The contribution of subsoil to sediment yield in the Murrumbidgee River basin, New South Wales, Australia

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Abstract There are very large differences between ^{137}Cs concentrations observed in sediment derived from topsoil erosion and those measured in sediment collected from the tributaries and main channel of the Murrumbidgee River, New South Wales, Australia. We argue that the difference between the high topsoil values and those observed in river sediment is due to dilution of ^{137}Cs by material derived from channel banks and gully walls. These are the most commonly observed forms of erosion in this region. The data indicate that the suspended sediment load in the lower Murrumbidgee River is dominated (90%) by material from these sources. The relationship between ^{137}Cs and ^{232}Th is believed to account for differences in radioactivity concentration due to particle size, but use of this ratio did not markedly alter the interpretation of the Murrumbidgee data. Concentrations of ^{137}Cs and ^{137}Cs normalized to ^{232}Th in suspended sediment collected during flood events from the larger tributaries and the main channel are lower than those collected during low flow. This implies that the subsoil contribution increases during floods and the relative yield from surface erosion processes alone decreased by about 50% under these conditions.

INTRODUCTION

The problem

In recent years there has been concern about high turbidity and the occurrence of toxic blue-green algal blooms in the lower Murrumbidgee River. It is widely believed that these blooms are due to high nutrient levels. In the generally turbid waters of rivers such as the Murrumbidgee, nutrients (such as phosphorus) are predominantly bound to particles (Oliver, 1993). Given that fertilized topsoils contain elevated concentrations of P, river and catchment managers need quantitative information about the relative contributions of topsoil (i.e. 0-10 cm depth) to the suspended sediment load in rivers. In this paper we compare concentrations of ^{137}Cs in sediment derived from sheet and rill topsoil erosion with those observed in suspended sediment in the Murrumbidgee River and calculate the relative contribution of topsoil-derived suspended sediment to the river.

The likely effect of particle size sorting during fluvial transport on ^{137}Cs concentration is discussed and the use of $^{137}Cs/^{232}Th$ ratios to reduce the variations due to particle size sorting is examined.

Anthropogenic ^{137}Cs and lithogenic ^{232}Th

Caesium-137 has been used extensively in erosion studies to distinguish surface soil from subsoil (e.g. Ritchie *et al.*, 1972; Burch *et al.*, 1988; Walling & Woodward, 1992). Caesium-137 fallout is derived from atmospheric testing of atomic weapons during and after the 1950s. In south east Australia, detectable ^{137}Cs is normally found in the top 100-200 mm of soil profiles (Campbell *et al.*, 1982). However, interpretation of ^{137}Cs concentrations in sediments can be complicated by particle size effects (e.g. Walling & Kane, 1984; Owens & He, 1995). Wallbrink & Murray (1993) propose that normalizing ^{137}Cs to ^{232}Th may reduce variability caused by particle size sorting because the concentration of both nuclides appears to be predominantly surface area controlled. Olley *et al.* (1996) demonstrated in a small forested catchment near Eden, NSW Australia, that differences in concentrations of these nuclides were related to particle size and that the ratio of $^{137}Cs/^{232}Th$ decreased the effect of particle sorting and separation.

