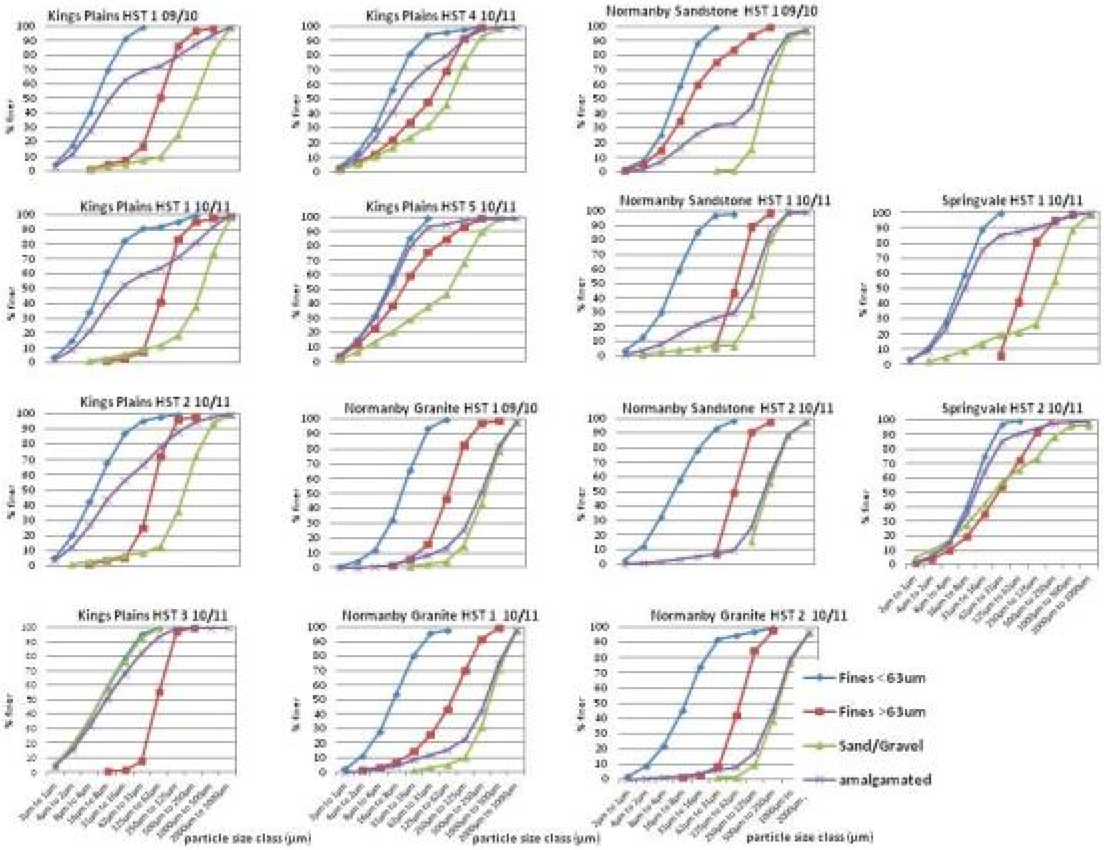

Figure 11 Particle size distribution plots for each sampling period for each HST. Note that the three sub-sample distributions (fines <63µm; fines >63µm; sand/gravel) are shown independently for each site as well as a weighted aggregate distribution (i.e. corrected for relative fraction load).

4.6 Trap performance

A final piece of information regarding the performance of the new HSTs designed for this study, is whether they are disproportionately trapping coarser sediment fractions, compared to the parent hillslope material, and hence whether our samples are biased towards the coarser fractions, and possibly under estimating suspended sediment production. To test this scenario, we compared parent material from Hodgkinson formation soils, given that we had five replicated traps on the same soil type at the Kings Plains site. Figure 12 shows the relationship between the parent material, showing the three different distributions according to the method of dispersion, and the weighted aggregate PSD for the five Kings Plains sites. From these plots it can be seen that, other than some downward bias in the coarser fractions, which would be expected, that the trapped material and the source material are essentially indistinguishable. Based on these data, we are confident that the HSTs are trapping a representative sample of the suspended sediment fraction on the sites at which they have been deployed.

