Available online at www.sciencedirect.com
ScienceDirect

Catena 67 (2006) 119 – 127

CATENA

www.elsevier.com/locate/catena

Analysis of gully dimensions and sediment texture from southeast Australia for catchment sediment budgeting

Paul Rustomji

CSIRO Land and Water, GPO Box 1666, Canberra ACT 2601, Australia

Received 25 July 2005; received in revised form 23 January 2006; accepted 6 March 2006

Abstract

Catchment scale sediment budgeting models are increasingly being used to target remediation works aimed at controlling erosion and improving water quality. Gully erosion is often a major sediment source and needs to be accounted for in such models in a manner consistent with the scale of analysis and available data. Using 130 measurements of gully cross-sectional area and 45 measurements of gully wall sediment texture, the variability in gully dimensions and particle size distribution for the Lake Burragorang catchment in Australia is examined. The distribution of gully cross-sectional area measurements is log-normally distributed and modelling indicates a representative value of 23 m^2 be used in catchment sediment budgeting applications. The proportion of gully eroded sediment contributing to the bedload budget (defined as particles > 63 μm diameter) of a river link is approximately half, though may be higher in igneous landscapes. A continental scale spatially distributed subsoil texture dataset provided limited capacity to predict the finer scale spatial variation in the proportion of sediment contributing to bedload from gully erosion within the Lake Burragorang catchment.

Crown Copyright © 2006 Published by Elsevier B.V. All rights reserved.

Keywords: Gully; Sediment budget; Bedload; Catchment

1. Introduction

Reducing sediment exports from river catchments requires an understanding of the erosion processes delivering sediment to the river as well as the downstream sediment transport and deposition upon floodplains and in reservoirs. Catchment sediment budgets are often used as a framework to compare different sediment sources and sinks and can be used to plan remediation works. The construction of accurate sediment budgets requires that the sediment source terms reflect the major erosion processes operating in a landscape and that these be defined as accurately as possible.

In many environments, the formation of permanent erosion gullies is a major sediment generation process that should be incorporated into catchment sediment budgets. Permanent erosion gullies are landforms created through incision of alluvial or colluvial deposits by overland or subsurface flow which, in an agricultural context, are too deep to be easily ameliorated with ordinary farm tillage equipment (Soil Science Society of America, 2001). They typically persist for decades to centuries after formation before gradually re-aggrading. Gully erosion in parts of Australia (Wallbrink et al., 1996; 1998; Wasson et al., 2002; Wallbrink, 2004), Africa (Liggitt and Fincham, 1989; Boardman et al., 2003; Flügel et al., 2003; Daba et al., 2003), Europe (Poesen and Hooke, 1997; Gábris et al., 2003; Sidorchuk and Golosov, 2003; Poesen et al., 2003; Belyaev et al., 2004), the United States (Gellis et al., 2001) and Asia (diCenzo and Luk, 1997; Nagasaka et al., 2005) is recognised as an important and often the dominant source of sediment delivered to rivers (Poesen et al., 1996; Olley and Wasson, 2003; Valentin et al., 2005), impacting negatively on water quality, reservoir or lake volumes and aquatic habitat. Thus, consideration of gully erosion processes in catchment sediment budgets is of widespread relevance.

At a regional catchment scale, modelling of erosion sources, sediment transport and deposition is typically required to provide an integrated and comprehensive sediment budget. Whilst detailed process based models exist to describe the

---

E-mail address: paul.rustomji@csiro.au.

0341-8162/$ - see front matter. Crown Copyright © 2006 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.catena.2006.03.004

development of individual gully segments (Sidorchuk, 1999, 2005), such detailed approaches cannot be applied at large spatial scales (e.g. catchments >1000 km^2). In these cases, one approach is to identify the long term yield from gully erosion within smaller sub-catchments of a river network. This approach has been applied in Australia in large scale sediment budgeting studies (Hughes and Prosser, 2003; Wilkinson et al., 2005; McKergow et al., 2005) and is incorporated into the SedNet model, which links hillslope, gully and river bank erosion at a sub-catchment scale with riverine transport and deposition (Prosser et al., 2000, 2001). The long term average contribution of sediment eroded by gully erosion, GC (t/yr), from a sub-catchment with n gully links, to the bedload budget of its associated river link, can be expressed as:

$$\mathrm{GC} = \frac{\sum_{i=1}^{n} (A_i L_i \rho P)}{\tau} \tag{1}$$

where A_i is the cross-sectional area of gully i (m^2), L_i is the length of gully i (m), ρ is the density of gully sediment

