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Impacts of native forest harvesting on in-channel erosion and sediment yields in unmapped headwater catchments

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Abstract The outlets of five unmapped headwater forest catchments on the Mid-North coast of New South Wales, Australia, 0.9–4.2 ha in area, were instrumented between 2002 and 2006 with flat-v weirs to measure streamflow; bed-load traps to measure bed load; and stage-activated automatic pump-samplers to allow water sample collection for analysis of turbidity and suspended-sediment concentration. Pressure transducers were installed in groundwater monitoring wells beneath the surface of each channel to measure subsurface flow. Additionally, 70 channel cross-sections were surveyed at least annually during the trial period while a total of 1037 erosion pins was installed at 180 locations of likely bank or nickpoint erosion and measured at 6-monthly intervals. Harvesting using BMPs occurred in three catchments in 2004, while two catchments were harvested, but total exclusion zones 10 m wide maintained on either side of the channels. On average, the channels flowed for 2–5% of the time. They are ephemeral features and surface flows that did occur were dominated by stormflows (79–95%) with a minor baseflow component. Groundwater monitoring indicated that 58–79% of annual channel flow was transmitted beneath the channel sediments as opposed to surface runoff. Because they flowed infrequently, sediment yields from the channels were extremely low. Pre-harvest values were recorded between 0.001 and 0.05 tonnes per ha per year, which are lower than typically recorded in larger forest catchments. Sediment yields and streamflow peaks increased in all channels following harvesting. However, harvesting using BMPs in selected catchments did not significantly alter the magnitude of the sediment response to harvesting, while channel bank and nickpoint erosion rates remained consistently low during the monitoring period.

Key words unmapped drainage lines; channel erosion; sediment yields; buffer strips; forestry impacts; southeastern Australia

INTRODUCTION

Drainage feature protection is one of the cornerstones of sustainable forest management. Retention of natural or semi-natural riparian vegetation during forestry activities is widely acknowledged as being important for controlling erosion and sedimentation, moderating stream temperature and light regimes, inputting fine and large wood and organic debris (Webb & Erskine, 2003), and hence the maintenance of invertebrate, fish, mammal and bird communities (Lee *et al.*, 2004). Broadmeadow & Nisbet (2004) indicate that there is no set pattern to either the framework used to classify streams, the buffer widths applied to those streams or the level of harvesting or other disturbance allowed within the buffer zone. Regardless of the classification system used to identify streams, it is acknowledged that not all drainage features are adequately mapped in the landscape (Hansen, 2001), requiring conditions for the protection of "unmapped" drainage features.

Forests NSW is a public trading enterprise responsible for managing both native State forests and government-owned timber plantations in the State of New South Wales (NSW), Australia. It is legislated to implement Best Management Practices (BMPs) aiming to protect the aquatic environment and domestic water supplies from the potential impacts of forestry activities (Webb & Haywood, 2005). In native State forests, harvesting exclusion zones or buffer strips of increasing width are applied on all mapped streams of increasing order. However, many channels are not adequately mapped, necessitating protection of so-called "unmapped drainage lines" (UDLs). Most native forests available for timber harvesting occur in steeper landscapes where the extent of unmapped channels is significant. Such features require protection from disturbance, but given their spatial extent, government timber supply commitments require that protection measures have a minimal impact on timber availability.

Forests NSW consequently developed trial BMPs aimed at allowing selective harvesting of timber adjacent to UDLs in native State forests whilst maintaining the sediment-trapping efficacy of buffer strips. The BMPs require adherence to strict soil conservation guidelines that include ground disturbance minimisation, rehabilitation of groundcover and the prevention of direct linkages between harvested areas and UDLs. This paper presents results of a four-year trial instituted to assess the effectiveness of these BMPs in protecting UDLs from increased sediment loads and in-channel erosion derived from harvesting disturbance. Specifically, this paper examines streamflow, suspended-sediment load, bed load and channel erosion characteristics within five UDL catchments and the efficacy of BMPs in mitigating the impacts of timber harvesting activities.

