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Multi-scale sediment dynamics in an upland catchment, southeastern Australia: a synthesis

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Abstract This paper presents a synthesis of multi-scale sediment dynamics within an upland catchment in southeastern Australia. Various process-based techniques were utilised for a period of nearly two years to monitor three nested spatial scales: hillslope (<250 m), sub-catchment (1.64 km^2) and catchment (53.5 km^2). Hillslope erosion rates were low, with sub-catchment and catchment-scale sediment dynamics dominated by sediment supply from channel banks. Assessment of sub-catchment to catchment sediment delivery was based on comparison of specific sediment yields, with peak yields and delivery in spring 2005. In-channel sediment storage responded to seasonal and drought-dependent discharge patterns, with storage increasing during extended low flow periods. Seasonal variation in processes and controls was observed across all spatial scales examined, demonstrating the important effect of seasonality in rainfall patterns, vegetation growth, and antecedent soil moisture, for sediment dynamics in the study catchment.

Key words scale; catchment sediment dynamics; sediment delivery; Australia

INTRODUCTION

The scales of space and time create a number of important issues in the examination of geomorphic systems. These issues include the identification of characteristic scales of processes, establishing linkages across scales, and ascertaining the range of scales over which patterns or relationships may apply (Phillips, 1999). Scale issues in catchment sediment dynamics have received increasing attention, primarily focusing on the spatial scale (e.g. de Boer & Campbell, 1989; Lane *et al*., 1997; Cammeraat, 2004) and with particular consideration of stream bank erosion (Lawler, 1995; Abernethy & Rutherfurd, 1998; Couper, 2004). This work reflects an increasing acknowledgement of the need to integrate findings at different scales within catchment systems. This challenge underlies the development of connections between detailed, generally short-term, process-based research on sediment dynamics conducted at the hillslope and very small catchment scale (<1 km^2) and the transport of sediment through catchments at larger scales.

In this study, the effect of spatial scale is examined through extensive monitoring of three nested scales: hillslope (<250 m), sub-catchment (1.64 km^2), and catchment (53.5 km^2). The study was situated within a gullied upland headwater catchment in southeastern Australia. The aims were to: (a) determine the dominant processes and controls of sediment flux at each spatial scale examined, and (b) consider the extent of linkages between scales in the transfer of fine sediment (<63 μm). Detailed investigation of such gullied upland catchments is important in the context of previous research, which suggests that the widespread gullies and incised channels in upland areas of the southern Murray-Darling basin are important sources of fine sediment delivered to lowland rivers (Wasson, 1994; DeRose *et al*., 2003; Wallbrink & Olley, 2004).

STUDY AREA

The study area is located in the Central Tablelands region of New South Wales and is part of Flyers Creek, a headwater catchment of the Lachlan River (tributary of the Murray-Darling Basin). Flyers Creek originates on steep basalt slopes (the remnants of Tertiary volcanics) and an adjacent elevated (~950 m) low relief plateau, and flows south through a narrow, steep-sided valley. Monitoring was limited to upper Flyers Creek, with detailed measurements taken in the sub-catchment nested within the 53.5 km^2 study catchment, which has an elevation range from 780 m at the outlet to 1140 m (Fig. 1). Incised channels and gullies are present throughout the study

