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Sediment Sourcing in the Lake Burley Griffin Catchment

Final Report

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1 Introduction

1.1 Background

Lake Burley Griffin was created by the construction of Scrivener Dam in 1963. The Lake Burley Griffin Catchment Protection Scheme (LBGCPS) was commenced in 1964 to address concerns about water quality and siltation in the new lake. The scheme has been implemented by the NSW and ACT Soil Conservation Services with funding from the Commonwealth. Landholders have also contributed to the scheme.

Sedimentation and turbidity in Lake Burley Griffin affect the longevity of the lake, its recreational value, and the biology of the water body. The long-standing agreement between LBGCPS members aims to reduce sedimentation and turbidity by promoting better land management and by soil conservation techniques. To efficiently target this effort, a joint research project was established between CSIRO (Division of Water Resources), the ACT Parks and Conservation Service and NSW CaLM (Conservation and Land Management). This project initially had the objectives of establishing the distribution of sediment in the lake and its rate of accumulation, and then to determine the sources of this sediment. Of these objectives the first has already been met (Caitcheon et al, 1988). This report deals specifically with the second objective.

Major tributaries of Lake Burley Griffin are the Molonglo, Queanbeyan, and Jerrabomberra catchments. Of these the Molonglo was identified for further research because it was already the focus of NSW CaLM erosion-mitigation works.

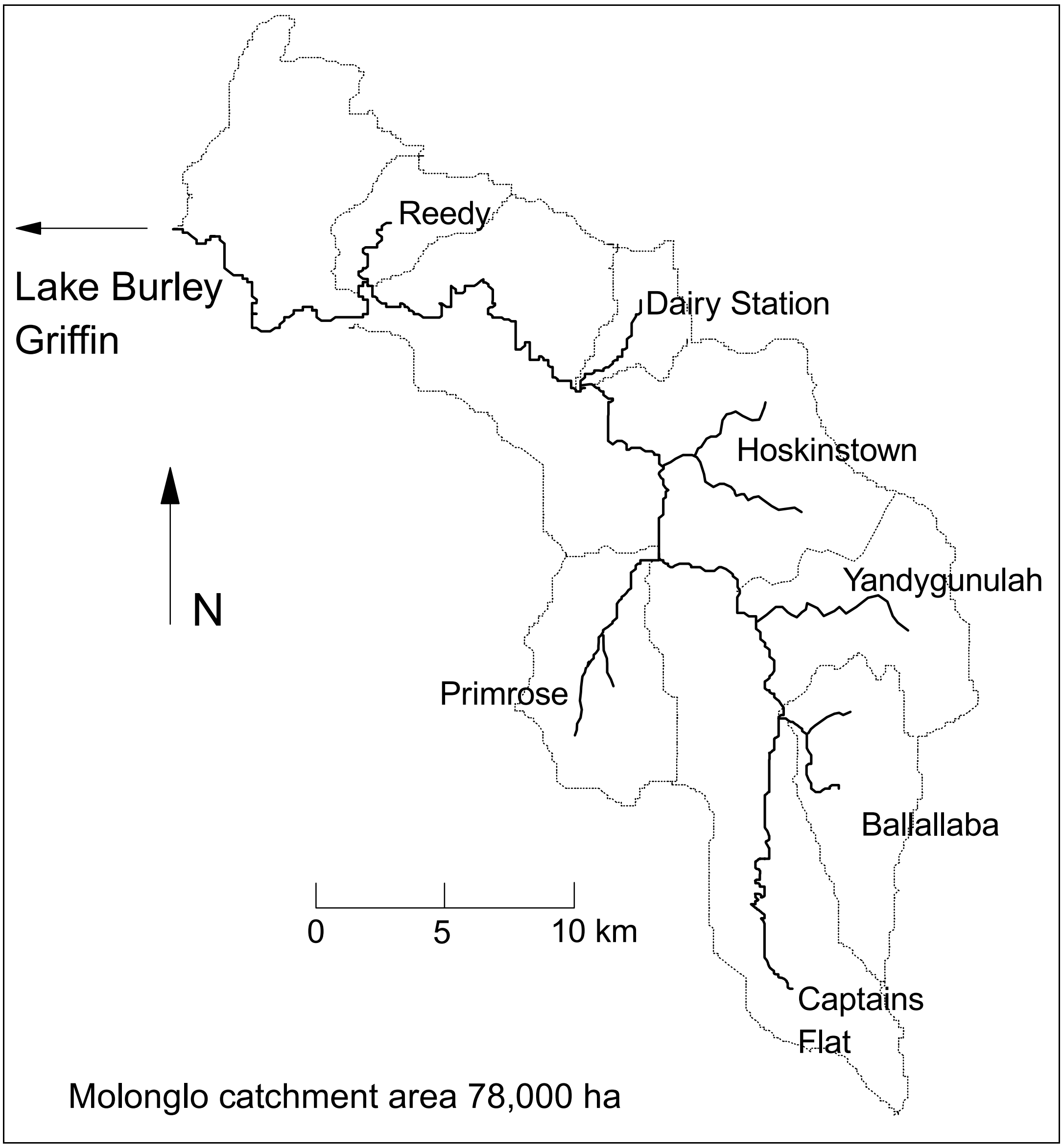
The aim of this investigation was to apply a number of tracing techniques to the Molonglo to determine sediment sources in that catchment, and then to compare the results with those obtained from conventional procedures based on soil conservation planning. The tracing program was implemented down to the subcatchment scale in two sub-catchments of the Molonglo river, the Ballallaba and Primrose Creeks. Tracer measurements were also used to provide indications of the extent and type of topsoil movement within the Molonglo. A subset of this tracer data was then used to estimate the proportional contribution of bank collapse to in-stream sediments in an upstream section of the Molonglo river channel.

2 Catchment Description

2.1 Geomorphological characteristics

The Molonglo catchment covers 78,000 ha on the Southern Tablelands of NSW and represents 37 % of the Lake Burley Griffin catchment. The sub-catchments on which this study focuses, Primrose, Yandygunulah, Ballallaba, Reedy, and Dairy Station Creeks, are the main tributaries of the Molonglo River.

Figure 2.1.1: Molonglo catchment showing tributaries and their boundaries



The physical characteristics of the Molonglo catchment are typical of much of the Southern Tablelands of NSW. The Molonglo catchment is fringed east and west by rugged hills (maximum elevation 1360 m) developed on metasediment and granite lithology. Within the catchment, the terrain is more rolling with long, low-angle colluvial slopes a common feature. The only flat land is limited to alluvial deposits along the major creeks and rivers, with the Hoskinstown Plain the prominent feature in the centre of the catchment. The lower end of the catchment is at 560 m. The range of soil types include lithosols on the more rugged terrain to red and yellow podzolics on the lower hills, with deep layered soils characteristic of the colluvial and alluvial flats.

The climate is one of mild summers and cold winters with annual average rainfall ranging between 620 and 850 mm from east to west across the catchment. Plant growth is limited by frequent winter frosts and a summer evaporation rate which on average exceeds annual rainfall by a factor of five (Gunn et al, 1969).

Figure 2.1.2: Aerial view of Molonglo Catchment

The catchment is largely cleared for grazing on native and improved pastures, with about one third remaining under timber or mature regrowth. Rural residential subdivision has affected about 15 % of the catchment while part of the urban and industrial areas of Queanbeyan drain into the lower end of the river.

2.2 Erosion in the Molonglo Catchment

The first white settlers when they arrived in the Molonglo catchment in the early 1820's found a drainage system that was largely non-incised apart from the Molonglo itself (Eyles, 1977). With the build up in stock numbers in the catchment came extensive clearing of the native timber and drainage of the swamps. Cropping of wheat and potatoes was common practice (Moore, 1981). Groundcover was severely reduced with heavy grazing pressure from sheep and the explosion of rabbit numbers during the 1880's. By the turn of the century, much of the sheet and gully erosion in the catchment would have been extant (Sebire, 1992, Fogarty et al, 1989).

In contrast, the period from the 1950's to the present has seen considerable advances in the level of farm management including widespread pasture improvement, subdivision fencing and control of rabbits. The overall effect of these changes has been improved ground cover and the regeneration of much of the land subject to sheet erosion 80 to 100 years ago.

A number of surveys of soil erosion have been carried out in the Lake Burley Griffin catchment, incorporating the Molonglo. In 1972, Higginson and Emery produced a survey of erosion and land use derived from 1:40,000 scale air photos and limited field checking. The survey analysed the relationships between soils, land classes, land use, and erosion. It was a broad survey and the areas of erosion were not based on subcatchments, nor did it identify individual gully systems. Table 2.2.1 shows the results of this survey.

Table 2.2.1: Extent of erosion in the Molonglo catchment from the survey by Higginson and Emery (1972)

Erosion Category	Extent (ha)
no appreciable erosion	25,075
minor sheeting	12,190
moderate to severe sheeting	260
minor gullying	10,250
moderate gullying	3,385
severe gullying	1,360
very severe gullying	300

A more detailed erosion survey was completed in 1985 as part of a systematic coverage of eastern NSW by the Soil Conservation Service. This survey was plotted at a scale of 1:100000. This survey gave a more accurate and detailed picture of all forms of erosion in the catchment, and formed the basis for programming subsequent catchment protection works.

2.3 The Lake Burley Griffin Catchment Protection Scheme

In 1962, with the construction of Scrivener Dam imminent, Strom (quoted in Sebire, 1991) reported to the Commonwealth as follows:

> *The soil and stream erosion in the lake catchment are not so bad as many Australian catchments,* ***not nearly as bad as in some****; they do not appear to threaten immediate disaster, except possibly if a series of bad floods occur, but they are bad enough to cause inevitable trouble in the future and should therefore be taken in hand as soon as practicable as they will take time and work to overcome.*

In 1964 an agreement was signed by the Commonwealth and NSW Governments the objective of which was to control erosion in the Lake Burley Griffin catchment and thus reduce the rate of sediment movement into the lake. The Commonwealth agreed to fund the cost of structural works. The NSW Soil Conservation Service was to design and implement the works, with landholders in the catchment to undertake land management measures. In order to divide the catchment into manageable units, erosion control works have been planned and implemented on a sub-catchment basis, each being called a Project. The Molonglo

Project commenced in 1989 and is funded until 1996. The present level of funding is around $250,000 per annum.

