Sediment supply from small upland catchments: possible implications of headwater channel restoration for stream management

Hugh G. Smith and Deirdre Dragovich

University of Sydney, Madsen Building F09, University of Sydney, NSW 2006. Email: hsmi7040@mail.usyd.edu.au

Abstract

Small upland headwater catchments with extensive eroding channels have been identified as likely important sources of fine sediment reaching large rivers. Sediment tracing research in the Murrumbidgee identified these small catchments as significant sources of fine sediment to the main channel. Hence understanding factors controlling the release of fine sediment from small upland catchments and the best approach for its reduction is an important component of stream management and restoration. Sediment transfer in a small upland catchment (53.5km^2) in the headwaters of the Lachlan River was monitored for a period of two years. A multi-method, scale-based approach was adopted with intensive monitoring of sediment flux in a sub-catchment (1.6km^2) and measurement of sediment yield at the catchment outlet. Channel walls dominated sediment supply in the study sub-catchment, with slopes largely decoupled from channels. Channel walls provide a significant supply of fine sediment readily available for transport, with the potential for rapid delivery to the catchment outlet during high flows. These findings emphasise the need for stream management to focus on channel restoration in small upland headwater catchments to reduce local sediment supply, with the potential for reductions in fine sediment loads in downstream reaches.

Keywords

Catchment sediment sources, sediment yield, sediment storage, channel restoration

Introduction

Fine sediment and organic matter are associated with the transport of much of the nutrients and contaminants that reach streams (Prosser *et al*., 2001). Nutrient and contaminant supply may have significant implications for eutrophication and algal blooms, degrading aquatic habitat and adversely affecting stream biota (Lake & Marchant, 1990). Therefore stream restoration involving the reduction of fine sediment reaching streams and rivers has major relevance for improving aquatic habitat and reducing nutrient flux.

Since the initial peak in hillslope and gully erosion following European settlement, erosion rates have greatly reduced (Wasson *et al*., 1998). Olley and Wasson (2003) estimate present erosion in gullied upland headwater catchments of the Murrumbidgee at six times pre-European rates. It seems supply of contemporary fine sediment to rivers may be dominated by such catchments (Wasson, 1994). These catchments are where slopes are relatively steep, drainage density high and hydrological response rapid, creating a high potential for erosion (Croke & Jakeman, 2001). Sediment tracing research in the Murrumbidgee identified channels and gullies as the dominant fine sediment sources, with a mean residence time of approximately 10±5 years (Wallbrink *et al*., 1998). Furthermore Wallbrink and Olley (2004) indicated the importance of small incised catchments as sources of sediment to downstream channels in a tributary (2170km^2) of the Murrumbidgee, previously shown to be a major contributor of fine sediment to this river. In contrast large volumes of predominantly coarse sediment eroded following European settlement are moving slowly through rivers, with extensive lowland channel and floodplain storage (Erskine, 1994; Fryirs & Brierley, 2001).

Understanding factors controlling the release of fine sediment from small upland catchments with eroding channels may provide useful information for upland stream restoration. In this study sediment transfer in a small upland headwater catchment of the Lachlan River was examined. The aim was to assess the link between fine sediment sources in a sub-catchment and delivery of sediment at the catchment outlet.

Study area

The study area is located 12km south of Orange and is part of Flyers Creek, an upland headwater catchment of the Lachlan River (Figure 1A). Flyers Creek originates on slopes below Mount Canobolas (1396m) and flows south through a narrow steep-sided valley, rapidly descending to join the Belubula River.

