Sediment sources in a dry-tropical catchment: central Queensland, Australia

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Abstract Rivers draining into the Great Barrier Reef lagoon are receiving increased attention from catchment managers and scientists, with the realisation that European land use changes over the last ~150 years may have increased river sediment yields with resultant adverse effects on the receiving marine environment. Mitigation of the effects associated with such changes is only possible if information on the spatial provenance and dominant types of erosion is known. This study uses fallout radionuclide (^{137}Cs and $^{210}Pb_{ex}$) and geochemical tracing of river bed sediments to examine sediment sources for Theresa Creek, a subcatchment of the Fitzroy River basin, central Queensland, Australia. Sheetwash and rill erosion from cultivated basaltic land and channel erosion from non-basaltic parts of the catchment were found to be contributing most sediment to the river system. Evidence indicates that the dominant form of channel erosion is gully head-cut and sidewall erosion. Sheetwash and rill erosion from uncultivated land (i.e. grazed pasture/woodland) is a comparatively minor contributor of sediment to the river network. Due to the limited extent of cultivation, on a basin-wide scale, channel sources are likely to be the largest contributor of sediment to the Fitzroy River basin; accordingly catchment managers should focus their efforts on reducing the sediment yield from these sources.

Key words geochemical tracing; fallout radionuclide tracing; channel erosion; human impact; Great Barrier Reef

INTRODUCTION

Rivers draining into the Great Barrier Reef (GBR) lagoon have received increased attention over the last few decades with the realisation that recent land use changes may have significantly increased erosion rates and river sediment yields with resultant adverse effects on the receiving marine environment. Previous large-scale modelling studies suggest that sheetwash and rill erosion (hereafter referred to as *hillslope erosion*) dominates in the GBR catchments (NLWRA, 2001; McKergow *et al*., 2005). While this is probably the case for the steeper wet coastal catchments, it is less certain for the extensive low-lying dry-tropical zones where there is greater opportunity for sediment storage. Over 70% of the 423 000 km^2 draining into the GBR lagoon can be classified as dry tropical (Furnas, 2003), therefore there is a need to consider both surface (soil) and subsurface (channel) erosion sources.

The issue of the relative contribution of hillslope and channel sources within Australian catchments was reviewed by Prosser *et al*. (2001), who stated that while there is information for some areas, particularly southeastern Australia, there are still significant regional gaps in our knowledge. Prosser *et al*. (2001) proposed that as catchment size increases, the likelihood of channel sources becoming more dominant also increases due to the buffering of hillslope sources in large catchments. Because of the size of the two main dry tropical catchments (Burdekin River ~ 130 000 km^2; Fitzroy River ~ 140 000 km^2) draining into the GBR lagoon, in addition to their low terrain, dry-tropical climate and land use history, channel sources may be more significant than have been previously identified.

This study uses fallout radionuclide (^{137}Cs and $^{210}Pb_{ex}$) and geochemical tracing to examine sediment sources within Theresa Creek, a 6000-km^2 subcatchment of the Fitzroy River basin, central Queensland, Australia. The relationship between source type and spatial provenance is described and its significance for the determining sources at the basin-wide scale is assessed. The data obtained from this study will improve our ability to construct accurate sediment budgets for this part of Australia, as well as provide information to assist future catchment management and rehabilitation efforts.

Study site

Theresa Creek is located within the Nogoa River subcatchment in the western Fitzroy River basin (Fig. 1). The Fitzroy River basin (143 000 km^2) has been identified by a number of studies as the single largest contributor of sediment to the GBR lagoon (e.g. McKergow *et al.*, 2005). The study catchment's climate is dry-tropical (Köppen BSh). The mean rainfall at Clermont is 649 mm year^{-1}, with most rainfall occurring between November and March (BoM, 2008).

