Proceedings of the Third Australian Stream management Conference, 27-29 August, Brisbane, Queensland, pages 87-93.

Effects of pre-Code forest clearfelling on the geomorphology and sedimentology of headwater streams in upland granite terrain, Tasmania

S.E.H. Bunce[1], P.D. McIntosh[2], P.E. Davies[3] and L.S.J. Cook[3]

SUMMARY: A retrospective comparison of clearfelled and minimally-disturbed headwater catchments in the upland granite terrain of northeast Tasmania indicates that pre-Forest Practices Code forestry operations 15 years ago have affected present-day stream geomorphology and sediment character. Some differences, such as the greater number of logs in and above streams in clearfelled and regenerated catchments, can be explained by direct effects of past logging. Others such as greater bank height and more exposed boulders can be explained by indirect hydrological changes (increased stream flow rates) resulting from clearfelling. Differences such as streams in clearfelled and regenerated areas having coarser sediments, a higher proportion of channels (rather than bars and pools), less in-stream coarse particulate organic matter, and containing <2mm sediment with a lower C/N ratio than undisturbed streams, could be attributed to either direct disturbance of streambeds by pre-Code clearfelling, or increased stream flow rates after clearfelling, or the greater mean catchment area of the clearfelled catchments. While the study indicates that medium-term effects of pre-Code forestry operations on the physical character of headwater streams in the upland granite terrain of northeast Tasmania have occurred, it also indicates the desirability of initiating monitoring of headwater streams in forested catchments to determine whether Code-conforming forestry operations have long-term impacts.

THE MAIN POINTS OF THIS PAPER

?? Pre-Code forestry operations have had medium-term effects on headwater streams in upland granite terrain in Tasmania

?? Streams in clearfelled catchments have less complex channels, coarser sediments and are more incised and have more exposed boulders than streams in minimally-disturbed catchments

?? Streams in clearfelled catchments have more in-stream logs but less in-stream coarse particulate organic matter, and their <2mm sediment fraction has a lower C/N ratio, than streams in minimally-disturbed catchments

?? The differences may attributed to both the direct effects of stream and riparian disturbance, and the indirect effect of higher stream flow rates after clearfelling, but a definitive study on the effects of forestry operations on headwater streams will require long-term monitoring

1. INTRODUCTION

1.1 Context of the Study

About 90% of catchment stream flow typically comes from first and second order streams (Descamps et al., 1999), therefore the number of small streams, and likelihood of cumulative downstream effects, make them an important land management issue. Descamps et al. (1999) suggested that the control of water quality in headwaters should be a priority for improving downstream river water quality.

Research into the effects of forestry operations on headwater streams has been conducted in many parts of the world (e.g. Carling and Reader, 1982; Grant et al., 1990; Montgomery and Buffington, 1997; Feller and Richardson, 1999; Kiffney and Bull, 1999; Millard, 2000), but apart from the study of Davies and Nelson (1993) in steeplands of the Dazzler Range, Tasmania, Australian research on forest streams has been largely directed to larger catchments (e.g. the case studies described in Croke and Lane 1999). Research in southwest Western Australia forest catchments, and in the Dazzler Range (Ruprecht and Schofield, 1989; Davies and Nelson, 1993) indicated that disturbance in headwater stream channels increases fine sediment movement and the amount of fine organic sediment in streams immediately after logging.

Figure 1: *Typical core sample layout across a stream, showing 5 cm diameter coring tubes in a pool (left), bar (centre) and channel (right).*

For operational reasons, headwater streams are defined in the Tasmanian Forest Practices Code as having catchments <50ha and are called Class 4 streams (Forest Practices Board, 2000). The Code provides limited protection measures for Class 4 streams (i.e. a

1. Department of Geography and Environmental Science, University of Tasmania, Hobart (email: Buncs@semf.com.au)
2. Forest Practices Board, 30 Patrick St, Hobart (email: peter.mcintosh@fpb.tas.gov.au) (author for correspondence)
3. Freshwater Systems, c/- Department of Zoology, University of Tasmania, Hobart (email: pedavies@postoffice.utas.edu.au)

10m no-machinery zone) but allows removal of timber trees. While burning of Class 4 stream riparian zones is discouraged, it often cannot be avoided. Implicit in the Code provisions is the assumption that if forestry operations affect Class 4 streams, the effects are likely to be temporary, reversible and local. To test this assumption we compared the geomorphological and sedimentological character of headwater streams in catchments that were clearfelled and regenerated fifteen years ago (before the Forest Practices Code governed forestry operations), with those in similar but minimally disturbed catchments.