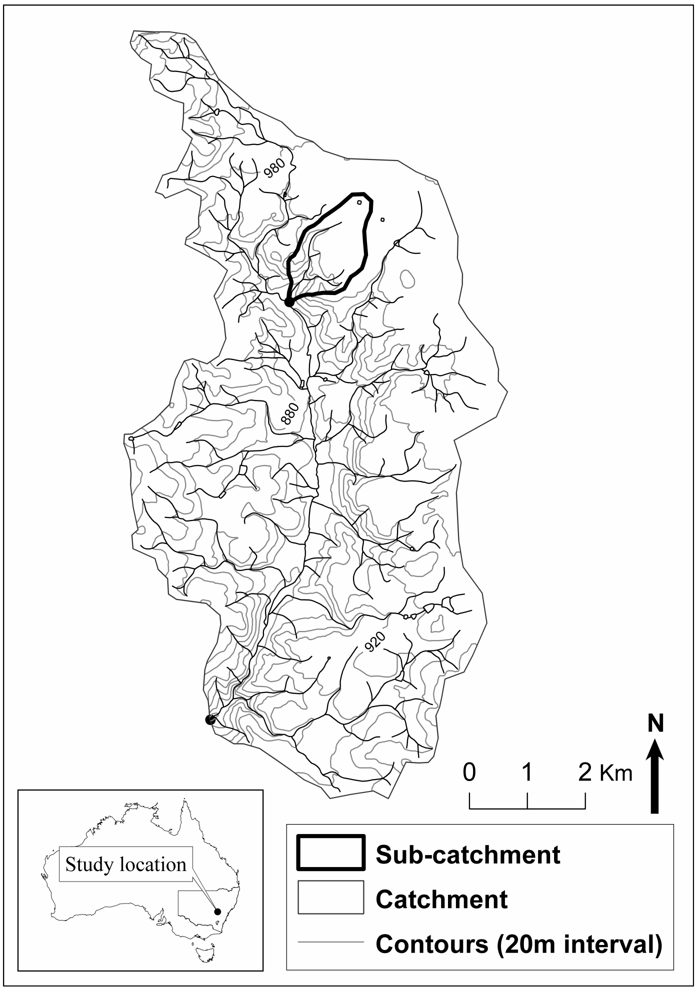

Fig. 1 Location of study area and map of monitored catchments.

catchment. Within the sub-catchment, channel incision is limited to the valley floor and joins directly to the main catchment channel. In the lower part of the catchment, the main channel contains an extensive willow infestation (*Salix* spp.).

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. Catchment soils are predominantly red silty clays. Suspended sediment transported through the catchments is generally fine grained. Composite suspended-sediment samples collected during multiple higher-flow events indicated that 96% of the sediment from the sub-catchment and 89% from the catchment was <63 µm. The study area experiences cool winters and mild summers, with a mean annual rainfall of 903 mm (Orange airport) and rainfall maxima in summer and late winter. Rainfall during summer months is generally dominated by high intensity localised storms, and during winter and spring months more widespread rainfall (and some snow) tends to occur. Land use in the study catchment in 2003 was predominantly pasture (74%), with some cultivation (19%) and a limited area of forest cover (6%).

METHODS

Intensive monitoring using a range of techniques was undertaken at the three spatial scales identified. Field measurements were conducted for two years, with monitoring data sets concurrent for a period of 19 months (March 2005 to October 2006).

Six, 2-m wide, open runoff plots were installed (with five operational throughout) and used to measure sediment yields from grass covered hillslopes within the study sub-catchment. The use of open plots made estimation of hillslope erosion rates problematic due to the lack of defined plot contributing areas. Therefore, plot data was supplemented by model estimates of hillslope sediment yields using SOILOSS (version 5.1) in conjunction with a Digital Elevation Model (DEM). SOILOSS is based on the Universal Soil Loss Equation (USLE) and was developed in conjunction with long-term erosion data collected in New South Wales (Rosewell, 1993). SOILOSS was applied to discrete hillslope sections with similar slope angles and slope lengths identified using the DEM (Smith & Dragovich, 2008b).

Bank erosion rates within monitored gullied channels were measured using erosion pins. Silicone bronze welding rods with lengths of 0.35–0.4 m and diameters of 3 mm were employed (Lawler, 1993), with 100 of these pins inserted into vertical bank profiles. Subaerial processes appeared to be the dominant cause of bank erosion, with evidence of bank failure only observed on two occasions, and flow scour limited to entrainment of loose sediment deposited on the lower bank profile below the pins. Measurement intervals were of 3–4 month periods, providing a total of six bank erosion measurements. Erosion pin data were used to estimate bank sediment inputs from gullied channels within the sub-catchment based on mean bank erosion rates, bank height, and estimated soil bulk density (Smith & Dragovich, 2008b). Change in channel floor sediment storage within the sub-catchment was measured by re-survey of 12 marked channel cross-sections. Channel observations indicated a layer of fine sediment generally overlying a gravel layer (>2 mm), with most channel floor change attributable to erosion and deposition of the fine sediment layer, rather than incision into the gravel.

