# A sediment budget for the Herbert River catchment, North Queensland, Australia

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**Abstract** A combination of spatial modelling, sediment tracing techniques and water-quality data were used to determine the major source of fine sediments in the Herbert River catchment, Queensland, Australia. Using modelling, hillslope erosion was predicted to be the dominant source of sediment, contributing 52% of the total sediment load at the estuary. Gully and stream bank erosion contributed equal loads to the estuary (~24%). The $^{137}Cs$ concentrations measured in this study support the modelled predictions for contributions from different land uses. Results from modelling and sediment tracing also predicted similar ratios of hillslope to channel erosion. The total suspended sediment loads predicted for the downstream freshwater limit of the catchment are within 10% of longer term measured values. These results suggest that the modelling approach used in this study is useful for determining sediment budgets for large tropical catchments.

**Key words** Australia; Queensland; sediment budget; sediment tracing; SedNet

## INTRODUCTION

Sediment supply to the coastal waters adjacent to the Great Barrier Reef World Heritage Area (GBRWHA) in Queensland, Australia, is of increasing concern (e.g. Baker, 2003; McCulloch *et al.*, 2003). The Herbert River is the largest of the wet tropical rivers along the Great Barrier Reef Coast, and is considered to be a "high risk" catchment in terms of its sediment export (Brodie *et al.*, 2001). In this paper, a combination of spatial modelling, sediment tracing techniques, and analysis of water-quality and flow data are used to determine the major source of fine sediments to the Herbert River. This work aims to enable catchment managers to effectively target remedial action to decrease sediment delivery to the GBRWHA.

### Herbert River catchment: location and characteristics

The Herbert River catchment covers an area of approximately 10000 km$^2$, and can be broken up into four distinct physiographic sections (Fig. 1). The upper catchment (~4735 km$^2$) is dominated by grazing, but has also been subject to various forms of mining, and has other mixed agriculture. The middle section of the catchment (~1825 km$^2$) is predominantly National Park, State Forests and timber reserves. The lower flood plain section (~3560 km$^2$) can be divided into two areas; the flood plain area around the Herbert River channel and the southern coastal section which contains streams that flow directly to the coast. Both these areas are dominated by sugarcane cultivation. The geology, geomorphology, soils, rainfall

