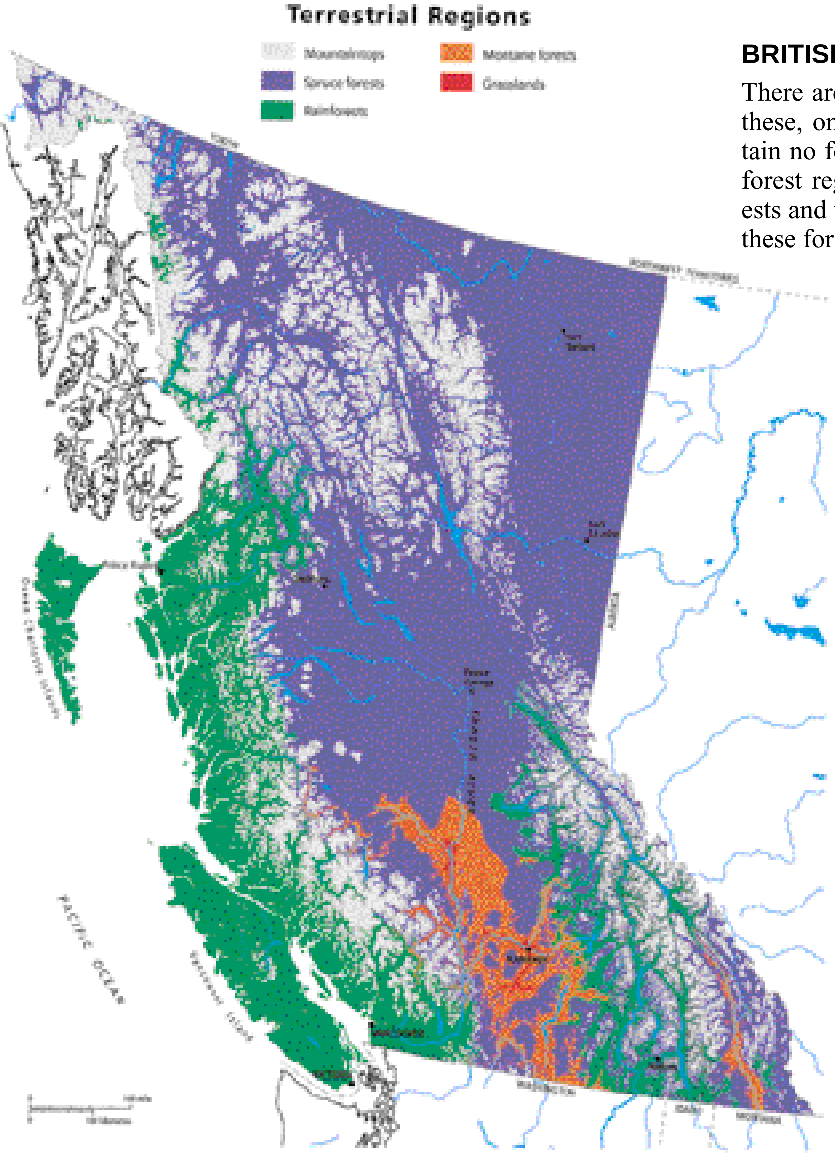
Olav Slaymaker

Assessment of the Geomorphic Impacts of Forestry in British Columbia

Timber harvesting in British Columbia influences (a) forest hydrology; (b) fluvial geomorphology; (c) terrain stability; and (d) integrated watershed behavior. Impacts on forest hydrology are well understood and include increased average runoff, total water yield, increased storm runoff and advances in timing of floods. Stream channels and valley floors are impacted differently by fine sediment, coarse sediment and large woody debris transport. Terrain stability is influenced through gully and mass movement processes that are accelerated by timber harvesting. Impacts on integrated watershed behavior are assessed through disturbed sediment budgets and lake sediments. The Forest Practices Code (1995) is a significant step towards sustainable management of the land in so far as it attempts to minimize these geomorphic impacts of forest in B. C.

Figure 1. Terrestrial regions of British Columbia (5). N.B.—The mountain tops (tundra) and grasslands (bunchgrass) are equivalent to biogeoclimatic zones (4). The forest regions include 12 biogeoclimatic zones that have been aggregated.



INTRODUCTION

Fifty-five cents out of every dollar earned by British Columbia's exports derive directly or indirectly from the forest industry; 64% of British Columbia's 95 million ha are forest land (1). Not only does forestry have major importance for the province's economy but, in the context of concerns over the increasing human domination of Earth's ecosystems (2), provincial policy on timber harvesting has a strong bearing on the style and amount of land transformation in British Columbia. Land transformation is the primary driving force in the loss of biological diversity worldwide and there is increasing realization of the intimate connections between such activity and human health, the economy, social justice and human security (3). Therefore, the provincial forest industry has attracted international attention over the past decade. This paper will address the nature of the land transformation from a geomorphologist's perspective and will suggest policy implications for sustainable management of the land.

We must first clarify the variety of forest regions in the province and, second, distinguish between total forest cover and land available for timber harvesting.

BRITISH COLUMBIA'S FOREST REGIONS

There are 14 biogeoclimatic zones in British Columbia (4). Of these, only 2 (the Alpine Tundra and Bunchgrass zones) contain no forest cover. We direct attention to 3 major contrasting forest regions (Fig. 1), namely the rainforests, the spruce forests and the montane forests (5). The main distinctions between these forest regions are as follows:

i) The temperate rain forests of British Columbia are one of the most biologically productive environments on earth. Fifteen tonnes of biomass per ha yr^{-1} is typical and the richer sites produce over 30 tonnes yr^{-1}. The forest region includes 4 biogeoclimatic zones (Coastal Western Hemlock, *Tsuga heterophylla*; Coastal Douglas-fir, *Pseudotsuga menziesii*; Mountain Hemlock, *Tsuga mertensiana*, and Interior Cedar-Hemlock, *Thuja plicata*). Because wildfires are rare in this forest region, the majority of forest growth greater than 250 years old is found here. More than half of coastal forests are over 250 years old (55%) whereas only 6% of interior forests are that old (Fig. 2).

ii) The spruce forests are the boreal and sub-boreal forests that are part of the great band of spruce forests that rings the Northern Hemisphere. White spruce (*Picea glauca*), Engelmann spruce (*Picea engelmannii*), and Sub-alpine fir (*Abies lasiocarpa*) are the dominant trees—White spruce dominating the true boreal (or northern) forests and Engelmann spruce is common in the high forests. These 2 species hybridize on the mid-mountain slopes and are frequently referred to as hybrid spruce (*Picea engelmannii x glauca*). Spruces above 1500 m are normally Engelmann whereas those below 900 m are usually White (5).