2.4 Soil Conservation Planning

The programming of catchment protection works conventionally has been a two-stage process:

i) the 1:100,000 soil erosion maps detail the extent and severity of the main forms of soil erosion in the catchment – sheet, gully and streambank. Interpretation of these maps, as outlined in section 4, can provide a quantitatively based assessment of the severity of soil erosion on a subcatchment basis.

ii) once a sub-catchment has been targetted, a farm-level survey is then carried out to check the veracity of the broadscale mapping and to develop a plan of works. The works include farm dams as sediment traps, flume construction and diversion banks to stabilise gully heads, gully fencing and gully filling where appropriate. Landholders are also enlisted at this stage by formal agreement to undertake land management measures such as ground cover improvement and fencing.

This approach is outlined further in section 4.

3 Erosion Assessment by Soil Conservation Planning

3.1 Erosion assessment

Erosion mapping for the Molonglo catchment is the result of a program that has mapped most of eastern NSW. These maps represent the conventional basis for soil conservation project planning, and are a means of assessing the severity of erosion in a catchment. The quantification of map information can be done in a number of ways:

i) In the original erosion survey of the catchment (Higginson and Emery, 1972) upon which much of the LBG CPS soil conservation planning has been based, the area of land affected by a particular form of erosion has been measured. This is straightforward in the case of sheet erosion. However in the case of gully erosion it was taken to mean the area of land upstream of the gully. Hence the statistics reported in Higginson and Emery (1972) for the erosion in LBG catchment, and quoted previously in table 2.1.1.

ii) In areas where gully erosion dominates such as the Southern tablelands, a better assessment can be obtained by measuring the length of gullies from the erosion maps produced in 1985. Although having broad resolution this procedure still permits a characterisation of each sub-catchmnent in terms of the actual gullies present. For the purposes of this assessment, the minor category (defined as isolated discontinous linear gullies) has been disregarded as they are generally discontinuous and confined to minor drainage lines. Also, the sub classes in each of the moderate and severe categories have been amalgamated. The data is presented in Table 3.1 and have been standardised on the basis of catchment area to give an indication of the density of gullying.

Table 3.1: gully erosion statistics for the main subcatchments of the Molonglo

	catchment area (ha)	moderate (km)	severe (km)	streambank (km)	gully length (m ha^{-1})
Dairy Station	2,052	2.6	20.8	4.3	13.5
Yandygunulah	5,532	5.5	8.8	9.4	4.3
Ballallaba	6,796	11.8	12.7	0	3.6
Primrose	6,329	1.8	3.7	8.4	2.2

The data suggest that Dairy Station creek is the most severely degraded catchment, with a gully density of 13.5 m ha^{-1}. Yandygunulah and Ballallaba Creeks are similar (4.3 and 3.6 m ha^{-1} respectively), while Primrose is the lowest at 2.2 m ha^{-1}. Also, the majority of the gullies in the Dairy Station Creek sub-catchment are classified as severe while in the remaining 3 subcatchments, the proportion of moderate to severe is roughly similar.

Note: For comparative purposes, many of the small catchments (<1000 ha) in southern NSW have gully densities in the range 3-6 m ha^{-1}, with the most extreme case 20 m ha^{-1}, as determined from the erosion maps.

iii) In order to check the veracity of the data derived from the erosion maps, a separate exercise to map continuous, connected gullies in each of the four sub-catchments was undertaken using 1:25,000 aerial photos, and subsequently plotting the gullies onto 1:25,000 maps for measurement. Wasson et al., (in press) and Neil and Fogarty (1989) have shown the significance of gullies which form a continuous system in generating and delivering sediment to trunk streams. The length of connected gully and the ratio to catchment area is shown in Table 3.2.

Table 3.2: Ratio of connected gully length to catchment area

Catchment	Length connected gully (m)	Gully length to area ratio (m ha^{-1})
Dairy Station	34800	16.9
Ballallaba	17780	3.2
Yandygunulah	23520	3.4
Primrose	12650	2.0

This table shows a reasonable correspondence with table 3.1. Again as demonstrated by the erosion mapping, Dairy Station Creek is the most significant in terms of gully length to catchment area although the original erosion mapping classified some of the gullies as streambank erosion. Both Ballallaba and Yandygunulah are comparable although considerably lower than Dairy Station Creek, with Primrose Creek catchment having the lowest gully to area ratio.

4 Sediment Yield Data

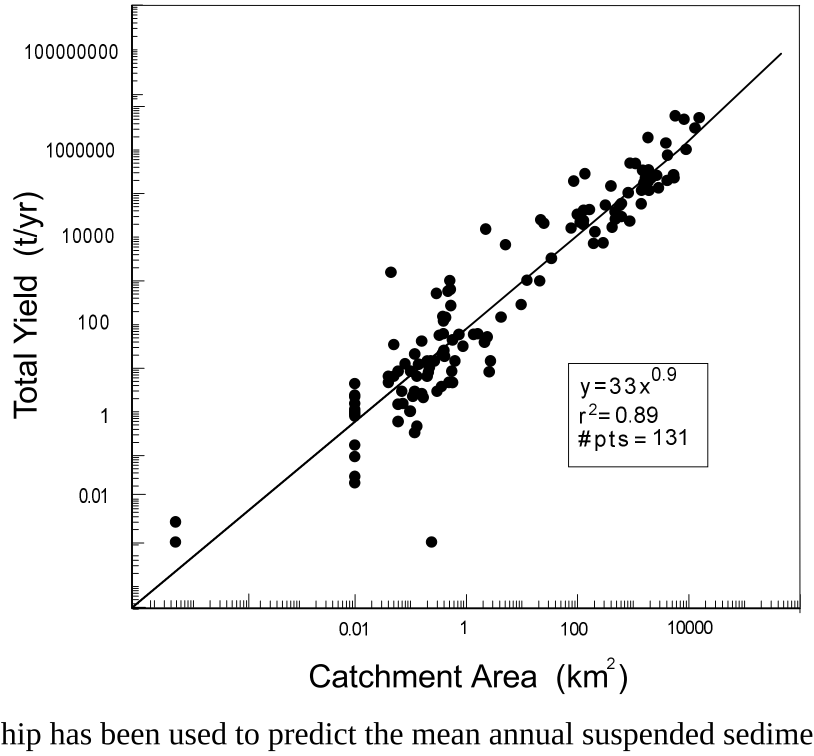
A simple first order estimate of catchment sediment yield can be obtained using catchmnent area as a surrogate. The sediment masses contained within 131 South Eastern Australia and Southern Tablelands storages have been tabulated against catchment area, mean annual yield (t/yr) and mean annual specific yield (t/km^2/y), Wasson (1994). This data all come from catchments in which the drainage net is incised and connected. The masses have been converted to volumes by applying a density correction of 0.9 t/m^3 based on measured densities in a number of sediment cores.

The mean annual suspended sediment yields (t/yr) for the catchments corrected for the trap efficiency of each storage, are shown plotted against catchment area (km^2) in figure 4.1. A regression relationship has been fitted to these data. The scatter in the data simply reflects differences in yield relating to differences in land use, drainage density, soil type and relief. This relationship is defined as:

$$y = 33\,x^{0.94} \qquad \text{equation (1)}$$

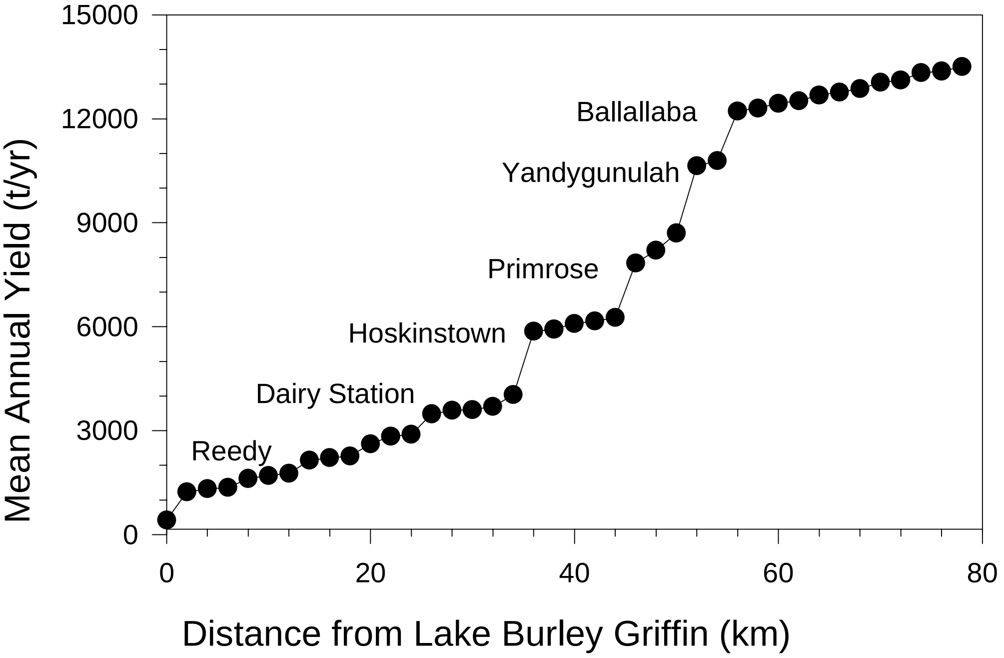
where y = Mean annual total yield in (t/yr) and x = catchment area (km^2)

Figure 4.1: South Eastern Australia sediment yield based on data from 131 locations



This relationship has been used to predict the mean annual suspended sediment yield from each of the tributaries to the Molonglo catchment. A diagram showing the cumulative mean annual suspended sediment yield along the Molonglo is shown in Figure 4.2, starting from East Basin and working upstream.

Figure 4.2: Cumulative mean annual suspended sediment yield from Molonglo tributaries.



For the purposes of this exercise the contribution from the Queanbeyan has not been included. From this diagram there appears to be small increases in yield (t/yr) up until Hoskinstown catchment above which it steps up uniformly following additions from Primrose, Yandygunulah and Ballallaba (see Table 4.1).

