

Hydrological Effects of Forest Harvest in the Pacific Northwest

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reporting to the Central Coast Land and Resource Management Plan

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Preface

The purpose of this report is to review experience on the Pacific Northwest coast of North America of the hydrological effects of forest harvesting. "Hydrological effects" is broadly interpreted to include consideration of water quality, sedimentation and stream channel stability. The intention is to contribute toward the improvement of forest land management by making the lessons from the experience available to inform the development of effective riparian land management procedures. The report is based on an earlier review that formed the basis for the hydrological recommendations of the Scientific Panel for Sustainable Forest Practices in Clayoquot Sound.

The coauthor of this report (Eaton) conducted literature reviews and wrote the section on the occurrence of bankfull stream discharge, the results of which underlie the definition of floodplains adopted in this report. Professor R.D. Moore provided important help in updating the literature review from 1996 to 2001. Craig Nistor gave a thoughtful review of the discussion on sediment-related effects. This help is gratefully acknowledged. However, the opinions expressed in the paper remain those of the senior author.

Readers interested primarily in the summary conclusions of the literature review and in the consequent recommendations may proceed directly to page 31 and may read pp.31 through 39 as an executive summary of the report.

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The Hydrological Effects of Forest Harvest in the Pacific Northwest

Introduction

This report reviews experience in the coastal part of the Pacific Northwest region of North America of the effects of forest harvest upon hydrological regime and water quality, upon sediment mobilisation and delivery to stream systems, and their impacts upon hydriparian habitat and ecosystems. For purposes of review, the “Pacific Northwest” is understood to encompass the forested Pacific slope between northern California and southern Alaska (see Church, 1998a). This forested coastal region of broadly similar marine climate is distinguished by the massive size and remarkable longevity of the principal coniferous tree species (Waring and Franklin, 1979). Climate and physiography impose a distinctive hydrological regime throughout the region. In consequence, practice and effects of forest management, including road building and forest harvest, are also in many respects regionally distinctive. These circumstances dictate that a review of land management impacts upon hydrology and sedimentation be regional in character. Knowledge of the environment and patterns of environmental disturbance within the Pacific Northwest are at least qualitatively indicative of conditions that may be expected at any particular place within the region.

The report has two major sections. The first gives a review of hydrological and sediment-related effects of forestry practices in the coastal Pacific Northwest. The second makes an interpretation of hydrological and sediment-related effects and presents recommendations for management of hydrology and hydriparian zones, based on the documented experience, that should lead to sustainable land use. These recommendations are similar to ones made in the final report of the Scientific Panel for Sustainable Forest Practices in Clayoquot Sound¹.

¹ Those recommendations are contained in the Panel’s Report 5, “Sustainable ecosystem management in Clayoquot Sound: planning and practice”, April, 1995: 296pp.

Forest land use effects in the coastal Pacific Northwest

Hydrological impacts of West Coast forestry practices

Introduction

The impact of forestry practices on hydrology has been investigated for most of this century (Rodda, 1976). Work in the Pacific Northwest, however, has occurred mainly since about 1950, by which time the major impacts of the pioneer logging period were abundantly evident. Studies have been focussed upon changes in water yields, peak flows and low flows following some treatment, usually consisting of clearcut harvesting and/or road building. Relatively little work has been undertaken in British Columbia. To estimate the probable impact of west coast forestry practices, one is forced to rely in major degree upon work done in the American states of Washington and Oregon.

Of the relevant studies considered herein, almost half have been conducted in the Cascade Range of western Oregon, of which half again were located in the H.J. Andrews Experimental Forest of the United States Forest Service. Other studies have been located in southwestern British Columbia, Washington, northern California, and the Alaskan "panhandle".

Most studies have used a paired approach in which "treatment" and "control" watersheds are identified and "calibrated" (i.e., hydrological conditions are observed and compared) during a pretreatment period (Rodda 1976). Calibration data are used to assess the rate and direction of hydrologic change following treatment, usually by comparing observations in the treatment watershed with predictions relative to the control obtained by simple linear regression of the calibration period data. The calibration period typically has varied from as few as three years to as many as ten. This type of study is generally limited to smaller watersheds, usually on the order of 100 ha or less. A variant of the approach is found in Carnation Creek, the major British Columbia experimental study. Two small watersheds within the Carnation Creek drainage are paired in the way described above. However, the control for this pair is also used as a control watershed to examine the changes within the entire drainage basin. That is, the control is nested within the larger experimental or treatment watershed. In the most recent studies, more sophisticated statistical analyses have begun to appear in the attempt to refine interpretation of the observations and to extend the results to multi-watershed comparisons.

Large watersheds have been relatively little studied. Some cases have been examined by comparing flow records with cumulative areas harvested in the basin. These studies tend to cover quite long periods, examining changes over several decades of harvesting, and this is one reason why they are rare. Another is the difficulty within this study design to ascertain, with certainty, that observed hydrological trends are the outcome simply of forest harvest.

Water yield

In the context of forest hydrology, water yield is defined as the total volume of surface runoff, measured as stream discharge, that leaves a drainage area. It represents the amount of precipitation that falls within the basin which is not lost either to evapotranspiration or to groundwater flow. In many studies, considerable efforts have been made to select for investigation basins from which groundwater discharge is expected to be minimal, so the net effect after harvest is the rebalancing of runoff and evaporation. Changes in water yield resulting

from deforestation have been extensively examined and have produced fairly consistent results. Studies have examined changes in water yields over entire years and over specific months and seasons.

Deforestation increases water yield. The increased yield occurs primarily in response to decreased evapotranspiration (Rothacher, 1965, 1970; Harr et al., 1982; Keppeler and Ziemer, 1990), although changed patterns of storm and snowmelt runoff may also influence the outcome. In a review of 94 catchment experiments worldwide examining water yield changes due to deforestation and afforestation, Bosch and Hewlett (1980) demonstrated broadly consistent results. Most of the catchments were between 50 and 100 ha in area, with an absolute range of 1 to 2500 ha. Water yields were found to increase in proportion with the removal of the forest cover. They reported that removal of 10% of a coniferous forest cover caused an average increase of 40 mm in water yield (measured as water depth over the entire drainage area). Removal of 10% of a hardwood forest cover resulted in a 25 mm average increase in water yield, and removal of 10% of a brush or shrub cover resulted in a 10 mm increase. These results are based on annual data and do not reflect seasonal variations between the various types of cover. They also confound plant water consumption patterns with canopy interception effects. The data are quite widely varied, and the numbers can be interpreted only as approximate indicators of the amount and direction of change resulting from deforestation.

Bosch and Hewlett also reported that changes in water yield are greatest in areas with high mean annual precipitation, and that the individual years with the largest increases in water yields correspond to the years with the largest quantities of precipitation. However, it was noted that increases in water yield in regions of high precipitation were less persistent than those in low precipitation regions. This was attributed to the relative rates of vegetation regrowth in the respective environments. The observations can be rationalized by realizing that in areas and years with low precipitation, the change in forest cover largely affects the magnitude of the potential evapotranspiration deficit, whereas in humid regions and during wet years the reduced actual evapotranspiration leaves additional water available for runoff.

The results reported by Bosch and Hewlett are derived from a wide range of environments. Thus the consistency of the increases in water yield following deforestation (and decreases in water yield following afforestation) should be evident in most, if not all environments. However the data are not suitable to assess the precise impact of deforestation in a particular region. Hetherington (1987) reported that, of 10 catchment experiments performed in Canada, 9 produced significantly smaller changes in water yield than predicted by Bosch and Hewlett's mean results (based on percent reduction in forest cover). He speculated that "This might be partly due to the limited soil water storage capacities and rapid drainage characteristics of the thin soils found in many forested areas of Canada." (p.192). It might also be due to peculiarities of hydrological regimes that include significant seasonal snowfall and melt or, as on the west coast, regimes with a strong winter maximum in precipitation.

At Carnation Creek on Vancouver Island² it was observed that, on a 90% clearcut tributary, annual water yield increased by 14% in the years immediately following harvest (Hetherington 1982). However, for the entire basin, which was subject to 40% clear cutting in total, annual water yield apparently did not change significantly (Hetherington, 1988). The drainage area of the entire creek is 10.1 km², or 1010 ha, which is dramatically different than the 145 and 254 ha controls. In addition, the nested experimental design may have adversely affected the analysis for Carnation Creek in that effects of aspect, precipitation distribution and the local hydrologic

conditions are not subsumed in the comparison between the control basin and the entire basin. In particular, the entire basin includes a considerable floodplain whereas the control watersheds are entirely steep land.

Another result from British Columbia is worth note, even though it does not derive from the coastal region as defined for this review. Cheng (1980) reported changes in water yield in the area west of Salmon Arm following a severe forest fire that destroyed more than 60% of the forest in a small watershed (18.1 km² or 1813 ha). The forest consisted of an altitudinally zoned sequence of interior stand types ranging from Ponderosa pine to Subalpine fir and including substantial interior Douglas fir stands. Such a fire might be considered to have effects on the runoff similar to those of clearcut logging followed by slash burning, a common experimental treatment. Increases in water yield of about 24% for the period from April to August were reported over 4 years following the fire. Increases were attributed to the reduced evapotranspiration resulting from the burning of the forest and to earlier, more rapid snow melt.

Monthly water yields for April and May were increased after the fire, as were the yields for August, September, October and November. Yields for June and July were reported to be variable in the four years following the fire. Cheng attributed this seasonal pattern to decreased transpiration during the growing season, which produces progressively greater contrasts in soil moisture as the growing season advances, thus creating the most significant increases in water yield in the period from August to November.

The strength of these conclusions is limited by the relatively short period under study. The entire data set consists of only 3 years of calibration data before the fire followed by 4 years of data after. In addition, the control basin has a drainage area of 143 km², which is significantly larger than that of the study basin, so that the pairing of the basins was somewhat imperfect. However, the study does confirm that one can expect water yields to increase following deforestation in southern British Columbia.