Because of the unusually high incidence of forest fires at the turn of the century associated with building of railways and mineral prospecting, large areas of spruce and fir were destroyed. In their place, Lodgepole pine (*Pinus contorta*) and Trembling aspen (*Populus tremuloides*) fire succession forests have grown up. Consequently, the greatest single species volume of logging is accounted for by Lodgepole pine.

iii) The montane forests are warm, open forests of Douglas-fir *Pseudotsuga menziesii* and Ponderosa pine (*Pinus ponderosa*) that are found on the lower plateaus and mountain slopes in the lee of the Coast, Cascade and Columbia Mountains. Although the Ponderosa pine is of limited commercial value for forestry the Interior Douglas-fir is an important producer of sawlogs and pulpwood. The richest sites occur along floodplains and in riparian depressions.

TIMBER HARVESTING

The 61 million ha of forest cover contain about 52 million ha of what the Ministry of Forests considers productive forest land (Fig. 2). This is land that is biologically capable of producing commercial timber. When economic viability and environmental sensitivity are considered, only about 50% of the productive forest land is available for timber harvesting (c. 26 mill. ha).

During the 1990s, approximately 190 000 ha have been harvested per year. Most of this harvesting is by clear cutting, following stringent guidelines since 1995, under the principles and practices of New Forestry. New Forestry is "an attempt to define forest management with timber production as a by-product of its primary function: sustaining biological diversity and maintaining long-term ecosystem health" (6). These principles now underlie the provincial Forest Practices Guidelines (7).

Although many of the specific features of the New Forestry are strictly applicable only to that sub-set of British Columbia's forests that are ecologically similar to the forests of Washington and Oregon (8), the general principles have wide applicability.

GEOMORPHIC IMPACTS OF TIMBER HARVESTING

There are 4 distinct literatures that address the geomorphic impacts of forestry. They can be classified as *i*) forest hydrology; *ii*) fluvial geomorphology; *iii*) terrain stability; and *iv*) integrated watershed impacts.

Forest Hydrology

Although hydrology and geomorphology are discrete sciences it is impossible to evaluate geomorphic impacts without understanding basic hydrologic processes. Surface runoff controls fluvial geomorphology and groundwater conditions control slope stability. Hence, any change in hydrology induced by timber harvesting will have both direct and indirect effects on geomorphic processes.

For the purpose of this paper we will summarize the well-established effects of forestry activity on hydrology and proceed to consider the implications of hydrologic change on rivers and slopes in greater detail.

Forest harvesting increases average runoff and total water yield. Clearcutting increases storm runoff volumes and advances the timing of floods. Small and moderate early autumn storms are most affected. Logging roads increase storm runoff and advance timing of floods. Water quality deterioration has been widely documented (9).

These results are consistent for the whole of the Pacific Northwest and present no surprises. Road layout also influences the hydrologic response (10). Rain-on-snow effects seem to be accentuated by forest harvesting but perhaps the most distinctive responses recorded in British Columbia concern subsurface water behavior at Carnation Creek, an experimental watershed on Vancouver Island. Clearcut areas generated higher water tables; yarding resulted in locally increased groundwater. The net effect in the lower floodplain of Carnation Creek was to raise water tables significantly. Road construction generated three effects: below roads, groundwater was reduced; when roads were constructed on soil, no change occurred; water flowing down impermeable road surfaces generated landslides by increasing pore pressures above the roads.