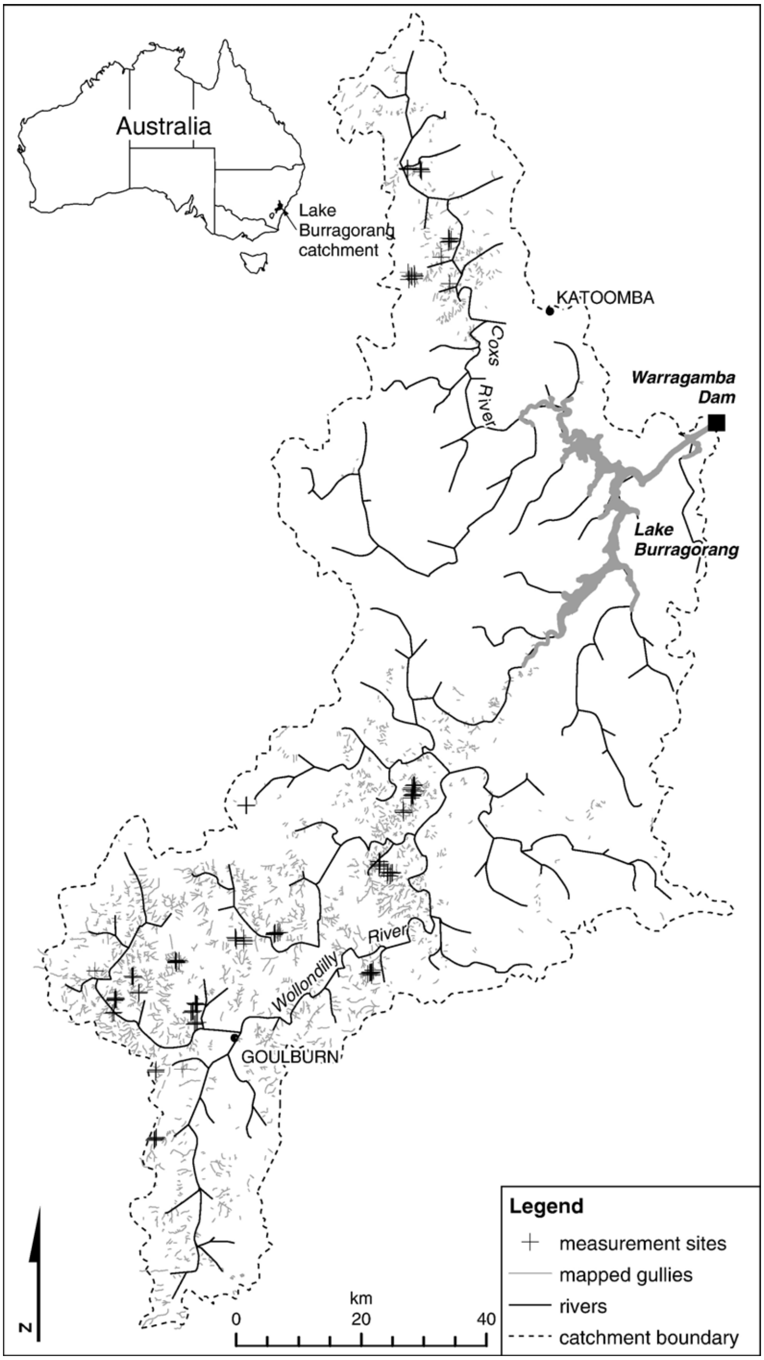

Fig. 1. Site map showing the position of Lake Burragorang's catchment within Australia and a catchment map showing the gully network, cross-sectional area measurement sites, major drainage lines and local towns.

(t/m^3), P is the proportion of gully sediment that contributes to bedload (assumed here to be the fraction greater than 63 μm) and τ is the duration over which the gully has formed in (years). L can be estimated from maps of gully network extent derived from air photos. In applications in Australia for example, ρ is typically assumed to be 1.5 t/m^3, P is assumed to be 0.5, A_i is assumed to be 10 m^2 and $\tau = 100$ or 150 years. Note that $1 - P$ is the proportion of sediment assumed to contribute to the suspended load budget of a river link.

Whilst spatial mapping of gully network extent across a landscape can often be obtained from land management agencies, basic data pertaining to the variability in gully dimensions at a landscape scale, required to estimate the sediment yield from gully erosion, are generally absent. Additionally, information on the sediment texture of eroded gullies is also often lacking. Here, we present observations of gully morphology that are used to refine the representation of gully erosion at the catchment scale. The methods employed to analyse the data should be of relevance in construction of catchment scale sediment budgets incorporating gully erosion in other environments and the observations from Australia will be of value for comparative purposes elsewhere. The texture of gully sediments is also examined to assist in determining the proportion of eroded sediment contributing to the bedload and suspended load budgets of a river network. The soil texture observations are compared to a national, gridded dataset of subsoil texture to investigate whether such data have utility for predicting how this proportion may vary across the landscape, at least in an empirical way.

2. Study sites

The study area, shown in Fig. 1, comprises the catchment for Lake Burragorang and is approximately 9000 km^2 in area and is part of the Hawkesbury–Nepean basin. Lake Burragorang is the main water supply reservoir for metropolitan Sydney and is dammed by Warragamba Dam. Targeted management of the reservoir's catchment is critical for maintaining water quality given the limited resources available for catchment remediation works, necessitating construction of a spatially explicit catchment sediment budget. The catchment comprises a diverse suite of landforms that can be broadly divided into a low relief Southern Tablelands region drained by the Wollondilly River and situated upon Palaeozoic metasediments and igneous rocks; a central forested gorge reach, within which Lake Burragorang is located and a northern region from which the Cox's River flows, dominated by Palaeozoic igneous rocks.