Study sites

Five unmapped headwater catchments were chosen for study in Kendall State forest on the mid-north coast of NSW, Australia (31º38′S, 152º41′E). The region generally experiences a mild mid-latitude humid subtropical climate featuring warm humid summers in the absence of a distinct dry season. There is a summer rainfall maximum with mean annual rainfall of 1380 mm. Geology in the catchments consists of Palaeozoic rocks of the Carboniferous Byabbara beds (Brunker *et al.*, 1970). Dominant lithologies are lithic sandstone, siltstone, tuff, shale and limestone. Soil textures range from sandy loams to silty clay loams with some light to medium clays (Murphy *et al.*, 1998).

Kendall State forest contains a range of regrowth eucalypt forests with stands that vary in age and structure as a result of a long history (>100 years) of intensive harvesting and silvicultural treatment. The lower slopes support Flooded Gum (*Eucalyptus grandis*), Sydney Blue Gum (*E. saligna*) and Brush Box (*Lophostemon confertus*) stands. Mid slopes carry Mahogany (*E. resinifera, E. acmenoides*), Grey Gum (*E. propinqua*), Tallowood (*E. microcorys*) and Ironbark (*E. paniculata*) stands while upper slopes and ridge tops support either Blackbutt (*E. pilularis*) or Mahogany/Grey Gum/Ironbark stands.

Forest harvesting and catchment treatments

Each catchment was harvested between December 2003 and January 2004 using a combination of single tree- and group-selection methods. Three of the catchments were designated as "impact" catchments whereby high quality timber was harvested from within the 10-m wide buffer adjacent to UDLs using trial BMPs. The remaining two catchments were designated as "control" catchments where harvesting also took place but was excluded from within the buffers adjacent to UDLs. The overall extent of harvesting varied between the catchments (Table 1).

Table 1 Details of forest harvesting by catchment.

Catchment	Area (ha)	Impact/control	Area harvested (ha)	% Area harvested
1	1.78	Impact	0.41	22.9
2	2.13	Control	1.09	51.5
3	0.87	Impact	0.25	29.3
4	4.23	Impact	1.29	30.4
5	2.41	Control	0.98	40.5

METHODS

A stream gauging station consisting of a 450-mm wide flat-v weir (Fig. 1) was installed at the outlet of each catchment in April 2002 and remained in place until April 2006. Instruments at each station comprised an optical shaft encoder with built-in datalogger, automatic pump water sampler and staff gauge. Electronic equipment was powered by 12 V batteries charged by a 30 W solar panel at each station. Stage measurements were logged at 2-min intervals to capture all variability as streamflows in the small channels rose and fell rapidly during storms. Stage measurements were converted to discharge (Q) using rating curves based on the relevant weir equations. Each rating curve was checked and modified following velocity-area gaugings undertaken, where possible.

Fig. 1 Flat-v weir at catchment 4 outlet during a runoff event, 25 October 2004.

Water samples, 500 mL in volume, were automatically pumped from each weir pool when flows were initiated within the channels and at rising and falling stage increments throughout runoff events. The sites were visited and data downloaded after each storm or at a maximum interval of 14 days during cease-to-flow conditions. Water samples were collected, refrigerated and couriered to the laboratory to be analysed for total suspended-sediment (TSS) concentration and turbidity using the appropriate methods (APHA, 1998). Two pluviometers with single-channel dataloggers and seven storage raingauges, read at each site visit, were located within the study area.

At each station, a well was constructed adjacent to the weir to the depth of bedrock beneath the channel surface. A pressure transducer was fitted to the base of each well to allow measurement of subsurface water depth. Data from the pressure transducers were collected at 1-min intervals and recorded on a datalogger. A bed-load trap, 450 mm × 400 mm × 400 mm, was installed within the bed of each channel upstream of the weir and bed load collected after each flow event. Bed-load samples were oven dried and weighed in the laboratory. Organic matter was separated from the samples using the method of carbon loss on ignition while the remaining clastic fraction was subjected to standard grain size analysis (Gee & Bauder, 1986). Grain size statistics were calculated by the method of moments using Gradistat Version 4.0 software (Blott & Pye, 2001).