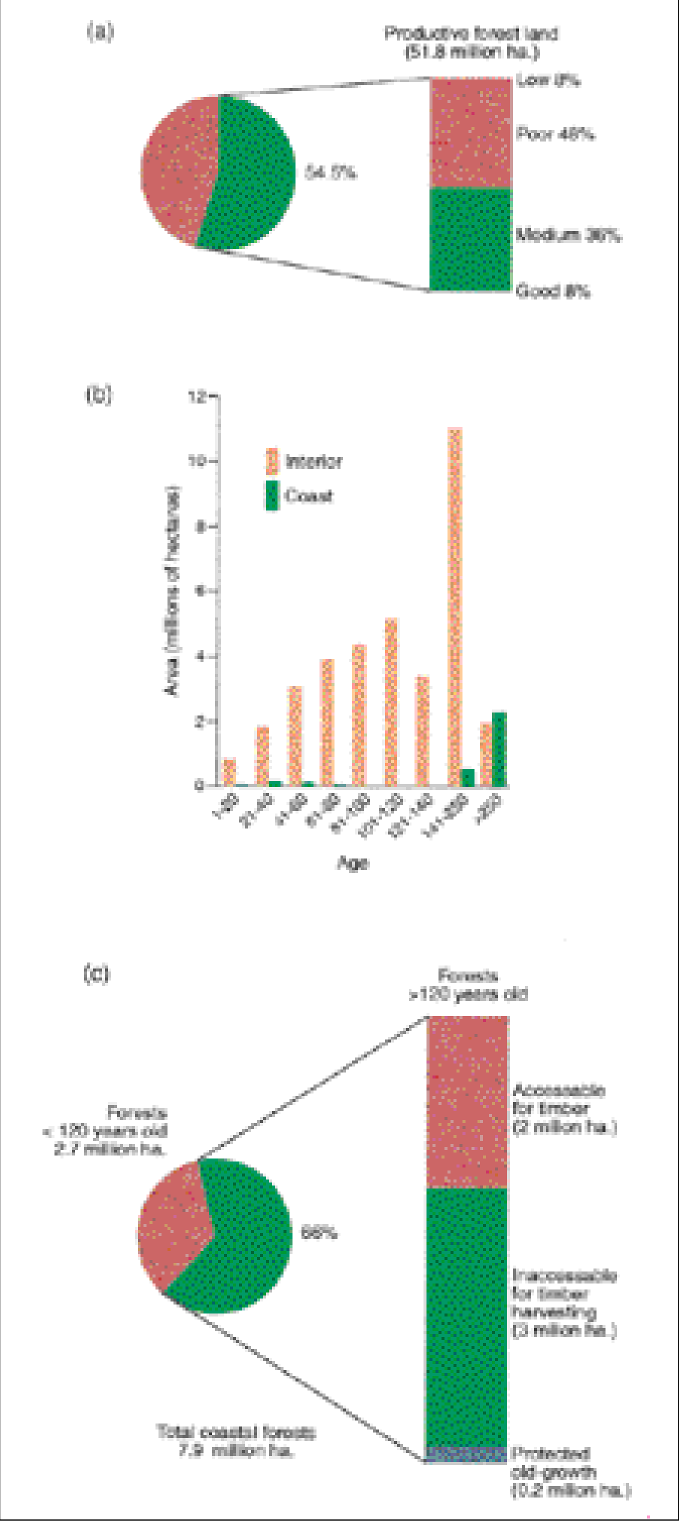


Figure 2. Productive forest land in British Columbia. a) Productive forest land as a percentage of British Columbia (54.5%) and its capability for the growth of trees. b) Trees older than 120 years of age as a percentage of productive forest land at the coast (rainforests) (66%); and c) their accessibility for timber harvesting. (Source: 45).

Fowler et al. (11) provide a summary of water quality and associated river water climate, especially temperature effects, following forest harvesting.

Effects of Timber Harvesting on Fluvial Geomorphology

Floods trigger cascades of physical processes that alter streams and riparian zones of mountain landscapes. Because forest cutting and road development can increase the delivery of water to soil and streams, especially in small and moderate storms, streamflow is increased, slope failures are induced, debris torrents and flows are initiated, sediment becomes more available to the stream and coarse woody debris also becomes entrained.

Church (in 10) has recommended that 3 kinds of sediment be considered separately (a) fine sediment, finer than 1 mm in diameter; (b) coarse sediment, coarser than 1 mm; and (c) large woody debris, whose "a" axis is longer than 10 cm. Although these are somewhat arbitrary size limits, fine sediment is primarily wash load; coarse sediment is confined to bed material and moves either in suspension or in traction and large woody debris behaves as distinctive bed material. Furthermore, Church proposes the consideration of processes of generation, movement and storage of these 3 kinds of sediment in relation to 4 land units *i*) hillslopes; *ii*) gullies; *iii*) stream channels; and *iv*) valley floors. It is probable that forest harvesting effects as reflected in the amounts and kinds of sediment mobilized differ on each of these 4 land units.

Figure 3. Timber harvesting impacts on stream channel. Note the high proportion of large, woody debris. Louise Island, Queen Charlotte Islands. Photo: O. Slaymaker.

In this section of our discussion we will consider stream channels and valley floors.

Stream channel impacts

Considerable attention has been directed to stream channel morphology (e.g. 12) because of implications for in-stream fish habitat and the prescient program of the British Columbia Ministries of Forests and Environment, Lands and Parks' Fish/Forestry Interactions Program (1981–1991).

Channel assessment procedures have been pioneered by Hogan and he was one of the first authors to measure the accumulation of large woody debris in British Columbia (13, 14). Large woody debris jam formation and deterioration appear to follow a 30–50 year cycle under pre-logging conditions, but logjam formation has accelerated since the commencement of logging in the 1960s.

Large woody debris is a crucial determinant of stream habitat, channel form, and sediment cascade dynamics (Fig. 3). Resource management of forested watersheds must appreciate the importance of large woody debris in order to minimize adverse impacts for all users.

Following logging, instream debris tends to be smaller and therefore more mobile. At least 3 factors account for the reduction in debris size noted by Hogan (13). First, the bucking of logs produces abundant small material on slopes adjacent to streams. Second, trees felled directly into the stream channel may fall on existing debris and break it into smaller pieces. Third, removal of newly added debris after logging is mandatory. This is often done at low flow by bucking large debris into smaller pieces which are then removed to the high water line. This material may subsequently be entrained by high flows.

These 3 practices increase the frequency of relatively small, unstable pieces of debris and remove large stabilizing elements. The net result is much greater large woody debris mobility. Downstream transport is therefore increased and debris tends to accumulate in fewer, much larger jams which are more widely spaced. In addition to this concentration effect, logging removes the future source of instream debris so that stable elements are only replaced after many decades.

The impact of these changes on channel morphology is substantial. Reduction in roughness due to the loss of steps and obstructions leads to increased local velocities. Morphological complexity is reduced as spatial variation in hydraulic competence declines. Width and depth are less variable, the frequency of pools and riffles declines, and there is a tendency for the pool area to decline and riffle area to increase as released sediment fills the pools (13). The reduction in morphological complexity and associated reduction in habitat diversity has been shown to have a significant impact on fish populations.

Tripp and Hogan discuss the effectiveness of the 1988 Coastal Fisheries Forestry Guidelines in reducing impact of forestry on instream fish habitat. The nature of large woody debris accumulation in channels influenced by logging; the nature of channel recovery processes and the assessment procedures for coastal channels have also been well documented in Hagan et al. (10).

Valley floors

Valley floors have an important ecological function as corridors for terrestrial organisms and as buffer zones for the protection of aquatic organisms from slope processes. This is often referred to as the terrestrial component of the hydro-riparian ecosystem (15). It is particularly important to maintain vegetation cover on the valley floors, to restrict rates of forest removal and to construct and locate roads carefully in such a sensitive zone. As a result, the 1988 Coastal Fisheries Forestry Guidelines included specific instructions on inappropriate streamside activities such as overharvesting, trespassing, machinery or trails in streams, burn piles in streams, stock-piling gravel in a stream or excessive clean-up on streams (Fig. 4). In addition, wide leave strips, selectively logged buffer strips and the retention of all nonmerchantable trees on valley floors have become standard guidelines. Tripp (in 10) reviewed compliance rate and determined an average of 70% compliance; however, compliance rate varied from 25–100%. He also demonstrated that for every 20% decline in compliance there was a 16-fold increase in damage to the valley floor.