The study area

The Murrumbidgee River is one of Australia's largest inland rivers and drains approximately 84 000 km^2 of the Murray Darling Basin (Fig. 1). The Murrumbidgee River basin can be divided into three distinct areas which define the upper, middle and lower sections of the river. The upper part of the basin has its headwaters in the Snowy Mountains and is characterized by mountainous and hilly terrain. The river in this section is impounded by the main storage reservoirs of the Burrinjuck and Blowering dams. Downstream of these dams, the middle section of the basin is characterized by undulating terrain to Wagga Wagga. Between Gundagai and Wagga Wagga the river has formed a well defined flood plain approximately 1-2 km wide (Page, 1994). The lower river basin downstream of Wagga Wagga is characterized by low river gradients and a flood plain width of between 5 and 20 km. The study area extends from the headwaters of the Molonglo River, which is a large tributary in the upper Murrumbidgee basin, downstream to Balranald. The upper section of the Murrumbidgee basin is partially regulated by a series of dams whose main purpose is generation of electricity and water supply. Flow from this area to the middle and lower sections is regulated by the two main storage dams. However, in times of intense and sustained rainfall, and when the storage dams are full, the entire system is left partially unregulated, resulting in flooding below Wagga Wagga. The flow regime before regulation was highly variable with a winter maximum, however flow is now spring and summer dominated when water demand by irrigators is highest. The majority of downstream flow is derived from the storage reservoirs (Burrinjuck and Blowering) and the tributaries upstream of Wagga Wagga. Maximum discharge is at Wagga Wagga. In the lower section the river enters a semiarid region and there is a progressive downstream decrease in flow.

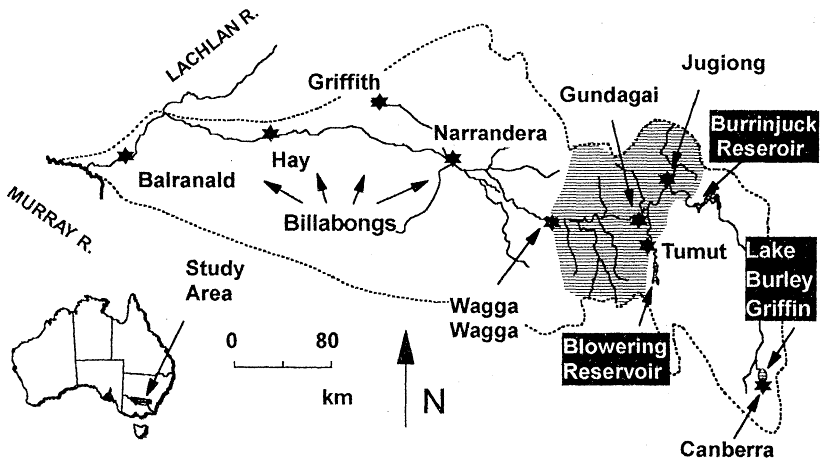

Fig. 1 Location diagram for the Murrumbidgee River basin, NSW, Australia (hatched area defines tributary catchments below Burrinjuck Dam).

MATERIALS AND METHODS

Catchment sampling strategy and analytical methods

Measurements of ^{137}Cs and ^{232}Th, using the methods described by Murray *et al.* (1987), were made on suspended and deposited sediment and on soils from various locations within the catchment. The suspended sediment samples were obtained using a continuous flow centrifuge (CFC, Alfa Laval model M102b) which accumulates masses up to 300 g. Suspended sediment samples were taken from the larger downstream tributaries which include the Adelong, Jugiong, Tarcutta, Billabung, Kyeamba, Tumut and Lachlan Rivers, just upstream of their junction with the main Murrumbidgee channel. Samples were also taken from 14 locations along the main channel between Jugiong and Balranald (approximately 1000 river km). All these suspended sediment samples were fine grained and generally < 63 μm. Sampling was undertaken over a period of 4 years in a range of conditions including baseflow and a one in 12 year flood. Sediment cores were taken from water bodies within the upper, middle and lower basins of the Murrumbidgee catchment, including Lake Burley Griffin, Burrinjuck Dam and a series of

Table 1 Measurements of ^{137}Cs concentrations and $^{137}Cs/^{232}Th$ ratios in topsoil-derived runoff and soils.