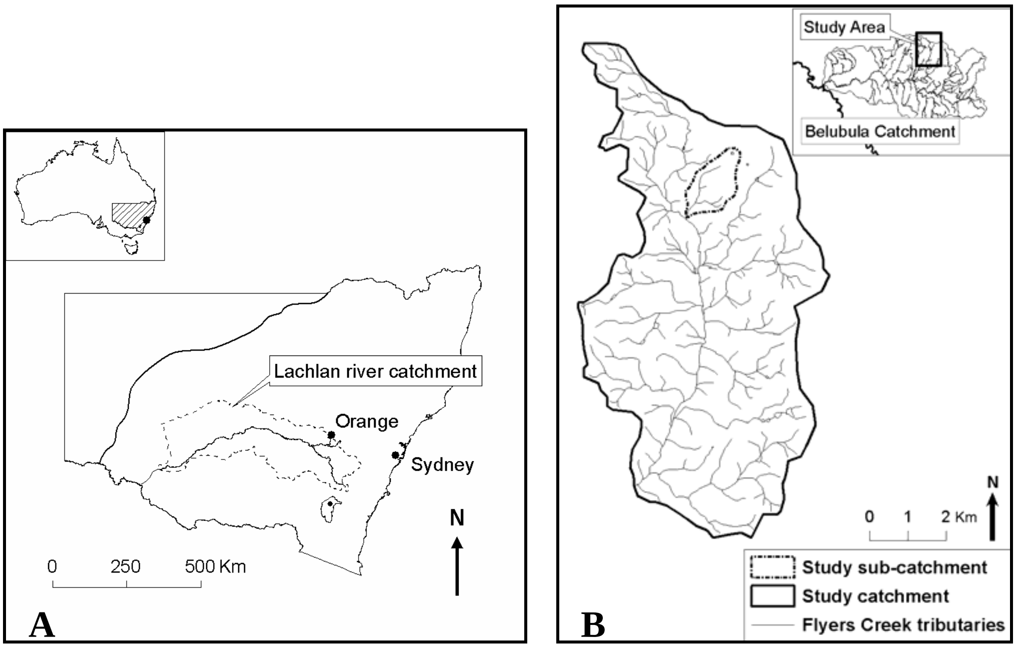

Figure 1. (A) Location of the study area and (B) map of channels in the study catchment, showing location within the Belubula River catchment

The study catchment was limited to the northern half of Flyers Creek, with an area of 53.5km^2 (Figure 1B). The upper part of the study catchment is dominated by Tertiary basalts, with Silurian shales, sandstones and limestones in the west and Ordovician volcanics in the south. Soils are predominantly red silty clays in much of the catchment. Channel incision and gullying are relatively widespread in Flyers Creek. The area experiences cool winters and mild summers, with a mean annual rainfall of 903mm (Orange airport) and rainfall maxima in summer and late winter. Land use in the study catchment (2003) was predominantly pasture (74%), with some cultivation (19%) and a limited area of forest cover (6%).

Methods

A multi-method, scale-based approach was adopted to examine the sediment dynamics operating in the study catchment. This type of integrated approach has been recommended for studies investigating catchment sediment budgets (Walling *et al*., 2001). Intensive monitoring was undertaken in a sub-catchment (1.6km^2) of the study catchment, with measurement of sediment yield at the catchment outlet (Figure 1B). Field measurements were conducted for a period of nearly two years.

Within the sub-catchment hillslope sediment yields were measured using five open erosion plots. Channel and gully bank erosion rates were measured using erosion pins, as recommended by Lawler (1993). A range of channel banks with different bank gradients and vegetation (grass) covers were selected for pin monitoring. To assess channel changes, particularly channel floor sediment storage, 20 monumented cross-sections were established and re-surveyed at the end of the monitoring period. Slope and channel sediment source contributions to sub-catchment channel deposits were determined using the fallout radionuclides caesium-137 (^{137}Cs) and excess lead-210 ($^{210}Pb_{ex}$) in a sediment tracing technique similar to that adopted by Wallbrink *et al*. (2003). The use of fallout radionuclides to trace surface and sub-surface sources of sediment is well established (e.g. Walling & Woodward, 1992; Wallbrink *et al*., 1998). To calculate relative contributions a mixing model developed by Collins *et al*. (1997) was used in which an optimal solution is obtained from the two radionuclide tracers.

Discharge and sediment yields from both the sub-catchment and catchment outlets were measured by stream gauging and stage-triggered automatic water sampling of flow events. Aerial photographs (2003) were used to assess land use and the extent of incised channels and gullies within the catchment.