Extensive experimental work has been conducted in western Oregon in the H.J. Andrews Experimental Forest. In a major study, three watersheds were selected for observation. HJA1, a 96 ha basin, was subject to clearcutting (without roads) between 1962 and 1966 after 10 years of calibration data had been collected. HJA2, a 60 ha basin, was used as a control. HJA3 was harvested in clearcut patches covering a total of 25% of the 101 ha basin (Harr 1983, Hicks et al. 1991). Both treated watersheds were subject to slash burning after logging. Annual water yields increased in HJA1 by 540 mm in 1965 (at which time 90% of the area had been clear cut) over a long term mean of about 1400 mm -- an increase of 40%. After that, annual yields decreased at a rate which led Harr (1983) to predict, on the basis of linear regression, a return to

² Carnation Creek is located on the southeast shore of Barkley Sound, on the west coast of Vancouver Island. It is the only site in coastal British Columbia to have been subjected to detailed hydrological study. Details may not be transferred uncritically to other sites on the coast since Carnation Creek is a small basin with a somewhat limited range of elevation and exposure, which does not match the physiography of most coastal drainage basins.

preharvest conditions after 25 to 30 years. However, a new analysis by Hicks et al. (1991) indicated that flows stabilized after about 1980 at about 25% above prelogging values. Their prediction is that water yield might return to prelogging values after about 50 years. Annual water yields for HJA3 were higher than before logging by between 100 and 200 mm, or about 8 to 16% of the annual total (Hicks et al. 1991). But water yield still remained somewhat elevated

more than 20 years after the treatment. Harr (1983) reported that most of the increase in water yield occurs during the wettest months, between October 1 and March 31. During this time, approximately 80% of the annual precipitation and runoff is observed.

In the Pacific Northwest, low flows in summer present a problem, especially from the perspective of salmonid habitat. Harr (1983) reported that only 5% of the annual water yield in the HJA watersheds occurs between July 1 and September 30. To examine the impact of deforestation on summer water yields, Hicks et. al. (1991) looked at the monthly water yield for August in HJA1 and HJA3. HJA1 showed increases in August monthly water yields for the first 8 years following clear cutting. Water yields were then observed to be lower than predicted for 18 of the next 19 years. In contrast, HJA3 exhibited monthly water yields for August that were higher than predicted for 16 years following patch cutting. In general, water yields for August in HJA3 have remained at or above the “expected” values based on preharvest calibration for the entire period of record from 1966 to 1988 (Hicks et. al. 1991). These observations have been explained by reference to particular characteristics of the two watersheds. Red alder has dominated the regrowth in the extensive riparian zone of HJA1. In contrast, the narrow valley of HJA3 has prevented extensive hardwood colonization in the limited riparian zone. In addition, HJA3 was impacted by debris flows in 1961, 1964 and 1965 which removed sediment deposits upon which hardwoods could grow (Hicks et. al. 1991). Hicks et. al. concluded that, because riparian hardwoods have higher stomatal conductances than do conifers, they would use more water than an equivalent cover of conifers, thus reducing the summer water yields. They speculated that the August monthly water yields may return to the expected values only after the conifer canopy closes over the phreatophytic hardwoods, which may occur after 40 to 60 years.

Other watersheds in the H.J. Andrews Experimental Forest have also exhibited increased water yields following clear cutting. In watersheds HJA6 (13 ha) and HJA7 (15.4 ha), which were clear cut and shelterwood cut respectively, annual water yields following harvest of 130-year-old second growth Douglas fir increased on average by 380 mm (30% of the former annual total) for HJA6, and 200 mm (22%) for HJA7 over the first four years following logging. Elsewhere in southern Oregon and neighbouring northern California, Harris (1977) and Keppeler and Ziemer (1990) have reported similar annual and summer increases in runoff following forest harvest.

Thus while it appears to be generally true that deforestation leads to increased water yields, it cannot be concluded that streams will not be subject to lower than average flows following logging during the critical summer months. While Cheng (1980) reported increased water yields during the growing season, one must consider that data are presented for only 4 years after the fire, whereas Hicks et. al (1991) reported that the effect of riparian hardwood colonization was recognised only 8 years after logging. These cases imply that time scales of 4 to 10 years following logging are not sufficient to determine the full impact of deforestation on stream flows. Unfortunately, this finding disqualifies many studies as significant indicators for long term forest and water management planning.

Contradictions of the generalisation on increased annual water yield can also be found. Harr (1983) reported small decreases in annual water yield in two patch-cut basins in the Fox Creek experimental watershed, near Portland, Oregon, for which an increase of 100 to 150 mm had been expected. The loss of water was ascribed to reduced interception of fog after tree removal. Harr (1982) demonstrated that net precipitation under forest cover in the area was indeed greater than that in open clear cuts, and that “fog drip eliminated by removal of trees during logging appears to explain why expected increases in postlogging annual water yield were not

observed.” (Harr 1982, p.788; see also Rothacher, 1963). This finding emphasizes that local conditions are important in determining how a watershed will respond to deforestation. The explanation may be germane to the frequently foggy outer coast and islands of British Columbia.

No mention has been found of specific impacts on water yield due to road construction. The primary influence of road building is on the timing and magnitude of runoff events. Water yield is predominantly controlled by evapotranspiration changes, with additional effects being produced by change in snow accumulation and fog interception. Consequently, it is believed that road construction alone will not significantly impact the net input of precipitation to the watershed, nor will it change the net runoff significantly.

Storm flow

The impacts on storm flows of clearcutting and road building have been extensively studied, both individually and in combination. The results vary widely, depending on a large number of factors including the type of event (rain; rain-on-snow; snow melt), the characteristics of the drainage basin, and the location in the basin of roads and cutblocks. Most attention has been paid to the magnitude of peak discharge, but consideration has also been made of event response time, event water volume, and hydrograph shape. The earliest reference to observations in the Pacific Northwest apparently is by Anderson and Hobba (1959), but significant experimental work was initiated mainly after 1960.

A study in the Alsea river basin in the Oregon Coast Range revealed that both roads and clearcutting seemed to increase peak flows (Harr et. al. 1975; cf. also Harris, 1977). While the effect of road building was examined over only one year, it was observed that peak flows increased significantly where roads occupied at least 12% of the watershed. The maximum increase in peak flow reported by Harr et. al. occurred after 82% clearcutting. It was also reported that the largest increases in peak flows occurred during the autumn, when soil moisture differences caused by deforestation would be at a maximum. These changes were attributed in the case of road building to reduced infiltration on compacted road surfaces and the increased drainage efficiency represented by road surfaces, ditches, and culverts. It was hypothesized that road surfaces on the one hand produce more excess surface water and, on the other hand, move that water to stream channels more quickly than if the roads were not present. In another study, Harr et al. (1979) reported stormflow runoff increases of up to 50% following shelterwood and clearcutting, and 11% following patch-cutting in small watersheds in southwestern Oregon (the Coyote watersheds). Similar results were obtained by Wright et al (1990) in northwestern California (Caspar Creek). In southern interior British Columbia, Cheng (1989) reported a significant increase in annual peak flows after 30% clearance of a 34 km² drainage basin, a considerably larger basin than that studied in most research investigations.

The foregoing results are based on a linear regression approach to comparing peak flows whereby calibration data are used to construct an equation for predicting the peak flows in the treatment watershed. This technique has been generally used in studies of peak flow changes but it should be noted that it is greatly influenced by exceptional individual events.

Regarding the influence of compacted road surfaces, Whipkey (1967) had noted that, in the eastern USA, subsurface routing of flood waters through soil “macropores”, not overland flow, is the major source of storm runoff in forests. Cheng et al. (1975), on the basis of a study in coastal southern British Columbia, also stated that “stormflow mainly results from flow through

subsurface pathways.”(p. 544). They further asserted that “soil channels (macropores) exist in most forest soils which provide pathways of low resistance to subsurface stormflow.” (p. 545). Interception of flow through these subsurface pathways by road cutbanks (cf. Megahan and Clayton, 1983) and its redirection into the surface drainage network probably affects the timing of runoff peaks to a much larger extent than the reduced infiltration rates related to surface compaction because a much larger volume of water moves through subsurface routes.

The results of Harr et al. on the seasonal occurrence of peakflow increases were corroborated by Ziemer (1981), who also reported that the maximum increases in stormflow following clearcutting occurred in the autumn. He attributed the phenomenon to soil moisture differences by the same argument used to explain variations in monthly water yields by Cheng (1980). He further reported that clearcutting affected only the smallest 25% of peak flows, while the larger flows were unaffected and that roads covering 5% of the watershed produced no detectable change in peak flows. King and Tennyson (1984) likewise examined the effect on peak flows resulting from road building on 5% of the watershed (in north-central Idaho), but found no consistent pattern of changes. These results are similar to those of Harr et al. (1975).

Several studies of logging effects on peak flows have reported no changes following harvesting. Rothacher (1965) reported negligible changes immediately following forest harvest at the Lookout Creek watersheds in western Oregon. Similarly, Harr et al. (1982) reported that patch-cut logging in Oregon of two small watersheds (the Fox Creek watersheds; those where a net reduction in annual water yield was observed) produced no changes in the timing or the size of peakflows. Cheng et al. (1975) reported a reduction in peak flows in a small watershed in the UBC Research Forest near Haney, British Columbia, ascribing the effect to changes in soil characteristics and conductivity following forest harvest. Finally, Duncan (1986) detected no change in peak flows in a much larger (232 km²) watershed in southwestern Washington which had been continuously harvested over the previous 30 years to a total of 49% of the watershed area.