The following points are important however when viewing Table 4.1:

- They are based on the average conditions for the Southern Tablelands, albeit with the majority of the data being derived from within or near the Molonglo catchment.
- They are based entirely on catchment area as a predictor yield and so do not incorporate any other factors such as land use, slope, drainage density etc., that may effect yield.
- They are a guide only.

Table 4.1: Yield estimates from major tributaries to Molonglo

Tributary	Area (km^2)	Yield (t/yr)
Reedy Ck.	29.8	650
Dairy Stn.	21.4	476
Hoskinstown	71.5	1,481
Primrose	61.2	1,279
Yandygunulah	76.4	1,575
Ballallaba	55.2	1,161

These estimates can be used as a form of comparison with estimates of proportional catchtment yield derived from tracer measurements.

5 Tracer Methods

5.1 Tracer Studies

Tracers have traditionally been used by geologists to track mineral suites through drainage networks. If the tracer property is well mixed with, and representative, of the bulk of the sediment load then it may be used to indicate relative proportions of sediment flux to the confluence channel from the contributing river arms. The strategy adopted therefore is to measure tracer properties through a drainage net, either starting at the outlet and working upstream towards the headwaters or conversely working from first order streams in the uplands down the stream net towards the catchment outlet. CSIRO has developed two tracer techniques. One uses radioactive elements and the other uses measurements of the mineral magnetic properties of sediment grains, both are detailed further in section 6. These methods have been used to measure the proportional contributions from the Molonglo tributaries in this project.

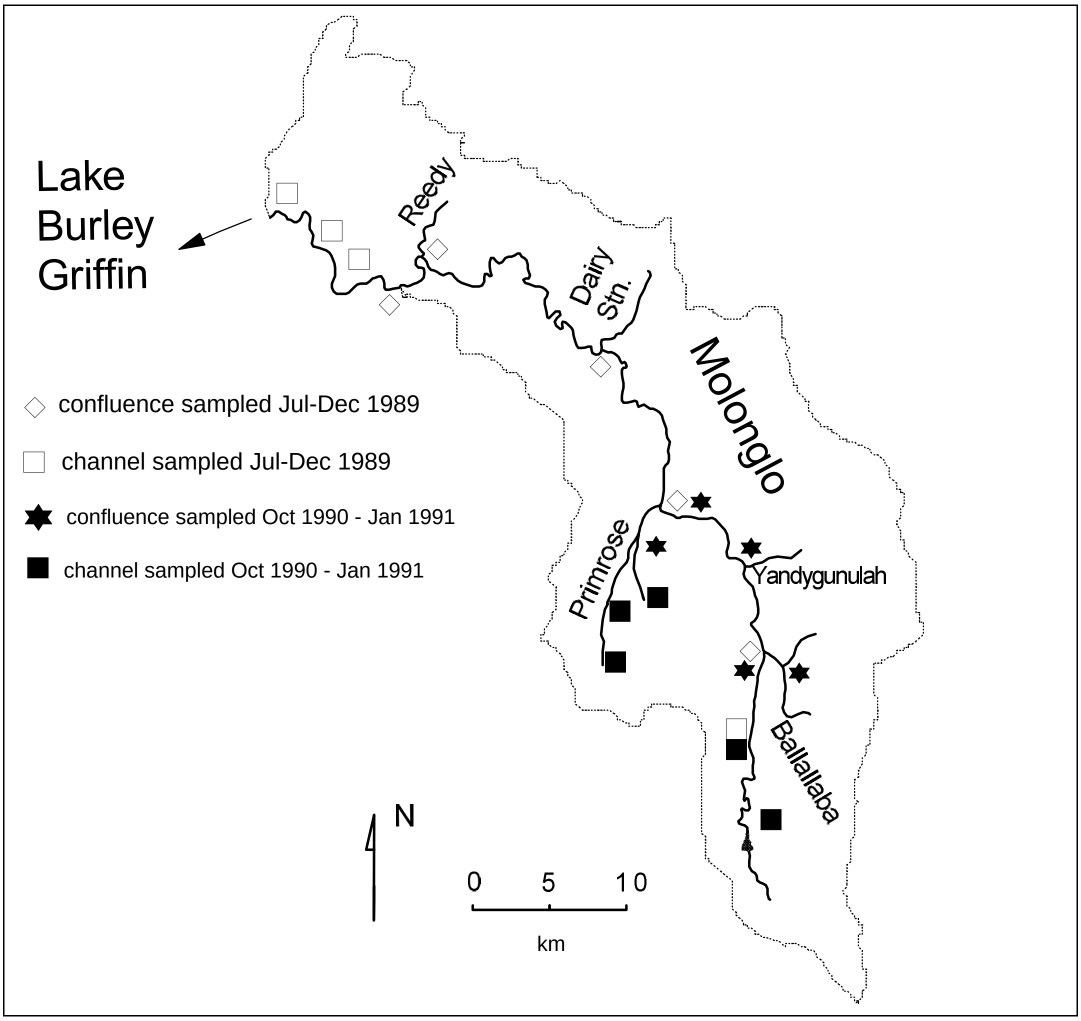
5.2 Sampling and sample treatment

The field sampling program was undertaken over the period November 1988 to February 1991, and initially consisted of taking a single sediment sample from the active beds of streams in each of the confluences' tributaries as well as downstream junctions (Figure 5.1). This sample contained multiple sub-samples (>40) ensuring representativeness. However by using this sampling method the population variability could not be derived. Consequently a sampling procedure was implemented that obtained five separate samples from the upstream, tributary and downstream reaches over a total distance of about one kilometre. Each sample was the combination of numerous, i.e >20 subsamples taken over a range of about 100-200 metres consecutively within that one kilometre reach. Downstream samples were obtained a sufficient distance below the confluence such that mixing had occurred from both contributing sources. Total sample weights were usually in the order of one to two kilograms. This allowed the proportionate contributions to be determined with greater statistical confidence.

Due to manpower and analytical constraints only those tributaries greater than 20 km^2 were measured. Thus observations were made at Reedy Ck., Dairy Station Ck., Yandygunulah Ck., Primrose Valley Ck., and Ballallaba Ck. Samples were not taken at Hoskinstown (area approx. 70 km^2) because this catchment is essentially flat, the boundary is defined by hills of low relief, the tributary spreads out on the Hoskinstown plain and thus the junction receives only a low proportion of sediment from the catchment.

All the samples were returned to the laboratory and wet sieved into <63, 63–125, 125–250, 250–500, >500 µm particle size ranges. Two of these fractions were subsequently analysed: i) the < 63um fraction which is considered representative of the suspended load and ii) the 125-250 µm sand fractions which normally form part of the bedload that is found as bars and deposits within rivers. After drying in a commercial dehydrator at 50^{0}C for 48 hours, some of the samples were homogenised in a ring grinder and cast in polyester resin to give a fixed geometry for radionuclide analysis while the remainder was set aside for magnetic analysis.

Figure 5.1: Molonglo River catchment – channel sampling strategy



5.3 Radionuclides

Radionuclide determinations were undertaken at the CSIRO, Division of Water Resources, radioanalytical facility, on a suite of high resolution germanium detectors according to the methods described in Murray et al., (1987). High resolution gamma spectrometry provides analysis of the terrestrial nuclides ^{226}Ra, ^{228}RA, ^{228}Th, ^{238}U, ^{40}K, ^{210}Pb, and anthropogenic ^{137}Cs. The activity of ^{232}Th can then be calculated from the activities of its daughters ^{228}Ra and ^{228}Th, assuming secular equilibrium. Absolute values of these nuclides are quoted in Bq/kg (Becquerels of nuclide per kilogram of mineral sample) whilst the ratios given are dimensionless.

5.4 Mineral Magnetics

The magnetic properties of the sieved samples were measured by placing them in a uniform geometry plastic container, known as a cuvette. They were then subjected to magnetic susceptibility and remanence measurements (Thompson and Oldfield, 1986). The remanence testing includes anhysteretic remanent magnetisation, known as ARM, and isothermal remanent magnetisations, (IRMs). These were imparted at 20,200 and 850 (Saturated IRM) milli Tesla. Remanence measurements were made on a Molspin fluxgate magnetometer. Susceptibility was measured using a Bartington meter, (see Oldfield, 1991 for further discussion of these magnetic parameters).

5.5 Tracer Methodology

Magnetic minerals and radionuclides such as radium and thorium, occur naturally in rocks and therefore the soils and sediments derived on and from them. These elements may be used as tracers and are highly variable spatially due to the heterogeneity of rocks and soils within a catchment and the different geochemical conditions that may apply to different areas of the landscape. However, sediment transport mechanisms are likely to have an averaging effect as sediment is delivered first to a stream channel and then transported within the channel. This means that more consistent tracer signatures may occur in channel systems as the result of natural sediment mixing processes, (Murray et.al., 1992, Olley et al., 1993).

Previous studies have shown that measured tracer parameters are usually constant in situations where there is only one averaged source of sediment, such as a section of channel with no bank contribution. Given that the tracers can provide reliable source labels in a channel system, it is then possible to compare tracer signatures at a stream junction (Murray et al., 1992, Caitcheon, 1993). If they are different it is then possible to calculate the proportionate contribution of the two tributaries from their numerical 'closeness' to the downstream reach. This is undertaken through a simple two component mixing model of the following form

$$AX + BY = C \qquad \text{Equation (2)}$$

Where X and Y are the relative contributions from the two sources, so that $X + Y = 1$ and A, B, and C are the ratios of the two input and output mix terms respectively, Olley et al., (1993). In this way sub-catchment sediment contributions to the primary stream can be discerned by a progressive sequence of confluence measurements.

The channel sediment sampling involves obtaining a number of representative samples from the two tributary arms and in the downstream reach of the trunk stream. This is undertaken adopting the strategy outlined in the previous section. The proportionate contribution of the tributaries to the trunk stream is calculated from tracer parameters measured directly from the sediment samples. Tracer parameters used to identify and label tributary sources include the ratio of ^{226}Ra to ^{232}Th as described in Murray et al., (1992), the ratio of ^{40}K to ^{232}Th, the strength of signature of the anthropogenic radionuclide ^{137}Cs, (Wallbrink and Murray, 1993) and ratios of mineral magnetic properties IRM_{850}/X and IRM_{850}/IRM_{20} (Caitcheon, 1993).