Results

The study period was characterised by mixed climatic conditions, with above average rainfall during late winter and spring 2005 followed by dry conditions for most of 2006. Total rainfall recorded at Orange airport (4km north-east of study catchment) was 1582mm (average for the period is 1893mm).

Direct monitoring of erosion indicated very low slope erosion rates, ranging from 0.04 to 0.50t km^{-2} yr^{-1} (based on survey estimates of slope contributing area). Channel bank erosion monitoring produced a mean annual rate of 12.6mm for the sub-catchment which was within the range of previous channel or gully erosion rates in south-eastern Australia (Prosser *et al*., 2000). Banks with the highest grass cover had significantly lower mean bank gradients and significantly lower mean bank erosion rates compared to rates recorded on steeper banks with low or no cover. However the relationship between bank gradient alone and net bank erosion was not significant.

Observations indicated a layer of accumulated fine sediment overlying a coarse sediment layer on channel floors; changes in the fine sediment layer were those which were primarily recorded in cross-sectional change. The repeated channel surveys indicated the proportion of channel floor cross-sectional change (due to bed aggradation/degradation) relative to whole channel cross-sectional change declined with distance up the sub-catchment from Flyers Creek (Table 1). This reflects the declining stream discharge and sediment transport capacity with declining catchment area.

Table 1. Net channel floor cross-sectional change and the proportion of channel floor change relative to whole channel change (which measures the change in cross-sectional area from bed elevation change and bank erosion)

Channel (see Figure 2)	Net channel floor change (m^2)	Proportion of change (%)
Flyers Creek	-0.081	28.4
Sub-catchment main channel	0.002	21.6
Sub-catchment gully	0.005	6.9

Sediment source analysis using ^{137}Cs and $^{210}Pb_{ex}$ indicated the dominance of channel fine sediment sources. The mixing model estimated a mean sub-surface contribution of 75% for the sub-catchment, most of which was sourced from channel or gully walls. The extent of sub-surface sediment contributions for the different channel sections examined (Figure 2) indicated an increase in surface source contributions with distance up the sub-catchment main channel and tributary gully.

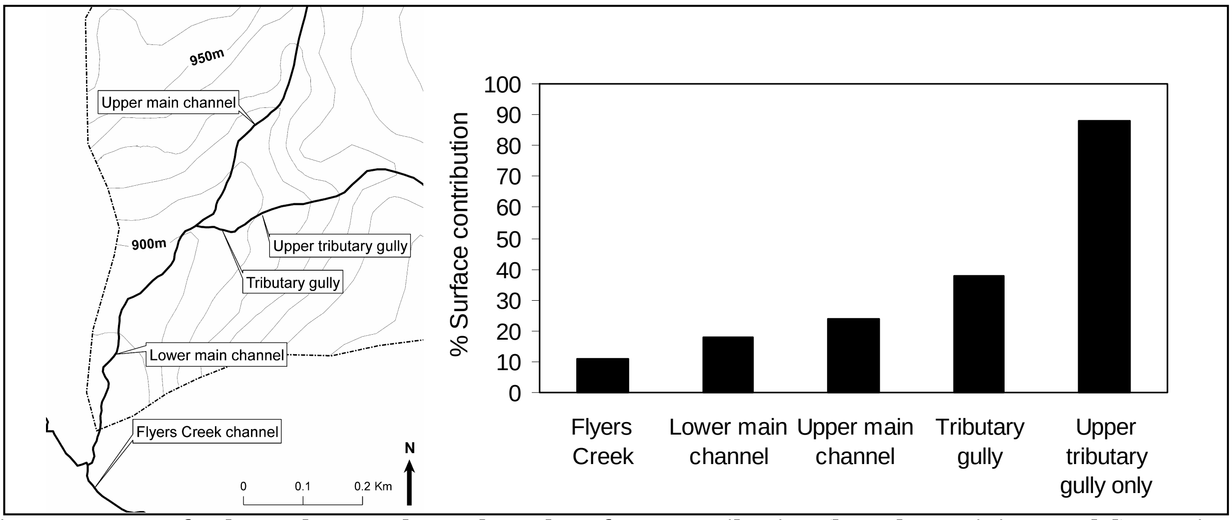

Figure 2. Map of sub-catchment channels and surface contribution (based on mixing model) starting at Flyers Creek and moving up the sub-catchment main channel and tributary gully.