Location	Process	^{137}Cs		$^{137}Cs/^{232}Th$		Samples
		(Bq kg^{-1})	standard error	(ratio)	standard error	(n)
Goulburn	Surface runoff	31.6	0.6	0.33	0.01	21
	$<2\mu$m core	23.9	4.0	0.39	0.05	11
Black Mountain	Topsoil runoff	17.3	1.9	0.35	0.04	43
Average		24.8	1.5	0.37	0.02	64

billabongs and overflow channels downstream of Wagga Wagga which receive sediment during flood events (Fig. 1). Only the top layer of these cores was used in this study, firstly because it is believed they are representative of the current sediment flux and secondly as ^{137}Cs is being used as a tracer of sediment origin there is the possibility that interpretation of ^{137}Cs concentrations further down these cores will be complicated by *in situ* fallout. The material in the top layers of these cores was dominated by fine silt and clay, again <63 μm.

RESULTS

Radionuclide concentrations in surface soils

The concentration of ^{137}Cs in fine particulates derived from topsoil erosion processes alone has been determined by (a) measurements of suspended sediment generated from two surface flow experiments; and (b) by analysis of the fine fraction from a soil profile excavated to 10 cm depth. These experiments were conducted on soils developed on three different lithologies that are considered typical of the region. The results of these studies are given in Table 1 and on the basis of these data the average ^{137}Cs concentration of sediment derived from topsoil erosion is about 25 ± 2 Bq kg^{-1} and the $^{137}Cs/^{232}Th$ ratio is 0.37 ± 0.02 ($n = 64$).

Radionuclide concentrations in tributary and main channel suspended sediment

The data from the major tributaries below Burrinjuck dam are summarized in Table 2. There is a difference between the average tributary ^{137}Cs concentrations and $^{137}Cs/^{232}Th$ ratios under low flow and flood conditions. The value during floods decreases by 29% and 31% for the ^{137}Cs concentrations and the $^{137}Cs/^{232}Th$ ratio respectively. The overall average tributary ^{137}Cs value is 2.4 ± 0.3 ($n = 51$). The average ^{137}Cs concentrations in the main channel based on the 14 locations between Burrinjuck and Balranald are generally low, <5 Bq kg^{-1} (Fig. 2(a)). The average value of all the channel samples

Table 2 Summary of tributary and main channel average ^{137}Cs concentrations and $^{137}Cs/^{232}Th$ ratios in the Murrumbidgee River, below Burrinjuck Dam.

Location	Condition	Average ^{137}Cs (Bq kg^{-1})	standard error	Average $^{137}Cs/^{232}Th$ (ratio)	standard error	Samples (n)
Channel	Low flow	2.9	0.4	0.031	0.003	47
Channel	Flood	2.1	0.1	0.024	0.001	116
Tributaries	Low flow	2.8	0.5	0.035	0.005	22
Tributaries	Flood	2.0	0.2	0.024	0.003	29
Tributaries	Average	2.4	0.3	0.028	0.002	51
Channel	Average	2.4	0.1	0.026	0.001	163