The valley floor is commonly divided into "quiet" and "active" valley floor. The active valley-floor suffers frequent severe flood disturbance; the quiet valley-floor is rarely inundated. If

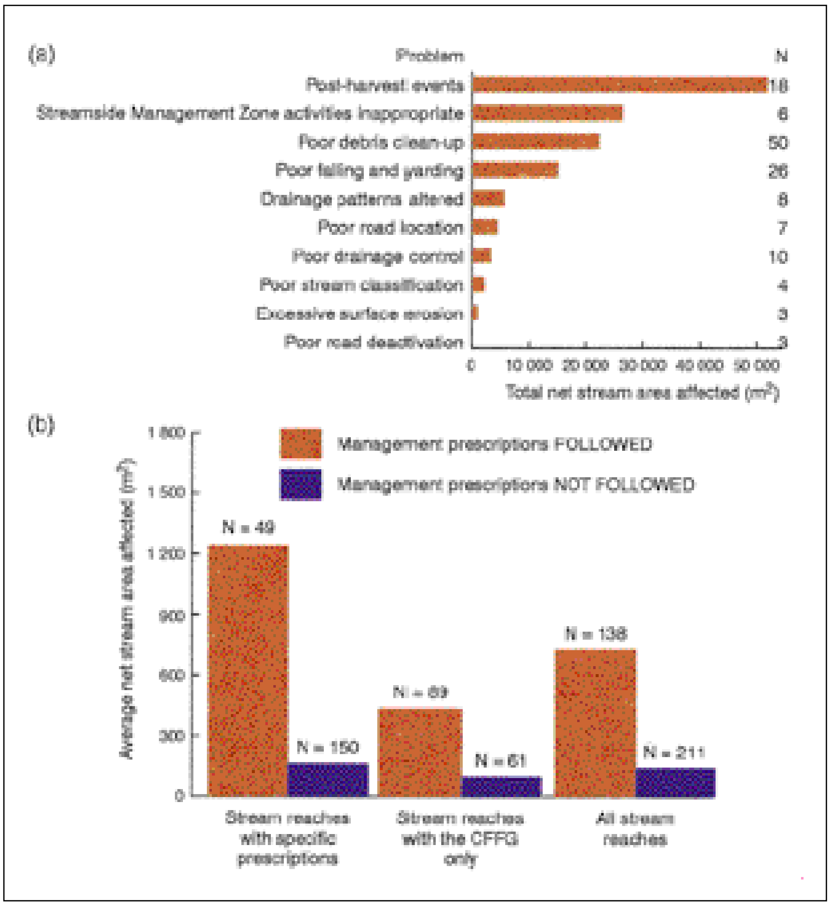


Figure 4. Impacts on stream channels resulting from noncompliance with the 1988 Coastal Fisheries Forestry Guidelines. a) Total net stream area (m^2) affected by each of 10 main problems and the number of times (N) each problem was observed (10). b) Average net stream area (m^2) affected as a result of compliance or noncompliance with the 1988 Coast Fisheries Forestry Guidelines and site specific prescriptions (10).

the magnitude and frequency of flood events change as a result of forest harvesting, the quiet valley-floor may be transformed into active valley-floor. The extent of the consequent geomorphic transformation is thus magnified where forest harvesting has been carried out on that previously quiet valley-floor.

Terrain Stability

The last two decades, commencing perhaps with a controversial editorial in the B.C. Professional Engineer (16), have seen a dramatic increase in research and debate over terrain stability in British Columbia. This lively debate has led to a demand for information about hazards and terrain stability (17), a recognition of ecological concerns associated with fish and forestry (18, 19) and speculation over possible implications of climate change (20). Because the province's population is growing at a rate of 2.5–3% per year, there is widespread pressure on the use of land (21). An exceptionally high magnitude, low frequency storm on the Queen Charlotte Islands in 1978 (22) was the trigger that galvanized 2 provincial ministries into action, i.e. the Ministries of Forests and Environment, Lands and Parks.

Slope failure, both naturally occurring and road-building related, causes productive forest site loss, increases industrial operating costs (to replace roads and bridges), interferes with fisheries by damaging habitat where fine sediment impinges on a productive watercourse and reinforces environmentalists' negative image of economic development activities in the province (23). Indeed, the whole concept of sustainable development may be viewed cynically by the public where there is lack of serious attention to sustaining the land base. The focus on terrain stability is therefore understandable in terms of the visibility of slope failure to the public; its evident impact on human security; its economic wastefulness; and its apparent contradiction of the principles of sustainability. Terrain stability is relevant to land use and resource development planning as well as to site specific project planning. Impacts of forestry on hillslopes and gullies are therefore considered next.

Gully impacts

Gullies constitute the links between hillslopes and stream channels. Debris slides, avalanches, flows and torrents are important agents of change; soil creep, surface wash and ravelling, fluvial transport and large woody debris are also featured. These processes are intensified following forest harvest but the woody debris and low water flow depths promote sediment deposition. This process of sediment recharge is thought to control the ultimate frequency of occurrence of debris flows-torrents that scour to bedrock. Large woody debris seems to be the regulator of this process and much effort has been directed towards the control of large woody debris in gullies, both during and after timber harvest (10).

Sediment output is greatest from torrented and slash cleared gullies; in the former by mass wasting and in the latter by fluvial channel erosion. The rate of sediment recharge drops off with time since the previous debris flow-torrent and the clearcut recharge rate drops off more rapidly than that of the old-growth gullies. It is suggested by Bovis et al. (in 10) that most gullies would be fully recharged within the 80 year time frame of a coastal forest harvest rotation (Fig. 5). The two torrented gullies illustrated were, respectively, 1 and 9 years since torrenting. Figure 5b illustrates the recharge process forming a fine sediment prism at the base of the sidewall (24). The frequency of torrenting within gullies depends in part on the recharge rate and is the subject of intensive research.