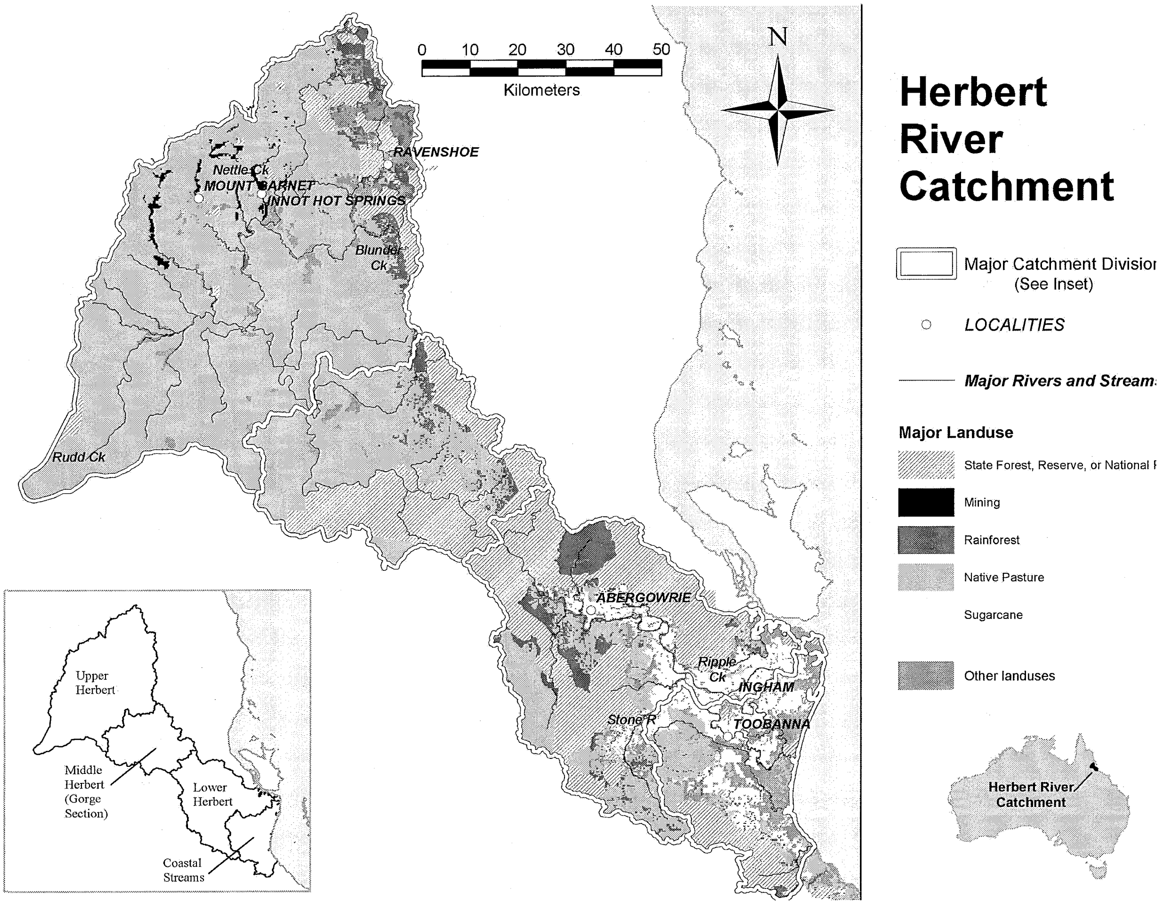


**Fig. 1** Major land use units and physiographic areas in the Herbert River catchment.

and land use characteristics are different for the four regions, resulting in differences in the history of erosion and sedimentation for each area. Further bio-geographic information on the Herbert River catchment can be found in Johnson & Murray (1997) and Bartley *et al.* (2003).

## METHODS FOR DETERMINING SEDIMENT SOURCES IN THE HERBERT CATCHMENT

Sediments originate from erosion of hillslopes, and from gully and stream bank erosion (channel erosion). The methods used to assess each of these sources and to propagate the sediment through the river network are described below and in more detail in Bartley *et al.* (2003).

### Hillslope erosion

Hillslope erosion from sheet and rill erosion was assessed using the Revised Universal Soil Loss Equation (RUSLE; Renard *et al.*, 1997) as applied in the National Land and Water

Resources Audit (NLWRA; Lu *et al.*, 2001). Soils mapping from various sources was collated into a "best available" map from which an erodibility map was derived. The slope length factor was set as a constant value of 1. The slope factor across the Herbert River catchment was derived directly from the 100 m digital elevation model. Land cover mapping at 1:50 000 scale was available over the whole catchment current to 1996. This mapping was used to delineate rainforest and eucalypt dominated areas in the middle and upper Herbert (with some improvements based on Landsat interpretation). Cover factors were estimated for each land cover type using tables from Rosewell (1993), except for sugarcane which was based on results published in Visser (2003).

## Gully erosion

The spatial pattern of gullies in the Herbert catchment was determined through aerial photograph interpretation. A gully was defined as a non-permanent watercourse with steep, actively eroding banks. Gullies were mapped using 50 stereo aerial photograph pairs spanning different geographic regions, geologic classes and land uses. Cubist data mining software (Rulequest Research, 2001) was used to predict gully densities throughout the unmapped portions of the catchment (Hughes & Prosser, 2003). Total sediment supplied from gully erosion was calculated as the product of gully density, watershed area, average gully cross-sectional area (~10 $m^2$) and average dry bulk density of soil (1.5 t $m^{-3}$), divided by the time over which gullies have developed (100 years). It was assumed that 50% of the gully erosion produced fine suspended sediment.