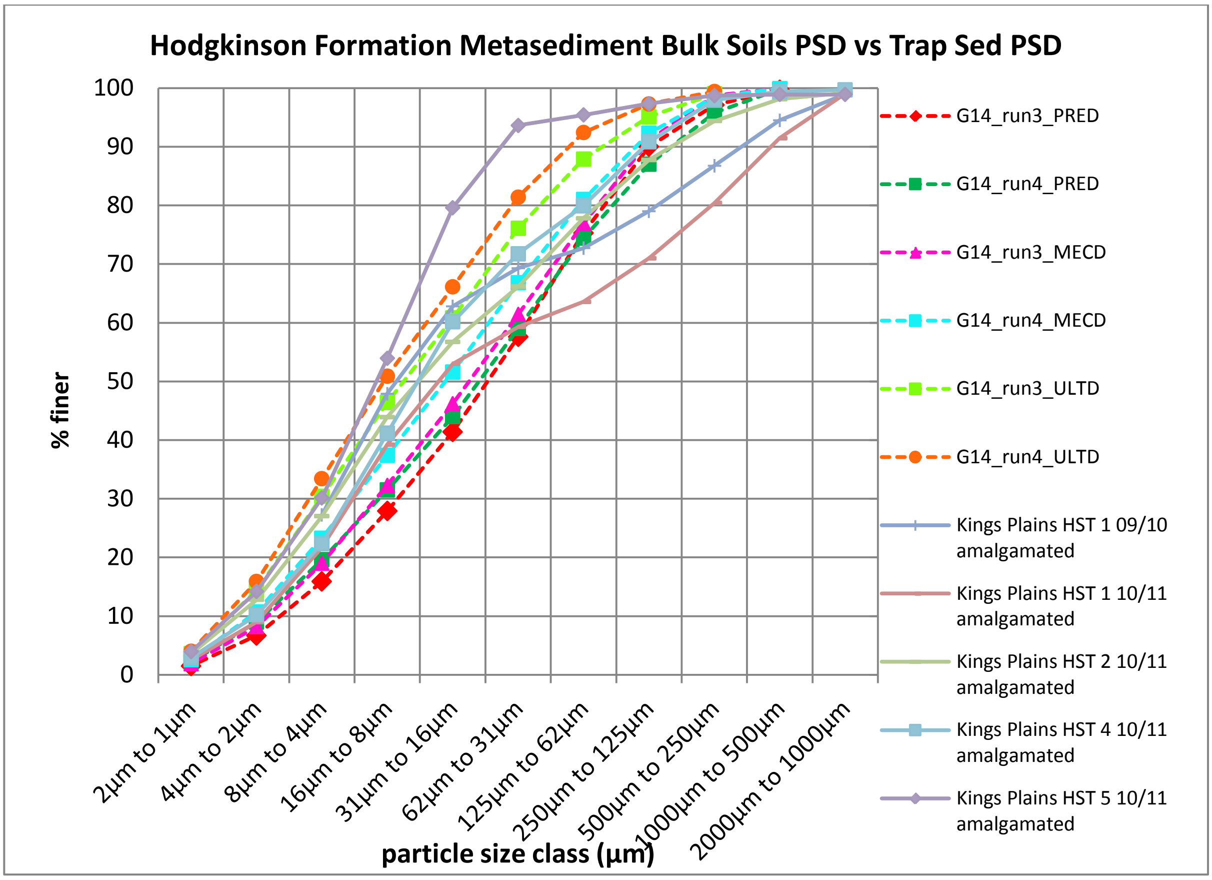

Figure 12 Particle size distribution plots for sediment retained in the 5 Hodgkinson formation (Kings Plains) metasedimentary HSTs (solid lines) plotted against Hodgkinson formation source materials G14 (dashed lines).

