Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. no. 224, 1994.

Sediment production and storage in an urbanizing basin, Lake Macquarie, New South Wales, Australia

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Abstract The study considers the effects of urbanization on the processes of soil erosion, sediment transport and sedimentation in a small basin which drains into Lake Macquarie, New South Wales. Total sediment sources were identified and quantified both in open forest and the urban area, with the caesium-137 (^{137}Cs) method indicating a soil loss of 714 t, and the USLE method 832 t. The results show that soil erosion from the forest is minimal in comparison with the urban area. The ^{137}Cs technique estimated channel storage at 531 t; a tentative sediment budget was developed for the basin, which resulted in a basin sediment yield of 143 t or 261 t, depending on the method used. The study illustrates the importance of in-channel sediment storage in response to environmental change.

INTRODUCTION

The effects of land-use change on drainage basin sediment dynamics have been well documented in basins undergoing urbanization (e.g. Walling & Gregory, 1970; Wolman, 1967). The study reported in this paper attempts to quantify the magnitude of sediment sources (soil erosion) from undisturbed and disturbed portions of a small basin which has undergone urban development, and the quantity of that sediment which has been stored within the channel system in the lower part of the basin. Because it was not possible to measure sediment output from the basin, sediment yield was estimated by subtracting the quantity of stored sediment from two calculations of soil loss.

The study drainage basin

The drainage basin (area 14.1 ha) is situated at Croudace Bay, Lake Macquarie, NSW, Australia (33°1′S; 151°38′30″E) (Fig. 1). Soils on the upper slopes are classified as gradational Gn 3.91 while lower slope soils are duplex, Dd 4.11 (Northcote, 1979).

Annual average precipitation is 1080 mm with a summer maximum. Erosive rainfalls and storm runoff occur frequently, with the years of basin disturbance (1989 and 1990) receiving 35% and 67% more than average rainfalls, respectively. In February 1990, there was six-times the average precipitation for that month.

Upper and lower slopes are dominated by open forest, between which is a developing urban area, with its potential sediment sources indicated on Fig. 1. Coarse sediments, mostly sands and gravels, had in places almost completely filled the natural channel to capacity.