1.2 Previous Research

Research on second and higher-order streams has shown that logging causes soil compaction (Slaymaker and McPherson, 1977), alters overland flow, stream bank stability and stream sediment retention, reduces shading of streams, and causes soil erosion and wind throw (Vanderwel, 1994). It modifies riffle sedimentation and the length of open stream and snag volume (Borg et al., 1988; Davies and Nelson, 1994; Scrivener, 1987), changes stream sediment particle size (Scrivener, 1987; Davies and Nelson, 1993) and changes stream chemistry and conductivity (Feller, 1999). These changes have direct impacts on in-stream ecological processes, the invertebrate community and fish populations (Bryant, 1985; Davies and Nelson, 1994).

Such results cannot be routinely extrapolated to headwater streams because these streams may have quite different character to larger streams. For example, headwater streams may be steeper or seasonally dry, may be more geomorphologically variable, have greater flow variability, have sediments ranging from sands to boulders, have very localised scour-fill processes and very variable amounts of woody debris. In addition, small streams are generally more shaded and receive more litter per unit of streambed area than larger streams (Richardson et al., 1999), and are significantly more heterotrophic.

1.3 Approach

Although a before-after-control-impact (BACI)-type design (Stewart-Oaten and Bence 2001) is the ideal approach for producing unequivocal results, such a design requires a 10-20 year commitment of land and funding by the forestry industry, and cannot provide an assessment of medium-term impacts until such time has elapsed. The alternative "retrospective" approach has the disadvantages that the prior condition of the study catchments may not be known, "treatment" placement is determined by past operational considerations such as access and cannot be assumed to be random, and processes causing differences cannot be monitored as they occur.

Despite these limitations, a retrospective approach was taken in this study, particular care being taken to choose study catchments that were likely to have been highly similar before forestry operations began: study catchments had similar altitude, geology, slopes, vegetation communities and catchment size. Because the study aimed to investigate medium-term effects, and forestry operations in Tasmania have only been constrained by the Forest Practices Code since 1987, when the first edition of the Code was published, it was necessary to choose study catchments which were clearfelled before the Code governed forestry operations.

Table 1. Mean particle size analysis of in-stream sediments.

	Mean CONTROL	Mean REGEN	sig
>2mm fraction (%)			
bar	52.3	54.5	NS
channel	51.0	57.0	NS
pool	48.7	44.5	NS
overall	*50.1*	*53.8*	*NS*
<2mm fraction over all geomorphic units (bars, pools, channels) (%)			
1-2mm	35.3	40.2	$p<0.05$
0.5-1mm	24.2	26.5	$p<0.0001$
0.25-0.50mm	20.7	19.3	NS
0.125-0.25mm	12.8	9.0	$p<0.0001$
<0.125mm	7.00	5.0	$p<0.01$

Table 2. Mean loss on ignition (LOI) and organic matter analysis of in-stream sediments.

	CONTROL	REGEN	sig
LOI (%)			
bar	4.6	5.1	NS
channel	4.6	4.4	NS
pool	5.8	7.2	NS
overall	*4.7*	*5.3*	*NS*
Total C (%)			
bar	2.7	2.0	NS
channel	2.3	1.6	NS
pool	3.3	4.0	NS
overall	*2.7*	*2.4*	*($p<0.10$)*
Total N (%)			
bar	0.085	0.080	NS
channel	0.077	0.068	NS
pool	0.100	0.162	NS
overall	*0.083*	*0.098*	*NS*
C/N ratio			
bar	34.9	23.4	$p<0.001$
channel	30.9	23.1	$p<0.001$
pool	34.4	25.9	$p<0.001$
overall	*33.3*	*24.2*	*$p<0.001$*

2. LOCATION AND PHYSICAL DESCRIPTION

The study streams were located in the upper South Esk catchment on the upland plateau (800-900m) east of Ben Nevis peak (1368m) in northeast Tasmania, at approximate latitude 41°25'S. The area is underlain by biotite granite/adamellite (Department of Mines, 1993). Acidic Mellic Brown Kandosols (Isbell, 1996), mapped as moderately erodible Memory soils with sandy clay loam textures (Grant et al., 1995), dominate the area.