5. Discussion

The results of these empirical measurements of hillslope sediment production in the Normanby catchment would seem to indicate that there are some major problems with the application of RUSLE-based sediment budget models in this landscape, when applied without detailed local empirically based estimates of soil erodibility (K Factor). Other RUSLE parameters can each be improved with higher resolution topographic data and more detailed time series of both R and C factors, however, these “fixes” alone, will only go a fraction of the way to solving the fundamental problems inherent within the current K factor values that have been derived in these remote areas based on little or no local data. It is also possible, that the sediment supply limited nature of the hillslopes mean that the basic assumptions underpinning the RUSLE, do not apply here. In particular, the assumption that erosion rates are always inversely proportional to vegetative ground cover.

Previous estimates are at best (for Gilbert sandstone soils) over-estimated by 1 – 2 orders of magnitude, while most other soil types are over-estimated by 2-4 orders of magnitude. These data are backed up by an associated radionuclide fallout tracer study (Olley et al., in prep), which shows that for most of the Normanby catchment hillslope sediment sources are an insignificant component of the overall sediment budget. It is acknowledged that the data presented here are limited in both spatial and temporal scope, and that there is a need to replicate these data across a broader range of soil types, slopes and over longer timescales. Nevertheless, we are confident that this study highlights that broad scale estimates of K factor in the tropical savannah landscapes of northern Australia are in need of major review, given that similar anomalies between SedNet based predictions and tracer based observations have been identified in other studies in northern Australia (Caitcheon & Olley, 2012; Rustomji et al., 2010). If sediment budget models are to be applied to the vast areas of savannah grazing land in the catchments of tropical northern Australia, there is a pressing need to develop a much greater empirical database of soil erodibility across all soil types found in these regions, to underpin predictions of sediment yield from hillslopes.

While this study only covers two wet seasons, we were fortunate that for the two water years over which the study was conducted, both experienced above average annual rainfall, but with very different lead up conditions. The 2009/10 water had an extreme dry season with a late onset wet, while 2010 was an unusually wet dry season, followed by an early onset wet. The data were compared with modeled mean annual sediment production at the same timescale, and as such are directly comparable.

Our ability to predict sediment sources, sinks and catchment loads, and hence target remedial activities, is compromised by inaccurate model input assumptions and model formulations. These data show emphatically that the previous model assumptions regarding hillslope erosion dominating the Normanby basin's sediment budget are clearly wrong and should be disregarded.

This study highlights the critical importance of empirically validated model predictions, and ideally using empirical data to parameterise each source. The study also highlights problems with only calibrating the total loads at the end of the system. This can lead to the situation where the model is believed to be correct because the total load predictions match the observed predictions, but in fact the model is highly inaccurate because the relative contribution from internal catchments sources are highly inaccurate.

While we have highlighted a major shortcoming in our understanding of soil erodibility in these critically important rangeland settings, which are undoubtedly the major source areas of sediment to the GBR , albeit not necessarily from hillslope erosion (e.g. Bartley et al., 2011; Wilkinson et al., 2012), we present a cost effective method for addressing the problem. The study demonstrates that the HSTs are an effective method for measuring hillslope erosion rates in these remote and inaccessible areas, at reasonable cost, with acceptable level of accuracy. Further evaluation of the HSTs should, however, be undertaken in a wider range of conditions.

We also propose a new method for quantifying hillslope sediment delivery ratio (HSDR), based on the proportion of suspended sediment (<63μm) mobilised on each major soil type. The ratio of suspended to bed material load is readily measured with the HST. This represents a major improvement on the approach first proposed by Prosser et al., (2001), and still widely used; which applies a uniform ratio for all soil types, with variation largely attributed to topographic landscape characteristics (Lu et al., 2006). It is our view that the vast majority of the suspended fraction actually ends up in the stream network once it is mobilised. Hence, a HSDR based on the ratio of suspended load to bed-material load will likely provide a much more realistic estimate of the proportion of sediment predicted from a total load estimate (e.g. RUSLE modeling) to be delivered to the stream network.

6. Conclusion

This study has highlighted that the current formulations of RUSLE based hillslope erosion models that have been widely used for predicting sediment loads delivered to highly valued natural assets such as the Great Barrier Reef, are potentially highly flawed, and are significantly over-estimating the proportion of the sediment load that is being contributed from hillslope erosion sources. In most instances where such models have been applied and are calibrated to the few discrete points in catchments with measured load data, this means that the overestimation of hill slope erosion is accompanied by an equivalent under estimation of other sources, which are the true sources of the sediment load. Management strategies that aim to reduce end of catchment sediment yields, based on flawed assumptions about the dominance of a hillslope erosion sources, will be similarly flawed.