Mass wasting

Although a great variety of mass-wasting processes occurs in the B.C. mountains, e.g. bedrock slides and earthflows, the most direct impact of logging on hillslope processes is expressed in the magnitude and frequency of occurrence of debris slide-avalanche-flow-torrent processes (10). This suite of related processes occurs almost universally throughout the Canadian Cordillera (25) but much effort has been dedicated to demonstrating their acceleration under the influence of forest management (26–28). Chatwin et al. have provided valuable recommendations on management of landslide prone terrain (29).

Schwab, in a survey of the 1978 storm impacts in the Rennell Sound area of the Queen Charlotte Islands, noted that 4.3% of clearcut terrain, 1.9% of roads, and only 0.1% of forested slopes were disturbed by debris avalanches (22). Although the majority of these failures were small (250–1000 m^3), there remains considerable uncertainty about the distribution of even smaller slope failures that cannot be detected on aerial photographs.

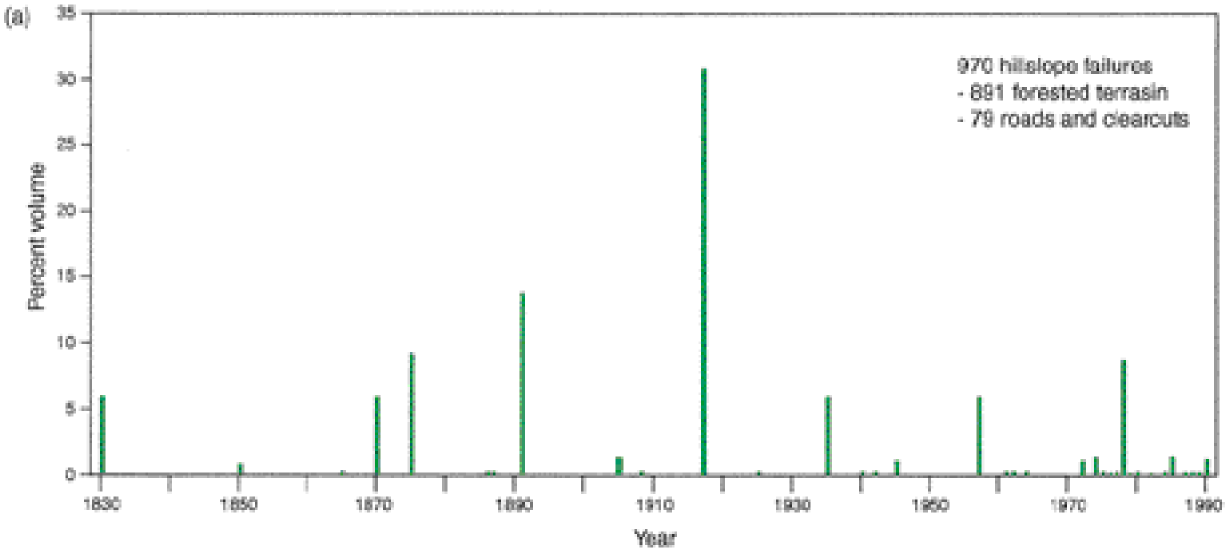
The effects of road building during forest harvesting is generally regarded as the dominant reason for accelerated slope failure in the Pacific Northwest (30), though Reid et al. were careful to distinguish between different kinds of roads and the relative roles of slope failure and surface wash (31). The main problems seem to arise from poor recognition of unstable terrain during road layout and poor recognition of road drainage requirements in road construction plans. Insufficient maintenance of road drainage structures is commonly the most significant factor in road-related failures.

a)

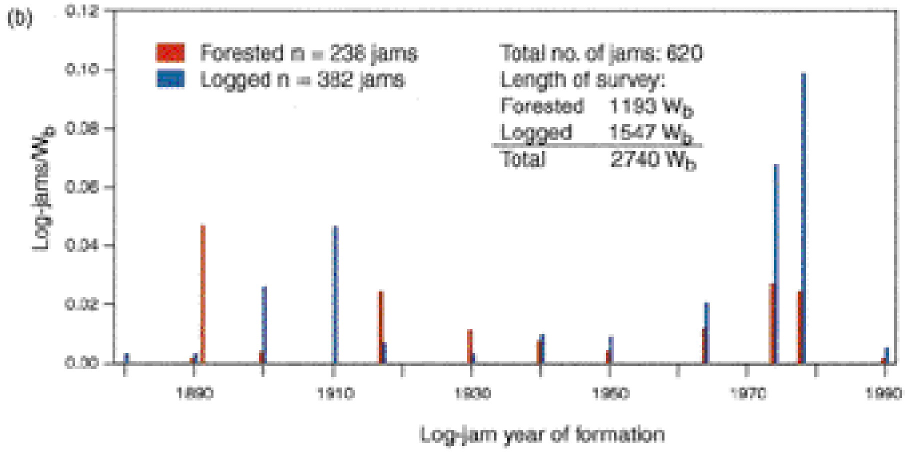
Figure 5. Debris-torrented gullies. a) In old-growth forest. Old-growth gully scoured to bedrock in previous winter (1991–92) Gregory Creek, Queen Charlotte Islands. b) In clearcut. Clearcut gully scoured to bedrock approximately 1984. Riley Creek, Queen Charlotte Islands. Photo: M. Oden.

b)

Figure 6. Historical record of large mass wasting and fluvial events in northwestern British Columbia (Note different time periods). a) % volume of sediment transported per year by debris slides-avalanches-flows-torrents (1830–1990) on Graham Island and in the Prince Rupert area (10).
b) Log-jam age distribution for forested and logged watersheds (1880–1990) in the Queen Charlotte Islands (10).