Gully erosion in the catchment has occurred primarily within the Southern Tablelands and amidst the igneous region of the Cox's catchment to the north, as evident in Fig. 1. Studies from the Southern Tablelands of New South Wales show that whilst gully incision occurred over the Holocene (Prosser, 1991), the rate of gully incision increased dramatically in the period following European settlement after AD 1820 (Eyles, 1977; Wasson et al., 1998; Olley and Wasson, 2003); this conclusion is similar to other locations where landuse intensification has been associated with gully development (Valentin et al., 2005). In some cases, slow re-aggradation may be occurring (e.g. Zierholz et al., 2001) through vertical accumulation of sediments within the eroded void, which generally changes little in width after formation (e.g. Martínez-Casasnovas, 2003). Erosion gullies can occur in the forested lands around Lake Burragorang, though at a much lower rate as the triggers responsible for their formation (vegetation clearance, over stocking etc.) have been less intense.

3. Methods

Measurement of 130 gully cross-sections (classified as rectangular, trapezoidal or triangular in cross-section) were made in the field. Up to 5 measurements were made from an individual gully network with care taken to space measurement sites well apart and to sample a number of branches within a network. The parent lithology was recorded along with the link's network position, categorised into headwater (no incised tributaries upstream) or downstream (incised tributaries present upstream). Fig. 1 shows the sampling sites and Table 1 lists the number of measurements made in each geologic map class. Overall, 87 cross-sectional area measurements are from igneous terrain and 43 from landscapes developed upon sedimentary rocks. This difference approximately reflects the catchment wide variation in gully density of 0.33 and

Table 1
Summary of the number of gully cross-sectional area measurements made in different geologic map classes

Geological map code	Rock type	*n*
Igneous		
Gg	Siluro–Devonian Wollogorang granite	14
Gf	Siluro–Devonian Forest Lodge granite	4
Clg	Carboniferous adamelite granite, granodiorite	24
ig	Carboniferous dolerite	6
Dlb	Devonian bindook porphyry	23
Dg	Devonian granite, granodiorite, porphyry	14
Tb	Tertiary basalt	2
Sedimentary		
θs-s	Ordovician–Silurian sandstones	13
θs	Orodovician sandstone	14
Dur	Devonian sediments	7
Su	Silurian limestone and shale	7
Psb	Permian sediments	2

The relevant maps are the Goulburn 1:250,000 (Geological Survey of New South Wales, 1970) and Sydney 1:250,000 (Geological Survey of New South Wales, 1966) sheets.

0.12 km/km^2 for landscapes of igneous and sedimentary parent lithology respectively.

To assess P, 45 gully wall sediment samples were collected and wet sieved into the following size classes: >2000 μm, 2000 to 125 μm, 125 to 63 μm, 63 to 10 μm and <10 μm and the relative proportions of each size class by weight calculated. P was calculated as the proportion of sediment coarser than 63 μm with this diameter taken to be the sand-silt boundary (Gale and Hoare, 1991). Spatially distributed subsoil particle size data from the Australian Soil Resources Information System (Henderson et al., 2001; Johnston et al., 2003; Henderson et al., 2005), referred to as ASRIS, were used to examine whether this data can be used to predict the spatial variation in P. The particle size class boundaries used in ASRIS define the sand-silt boundary as 20 μm (Carlile et al., 2001a). This differs from the 63 μm sand-silt boundary used in SedNet for the boundary between suspended and bedload material and the boundary used when sieving the sediment samples.

ASRIS predictions of the percentage of clay in the subsoil are made using two methods: the first is spatial modelling of point based particle size data using environmental predictors (Henderson et al., 2005) and the second is based on modelling of soil polygons with percentage clay values defined by look-up tables (Carlile et al., 2001b). Silt content is modelled by the second method but not the first. In the case of the soil polygon modelling, percent silt and clay values fall within a limited number of discrete values assigned to different soil polygons. In theory, P should be inversely related to the ASRIS polygon based percentage silt plus clay, however, discrepancies would be expected given the different particle size class boundaries. Potentially these discrepancies could be a minor component of the variability around an empirical, fitted relationship between P and the ASRIS data at the same location, which is currently the best available spatially distributed dataset of subsoil texture. If so, the ASRIS data could be used as a basis for predicting the spatial variation in P across a catchment. To investigate this, comparisons are made between the measured proportion of gully wall sediments >63 μm and:

(1) point based clay proportion;
(2) point based clay proportion plus polygon based silt proportion;
(3) polygon based clay proportion plus polygon based silt proportion.

4. Results

4.1. Gully cross-sectional area

Gully cross-sectional area measurements ranged from 2.6 to 105 m^2 and the distribution of values is strongly positively skewed. Table 2 lists summary statistics for the data, collectively and divided according igneous or sedimentary parent lithology and headwater or downstream position. Fig. 2 shows the proportion of cross-sectional area measurements smaller than a given value for the two rock types; the positive skewness and similarity of the distributions is clearly evident. The distribution of cross-sectional area of headwater and downstream gullies, illustrated as boxplots in Fig. 3 shows considerable overlap, though downstream gullies have a higher median cross-sectional area of 27 m^2 relative to headwater gullies with a median cross-sectional area of 12.3 m^2.