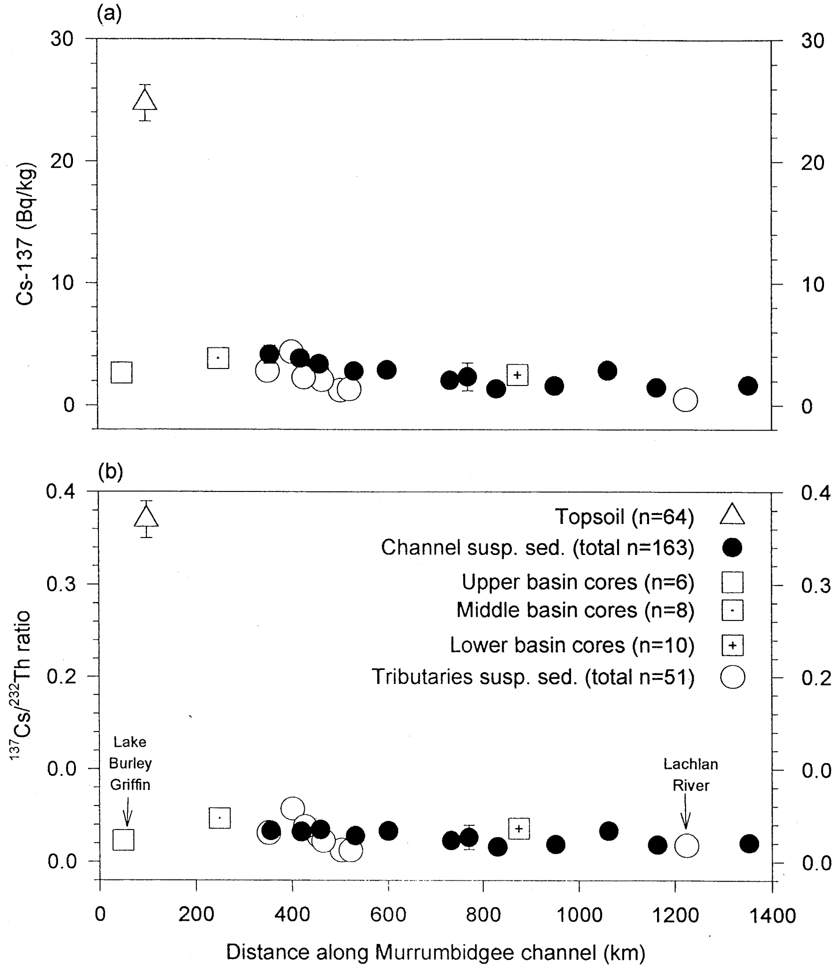

Fig. 2 (a) Measurements of ^{137}Cs concentrations associated with suspended sediment, deposited cores and surface soil fines in the Murrumbidgee River basin, NSW, Australia; (b) $^{137}Cs/^{232}Th$ ratio values for the same sediments at the same locations.

collected is 2.4 ± 0.1 (n = 163). The channel data have also been summarized for low flow and flood conditions (see Table 2) and a 30% difference occurs between their respective average concentrations and ratio values. This difference is comparable to that observed within the tributary sediments. The average ^{137}Cs concentration and normalized $^{137}Cs/^{232}Th$ ratio values from the channel and tributary sediments collected under the two main flow conditions are within analytical uncertainty of each other.

Radionuclide concentrations in sediment cores

The average ^{137}Cs concentrations and normalized $^{137}Cs/^{232}Th$ ratio values for sediment cores obtained from Lake Burley Griffin, Burrinjuck Dam and lower basin billabongs are given in Table 3 and plotted in Fig. 2(a) and Fig. 2(b). The concentrations of ^{137}Cs

Table 3 Summary of average ^{137}Cs concentrations and $^{137}Cs/^{232}Th$ ratio values from deposited cores in water bodies and overflow channels within the upper and lower Murrumbidgee River basin.

Location	Catchment area	Mean depth	Average ^{137}Cs		Average $^{137}Cs/^{232}Th$		Samples
	(km^2)	(cm)	(Bq kg^{-1})	standard error	(ratio)	standard error	(*n*)
Lake Burley Griffin	2100	5	2.6	0.4	0.039	0.009	6
Burrinjuck Dam	13000	5	2.9	0.3	0.038	0.003	8
Billabongs	50-70000	2	2.5	0.4	0.036	0.006	10
Average			2.7	0.3	0.037	0.004	24

in sediment from these water storage bodies are all low, <5 Bq kg^{-1}. For the Lake Burley Griffin, Burrinjuck and billabong cores, ^{137}Cs concentrations and normalized ratios are all within analytical uncertainty of one another. There appears to be no relationship between ^{137}Cs concentrations or $^{137}Cs/^{232}Th$ ratios and the size of the upstream basin area.