Seventy channel cross-sections were established and marked during the study period using standard survey pegs. The cross-sections were surveyed at least annually using an automatic level and surveyor's tape to assess any macro-changes in channel morphology. There were 12, 12, 12, 15 and 19 cross-sections established in catchments 1–5, respectively. A longitudinal profile was surveyed of each channel to determine channel slope and step characteristics. To assess micro-changes in channel morphology, a total of 1037 erosion pins, 100 mm in length, was installed at 180 locations of likely bank or nickpoint erosion and measured at 6-monthly intervals during the study period. On each profile, pins were spaced at approx. 100 mm intervals.

RESULTS AND DISCUSSION

Channel morphology

Catchments 1 and 2 are north facing and comprise slopes of up to 29° while catchments 3, 4 and 5 are south facing with slopes up to 32° in catchments 4 and 5. Catchment 3 comprises more gentle slopes up to 22°. In each catchment, channels have been formed in a dendritic pattern. The total channel length was 125 m, 144 m, 98 m, 230 m and 395 m in catchments 1–5, respectively. The

Table 2 Summary of channel morphology in each catchment. Values recorded are means ±2 standard errors.

Catchment	Depth (m)	Bed width (m)	Bankfull width (m)
1	0.62 ± 0.21	1.95 ± 0.73	3.24 ± 0.96
2	0.46 ± 0.10	2.10 ± 0.79	3.59 ± 1.10
3	0.79 ± 0.11	1.97 ± 0.82	4.25 ± 1.37
4	1.19 ± 0.31	1.78 ± 0.61	3.95 ± 0.90
5	0.93 ± 0.26	0.93 ± 0.23	2.93 ± 0.72

majority of fall in each channel occurred over a combination of nickpoints, boulder steps, log steps and root steps (Webb & Erskine, 2005). Channels in catchments 1 and 2 were the smallest of those studied, whilst those in catchments 4 and 5 were of larger dimensions (Table 2). Catchment 3 comprised channels of intermediate dimensions despite having the smallest catchment area.

Surface flow

During the study period, annual rainfall was 1130 mm, 1386 mm, 1154 mm and 1410 mm in the 2002, 2003, 2004 and 2005 water years (i.e. April–March), respectively. Surface runoff measured at catchment outlets varied from a minimum of 9 mm in the 2002 water year in catchment 5 to 275 mm in the 2003 water year in catchment 1. These values represent runoff coefficients of 0.8% and 19.8%, respectively, indicating that the unmapped channels studied are ephemeral. The minimum annual duration of flow was 3.65 days (1%) in the 2002 water year in catchment 5 while the maximum annual duration of flow was 28.9 days (7.9%) in the 2003 water year in catchment 2. On average, the channels flowed for 2–5% of the time. Streamflows were separated into baseflow and stormflow components using the digital filtering method of Lyne & Hollick (1979) using appropriate parameter values for small forest catchments (Cornish & Vertessy, 2001). The majority of runoff occurred at all sites as stormflow, further indicating that these channels are ephemeral (Fig. 2).