Discharge and sediment yield monitoring at the sub-catchment and catchment outlets indicated the relationship between suspended sediment and discharge underwent generally clockwise hysteresis, with sediment peaks generally leading hydrograph peaks at both sites. Furthermore sediment exhaustion effects were observed at both sites during multi-peak events, with sediment concentrations in subsequent peaks much reduced.

Comparing flow data for 21 events recorded at both sites produced a mean time difference in hydrograph peaks of 0.99 hours for summer-autumn and 4.48 hours for winter-spring (for a channel distance of 8.57km between the sites). A further six events experienced hydrograph peaks at the catchment outlet before the sub-catchment, associated with storm rainfall moving up the catchment. Specific sediment yield (SSY) per unit catchment area (SSY_{area}) and per length of incised channel/gully (SSY_{length}) in the catchments was calculated (Table 2). Events included in this analysis were limited to those with flow and suspended sediment data for the same flow pulse at both outlets. The length of incised channel/gully was determined from aerial photographs (2003) aided by field assessments. Incised channel density in the sub-catchment is 0.449km km^{-2} and for the catchment it is 0.328km km^{-2}. Since channels dominated sediment supply in the sub-catchment and this seems likely for the catchment also (based on the extent of channel incision and previous research, e.g. Wallbrink & Olley, 2004), the new measure used here of length of incised channel may be a more useful indicator of SSY. The ratio of catchment to sub-catchment SSY provides an indication of the extent of downstream sediment transfer for each event.

Table 2. Specific sediment yields (SSY) for flow events with data available from both sub-catchment (SC) and catchment (C) outlet monitoring sites.

Event	Rainfall (mm)	SSY_{area} (kg km^{-2})		Ratio $C:SC_{area}$	SSY_{length} (kg km^{-1})		Ratio $C:SC_{length}$
		SC	C		SC	C	
20-Feb-05	18	9.5	1.1	0.11	21.0	3.3	0.16
8-Jul-05	23	1.9	0.9	0.47	4.3	2.9	0.67
20-Aug-05	21	1.6	0.8	0.47	3.6	4.6	0.64
4-Sep-05	13	2.3	0.7	0.32	3.6	2.3	0.44
11-Sep-05	45	886.0	404.2	0.46	1971.5	1230.9	0.62
17-Jan-06	78	380.1	20.4	0.05	845.7	62.0	0.07
16-Feb-06	13	13.5	0.4	0.03	30.0	1.2	0.04
25-Jul-06	15	3.5	0.2	0.06	7.8	0.7	0.09

Discussion

Channel sources dominate the supply of fine sediment at the sub-catchment scale. The contribution of sediment from slopes is relatively low for all but the upper tributary gully. Hillslopes are increasingly separated from channels with distance down the sub-catchment and with increased bank erosion rates it is unsurprising slopes are largely de-coupled from channels in the lower-sub-catchment. The limited amounts of sediment delivered to the valley floor would mostly be deposited before reaching the channel. Furthermore the highest bank erosion rates recorded were on bank profiles along the lower main channel of the sub-catchment.

Recent aerial photograph analysis indicated eroding tributary channels were generally situated in the lower part of sub-catchments of Flyers Creek and were mostly linked directly to the main channel (the upper part of which is also eroding). This suggests patterns observed in the study sub-catchment may be reflected throughout Flyers Creek catchment. Therefore stream restoration efforts with the aim of reducing downstream fine sediment supply would benefit from targeting eroding channels in the lower part of these sub-catchments. Re-vegetation of sloping banks with grass species would reduce erosion rates from these banks, but steeper banks would require re-shaping before grasses could be established. Stock exclusion from the riparian areas of the eroding lengths of channels in these small catchments could also reduce sediment supplied to downstream reaches. Previous research has reported the role of livestock (particularly cattle) in reducing stream bank erosion resistance by trampling and vegetation cover reduction (Trimble & Mendel, 1995).