Sediment source contributions from hillslope surface and subsurface (channel bank) sources in the sub-catchment were examined using ^{137}Cs and excess ^{210}Pb (^{210}Pb$_{ex}$) as sediment tracers (Smith & Dragovich, 2008a). Soil samples were collected at both the surface (0–2 cm) and sub-surface (>30 cm) from 23 locations across hillslopes and valley floor areas adjacent to channels. These individual samples were combined to form six composite samples from surface sources and six from sub-surface sources. Deposited sediment samples (8) were collected from channel floors, and a composite suspended sediment sample was collected at the sub-catchment outlet from 10 flow events, to assess relative source contributions to channel storage and output, respectively. The mixing model outlined by Collins *et al.* (1997), which incorporated both tracers, was used to estimate the relative source contributions.

Discharge and suspended sediment monitoring was undertaken at both the sub-catchment and catchment outlets (Smith, 2008). Gauging sites consisted of stable channel sections (with rock outcrop controls) and flow measurement based on stage–discharge ratings. Water level measurements were collected using pressure transducers with data loggers recording measurements at 10 and 15-min intervals. Flow event sampling was undertaken using Gamet automatic water samplers, which contained 24 × 0.5-L bottles. Initial sampling regimes were adjusted with the final sampling regime taking four samples at 0.25-h intervals, and the remaining samples taken at hourly intervals. Suspended sediment concentration of water samples was determined by vacuum filtration through 47-mm diameter glass microfibre filters (retains particles >1.2 μm). Suspended sediment loads were calculated using various suspended sediment–discharge rating curves and compared with sampled event sediment loads to assess rating curve accuracy (Smith, 2008). The model efficiency criterion, developed by Nash & Sutcliffe (1970), was also used to assess rating curves and the optimal rating curve was applied to the discharge data measured at each site.

Land use, channels and farm dams were mapped using 2003 aerial photographs in conjunction with field inspections. Channels were classified as incised or unincised. The incised channel category (including gullies) consisted of clearly defined channels, with steep and/or sloping, mostly unvegetated banks of likely increased erosion potential. The unincised channel category consisted of visible lines of flow mostly taking the form of shallow channels with sloping vegetated banks of probable low erosion potential.

RESULTS

Measured hillslope erosion was low during the study period. The combined runoff-plot sediment yield was 218 g, with peak yields in late spring 2005. The SOILOSS estimate of total hillslope sediment yield used in the sub-catchment sediment budget was 10.1 t, with an estimated mean slope erosion rate of 0.22 t ha^{-1} $year^{-1}$ (Smith & Dragovich, 2008b). Pasture cover height was least (mean 130 mm) during spring months (compared to 660 mm over summer), although visual estimates of percent surface cover remained >90% throughout the study period. Mean event rainfall intensity in spring (13.7 mm h^{-1}) was greater than winter months (4.3 mm h^{-1}), but less than during the summer–autumn period (28.7 mm h^{-1}). Rainfall measured 4 km from the study sub-catchment totalled 1140 mm during the study period, which was 18% below the long-term average (1969–2006). During 2005 rainfall was slightly above average (101%), with the highest falls during winter and spring, and well below average (53%) in 2006.

Sub-catchment scale sediment flux was determined from measurements of bank erosion rates, suspended sediment output, and source contributions from hillslopes and channel banks. Mean net bank erosion from the gullied channels was 19.2 mm for the total monitoring period, and ranged from 1.1 to 5.2 mm for the bank measurement intervals. Channel bank erosion rates were used to estimate bank sediment inputs to channels (Table 1). In the absence of data for hillslope sediment inputs to channels, the proportional bank sediment contribution to in-channel sediment deposits (88%) was used with measured bank sediment inputs to estimate hillslope inputs. Sub-catchment suspended sediment output totalled 24.1 t and ranged from 0.1 to 19.7 t for the measurement intervals. The difference between total inputs to channels and outputs provided a measure of net in-channel sediment storage change and the measurement interval sediment delivery ratio (SDR). The estimated net storage gain for the study period was supported by net channel floor aggradation recorded by the channel cross-sectional surveys. The SDRs (which do not include gross hillslope erosion) ranged from 1 to 153%, with the maximum SDR for the period October 2005 to early January 2006, which included the largest flow event that accounted for an estimated 59% of the total sub-catchment suspended sediment output.