Of the above radionuclides, ^{226}Ra and ^{232}Th are from the uranium and thorium decay chains, respectively, and are thought to be independent as they have no direct influence on one another. This label or fingerprint is considered to be quite robust, in that wrong or illogical results have not been observed to occur. However, in some cases due to similarities in catchment geologies and sediment species, this ratio may not be able to discriminate between the two contributing sources and the output term at their confluence. In other words there is not sufficient difference in the arithmetic ratio values to discern one input term both from the other input and the output term. This is called a null result and sometimes occurs in the magnetic ratios such as IRM_{850}/X and IRM_{850}/IRM_{20} for similar reasons. In these circumstances it is often useful to look at other parameters in conjunction as these. One such parameter is ^{40}K which is a terrestrial nuclide that can produce unambiguous results when normalised to ^{232}Th. However, its affinity with some minerals, i.e. feldspars, indicates that in some cases it may be tracing its host mineral suite rather than being representative of the whole sediment body. In general, ^{40}K is a useful environmental tracer though its behaviour is less well understood than ^{226}Ra to ^{232}Th ratios.

The anthropogenic nuclide ^{137}Cs is not generated from within rock or soil bodies. It is a product of above ground atmospheric nuclear bomb testing by the northern hemisphere superpowers during the period 1950 to 1978. It is brought to earth via precipitation and dry fallout and labels exposed soils. Most of this fallout occurred in the Northern hemisphere, and as a result of the poor mixing between Northern and Southern stratospheres, Australian soils received about one tenth of the radioactivity as those in the Northern hemisphere. The ^{137}Cs in Monaro region soils is found in decreasing concentrations from the surface to a depth of about 10–15 cm due to soil processes such as soil wetting, particle migration–translocation, chemical sorbtivity, bioturbation, and macropore flow (Wallbrink and Murray, 1993).   Its presence in sediments suggests that some of the sediment particles may have originated from the surface of a soil within the last 30 years or so. Interpretations of ^{137}Cs concentrations on transported particles can be limited due to particle size and heterogeneity effects. However because the data presented here are for specific particle sizes, i.e. <63 mm and between 125–500 mm, their relative concentrations may be used to infer relative differences at least.

These data when obtained from tributary channel sediments however, only give information on relative contributions for a time interval controlled by climatic and catchment conditions. For example, a storm may occur locally in one catchment resulting in a pulse of sediment delivered to the trunk stream. There may also be longer term climate changes which alter the balance of sediment delivery to a confluence. Similarly, a change in the nature of erosion in a catchment will affect sediment delivery. Consequently, the time of sampling may well affect the value and subsequent interpretation of the measured tracer parameters.

Unless there is evidence for a substantial amount of stability within a catchment system for an extended period, it is probable that the relative contribution of sediment to a confluence will vary with time. Information on the magnitude of the variability can only be obtained by a monitoring program conducted at intervals sufficient to sample the changes, or by sampling from a sedimentary sink. The data presented in this report are the outcome of mostly single, though in some cases duplicate, sampling of confluences and so care should be taken in any extrapolations from this data.

6 Tracer Results of Tributary contributions to the Molonglo River

6.1 Ballallaba Confluence

The Ballallaba Creek is the first major input to the Molonglo from the upstream end and enters the river from the eastern side (see Figure 2.1). It drains a catchment (5,530 ha) that represents approximately 38 % of total upstream Molonglo catchment and is substantially cleared, in contrast to the Molonglo which remains relatively forested to this point. It is also possible that a significant proportion of the coarser sediment that would otherwise be finding its way into the Molonglo river is retained by the Captains flat dam. Magnetic measurements undertaken at this confluence (Table 6.1.1) suggest that the sediment contribution from the Ballallaba is variable but generally exceeds that of the upstream Molonglo in all but the 125–250 µm range.

Table 6.1.1: Ballallaba contribution to Molonglo – Mineral magnetics

Particle size range (microns)	63–125	125–250	250–500	500–1.4
Ballallaba % contribution	59	39	73	98
uncertainty* (±)	6	4	7	10

* given as 1 s.e. in all tables, and pertains to the least significant digit

Multiple radionuclide measurements from each confluence arm have been undertaken on the suspended, <63µm fraction. These results are presented in table 6.1.2. However, the ^{226}Ra/^{232}Th and ^{40}K/^{232}Th ratios are sufficiently similar at this location that contributing sources cannot be distinguished. Reasons for this may include similarities in the geological and geochemical histories of these two contributing areas.

Table 6.1.2: Molonglo - Ballallaba radionuclides – fines

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th
Molonglo upstream Ballallaba	0.13 7	0.73 1	7.81 13
Ballallaba	0.80 32	0.74 2	7.81 20
Molonglo downstream Ballallaba	0.83 25	0.74 1	8.08 8

From the ^{137}Cs data it can be seen that there is negligible topsoil in Molonglo sediments upstream of the Ballallaba input. However, there is a topsoil signal coming from the Ballallaba tributary, suggesting that some topsoil is present in the Ballallaba sediments collected at this time. The value in the downstream Molonglo river sediments are very similar to those from the Ballallaba value, indicating that they are probably derived from within that catchment. This tracer signal can also be used as a measure of relative contributions of sediment flux at this point if the assumption is made that the ^{137}Cs is thoroughly mixed with the bulk sediment at both ends of the input arms. In this case, if Molonglo arm suspended sediments were dominating we would expect this to influence the side arm value of 0.80_{32} and thus decrease it to a lower value. The fact that it does not suggest that Ballallaba sediments are not significantly influenced by those from the Molonglo and that they dominate in this <63µm range. If these three ^{137}Cs values are put through equation (1), then the Ballallaba can be seen to have a relative contribution of essentially 100 % with an uncertainty of about 60 %.

The radionuclide data for coarser sediments (125–500µm) are summarised in Table 6.1.3. The ^{226}Ra/^{232}Th and ^{40}K/^{232}Th ratios suggest, with values of 100 and 80 % respectively, that the dominant flux of material in this size range is coming from the Molonglo upstream arm . The percentage contributions from the Ballallaba arm fall in the range of 0–20 %.

Table 6.1.3: Molonglo - Ballallaba radionuclides – Coarse

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th
Molonglo upstream Ballallaba	0.16 19	0.73 3	15.4 6
Ballallaba	0.20 24	0.69 4	30.4 13
Molonglo downstream Ballallaba	0.07 16	0.75 2	18.6 4

This finding is not supported by the mineral magnetic data however, which suggest (when the 125-250, and 250-500µm data are combined) that about 60 % is coming from the Ballallaba confluence arm. However these magnetic results were from samples that were obtained at a different time to that for the radionuclides. This highlights the variability in temporal distribution of sediment yield from these subcatchments and suggests that pulses of sediment may be driven by the specific rainfall regime within their catchment. The non uniformity of rainfall across the Molonglo catchment enhances this pulsing effect and will result in variability of proportionate subcatchment sediment yield contribution to the Molonglo channel.

Summary: The radionuclide data (in particular ^{137}Cs) suggest that the majority of suspended sediment (<63 µm) that enters the Molonglo below the Ballallaba confluence is from the Ballallaba tributary, however about 80 % of the bedload in the 125–500µm range is generally from the Molonglo upstream arm. However, mineral magnetic measurements on samples taken at a different time indicate that, for particle size ranges above 63µm, the Ballallaba arm tends to dominate.

6.2 Yandygunulah Confluence

The Yandygunulah catchment is approximately 6,790 hectares in size, enters the Molonglo river from the south east and represents about 28 % of total upstream catchment area. Radionuclide measurements have been undertaken at its confluence with the Molonglo, and data is available for the <63μm suspended sediment size fraction only. From table 6.2.1 it can be seen that ^{226}Ra/^{232}Th ratios are unable to discriminate from the contributing sources here. The downstream term appears to lie outside the input terms although the errors overlap. However, the ^{40}K/^{232}Th ratio is able to resolve between them and suggests that 40 ±17 % of total flux to the Molonglo is contributed from this tributary at this point.

Table 6.2.1: Molonglo Yandygunulah confluence – Radionuclides

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th
Molonglo upstream Yandygunulah	0.35 12	0.72 1	7.91 8
Yandygunulah	0.48 58	0.71 2	6.12 10
Molonglo downstream Yandygunulah	0.73 35	0.73 1	7.21 30

There were no magnetic measurements undertaken at this confluence to confirm the estimate of contribution from the ^{40}K/^{232}Th ratios. The ^{137}Cs data are ambiguous in that the downstream Molonglo value of 0.73 Bq/kg appears to be consistent with the input terms, however there is considerable overlap in the uncertainties. In any case the ^{137}Cs concentrations measured are not high and indicate that gully erosion is occurring and probably dominates sediments both within the Yandygunulah catchment and in the Molonglo upstream of their confluence.

Summary: There is a 40 ±17 % contribution of <63μm sediment from Yandygunulah catchment to the Molonglo. This is determined from the ^{40}K/^{232}Th ratio data.

6.3 Primrose Confluence

The Primrose valley (6,330 ha) represents about 19 % of total Molonglo upstream area. Its confluence with the Molonglo has been sampled using Primrose sediments obtained both from within the floodplain itself, and that part of the river above the floodplain level. The former strategy gave ambiguous results presumably because of the possibility that flood events deposited homogenous material over the entire floodplain surface. This made it difficult to resolve the input sources using the tracing methods described in this report. However, the samples obtained from Primrose Creek above the level of the Flood plain enable a clear differentiation between its signature and that of the Molonglo and are presented below in Table 6.3.1.

Table 6.3.1: Molonglo Primrose confluence – Radionuclides - fines

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th
Molonglo upstream Primrose	2.93 77	0.73 1	7.58 26
Primrose	0.23 9	0.78 2	8.83 39
Molonglo downstream Primrose	3.54 35	0.73 1	8.26 14

The proportional estimates of contribution using ^{40}K/^{232}Th and ^{226}Ra/^{232}Th ratios in the <63µm sediment fraction are 54 ± 23 % and 0 ± 28% respectively. The mineral magnetic measurements, suggest that the Primrose contribution is in the order of 50 ± 36 % although this sample was derived from floodplain sediments. The weighted average of these estimates, excluding the magnetic data because it was obtained from floodplain deposits, is 32 ± 26 %.