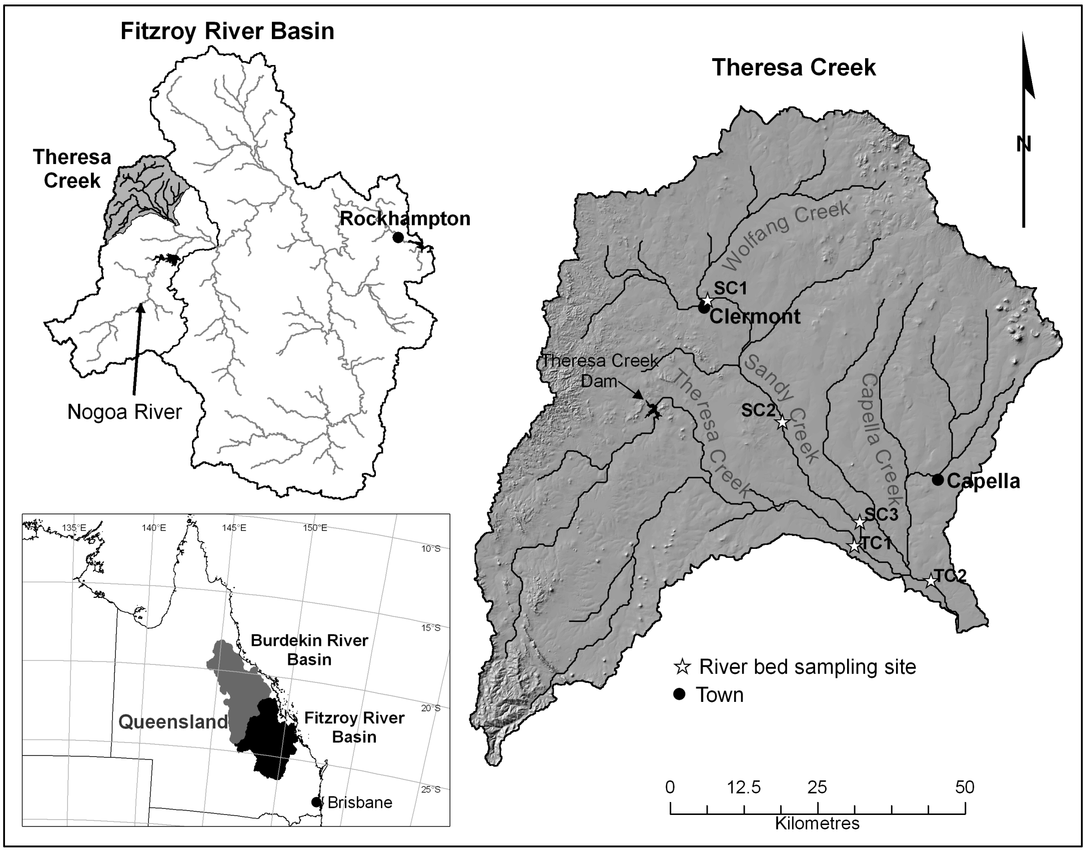

Fig. 1 Location map of Theresa Creek showing the river bed sampling sites.

METHODS

Radionuclide and geochemical tracing of sediment sources

Radionuclide tracing involves characterising potential sources of sediment (e.g. cultivated land, uncultivated pasture and channels) on the basis of their radionuclide concentrations. These concentrations are then compared with the radionuclide concentrations samples from downstream sediment deposits and a numerical mixing model is generally used to determine the relative contribution of each of the sources. The method is dependent on the documented observation that the concentration of radionuclides (such as ^{137}Cs, $^{210}Pb_{ex}$) varies significantly with soil depth (e.g. He & Owens, 1995).

Sediment samples were collected throughout the study catchment from each of the three principal source types (hillslope erosion of cultivated land, hillslope erosion of uncultivated pasture and channel erosion). Five river bed sites were sampled on two occasions between August and November 2006. The sites were located on the main channel of Sandy Creek (SC1, SC2 and SC3), Theresa Creek (TC1) and the confluence of Sandy and Theresa Creeks near the outlet of the catchment (TC2) (Fig. 1).

Geochemical tracing involves characterising the spatial provenance of eroded sediment on the basis of its geochemical signature. The method is dependent on contrasting chemical signatures of the underlying bedrock of different source areas. Catchments are usually divided into broad geological units and the geochemical signature of these units are characterised and compared to the geochemical signature of suspended or deposited sediments. As with the radionuclide tracing technique, a mixing model is used to determine the relative contribution of the different spatial sources.

For the purpose of characterising source areas, the catchment was classified into four main geological units: Tertiary basalts (33%), Devonian granites (15%), Neoproterozoic to Cambrian metasediments (13%), and Tertiary to Quaternary clastic sediments (13%). The river bed sampling sites were the same as those used for the radionuclide tracing (Fig. 1).