Comparison of sub-catchment and catchment scale suspended sediment output enabled assessment of the extent of sediment delivery between the sites. Specific sediment yields per length of incised channel (SSY_{length}) were used to compare sites, and ratios of catchment to sub-catchment (C:SC) SSY_{length} were used to provide an indication of the extent of between-scale

Table 1 Sub-catchment sediment budget components and catchment sediment yields for bank measurement intervals and for the complete study period.

	Measurement intervals						
	2 Jul 2005	4 Oct 2005	4 Jan 2006	10 Apr 2006	10 Jul. 2006	05 Oct. 2006	Study period
Sub-catchment (SC)							
Input to channels (t):							
Hillslope	1.2	0.3	1.5	1.0	0.8	0.8	5.7
Channel banks	8.8	2.3	11.4	7.2	5.9	6.1	41.6
Total	10.0	2.6	12.9	8.2	6.7	6.9	47.3
Suspended sediment output (t)	0.8	2.4	19.7	0.9	0.1	0.2	24.1
Specific sediment yield SSY_{length} (t km^{-1} $year^{-1}$)	3.6	12.8	106.1	4.7	0.5	0.8	20.7
Net in-channel sediment storage change (t)	9.2	0.2	–6.8	7.3	6.6	6.7	23.2
Sub-catchment SDR (%)	8	91	153	11	1	2	51
Catchment (C)							
Suspended sediment output (t)	1.5	82.6	462.5	2.2	0.3	0.9	550.0
Specific sediment yield SSY_{length} (t km^{-1} $year^{-1}$)	0.3	18.3	104.4	0.5	0.1	0.2	19.8
Ratio C:SC SSY_{length}	0.07	1.43	0.98	0.10	0.15	0.25	0.96

suspended sediment transfer. Channels dominate sediment supply in the sub-catchment (Smith & Dragovich, 2008) and this seems likely for the catchment also, based on findings for a comparable upland catchment with incised channels (Wallbrink *et al.*, 2003). Therefore, SSY_{length} was employed because variability in sediment yields across the two scales is probably primarily dependent upon variation in the extent of incised channels, rather than catchment area. The length of incised channels (including gullies) was 0.74 km in the sub-catchment and 17.57 km in the catchment.

The peak in C:SC ratios occurred between July 2005 and early January 2006, which indicates that much of the sediment exiting the sub-catchment was probably delivered to the catchment outlet during this time (Table 1). This period accounted for 86% of the study period discharge at the sub-catchment outlet and 80% at the catchment outlet. It also coincided with the peak in sub-catchment SDRs. The highest C:SC ratio of 1.43 (July–October 2005) probably reflects additional sediment contributions from other tributaries, and particularly the catchment main channel (with remobilisation of in-channel fine sediment stores), resulting in a proportional increase in downstream SSY_{length}. Accumulation of fine sediment in the main catchment channel was observed during extended low-flow periods, particularly over summer and autumn. Removal of much of this material occurred during the higher-flow period of late winter and spring 2005, followed by re-accumulation during most of 2006.

Seasonal comparison of SSYs indicated that spring was the period of highest sediment yields and peak SSY_{length} C:SC ratios, with the lowest yields and ratios in summer and autumn (Smith, 2008). Examination of the longer-term flow record (1976–2006) supports the importance of the winter–spring higher-flow period. A total of 18 distinct periods of repeated higher flows (from 26 years with complete flow data) occurred during winter and/or spring. There was a large range in maximum daily peak discharge from each period, which varied from 185.7 to 1720.9 ML. Although isolated large events occurred outside the winter–spring period, most events were comparatively small. Failure of this seasonal higher-flow period to occur leads to a very dramatic reduction in annual sediment loads, as shown in the comparison of sediment yields between the contrasting rainfall years of 2005 (546.9 t at the catchment outlet) and 2006 (3.4 t).