Schwab (in 10) made an analysis of 180 years of mass wasting in northern British Columbia with the aid of increment core analysis on trees affected by such events. He notes that 6 events (1875, 1891, 1917, 1935, 1957 and 1978) are responsible for 77% of sediment moved in debris slides, avalanches, flows and torrents over the 180-year period. The fact that 1978 is only the fourth largest of these events and is the only one that has occurred since the onset of extensive forest harvesting, raises difficult questions about the role of clearcutting (Fig. 6). The other interesting feature of these plots is the difference in timing of the mass wasting events and the log-jam formation. In part, this results from the



replacement of older jams (e.g. from 1917) by younger jams initiated in 1978.

Integrated Watershed Impacts

Two broad approaches to integrated watershed impacts can be identified: *i*) Sediment budgets; *ii*) Integrated lake sediments.

Sediment budgets

A sediment budget approach requires quantification of the sources of sediment, changes in sediment storage in the stream channel network and sediment discharge at the stream outlet. This can be expressed as a simple equation

$$1 = O + \Delta S \qquad \text{Eq. 1}$$

where 1 is input over time (t), O is output over time (t) and ΔS is change in stored sediments over the same time (t).

The equation can be applied at any time or space scale of interest, from an entire watershed to a single reach of stream channel. In practice, the equation is often applied separately for fine sediment, coarse sediment and large organic debris as the transport mode and storage of the three types of sediment are so different.

The largest watershed sediment budget reported in the literature is that for the 3500 km^2 Lillooet River basin in British Columbia (32). In practice, documentation of sediment systems unambiguously impacted by forestry activities has been limited to watersheds of a few tens of km^2 or smaller. This is both a tribute to the capacity of larger systems to absorb the effects of forestry activities and indicates that stored sediments may remain in transit within larger watersheds for decades and even centuries (33).

Roberts and Church, using estimates of process rates of sediment production from the literature of the Pacific Northwest USA, generated the first estimates of forest harvesting effects using a sediment budget approach (34). Since that study, more information from British Columbia has been compiled and the following "order of magnitude" rates can be plugged into the sediment budget equation.

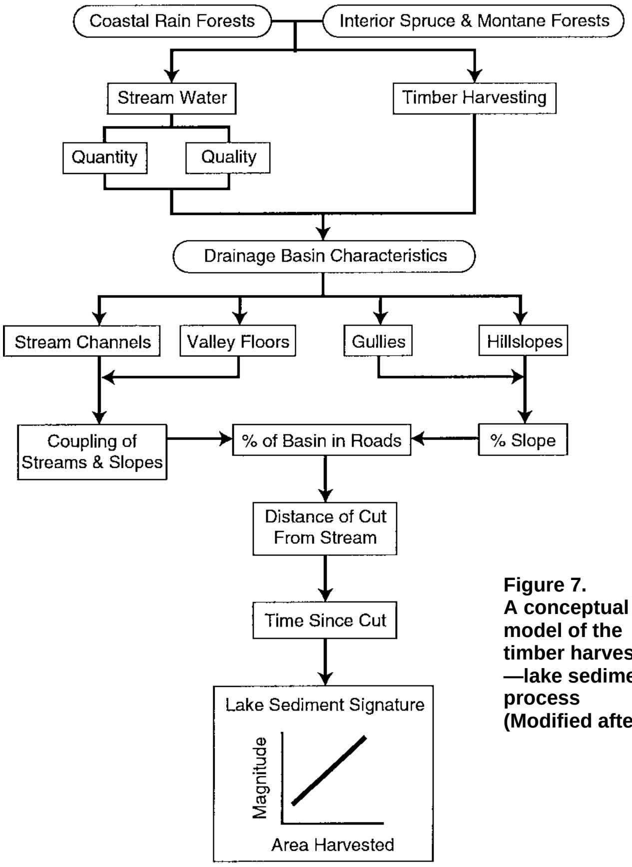


Figure 7. A conceptual model of the timber harvesting —lake sediment process (Modified after 46).

In unlogged forested areas, landslides, debris slides and debris flows produce c. 10^3 m^3 of sediment, surface erosion c. 10 m^3 and soil creep perhaps c.1 m^3 km^{-2} yr^{-1}. In harvested areas, debris slides and flows produce of the order of 10^4 m^3 km^{-2} yr^{-1}; unpaved roads, covering no more than 10% of a watershed, generate about 10^3 m^3 km^{-2} yr^{-1}. Abandoned, deactivated roads produce only 1% of that produced by unpaved roads. Bank erosion is estimated to generate 1–10 m^3 yr^{-1} km^{-1} length of channel.

But these numbers are averages for a wide range of conditions and are not broken down in terms of the 3 main varieties of sediment. They do, however, serve to alert forest managers to the 10-fold increase in sediment production associated with forest harvesting activity in British Columbia's mountains. They also show that debris flows and unpaved logging roads are the chief agents of this accelerated sediment production. Much work is still needed to provide reliable sediment budgets for the different forest regions of British Columbia.

Integrated lake sediments

Analyses of accumulated lake sediments can obviate some of the major limitations of drainage basin studies of land-use disturbance. Since lake sediments are a record of historical lake catchment conditions, an appropriate time scale of system response and recovery can be selected, and background conditions and long-term trends can be established (35). Another advantage of this approach is that it addresses the sedimentary system at the basin scale, thereby inherently taking into account the cumulative effects of all interacting processes within the catchment (Fig. 7), which are usually difficult to predict.

In Lake Whatcom, Orme investigated debris production under coniferous forests in northwest Washington (36). That record indicated that major debris production in the basin over the past 3400 years is a recurrent process. The record also suggested that the magnitude of debris production is not significantly altered by timber harvesting alone, but may be locally accentuated by slope failures associated with forest roads.