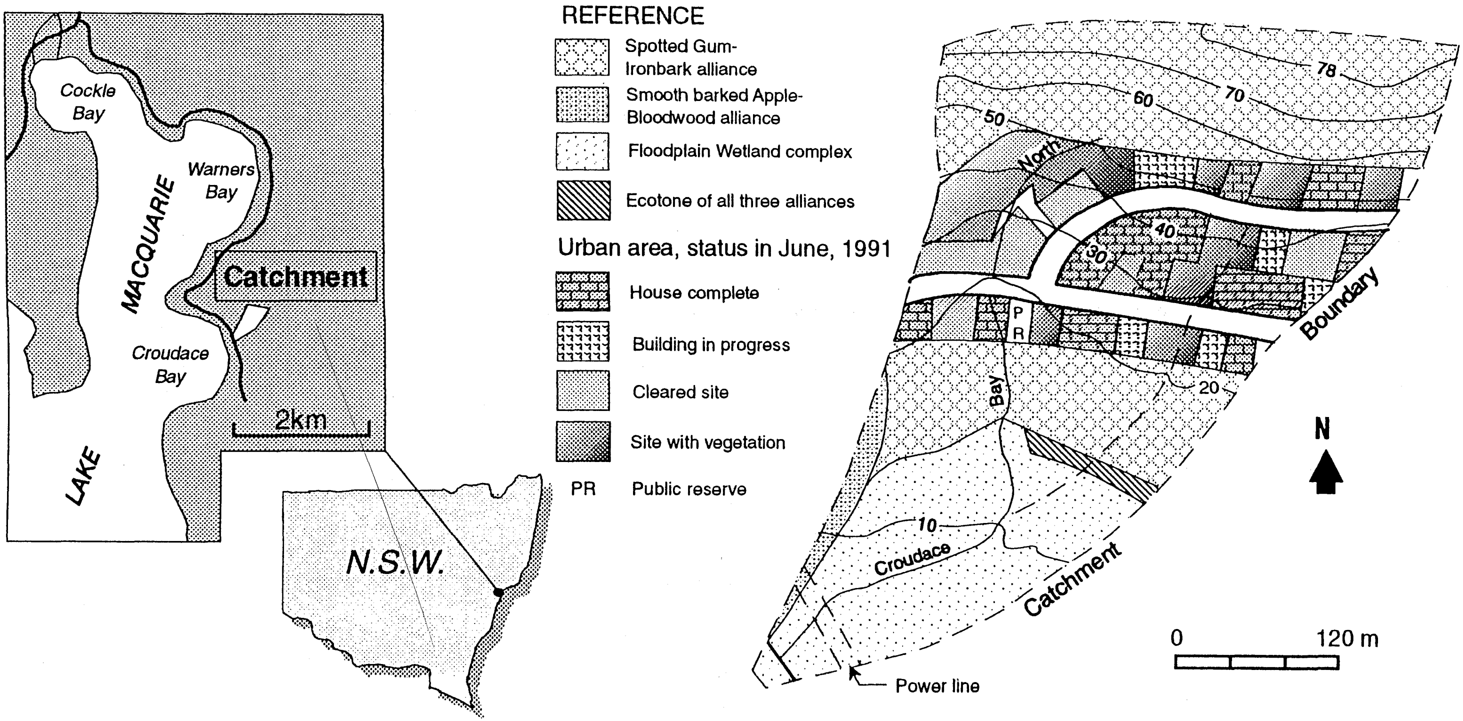

Fig. 1 Location and land-use, Croudace Bay catchment, Lake Macquarie, NSW. Contours in metres.

METHODS

Sediment sources

Three methods were used to assess the magnitude of sediment sources, the caesium-137 method (^{137}Cs), the Universal Soil Loss Equation (USLE) (Grierson, 1987) and surveying of rills. The fallout isotope ^{137}Cs has been widely used to measure soil erosion (e.g. Campbell *et al.*, 1988; Loughran, 1989; Ritchie & McHenry, 1990; Walling & Quine, 1990). The calibration curves derived from Australian erosion plot data (Elliott *et al.*, 1990) were employed to estimate erosion from ^{137}Cs measurements within the forest and urbanizing areas, respectively:

for forest: $Y = 7.74\,(1.09)^x \quad (n = 31,\ r = 0.82)$ (1)

for urban: $Y = 80.6\,(1.07)^x \quad (n = 60,\ r = 0.85)$ (2)

Y is net soil loss kg ha^{-1} year^{-1} and x is ^{137}Cs loss as a percentage of the reference value.

Sediment storages

To estimate the volume of sediment stored along the stream, nine sites were sampled by a single auger hole in the centre of the channel at approximately 10 cm depth intervals