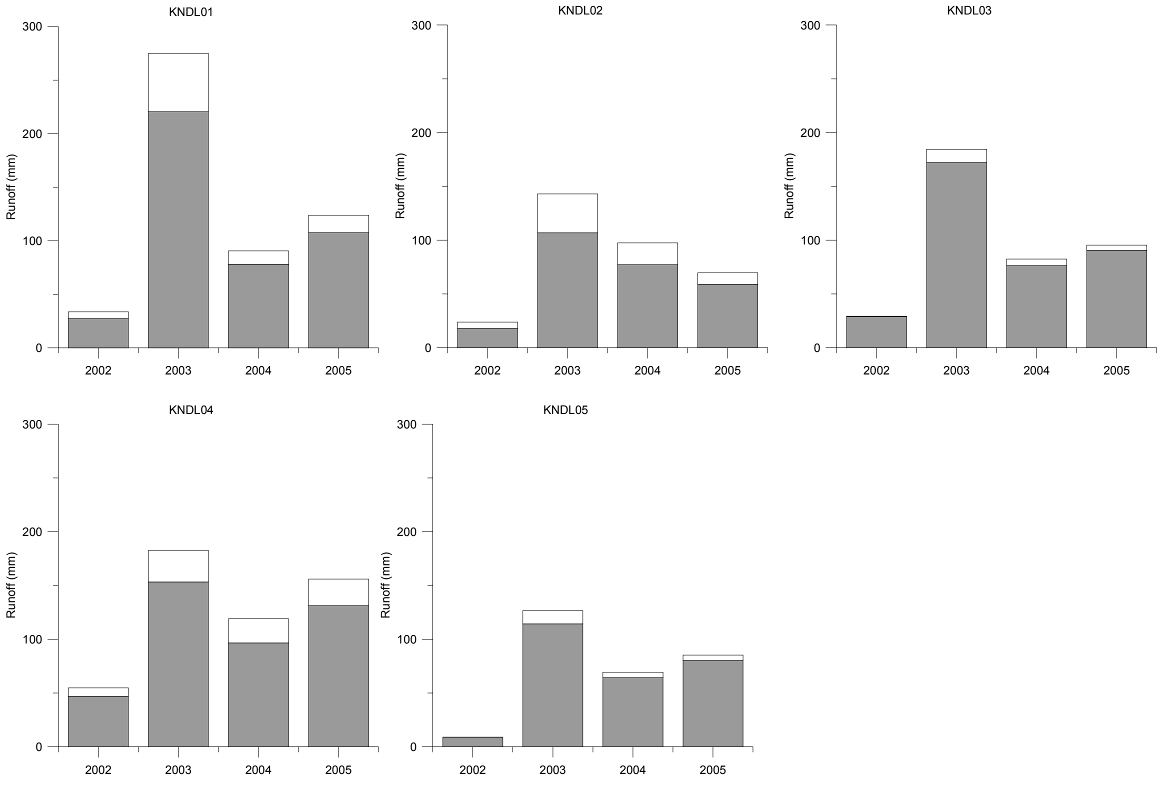

Fig. 2 Annual runoff by water year (April–March) for each catchment separated into stormflow (shaded) and baseflow (unshaded) components.

Subsurface flow

Throughout the study period a significant proportion of rain events did not result in any surface flows at catchment outlets. However, groundwater data indicated that during the majority of events there was a considerable degree of subsurface water movement. For example, from 16–26 February 2003, total rainfall was 263 mm, which resulted in two recorded surface flow events in catchment 3 (Fig. 3). However, there were at least 12 peaks in subsurface flow recorded during the same period. This indicates that a substantial proportion of rain falling on the catchment is being transferred from the catchment as subsurface or hyperheic flow within the channel sediments. Similar responses were found in all catchments throughout the study period.

An assessment of the relative proportions of surface and subsurface flow from each of the catchments was completed by modelling of annual data. To solve for subsurface flows requires re-arranging the water balance equation, as follows:

$$SS = P - R - ET \tag{1}$$

where SS is subsurface flow yield (mm), P is precipitation (mm), R is surface flow yield (mm) and ET is evapotranspiration (mm). Accurate measurements were made in this study of P and R; however, it was necessary to use the 2-parameter models of Zhang *et al.* (2001) to estimate catchment evapotranspiration. Zhang *et al.* (2001) used data from 250 catchments worldwide to present models of evapotranspiration in forests and grasslands as a function of annual precipitation. The two equations produced take the form:

$$ET_{\text{forest}} = P\,[1 + (2820/P)] \,/\, [1 + (2820/P) + (P/1410)] \tag{2}$$

$$ET_{\text{grass}} = P\,[1 + (550/P)] \,/\, [1 + (550/P) + (P/1100)] \tag{3}$$

where ET_{forest} is evapotranspiration from forests and ET_{grass} is evapotranspiration from grasslands. For data collected in the pre-harvest period during the present study, equation (2) was used to estimate ET and solve equation (1) for SS. In the post-harvest period where a proportion of each catchment had been harvested, it was necessary to assume that ET could be estimated by:

$$ET = [A_{\text{frac}}\, ET_{\text{grass}}] + [(1 - A_{\text{frac}})\, ET_{\text{forest}}] \tag{4}$$

where A_{frac} is the fraction of the catchment area harvested. As a result, subsurface flows were estimated to account on average for 58–79% of the total annual flow (surface and subsurface combined) from the unmapped headwater catchments. Figure 4 shows a breakdown of subsurface and surface flows estimated by water year for each catchment and highlights variability amongst catchments. Namely, subsurface flows contributed the least to total flows in catchment 1, particularly in the 2003 water year when 81% of the total flow was contributed by surface runoff. Conversely, in catchment 5 subsurface flows contributed proportionally the greatest to total flows. In particular, in the 2002 water year 96% of the total flow was contributed by subsurface runoff.

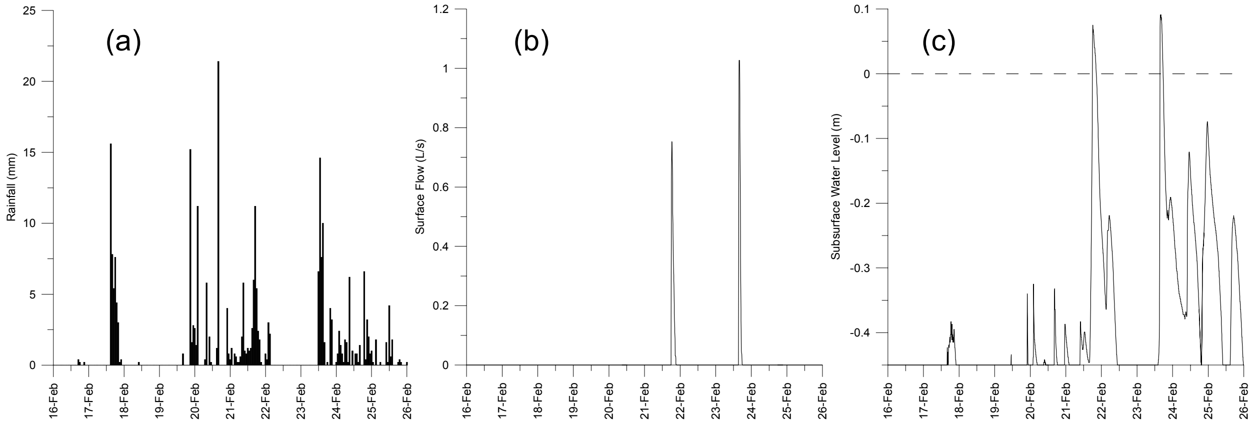

Fig. 3 Recorded observations of: (a) hourly rainfall, (b) instantaneous surface discharge, and (c) instantaneous subsurface water level changes for the period 16–26 February 2003 in catchment 3.