## River bank erosion hazard

A global review of river bank migration data (Rutherfurd, 2000) suggested that the best predictor of bank erosion rate was bankfull discharge ($Q_{bf}$) (equivalent to a 1.58 year recurrence interval). Rutherfurd (2000) also found a significant relationship between bank erosion and stream power ($\rho g Q_{bf} S_x$, where $\rho$ is the density of water, $g$ is the acceleration due to gravity, $Q_{bf}$ is bankfull discharge in $m^3\ s^{-1}$ and $S_x$ is the energy slope approximated to the channel gradient). The linear relationship with stream power was modified using two factors: (a) it is assumed that the bank erosion rate decreases as the proportion of remnant riparian vegetation ($PR_x$) along the river link increases; and (b) the erosion rate is reduced in narrow valleys, and an exponential relationship between rock exposure and flood plain width ($F_x$) applied (Hughes & Prosser, 2003). The resultant equation used in this study to predict bank erosion ($BE$ in m $year^{-1}$) is:

$$BE = 0.00002 \times \rho \times g \times Q_{bf} \times S_x (1 - PR)(1 - e^{-0.008 F_x}) \qquad (1)$$

The average proportion of riparian vegetation within each link was determined from Moller (1996). The predicted bank erosion rate is converted into sediment supply (kt $year^{-1}$) by multiplying $BE$ by channel length (m), bank height (m), average particle density of bank materials (1.5 t $m^{-3}$) and dividing by a conversion factor of 1000. It was assumed that 50% of the sediment generated from bank erosion contributed to the suspended sediment supply.

## Mine site sources

Mining has long been considered one of the major sources of sediment in the Herbert River catchment. Various forms of mining, particularly tin mining, have been extensive in the upper catchment. There are no published data on the rates of soil loss from mined areas in the upper Herbert catchment. As a result, both the hillslope erosion and gully erosion factors were derived from knowledge of erosion rates from other mine sites around Australia (Carroll *et al.*, 2000). A total erosion rate of 25 t ha$^{-1}$ year$^{-1}$ (as a combination of hillslope and gully sources) was applied to the mine sites.

## Sediment transport

To calculate the supply of sediment, deposition and delivery downstream, we used SedNet: the Sediment River Network model. SedNet was developed for the Australian National Land and Water Resources Audit (NLWRA, 2001). The methods used in the construction of input data and implementation of the SedNet program itself are described in detail in a number of CSIRO technical reports (e.g. Prosser *et al.*, 2001a,b, DeRose *et al.*, 2003; Wilkinson & Young, 2004).

The model divides the river into a series of links; a link being the stretch of river between any two stream junctions. Each link has an internal watershed, from which sediment is delivered to the stream network by hillslope, riverbank and gully erosion. Sediment is processed sequentially through the river network, beginning with first order links and terminating at the catchment outlet. The sediment load output from each link is calculated from the supply of sediment from tributary links and the local watershed, less losses though flood plain, reservoir and bed deposition. Flood plain deposition is calculated as the proportion of fine sediment that goes over-bank and settles out during a typical flood. It is calculated as the ratio of the median over-bank flow multiplied by the proportion of fine sediment that would be expected to settle out during over-bank flow. Deposition of coarse sediments on the bed of the river are predicted to occur when there is an excess of sediment supply to a river link beyond the capacity of the link to transport sand sized sediment (Bartley *et al.*, 2003). The sediment yield at the terminating link constitutes the total yield (inputs–storage) of the river network. The model also predicts sediment load and the relative contribution of hillslope and channel (gully and riverbank) erosion throughout the network.

## Testing the model predictions

The SedNet sediment load predictions for the Herbert River catchment were tested using two different techniques: (a) $^{137}$Cs concentrations; and (b) comparison with measured sediment load data.