Natural vegetation is mostly *Eucalyptus delegatensis* and *E. dalrympleana* with a dry heathy understorey but in the c.20m riparian zone th vegetation is in places dominated by *Leptospermum* species and rainforest communities containing *Nothofagus cunninghammii* and *Atherosperma moschatum*. Slopes are mostly 0-11^{o}. Rainfall probably exceeds 1400mm, with a winter rainfall maximum.

Pre-european human impact on the study streams is likely to have been minimal although the seral eucalypt forest was probably maintained by natural or deliberate fires. Since european settlement the entire area has been selectively logged. Clearfelling using heavy machinery occurred locally in the 1980s. Activities were not limited by Code rules and operations next to streams are likely to have included crossings of streams with machinery and felling of trees into streams. Environmental impacts are likely to have been greater than those occurring in clearfell operations at present.

3. METHODS

Five Class 4 streams were selected in catchments that had been clearfelled and regenerated in 1985 (REGEN; mean catchment area 23.5ha, range 8.5-40.4ha), and five in minimally disturbed control catchments that had had individual trees removed but had not been clearfelled (CONTROL; mean catchment area 16.0ha, range 6.0-22.6ha). Ideally, streams would have been randomly selected from a population of streams that were known to have had very similar characteristics before any logging occurred. In practice, the historical pattern of clearfelling in the area meant that the five REGEN treatments were geographically separated from the five CONTROL treatments by about 5km. However, the uniformity of the geology, slope, forest communities and altitude over the study stream catchments indicated that it was most unlikely that there were systematic natural differences between REGEN and CONTROL sites.

The five REGEN sites were located around map reference Tasmap Sheet 5441 (Ben Nevis) 5550 54185 and the five CONTROL sites were located around map reference 5530 54165. Fire was probably used to induce regeneration following clearfelling but the regeneration pattern indicates that burns may have been patchy.

A representative 50m reach of stream with flowing water was marked out in each stream. In each reach, at 2.5m intervals, the bankfull and wetted width, bank height and stream slope were measured. For each 2.5m section, the areal proportions of three geomorphic units (channels, bars and pools) were estimated. In addition the percentage cover of coarse particulate organic matter (CPOM) (primarily leaves, twig and bark fragments), organic silt, benthic algae and macrophytes was estimated, and also the proportion of the stream substrate area consisting of boulders, cobbles, gravel, sand or silt. The number of overlying and in-stream logs (>10cm diameter) was also counted**.**

At three locations in each stream reach (upper 10m, middle 10m and lower 10m) undisturbed 20cm deep cores of sediment were obtained from channels, bars and pools (if present) or from the dominant geomorphological units (**Figure 1**), giving a total of 9 cores per stream. The cores were extruded and split