Hetherington (1982) reported that, in Carnation Creek, peak flows increased following logging and road building. The average increase was 20% and was primarily attributed to roads, which occupied about 6.5% of the watershed. “Roads intercept seepage water and precipitation, creating overland flow and speeding water delivery to the stream channel. This road effect was probably the main cause of increased peak flows and decreased time-to-peak.”(p.58).

Hetherington (1987) discussed the general nature of changes in peak flows following logging activities, stating that the resultant changes depend on the source of the runoff and hence are expected to be quite variable.³

³ A new analysis of Carnation Creek storm runoff data has recently been completed. It has not yet been reviewed and cannot yet be cited.

For rain events in small, steepland drainage basins, the primary factor controlling storm flow is the ability of the soil to store water. Deforestation may reduce the incremental storage capacity of a watershed by increasing the antecedent soil moisture as the result of reduced transpiration. This will produce the largest increases in peak flows when the seasonal contrast between soil moisture

in cut and uncut areas is greatest. This occurs at the end of the growing season. Increases in soil moisture at this time by as much as 300% have been reported (Ziemer 1981). Hetherington reported that, on the British Columbia coast, the proportion of rainfall that becomes stormflow

during winter storms may be as high as 90%, in which case the incremental storage capacity of a watershed is no longer significant. Road building also affects rain events by intercepting subsurface flow at cutbanks and by decreasing the time it takes water to reach the channel. These changes are not associated with increased volumes of runoff, but with increased speed of delivery (Hetherington 1987; cf. also Wemple, 1994; Wemple et al., 1996). This effect may influence peak flow one way or the other, depending upon the structure of the drainage network and the location of the roads. Changes associated with roads may be quite long lasting, while those due to clear cutting will likely persist for the same time frames as increased water yields.

Because, in most studies, forest harvest quickly follows road construction, the question whether harvest or roads has the greatest effect on peak runoff remains poorly studied. LaMarche and Lettenmaier (1998) and Bowling and Lettenmaier (2000) report, on the basis of studies in Washington state, that the two effects are of similar magnitude.

The behavior of peak flows due to snow melt is variable. According to Hetherington (1987) forests act to regulate snowmelt by reducing melt rates. This means that the distribution of clearcut areas determines how peak flows will respond, for it is possible to reduce peak flows by desynchronizing the melt across the drainage basin or to increase peak flows by synchronizing it.

In coastal regions the largest peak flows result from rain-on-snow events (Harr, 1981; 1986; Storck et al., 1999). The major incremental effect is created by the advection of warm, moist air through the forest, which leads to condensation of moisture onto the cold, snow-covered surfaces and sustains rapid snowmelt using the latent energy of the condensation process. Beaudry and Golding (1985) concluded from a study in coastal southwestern British Columbia that the single most important factor controlling whether rain-on-snow events will produce higher runoff peaks in clearcut areas than in forested areas is the interception of snow by the forest canopy, which greatly increases the snow surface area. They observed a decrease in the annual peak flow following harvesting that they attributed to altered snow accumulation and reduced forest canopy area.

In a study of the impacts of clearcutting a 10.2 ha basin in the H.J. Andrews Forest, Harr and McCorison (1979) reported that the annual peak flow was reduced by 32%, based on a single year of observation following logging. The decrease was attributed to altered snow accumulation in the clearcut. But they also concluded that rapid melting of snow intercepted in the forest canopy was highly significant in producing large peak flows before harvest. However, Golding (1987) reported post-harvest increases in peak storm runoff of up to 13.5% in a small, south-facing basin that was 19% patch-cut, the largest increases resulting from rain-on-snow. In this case, most of the canopy remained intact and so canopy-related effects did not offset accelerated melt rates in the cleared area.

Hetherington (1987a) concluded that if no snow is present on the trees, then the rain-on-snow problem is similar to that for snowmelt events (producing variable results). However, if snow is present in the forest canopy, melt rates in the forest will tend to be higher than in the clearcuts, producing lower peakflows from clearcuts than from a completely forested area. This conclusion is supported by Harr and McCorison's work as well as that of Beaudry and Golding. It is probable that these results are not general. In colder, drier regions and at high altitude, removal of snow from the forest canopy by wind and by sublimation may redistribute or reduce the total snow burden substantially, hence reduce the potential flood magnitude when melt occurs.

The analysis of Jones and Grant (1996) and its sequelae

Jones and Grant (1996) have claimed that regression methods, which emphasise the mean response in a group of events, may not be suitable for assessing changes in peak flows. They used categorical analysis and analysis of variance, approaches which appear to be more sensitive than standard regression techniques, to reanalyse stormflow data from H.J. Andrews experimental watersheds 1, 2 and 3. They categorized data according to the relative size of the peak flow, season of flow, and time since treatment (forest harvest). Their results indicate that significant changes in peak flows have occurred following clearcutting and patch-cutting, but not after road building alone. In event size-delimited analyses, small events, but not large ones, showed significant differences. A major problem in the analysis of large events is their limited number, even after a long period. The same data analysed by regression (Thomas and Megahan, 1998) revealed significant changes only in the small floods occurring in autumn (at the beginning of the wet season), from which it was concluded that harvesting and road building do not affect large peak flows.

Categorical analysis tests the changes between periods of the numbers of occurrences of certain events. It was used by Jones and Grant to examine several storm hydrograph characteristics. Data for analysis were constructed as response ratios between control and treatment basins for *paired individual storm events*. The pairing procedure was to ensure, so far as possible, that appropriately comparable phenomena were indeed compared. The ratios between the treatment and control watersheds following treatment were grouped into several five-year periods, each of which was compared to the calibration data.

In watershed HJA1, which was 100% clearcut with no permanent roads, it was found that, during the first five years following treatment, small peak discharges were increased by an average of 75% while large ones were increased by an average of 25%. In addition, increases of spring peaks were higher than those of autumn peaks over the first five years. It was also found that the average peak discharge in autumn and winter was still significantly higher by 25% in this watershed 16-22 years after treatment. The volume of storm flow also increased following clearcutting. The largest increases in storm flow volume occurred during small, early wet season events, while large events showed little change. This effect is attributed to the previously noted reduction in evapotranspiration caused by deforestation, leading to greater soil moisture.

The timing of the floods was significantly changed for 10 years after treatment. The beginning of the storm flow hydrograph occurred earlier than before treatment, and the peak of the event occurred later. Roads covering 6% of the drainage area of watershed HJA3 were examined for the 4 years after construction and before partial cutting. The mean peak discharge increased 20%, although this result was not statistically significant because of the considerable variability in the observations. Increases were largest in the large events, and in winter events. The beginning of the storm hydrograph advanced by 10 hours, indicating that the time necessary for precipitation to translate into storm flow had decreased following road building. The results are consistent with the observation that roads intercept and redirect subsurface drainage into rapidly flowing surface channels.

Four years after road building, the watershed was clear cut in patches totaling 25% of the drainage area. The average peak flow for the first five years increased 50%, which is the same result produced by 100% clearcutting with no roads. After 25 years peak flows were still 25% larger on average. The timing of the flows also changed, with storm hydrographs starting 7 to 10

hours earlier than they did prior to treatment. These advances were consistent over the entire 25 year post-treatment period.

From these results, Jones and Grant suggested that the increased efficiency with which roads cause water to be delivered to the channels is the most significant factor responsible for increased peak flows. In this case, only 6% of the drainage basin was impacted by roads, well below the previously observed 12% density (Harr et. al. 1975). A reason for these results was elaborated by Wemple (1994), who found that the effect of roads during a storm event may be to extend the surface drainage network by as much as 40%. Wemple cautioned that the magnitude of changes resulting from a road depends upon its position in the basin and its condition, the character of the local substrate, and the climate.

Jones and Grant also studied three pairs of larger watersheds, with areas between 60 and 640 km². They focused on the relation between peak storm discharges and cumulative area cut, and found that the degree to which a peak flow was increased was related to the difference in cumulative cut area. The observed relation was roughly linear, with a 20-30% increase in peak flow resulting from a 5% difference in cumulative cut area. Their results suggest that harvesting activities have much greater impact upon relatively large watersheds than was previously thought. It was also observed that the changes in flood hydrographs in these basins were consistent with the changes identified in the HJA watersheds 1,2, and 3.

All of the results of Jones and Grant exhibit large scatter, which suggests that studies of small numbers of events, and of short total duration probably will not identify significant effects. Variability presumably stems from synoptic variability of precipitation events and from the variability of antecedent conditions, both of which make it practically impossible to ensure perfect event matches for comparison.

The results of Jones and Grant have been challenged by Thomas and Megahan (1998; see also Jones and Grant, 2001, with reply by Thomas and Megahan), who showed that the ANOVA model they employed actually conforms with a constrained regression model. Relaxing the constraint, they reanalysed the data of the small watersheds study and arrived at largely similar results. They also claimed that inconsistencies in event matching rendered the results on runoff timing invalid. Since these results were ascribed by Jones and Grant to the effect of forest roads, Thomas and Megahan claim that no influence of forest roads on runoff was demonstrated.

Adopting a regression model for the large drainage basin study, Thomas and Megahan detected significant results in two of the three cases, but not in the third case. However, they applied a further and more stringent test to these results to determine the worth of the results for prediction of the cumulative effect on runoff peak flows of progressive harvest of a drainage basin, and they concluded that the results were of no use. This outcome has largely to do with the great scatter in the data, which yields a standard error for an individual prediction that is comparable with the detected treatment effect. It is important to recognise that the detection of a collective effect in the ensemble of data and the prediction of an individual outcome are two distinct problems. Failure to achieve the latter does not invalidate the former. Demonstration of an effect was what was intended in the original analysis and that result appears to stand by either approach.