The predicted relative contribution of hillslope and channel (combined gully and riverbank) erosion to stream sediments was assessed using concentrations of $^{137}$Cs. $^{137}$Cs is a product of atmospheric nuclear weapons testing and is concentrated in surface soil. Sediments derived from hillslope erosion have high concentrations of this radionuclide. While those eroded from gullies or channels have little or none. By measuring the concentration in suspended sediments moving down the river, and comparing them with concentrations in sediments derived from hillslope and channel erosion, we determined the relative contributions of each of these processes.

Recently deposited sediment samples were collected from 20 locations along the river during low flow conditions. Source area concentrations were assessed using data from the adjacent Johnstone River catchment (data supplied by Dr Wallbrink, CSIRO). $^{137}Cs$ concentrations were measured by high resolution gamma spectrometry (Murray *et al.*, 1987). Measurements were made on the <10 μm size fraction (clay and fine silt).

The Australian Institute of Marine Science (AIMS) conducted sediment sampling in the Herbert River between 1995 and 2000. The results indicate that for this period the sediment loads for the Herbert River range between 143 000 t year$^{-1}$ to 900 000 t year$^{-1}$, with a mean value of ~540 000 t year$^{-1}$ (Furnas, 2003).

## RESULTS

Hillslope erosion is predicted to be the dominant source of sediment, contributing 490 000 t year$^{-1}$ (or 52%) of the total sediment load at the river mouth (Table 1). Gully and stream bank erosion contribute equally with approximately 220 000 t year$^{-1}$ (~24%). The highest overall losses from hillslope erosion were from grazing lands and forested areas, however, losses per hectare from hillslopes are greatest from the mine sites, forested areas and agricultural cropping land (Table 2). It is important to note that the areas covered by "forest" (30% of the catchment area) contribute almost the same amount of sediment as grazing (60% of the catchment area). This is because most of the forested sites are on extremely steep slopes with much higher rainfall. The main forest type that contributed to the high loads is the open eucalypt dominated woodland areas that occupy the Herbert River gorge. The erosive potential in the forested areas is much greater than the flat depositional landscapes of the upper catchment grazing lands.

Gully erosion also varies significantly across the catchment with the worst areas being around the mine sites in the Upper Herbert and the steeper grazing areas upstream of the Herbert River gorge. Most of the remainder of the catchment does not suffer from significant gully erosion. Riverbank erosion contributes the same amount of sediment to the stream network as gully erosion, yet there is no obvious pattern to bank erosion in the catchment. The main areas that appear to undergo higher than average rates of bank erosion are in the upper catchment and various sections of the main Herbert River channel. Bank erosion is generally at its worst in river reaches lacking a good riparian zone and where stream power is greatest. The model predicts that roughly 40 000 t year$^{-1}$ of fine sediment is stored on the flood plain.

**Table 1** Summary of sediment budget for the Herbert River catchment.

| Sediment budget item | Predicted mean annual rate (t year$^{-1}$) |
|---|---|
| Hillslope Delivery | 490 000 |
| Gully erosion rate | 220 000 |
| Riverbank erosion rate | 220 000 |
| Total sediment supply | 930 000 |
| Total suspended sediment stored | 40 000 |
| Total bed sediment stored | 210 000 |
| Sediment delivery to the estuary | 680 000 |
| Total losses | 930 000 |

**Table 2** Contribution of hillslope erosion from each of the major land use areas with the Herbert River catchment.

| Land use | Area ($km^2$) | Proportion of total area (%) | Predicted total soil loss ($t\ year^{-1}$) | Average erosion rate ($t\ ha^{-1}\ year^{-1}$) |
|---|---|---|---|---|
| Native pastures | 5840 | 60 | 200 000 | 0.34 |
| Improved pastures | 48 | 0.5 | 1000 | 0.10 |
| Forest and other reserves[(1)] | 2881 | 30 | 200 000 | 0.69 |
| Sugar cane | 690 | 7 | 35 000 | 0.51 |
| Other agriculture | 79 | 0.8 | 5000 | 0.64 |
| Residential or industrial | 22 | 0.2 | 0 | 0.01 |
| Mining | 52 | 0.5 | 40 000 | 7.76 |
| Other (e.g. quarries) | 135 | 1.4 | 10 000 | 0.74 |

[(1)]The forest and other reserves category contains a range of forest types from open eucalypt woodland to rainforest and melaleuca species.