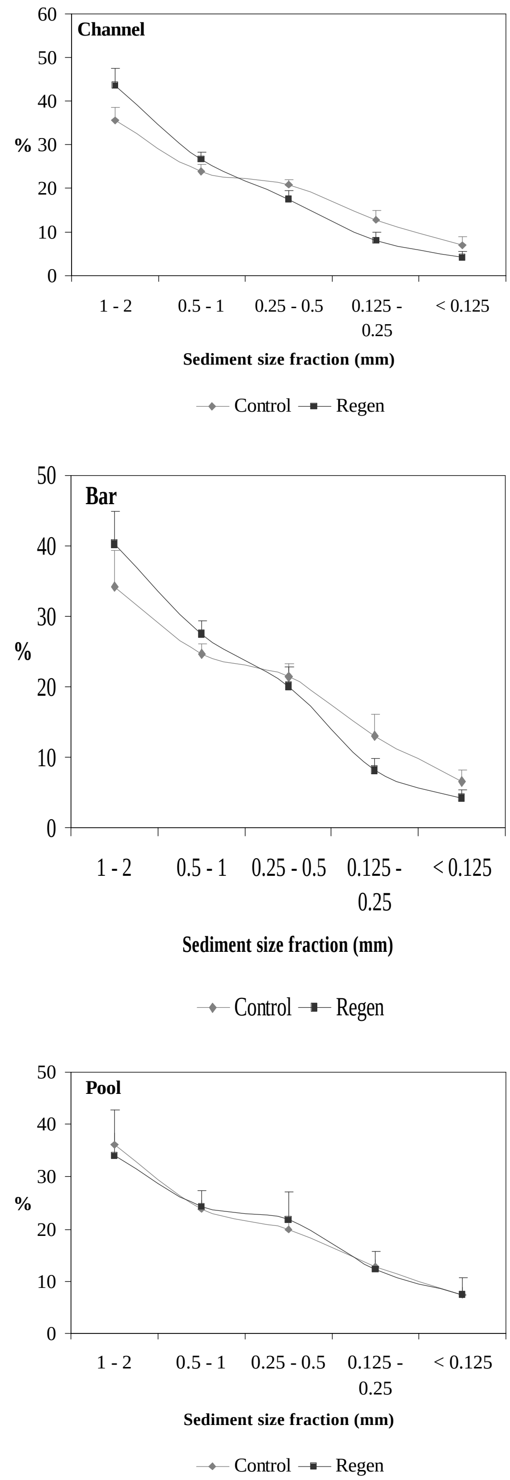

Figure 2: *Particle-size distribution of <2mm sediments, by in-stream geomorphic unit. Upper 95%CL limits shown.*

into two halves in the laboratory. One half was retained as a stratified sample for photographs. The other half was dried at 80^{o}C to constant weight for over 24h and was split into two parts. One part was sieved through a 2mm sieve and the >2mm fraction weighed. A muffle furnace was used to burn off the organic component and loss on ignition (LOI) was measured (Blakemore et al., 1987). The particle-size distribution in the <2.0mm fraction of ignited soils was measured by sieving (Krumbein and Pettijohn, 1938; McCave and Syvitski, 1991) resulting in a continuous frequency distribution of material (<0.125mm to 2mm). Silt and clay fractions were not studied as the sediments were predominantly sandy, with less than 2% of the <2mm fraction being less than 63?m (results not shown). The other part of the <2mm fraction was analysed for total C and total N using a LECO furnace (Blakemore et al., 1987).

Riparian soils were sampled by taking 20 0-10cm topsoil samples from shallow pits on each bank of each 50m reach of stream. The 20 samples were bulked, giving 10 riparian samples for each of the CONTROL and REGEN sites.

Statistical analysis of stream data was conducted using SYSTAT (Wilkinson, 2001). Analysis of variance (ANOVA) was conducted on the sediment composition data with two factors (logging treatment - CONTROL vs REGEN; and geomorphic unit - channel, bar or pool), with overall stream slope and catchment size as covariates. One-way ANOVA was used to compare values of all other variables between CONTROL and REGEN streams. An alpha of 0.05 was used for all stream analyses.

4. RESULTS

Mean particle size data (**Table 1** and **Figure 2**) shows that bars and channels in REGEN streams have more sand in coarser (>0.5mm) size fractions and less in finer fractions (<0.25mm) than CONTROL streams. There was no difference of either LOI or total N between sediments of CONTROL and REGEN streams, but total C was slightly lower and C/N ratio was substantially lower (p<0.001) in REGEN stream sediments (**Table 2**).

There were a number of significant (p<0.05) and substantial geomorphological and other differences between CONTROL and REGEN streams (**Table 3**). REGEN streams had double the number of above- and in-stream logs of CONTROL streams. When compared to CONTROL streams, REGEN streams had 67% more channel area, 40% greater mean bank height, and 45% less CPOM. REGEN streams also had 10 times as much algal cover (mean of 5 patches per 50m reach, cf. 0.2 in CONTROL), 75% more macrophyte cover (mean of 2 patches per 50m reach, cf. 0 in CONTROL), 7 times more boulder substrate area, and 51% and 49% greater variability (CV) of bed-slope and bankfull channel width respectively.