A reanalysis of Jones and Grant's data was also conducted by Beschta et al (2000). These authors attempted some additional quality control exercises that led to minor modifications of the data set, but their major departure was to apply traditional regression methods, conceptually in conformity with many prior analyses discussed above. Again, they found that peakflows

increased following treatment of the Andrews basins, with a decreasing effect for successively larger events. However, all effects were smaller than those reported in the earlier analyses, being 13-16% for events of recurrence interval one year and 6-9% for 5-year events. The authors conclude that there is no strong evidence that the largest events are significantly affected by forest harvest -- a conclusion in conformity with many earlier studies. The results of Beschta et al. on the large basins yielded some significant results but low explanation and small effects (in the range 1-7%)⁴.

Bowling et al. (2000) have further extended the analysis of larger drainage basins by examining 23 drainage basins in Washington state using data selected from regular stream gauging and forest history records. The study basins vary in area between 14 km² and 1600 km². Annual mean and annual minimum flows in the study basins are shown to be significantly correlated with climatic

controls of regional hydrology, which represents an additional complication for analysis, since others have shown the absolute magnitude of landuse effects to be proportional to the absolute magnitude of the water fluxes. Forming pairs for analysis from the set of study basins, the trends relative to land cover change are mainly within the limits of statistical variability. Significant changes in annual minimum flow were detected, but they occur in either direction in different basins. Plausible reasons for such an outcome have been discussed above. The pattern of changing maximum flows is consistent with prior results, with the main effect being increased flows at frequent return periods. The authors conducted a novel analysis by comparing flood flows with ones predicted by a hydrological model (in effect, a theoretical control sequence). The residual analysis showed the same patterns as those just described, but with increased sensitivity. This result is ascribed to the lack of random variability and post-treatment transient effects in the model outcomes.

Most recently, Jones (2001) has analysed peak flows in 10 pairs of small drainage basins in Oregon (all of them mentioned in results reported earlier in this review) by stratifying events according to the likely dominant contributing water budget factors. Analysis of variance was used to examine treatment effects. Changes in evapotranspiration resulting from forest canopy removal are judged to account for increases in peak flows (31% to 116%) in the first decade after harvest, with the significant effects being small events occurring in the autumn. For a given reduction in forest canopy, increases were greater in dry areas than in wet ones. Reduction in fog drip offset

⁴ Underlying the analyses in the papers of Jones and Grant, Thomas and Megahan, and Beschta et al. are disagreements about what statistical methods are appropriate for the problem. These issues have not been emphasised in this review.

reductions in evapotranspiration in partially cut coastal basins. The magnitude of runoff from rain-on-snow events increased (25 to 31%) but other snow-related effects did not change. Changes in flow routing produced peakflow increases of 13 to 36% in large runoff events in most basins with roads, with the greatest increases being associated with higher densities of midslope roads. These results confirm the conclusions drawn in earlier studies and the study approach introduces the concept of gaining consensus by identifying the dominant response in multiple comparisons.

Low flow changes

Low flow characteristics of interest include the magnitude and duration of flows below critical levels which may be defined by various needs for water (e.g., fish habitat; fish passage; water quality criteria; water supply). The impacts of logging practices have been summarized generally by Hetherington (1987). He stated that changes to low flows closely parallel the changes to water yields following harvesting. This condition can be grasped intuitively by recognizing that an increase in water yield implies an increase in stream flow. That low flows should become less extreme (or the number of days during which stream flows are below a given threshold should be reduced) can be inferred from the fact that reductions in evapotranspiration following harvesting will be greatest during the summer and autumn, when low flows are most often observed in coastal locations (Rothacher, 1965; Keppeler and Ziemer, 1990).

Harr et. al. (1982) stated that, in watersheds HJA 6 and 7 of the H.J. Andrews Experimental Forest, logging resulted in significantly fewer days of low flow for most of the years of record. Hetherington (1982) reported that in H watershed in the Carnation Creek drainage basin, summer low flow levels were increased by 78% for two years after logging, and that the entire watershed exhibited increases in low flow levels of 47% in 3 of 5 years following treatment.

However, in coastal areas it has been observed that fog drip may contribute as much as 30% of the total precipitation during the period from May to September, most of which is lost to a watershed once the trees have been harvested (Harr 1982). It has been proposed that such a change in water yield might offset the decreased evapotranspiration rates resulting from deforestation and could even lead to reduced summer low flows.

In addition, it has been reported that vigorous regrowth of phreatophytic hardwoods in the riparian zone can significantly increase evapotranspiration rates during the growing season, resulting in lower water yields during summer months (Hicks et. al. 1991). This phenomenon results in decreased low flows some years after harvest.

Thus, while deforestation appears in general to increase low flows, the effects of reduced fog interception and of increased evapotranspiration following riparian hardwood colonization must be considered as well. Either factor may be capable of significantly reducing low flow levels (Harr, 1983).

Summary

Water yield in general increases following clearcutting of a watershed due to decreased evapotranspiration. Simply put, water is consumed by trees, therefore removing the trees increases the total volume of runoff. The amount by which water yields increase depends on the climatic regime of the area in question, the character of the forest, the percent of forest removed, and the time since forest removal. The time necessary for water yields to approach pre-harvest levels depends on the rate of vegetative regrowth. If the riparian zone is extensive, colonization by phreatophytic hardwoods may be significant, and has in some studies resulted in summer water yields lower than those observed before harvesting. In addition, coastal environments in which fog interception is significant may receive less total water following clearcutting which, in some cases, might seasonally offset evapotranspiration reductions, resulting in lower water yields. Thus, while water yield does generally increase following clearcutting, the magnitude and duration of such changes is quite variable, and the hydroclimatic region exerts significant control over the response of this hydrologic variable to clearcutting.

Impacts on peak flows from both road building and clearcutting seem to be quite variable. However, it appears that peak flows usually increase following treatment, and that this increase tends to be larger for the smaller events. One major factor contributing to the variability of the results is the spatial distribution of cut blocks and roads, which affects the timing of water delivery to the stream. It has been noted that road ditches can extend the surface drainage network significantly, and that cut banks intercept subsurface flow, thus decreasing the time necessary for water to reach the stream channel. Roads therefore have the potential to speed the delivery of water to the stream channel, shortening the length of the storm response time and consequently increasing its peak. Whether or not this occurs depends upon how much of the watershed is covered by roads, and the location of those roads. The impacts caused by roads are quite persistent and are possibly permanent over forest management time scales, even though the roads are retired. Cut blocks have the potential to increase peak flows by altering snow accumulation and increasing ambient soil moisture levels by reduced evapotranspiration. Whether or not this occurs depends on the nature of the storm event (i.e. rain-on-snow; snow melt; rain) the time of year, and the watershed elevation.

Low flows generally follow the pattern of water yield, increasing following clearcutting. However, low flows are also affected by reduced fog drip at coastal sites and by the establishment of phreatophytic hardwoods. The period of time during which low flows can be expected to persist following harvesting is similar to that of altered summer water yield.

Most of the critical results derive from American work, although some have been confirmed at Carnation Creek. Results from Washington and Oregon will not necessarily apply in detail to British Columbia landscapes. These states are situated beyond the general glacial limit. The soils found there are deeper on average than those in British Columbia, suggesting a greater water storage capacity and so, possibly, a greater capacity to buffer short-term effects of reduced forest cover. This might lead to smaller increases in post-harvest water yield in British Columbia than have been observed in American experiments -- in particular to a smaller increment to late-summer low flows. Conversely, storm peak flows and runoff timing might exhibit greater changes than have been observed farther south. In short, stormflow response may be more sensitive, and water yield response less sensitive on shallower steepland soils in humid regions. (Hetherington (1995) reported extremely high subsurface water flow rates over bedrock at certain sites in Carnation Creek, although a regional summary by Cheng (1988) implies values similar to ones measured elsewhere in the Pacific Northwest.) Additionally, local relief in much of Washington and Oregon is not so great as in coastal British Columbia, whereas topographic dissection of the landscape is more intense. The consequence is that most slopes are considerably shorter than on the British Columbia coast, so that road layouts in steep terrain may be quite different. The observed effects of roads in Washington and Oregon at best give a qualitative indication of the phenomena that might be expected in British Columbia.

Sediment related impacts of West Coast forest practices

Introduction

Forest harvesting practices consisting of road building, logging and slash burning can significantly alter the production and transport of clastic sediment. The impacts of forest

harvesting have been studied in the Pacific Northwest and elsewhere for several decades, allowing some general inferences to be made. In most cases, study basins have been drained by relatively steep, low order streams with rock or gravel-bed channels. Changes related to harvesting are easily identified in these systems. However, detection of logging related changes in large systems has proven difficult, which limits generalisation about harvesting impacts at larger scales.

Harvesting can indirectly influence sediment transfer by altering the hydrology of harvested basins. Road building and clearcutting can alter both the timing and the magnitude of storm runoff events, which can cause changes in fluvial sediment transport. However, land use may have more direct effects by making much more sediment available for transfer as the result of soil exposure and disturbance, altered slope stability, damage to streambanks, and the emplacement of forest debris in gullies and stream channels. The consequences of harvesting-related changes of streamflow are almost always confounded with changes in sediment mobilisation due to surface disturbance and altered stability of stored sediment. This review emphasizes sources and mobilisation of sediments. Effects of the altered hydrological cycle are discussed within this framework.

Sediment transfer refers to the mobilisation, transport and deposition of sediment. These phenomena define the linked set of processes and pathways by which sediment is moved through the landscape. In the humid Pacific Northwest, these pathways are largely coincident with the drainage lines of water, and the processes are intimately associated with water. Accordingly, we will consider sediment mobilisation on hillslopes, sediment delivery to the drainage network, transport and storage within the drainage network, and sediment yield from drainage basins. The summary effect of these processes is the “sediment budget” of a drainage basin. Methods for rapid evaluation of sediment budgets suitable for evaluation of land-use effects have been presented by Reid and Dunne (1996).