The very small Primrose ^{137}Cs value of 0.23 ± 9 indicate that at the time of sampling there was very little top soil moving out of the Primrose valley system and that the ^{137}Cs observed within the Molonglo river is mainly derived upstream of its confluence with the Primrose. The maximum possible contribution of topsoil from the Primrose Valley to the Molonglo is 19% . It should be noted however that the Molonglo downstream ^{137}Cs values, given the uncertainties, are consistent with those from the upstream Molonglo, and suggest that all the topsoil could be derived from above the confluence itself. This is quite feasible as the Primrose valley creek, and its tributaries, have substantial lengths of deeply incised gullies that would contribute relatively little in terms of topsoil. The Molonglo river at the confluence point however meanders through the Hoskinstown floodplain on which cattle are allowed free access to the river and there are many disturbed areas along its length.

Unfortunately, samples in the coarse sand fraction (125–500µm) were not available for radionuclide analysis, although because this catchment has a long low-slope and elevation valley prior to its confluence with the molonglo, coarse sediment storage is significant and contribution from this catchment is not expected to be large. This is supported by the mineral magnetic data in this size fraction which suggests that the relative Primrose coarse sediment flux is negligible.

Summary: The estimated proportionate contribution from the Primrose to the Molonglo is calculated to be about 32 ± 26 % for sediments <63µm. The contribution of coarser grained material is negligible.

6.4 Dairy Station Confluence

The Dairy Station Creek represents only 4 % of total upstream catchment area and its confluence with the Molonglo has been characterised by a combined sediment sample. This catchment is largely under native pasture and has had a history of heavy grazing. The radionuclide data is presented in Table 6.4.1 for the coarse sediment fraction and Table 6.4.2

for the fine fraction. The ^{40}K/^{232}Th data were not used at this junction because of sampling and analytical uncertainties.

The radionuclide data from Table 6.4.1 suggest that about 33 ± 25 % of the coarse sediment is derived from the Dairy Station Creek catchment. Mineral magnetic data for this size sediment also show a maximum 30 % contribution from this source although these results are tentative due to sampling problems and a figure of 15 ± 15 is thought to be realistic. A weighted mean of these estimates is 20 ± 13 %. The very low concentrations of ^{137}Cs observed on all of the samples is consistent with subsoil sources dominating flux of this size sediment both up and downstream of this confluence.

Table 6.4.1: Molonglo Dairy Station Ck. – Radionuclides - Coarse

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th
Molonglo upstream Dairy Station Ck.	0.29 16	0.71 2	14.6 3
Dairy Station Ck.	0.48 16	0.65 1	9.8 2
Molonglo downstream Dairy Station Ck.	1.01 18	0.69 1	9.7 2

The ^{226}Ra/^{232}Th data suggest that for fine grained sediment the Dairy Stn. catchment was contributing 66 ± 28 % to the Molonglo channel at the time of sampling. Mineral magnetic measurements confirm these results and suggest that the contribution from this source in the <63μm particle size range is about 65 %. On the other hand the ^{137}Cs concentration data infers that either i) there is little or no fine grained topsoil material leaving the Dairy Station CK. and Upstream Molonglo drainage systems, or ii) that the topsoil that is entering their drainage networks is being thoroughly diluted by subsoil. In either case sediments leaving Dairy Station creek are being dominated by erosion processes that generate subsurface soil.

Table 6.4.2: Molonglo Dairy Station Ck. – Radionuclides Fines

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th
Molonglo upstream Dairy Station Ck.	0.2 3	0.67 1	7.9 2
Dairy Station Ck.	0.5 3	0.64 1	8.4 2
Molonglo downstream Dairy Station Ck.	1.6 3	0.65 1	7.8 2

Summary: The Dairy Station Ck. catchment supplied approximately 20 ± 13 % and 65 ± 23 % of the coarse and fine grained material to the Molonglo at its confluence point respectively. Most of this material is derived from subsoils.

6.5 Reedy Confluence

The Reedy Creek catchment joins the main river channel below the Molonglo Gorge (see Figure 2.1). Land use in this catchment is mixed with a large portion under commercial radiata pine and grazing interests and a smaller relative proportion set aside for recreational motorsport use. The results presented here are for combined samples taken from each confluence arm.

The coarse grained sand data in the size range 125–500μm is presented below in Table 6.5.1. In this size range the ^{226}Ra/^{232}Th values from the three stream arms are indistinguishable. However there are differences in the ^{40}K/^{232}Th data, which infer that there is only a 10 ± 20 % contribution from Reedy in this sediment range. The mineral magnetic measurements suggest a contribution in the order of 36 ± 16 %, a value which is reasonably consistent with that from the radionuclides. The ^{137}Cs values are also consistently low in samples measured in this sediment size range from all the confluence arms, implying that subsurface sources are dominating sediment supply.

Table 6.5.1: Molonglo Reedy Creek – Radionuclides Coarse

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th
Molonglo upstream Reedy Ck.	0.44 25	0.66 2	11.6 4
Reedy Ck.	0.15 17	0.66 2	9.8 2
Molonglo downstream Reedy Ck.	0.85 19	0.67 1	11.4 3

The fine grained <63μm mineral magnetic data is difficult to interpret at this confluence because of anomalies due to large variations in magnetic grain size. However both the ^{226}Ra/^{232}Th ratio data and the ^{137}Cs data (see Table 6.5.2), with proportionate contributions of 100 ± 60 and 110 ± 26 % respectively, suggest that the Molonglo upstream arm dominates in the <63μm range and that the Reedy contribution is negligible. The ^{40}K/^{232}Th upstream and downstream values are within analytical uncertainty of one another.

Table 6.5.2: Molonglo Reedy Creek – Radionuclides Fines

	^{137}Cs	$^{226}Ra/^{232}Th$	$^{40}K/^{232}Th$
Molonglo upstream Reedy Ck.	2.8 3	0.66 9	8.3 2
Reedy Ck.	0.9 3	0.64 4	8.5 2
Molonglo downstream Reedy Ck.	3.3 3	0.66 9	7.9 2

The ^{137}Cs values also suggest that there is some topsoil in both the upstream and downstream Molonglo samples. There appears to be very little topsoil produced from Reedy Creek, and it is probable that the sediment yield from this catchment is dominated by gully erosion or some other form of subsoil yielding erosion processes.

Summary: The Reedy Creek catchment, at the time of sampling, delivered between 10 and 35 % of coarse sediment to the Molonglo River at its confluence. The dominant source of suspended sediments in the <63µm range are derived from the upstream Molonglo, to which the Reedy Ck. input is negligible.

6.6 Queanbeyan Confluence

The Queanbeyan River is the last tributary to contribute sediments to the Molonglo above Lake Burley Griffin, and drains a catchment larger in size (960 km^2). Of this catchment 85 % drains into Googong Reservoir. The Queanbeyan catchment also has a diverse lithology - containing granites, basalts and sedimentary sequences.

The radionuclide data from this junction include measurements made on several samples from the downstream reach, 3 samples from the Molonglo upstream, and 1 series of combined samples from the Queanbeyan. The Mineral Magnetic data infers that approximately 85 % of the 125–500µm coarse material is derived from the Queanbeyan. However, this finding is not supported by the radionuclide data, (Table 6.6.1).

Table 6.6.1: Molonglo Queanbeyan Confluence – Radionuclides coarse

	^{137}Cs	$^{226}Ra/^{232}Th$	$^{40}K/^{232}Th$
Molonglo upstream Queanbeyan	0.29 17	0.65 1	18.2 4
Queanbeyan	1.17 16	0.67 1	11.2 2
Molonglo downstream Queanbeyan	0.41 15	0.65 1	16.0 3

The radionuclide $^{226}Ra/^{232}Th$, $^{40}K/^{232}Th$ ratio and ^{137}Cs data suggest that the Molonglo contributes between 68 and 100 % of total coarse load. The weighted mean of the estimates from these three approaches is 70 ± 10 %. The proportional contribution estimates derived for magnetics and radionuclides were made from samples taken at different times and thus it is possible that they represent genuine contributions. If this is so then the cyclical nature of the contribution from these two large basins is very interesting.

The <63µm mineral magnetic data is difficult to interpret, and the downstream values are difficult to reconcile with the two upstream input values. It is possible that this reflects an input from the large urban environment adjacent to the river at this point. Field visits to the river during storm events confirmed that urban runoff was occurring – although this appeared to vary substantially over a period of days.

The ^{137}Cs, $^{226}Ra/^{232}Th$ and $^{40}K/^{232}Th$ ratio data for the fine sediment fraction are presented in Table 6.6.2 below. Because of the perceived problem with urban runoff from Queanbeyan city the Molonglo downstream values were taken to be the average of the samples taken along theMolonglo reach itself, between its confluence with the Queanbeyan and East basin in Lake Burley Griffin. Using these values as a more representative downstream mixed value the proportional estimates of contribution from the Molonglo were 42 ± 23%, 50 ± 31% and 18 ± 56% respectively. The weighted mean of these samples is 42 ± 17%, indicating that over the time of sampling the Queanbeyan was contributing approximately 60 % of the fine grained sediment to the Molonglo.

Table 6.6.2: Molonglo Queanbeyan confluence - Radionuclides Fines

	^{137}Cs	$^{226}Ra/^{232}Th$	$^{40}K/^{232}Th$
Molonglo upstream Queanbeyan	5.9 5	0.65 1	7.04 16
Queanbeyan	2.6 5	0.69 1	7.48 17
Molonglo downstream Queanbeyan	4.0 7	0.67 5	7.40 20

Summary: Mineral magnetic measurements on stream samples suggest that 85 % of sediment flux in the 125–500µm range is derived from the Queanbeyan River. This is not supported by the radionuclide data which suggest that the dominant flux is actually 70 % derived from the Molonglo. These samples were taken at different times however and they may reflect genuine contributions at the time. The <63µm data appears suggests 60 % contribution from the Queanbeyan at the time of sampling.