Concentrations of $^{137}Cs$ measured in the <10 μm size fraction of sediment samples collected from along the Herbert River range from 0.0 ± 0.3 to 4.5 ± 0.8 Bq $kg^{-1}$, with a mean of 2.4 ± 0.3 Bq $kg^{-1}$. They generally increase towards the coast indicating a greater contribution from hillslope sources along the river (Fig. 2). Concentrations in sediments derived from hillslope erosion on cultivated and uncultivated land in the adjacent Johnston River catchment were 3.6 ± 0.2 ($n$ = 12) and 8.4 ± 0.6 ($n$ = 9) Bq $kg^{-1}$, respectively. Those on sediments derived from channel erosion were estimated to be 0.8 ± 0.1 Bq $kg^{-1}$. The SedNet model predicted that 52% (490 000 t $year^{-1}$) of the sediment at the mouth of the river was derived from hillslope erosion; with 401 000 t $year^{-1}$ of that coming from uncultivated areas (i.e. 42% of the total load). If the model predictions were correct then the $^{137}Cs$ concentrations in the lower river should be 4.25 ± 0.25 Bq $kg^{-1}$. This is consistent with measured concentration in the sample from the river mouth (4.5 ± 0.8 Bq $kg^{-1}$) and with the average concentration in the samples collected in the lower 30 km (3.7 ± 0.5 Bq $kg^{-1}$) (Fig. 2). Therefore the measured $^{137}Cs$ concentrations support the predicted relative contributions from different land-uses, and the predicted ratio of hillslope to channel erosion.

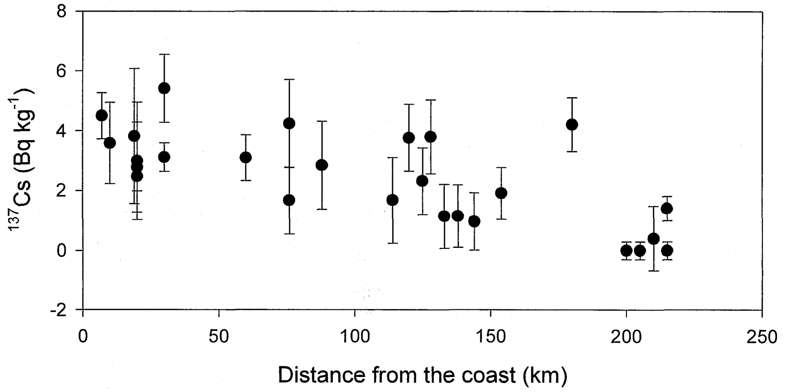


**Fig. 2** Concentrations of $^{137}Cs$ in the <10 μm size fraction of sediment samples collected from along the main channel of the Herbert River.

The model predicted the sediment load at Gairloch Bridge (Ingham) to be ~600 000 t year$^{-1}$. This compares with the 143 000 t year$^{-1}$ to 900 000 t year$^{-1}$, with a mean value of ~540 000 t year$^{-1}$ estimated from water quality and flow data (Furnas, 2003).

## DISCUSSION AND CONCLUSION

This study has used a set of GIS-based models (SedNet) to predict the major sediment sources and sinks within a large tropical catchment. The results suggest that hillslope erosion is the dominant source of sediment, however, both gully and bank erosion present significant sources. These results were supported by sediment tracing analysis. The modelled sediment loads estimated at downstream freshwater limit of the catchment were also within 10% of longer term measured values. These results will help better target catchment management practices aimed at reducing soil erosion.

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