7. References

Bartley et al., (2007)

Bartley et al., (in press)

Bartley, R., Corfield, J.P., Hawdon, A.A., Abbott, B.N., Wilkinson, S.N. and Nelson, B., (2010). Impacts of improved grazing land management on sediment yields, Part I: hillslope processes. Journal of Hydrology, 389: 237-248, doi:10.1016/j.jhydrol.2010.06.014

Bartley et al., (2011)

Belperio, A.P., (1983). Terrigenous sedimentation in the central great barrier reef lagoon: a model from the burdekin region. BMR Journal of Australian Geology and Geophysics 8 (3), 179-190.

Brodie, J., Jane Waterhouse, Stephen Lewis Zoë Bainbridge and Johanna Johnson (2010) Current loads of priority pollutants discharged from Great Barrier Reef Catchments to the Great Barrier Reef; ACTFR REPORT NUMBER 09/02, Austalian Centre for Tropical Freshwater Research, Townsville, Qld.

Brodie, J., McKergow, L.A. Prosser, I.P., Furnas, M., Hughes, A.O. and Hunter, H. (2003).Sources of sediment and nutrient exports to the Great Barrier Reef World Heritage Area. Australian Centre for Marine and Tropical Freshwater Research Report No. 03/11, James Cook University, Townsville.

Brodie, J., Waterhouse, J., Lewis, S., Bainbridge, Z., and Johnson. J. (2010). Current loads of priority pollutants discharged from Great Barrier Reef Catchments to the Great Barrier

Reef; ACTFR REPORT NUMBER 09/02, Austalian Centre for Tropical Freshwater Research, Townsville, Qld.

Brooks. A.P., Borombovits, D., Spencer, J., Pietsch, T., Olley, J. (subm.). A low budget, low maintenance, hillslope sediment trap for remote area quantification of total hillslope sediment production

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

Brooks, A. P., Spencer, J. Shellberg, J.G., Knight, J. & Lymburner, L. (2008) Using remote sensing to quantify sediment budget components in a large tropical river - Mitchell River, Gulf of Carpentaria *Sediment Dynamics in Changing Environments* (Proceedings of a symposium held in Christchurch, New Zealand, December 2008). IAHS Publ. 325.

Caitcheon & Olley (2012)

Croke et al., (2006)

Desmet & Govers 1996

DNRM (2012)

Furnas (2003)

Graczyk et al., (1993)

Graczyk, D.J., Robertson, D.M., Rose, W.J. and Steuer, J.J., (2000). Comparison of Water-Quality Samples Collected by Siphon Samplers and Automatic Samplers in Wisconsin. U.S. Geological Survey, Fact Sheet FS-067-00.

Hancock & Evans (2010).

Hawdon, A. A., R. J. Keen, et al. (2008). Hydrologic Recovery of Rangeland following Cattle Exclusion. Sediment Dynamics in Changing Environments, Christchurch, New Zealand, IAHS Publ.

IACWR (1961) Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, The single-stage sampler for suspended-sediment: Minneapolis, Minnesota, St. Anthony Falls Hydraulics Laboratory, Report 13, 105 p.

Joo, M., Raymond, M., McNeil, V., Huggins, R., Turner, R. and Choy, S. (2012) Estimates of sediment and nutrient loads in 10 major catchments draining to the Great Barrier Reef during 2006-2009. Marine Pollution Bulletin in press. doi:10.1016/ j.marpolbul.2012.01.002

Kondolf (XX)

Kroon, F., Kuhnert, P., Henderson, B., Henderson, A., Turner, R., Huggins, R., Wilkinson, S., Abbott, B., Brodie, J., Joo, M., (2010). Baseline pollutant loads to the Great Barrier Reef. CSIRO: Water for a Healthy Country Flagship Report series ISSN: 1835-095X.