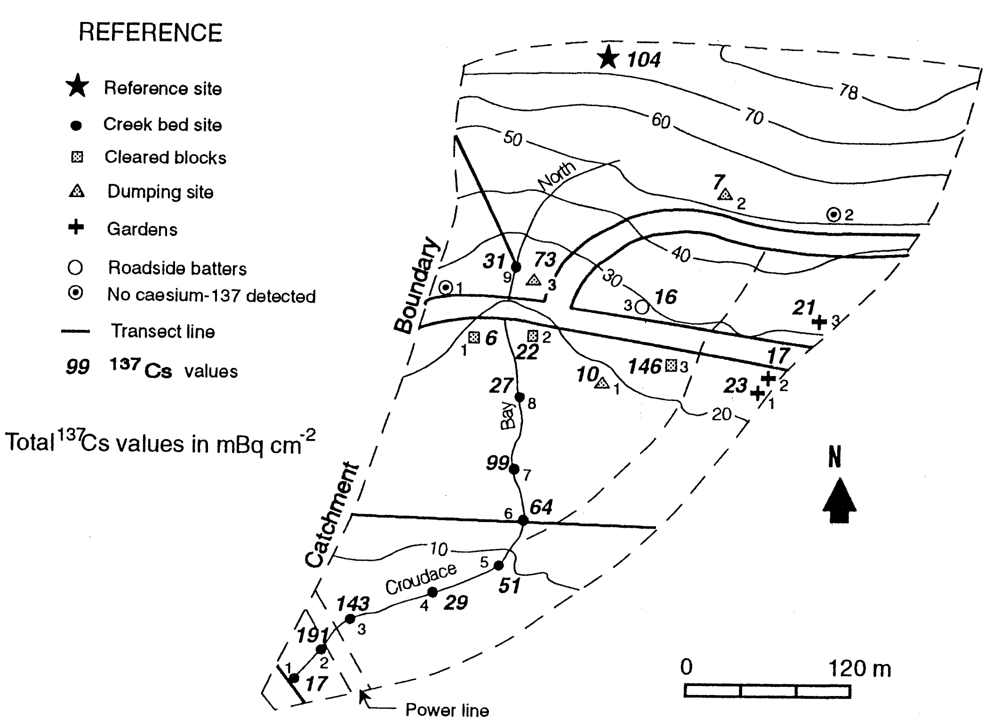

Fig. 2 Croudace Bay catchment, soil sampling sites and ^{137}Cs data. Contours in metres.

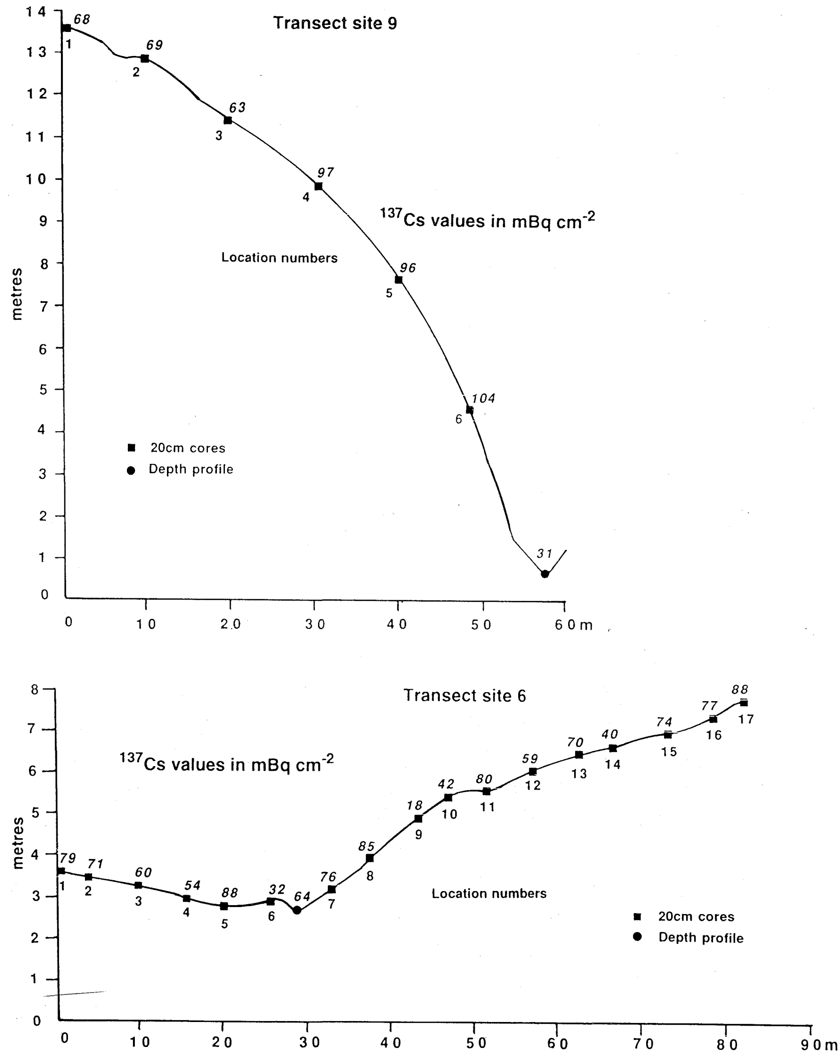

Fig. 3 Caesium-137 data for slope transects in the upper forest (transect site 9) and the lower forest (transect site 6).

(Fig. 2). Sediments without ^{137}Cs were assumed to have been laid down before the mid-1950s, and that the "original" channel cross section was parabolic.

RESULTS

Soil erosion

The reference site had 103.7 $\pm$ 1.9 mBq cm^{-2} of ^{137}Cs (Figs 2), while on the upper forest slope at transect site 9, ^{137}Cs values showed comparatively small losses (Figs 2 and 3). Net soil erosion was estimated from equation (1) to be 0.08 t ha^{-1} year^{-1}. Caesium-137 losses were greater on the lower forested slope (Fig. 3), with average net

Table 1 Net soil loss by the caesium-137 method.