6.7 Molonglo tributary contributions – Discussion, Summary and Ranking

The mineral magnetic and radionuclide results for relative contributions from tributary catchments to the Molonglo river are tabulated in Tables 6.7.1 and 6.7.2 for the size ranges 125–500µm and <63µm respectively.

Table 6.7.1: Contribution from Tributaries to Molonglo River – Coarse fraction

Catchment	Radionuclides	Magnetics	Average
	(percent)	(percent)	
Ballallaba !	< 20	57 ± 7	!
Primrose Valley	N.A.	0 ± 10	0 ± 10
Dairy Station Ck.	33 ± 25	< 30	20 ± 13
Reedy Ck.	10 ± 20	36 ± 16	26 ± 13
Queanbeyan !	30 ± 10	90 ± 35	!
Note i) ! denotes magnetic and radionuclide sampling undertaken at different times and thus results not directly comparable ii) N.A. denotes results unavailable due to sampling or analytical problems.			

The episodic and pulsing nature of sediment flux in these catchments can be seen by the estimates of flux by samples taken at different times at the Ballallaba and Queanbeyan confluences. In the latter instance the high potential contribution, estimated by magnetics at 90 ± 35 %, is notable because of the existence of Googong Dam situated about 15 km upstream of the confluence. This dam, in place for about 18 years, should act as a sediment trap for particles that do not remain in suspension, i.e. particularly those that are greater than 125µm. Thus the majority of coarse grained material that reaches its confluence with the Molonglo must be generated in the stretch of river that is below the dam, yet above the confluence point. Field surveys reveal the existence of large sand bars along this 15 km reach and these must, on occasions, be active given the absence of any significant side streams. It should be noted however that the frequency of flows required to shift these sand bars will be reduced because Googong Dam will tend to buffer this lower reach from most flow perturbations. Optimum conditions for this to occur would be the occurrence of heavy and sustained rainfall whilst the dam is at or near to full capacity, thus ensuring a high throughflow to dam storage ratio of rainwaters. These conditions may not prevail often due to the demands on Googong for town water supply. The confluence data for the <63µm suspended sediment fraction is given in Table 6.7.2.

Table 6.7.2: Contribution from Tributaries to Molonglo River – <63µm fraction

Catchment	Radionuclides	Magnetics	Average
	(percent)	(percent)	
Ballallaba	100 ± 60	N.A.	100 ± 60
Yandygunulah	40 ± 17	N.A.	40 ± 17
Primrose Valley	32 ± 26.	50 ± 36	38 ± 21
Dairy Station Ck.	66 ± 28	65 + 7	65 ± 23
Reedy Ck.	0 ± 20	N.A.	0 ± 20
Queanbeyan	42 ± 17	N.A.	42 ± 17

Dairy Stn and Ballallaba both appear to be major contributors of fine grained sediment although the uncertainties on the Ballallaba value are high. The Yandygunulah catchment also makes a significant contribution to the Molonglo. The Primrose catchment does appear to have a small but measurable influence on downstream Molonglo sediment flux, although the magnetic estimate of contribution was derived from floodplain sediments and there is some question as to their representativeness due to the possibility of flood waters homogenising sediment signatures over the sampled area. The Reedy Ck. catchment has a very low measured fine sediment contribution and this probably reflects its low relative relief and contributing catchment area.

It is possible to weight the data from these catchments by taking into account their relative differences in catchment area, shown in Table 6.7.3 for coarse particles and Table 6.7.4 for fines. In Table 6.7.3 there are two separate estimates of coarse grained contribution from Ballallaba, these represent estimates of fluxes derived from sampling undertaken at different times. The Queanbeyan catchment is not included in this exercise.

Table 6.7.3: Weighted ranking by catchment size of coarse grained sediment contribution from tributary arms.

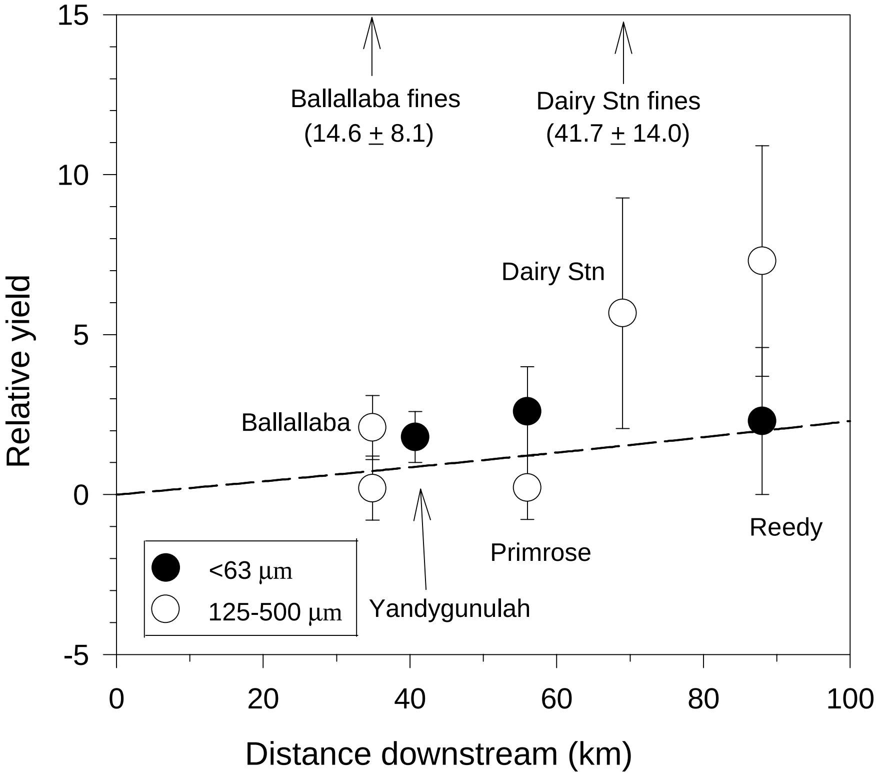
Catchment	Catchment area	Total Upstream less tributary area	Ratio	Ranking
	(km^2)	(km^2)		
Ballallaba (2 possibilities)	55.2	89.8	0.2 ± 0.3 2.1 ± 0.3	3
Primrose Valley	61.2	261	0.22 ± 0.22	4
Dairy Station Ck.	21.4	503	5.7 – 3.6	2
Reedy Ck.	29.8	582	7.3 ± 3.6	1

Table 6.7.4: Weighted ranking by catchment size of fine grained sediment contribution from tributary arms.

Catchment	Catchment area	Total Upstream less tributary area	Ratio	Ranking
	(km^2)	(km^2)		
Ballallaba	55.2	89.8	14.6 ± 8.1	2
Yandygunulah	76.4	207	1.8 ± 0.8	3
Primrose Valley	61.2	261	2.6 ± 1.4	4
Dairy Station Ck.	21.4	503	41.7 ± 14.0	1
Reedy Ck.	29.8	582	2.3 ± 2.3	5

The percentage contribution from each tributary catchment, derived from data Tables 6.7.1 and 6.7.2, has been normalised by dividing by its catchment area. A similar value is also obtained from the trunk stream. The tributary and trunk values can then be compared as a ratio. (This assumes that the channel values are representative and that factors such as gully density and land use have been taken into account as a result of mixing by stream transport processes). This ratio would be expected to increase steadily downstream if the tributaries were yielding sediment proportionally to their surface area. This is because in-channel storage becomes larger as the relative size of the trunk-to-contributing-stream increases. This effect is defined by equation 2 in Section 4 and can be seen as the dashed line in Figure 6.1.

Figure 6.1. Yield from tributaries to the Molonglo River downstream of Captains Flat for coarse and fine grained sediments. Dashed line represents yield curve assuming that the dominant control is by catchment area, based on data from Wasson (1994).



Values from catchments that are contributing disproportionately high loads, relative to total upstream catchment area, will sit away from this trend. The derived ratios of tributary yield versus that of the trunk stream, can be compared to the predicted yield curve. A cursory examination suggests that the tributaries contributing the largest proportional flux of coarse sediment (presented as open circles in Figure 6.1), are Reedy and Dairy station, followed by Ballallaba and then Primrose. However, when the uncertainties on the derived ratios and the yield curve are taken into account it is argued that all these tributaries are yielding coarse sediment at a rate that is consistent with that expected from their catchment area.

The <63 µm data is presented as closed circles in Figure 6.1 and from this it is clear that Dairy Station Ck. is delivering fine sediment well in excess of other tributaries to the Molonglo. Ballallaba is also contributing at a rate greater than that expected from its catchment area. (Note that the Dairy Stn and Ballallaba values are shown off the scale of the diagram). Yandygunulah, Primrose and Reedy Creek appear to be delivering fine sediment at, or below, a rate consistent with that expected from their catchment area.

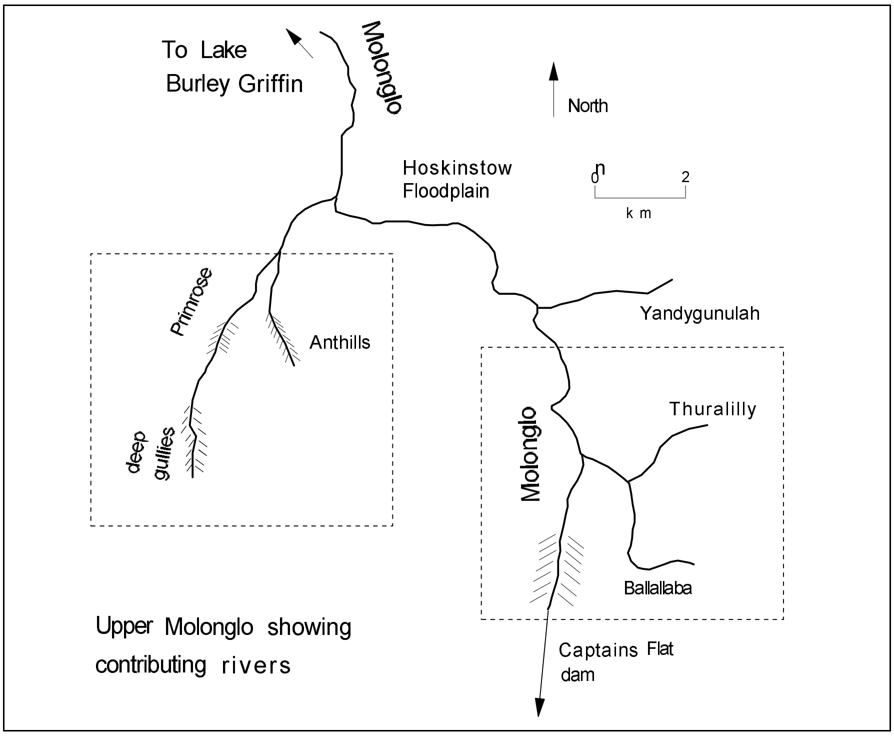
In summary, it was not possible to discriminate between the tributary and trunk input sources using all tracing methods at some junctions. In this case contributing amounts were determined using those parameters that gave logical answers. In addition some values may represent samples taken at a single point in time only, and thus may reflect recent catchment rainfall/sediment history rather than long term trends. Although the averaging and mixing processes that occur in the larger fluvuial systems should tend toward this more averaged condition.