Table 2
Summary statistics for gully cross-sectional area measurements, categorised by source lithology and network position

	Combined	Igneous	Metasediment	Headwater	Downstream
Original data					
n	130	87	43	73	57
Min (m^2)	2.6	2.6	2.6	2.6	3.2
Max (m^2)	105	105	95	69	105
Median (m^2)	17.4	17.3	18.2	12.3	27.0
Skewness	2.00	1.96	1.89	1.95	1.41
Base-10 logarithms					
Mean	1.21	1.20	1.21	1.07	1.38
Standard deviation	0.37	0.38	0.34	0.33	0.35
Shapiro–Wilk normality test					
W statistic	0.99	0.99	0.99	0.99	0.98
p value	0.39	0.61	0.98	0.56	0.37
t-test H_0: mean = 1					
t statistic	6.34	29.00	4.13	1.82	8.19
p value	<0.001	<0.001	<0.001	0.07	<0.001

A Shapiro–Wilk test was used to assess the normality of the data after transformation by taking the base 10 logarithms. The null hypothesis that the data are normally distributed once log-transformed could not be rejected at the 95% confidence level for either the data as a whole or for any sub-category (Table 2). The null hypothesis that the mean of the log transformed data was equal to $\log10(10) = 1$ (the value for A adopted in past applications of SedNet e.g. Prosser et al., 2001; Lu et al., 2004; McKergow et al., 2005; Wilkinson et al., 2005) could be firmly rejected at the 95% confidence level for the data as a whole and for all sub-categories except for headwater gullies.

4.2. Estimating a representative cross-sectional area value

The order-of-magnitude range and skewness of the cross-sectional area distribution raises the question of whether it is appropriate to use a single value of gully cross-sectional area to estimate eroded gully volume in a model such as SedNet and if so, how it should be chosen. Given the positively skewed cross-sectional area distribution, the mean of the raw data is not a particularly robust

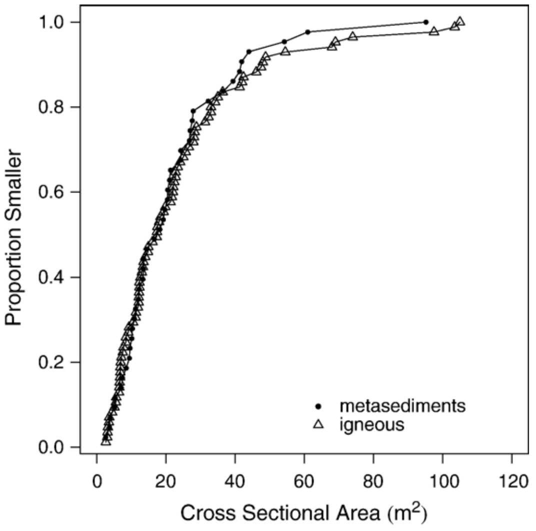

Fig. 2. Distribution of gully cross-sectional area measurements classified by parent lithology.

representation of the data. Simply selecting the median value as being representative provides little insight into the significance of the order of magnitude range observed in the data upon potential sediment yields from gully erosion at the catchment scale. In order to more comprehensively explore the significance of the observed distribution of gully cross-sectional area upon potential gully erosion volumes across the Lake Burragorang catchment, a modelling approach has been adopted.

As shown in Table 2, the log transformed cross-sectional area measurements are normally distributed, with mean of 1.21 and standard deviation of 0.37 log units and this observation provides the basis for the modelling. Each element of the mapped gully network (as shown in Fig. 1) was assigned a cross-sectional area randomly drawn from a normal distribution with mean = 1.21 and standard deviation of 0.37 log units (i.e. equal to the mean and standard deviation of the log transformed data). The total volume of gully incision that this represents over the Lake Burragorang catchment was then calculated by multiplying the length of each gully link by its randomly assigned cross-sectional area (converted back to m^2 units) and summing for all gully links. This process was then repeated 1000 times to produce a frequency distribution of total gully volume, shown in Fig. 4. This figure shows the variability in total gully volume arising from repeated hypothetical episodes of catchment-wide gully erosion. A distinct peak is evident in the simulated total gully volume values. By dividing the modal volume by the total length of mapped gullies (1630 km), the

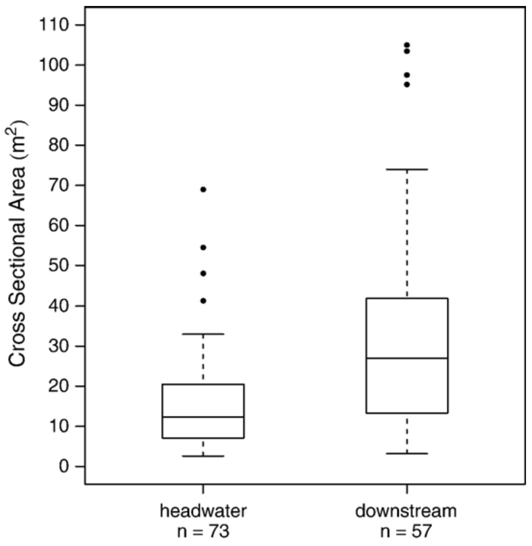

Fig. 3. Boxplots of gully cross-sectional area measurements classified by position in the drainage network.