Landscapes in the Pacific Northwest are mountainous with deep valleys. In British Columbia and within the mountains farther south the valleys have been glacially scoured to produce smooth, steep sides. These landscapes have four characteristic landform units. **Hillslopes** in British Columbia are typically covered with veneers of glacial till and colluvium. Farther south, hillsides at moderate and low elevations may have much older and deeper residual soils. **Gullies** are narrow, steep, linear defiles incised into the hillslopes which contain first and second order streams, many of them flowing only seasonally or ephemerally over bedrock or boulders. **Stream channels** in the valleys are boulder- or cobble-gravel bedded, and exhibit step-pool, rapid or riffle-pool morphology (cf. Grant et al. 1990; Church 1992). **Valley floors** consist of toe slopes and valley flats, principally colluvial and alluvial fans, minor floodplains and, often, incised Pleistocene⁵ deposits. These represent relatively long-term sediment storage reservoirs.

Gullies represent the primary conduits for hillslope-derived sediment into the drainage network. Total channel length within a drainage basin is typically greatest for the lowest orders; therefore, gully channels have the greatest cumulative length along which to intercept hillslope delivered sediment. Higher order streams are more often at least partly buffered from direct delivery of hillslope derived sediment by toe slopes and valley flats. Gullies are directly coupled to the adjacent hillslopes. Finally, gullies are both the product of and enhance hillslope processes. Gullies are axes of hillslope erosion.⁶

Primary sediment mobilisation occurs on hillside slopes and in the sides and heads of gullies. Sediment may subsequently be remobilised from storage points along gullies, in footslopes and valley flats, and along stream channels.

Primary Sediment Mobilisation

Sediment production in the Pacific Northwest was reviewed in Swanson et al. (1982a) and data on changes in sediment production and delivery to stream channels associated with forest land use have been summarised by Roberts and Church (1986). Processes can usefully be subdivided into “normal regime” processes that are more or less pervasive and occur regularly, and episodic or “catastrophic” events which occur more or less rarely. The former include soil creep, tree throw, animal effects, and surface erosion from exposed soils (including unmetalled road surfaces). The latter include rockfalls, rockslides, earthflows, landslides, debris slides and flows. In the following paragraphs, regional data are summarised to order of magnitude (i.e., to the nearest factor of 10). In general, values might be expected to vary by between 0.3x and 3x the quoted magnitudes. Locally, geological conditions produce even larger variations.

Soil creep is predominantly controlled by soil wetting and drying, and by freeze-thaw cycles. Both processes tend to increase in severity in clearcut openings. The rates of sediment delivery to stream channels via this process appear to be small. Downslope movement rates in the forest are reported to be of order 1 mm yr^{-1} (Dietrich and Dunne 1978; Lehre 1982; Madej 1982; Swanson et al. 1982b: all results from outside the glacial limit), which would deliver the order of $1 \text{ m}^3 \text{ km}^{-1}$ of channel per year. These data probably incorporate the effects of animal burrowing and traffic, which have not been separately considered on forested slopes. Soil creep rates may be doubled in clearcuts. Barr and Swanston (1970) and Swanston (1981) reported delivery rates of order $10 \text{ m}^3 \text{ km}^{-1} \text{ yr}^{-1}$ in disturbed and slideprone terrain, but deeply seated earthflow movements may have been involved. Roberts and Church (1986) summarized data which show that the effect of tree throw is comparable with soil creep in undisturbed areas. Tree throw can not be a significant process in clearcut areas until the second growth trees are large enough to be susceptible to

⁵ The Pleistocene Epoch is the period of geological time immediately preceding the present, Holocene Epoch. It lasted from about 2 million years ago until 10 000 years ago and is characterised, in Canada, by repeated major glaciations. Hence, “Pleistocene deposits” refers mainly to glacial deposits in this country. They form the surficial materials (soils, in the engineering sense) in virtually the entire country.

⁶ The preceding two paragraphs are largely paraphrased from Nistor (1996).

blowdown, which involves time scales on the order of several decades. However, blowdown in “leave strips” along stream courses may be a significant cause of soil disturbance and streambank erosion.

Surface erosion by running water is rare on the undisturbed forest floor because overland flow is rare. Plot studies (cf. Lehre 1982; Swanson et al. 1982b) have indicated mobilisation of less than $10 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$, and delivery to a channel of less than $1 \text{ m}^3 \text{ km}^{-1}$ of channel per year. The erosion volume amounts to 0.01 mm of surface lowering per year averaged across the landscape and is probably offset at most sites by organic and mineral matter addition. In comparison, landslide scars may yield more than $10^3 \text{ m}^3 \text{ km}^{-2}$ of slide area per year. If 1 per cent of the basin area is slide-affected, mobilisation is comparable with that indicated for the forest floor.

Furthermore, if the slide is connected to a stream channel, most of the mobilised material may be delivered to the stream. Data (Reid 1981; Lehre 1982) suggest that slides may be up to an order of magnitude more important than general surface erosion, even though their effect is produced from only a few places. Furthermore, slides that do not become repaired quickly may remain a source of elevated volumes of fine sediment for years or decades. Nistor (1996) has shown that unvegetated gully walls may act similarly, with dry ravel in summer and needle ice development in winter delivering material to the gully bottom.

Unpaved roads are well-known to be a significant source of fine sediment. Reid (1981; also Reid and Dunne 1984) have measured sediment yields from test sections that amount to $10^4 \text{ m}^3 \text{ km}^{-2}$ of road surface per year. Recently inactivated roads may still yield $10^3 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$, whilst abandoned roads may deliver of order $10^2 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$. In significantly developed drainage basins, roads typically occupy 5 per cent to more than 10 per cent of the surface. On a whole watershed basis, these figures amount, then, to order 10^3 , 10^2 , and $10 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$, making this apparently the most important surface erosion process. Furthermore, whilst a substantial proportion of sediment mobilised by surface erosion may not reach stream channels, being intercepted in depressions at slope base, a high proportion of road-related surface erosion directly enters the drainage system via ditches.

Amongst episodic processes, rockfall, rockslides, and deep-seated earthflows and landslides have not been connected specifically with forest land management, although it remains possible that earthflow activity might be affected by changing groundwater levels associated with the altered water budget that follows forest harvest. Mass failures in shallow surficial material, including debris slides, which involve shallow, rapid movement of soil, rock, and organic material, and debris flows, which involve fluid-like flow of the material, may be significantly influenced by logging activity. Debris slide and debris flow frequency may increase significantly in the short term following logging and, especially, road building. Roberts and Church (1986), summarising a number of studies in Washington, Oregon, and northern California, reported sediment mobilisation rates due to shallow mass wasting varying from 10 to $10^2 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$ on forested slopes and from 10 to $10^3 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$ on logged and roaded slopes. These volumes yield on the order of 10 to $10^2 \text{ m}^3 \text{ km}^{-1}$ channel per year to the stream system, nearly all of it to headwaters. More important than this general result is the high impact at a specific point in the channel system when a failure lands in a channel. Debris slides which reach the stream channel often deposit coarse material in the form of a sediment wedge which induces severe channel modification.

Rood (1984) inventoried 807 debris slides and flows on forested slopes in the Queen Charlotte Islands and 530 events in logged areas. The Queen Charlottes represent an extreme condition in British Columbia, being very steep, hyperhumid, and including extremely erodible rock lithologies. Certain areas on the west coast of Vancouver Island have similar environmental characteristics. Order of magnitude mobilisation rates were $10^2 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$ in forested terrain and $10^4 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$ in logged areas. Both averages are about 2x the largest individual result reported from the American studies, but the 15x acceleration observed between forested and logged sites substantially exceeds the normal acceleration of 2 to 4x reported elsewhere. Volumes delivered to streams were 10^2 to $10^4 \text{ m}^3 \text{ km}^{-1} \text{ yr}^{-1}$, with a large preponderance of the material landing in channels with gradient greater than 3%.

In a number of studies, debris slide activity has been partitioned between open slopes, roadsides, and gullies (that is, directly in the channel system). Anderson (1971) reported a survey of 725

soil and debris slides in western Oregon in which 22% occurred in undisturbed areas, 24% in logged areas, and 54% in relation to roads. Beschta (1978) also reported that most debris avalanches within the Oregon Coast Range were associated with logging roads. However, slides did not occur until almost 7 years had passed since the roads were built. The delay was possibly due to the rotting of organic debris incorporated into the road fill and/or undercutting of road fill by culvert drainage. More generally, the peak in post-logging slope instability has been observed 5 to 15 years after logging, when old root networks have largely decayed (cf. O'Loughlin 1972).

In the Queen Charlottes study, open slope failures accounted for about 39% of volume mobilised in the forest, and 23% of volume mobilised in logged areas, the balance being associated with gullies. Debris flows contributed one-third of gully-related volume in the forest, but more than three-fifths in logged areas. In logged areas, 18% of the failures were associated with roads, and they contributed about 20% of the volume. A large reduction in road-related failures was noted after the adoption of modified road-building techniques in the mid-1970s.