Sediment samples were wet sieved to retrieve sediment < 63 μm, then fractionated by water column settling to obtain the < 10 μm fraction (clay and very fine silt). The samples were oven-dried then homogenised by grinding in a tungsten ring mill. Organic material was removed by ashing the samples at 450°C for 48 h. Major and trace element concentrations for geochemical tracing were determined using X-ray fluorescence analysis. Radionuclide concentrations of sediment source samples were determined using high resolution gamma spectrometry.

Stepwise linear discriminant analysis (LDA) was used to determine the combination of geochemical properties that provide the best differentiation between geological source areas. Stepwise selection was made on the basis of smallest p-value. The combination of geochemical properties that successfully classified all source samples with the lowest Wilks' lambda value was chosen. Wilks' lambda is a multivariate test statistic that measures the significance of the discriminatory power of the model. Wilks' lambda values close to zero indicate high discriminatory power while values close to one indicate low discriminatory power.

Mixing model

A Monte Carlo mixing model was used to predict the relative contributions of each of the sources to the channel and flood plain deposit samples. The mixing model, which is a modification of the approach outlined by Olley & Caitcheon (2000), was used for both the geochemical and radionuclide tracing.

In the mixing model individual sample concentrations are denoted by $C_{i,j,k}$, where i = source index ($i = 1,\ldots, I$; $I = 3$ for erosion sources and $I = 4$ for rock type sources), j = sample number index ($j = 1,\ldots, J$; J is 10 for both the geochemical and radionuclide tracing) and each sample has k constituent concentrations ($k = 1,\ldots, K$; $K = 2$ for radionuclide tracing and $K = 9$ for geochemical tracing).

For each Monte Carlo iteration (l) and for each source (i), j is randomly selected and $C_{i,j,k,l}$ is used to calculate source-weighted composite concentrations:

$$\overline{C}_{k,l} = \sum_{i=1}^{I} \hat{\rho}_i C_{i,j,k,l} \tag{1}$$

Where $l = 1,\ldots, 1000$ and $\hat{\rho}_i$ is the proportion contributed from each erosion type/rock type source. The relative contribution of each erosion type/rock type source must non-negative and not greater than 1:

$$0 \le \hat{\rho}_i \le 1 \tag{2}$$

and the contributions of the individual erosion type/rock type sources must sum to 1:

$$\sum_{i=1}^{I} \hat{\rho}_i = 1 \tag{3}$$

For each geochemical property/radionuclide tracer the average concentration of C is calculated over 1000 iterations using:

$$\overline{\overline{C}}_k = \sum_{l=1}^{1000} \overline{C}_{k,l} \Big/ 1000 \qquad (4)$$

The best estimate of the relative contribution ($\hat{\rho}_i$) of each erosion type/rock type was determined by minimising the sum of squares of the deviations of the concentration calculated in equation (4) from the measured geochemical property/radionuclide tracer concentration of the deposit (C_d):

$$\sum_{k=1}^{K} \left(\frac{\overline{\overline{C}}_k - C_d}{C_d} \right)^2 \qquad (5)$$

RESULTS

Geochemical differentiation of geological source areas

The results from the step-wise LDA (Table 1) show that MgO, ZrO_2, K_2O, V_2O_5 and NiO were able to correctly differentiate all of the geological source area samples. However, the inclusion of further tracer properties into such an analysis improves the reliability of the resulting model (Collins *et al*., 1998). Accordingly, a further four geochemical properties (CeO_2, TiO_2, P_2O_5, SrO) were added by the step-wise process and, as indicated by the decrease in the Wilks' lambda value, the model improved as a result (Table 1). The nine geochemical properties selected by the stepwise LDA are used in the mixing model to estimate the relative contribution of the four geological source areas.

Table 1 Geochemical properties that provide the best differentiation of geological source areas by stepwise linear discriminant analysis.

Geochemical property	% of source samples correctly classified	Wilks' lambda
MgO	82.05	0.1524
ZrO_2	87.18	0.0324
K_2O	92.31	0.0106
V_2O_5	97.44	0.0057
NiO	100.00	0.0028
CeO_2	100.00	0.0016
P_2O_5	100.00	0.0010
TiO_2	100.00	0.0006
SrO	100.00	0.0004

Table 2 Mean ^{137}Cs and ^{210}Pb concentrations of the <10 μm fraction of sediment from uncultivated pasture, cultivated land and channels (errors are one standard deviation).