Kroon et al., (2011)

Kroon, F.J., et al. (2012). River loads of suspended solids, nitrogen, phosphorus and herbicides delivered to the Great Barrier Reef lagoon. Marine Pollution Bulletindoi:10.1016/ j.marpolbul.2011.10.018

Lu, H., Moran, C. J. and Prosser, I. P. (2006). Modelling sediment delivery ratio over the Murray Darling Basin, *Environmental Modelling and Software* **21**: 1297-1308.

Lu, H., Prosser, I. P., Moran, C. J., Gallant, J., Priestley, G. and Stevenson, J. G. (2003). Predicting sheetwash and rill erosion over the Australian continent, *Australian Journal of Soil Research* **41**: 1- 26.

McKergow, L.A., Prosser, I.P., Hughes, A.O. and Brodie, J. (2005) Sources of sediment to the Great Barrier Reef World Heritage Area. Marine Pollution Bulletin 51(1-4), 200-211.

NLWRA, (2001) – downloadable from http://adl.brs.gov.au/anrdl/metadata_files/pa).

Olley, J.M., Brooks, A.P., Spencer, J., Pietsch, T, Borombovits, D. (in prep) The dominant erosion process supplying sediment to rivers draining into Princess Charlotte Bay, Australia.

Prosser et al., (2001)

Reefplan (2003). http://www.reefplan.qld.gov.au/about.aspx

Reefplan (2009)

Renard et al., (1993)

Renard (1996)

Renard, K. G., Foster, G. A., Weesies, G. A., and McCool, D. K. (1997). `Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE).' Agriculture Handbook No. 703. (USDA: Washington, DC.)

Reid, L. M. & Dunne, T. (1984) Sediment production from forest road surfaces. *Water Resources Research,* 20, 1753-1761.

Rustomji, P., Shellberg, J., Brooks, A., Spencer, J., Caitcheon, G., (2010). A catchment sediment and nutrient budget for the Mitchell River, Queensland. A report to the Tropical Rivers and Coastal Knowledge (TRaCK) Research Program. CSIRO Water for a Healthy Country National Research Flagship, Canberra. Available at: http://track.gov.au/publications/registry/876

Rolfe, J et al. (2004). …

Roswell et al., (1993a)

Roswell et al., (1997)

Shellberg, J., Brooks, A., Spencer, J., 2010. Land-use change from indigenous management to cattle grazing initiates the gullying of alluvial soils in northern Australia, 19th World Congress of Soil Science, Soil Solutions for a Changing World. (1-6 August 2010), Brisbane, pp. 59-62.

Shellberg, J.G., 2011. Alluvial Gully Erosion Rates and Processes Across the Mitchell River Fluvial Megafan in Northern Queensland, Australia. Griffith University, PhD Thesis, Brisbane, Australia.

Shellberg, J.G., Brooks, A.P., Spencer, J., Ward, D., 2012. The hydrogeomorphic influences on alluvial gully erosion along the Mitchell River fluvial megafan, northern Australia. Hydrological Processes. DOI: 10.1002/hyp.9240

Shellberg (unpublished data)?

Simon, A., Bingner, R., Langendoen, E.J., Yuan, Y., Wells, R.R., and Alonso, C.A., (2003a), Combined geomorphic and numerical-modeling analyses of sediment loads for developing water-quality targets for sediment. TMDL 2003, Water Environment Federation, 18p. (on CD). (Peer-Reviewed Proceedings Paper)

Simon, A., Langendoen, E., Bingner, R., Wells, R.R., Heins, A., Jokay, N., and Jaramillo, I., (2003b), Lake Tahoe framework implementation study: Sediment loadings and channel erosion. National Sedimentation Laboratory Research Report No. 39, 375 p. (Peer-Reviewed Agency Report)

Source (2012). (http://www.ewater.com.au/products/ewater-source/for-catchments/)

Thompson et al., (2009)

Wallace, J., Karim, F. and Wilkinson, S., (2012). Assessing the potential underestimation of sediment and nutrient loads to the Great Barrier Reef lagoon during floods. Marine Pollution Bulletin, 65(4-9): 194-202.