The effect of harvesting on long term sediment delivery to the channel from debris slides has not been well studied. Swanson and Fredriksen (1982) suggested that, following a period of increased activity, harvested areas exhibit landslide rates below normal, reflecting the depletion of sediment stored on hillslopes. Furthermore, long term changes in sediment delivery to stream channels will be controlled by the processes and rates of sediment recharge in areas subject to sliding. They concluded that "soil formation is the ultimate controlling factor." (p. 136)

Detailed studies have been conducted by Dietrich and his collaborators of sediment accumulation and episodic evacuation from "hollows" at the extreme upper limit of the drainage system (Dietrich and Dunne 1978; Dietrich et al. 1987). Such hollows are convergence zones for shallow subsurface drainage as well as accumulating soil and forest debris. Ultimately, a debris slide or debris flow clears out the hollow and the downstream gully. The time for filling and discharge was found to be on the order of centuries to millenia. Hydrological changes and debris surcharge associated with forest harvest may easily set off a sequence of failures, after which natural failure rates decline. This process has been defined in basins beyond the glacial limit. On slopes in British Columbia, bedrock depressions are often filled with till which may yield a similar sequence of failures as the mineral weathering front penetrates the till from the surface (J.M.Ryder, personal communication 1996). Certainly, there is evidence for episodic filling and discharge of gullies on time scales between several decades and probably millenia. Oden (1994) reported gully debris recharge rates of order $10^2 \text{ m}^3 \text{ yr}^{-1}$ per hectare of gully area in the Queen Charlotte Islands in both forested and logged terrain. These rates are maintained for some decades after a debris flow and are reduced to order $10 \text{ m}^3 \text{ yr}^{-1} \text{ ha}^{-1}$ after a century. They would permit major debris flows to recur on a time scale of considerably less than a century. Data on gully failures in logged terrain suggest that forest harvest has accelerated the evacuation phase of the cycle in this region.

Sediment transport: introduction

Sediment transport requires both a supply of transportable sediment and streamflow conditions competent to entrain the sediment (Beschta 1987). Measurement techniques make it convenient to distinguish between suspended load and bed load in streams. Both are affected by harvesting activities, though in different ways. Bed load transport is both spatially and temporally episodic, occurring only when stream discharges are relatively high. Direct measurements are both expensive and difficult. Suspended load can be measured by taking water samples, or estimated

by using turbidity as a surrogate variable. For this reason, most studies of sediment yield have entailed measurements only of suspended sediment. Suspended sediment transport tends to be determined not by flow levels, but by sediment supply. Work by Nistor (1996) using continuous turbidity monitoring has shown that suspended sediment transport is intermittent at all scales down to order 1 minute. This leaves unclear the question how adequate even suspended sediment monitoring is which relies on periodic, instantaneous samples.

Changes in bed load transport have been inferred in some studies by changes in the total volume of material stored in the channel. This distinction is complicated by processes of sediment delivery to the stream channel, such as debris slides and flows, which transfer both fine and coarse sediment. In addition, gravel bed channels store fine sediment within the coarse gravel framework, releasing it once the gravel armor layer is disturbed by bed load entrainment. Thus separation of the two is somewhat artificial.

A more useful distinction may be between “fine” sediment and “coarse” sediment. In a recent review of fine sediment studies in coastal British Columbia, Church (1998b; see also Beschta 1987) suggested that 1 mm is a useful distinguishing criterion (which is not significantly different than the 0.85 mm criterion often used by fisheries investigators). In most places and times, the coarse fraction will move as bedload, but sands down to about 0.1 mm may move in either mode, according to the flow condition. Finer material always moves in suspension.

Transport of Fine Sediment

Sediment supply has generally been considered the limiting factor in fine sediment transport (Paustian and Beschta 1979; Van Sickle and Beschta 1983). External sources of fine sediment include bank erosion, rapid mass movement, sheet wash, dry ravel, and soil creep. Bank erosion dominates external sediment supply where the channel is bordered by a floodplain or valley flat; rapid mass movement dominates supply where the channel is confined by valley walls. In the case of rapid mass movement, the effect on suspended sediment transport is relatively intense but possibly short-lived. Bank erosion in undisturbed forest stream reaches with erodible banks was reported by Roberts and Church (1986) to be of order 1 to 10 m³yr⁻¹ per kilometre of channel. Rates in disturbed reaches have been reported to vary between 10² and 10³ m³yr⁻¹km⁻¹. In a disturbed state, rates depend upon the severity of the disturbance. The quoted rates reflect averaging over short, disturbed reaches, and would rarely be approached along the entire channel network. Roots provide strength to bank materials (Hickin 1984; Millar, 2000); therefore, bank materials may be much more susceptible to erosion below the rooting zone, resulting in undercutting and periodic collapse (Mosley 1981). Large woody debris (LWD) in channels can greatly alter bank erosion rates, either positively or negatively (Keller and Tally 1979; Keller and Swanson 1979). LWD positioned along banks protects them from direct attack by stream flow, while diagonally-oriented LWD may divert and concentrate stream flow attack at channel banks (Hogan 1986).

Bed material represents an in-channel source of fine sediment. Most of the fine sediment is stored as matrix material within riffle and bar gravels where it is protected from entraining flows by the coarse armour layer at the stream bed surface. Once the armour is disturbed, fines are released.

In the Alsea watershed of western Oregon, monitoring of suspended sediment concentration and annual yield revealed that road building, as well as clearcutting and burning, increased the rate of

fine sediment transport (Brown and Krygier, 1971). In the year following road building, suspended sediment yield increased significantly in Deer Creek (a treatment basin within the Alsea watershed), though one road-related slide accounted for 40% of the total yield. In Needle Branch (also a treatment basin), no road related slide occurred but sediment yield was also significantly higher than pre-road building levels. After logging of Deer Creek basin, sediment yield was significantly higher for the following year only, and subsequently returned to pre-logging levels. Logging combined with burning in Needle Branch basin produced an annual sediment yield 4x that of the pre-logging mean in the following year and increases remained significant in subsequent years, though sediment yield continually declined toward pre-logging levels. Roads were carefully located and well constructed by the standards of the time, yet still produced significant changes in the sediment yield. It was reported that “the slash fire in Needle Branch was extremely hot: mineral soil was exposed throughout most of the watershed.” (Brown and Krygier 1971, p.1196). This soil exposure appears to have been critical in producing elevated suspended sediment yields. Suspended sediment concentrations were quite difficult to compare because of the hysteretic relation between sediment concentration and discharge, and the changes in watershed hydrology that result from logging and road building. Only large changes in suspended sediment concentrations due to harvesting could be separated from the natural variations. Brown and Krygier concluded that “clear-cut logging may produce little or no change in sediment concentrations in small streams. The greatest changes were associated with the road building...and the controlled slash burning.” (p.1197).

Beschta (1978) also examined the Alsea watershed. He concluded that “land use on these drainages increased annual [sediment yields] as much as 5 times and monthly [sediment yields] as much as 10 times.” (Beschta 1978, p.1015-16). His analysis of sediment concentrations indicates that significant increases occurred more often on the rising stage of the flood hydrograph than on the falling stage, suggesting that bank and in-channel sources were the main sources of the mobile sediment.

Sullivan (1985) examined suspended sediment concentrations and turbidity upstream and downstream of an 8000 ha area of intensively harvested land. In all, 180 km of roads were built in the area (for an areal density of about 3%) and 3400 ha of old-growth forest were harvested. No significant, long-term increase in suspended sediment was reported. However, 7 landslides did occur, resulting in temporary increases in suspended sediment concentrations. Suspended sediment concentrations upstream of the treated area were higher than those downstream (reflecting different geology), indicating that suspended sediment tended to be stored in the study reach (or, at least, that dilution effects were produced by the addition of relatively clean runoff from the study area). It is possible that sediments mobilized by harvesting in headwater basins, as occurred in the Alsea watersheds, was subsequently deposited in the bed material of higher order channels downstream.

Studies of suspended sediment yield from the 10.1 km² basin of Carnation Creek have not identified a definitive signal of forest harvesting (Tassone, 1988; Hartman and Scrivener, 1990). However, Church (1998b) has shown that prior analyses have been too highly aggregated in time to detect the likely effects: fine sediment transport must be examined within individual events to identify the signal of source events, and these sources must be known in order to provide an unequivocal connection with land use. Church suggested that there probably are two principal sources of observed fine sediment “spikes” in Carnation Creek: release of fine sediment associated with sediment mass movements into the channel, including major bank collapses and

debris flows from gullies, and release of substantial volumes of fine sediment in the channel when a log jam fails. Both sources operate episodically.

Fine sediment in the streambed

Many attempts have been made to relate changes in the quantity of fine material found within stream bed material to land use. The following paragraphs review some key findings from coastal streams apt to be relevant on the British Columbia coast. Sheridan and McNeil (1968) examined changes in fine sediment quantities in spawning gravels in Harris River and Twelvemile Creek, Prince of Wales Island, Alaska. Seasonal fluctuations were observed in the amount of fine material in the stream bed. Increases in fine sediment in 1959 were attributed to logging activities, though the limited data collected do not conclusively illustrate a significant increase above background levels. Decreased amounts of fine sediment during the early spring were attributed to flushing of the fine sediment by high winter flows. The amount of fine sediment found in the bed material during the summer months was used to examine long term changes. While the amount of fine sediment within the bed did seem to increase in association with logging activities, increases were relatively small and had disappeared by 1964, two years after the completion of logging.

Adams and Beschta (1980) examined five streams in the Oregon Coast Range. They found that “temporal variability was caused by an occasional flushing of fines from the gravel beds during high flows. Percent fines also varied greatly between streams, between locations in the same stream, and between locations in the same riffle.” (p. 1514) These results were based on samples taken during summer low flow periods. Regression analysis of the data revealed that the amount of fine sediment in the bed material was influenced by land use as well as basin characteristics. The analysis “suggested that road construction and logging operations can increase the amount of fines; however, such increases may be temporary if high flows flush the gravels.” (p. 1513) The conclusions cannot be asserted with complete confidence because the natural variability of fine sediment amounts tended to obscure the changes due to land use. Adams and Beschta also reported that basin hydrology, especially the peak flows, was responsible for changes in gravel bed composition. Since harvesting activities tend to alter basin hydrology, the changes in the bed composition may have been a product of both fine sediment input and modified hydrology.