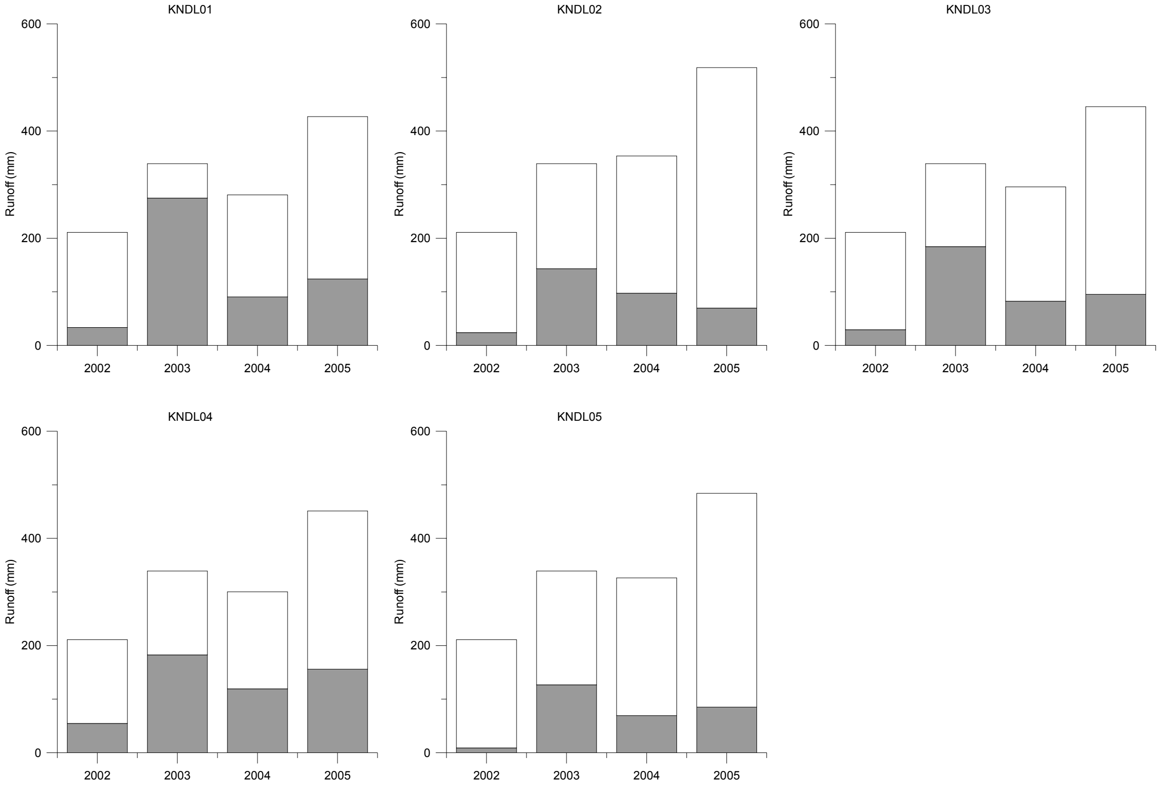

Fig. 4 Total annual runoff by water year (April–March) for each catchment separated into surface flow (shaded) and subsurface flow (unshaded) components.

Pre-harvest sediment yields and in-channel erosion

Due to the infrequency of surface runoff it was not surprising that sediment yields from the catchments during the pre-harvest period were extremely low. In the two pre-harvest water years sediment yields ranged from 0.001 tonnes ha^{-1} in the 2002 water year at catchments 1 and 5, to 0.05 tonnes ha^{-1} in the 2003 water year at catchment 3.

The nature of bed load was variable between runoff events and between the different catchments. Bed load comprised between 2.4% of the pre-harvest sediment load in catchment 4 and 8% of the pre-harvest sediment load in catchment 1. Interestingly, 70–85% of the annual bed load pre-harvest across all catchments was comprised of organic matter. The organic matter fraction was predominantly made up of eucalypt leaves, “gumnuts” and small twigs. Of the remaining clastic fraction, bed-load samples displayed a range of median grain sizes (d_{50}) from 0.5 to 27.6 mm, corresponding to very fine gravelly coarse sand through to very coarse gravel (Folk, 1954).