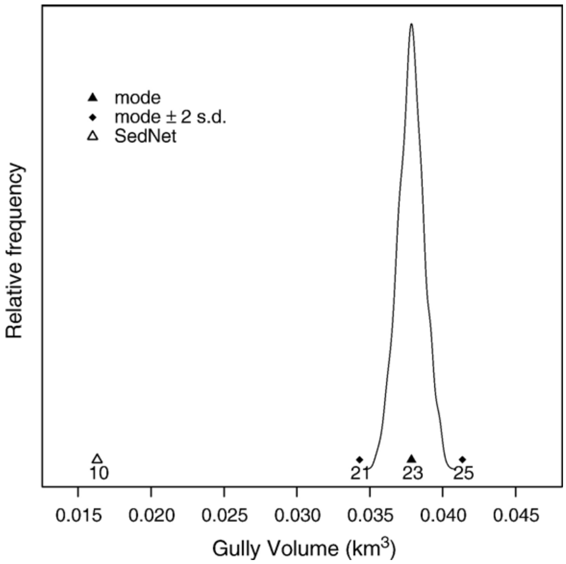

Fig. 4. Relative frequency of total gully volume for the Lake Burragorang catchment derived from applying randomly selected cross-sectional area values to the catchment's gully network. The SedNet point refers to the total gully volume calculated using $A = 10$ m^2, whilst the modal data point shows the cross-sectional area value (23 m^2) that would give a total gully volume equivalent to the modal value of the modelled distribution. Equivalent cross-sectional area values at the mode ± two standard deviations of the synthetic volume distribution are also shown.

Table 3

Summary of bedload proportion, categorised by source lithology

	Combined	Igneous	Metasediment
n	45	31	14
Minimum	0.09	0.24	0.09
Maximum	0.87	0.87	0.72
Median	0.56	0.57	0.50
Mean	0.54	0.57	0.48
Standard deviation	0.16	0.16	0.15
Shapiro–Wilk normality test			
W statistic	0.98	0.98	0.93
p value	0.78	0.68	0.28
t-test H_0: *mean = 0.5*			
t statistic	1.74	2.38	−0.39
p value	0.09	0.02	0.70

Table 4
Summary of linear model coefficients calculated between measured proportion bedload P and ASRIS soil texture datasets

	Standard					
	Intercept	Coefficient	Error	t value	p value	R^2
Full dataset						
% clay (point)	0.71	−0.58	0.30	−1.91	0.06	0.08
% clay (point)+ % silt (poly)	0.73	−0.39	0.21	−1.80	0.07	0.07
% clay (poly)+ % silt (poly)	0.72	−0.28	0.15	−1.80	0.07	0.07
Outlier removed						
% clay (point)	0.75	−0.67	0.27	−2.49	0.01	0.14
% clay (point)+ % silt (poly)	0.77	−0.47	0.19	−2.44	0.02	0.12
% clay (poly)+ % silt (poly)	0.74	−0.29	0.14	−2.14	0.04	0.10

The terms point and poly refer to the point and polygon derived ASRIS predictions. The null hypothesis that the slope coefficient=0 could not be rejected at the 95% confidence level for any model.

modal volume can be expressed in terms of an equivalent cross-sectional area. The equivalent cross-sectional area, which in this case is 23 m^2, is the cross-sectional area value that would have produced the same volume of sediment if applied uniformly to all elements in the mapped gully network. The range in the gully volume simulations completely falls within two standard deviations either side of this modal value, equivalent to 21 and 25 m^2, respectively. In comparison, it can be seen that the volume of gully sediment predicted using $A=10$ m^2 is less than half the volume of sediment estimated to have been eroded according to the simulation.

4.3. Gully sediment texture

Table 3 lists a range of summary statistics concerning the proportion of gully wall sediment that is coarser than 63 μm and hence classified as contributing to the bedload budget of a river link. This proportion varies over the range 0.09 to 0.87. Whether the proportion-bedload data are considered collectively or divided according to parent lithology, the null hypothesis that the data are normally distributed could not be rejected at the 95% confidence limit using a Shapiro–Wilk normality test. To test whether the mean proportion-bedload values listed in Table 3 differed significantly from $P=0.5$, two-sided t-tests were conducted. The null hypothesis that the mean does not significantly differ from 0.5 could only be rejected at the 95% confidence level for the igneous sub-category which had the highest mean proportion ($P=0.57$) of particles >63 μm diameter.

Table 4 lists summary statistics from the linear regression models shown in Fig. 5 of measured bedload proportion against the ASRIS subsoil particle size data for the same geographic location. The expected inverse relationship between the measured bedload proportion and the ASRIS subsoil data is weak, with R^2 values of 0.07 to 0.08. The null hypothesis that the regression coefficient equals zero could not be rejected at the 95% confidence level for each of the three models using the full dataset, suggesting little predictive value in the ASRIS data. After removing a single outlying data point (with the lowest proportion bedload value of 0.09), the strength of the relationships become marginally stronger for all three models and the null hypothesis that the regression coefficient equals zero could be rejected at the 95% confidence level in all cases. Whilst the ASRIS point based percentage clay data gave the highest R^2, the standard error associated with the slope coefficient was also the highest of all the models indicating it was the least well constrained. These results suggest that there is at best marginal utility in using the ASRIS subsoil data to derive spatially distributed values of the proportion of gully sediment contributing to the bedload sediment budget of a river network, at least within this catchment. Using a mean value would in this case be appropriate.