Fine sediments in the bed of Queen Charlotte Islands streams were studied during the Fish/Forestry Interaction Program. They were similarly found to build up during the summer low flow period and then to be rapidly flushed in autumn floods (Church, 1998b). It was also noted that the occurrence of a debris flow upstream would significantly increase the incidence downstream of fine sediments. However, flushing was, again, remarkably rapid, being largely complete within weeks to several months after an event, depending on the streamflows. In this study, it was also noted that fine sediment content in the bed -- particularly of the more persistent sands -- varied systematically amongst instream depositional environments (e.g., between barhead, bar flank, riffle crest, pool, etc.), so that sampling protocols must be carefully standardised to attain consistent results.

Scrivener and Brownlee (1982) examined the changes in fine sediment amounts in Carnation Creek, Vancouver Island. Frozen gravel core samples were split into three 12 cm thick layers and then analyzed. A seasonal trend in the amount of fine sand, silt and clay was observed in the upper two layers. Fine sediment amounts increased through the summer and decreased during the fall and winter. In the bottom layer, these fine sediments decreased following a flood in

November, 1978 which was the first major flood following the completion of logging. In a followup to this work Scrivener (1987) reported that “sudden pulses of fines entering a stream would tend to be deposited, and then cleaned away within a few years provided the system was not overloaded with sediment and provided that erosion sources healed. After a few years, when source areas of sediment became chronic and fines intruded deeper in the bed, prospects diminished for a rapid return to pre-logging conditions.”(p. 59; see also Hartman and Scrivener 1990). These observations illustrate the need for longer term studies of changes in fine sediment transport related to logging activities.

Transport of Coarse Sediment

Coarse clastic material is transported as bed load, which is the movement of sediment particles along the bed of a stream by rolling, sliding, or saltating. Generally, bed load transport has been considered to be primarily limited by flow conditions. Bed load sediment supply has been considered to be effectively constant, in the form of ubiquitously available, stored bed material. However, constant supply is an oversimplification in small, gravel-bed, forest streams. Mosley (1981) reported that in a small stream in New Zealand the transport of bed load was controlled primarily by sediment availability within the channel, not by flow conditions. Moreover, even under conditions of practically unlimited bed material supply, particle arrangement and bed structure influence the likelihood of particle mobilization by given flow conditions.

Bed material stored in stream channels which is available for transport constitutes the internal sediment source. In streams with riffle-pool morphology, the bars and riffles are the main bed material storage units. Despite the periodic mobility of the bed material, these storage units are often stable with respect to position in the channel (Church 1992). In streams with step-pool morphology, the steps are keyed by large particles which are rarely mobile. Bed material supply consists of finer particles which are stored in the pools (Whittaker 1987).

Bank erosion is probably the greatest external source of coarse material across the channel network as a whole. However, rapid mass movement is an important source of bed material which is dominant in gullies and headward channels, as is shown by the data on sediment mobilisation given above. When debris slides enter small streams from valley slopes, or debris flows enter from tributaries, they may travel down-channel for some distance. Deposition in lower-gradient reaches or at channel constrictions and obstructions creates sediment “wedges” in the channel. Rapid wedge deposition and slower fluvial mobilization operate in cycles with time scales of decades or centuries (Lisle 1982; Pearce and Watson 1983; Benda 1990).

In-channel obstructions, especially large woody debris (LWD), commonly store large volumes (relative to channel total) of bed material (Hogan et al. 1998). For example, Megahan (1982) reported that, in the Idaho Batholith area, LWD was the most significant in-channel obstruction, storing 15 times more sediment than was exported from the basin annually. Swanson and Fredriksen (1982) reported that “The potential significance of sediment stored in channels is revealed by estimates that average annual export of coarse particulate material from small basins is less than 5 or 10 percent of sediment stored...consequently, moderate changes in volume of stored sediment can account for large year-to-year changes in sediment yield, even if sediment supply from hill slopes is constant.” (p. 133) On the other hand, in-channel LWD tends to act as a buffer of large inputs of sediment, moderating the short-term sediment transport rates. In headward and intermediate channels in Pacific Northwest forests, the regular formation and decay of LWD jams represents a principal regulator of the transport rate of coarse sediment

through the stream system (Hogan 1987; Hogan et al. 1998). Remobilisation of sediment from storage behind obstructions occurs upon displacement or disintegration of the obstruction (Mosley 1981; Heede 1985; Sidle 1988; Smith et al. 1993). Hence, LWD is a vital regulator of spawning gravel supply and quality downstream.

Keller and Tally (1979) reported that, in the coastal redwood forests of California, the influence of LWD generally increases as channel gradients become steeper. The total debris loading was found to decrease with increased stream size. Table 1 summarises available data, which suggest that LWD loadings peak in small, but not the smallest, channels. Altering the quantity and distribution of LWD may, then, alter the transport regime for coarse clastic sediment.

Beschta (1979) reported that removal of LWD from a low order stream in the Oregon Coast Range resulted in rapid mobilization of previously stored sediment. Increases in suspended sediment concentrations were observed during several storms which followed debris removal. After the first winter following debris removal, the suspended sediment concentrations had returned to normal and more than 5000 m³ of coarse material had been eroded from a 250 m reach of the study channel. In contrast, Smith et al. (1993) found that the storage of coarse material increased in a reach of a small gravel bed stream on Chichagof Island, Alaska after LWD was removed. The channel effected this by eroding its banks, producing channel widening, and by developing a series of regular alternate bars. The authors concluded that “regardless of changes in sediment delivery, increased sediment storage following debris removal indicated that [LWD] may have limited storage by altering bar development, and creating local sites of turbulent scour.”(p. 176) It is more likely that the increased storage was the simple product of the bank erosion (i.e., additional sediment delivery), the yield from which was not evacuated from the reach within the time scale of the study.

Swanson and Fredriksen (1982) reported that “the net effect of intensive forest management is likely to be a gradual, widespread decrease in large organic debris in streams. The sediment-storage capacity of high-gradient, low-order portions of channel systems would decline greatly,

Table 1. LWD loadings in headwater stream channels: reported data

stream order	drainage area (km ²)	width (m)	gradient (%)	LWD load (kg m ⁻²)
(a) McKenzie River system, western Oregon; Douglas fir forest (Keller and Tally 1979)				
1	?	?	?	40
3	6	12	?	28.5
(b) Willamette Nat'l Forest, Oregon; old-growth Douglas fir (Lienkaemper and Swanson 1987)				
1	0.1	3.5	37	20
2	0.8	5.2	20	30
3	6.0	11.9	13	22.8
4	11.7	15.5	8	13.6
5	60.5	24.0	3	9.2
(c) Redwood Creek, California; old-growth redwood (Keller and Tally 1979)				
2	1.1	6.4	3.3	141.6
3	4.9	9.6	4.8	49.0
4	19.8	18.5	0.5	19.6

Data collated by K. Halwas

and travel time of coarse particulate matter through such stream reaches presumably would be reduced.” (p.136) Thus, long term supplies of LWD must be considered.

Harvesting-related changes in LWD

Stream side forest removal eliminates the supply of large organic debris (LWD), while at the same time increasing the supply of small organic debris (the product of logging slash and breakage), at least in the short term. Consequently, total organic debris load may increase following logging. Bryant (1980) reported an initial increase in organic debris in Maybeso Creek, southeastern Alaska, after riparian zone logging. The new debris was smaller and formed more jams and larger jams than existed before logging. Eighteen years after logging, however, most of the jams had washed out and debris load was lower than the pre-disturbance level. Lisle (1986), in a paired study of first and second order streams in the same region, found that logged streams contained three times more organic debris than the forested streams between 1 and 3 years following harvesting. Hogan (1987) reported a similar tendency for logged streams to contain larger, less stable debris jams composed of smaller pieces. However, long-term debris load will generally be lower in logged streams because of the rapid decomposition and relatively high mobility of small organic debris, combined with the lack of a stream side supply of LWD. Andrus et al (1988) discussed the temporal cycle of LWD supply in Big Creek, Oregon, which was logged and then burned by wildfire. Fifty years after the fire, 14% of the LWD in the channel was “new” (post-disturbance); moreover, only 7% of LWD-related pools were formed by new debris. Andrus et al (1988) concluded that significantly more than 50 years were required for riparian zone LWD supply to recover, and that old debris was important in the interim. In fact, it seems that 100 to 150 years may be the time scale for riparian LWD “recovery”, simply in view of the growth cycle of the Pacific Northwest forests.

Effects of sediment transfers on hydroriparian habitat

Stream channels can be classified into two basic types; alluvial and non-alluvial (Church, 1992). Alluvial channels are ones formed in their own sediment deposits, which they are able to remobilise. Non-alluvial channels are formed in other materials, notably bedrock. The balance of sediment supply to a stream channel and sediment transporting capacity of the channel determines whether or not the channel is alluvial in character. Two classes of non-alluvial sediments which are nonetheless partly mobilisable by streams are significant. In headwater streams which are “coupled” to adjacent hillslopes, landslide and debris flow deposits into the channel both radically alter channel morphology and form a significant source of sediment for onward transport by the stream. In the Pacific Northwest, various glacial and colluvial deposits form non-alluvial channel boundaries which are episodically eroded by streams. In British Columbia, glacial drift forms the ultimate source of most mobilisable sediment in the landscape.

Mobilisable sediments (or their absence) along the stream channel determine hydroriparian habitat in many critical ways:

- When the supply of relatively coarse (bed) material into a reach exceeds the capacity of the channel to transport it onward, aggradation occurs, the stream is diverted around the initial deposits, bank attack becomes vigorous and additional sediment is recruited (Roberts and Church 1986). The channel becomes relatively wide and shallow, pools become shallow, and habitat conditions for many stream organisms become relatively unfavourable (cf. Tripp and Poulin 1986).
- When the transport capacity of the channel outstrips the supply of bed material, the channel degrades, becoming narrower and possibly incised into earlier deposits. If the condition persists the stream will eventually occupy a lag cobble- or boulder-lined channel, or a bedrock-floored channel. Pool characteristics depend upon gradient and boundary geometry. Habitat conditions vary widely but usually are unfavourable for fish spawning.