Source type	^{137}Cs (Bq kg^{-1})	$^{210}Pb_{ex}$ (Bq kg^{-1})
Uncultivated (*n* = 11)	7.3 ± 3.3	126.8 ± 58.6
Cultivated (*n* = 10)	0.7 ± 0.3	3.5 ± 2.7
Channel (*n* = 10)	0.0 ± 0.4	–6.9 ± 5.0

Fallout radionuclide differentiation of sediment sources

Concentrations of both ^{137}Cs and $^{210}Pb_{ex}$ are highest in the uncultivated pasture derived sediment, lowest in the sediment derived from channel sources, and of low/intermediate concentration from cultivation sources (Table 2). The radionuclide concentrations of the cultivated and channel sources are both low, however, they are significantly different from each other ($P < 0.001$ for $^{210}Pb_{ex}$ and $P < 0.05$ for ^{137}Cs). The concentrations of ^{137}Cs are low compared to studies using similar methodologies (cf. He & Owens, 1995; Wallbrink *et al.*, 1998). This can be attributed to the relatively small amount of atmospheric nuclear testing that occurred in the southern hemisphere which resulted in levels of soil ^{137}Cs being an order of magnitude lower than the northern hemisphere (Wallbrink *et al.*, 1998). In addition, the catchment's relatively low latitudinal position (23°S) means that it was subjected to a lower level of fallout than that experienced in the mid-latitudes.

Previous studies have found that the concentration of fallout radionuclides at cultivated sites is approx. 50% less than at uncultivated sites (e.g. He & Owens, 1995; Wallbrink, *et al.*, 1998). In this study, however, the concentration of both ^{137}Cs and $^{210}Pb_{ex}$ are at least one order of magnitude lower at cultivated sites (Table 2). Although extensive and deep (~50 cm) ploughing of cultivated soils has contributed to the lower fallout radionuclide concentrations, these cannot be explained by ploughing dilution alone. The lower than expected concentrations may be due to the highly disturbed nature of the soils in the catchment which have undergone extensive redistribution during the construction of erosion control measures, such as contour banks.

Sources of fine channel sediment

Radionuclide data indicate that hillslope erosion from cultivated land (41–43%) and channel erosion (50–57%) dominate sediment sources on the main stem of Sandy Creek (SC1–SC3; Fig. 2(c)). Hillslope erosion derived sediment from uncultivated land only makes up a small proportion (2–7%) of the total sediment delivered to the stream network. The geochemical data show that basaltic, metasediment, and to a lesser extent, clastic sources make up the majority of sediment at all three Sandy Creek channel sites. The low level of granitic derived sediment (0–7%)