Wallace et al., (in press)

Wilkinson, S (2008). Testing the capability of a sediment budget model for targeting remediation measures to reduce suspended-sediment yield *Sediment Dynamics in Changing Environments* (Proceedings of a symposium held in Christchurch, New Zealand, December 2008). IAHS Publ. 325, 2008, 559-566.

Wilkinson, S., A. Hawdon, et al. (2008). Ecological Monitoring of the Townsville Field Training Area (TFTA) 2007/08, CSIRO Land and Water and ACTFR Client Report to Department of Defence.

Wilkinson et al., (2012)

Wischmeier, W. H., and Smith, D. D. (1978). `Predicting Rainfall Erosion Losses: A Guide to Conservation Planning.' Agriculture Handbook No. 537. (USDA: Washington, DC.)

Yu, B. (1998). Rainfall erosivity and its estimation for Australia's tropics. *Aust. J. Soil Res.*, 1998, 36, 143–65.

Table 3 Table showing the HST trap hydrological characteristics for the sampling period and associated sediment delivery. Also shown is a breakdown of how the event mean sediment concentrations were derived for each trap, and the SSC data collected at some sites – which provide an upper limit for the sediment concentrations collected on the rising stage of early wet season events. Note that these will, by definition, provide higher than average sediment concentrations, having been most likely collected in the first storms at the start of the wet season. The backwater conditions in the trap will also likely increase the sediment concentrations as the sediment is progressively retained, with lower concentration water passing through the trap. Hence by the time the Rising Stage Sampler is overtopped, considerable sediment concentration could have occurred. Note that KP3-5 uses the same annual rainfall as KP2 – given that they are all in the same area. Rain gauge failures also occurred at NSG1&2 in 2010/11 and NSS1_2010/11; and in each of these cases the data from NSS2_2010/11 has been substituted.

	Metasediments						**Granitic**			**Sandstone**			**Basalt**	
	KP1-2009-10	KP1-2010-11	KP2-2010-11	KP3-2010-11	KP4-2010-11	KP5-2010-11	NSG1_2009-10	NSG1_2010-11	NSG2_2010-11	NSS1_2009-10	NSS1_2010-11	NSS2-2010-11	SPV1-2010-11	SPV2-2010-11
1. catchment area (m^2)	3985	3985	1567	868	1769	2029	2588	2588	613	714	714	2637	19383	7853
2. Total wet season rainfall (mm)	1082	1450	1291	1291	1291	1291	1167	1150	1150	1323	1150	1150	1038	1038
3. Total Rain from events > 11 mm (mm)	926.8	1215	1161	1161	1161	1161	965	900	900	1179	900	900	905	905
4. Num Events > 11mm	32	43	42	42	42	42	28	30	30	36	30	30	33	33
5. Ave event rainfall (mm)	29.0	28.3	27.6	27.6	27.6	27.6	34.5	30.0	30.0	32.7	30.0	30.0	27.4	27.4
6. Ave incident vol/event (m^3)	115.4	112.6	43.3	24.0	48.9	56.1	89.2	77.6	18.4	23.4	21.4	79.1	531.3	215.3
7. RO Co-efficient	0.25	0.25	0.50	0.50	0.50	0.50	0.35	0.35	0.35	0.25	0.25	0.25	0.05	0.05
8. Event av. Runoff vol (m^3)	28.9	28.2	21.7	12.0	24.4	28.0	31.2	27.2	6.4	5.8	5.4	19.8	26.6	10.8
9. Trap volume before spilling (m^3)	9.9	9.9	15.7	15.5	15.8	14.4	10.8	10.8	9.9	7.1	7.1	12.9	9.6	5.9
10. infiltration rate (l/min/trap)	471	471	599	556	579	565	564	564	484	341	341	523	557	286
11. # events > trap vol	27	47	26	11	28	35	23	23	8	12	7	19	32	24
12. Est # events > trap vol x infiltration rate	2	2	1	1	2	2	0	0	0	2	0	0	2	1
13. Total sed trap load – crctd (g)	**1137**	**677**	**3021**	**7468**	**3301**	**4549**	**26768**	**868**	**3968**	**18281**	**4895**	**43061**	**674**	**1302**
14. Ave event sed delivery (g/event)	36	16	72	178	79	108	956	29	132	508	163	1435	20	39
15. conc mg/l (total load)	**1.2**	**0.6**	**3.3**	**14.8**	**3.2**	**3.9**	**30.6**	**1.1**	**20.6**	**86.9**	**30.5**	**72.6**	**0.8**	**3.7**