DISCUSSION AND CONCLUSIONS

Hillslope sediment yields remained low because of the consistent extent of surface cover maintained throughout the study period. Temporal variation in hillslope yields reflected seasonal patterns in pasture growth and rainfall intensity influencing sediment supply. Hillslope runoff generation appeared to be largely controlled by vegetation (with cover height greatest in summer, maximising raindrop interception) and soil moisture (maximum generally in early spring with sufficient rainfall), both of which respond to seasonal differences in rainfall and temperature. These variables were also important controls of hydrological response at the sub-catchment and catchment scales, as evident from discharge patterns. Comparatively low discharge occurred during high magnitude and intensity summer storms at both scales, in contrast to increased hydrological response to lower magnitude and intensity rainfall during spring.

At the sub-catchment scale there was a shift to channel dominance of sediment supply, with minor sediment contributions from hillslopes to channels. The shift from slope to channel erosion process dominance occurred rapidly with the transition from unincised to incised channels in the sub-catchment (Smith & Dragovich, 2008a). Pronounced seasonal variability was also apparent at the sub-catchment scale in patterns of discharge, suspended sediment yield and in-channel sediment storage. The peak in sub-catchment discharge and sediment yields occurred during spring 2005 when pasture height was least, soil moisture was high and rainfall intensity greater than during winter (but less than summer, the effect of which was mitigated by enhanced interception with pasture growth). Therefore, sub-catchment sediment flux reflects the combination of sediment supply dominated by channels, and flow generation dependent on hillslope variables in conjunction with rainfall characteristics.

The catchment-scale suspended sediment response was also probably dependent on sediment supply from eroding banks of incised channels, both within sub-catchments and from sections of the main channel. Given the dominance of channel bank sediment supply, varying land use across the catchment was probably of less importance for sediment flux at this scale. Catchment discharge and sediment yields showed similar seasonal variability to that observed for the other spatial scales. Average to above-average rainfall, seasonally distributed, is probably required to achieve maximum sediment delivery between the sub-catchment and catchment scales. For example, high rainfall during summer with less in spring would probably produce annual discharge and sediment loads at the catchment outlet less than that generated with high rainfall during winter–spring because of the differences in antecedent conditions. Also, a proportionally larger reduction in catchment sediment yields, compared to the sub-catchment, was observed during the low rainfall year of 2006, in contrast to the near average year of 2005. Smaller flow events during below-average rainfall periods may erode and transfer sediment the shorter distance between the source and outlet in the sub-catchment, in contrast to the catchment. An outcome of this was that catchment main channel sediment accumulation occurred from tributary sub-catchment contributions during extended low rainfall periods. Net channel sediment accumulation was also prominent during summer and autumn due to the tendency for flow dissipation downstream during this time, leading to in-channel deposition between outlets. The extensive willow infestation would have contributed to enhanced in-channel fine sediment storage along the mid and lower catchment main channel.

Processes operating at the sub-catchment and catchment scales are similar, but main channel flow dissipation and in-channel sediment storage differentiate sub-catchment and catchment discharge, and suspended-sediment response. Furthermore, with increasing spatial scale, the potential for enhanced variability in rainfall distribution (both magnitude and intensity) increases, also distinguishing response. Seasonal variation in processes and controlling factors was observed across all spatial scales examined, demonstrating the important effect of seasonality in rainfall patterns, vegetation growth, and antecedent soil moisture for sediment dynamics in the study catchment. Superimposed on this seasonal variation are longer-term hydroclimatic patterns (e.g. El Niño-Southern Oscillation and Interdecadal Pacific Oscillation) that may delay removal of accumulating sediment stores during extended low rainfall periods until subsequent higher flows occur.

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