Thus REGEN streams contained more logs, were more incised, had more channel habitat (and less "complex" pool/bar habitat), stored less CPOM and had more benthic algae and macrophytes, had more variable bankfull widths, and had more exposed granite surfaces and more locally variable slopes than CONTROL streams.

Riparian soils (**Table 4**) contained less coarse sand and more fine sand than stream sediments. There were no significant differences between particle size in riparian soils of CONTROL and REGEN streams (p>0.05). However, total N levels were 58% higher in REGEN riparian soils (p<0.05) than in CONTROL soils and the C/N ratio of REGEN soils was lower (p<0.05).

Table 3. Mean geomorphological characteristics of streams.

	CON[1]	**REG**[1]	**sig.**
Stream slope (%)	0.048	0.049	NS
No. above-stream logs	18	36	p<0.05
No. in-stream logs	19	37	p<0.05
Channel (%)	43	72	p<0.05
Pool (%)	38	25	NS
Bar (%)	19	17	NS
Bank height (m)	0.23	0.32	p<0.05
Wetted width (m)	1.41	1.15	NS
Bank-full width (m)	1.92	1.87	NS
Sand cover (%)	18	21	NS
Gravel cover (%)	21	22	NS
Cobble cover (%)	1.7	4.5	NS
Boulder cover (%)	0.9	6.5	NS
CPOM cover (%)	31	17	p<0.05
Organic silt cover (%)	21	14	NS

[1]CON=CONTROL; REG=REGEN

Table 4. Mean riparian soil characteristics.

	Soil chemical properties				**LOI**
	pH (H_2O)	C (%)	N (%)	C/N	(%)
CONTROL	4.39	9.3	0.34	28	22.5
REGEN	4.21	11.6	0.51	23	27.8
2-tailed t-test, p =	*<0.10*	*<0.10*	*<0.05*	*<0.05*	*<0.10*

	Particle size (<2mm fraction)				
	1-2 mm (%)	0.5-1 mm (%)	0.25-0.5 mm (%)	0.125-0.25 mm (%)	<0.125 mm (%)
CONTROL	28.9	22.4	19.5	14.6	14.5
REGEN	26.6	23.6	20.6	13.7	15.6
2-tailed t-test, p =	*NS*	*NS*	*NS*	*NS*	*NS*

5. DISCUSSION

Because the study was retrospective, caution must be used before attributing differences between CONTROL and REGEN streams to forestry operations. However, the similarity of particle-size distribution in CONTROL and REGEN riparian zones (**Table 4**) supports the initial geological, topographical and botanical observations that stream environments were likely to have been similar before logging began.

For some observations, such as the greater number of logs both above and in REGEN streams, it is clear that a direct effect of forestry operations is responsible. (We note that in the Forest Practices Code (Forest Practices Board, 2000) felling of trees into streams is not allowed, so this amount of logging debris in and above streams is no longer sanctioned in present practice.) Other observations, however, are consistent with the effects of the well-established higher rates of flow of streams after their catchments have been clearfelled (Vertessy, 1999). These are greater bank height (deeper incision), higher proportion of channels (at the expense of pools and bars), reduced storage of CPOM and fine sediments, a coarser sediment load and lower C/N ratio of sediments in REGEN streams. The shift of in-stream sediment size to coarser fractions is similar to that noted immediately following clearfelling by Davies and Nelson (1993) in steeper Tasmanian Class 4 streams subject to cable logging and broadcast burning. However, given the larger mean catchment area of the REGEN catchments compared to the CONTROL catchments, a causal relationship between clearfelling and these observations cannot be proven.

The lower C/N ratio in REGEN streams is probably explained by the CONTROL streams having more charcoal in sediments: higher rates of flow in the REGEN streams would wash charcoal downstream, along with the finer (lighter) mineral sediment (**Table 1**), leaving behind charcoal-depleted sediment with lower C/N ratio. The C/N ratio of sediments is easily measured and appears to have potential to be used as a disturbance indicator in headwater streams.

The lower C/N ratio of the riparian soils of REGEN streams can be explained by the soils receiving more light, and having more pioneering N-fixing trees such as *Acacia dealbata* (M. Wapstra, Forest Practices Board, personal communication). Greater algal cover in the REGEN streams is also likely to be a response to light.