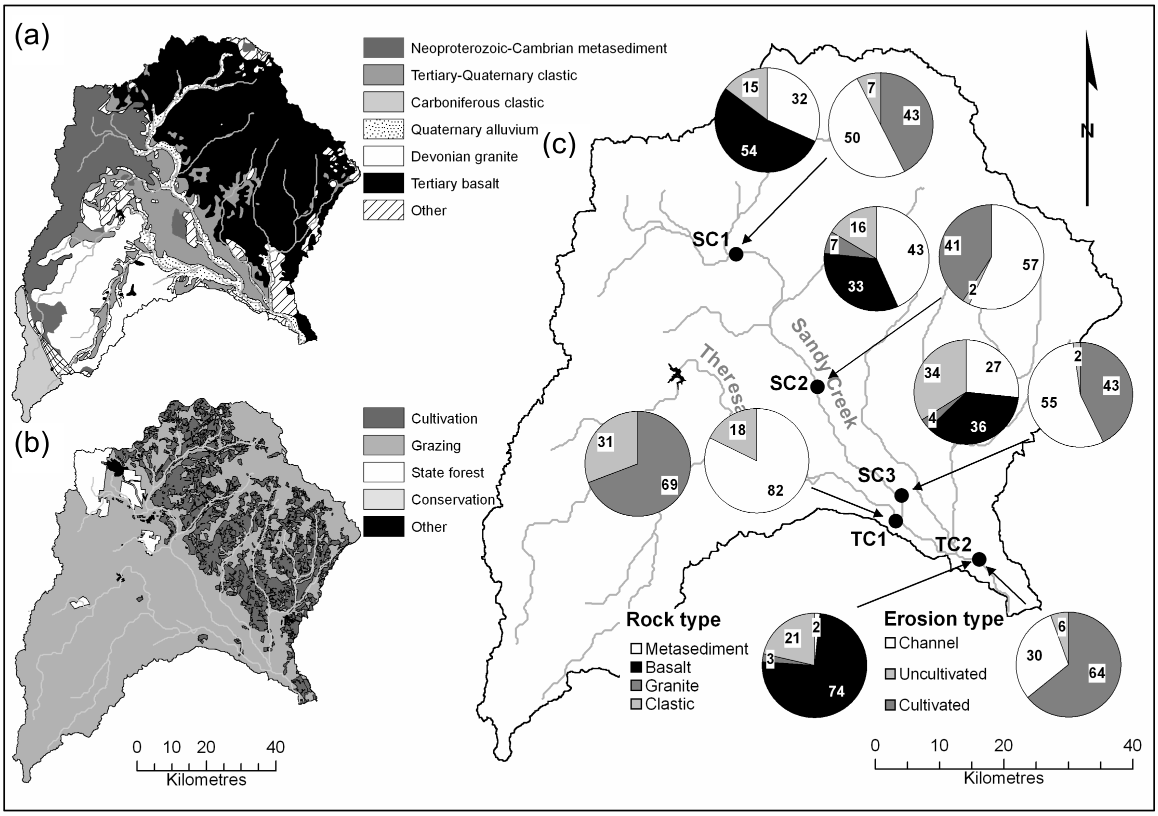

Fig. 2 (a) Geology of Theresa Creek showing the principle geology classes referred to in the text, (b) land use map of Theresa Creek and, (c) sediment source contributions to each river bed sampling site. Each sampling site has two associated pie graphs, the left graph illustrates the relative contribution from each geological source area and the right graph indicates the relative contribution from each erosion type.

is indicative of the limited extent of granite in the contributing areas of the Sandy Creek sites. The fact that cultivation only occurs on the catchment's basaltic soils suggests that the areas underlain by metasediment and clastic lithologies contribute sediment mainly from channel sources. Field observations confirm that upper Sandy Creek (upstream of the confluence with Wolfang Creek (Fig. 1)) is an area of significant active gully erosion. It is likely that the basaltic areas also contribute channel derived sediment. However, due to land management practices such as the construction of contour banks to prevent flow convergence, the development of gullies on cultivated land is uncommon.

The sediment at site TC1 (upstream of the confluence of Sandy and Theresa Creeks) is largely comprised of granitic sources (69%), which is consistent with the dominance of granite in the contributing catchment. Clastic derived sediment comprises the rest of the sediment. The mixing model predicted no contribution from metasediment derived material. Metasediment is present upstream of site TC1, but it is located entirely upstream of Theresa Creek Dam (Fig. 1). This suggests that the dam is effectively trapping most, if not all, sediment from this part of the catchment.

Channel derived sediment dominates (82%) the sediment sources contributing to site TC1 while the remainder is derived from uncultivated hillslope sources. This is strong evidence that the granitic terrain is an important source of channel derived sediment. This is supported by field observations and previous gully density modelling that predicted severe gully erosion in the granitic-based soils of Theresa Creek (NLWRA, 2001). Uncultivated sources upstream of TC1 contribute a relatively high proportion of sediment (18%) compared to other sites.

Basaltic derived sediment dominates (74%) downstream of where all the major tributaries join Theresa Creek (i.e. site TC2). Notably Capella Creek joins the main branch of Theresa Creek upstream of this site (Fig. 1). Capella Creek drains a large proportion (~55%) of the eastern side of the catchment and is almost completely underlain by Tertiary basalts. Although there is an input of sediment from the largely granitic-based tributary upstream of site TC1, this is largely masked at site TC2 by the basaltic input from the eastern catchment. The proportion of sediment derived from cultivated land (64%) closely mirrors the proportion of basaltic derived sources (74%) of the geochemical tracing results, again pointing towards the dominance of cultivation sources from this geology type.

DISCUSSION

This study indicates that most fine river sediment in this catchment is derived from hillslope erosion of cultivated land and channel erosion. Hillslope erosion of uncultivated land is a comparatively minor contributor of sediment to the river network. The large contribution of sediment from cultivated sources is attributed to the relatively large proportion (22%) of the catchment with highly erodible Vertisols used for intensive cultivation.