Date	Land use	Area (ha)	Net soil loss (t ha^{-1} year^{-1})	Total soil loss (t)
1954-1988	Upper forest	6.2	0.08	16.9
(34 years)	Lower forest	7.9	0.79	212.5
	Urban	0.0	0.0	0.0
1988-1991	Upper forest	3.9	0.08	0.6
(2 years)	Lower forest	5.4	0.79	8.5
	Urban	4.8	49.6	475
TOTAL (1954-1991)		14.1	-	713.5

soil loss on transect site 6 estimated from equation (1) to be 0.79 t ha^{-1} year^{-1}. Net soil losses for the two forested areas were 16.9 t and 212.5 t, respectively, for the 34 year period of ^{137}Cs accession (Table 1).

Only two urbanizing sites had ^{137}Cs amounts greater than 25 mBq cm^{-2}, and two samples were below the level of detection for ^{137}Cs (Fig. 2). The urbanizing area is geomorphologically similar to the lower portion of forest slope transect 9 (sites 4, 5 and 6: Fig. 3), and average percentage ^{137}Cs loss at these three sites has been 4%. Assuming that 4% of the total ^{137}Cs had been lost from the urbanizing area prior to forest clearance, the percentage ^{137}Cs lost from the 12 urban ^{137}Cs sites as a result of urbanization can be estimated. The 12 urban sites are classified according to type: cleared blocks, soil dumping sites, gardens and roadside batters (Fig. 2). For each of these four types the average net soil loss was calculated from equation (2). The weighted net soil loss from the urban area (t ha^{-1} year^{-1}) was estimated according to the site condition shown in Fig. 1 (house complete, building in progress, cleared site and site with vegetation), and was 13.4 t ha^{-1} year^{-1}. Calibration curve equation (2) has been derived largely from erosion plots of the NSW Soil Conservation Service, and Lang (1992) has shown that the sediment load data have been underestimated by a factor of 3.7. Allowing for this error, the average net soil loss from the urbanizing area becomes 49.6 t ha^{-1} year^{-1}, and the total loss for the two-year period (1988-1991) 475 t (Table 1). From the ^{137}Cs method, the total net soil erosion from the basin has been 713.5 t (1954-1991) (Table 1).

For the period prior to urban development (1954-1988), the USLE was used to calculate soil erosion for the upper and lower forest using soil, ground cover and slope parameters from transects 9 and 6, respectively (Figs 2 and 3). For the period 1954-1988, soil loss was 364 t (Table 2). The basin was subdivided into upper and lower forest, and steeply and gently sloping urban areas for USLE estimates for the two-year period of urbanization, while erosion from the roadside batter rills was calculated by survey (Table 2). It was estimated that 467.9 t had been eroded from the basin during this time, with a total loss of 832 t between 1954 and 1991.

Sediment storage in the channel

The channel ^{137}Cs sediment data for nine sites are given in Table 3, and cross section reconstructions are shown in Fig. 4. Caesium-137 was found to depths between 58 and

Table 2 Net soil loss by the USLE.

Date	Land use	Area (ha)	Soil loss ($t\ ha^{-1}\ year^{-1}$)	Total soil loss (t)
1954-1988	Upper forest	6.2	1.09	230
(34 years)	Lower forest	7.9	0.50	134
	Urban	0		0
1988-1991	Upper forest	3.9	1.09	8.5
(2 years)	Lower forest	5.4	0.50	5.4
	Urban steep	2.14	50.4	216
	Urban gentle	2.5	39.4	197
	Rills	0.14	147.6*	41*
TOTAL (1954-1991)		14.1		832

* Rill erosion rate from surveying method.