16. total mass for 30 l expt. (g)	0.037	0.017	0.100	0.445	0.096	0.116	0.918	0.032	0.617	2.606	0.914	2.178	0.023	0.110
17. Average fines (<63um)	**841**	**600**	**2509**	**4545**	**2615**	**4254**	**2851**	**415**	**559**	**8717**	**2295**	**6711**	**648**	**1203**
18. Ave event sed delivery (<63um)	26.3	14.0	59.7	108.2	62.3	101.3	101.8	13.8	18.6	242.1	76.5	223.7	19.6	36.5
19. Event mean conc mg/l (<63um)	**0.91**	**0.50**	**2.76**	**9.02**	**2.55**	**3.61**	**3.26**	**0.51**	**2.89**	**41.43**	**14.29**	**11.31**	**0.74**	**3.39**
20. Measured pk Inst Sed conc. (mg/l) from RS Samplers		137	16	379	320					360	88		60	27

Table 4 HST site characteristics used for parameterising the RUSLE model runs shown in Figure 7. Also shown are the corrected measured loads from each trap and the new back calculated K values for the four main soil types tested as part of this study.

		Metasediments						**Granitic**			**Sandstone**			**Basalt**		
		KP1-2009-10	KP1-2010-11	KP2-2010-11	KP3-2010-11	KP4-2010-11	KP5-2010-11	NSG1_2009-10	NSG1_2010-11	NSG2_2010-11	NSS1_2009-10	NSS1_2010-11	NSS2-2010-11	SPV1-2009-10	SPV1-2010-11	SPV2-2010-11
DNRM_2012_data	**trap catchment Area_m^2**	***3984***	***3984***	***1601***	***868***	***1768***	***2028***	***2587***	***2587***	***613***	***714***	***714***	***2636***	***19375***	***19375***	***7850***
	R	9803	9803	9788	9788	9788	9793	8851	8851	8908	8940	8940	8931	8538	8538	8532
	K	0.0476	0.0476	0.0476	0.048	0.048	0.048	0.082	0.082	0.082	0.035	0.035	0.028	0.036	0.036	0.036
	L	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	S	0.502	0.502	0.375	0.375	0.374	0.326	0.628	0.628	0.203	0.671	0.671	0.755	0.601	0.601	0.394
	C	0.024	0.024	0.005	0.005	0.006	0.005	0.021	0.021	0.015	0.005	0.005	0.016	0.019	0.019	0.018
	1) RUSLE mean annual soil loss (t/ha/yr)	**5.68**	**5.68**	**0.93**	**0.96**	**1.03**	**0.73**	**9.68**	**9.68**	**2.29**	**1.09**	**1.09**	**2.97**	**3.43**	**3.43**	**2.16**
JCU_2003_data	**R**	9803	9803	9788	9788	9788	9793	8851	8851	8908	8940	8940	8931	8538	8538	8532
	K	0.051	0.051	0.051	0.051	0.051	0.051	0.078	0.078	0.078	0.012	0.012	0.012	0.061	0.061	0.061
	L	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	S	2.282	2.282	2.13	2.13	2.13	2.1005	0.564	0.564	0.615	0.8	0.8	1.066	0.3505	0.3505	0.357
	C	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	2) RUSLE mean annual soil loss (t/ha/yr)	**57.04**	**57.04**	**53.16**	**53.16**	**53.16**	**52.45**	**19.47**	**19.47**	**21.37**	**4.29**	**4.29**	**5.71**	**9.13**	**9.13**	**9.29**
GU Plot data incl. 3 C factor options	**R**	3850	6802	5838	5838	5838	5838	4807	4807	4807	6657	6657	7270	4482	4482	4482
	K	0.048	0.048	0.048	0.048	0.048	0.048	0.082	0.082	0.082	0.035	0.035	0.028	0.036	0.036	0.036
	L	4.71	4.71	2.78	2.96	3.57	3.83	3.87	3.87	2.30	1.95	1.95	3.74	4.80	4.80	5.84
	S	0.98	0.98	1.16	2.12	1.93	1.58	1.36	1.36	0.84	0.60	0.60	0.88	0.51	0.51	0.62
	3) Late Dry C	0.018	0.009	0.042	0.042	0.039	0.021	0.098	0.039	0.039	0.081	0.067	0.021	0.018	0.008	0.006
	3) RUSLE mean annual soil loss (t/ha/yr)	**14.92**	**13.25**	**38.00**	**73.84**	**73.70**	**34.57**	**204.71**	**80.31**	**29.57**	**21.95**	**17.97**	**13.75**	**7.00**	**2.99**	**3.26**