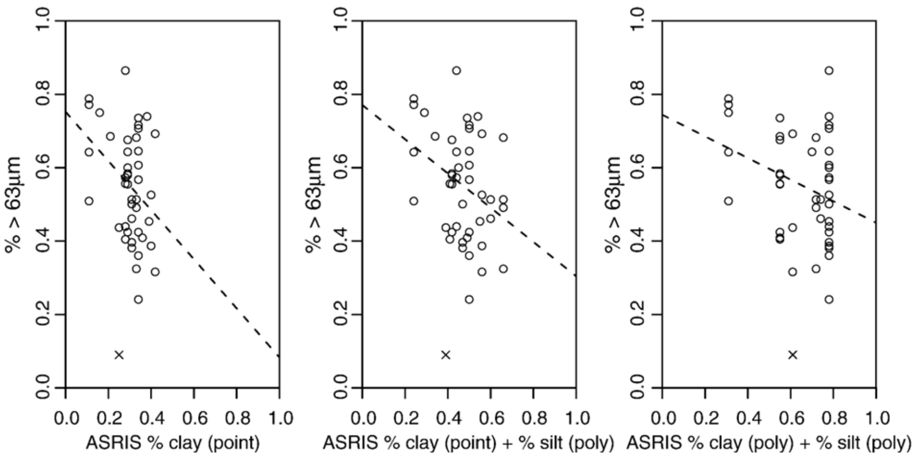

Fig. 5. Linear regression models between the proportion of gully wall sediment coarser than 63 μm and ASRIS subsoil datasets. The dashed lines show the fitted models; note that the point shown by the × has been omitted from that used to fit the curves. See Table 4 for statistics pertaining to the model fitting.

5. Discussion and conclusions

The order of magnitude range in gully cross-sectional area in this study is not surprising given that the gullies have formed amidst Australia's relatively old, flat and tectonically quiescent landscape. The large variability in age, degree of weathering and induration of the regolith into which the gullies have incised could be expected to contribute to different erodibilities of valley fill sediments. This diverse geomorphic heritage also arguably accounts for much of the variability in the measured sediment texture. Similar influences are likely to be found in many other landscapes. Perhaps surprisingly, there appeared to be little difference in the distribution of cross-sectional area between gullies with either igneous or sedimentary parent lithology, despite evidence for a coarser particle size distribution of the former. The poor relationships between the ASRIS particle size data and that measured in this study, whilst partly being a product of differing definitions of particle size class boundaries, are also likely to be driven by the age and heterogeneity of the landscape. The ASRIS data has the greatest power predicting the variability of P at larger spatial scales, such as a continental scale, where regional differences in sediment texture are stronger due to greater differences in geology and landscape evolution. Within this study, only a limited number of geologic classes and physiographic environments represented in the full ASRIS database were sampled.

There are clear statistical patterns evident in the cross-sectional area data, most notably that the data are log-normally distributed. Modelling revealed that if a single representative cross-sectional area were to be chosen for modelling gully erosion at a catchment scale, there is evidence that it should be approximately 44% larger (23 m^2) than the mean of the log-transformed observations ($101.21 = 16.2$ m^2). This difference arises from two reasons. First, the modelling captures the effects of the positive skewness in the cross-sectional area data through the standard deviation parameter, which is used to define the normal distribution from which the random cross-sectional area sampling occurred. Larger standard deviations in the log transformed distribution result in greater skewness in the cross-sectional area distribution upon conversion back to the original units through indexation. As the simulated gully volumes are calculated as the product of length and area, the volume grows geometrically with increases in either variable. Consequently, total gully volume estimates are simulated with equivalent cross-sectional area values larger than that equivalent to the mean of the log-transformed data. Clearly, the variability in gully dimensions is of equal importance as some central measure of the distribution when the data are positively skewed. Evidence that gullies in "downstream" positions had a greater mean cross-sectional area than first order links could potentially be used in future sediment budgeting studies if the topology of the gully network links was defined such that headwater links could be distinguished from those downstream. Such information is not currently available in standard gully maps, but future gully mapping efforts could incorporate this.

The method presented here for estimating a suitable value for gully cross-sectional area for construction of catchment scale sediment budgets is computationally simple and could be applied to other catchments or incorporated into other sediment budgeting models, given sufficient data to define the distribution of cross-sectional area. The cross-sectional area data can be readily obtained from a modest amount of fieldwork. If gully links within a catchment can be divided upon an igneous sedimentary basis there is support for assigning a greater proportion of sediment ($P = 0.57$) to the bedload budget for those river links in igneous landscapes. ASRIS subsoil texture properties provided little capacity to predict the spatial variation in the proportion of gully sediment contributing to the bedload and suspended load budgets of river links, at least within this catchment.