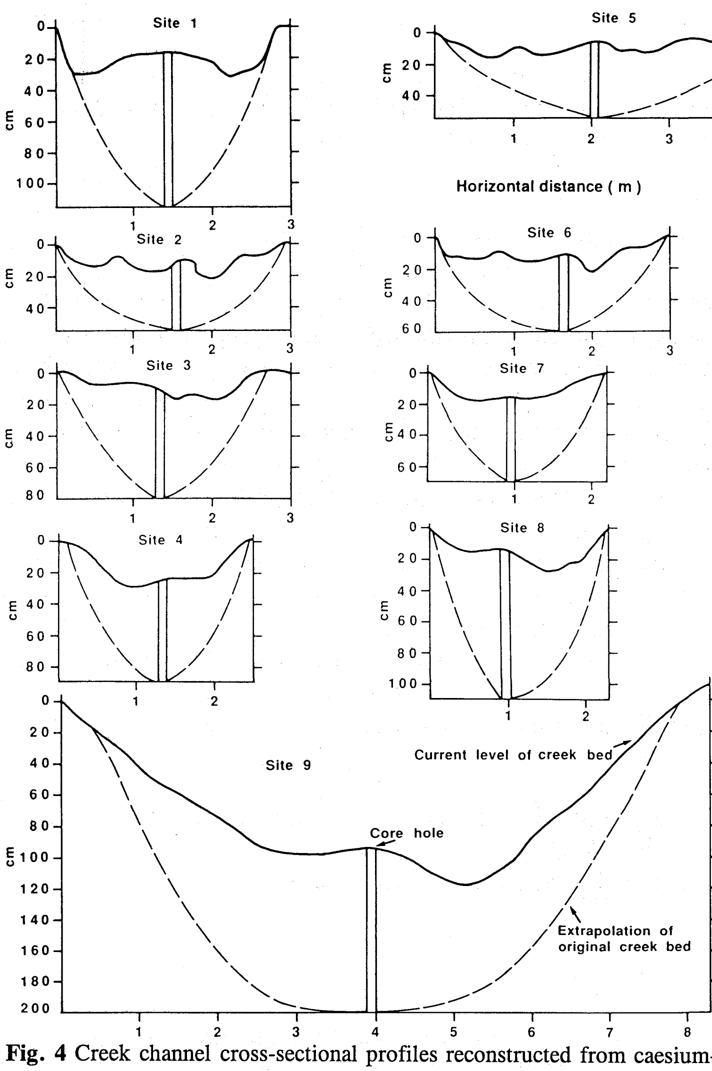

Fig. 4 Creek channel cross-sectional profiles reconstructed from caesium-137 depth measurements.

Table 3 Summary of channel caesium-137 data at sedimentation sites.

Site	Total ^{137}Cs (mBq cm^{-2})	Layer with max. ^{137}Cs (cm)	Deepest layer with ^{137}Cs (cm)	Max. depth sampled (cm)	Mass of stored sediment between sites (t)
1	17.1	10-20	85-98.5	98.5	
2	191.0	0-10	33-38	68	51.3
3	143.2	40-49.5	59-66	66	45.2
4	28.7	22-27	51-62	75	55.9
5	51.0	10-20	39.5-50	58	115.7
6	64.2	0-10	38-48	63	54.7
7	99.0	10-25	42-53	53	39.0
8	27.3	68-82	82-91.5	91.5	40.3
9	31.0	62-72	90-104	104	168.8
TOTAL					570.8

104 cm in channel sediments, and at only four sites was it certain that the total ^{137}Cs profile had been sampled (Table 3). Table 3 lists the estimated mass of sediment stored between each site and the total for the channel, which was 570.8 t.

DISCUSSION AND CONCLUSION

Basin sediment yield (erosion minus storage) is estimated to be 142.7 t by the ^{137}Cs soil erosion-method and 261.2 t by the USLE-surveying methods. The ^{137}Cs technique may have under-estimated net soil loss because the tracer capability had been lost at two urban sites, while the USLE may have over-estimated soil erosion because the model makes no allowance for the deposition of soil materials on the slope. The rate of soil loss in the basin probably lies between these two estimates, therefore. Both methods suggest that soil erosion in the urbanizing area is at least 40 times greater than in the forested portions of the basin.

A greater number of channel sediment profiles and sampling of the flood plain would have increased the accuracy of the storage estimate. However, the results show that a significant quantity of the sediments released from the urbanizing area have been deposited in the channel system and not delivered to Lake Macquarie. The retention of areas of open forest as buffer zones between urban areas and the lake may therefore be critical for sound sediment management.

Acknowledgements The assistance of Chris Dever and David Wilks is gratefully acknowledged. Funding for the research was provided by the Australian Research Council and the Lake Macquarie City Council.

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