6. CONCLUSIONS

The study indicates that there are differences between control streams and streams in catchments that were clearfelled and regenerated 15 years previously. Streams in clearfelled and regenerated catchments have more in-stream logs, more algal cover, coarser sediments, a higher proportion of channels (rather than bars and pools), less coarse particulate organic matter, have sediments with a lower C/N ratio and are more incised (with greater bank heights and more exposed boulders) than streams in minimally-disturbed catchments.

Some of the above effects e.g. increased number of in-stream logs and more algal cover, can be attributed to the *direct* influence of clearfelling. Others such as greater incision of streams and less coarse particulate organic matter may be caused by *indirect* effects such as greater flow rates of streams in clearfelled catchments. Coarser sediments in clearfelled streams could be caused by both greater disturbance of these streams and increased flow rates after clearfelling. However, in this study, the greater mean catchment area of the REGEN catchments compared to CONTROL catchments could also have influenced stream character.

Indirect stream effects that can be attributed to flow rate changes after clearfelling can be expected to occur in similar terrain, under present Forest Practices Code rules and guidelines. Those effects attributable to direct disturbance of the stream channel can be expected to be less pronounced in present operations that conform to the Forest Practices Code. For those effects such as sediment coarsening, that may have been influenced both by disturbance and flow rate changes, this study does not provide a definite answer to the question "are such effects also likely to result from present Code-conforming clearfell operations in similar terrain?"

In order that effects on stream character attributable to direct disturbance, changed hydrological balance, and catchment size can be separated, a replicated experiment with a BACI design, incorporating monitoring of disturbance, flow rates and stream characteristics before, during and after forestry operations, is required. Such an experiment should be a priority for headwater stream research in forestry catchments in Tasmania.

7. ACKNOWLEDGEMENTS

We thank Bill Manning (Forest Practices Board) and Garry Richardson (Forestry Tasmania), for helping to select study sites; Kate Brown (University of Tasmania) for field and supervisory assistance to S.E.H.B.; and North Forest Products (now Gunns Ltd) and the Regional Forest Agreement Trust Fund for financial assistance.

8. REFERENCES

Blakemore, L.C., Searle, P.L. and Daly, B.K. (1987). Methods of chemical analysis of soils. New Zealand Soil Bureau Scientific Report **80**.

Borg, H., Hordacre, A. and Batini, F. (1988). Effects of logging in stream and river buffers on watercourses and water quality in the southern forest of Western Australia. Australian Forestry **51**(2): 98-105.

Bryant, M.D. (1985). Changes 30 years after logging in large woody debris and its use by salmonids. In: Riparian ecosystems and their management: reconciling conflicting uses. First North American Riparian Conference. USDA Forest

Service General Technical Report **RM-120**. Tuscon, AZ, U.S.A.

Carling, P.A. and Reader, N.A. (1982). Structure, composition and bulk properties of upland stream gravels. Earth Surface Processes and Landforms **7**: 349-365.

Croke, J. and Lane, P. (Editors) (1999). Forest management for water quality and quantity. Proceedings of the 2nd Forest Erosion Workshop, May 1999. Report **99/6**, CRC for Catchment Hydrology, Melbourne, 108 p.

Davies, P.E. and Nelson, M. (1993). The effects of steep slope logging on fine sediment infiltration into the beds of ephemeral and perennial streams of the Dazzler Range, Tasmania, Australia. Journal of Hydrology **150**: 481-504.

Davies, P.E. and Nelson, M. (1994). Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Australian Journal of Marine and Freshwater Research **45**: 1289-305.

Department of Mines (1993). Geological Atlas 1:50 000 series. Alberton. Tasmania Department of Mines, Hobart.

Descamps, H., Pinay, G. and Naiman, R.J. (1999). Trees along river banks. In: Farina, A. (ed.) Perspectives in Ecology. Backhuys Publishers, Leiden, Holland.