Linking erosion from channels in small catchments to sediment output was assessed through measurement of channel floor fine sediment storage and suspended sediment output. The small net channel floor fine sediment gains in the sub-catchment over the two year period indicate sediment supplied to the channel approximately equated to sediment removed. Observation during this time indicated sub-catchment fine sediment storage appeared quite seasonal, accumulating in summer-autumn and being largely removed during the high flow period in winter-spring 2005. Total sediment flux was greater during winter-spring 2005, relative to summer-autumn 2004-05 and 2005-06. Winter-spring 2006 was dry with little flow. This suggests under near to above average seasonal rainfall conditions, most fine sediment supplied to channels in the sub-catchment will probably be removed. When rainfall is well below average fine sediment will temporarily accumulate in the channels.

The efficiency of suspended sediment transfer from the sub-catchment to catchment outlet was examined using event based specific sediment yields per area and per length of incised channel. Since slope sediment contribution to the main channel of Flyers Creek is low, the use of catchment area to calculate SSY is potentially misleading (De Boer & Crosby, 1996). Therefore SSY_{length} provides a better indication of downstream sediment yield change as it relates sediment yield to the likely dominant source of sediment in the catchment. The mean ratio of catchment to sub-catchment SSY_{length} was 0.34, but this masks considerable seasonal variability, with a mean summer ratio of 0.09 and winter-spring of 0.49. Whilst the flow pulse travelled more rapidly downstream in summer, there was a decline in specific water yield (Ml km^{-2}) downstream, due to the localised nature of the rainfall.

Sediment delivery to the catchment outlet was greater in winter-spring 2005, a consequence of the catchment being hydrologically more responsive during this time, with generally higher soil moisture, lower evaporation and higher rainfall. However the decline in SSY from sub-catchment to catchment outlet indicates considerable storage. Despite identifying 170 farm dams in the catchment, they were largely discounted as fine sediment storage sites. Most dams were located above the extent of incised channels in the upper part of Flyers Creek tributaries and therefore unable to trap fine sediment from the dominant sediment sources in the catchment. The main channel of Flyers Creek appears to be an important location for temporary fine sediment storage. Extensive in-channel willow infestation of the mid and lower reaches, combined with lower channel gradient mid-catchment, suggests considerable scope for temporary storage along this part of the channel. Observations along this channel indicated the presence of fine sediment accumulations in pools. The catchment main channel appears to undergo a similar seasonal pattern of sediment storage gain and loss to the sub-catchment channels. Increased sediment flux during spring 2005 was apparent in larger sediment loads, with the largest flow event recorded at the catchment outlet transporting approximately 282t (SSY_{length}= 16.1 t km^{-1}). The extent of fine sediment transfer beyond upland headwater catchments may largely depend on the presence of significant dams downstream, which may trap much of the sediment leaving upland headwater regions, therefore limiting the extent to which upstream channel restoration effects will influence downstream reaches (Brizga & Finlayson, 1994).

Management implications

The findings of this research emphasise the need for stream management to focus on channel restoration in small upland headwater catchments to reduce local sediment supply, with the potential for reductions in fine sediment loads in downstream reaches. In the study catchment a reduction in fine sediment inputs from incised channels mostly located in the lower part of tributary sub-catchments could lead to a large reduction in temporary fine sediment storage along the main channel and suspended sediment exiting the catchment. If other small upland catchments with extensive channel erosion make significant fine sediment contributions to downstream rivers, then widespread reduction in upland channel erosion rates may have an appreciable effect (in the absence of large dams) on downstream fine sediment loads over management timescales.

Acknowledgements

The authors acknowledge the financial support of an Australian Postgraduate Award (APA) research scholarship for the first author and an Australian Institute of Nuclear Science and Engineering (AINSE) Award for sample analysis using gamma spectrometry. Carol and Eric Hayward are thanked for kindly allowing use of their property and Alan Smith for his assistance with field work. The two anonymous reviewers are thanked for their comments which helped improve this manuscript.

References

Brizga, S. O., & Finlayson, B.L. (1994). Interactions between upland catchment and lowland rivers: an applied Australian case study. *Geomorphology, 9*, 189-201.