Nonetheless it appears that tracers were generally able to describe the contributions from tributaries to the main Molonglo channel. Of the tributaries sampled, the data suggested that, given uncertainties, all were contributing 125–500 µm sediment at a rate consistent to that expected from a relationship derived from similar south eastern Australian catchments of the same approximate size. The data for fine grained, <63 µm, samples suggest very strongly that Dairy Station Ck. and Ballallaba Ck. are contributing at a rate in excess of that expected from average catchments of the same area.

7 Farm Scale Tracing

The proportional contribution of second order streams within the Primrose and Ballallaba catchments was also estimated by tracers (Figure 7.1). This was to further examine sources of sediment within these tributaries, and thus apply the technique at scales approximating the farm unit. Although it should be noted that the tracing methods in this report are landscape based, and thus are used to discriminate sources and processes operating within units such as closed drainage basins. Farm properties and their boundaries however often are not determined by such topographical features. Fencelines may bisect drainage lines for instance, and thus their influence may be more difficult to describe on this basis. Nonetheless if there is broad agreement between farm and catchment boundaries then it may be reasonable to draw inferences about relationships between them.

Figure 7.1: Upper Molonglo River showing Primrose and Ballalaba tributary morphology



7.1 Ballallaba Catchment - Thuralilly Confluence

In section 6.1 a positive ^{137}Cs signature indicating the presence of some surface soil, was identified at the outlet of the Ballallaba catchment. A possible source of this signature within the Ballallaba catchment is the Thurallily subcatchment which joins the Ballallaba about 200 metres upstream from its confluence with the Molonglo (see Figure 7.1). Sampling of sediments at the Ballallaba - Thuralilly confluence show ^{137}Cs concentrations that are roughly equal in value (given uncertainties) in each arm. The ratio values of ^{226}Ra/^{232}Th and ^{40}K/^{232}Th (Table 7.1) however give proportionate estimates of contribution from the Thuralilly of 60 ± 48 % and 65 ±100 respectively, with weighted average of 61 ± 45 %.

If this estimate of contribution is weighted according to relative catchment area, then it is clear that the Thuralilly catchment is producing sediment in excess of the per unit area rate of the Ballallaba catchment upstream of their confluence. It should be noted that below this point the Ballallaba Ck. is stable and firmly sited on bedrock channels for the 200 m of distance to its confluence with the Molonglo. In this condition it is probably acting more as a conduit for sediment derived from upstream than as a source in itself.

Table 7.1: Estimate of contribution of <63 μm material by Thuralilly to Ballallaba Ck.

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th	Sample (n)
Ballallaba upstream Thuralilly (Catchment area = 44.5 km^2)	0.97 36	0.77 3	7.6 3	5
Thuralilly (Catchment area = 9.9 km^2)	1.07 22	0.72 1	7.9 3	5
Ballallaba downstream Thuralilly	0.80 33	0.74 2	7.8 2	5

In summary, the Ballallaba catchment was identified in section 6 as being a tributary with fine sediment flux greater than that expected from its catchment area. Tracing work within this catchment has identified the Thuralilly subcatchment, with area of only 9.9 km^2, as a significant potential source of this sediment. Within the Thuralilly subcatchment however most of the eroded material is probably derived from subsoils. This is because the ^{137}Cs concentrations of Thuralilly sediments are not sufficiently high to indicate a substantial contribution from topsoils.

7.2 Primrose Catchment – Anthill Confluence

The Primrose valley has not been identified as a major source of sediment to the Molonglo. However further tracing was undertaken within this catchment to determine the contribution to it from the Anthills subcatchment (Figure 7.1). Anthills drains predominantly Ordovician metasedements in the southeast of the Primrose Valley and has an area of approximately 16.2 km^2. This catchment has a well developed, deeply incised gully with vertical walls up to 6 m, along approximately 4 km of its length as a result of poorly implemented drainage of low lying land prior to 1940. A well incised gully, formed within valley fill deposits, also exists within the channel draining the southernmost headwaters of the Primrose Valley. This gully has walls to approximately 4 m high along a length of about 1 km. Both gullies have significant alluvial fans at their outlet with surface areas in excess of 1 ha. Both have been sampled and the results presented in Table 7.2 .

There is a similarity in the ^{226}Ra/^{232}Th and ^{40}K/^{232}Th from both these two gullied catchments which may reflect the predominance of sedimentary and volcanic rock suites within this area. However, this is not consistent with the downstream ratio values, which lie well outside the two input terms. This strongly suggests that an additional source of sediment is influencing the Primrose river below its confluence with Anthills, yet above the sampling site. This source has not been identified.

Table 7.2: Estimate of contribution of <63 µm material by Anthills to Primrose Ck.

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th	Sample (n)
Primrose upstream Anthills	0.70 7	0.70 1	8.5 1	5
Anthills	0.74 15	0.70 1	8.5 2	5
Primrose downstream Anthills	0.25 8	0.78 2	8.8 4	5
Gully Collapse (above Primrose upstream Anthills)	0.22 11	0.68 1	8.7 2	5
Erosion Gully at Top of Primrose	0.11 4	0.71 2	8.9 4	5

A section of gully collapse in the Primrose system was sampled above the Primrose - Anthills confluence (Figure 7.1) as well as the extensive gully network in the upper reaches of the Primrose. This was to determine the possible influence of collapse material to river signature at this point and this data is given in Table 7.2. The ^{137}Cs signature suggest either that there is very little topsoil being transported by this gully system or that it is being diluted by a large amount of subsoil. In either case it is interesting to note that despite these low values there is an increase in the ^{137}Cs signature at the Primrose upstream Anthill site to 0.7 ± 0.1 Bq/kg which then becomes diluted further downstream. This combined with the signature observed within Anthills creek itself suggests that there are zones around its confluence with the Primrose where topsoil may be able to enter the river system, although clearly this is also dominated by subsoil and does not persist further downstream in the Primrose as the signature then drops to 0.25 ± 0.1 Bq/kg.

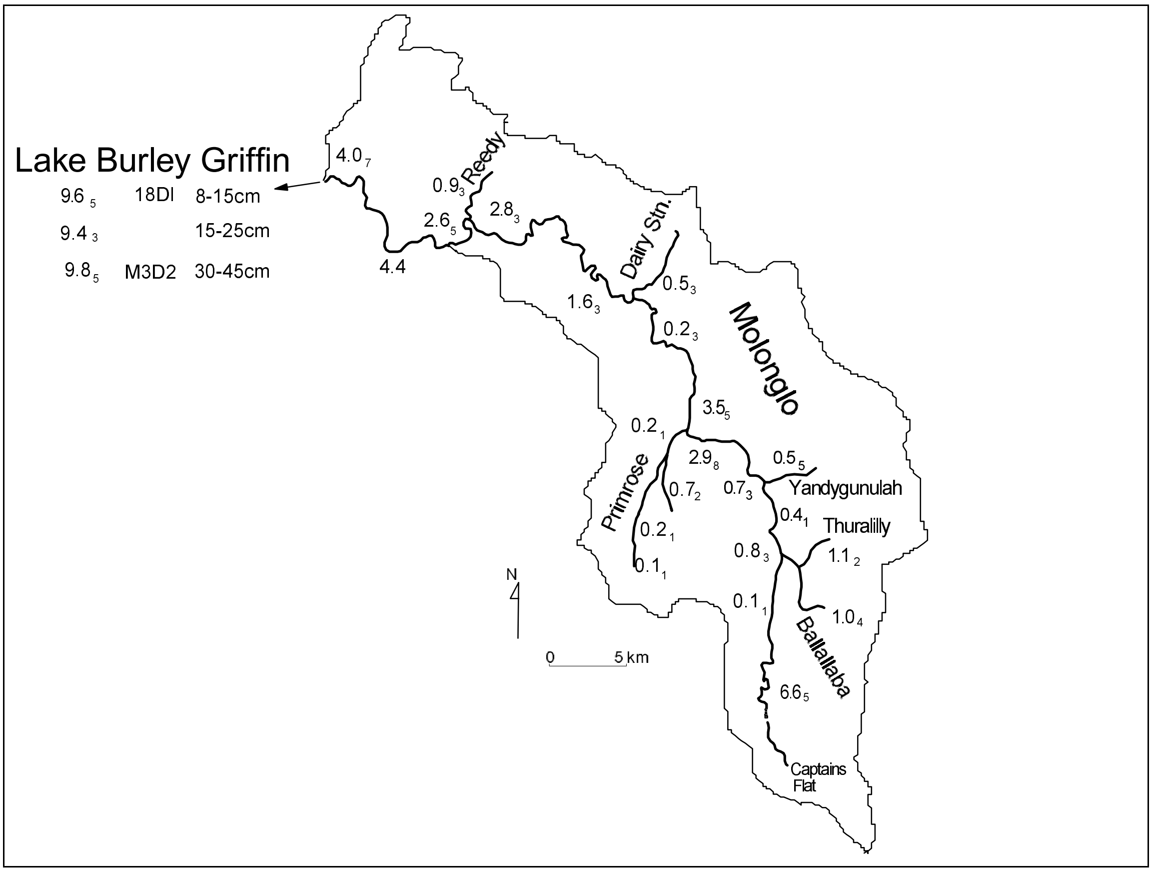
In conclusion it appears that the application of tracers to landscape systems of the size described above can produce useful data. This data can be used to describe or infer the type(s) of erosion process occurring within small landscape units, and their potential influence on larger landscape units. These methods could conceivably be applied to consecutively smaller landscape units, thus providing finer detail on perhaps the individual effects of alternative treatments on different paddocks, however time and resources did not permit this to be undertaken within the current project.