DISCUSSION

^{137}Cs concentration and ratio value changes with river length

The low ^{137}Cs concentration values of the fine-grained sediment in tributary, core and main channel sediment can be compared with the equivalent high values observed in fine sediment runoff from topsoils (Fig. 2(a)). There is a clear difference in these values. It may be expected for a basin of this size (84 000 km^2) that a degree of particle sorting by density and size may occur. That is, the particle size composition of sediment in the Murrumbidgee River could become gradually finer and this would possibly result in an increase in ^{137}Cs concentrations, by the mechanisms described in the Introduction. However, it appears there is no net increase, and in fact a slight decrease may be present. This could be due to a progressive addition of bank material along the main channel, but this is complicated by the decreasing flow and sediment load that characterize the river below Wagga Wagga (Olive *et al.*, 1994). The $^{137}Cs/^{232}Th$ ratios show that the differences between, and within, topsoil and suspended sediment samples remain relatively the same (Fig. 2(b)). This implies either that sorting of particles in suspension within the Murrumbidgee channel is not occurring, or that this process has already taken place within the tributaries. This is partially supported by the ^{137}Cs concentration and $^{137}Cs/^{232}Th$ values observed at the tributary outlets entering the Murrumbidgee below Burrinjuck (noted as open circles in Fig. 2(a) and Fig. 2(b)) which are largely consistent with those immediately upstream and downstream of the junctions in the main channel. Alternatively, it may suggest that the relationship between ^{137}Cs concentration and particle size is weak, but this hypothesis is not supported by our measurements of particle size dependence from a representative soil, which demonstrates that the opposite is true (Fig. 3).

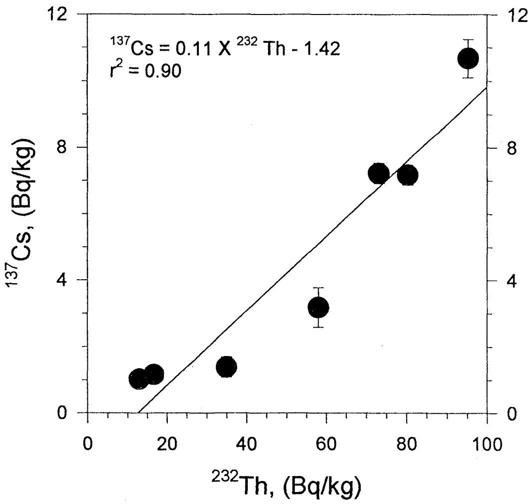

Fig. 3 Relationship between ^{137}Cs and ^{232}Th for different particle sizes in a clay-rich soil within the Murrumbidgee River basin. Finer particles have highest concentrations of radioactivity and coarser particles have lower concentrations.

Sediment sources

The considerable difference between the high topsoil ^{137}Cs and ^{137}Cs/^{232}Th values compared to the low values associated with the suspended and deposited sediment can best be explained in terms of dilution by subsoil material which is not labelled by ^{137}Cs. The relative amount of non-labelled subsoil required to dilute these surface concentrations to those observed in the Murrumbidgee system is about 90%. Similar contributions are calculated when the normalized ^{137}Cs/^{232}Th ratio values are used (Fig. 2(b)). These findings are consistent with those of Starr (1989) and Olley *et al.* (1993), suggesting that gullies are the dominant form of sediment supply in this region. Ritchie *et al.* (1972) also observed low concentrations of ^{137}Cs in reservoir sediments which they attribute to drainage of gullied basins. It also appears from the low ^{137}Cs concentration and ratio values from the Lake Burley Griffin and upper basin cores, and from the downstream tributaries, that dilution of topsoil tracers by channel bank erosion processes occurs within the tributary system itself. This probably occurs at the point at which the stream first becomes incised. Further work is being undertaken to confirm this. Another possibility is that the low concentrations currently in transport represent contemporary surface erosion from surfaces that have lost their initial inventory of ^{137}Cs. However, numerous measurements of ^{137}Cs in soil cores throughout the basin reveal inventory values that are consistent with that expected from deposition during the 1950s and 1960s, suggesting that the great majority of fallout ^{137}Cs remains *in situ* (Wallbrink, unpublished data).