Collins, A. L., Walling, D.E., & Leeks, G.J.L. (1997). Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. *Catena*, *29*, 1-27.

Croke, B. F. W., & Jakeman, A.J. (2001). Predictions in catchment hydrology: an Australian perspective. *Marine and Freshwater Research*, *52*, 65-79.

De Boer, D. H., & Crosby, G. (1996). Specific sediment yield and drainage basin scale. In D. E. Walling, & B.W. Webb (Ed.), *Erosion and sediment yield: Global and regional perspectives* (Vol. 236, pp. 333-338). Exeter: IAHS.

Erskine, W. (1994). River response to accelerated soil erosion in the Glenelg River Catchment, Victoria. *Australian Journal of Soil and Water Conservation, 7*(2), 39-47.

Fryirs, K., & Brierley, G.J. (2001). Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. *Geomorphology, 38*, 237-265.

Lake, P. S., & Marchant, R. (1990). Australian upland streams: ecological degradation and possible restoration. In D. A. Saunders, A.J.M. Hopkins, & R.A. How (Ed.), *Australian ecosystems: 200 years of utilisation, degradation and reconstruction* (Vol. 16, pp. 79-91). Geraldton: Ecological Society of Australia.

Lawler, D.M. (1993). The measurement of river bank erosion and lateral channel change: a review. *Earth Surface Processes & Landforms*, 18, 777-821.

Olley, J. M., & Wasson, R.J. (2003). Changes in the flux of sediment in the Upper Murrumbidgee catchment, Southeastern Australia, since European settlement. *Hydrological Processes, 17*(16), 3307-3320.

Prosser, I. P., Hughes, A.O., & Rutherfurd, I.D. (2000). Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. *Earth Surface Processes and Landforms, 25*, 1085-1101.

Prosser, I. P., Rutherford, I.D., Olley, J.M., Young, W.J., Wallbrink, P.J., & Moran, C.J. (2001). Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Marine and Freshwater Research, 52*, 81-99.

Trimble, S. W., & Mendel, A.C. (1995). The cow as a geomorphic agent- a critical review. *Geomorphology, 13*, 233-253.

Wallbrink, P., & Olley, J. (2004). Sources of fine grained sediment in incised and un-incised channels, Jugiong Creek, NSW, Australia. In V. Golosov, V. Belyaez & D.E. Walling. (Ed.), *Sediment transfer through the fluvial system* (Vol. 288, pp. 165-169): IAHS.

Wallbrink, P. J., Murray, A.S., Olley, J.M., & Olive, L.J. (1998). Determining source and transit times of suspended sediment in the Murrumbidgee River, New South Wales, Australia, using fallout Cs-137 and Pb-210. *Water Resources Research, 34*(4), 879-887.

Wallbrink, P. J., Martin, C.E., & Wilson, C.J. (2003). Quantifying the contributions of sediment, sediment-P and fertiliser-P from forested, cultivated and pasture areas at the landuse and catchment scale using fallout radionuclides and geochemistry. *Soil and Tillage Research*, *69*, 53-68.

Walling, D. E., & Woodward, J.C. (1992). Use of radiometric fingerprints to derive information on suspended sediment sources. In J. Bogen, D.E. Walling & T.J. Day (Ed.), *Erosion and Sediment Transport Monitoring Programmes in River Basins* (Vol. 210, pp. 153-164). Oslo: IAHS.

Walling, D. E., Collins, A.L., Sichingabula, H.M., & Leeks, G.J.L. (2001). Integrated assessment of catchment suspended sediment budgets: a Zambian example. *Land Degradation and Development*, *12*, 387-415.

Wasson, R. J. (1994). Annual and decadal variation of sediment yield in Australia, and some global comparisons. In L. J. Olive, R.J. Loughran & J.A. Kesby (Ed.), *Variability in stream erosion and sediment transport* (Vol. 224, pp. 269-279). Canberra: IAHS.

Wasson, R. J., Mazari, R.K., Starr, B., & Clifton, G. (1998). The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australia: sediment flux dominated by channel incision. *Geomorphology, 24*, 291-308.