Arnaud assessed the effects of forestry on lacustrine sedimentation in 4 lakes on the west coast of Vancouver Island (37). The results indicated that increases in sediment yield coincided with forestry activities, as well as natural disturbances and other human activities. The study demonstrated that the lake sediment approach may be useful in monitoring the effects of forestry activities, although the sedimentary signature may be confounded by other catchment disturbances. Precise chronological control, rigorous sampling strategies, and careful choice of analysis techniques, were all identified as important factors for successful lake sediment research. Pack et al. applied ^{210}Pb dating to determine sediment accumulation rates to assess relative sedimentation impacts in Trout Lake, southern British Columbia (38). Variables describing the extent of land-use activities were back-calculated from a GIS database of the Trout Lake catchment area. These land-use variables were correlated with relative changes in sediment accumulation rates derived from ^{210}Pb dating. A relation was noted between sediment accumulation rates and the magnitude of forest road construction, especially the amount of road construction on erodible soils within 100 m of streams. Sediment pulses lasting for 5 to 7 years with accumulation rates 10 times greater than background, coincided with the observed anthropogenic disturbances in the lake catchment.

The precise factors that control the retention of a land-use signature in lake sediments are the subject of ongoing research (Fig. 7).

PERSPECTIVES FOR THE COMING DECADE

Slope failure has become a central concern and has generated implications for the whole natural hazards problematique. A cursory glance at the topics of recent publications in the terrain stability field in British Columbia reveals the following:

- *i* terrain stability mapping;
- *ii* terrain inventory;
- *iii* terrain engineering analysis;
- *iv* applications of Geographic Information Systems to terrain stability;
- *v* guidebooks for the Forest Practices Code;
- *vi* watershed management and terrain stability;
- *vii* terrain stability in sediment budget studies;
- *viii* river response to terrain instability;
- *ix* effects of terrain instability on fish;
- *x* slope instability predictive studies

These activities are now judged to be highly relevant to the economic and political future of the province. The British Columbia Ministry of Transportation and Highways provides interesting perspectives over the developments of this decade and a half (39). As a result of this activity there has been an increased focus on low magnitude, high frequency events (40). At the same time, recognition of the socioeconomic context in which this work has been occurring has led to a gradual awareness of the importance of risk concepts (41). These developments have led inexorably to involvement with the hazard communication field (42). Hogan et al., Bobrowsky, and Clague et al. appear to be some of the first Canadian environmental scientists to respond to this challenge (10, 43, 44).

CONCLUSION

Excellent environmental science has been practiced for many years in British Columbia. Nevertheless, as in many administrations around the world, damages and costs from natural hazards have continued to escalate. The intensification of forest harvesting during the 1960s–1980s has contributed to this escalation of socioeconomic and ecological costs. Lack of progress has resulted from the isolation of individual groups of scientists from each other and from the independence of various levels of government that have the legal responsibility for environmental management. The gap between environmental scientists' understanding of the phenomenon, social scientists' understanding of the dimension of associated risk, and government professionals lacking a consistent interagency policy continues to exist. The Forest Practices code of British Columbia is a significant step forward towards sustainable management of the land (7). There remain, however, large questions of social policy, interagency discussion and broader societal concerns. Extensive contesting of the Code has already commenced.