Estimating the contribution from surface erosion process alone

The ^{137}Cs concentrations from the tributaries, channels and soil surface can be used to estimate the proportion of fine sediment derived from surface erosion processes alone. That is, the amount of material entering channels from processes such as sheet and rill erosion that occur on the soil surface above the gully and channel network. Subsoil sediments are typically generated from collapsing channels or gully walls. This material will be unlabelled by ^{137}Cs, but when a bank collapse occurs a small topsoil contribution, labelled by ^{137}Cs, will also be added to the sediment entering the drainage line. Consequently, a small ^{137}Cs signal will be generated from what is otherwise predominantly a subsoil-derived sediment generating process. The fine-grained fraction of the topsoil component will be labelled by ^{137}Cs (at 25 ± 2 Bq kg^{-1}). However, it will be diluted to 0.7 ± 0.2 Bq kg^{-1}, on average, if the channel banks are about 4 m in height (a reasonable estimate of bank height within the Murrumbidgee channel). The collapse of a 2 m section of bank (such as typically found within the tributary catchments) would produce fine-grained sediment with an average ^{137}Cs signature of approximately 1.3 ± 0.3 Bq kg^{-1}. These data can then be used to calculate an upper limit to the ratio of the relative contribution of sediment derived from surface erosion processes alone to the total sediment load carried by the Murrumbidgee. If the average tributary ^{137}Cs concentration is C_T, the predicted concentration from channel/gully erosion is C_G and the concentration from sheet/rill erosion is C_S, then the fractional contribution of sheet/rill F_S erosion to the sediment derived from the tributaries is:

$$F_S = \left[\frac{C_T - C_G}{C_S - C_G} \right] \times 100 \qquad (1)$$

Substituting the values of average tributary concentration, given in Table 2, equation (1) gives an upper limit to the sheet/rill contribution of $<5\%$. If the same analysis is undertaken using the average normalized ^{137}Cs ratio values for the tributaries, then a maximum contribution of $<3\%$ is obtained. An estimate of the different contributions from sheet/rill erosion sources during floods and low flows can also be obtained from the calculated concentrations and ratio values given in Table 2. Calculations using these data give 3% and 7%, for floods and low flows respectively, using ^{137}Cs concentrations, and 2% and 5% respectively, using $^{137}Cs/^{232}Th$ ratio values. These estimates represent a relative decrease in the topsoil tracer value of approximately 50% during floods. This change presumably results from an increase in the subsoil channel/gully contribution during floods.

CONCLUSIONS

Measurements of ^{137}Cs and ^{232}Th have been made on suspended and deposited sediments from the main channel and major tributaries and water storage bodies in the Murrumbidgee River basin to determine the origin of this material. Concentrations of ^{137}Cs and values of the $^{137}Cs/^{232}Th$ ratio associated with suspended sediment derived from topsoil erosion processes are high. In contrast, the values observed on similar sized particles in the Murrumbidgee River, its tributaries and water storage bodies, are low. The difference between the topsoil and the transported river sediment contributions is most probably due to dilution by a substantial amount of unlabelled subsoil derived from gully wall and channel bank erosion. The contribution of topsoil to total suspended sediment is estimated to be < 10%. The contribution from surface erosion processes is no greater than 5%, on average, although there is a difference in the magnitude of material from this source under low flow versus flood conditions. Average ^{137}Cs concentrations measured in the main channel are consistent with those from the cores collected from Lake Burley Griffin, Burrinjuck Dam and suspended sediment from the upstream tributaries. There is little difference in the interpretation of these data when using either absolute ^{137}Cs concentrations or the $^{137}Cs/^{232}Th$ ratio values, suggesting that the major effect of particle size sorting has occurred at a scale smaller than the tributary channels. There are differences between low flow and flood ^{137}Cs concentrations and $^{137}Cs/^{232}Th$ ratio values from the channels and tributaries, indicating that the subsoil contribution increases during floods. The low ^{137}Cs concentrations and ratio values at the tributary outlets also suggest that most of the subsoil contribution has occurred within these basins prior to entering the main channel and that material from these sources dominates sediment delivery in this river.

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