Feller, M.C. (1999). Physical and chemical behaviour of streams in the U.B.C. Research Forest at Maple Ridge. In: Feller, M.C. and Richardson, J.S. (eds.), Ecology and management of riparian stream ecosystems: a large scale experiment at the University of British Columbia Malcolm Knapp Research Forest, Proceedings. Department of Forest Sciences, U.B.C., Vancouver, B.C., Canada.

Feller, M.C. and Richardson, J.S. (eds.) (1999). Ecology and management of riparian stream ecosystems: a large scale experiment at the University of British Columbia Malcolm Knapp Research Forest, Proceedings. Department of Forest Sciences, U.B.C., Vancouver, B.C., Canada.

Forest Practices Board (2000). Forest Practices Code. Forest Practices Board, Hobart, Tasmania. 120 p.

Grant, G.E., Swanson, F.J. and Wolman, M.G. (1990). Pattern and origin of stepped-bed morphology in high gradient streams, Western Cascades, Oregon. Geological Society of America **102**: 340-352.

Grant, J., Laffan, M. and Hill, R. (1995). Soils of Tasmanian State Forests. 2. Forester Sheet. Forestry Tasmania, Hobart. 246 p.

Isbell, R.F. (1996). The Australian Soil Classification. CSIRO Publishing, Collingwood, 143 p.

Kiffney, P.M. and Bull, J.P. (1999). Effects of clearcutting on periphyton accrual in coastal headwater streams of southwestern British Columbia. In: Feller, M.C. and Richardson, J.S. (eds.), Ecology and management of riparian stream ecosystems: a large scale experiment at the University of British Columbia Malcolm Knapp Research Forest, Proceedings. Department of Forest Sciences, U.B.C., Vancouver, B.C., Canada.

Krumbein, W.C. and Pettijohn, F.J. (1938). Manual of Sedimentary Petrography. D. Appleton-Century Company, Inc., USA.

McCave, I.N. and Syvitski, J.P.M. (1991). Principles and methods of geological particle size analysis. In: Syvitski, J.P.M. (ed.) Principles, methods and applications of particle size analysis. Cambridge University Press, Cambridge, U.K.

Millard, T. (2000). Channel Disturbance in S5 and S6 streams. Forestry Research Technical Report ***005*** Geomorphology. Forest Service, British Columbia, Canada.

Montgomery, D.R. and Buffington, J.M. (1997). Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin **109**(5): 596-611.

Richardson, J., Feller, M. and Kiffney, P. (1999). Riparian and stream ecosystem function in small, coastal British Columbia. streams and the effectiveness of riparian buffers. In: Feller, M.C. and Richardson, J.S. (eds.), Ecology and management of riparian stream ecosystems: a large scale experiment at the University of British Columbia Malcolm Knapp Research Forest, Proceedings. Department of Forest Sciences, U.B.C., Vancouver, B.C., Canada.

Ruprecht, J.K. and Schofield, N.J. (1989). Analysis of streamflow generation following deforestation in southwest Western Australia. Journal of Hydrology **105**: 1-17.

Scrivener, J.C. (1987). Changes in composition of the streambed between 1973 and 1985 and the impacts on salmonids in Carnation Creek. In: Chamberlain, T.W. (ed.), Proceedings of the workshop: applying 15 years of Carnation Creek results. Carnation Creek Steering Committee, Nanaimo, B.C., Canada.

Slaymaker, O. and McPherson, J. (1977). An overview of geomorphic processes in the Canadian Cordillera. Zeitschrift fur Geomorphologie **21**(2): 169-186.

Stewart-Oaten, A. and Bence, J.R. (2001). Temporal and spatial variation in environmental impact assessment. Ecological Monographs **71**: 305-339.

Vanderwel, D. (1994). Impacts of Logging and subsequent land use. Alberta Agriculture Food and Rural Development. <http://www.agric.gov.ab.ca/agdex/500/8100002a.html. (accessed July 2000).

Vertessy, R.A. (1999). The impacts of forestry on streamflows - a review. In: J. Croke and P. Lane, (eds.), Forest management for water quality and quantity. Proceedings of the 2nd Forest Erosion Workshop, May 1999. Report **99/6**, CRC for Catchment Hydrology, Melbourne, 108 p.

Wilkinson, L. (2001). SYSTAT Version 10.0. SSPS Inc., Chicago, IL, U.S.A.