4) Wet season av. C	0.016	0.005	0.020	0.014	0.020	0.011	0.095	0.020	0.020	0.051	0.025	0.014	0.011	0.004	0.003
4) RUSLE mean annual soil loss (t/ha/yr)	**13.23**	**7.95**	**18.09**	**24.19**	**38.43**	**18.67**	**197.7**	**41.75**	**15.53**	**13.87**	**6.81**	**9.40**	**4.21**	**1.71**	**1.94**
5) DNRM 2012 C	0.024	0.024	0.005	0.005	0.006	0.005	0.021	0.021	0.015	0.005	0.005	0.016	0.019	0.019	0.018
5) RUSLE mean annual soil loss (t/ha/yr)	**20.46**	**36.14**	**4.78**	**9.56**	**11.36**	**8.02**	**44.08**	**44.08**	**11.75**	**1.41**	**1.41**	**10.54**	**7.38**	**7.38**	**10.38**
6) M'srd trap total yield (t/ha/yr)	**0.0029**	**0.0017**	**0.0189**	**0.0860**	**0.0187**	**0.0224**	**0.1034**	**0.0034**	**0.0647**	**0.2560**	**0.0686**	**0.1633**	**0.0003**	**0.0003**	**0.0017**
Calc K (using wet season av C + trap measured R, L & S)	1.03 E-05	1.02 E-05	4.96 E-05	1.69 E-04	2.31 E-05	5.71 E-05	4.31 E-05	6.62 E-06	3.43 E-04	6.41 E-04	3.49 E-04	4.85 E-04	2.95 E-06	7.30 E-06	3.06 E-05

Table 5 Suspended sediment (<63um) correction factors for each trap based on the measured sediment retained in the geofabric after the sample has been collected according to the methods outlined in the text. Separate correction factors were applied for the trap wall and the trap apron. Note the trap wall area varies for each site due to the different slopes of each trap, whereas a consistent apron area of 7.31 m^2 has been applied to all sites. In reality this will over-estimate the effective apron area, and as such this correction factor is highly conservative (i.e. likely over-estimating the retained fine sediment).

Sediment correction factors for Fine sediment retained in Geofabric					
Trap	trap front area (m^2)	apron area (m^2)	front (g/m^2)	apron (g/m^2)	total sed (g)
KP MetaSed HST 1_09-10	3.92	7.31	41.78	25.49	350
KP MetaSed HST 1_10-11	3.92	7.31	41.78	25.49	350
KP MetaSed HST 2	4.99	7.31	46.85	79.58	816
KP MetaSed HST 3	4.63	7.31	29.11	42.28	444
KP MetaSed HST 4	4.82	7.31	21.43	59.75	540
KP MetaSed HST 5	4.71	7.31	86.95	197.81	1856
NS Granite HST 1_09-10	4.70	7.31	9.79	46.44	386
NS Granite HST 1_10-11	4.70	7.31	9.79	46.44	386
NS Granite HST 2	4.04	7.31	6.06	19.89	170
NS Sandstone HST 1_09-10	2.84	7.31	448.49	392.31	4142
NS Sandstone HST 1_10-11	2.84	7.31	36.29	109.84	906
NS Sandstone HST 2	4.36	7.31	11.96	182.66	1388
SV Basalt HST 2	2.39	7.31	17.92	48.84	400
SV Basalt HST 1	4.64	7.31	50.76	64.43	707