There are important implications of the finding that a representative value of gully cross-sectional area may be higher in some parts of Australia than that adopted in previous studies. The most obvious implication is that there may have been systematic under-prediction of sediment delivered to river networks from gully erosion by a factor of roughly 2 in previous sediment budgeting studies (e.g. Prosser et al., 2001). This is of significance for calculating the bedload budget of river networks and also for the relative contribution to a catchment's sediment yield from subsoil and surface soil sediment sources. Geochemical tracing studies have been used to distinguish the relative contributions of subsoil (gully and river bank erosion) and surface-soil (hillslope erosion) sourced sediments in river networks. In the cases where these empirical assessments of the relative proportion of each sediment source to catchment yields are compared to predictions, the proportions are generally in close agreement when a value of $A = 10$ m^2 has been used in constructing the sediment budget (Olley and Deere, 2003; Wallbrink, 2004). If A is actually closer to 23 m^2, it could be interpreted that approximately half the sediment eroded through gully erosion has not actually entered the river network since being eroded. By default, Eq. (1) implies that 100% of gully eroded sediment is delivered to the river network. If gully dimensions were roughly twice as large as has been assumed to date, but only half the gully eroded sediment was actually delivered to the river network, with the other half deposited on footslopes or outwash fans for example, then it is plausible that the relative proportions of surface to subsoil sediment predicted at catchment outlets could match that observed by the geochemical tracing. A similar argument follows for comparisons of catchment sediment yields. This suggests a need to better define the linkages between gully erosion and delivery of the eroded sediment to the channel network.

In conclusion, the widespread formation of permanent erosion gullies makes them a major source of the sediment delivered to rivers around the world, particularly in agricultural catchments. This paper builds upon an existing catchment scale model of sediment generation from gully erosion, applicable across catchments several thousand square kilometres size, by demonstrating how readily collected field data showing a high degree of variability can be used to derive representative gully cross-sectional area and sediment texture parameters and thus contribute to a more accurate representation of gully erosion in catchment sediment budgeting studies.

Acknowledgements

Tim Pietsch and Evan Harrison helped collect the cross sectional area data and sediment samples in the field and Colin McLaughlin conducted the particle size measurements. Scott Wilkinson, Lachlan Newham and two anonymous reviewers provided useful suggestions and improved the manuscript. The research was funded by the Sydney Catchment Authority.

References

Belyaev, V.R., Wallbrink, P.J., Golosov, V.N., Murray, A.S., Sidorchuk, A., 2004. Reconstructing the development of a gully in the Upper Kalaus Basin, Stavropol Region (Southern Russia). Earth Surface Processes and Landforms 29, 323–341.

Boardman, J., Parson, A., Holland, R., Holmes, P., Washington, R., 2003. Development of badlands and gullies in the Sneeuberg, Great Karoo, South Africa. Catena 50, 165–184.

Carlile, P., Bui, E., Moran, C., Misasny, B., McBratney, A., 2001a. Estimating soil particle size distributions and precent sand, silt and clay for six texture classes using the Australian Soil Resource Information System point database, Technical Report, vol. 29/01. CSIRO Land and Water.

Carlile, P., Bui, E., Moran, C., Simon, D., Henderson, B., 2001b. Method used to generate soil attribute surfaces for the Australian Soil Resource Information System using soil maps and look-up tables, Technical Report, vol. 24/01. CSIRO Land and Water.

Daba, S., Rieger, W., Strauss, P., 2003. Assessment of gully erosion in eastern Ethiopia using photogrammetric techniques. Catena 50, 273–291.

diCenzo, P., Luk, S., 1997. Gully erosion and sediment transport in a samell subtropical catchment, South China. Catena 29, 161–176.

Eyles, R.J., 1977. Changes in drainage networks since 1820, Southern Tablelands, N.S.W.. Australian Geographer 13, 377–387.

Flügel, W.M.M., Moretti, S., Rodolfi, G., Sidorchuk, A., 2003. Integrating geographical information systems, remote sensing, ground truthing and modelling approaches for regional erosion classification of semi-arid catchments in South Africa. Hydrological Processes 17, 929–942.

Gábris, G., Kertész, A., Zámbo, L., 2003. Land use change and gully formation over the last 200 years in a hilly catchment. Catena 50, 151–164.

Gale, S., Hoare, P., 1991. Quaternary Sediments: Petrographic Methods for the Study of Unlithified Rocks. Belhaven Press.

Gellis, A., Cheama, A., Lalio, S., 2001. Developing a geomorphic approach for ranking watersheds for rehabilitation, Zuni Indian Reservation, New Mexico. Geomorphology 37, 105–134.

Geological Survey of New South Wales, 1966. Sydney 1:250,000. Geological Series Sheet 56–5.

Geological Survey of New South Wales, 1970. Goulburn 1:250,000. Geological Series Sheet 55–12.

Henderson, B., Bui, E., Moran, C., Simon, D., Carlile, P., 2001. ASRIS: Continental-scale soil property predictions from point data, Technical Report, vol. 28/01. CSIRO Land and Water.

Henderson, B., Bui, E., Moran, C., Simon, D., 2005. Australia-wide predictions of soil properties using decision trees. Geoderma 124, 393–398.