During the pre-harvest period, no changes in channel morphology were evident from re-surveying of channel cross sections, within the accuracy of the methods used. However, erosion pin measurements provided a useful indication of micro-scale bank and nickpoint erosion rates in each channel. Following the methods of Saynor & Erskine (2006) the mean of pin measurements from each profile was calculated. Negative values indicate deposition whereas positive values indicate erosion. In the two-year pre-harvest period, bank erosion rates ranged from –0.5 ± 1.6 mm to 1.6 ± 1.1 mm while nickpoint erosion rates were between 1.7 ± 2.2 mm and 6.5 ± 1.2 mm (values are means ± 2 standard errors).

Impacts of harvesting

Stormflow data were used to calculate Event Mean Concentrations (EMC) of suspended sediment and Event Mean Turbidity (EMT) values for each flood event using the methods of US EPA (1999). Events were included only when three or more samples had been taken, and only when the samples had been collected at sufficient intervals to represent the rising and falling limbs of the hydrograph. Event mean concentrations at all sites were generally low and below 100 mg/L. Similarly, EMT values were low and below 100 NTU at all sites. Following harvesting activities in 2004, suspended-sediment concentrations and turbidity were increased in all catchments. Figure 5 is an example time series plot from catchments 4 and 5 illustrating that in general EMC TSS values were higher in the post-harvest period.

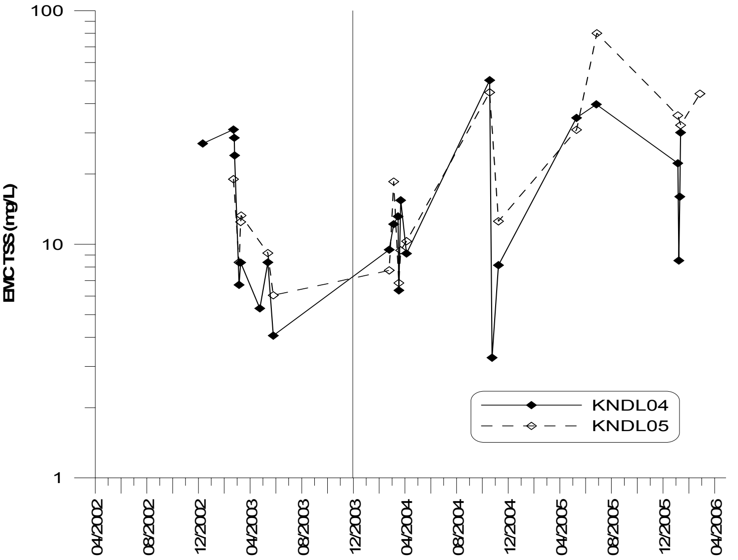

Fig. 5 Time series plot of event mean concentration (EMC) of total suspended-sediment (TSS) concentration in catchments 4 and 5. The vertical line represents the onset of forest harvesting.

Where data were available, EMC and EMT values were paired between the control (catchments 2 and 5) and impact (catchments 1, 3 and 4) sites for the pre- and post-harvest periods to assess whether or not harvesting BMPs impacted upon suspended-sediment concentrations and/or turbidity. Control site values were subtracted from impact site values (to give IMC or Impact Minus Control values) and differences between pre- and post-harvest values were then tested for statistical significance using a 1-tailed *t*-test. As each flood event was discrete, autocorrelation was assumed to be negligible. If data did not conform to a normal distribution, they were log-transformed to meet the assumptions of a *t*-test. Where F-tests revealed heterogeneity in the data sets, *t*-tests for unequal variance were used. Where the variances were not significantly different, *t*-tests for equal variance were used. A total of 134, 181, 227, 260 and 219 samples were analysed respectively from catchments 1–5.

There were no statistically significant differences observed between control and impact sites as a result of harvesting for either EMT or EMC values. The most significant change ($p = 0.06$) post-harvest was observed for EMC values in impact catchment 4 relative to control catchment 2. Similarly, there was a non-significant increase in EMT values at catchment 4 relative to catchment 2 after harvesting. However, in general there was no clear trend in the data recorded to suggest that the use of harvesting BMPs had any effect on in-stream EMC or EMT values. Non-significant observed increases were counter-balanced by non-significant decreases during the post-harvest period.