References

1. Canadian Council of Forest Ministers 1997. *Compendium of Canadian Forestry Statistics.* Ottawa, 233 pp.
2. Vitousek, P.M., Mooney, H.A. Lubchenco, J. and Melillo, J.M. 1997. Human domination of Earthís ecosystems. *Science 277*, 494–499.
3. Lubchenco, J. 1998. Entering the century of the environment: a new social contract for science. *Science 279*, 491–497.
4. Meidinger, D. and Pojar, J. (eds). 1991. *Ecosystems of British Columbia*. B. C. Ministry of Forests: Victoria. Canada.
5. Cannings, R. and Cannings, S. 1996. *British Columbia: A Natural History*. Greystone Books: Vancouver, B. C.
6. Lertzman, K. 1970. What's new about New Forestry? *Forestry Planning Can. 6*, 5–6.
7. B. C. Ministry of Forests 1995. *A. Mapping and Assessing Terrain Stability Guidebook. B. Gully Assessment Procedure Guidebook. C. Soil Conservation Guidebook. D. Hazard Assessment Keys for Evaluating Site Sensitivity Guidebook. E. Coastal Watershed Assessment Procedure Guidebook. F. Interior Watershed Assessment Procedure Guidebook*. Forest Practices Code of British Columbia, Victoria, B. C. Canada.
8. Kimmins, J.P. 1990. Designing disturbance in the B. C. forest landscape. In: *Forests-Wild and Managed*, Pearson, A.F. and Challenger, D.A. (eds). University of British Columbia, Vancouver, Canada, pp. 177–192.
9. Brownlee, M.J., Shepherd, S.G. and Bustard, D.R. 1988. Some effects of forest harvesting on water quality in the Slim Creek watershed in the central interior of B. C. *Can. Tech. Rep. Fish. Aquatic Sci. 1613*, 41 pp.
10. Hogan, D.L., Tschaplinski, P.J. and Chatwin, S. (eds). 1998. *Applying 20 Years of Coast Research*. B. C. Ministry of Forests, Land Management Handbook 41.
11. Fowler, W.B., Anderson, T.D. and Helvey, J.D. 1988. *Changes in Water Quality and Climate after Forest Hazards in Central Washington*. USDA Forest Service Research Paper PNW-RP-388, Portland.
12. Toews, D.A. and Moore, M.K. 1982. The effects of three streamside logging treatments on organic debris and channel morphology. In: *Carnation Creek Workshop: A 10 Year Review*, Hartman, G.J. (ed.). Pacific Biological Station, Nanaimo, pp. 129–153.
13. Hogan, D.L. 1987. The influence of large organic debris on channel recovery in the Queen Charlotte Islands. In: *Erosion and Sedimentation in the Pacific Rim*, Beschta, R.L. et al. (eds). IAHS Pub. 165, 343–354.
14. Hogan, D.L. 1989. Channel response to mass wasting in the Queen Charlotte Islands In: *Proc. Watershed '89, Conference*, USDA Forest Service R10-MB-77, 125–144.
15. Clayoquot Sound Scientific Panel 1995. *Sustainable Ecosystem Management in Clayoquot Sound* Report 5. Cortex Consultants Inc., Victoria, 296 pp.
16. Farquharson, K.G., Russell, S.O. and Skermer, N.A. 1976. Provincial natural hazards policy-an editorial. *B. C. Professional Engineer*, January, 4.
17. Ryder, J.M. and Howes, D.E. 1984. *Terrain Information, a User's Guide to Terrain Maps in British Columbia*. B. C. Ministry of Environment, Victoria, B. C. Canada.
18. Church, M. 1983. *Concepts of Sediment Transfer and Transport on the Queen Charlotte Islands*. Fish/Forestry Interaction Program-Working Paper 2/83, Vancouver, B. C.
19. Hartman, G.F. and Scrivener, J.C. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. *Can. Bull. Fish. Aquatic Sci*. 223.
20. Slaymaker, O. 1990. Climate change and erosion processes in mountain regions of western Canada. *Mountain Res. Develop. 10*, 183–195.
21. Eisbacher, G. 1982. Slope stability and land use in mountain valleys. *Geosci. Can. 9*, 14–27.
22. Schwab, J.W. 1983. *Mass Wasting: October–November 1978 Storm, Rennell Sound, Queen Charlotte Islands, British Columbia*. Land Management Report No. 91. B. C. Ministry of Forests and Lands. Canada.
23. Chatwin, S.C. and Smith, R.B. 1992. Reducing soil erosion associate with forestry operations through integrated research, an example from coastal British Columbia. In: *Erosion, Debris Flows and Environment in Mountain Regions*, Walling, D.E., Davis, T.R. and Hasholt, B. (eds). International Association Hydrological Sciences Publication No. 209, 377–385.
24. Oden, M.E. 1994. *Debris Recharge Rates in Torrented Gullies in the Queen Charlotte Islands*. MSc. Thesis, Department of Geography, University of British Columbia, Vancouver. Canada.
25. Van Dine, D.F. 1984. Debris flows and debris torrents in the southern Canadian Cordillera. *Can. GeoTech. J. 22*, 44–68.
26. O'Loughlin, C.L. 1972. A preliminary study of landslides in the Coast Mountains. In: *Mountain Geomorphology*, Slaymaker, O. and McPherson, H.J. (eds). Tantalus: Vancouver, 110–111.
27. Rood, K.M. 1990. *Site Characteristics and Landsliding in Forested and Clearcut Terrain, Queen Charlotte Islands, B. C.* B. C. Ministry of Forests, Land Management Report No. 64. Canada.
28. Jakob, M. The impacts of logging on landslide activity at Clayoquot Sound. *Catena*, (in press).
29. Chatwin, S.C., Howes, D.E., Schwab, J.W. and Swanston, D.N. 1994. *A Guide for Management of Landslide Prone Terrain in the PNW*. B. C. Ministry of Forests Land Management Handbook 34, Victoria, B. C. Canada.
30. Reid, L.M. and Dunne, T. 1984. Sediment production from forest road surfaces. *Water Resources Res. 20*, 1753–1761.
31. Reid, L.M., Dunne, T. and Cederholm, C.J. 1987. Application of sediment budget studies to evaluation of logging road impact. *J. Hydrol. 20*, 49–62.
32. Jordan, P. and Slaymaker, O. 1991. Holocene sediment production in Lillooet River basin, B. C. *Geogr. Phys. Quatern. 45*, 45–57.
33. Trimble, S. 1995. Catchment sediment budgets and change. In: *Changing River Channels*. Gurnell, A. and Petts, G. (eds). John Wiley. Chichester, 207–215.
34. Roberts, R.G. and Church, M. 1986. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. *Can. J. Forestry Res. 16*, 1092–1106.
35. Slaymaker, O. and Spencer, T. 1998. *Physical Geography and Global Environmental Change*. Adison Wesley Longman: Harlow.
36. Orme, A.R. 1990. Recurrence of debris production under coniferous forest, Cascade foothills. In: *Vegetation and Erosion*, Thornes, J.B. (ed.) John Wiley. Chichester.
37. Arnaud, E. 1997. *Effects of Forestry on Lake Sedimentation*. MSc Thesis, Department of Geography, University of British Columbia. Canada.
38. Pack, R.T., Gubala, C.P. and Lang, D. 1997. *Assessment of Relative Sedimentation Impacts, Trout Lake basin*, B. C. FRBC. Project No. KB96041-RE. Unpublished Report.
39. B. C. Ministry of Transportation and Highways 1996. *Natural Hazards in British Columbia*. B. C. Ministry of Transportation and Highways, Geotechnical and Materials Branch, Victoria, B. C. Canada.
40. Fannin, R.J. and Rollerson, T.P. 1993. Debris flows: some physical characteristics and behaviour. *Can. Geotech. J. 30*, 71–81.
41. Fell, R. 1994. Landslide risk assessment and acceptable risk. *Can. Geotech. J. 31*, 261–272.
42. Plough, A. and Krimsky, S. 1987. The emergence of risk communication studies: social and political context. *Sci. Tech. Human Values 12*, 4–10.
43. Bobrowsky, T. (ed.). 1992. *Geologic Hazards in British Columbia*. B. C. Geological Survey Branch, Open File 1992-15, Victoria, B. C. Canada.
44. Clague, J.J., Turner, R.J.W. and Groulx, B.J. 1997. Reinventing the geological map: making geoscience more accessible to Canadians. *Geosci. Can. 24*, 161–172.
45. Environment Canada and B. C. Ministry of Environment, Lands and Parks 1993. *State of the Environment Report for British Columbia*, 127 pp.
46. Miller, L.B., McQueen, D.J. and Chapman, L. 1997. Impacts of forest harvesting on lake ecosystems. *B. C. Environ.Wildlife Bull. B-84.*

Olav Slaymaker is professor of geography and Director of the Liu Centre for the Study of Global Issues at the University of British Columbia. His research over the past 30 years has focussed on the geomorphology, hydrology, and environmental sustainability of mountain environments, especially those of western Canada. He has written and edited 16 books and has written over 90 research papers. His address: Department of Geography, The University of British Columbia, 1984 West Mall, Vancouver, BC, Canada V6T 1Z2.
E-mail: olav@geog.ubc.ca