Hughes, A., Prosser, I., 2003. Gully and riverbank erosion mapping for the Murray Darling Basin, Technical Report, vol. 3/03. CSIRO Land and Water.

Johnston, R., Barry, S., Bleys, E., Bui, E., Moran, C., Simon, D., Carlile, P., McKenzie, N., Henderson, B., Chapman, G., Imhoff, M., Maschmedt, D., Howe, D., Grose, C., Schoknect, N., Powell, B., Grundy, M., 2003. ASRIS: the database. Australian Journal of Soil Research 41, 1021–1036.

Liggitt, B., Fincham, R.J., 1989. Gully erosion: the neglected dimension in soil erosion research. South African Journal of Science 85, 18–20.

Lu, H., Moran, C., Prosser, I., De Rose, R., 2004. Investment prioritization analysis based on a broadscale spatial budgeting approach to meet downstream targets for suspended sediment loads. Water Resources Research 40 (W09051).

Martínez-Casasnovas, J., 2003. A spatial information technology approach for the mapping and quantification of gully erosion. Catena 50, 293–308.

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

Nagasaka, A., Yanai, S., Sato, H., Hasegawa, S., 2005. Soil erosion and gully growth associated with cultivation in southwestern Hokkaido, Japan. Ecological Engineering 24, 503–508.

Olley, J., Deere, D., 2003. Targeting Rectification action in the Wingecarribee Catchment, Technical Report, vol. 47/03. CSIRO Land and Water.

Olley, J., Wasson, R., 2003. Changes in the flux of sediment in the Upper Murrumbidgee catchment, southeastern Australia, since European settlement. Hydrological Processes 17, 3307–3320.

Poesen, J., Hooke, J., 1997. Erosion, flooding and channel management in Mediterranean environments of southern Europe. Progress in Physical Geography 21, 157–199.

Poesen, J., Vandaele, K., Van Wesemael, B., 1996. Contribution of gully erosion to sediment production on cultivated lands and rangelands. Erosion and Sediment Yield: Global and Regional Perspectives, IAHS Publication, vol. 236, pp. 251–266.

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena 50, 91–133.

Prosser, I.P., 1991. A comparison of past and present episodes of gully erosion at Wangrah Creek, southern tablelands, New South Wales. Australian Geographical Studies 29, 139–154.

Prosser, I., Rutherfurd, I., Olley, J., Young, W., Wallbrink, P., Moran, C., 2000. Large-scale patterns of erosion and sediment transport in river networks with examples from Australia. Marine and Freshwater Research 52, 81–99.

Prosser, I., Rustomji, P., Young, W., Moran, C., Hughes, A., 2001. Constructing River Basin Sediment Budgets for the National Land and Water Resources Audit, Technical Report, vol. 15/01. CSIRO Land and Water.

Sidorchuk, A., 1999. Dynamic and static models of gully erosion. Catena 37, 401–414.

Sidorchuk, A., 2005. Stochastic components in the gully erosion modelling. Catena 63, 299–317.

Sidorchuk, A., Golosov, V., 2003. Erosion and sedimentation history on the Russian Plain: II. The history of erosion and sedimentation during the period of intensive agriculture. Hydrological Processes 17, 3347–3358.

Soil Science Society of America, 2001. Internet Glossary of Soil Science Terms. [Online, 13 May 2005], uRL: http://www.soils.org/sssagloss.

Valentin, C., Poesen, J., Li, Y., 2005. Gully erosion: impacts, factors and control. Catena 63, 132–153.

Wallbrink, P., 2004. Quantifying the erosion processes and landuses which dominate fine sediment supply to Moreton Bay, southeast Queensland, Australia. Journal of Environmental Radioactivity 76, 67–80.

Wallbrink, P.J., Olley, J., Murray, A., Olive, L., 1996. The contribution of subsoil to sediment yield in the Murrumbidgee River basin, New South Wales, Australia. Erosion and Sediment Yield: Global and Regional Perspectives, IAHS Publication, vol. 236, pp. 347–355.

Wallbrink, P., Olley, J., Murray, A., Olive, L., 1998. Determining sediment sources and transit times of suspended sediment in the Murrumbidgee River, NSW, Australia using fallout ^{137}Cs and ^{210}Pb. Water Resources Research 34, 879–887.

Wasson, R., Mazari, R., Starr, B., Clifton, G., 1998. The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australia: sediment flux dominated by channel incision. Geomorphology 24, 291–308.

Wasson, R.J., Caitcheon, G., Murray, A., McCulloch, M., Quade, J., 2002. Sourcing sediment using multiple tracers in the catchment of Lake Argyle, northwestern Australia. Environmental Management 29, 634–646.

Wilkinson, S., Olley, J., Read, A., DeRose, R., 2005. Targeting erosion control using spatially distributed sediment budgets. Sediment Budgets 2, IAHS Publication, vol. 292, pp. 65–72.

Zierholz, C., Prosser, I., Fogarty, P., Rustomji, P., 2001. In-stream wetlands and their significance for channel filling and the catchment sediment budget, Jugiong Creek, New South Wales. Geomorphology 38, 221–235.