The grain size of bed-load samples collected did not change significantly during the post-harvest period, nor did the contribution of bed load to overall sediment loads. However, as suspended-sediment concentrations increased at all sites after harvesting there was an increase in overall sediment yields. The most dramatic increase in sediment yields occurred in catchment 3 where the mean post-harvest yield was 17.8 times greater than the pre-harvest mean. Catchment 3 was the only catchment containing a gravel road used for log haulage. The road was side-cut with several relief pipe culverts draining towards the unmapped channel network, which could account for the sediment yield increase (Croke & Mockler, 2001). Mean post-harvest sediment yields in catchment 5 were 8.2 times greater than the pre-harvest mean; while mean sediment yields were 4.1, 1.6 and 4 times greater during the post-harvest period in catchments 1, 2 and 4, respectively. Concurrent with the increase in suspended-sediment concentrations was an increase in the peak to mean ratio of storm events, which may have contributed to greater sediment delivery within the unmapped catchments.

In-channel erosion rates remained low at all sites during the post-harvest period (Table 3). However, in catchment 1 there was a significant increase in bank erosion rates after harvesting. Conversely, this corresponded with a significant decrease in nickpoint erosion rates post-harvest. Catchment 5 also experienced a significant increase in bank erosion rates post-harvest, coupled with a non-significant increase in nickpoint erosion. Overall, erosion rates within the channel network were variable in both the pre- and post-harvest periods across all catchments. The observed increases in total sediment yields cannot be attributed to any changes in the low rates of channel erosion observed.

Table 3 Bank and nickpoint erosion results by catchment for the two-year pre- and post-harvest periods. Erosion values are profile means ± 2 standard errors.

Catchment	No. profiles	No. erosion pins	Bank erosion pre-harvest (mm)	Bank erosion post-harvest (mm)	Nickpoint erosion pre-harvest (mm)	Nickpoint erosion post-harvest (mm)
1	26	178	0.3 ± 1.4	4.3 ± 1.8*	6.5 ± 1.2	2.9 ± 2.1*
2	29	138	0.7 ± 0.9	4.3 ± 2.7	2.1 ± 2.7	1.3 ± 5.1
3	24	153	–0.5 ± 1.6	5.0 ± 4.1	5.5 ± 1.6	3.8 ± 2.9
4	42	269	1.6 ± 1.1	2.3 ± 3.4	4.4 ± 2.6	3.6 ± 1.7
5	59	299	–0.2 ± 1.0	2.9 ± 1.2*	1.7 ± 2.2	7.2 ± 3.9

* denotes significant difference between pre- and post-harvest periods.

CONCLUSIONS

The unmapped headwater channels studied flowed on average for 2–5% of the time during the four-year study period. They are ephemeral features and surface flows that did occur were dominated by stormflows (79–95%) with a minor baseflow component. Groundwater monitoring indicated that 58–79% of the annual channel flow was transmitted beneath the channel sediments as opposed to surface runoff. Because they flowed infrequently, sediment yields from the channels were extremely low. Pre-harvest values were recorded between 0.001 and 0.05 tonnes per ha per year, which are lower than typically recorded in larger forest catchments. Bed load contributed 2–8% of the total sediment loads recorded and consisted of 70–85% organic matter. Sediment yields and streamflow peaks increased in all channels following harvesting. However, harvesting using BMPs in selected catchments did not significantly alter the magnitude of the sediment response to harvesting. Channel bank and nickpoint erosion rates remained consistently low during the monitoring period.

These results support the conclusion that forest harvesting has the potential to significantly increase sediment loads in the short-term. However, with respect to unmapped headwater channels, complete harvesting exclusions may not be necessary if BMPs are applied to mitigate the potential for additional sediment delivery to the drainage network. However, it is recommended that further studies be funded to enable robust assessments of the hydrological functioning of unmapped drainage lines and sediment responses to harvesting using BMPs in differing geomorphic settings.

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