Perhaps of more significance, given that cultivation throughout the Fitzroy River basin only accounts for 7% of total land use, is the contribution of sediment from channel erosion. Previous studies have attributed increased catchment sediment yield from dry-tropical GBR catchments to increased hillslope erosion rates due to pressure from grazing activity and intensive cultivation with limited consideration of channel sources. This study shows that channel erosion is a significant contributor of sediment to Theresa Creek. Site TC1 is the only river bed sampling site without a significant area of cultivation in its catchment and channel sources account for over 80% of the fine channel sediment. This level of channel erosion contribution is similar to that found by previous studies within southeastern Australia (e.g. Wasson *et al.*, 1998). The methods used in this study are not able to distinguish between channel sediment derived from river banks and that derived from gully erosion. However, based on field observations and findings from previous studies in the region (e.g. Bartley *et al.*, 2007) it is likely that gully sidewalls and head-cuts contribute significantly more sediment than river banks. Extensive sediment slugs or waves found throughout the channel network also suggest a large flux of sediment from gully sources. The sand

and gravel in these sediment slugs are similar to sediment found in gully sidewalls and beds while it is completely absent from the finer flood plain deposits found in most river banks. Hillslope erosion processes are unlikely to contribute large volumes of coarse sediment to the river network (Bartley *et al*., 2006).

As summarised in Table 3, the channel sediment tracing results suggest that the majority of basaltic sediment is derived from cultivated land, while the granitic, clastic and metasediment areas contribute mostly channel derived sediment.

Table 3 Qualitative assessment of the relative importance of each source type by geological source area as determined by the geochemical and radionuclide tracing results (*** = high, ** = moderate, * = low).

Rock type source	Source type Channel	Cultivated	Uncultivated
Granite	***	n/a	**
Basalt	*	***	*
Metasediment	***	n/a	*
Clastic	***	n/a	*

Basaltic-derived material is clearly an important source of sediment within Theresa Creek. This is evident from the results for site TC2 that indicate a high proportion of cultivation derived basaltic sediment in the lower reaches of the river, despite a large input of channel derived granitic sediment from the main branch of Theresa Creek. This indicates that the fine sediment yield from the extensively cultivated basaltic areas may be significantly greater that that of the largely grazed granitic-based areas. The clay-rich composition of the basaltic soils suggests this is likely, although it may also be indicative of different runoff responses from the different geologies. The importance of basaltic sources at a basin-wide scale is, however, uncertain. Previous studies in large Australian catchments have predicted that, despite extensive headwater contributions, basalt derived sediment may only contribute a small proportion of the sediment found in the lower reaches of a catchment (e.g. Olley & Caitcheon, 2000). While the reasons for this are unclear, the highly aggregated nature of the sediment derived from the Vertisols (Freebairn & Wockner, 1986) may result in a high proportion being transported as bed material, which may be stored for long periods of time within channels. The view that basaltic sources comprise a limited contribution at the basin-wide scale is supported by the results of Douglas *et al*. (2006), who found that sediment deposited in catchment impoundments is mainly derived non-basaltic sources.

CONCLUSIONS

This study uses geochemical and radionuclide properties of channel and flood plain sediments to determine the spatial provenance and relative contribution of different source types to fluvial deposits within Theresa Creek, a subcatchment of the Fitzroy River basin. The data indicate that the river sediments are derived primarily from both cultivated basaltic-based land (0–64%) and channel erosion from non-basaltic parts of the catchment (30–82%). While cultivated areas of the catchment are identified as a major source of sediment within Theresa Creek, on a basin-wide scale, cultivation only accounts for 7% of the total land use, with 80% of the basin grazed with beef cattle.

Evidence indicates that the dominant form of channel erosion is gully head-cut and sidewall erosion. Hillslope erosion from uncultivated land (i.e. grazed pasture/woodland) is a comparatively minor contributor of sediment to the river network. These findings are in contrast to previous studies that have assessed hillslope erosion from grazing land to be the principle contributor of sediment from the dry-tropical river systems draining into the Great Barrier Reef lagoon.

This study provides field-based information on the regional patterns of erosion in Australia and supports previous claims that channel erosion is the largest contributor of sediment to many

Australian rivers. Further work to determine the relative contribution of the different forms of channel (gully and river bank) erosion is warranted.

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