8 Topsoil Movement Within the Molonglo Catchment

The anthropogenic radionuclide ^{137}Cs was uniformly distributed across exposed landscape surfaces during the 1950's - 1970's where it then became bound to soil particles. Thus its presence or absence in stream sediments can be used to indicate that topsoil material is present. Although techniques for quantifying the actual amount of topsoil are not yet readily available, the relative magnitude of ^{137}Cs concentrations on measured channel particles may be used as a gross indicator of the extent of topsoil contribution within different parts of the catchment. These estimates are necessarily complicated by the very strong relationship observed between particle size and ^{137}Cs concentrations, with smaller particles having highest concentrations by mass as a function of increased surface area to volume ratios.

Nonetheless, given that the samples here have been sieved to a size range of <63 µm then this effect will be reduced and relative comparisons between values at different locations may usefully be made. Measurements of ^{137}Cs within the Molonglo catchment are shown in Figure 8.1.

Figure 8.1: Topsoil movement indicated by ^{137}Cs concentrations within the Molonglo catchment.



Importantly, there are positive values of ^{137}Cs within some stretches of the main river channel, particularly up and downstream of the Reedy Creek confluence of about 2.7 ± 0.5 (n=5) and along Molonglo reach into east basin, where the highest observed concentrations were about 9.5 ± 0.5 Bq/kg from sections of cores taken at between and 8 and 45 cm depth. There are also positive values in Molonglo sediments up and downstream of the Primrose confluence on the Hoskinstown floodplain and towards the top end of the catchment at Captains flat where the highest measured value was 6.6 ± 0.5. Lower concentrations of about 1.0 Bq/kg were observed in the Thuralilly arm of Ballallaba, Primrose, Yandygunulah and Reedy creeks. Elsewhere the concentrations were non detectable from zero given the uncertainties on their measurement. These values can be compared to ^{137}Cs concentrations of about 30 Bq/kg, observed on suspended particles in this region, derived purely from topsoil erosion by Wallbrink and Murray (1993).

Clearly none of the Molonglo samples approach this ^{137}Cs concentration and it is evident that sheet or topsoil erosion is not a significant contributor of sediment, in itself, to sediments within channels of the Molonglo or its tributaries. Either surface erosion is occurring, but only to a small degree, or it is more likely that these surface particles are being significantly diluted. This is presumably by addition of subsoil material derived from gully wall collapse and channel scour of gully floor material, and an estimate of this is given in the following section.

9 The Contribution of Bank Collapse to Molonglo Channel Sediments

In the previous section, and elsewhere (Dunne, 1990, Wallbrink and Murray, 1993) it has been proposed that material derived from scour within gullies and active gully wall collapse may be a significant source of sediment in catchments with erodible subsoils. An estimate of the extent of channel bank collapse to Molonglo sediment flux can be obtained by determining the extent to which the upstream tracer signal is altered by the signature from the section of channel collapse.

Figure 9.1: Photograph of channel collapse in Molonglo catchment

Samples have been taken (see figure 9.1) to the north of the Captains Flat road where it crosses the Molonglo to determine the signature from the top end of the catchment, using the method described in section 3.1. Further samples were obtained from a section of active channel collapse about 500 m long about 3 km below this and about 2 km from its confluence with the Ballallaba.

Table 9.1: Estimate of contribution of channel collapse to Molonglo sediments above its confluence with Ballallaba Ck.

	^{137}Cs	^{226}Ra/^{232}Th	^{40}K/^{232}Th
Molonglo at Captains Flat	1.45 30	0.98 3	5.9 3
Channel collapse signature below Captains Flat	0.3 2	0.71 4	7.8 4
Molonglo upstream Ballallaba	0.20 3	0.73 1	7.8 3
Proportionate contribution (percent)	111 ± 37	93 ± 14	100 ± 26

If it is assumed that the Molonglo river channel in this part of the catchment is well mixed and that the section of gully collapse is the only major contributing source of material (reasonable given visual observations) then the tracer signals obtained from each section (Table 9.1) can be used to indicate contribution from this gully collapse source.

The weighted mean of the tracer estimates of proportionate contribution is 96 ± 11 %. Thus, given the assumptions outlined above, it is evident that the signature from sediments derived from this section of gully collapse have a major influence on the tracer signatures of Molonglo sediments below this point. This infers that the collapse of gully walls is a significant contributor of sediment to the Molonglo river within this section of channel and suggests a comparable influence in similar sections of channel undergoing bank or wall collapse.

10 Provisional Guidelines for the Application of Tracer Methods by Land Managers

10.1 Preamble

Some brief guidelines have been developed from this project. They are primarily directed at Land Managers who have some general understanding of the principles of tracing. In this case the guidelines will improve individuals understanding of the technique and help them to decide on the way in which they can be applied. This should increase the confidence of land managers in their efforts to target erosion sources within landscapes.

10.2 Guidelines

i) Define the problem

Is there a significant sediment yield problem?
What is the scale of the problem?
How is it manifest? Excessive turbidity, decline in water quality, dam siltation.
Are sediment sources apparent?
Are catchments complex, multiple land use?

ii) Define the landscape

Is the affected area composed of discrete landscape units?
Can these be separated geomorphologically, fluvially?

iii) Devise a sampling strategy in response to i) and ii)

confluence sampling
channel sampling
depth cores in alluvial deposits
transported sediments
suspended sediments in channels

iv) Undertake/initiate sampling

Collection of samples through time and space as defined in iii)
Observe strata/laminations in cores for coarse differences
Undertake detailed core and site descriptions, submit samples to laboratory for analysis
Identify potential time markers such as tin cans, wire, pigs jaws, etc.

v) Review and interpretation of results

Graph data
Observe trends
Identify sources and/or processes

vi) Review catchment control/land rehabilitation options

Is the perceived problem within the scope of land management tools?

vi) Catchment management

Implement measures appropriate for particular soil erosion problems, including dams, diversion banks, strategic fencing, tree planting, streambed revegetation, gully wall moulding, etc

11 Concluding Remarks

11.1 This Project

This project was initiated to combine and compare predictions of sediment source areas by the traditional land survey mapping and the newer methodology of radionuclide and mineral magnetic tracer technology. Over the course of this project both the experimental technique and the scientific interpretation of the data evolved from that originally proposed. This was a result of interaction between staff of CSIRO and CALM, familiarity with the landscape, and the evolution of the technology.

The results were very encouraging and suggest that soil erosion mapping will sufficiently describe landscapes such that potential areas of high sediment yielding risk will be identified. On the other hand, a new technology has been developed and tested that provides similar results independent of this that do not require extensive mapping and aerial photography resources. However these new methods are expensive, based on relatively high level technology, the application and interpretation is complex and the results are not always guaranteed. To obtain maximum benefit from tracers they are best used in conjunction with independent data obtained from measurement techniques such as stream gauging, geochemical analysis, and traditional airphoto and gully mapping techniques. In this study the tracing results independently confirmed traditional CALM techniques for targeting areas suitable for land rehabilitation and erosion mitigation work. However they were unable to provide quantitative estimates of the volume of sediment transported nor, because the sampling represented a snapshot in time, were they able to provide a comprehensive picture of temporal distribution of the tributary sediments.

11.2 Rehabilitation works within the Molonglo River catchment

Within the Molonglo river, two tributaries, Dairy Stn and Ballallaba Ck. were identified by both traditional soil conservation planning and tracer techniques as contributing fine grained (<63 μm) sediment in excess of that from their neighbouring catchments and the average expected from their catchment area. Thus CALM are now able to, and have begun, land rehabilitation work within these areas. In particular the upper sections of Dairy Stn Ck. are now contained by a series of earth dams controlling extensive sections of gully erosion.

If more catchment work is to be undertaken then the next location for this would logically be the Thuralilly subcatchment within Ballallaba Ck. This subcatchment was identified in section 8.1 as being a major contributor of sediment to the Ballallaba which in turn was deemed to be yielding fine sediment at a rate greater than adjacent comparable catchments.

The results from this project indicate that major catchment work is probably not necessary in most other parts of the Molonglo catchment, as they are yielding sediment at a rate that is approximately consistent with that expected from other Southern tablelands catchments of similar size. However there will always be a downstream benefit if local areas of erosion or channel collapse are rehabilitated such that net yield from these areas are reduced.

Figure 11.1: Photograph showing catchment improvement works undertaken in the Dairy Station Ck catchment.

11.3 Future work

The combination of the traditional land mapping approach from CALM and the tracer methods of CSIRO in this project have proved effective and have produced results that are consistent with one another. However there are still gaps in the understanding of sediment flux within the Molonglo, identified by the tracers, and to address these more work needs to be undertaken. In particular this study identified the potential for some of the tributary catchments to deliver sediment in discrete pulses, presumably in response to localised catchment rainfall. However, this work was not able to describe the temporal variation of this phenomenon or its degree of influence over medium or long time scales, and any future work should seek to do this. A second feature identified by this study, which was not fully tested, is the degree and extent of contribution by subsoil sources such as bank and gully wall collapse or channel scour to the total downstream sediment flux. Although this was explicitly measured in one location by measurements of ^{137}Cs, it can only be inferred elsewhere in the catchment. Therefore the context of the sediment sourcing in this project remains spatial and little information is presented about the depth from which eroded particles are derived or erosion process responsible for soil particle movement. However advances in this area will probably only occur when further developments to the tracer techniques are undertaken.

The co-application of the traditional (CALM) and high technology (CSIRO) predictive sediment yield techniques is seen to have produced positive results thus far. To improve their veracity the apparent agreement between these methods in the Molonglo should be tested elsewhere within catchments of different scales, soil types and land use. These tools should also be developed to incorporate the needs of land managers who increasingly require information on variables such as the rate, volume, and source (either natural or anthropomorphic) of nutrient export from catchments.

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