Streams with the most favourable on-channel habitat are ones with sediment supply not dramatically out of proportion to the transporting capability of the channel, so that a regular sequence of bars, riffles, and pools is maintained with periodic gravel turnover. This requires regular but not excessive replenishment of gravel supplies to the channel.

- Sediment calibre in stream bed and banks, along with bank vegetation, determines the channel stability and geometry (Church 1992), hence the hydraulic geometry of depth and flow velocity distributions (cf. Hogan and Church 1989).
- Sediment calibre, determined by the texture of source sediments and the size sorting capability of streamflows, exercises critical influence over the character of the benthic habitat, hence streambed fauna (see Culp and Davies 1983), and the quality of gravels for fish spawning (see Everest et al 1987). Hence it has a pervasive influence over fish spawning and rearing, and over the diversity of fish species in the channel.
- In particular, significant volumes of fine sediment in the channel clog or bury streambed gravels, degrading habitat quality, and abrade the streambed, adversely affecting both periphyton and invertebrate densities (Culp et al. 1986).
- Channels are subject to epicycles of sediment loading and evacuation -- hence aggradation and degradation -- according to fluctuations in sediment delivery from the land surface. These create successions of bottomland flooding and floodplain construction, followed by terrace formation. Accordingly, terrestrial habitats adjacent to the stream channel are strongly affected, especially in terms of frequency and duration of inundation by water.
- Aggradation and degradation are most extreme where substantial transient sediment accumulations are induced by stream blockage. This may occur at tributary junctions, where active tributary alluvial fans or debris flow deposits may enter the higher order stream and block it, and at log jams. Landslides and debris flows may contribute large volumes of large wood to the channel, so these two circumstances often are related (Hogan et al. 1998).

Log jams are an especially significant mechanism creating epicycles of sediment accumulation and onward transfer on time scales of order decades. In particular, large jams in relatively wide valley bottoms induce lateral migration of the channel around them (and around the associated sediment wedge), creating in the long term a rich diversity of wood infested side-channels, ponds and swamps. Hogan et al. (1998; see also Keller and Tally 1979) described the evolution of these large jams and associated sedimentation over a century time scale and emphasised their key role in creating superior habitat in valleybottom streams of intermediate (say, third to fifth) order.

The maintenance of this intermediate term cycle of habitat renewal depends upon the maintenance of large wood and gravel transfers into the channel at rates which, over a century or so (e.g., the harvest rotation time scale) are not dramatically out of proportion with the capability of the stream to evacuate most of the sediment and with the rate of decay of the resident wood, so that renewal and relocation of active jams occurs.

Whilst excessive accumulations of coarse sediment in channel beds degrade habitat quality in the short term, substantial accumulations (most typically, forming sediment wedges upstream of log jams) appear to be a critical factor in the creation of a superior range of habitat types and quality in the intermediate to long range, and in creating a variety of adjacent riparian habitats. Streams in the Pacific Northwest appear to be adapted to epicycles of change, in which the best habitat locations shift along the stream system as sediment waves -- created perhaps by major landslides or debris flows accompanying major storms -- move through the system. The system-scale productivity and stability appear to depend not upon stability at individual sites (quite the reverse, in the long run) but upon the maintenance of a reasonable area of accessible and productive habitats in the system. This implies that sedimentation processes should not be perturbed too far from natural rates in the intermediate to long run.

Another important observation is that the elimination of sediment transfer through a reach certainly reduces overall habitat diversity and quality. Sediment movement is a significant part of the system dynamics. Since significant sediment inputs (e.g., debris slides, debris flows) are highly episodic, the role of log jams in storing and then more slowly releasing sediment for onward movement represents an important modulating effect on changes in the sedimentary environment. In summary, then, the maintenance of LWD supply to mountain channels appears to be vital for maintaining their ecological productivity.

Fine sediment movement directly influences organisms near the base of the food chain (and influences fish directly if sufficiently high concentrations persist). Only very modest levels of fine sediment concentration are tolerable or desirable in the streams. But since fine sediment moves quickly through the stream system, once entrained, the effect of a slug entry is short-term. The effects of fine sediment in the stream system present a particularly serious challenge for road construction and management, since unpaved roads are the major persistent source of fine sediments in most exploited drainage basins.

Water Quality

Water quality depends upon the quality of incoming precipitation, the minerals in rocks and soil with which the water comes into contact in the surface environment, the cycles of nutrient uptake and release associated with the growth and decay of terrestrial vegetation, and physical conditions along water flow lines in the landscape. Together, these factors create major regional variability. Accordingly, a review of water quality conditions pertinent to a particular study area should depend upon relatively local observations. Such observations are available on the British Columbia coast only from Carnation Creek (Scrivener, 1988; Hartman and Scrivener 1990) and from the UBC Malcolm Knapp Research Forest at Haney (Feller and Kimmins, 1984). Both are low elevation sites. Overall, the concentrations of dissolved constituents are very low in west coast waters.

In Carnation Creek, most dissolved ions are derived from soil and bedrock weathering. Consequently, concentrations are directly related to the time the water spends in intimate contact with soil and rock. The highest concentrations occur during low flows, which are sustained by slow seepage of shallow groundwater, mainly from relatively near the channel. Even though ion concentration is reduced during higher flows, total ion export increases because the source areas for flow extended over a much larger proportion of the drainage basin. Logging activity at Carnation Creek increased total dissolved solids concentration during high and moderate flows; low flows were not affected. Increases were in the range 50% to 90% (the latter figure in the most intensively treated sub-basin), probably as the result of additional materials flushed from the surface after slash burning. The effects disappeared after 2 years.

Nitrates, an important nutrient source, also exhibit concentrations inversely related to flow, but there is a notable flush in early autumn storms. This is because nitrates (along with sulphate and chloride) is largely derived from precipitation and dry fallout from the atmosphere. In storm runoff after harvest nitrate concentrations increased by about 2x over the full range of flows, a modest change in comparison with results in some studies elsewhere (e.g., Brown et al. 1973; observations in the Alsea Forest, Oregon; Binkley and Brown, 1993). Increases were short-lived, disappearing within 2 to 7 years, and falling below pre-logging values at low flows after 3 to 5 years. This behaviour is related to the status of nitrogen as an important macronutrient in both the forest and stream. It was aggressively conserved once new growth became established.

Phosphorus is another scarce -- possibly limiting -- nutrient in the system. No changes in phosphorus mobility were observed following forest harvest. This finding repeated observations previously made in the Alsea Forest (Brown et al. 1973).

At the UBC Research Forest, two small watersheds (10s of ha) were partially clearcut and one was subsequently slash-burned. Both were then planted with Douglas fir. Nutrient losses were elevated for 2 or 3 years following treatment but then declined, in some cases to lower levels than those observed before treatment. Clearcutting and burning caused the greatest losses, particularly of nitrogen. In general, nitrogen and phosphorus were strongly retained in the basins.

In a comparison of partially cut (7% and 33%) small watersheds with an old-growth watershed on the Olympic Peninsula a decade after the logging, Murray et al. (2000) detected some variations amongst ion loadings, but the higher loadings were, in general, in the old-growth stream, suggesting that nutrients were being aggressively scavenged in the recovering basins, where riparian areas are dominated by red alder. No difference was detected in nitrate concentrations.

Water temperature is an important water quality parameter with a substantial influence upon life cycle timings and the activity of aquatic organisms. In Carnation Creek, temperatures increased after logging. Summer daytime temperatures increased by several degrees (Holtby 1988; Hartman and Scrivener 1990), but the most surprising change was a persistent increase of order 1C in winter stream temperatures, notably during low flows. The reason for this has not been determined definitively, but it appears most reasonable to ascribe it to an increase in shallow groundwater temperatures. This, in turn, points to an increase in soil temperature. This effect deserves substantially more study, since it may be related to rate-of-cut and the proportional area of recently harvested land.

In the UBC Research Forest Feller (1981) clearcutting (to stream edge) increased summer water temperatures during the succeeding 7 years, and longer in the slash-burned basin. Incidence of

very elevated temperatures ($> 17^{\circ}\text{C}$), unobserved before treatment, was of order 100 hours/year immediately after harvest and persisted for several subsequent years in the slash-burned basin. Winter temperatures increased in the clearcut basin, but decreased in the slash-burned one. These effects persisted for 4 years.

In the recovering, partially-cut basins of the Olympic Peninsula (Murray et al., 2000), temperatures remained more seasonally variable after a decade, with a summertime elevation of 3.5°C over the control stream. However, values were not near critical for fish survival.

Thermal effects are apparently complex. They depend upon the sources of water, upon water routes through the soil, upon streambank conditions, and upon the distribution of harvested areas within the basin.

Interpretations and recommendations

Interpretation of hydrological studies in the Pacific Northwest

The rate at which timber is removed from a watershed (the “rate-of-cut”) and the area of timber cumulatively removed are of concern because of potential impacts on the hydrological regime and associated impacts on the hydriparian ecosystem⁷. Knowledge about the hydrological impacts of forest harvesting is derived from many observations, but is most clearly revealed in experimental studies deliberately planned to evaluate the effects of specific forestry practices. Because of the administrative and practical difficulties to control forest land management on land areas of more than a few hundred hectares over the long periods of time required for experimental observations, hydrological effects in larger drainage basins have mainly been inferred from *ex post facto* analyses of trends in land clearance and hydrological changes.

Following are major conclusions which may be drawn from studies conducted in the Pacific Northwest forests reviewed above:

- Forest harvest increases average total (and therefore mean) runoff. This result has been observed in all experimental studies and the fundamental reason for it is reduction of forest transpiration. Absolute effects in the Pacific Northwest forests may be relatively large because standing mature biomass is large and the region is very humid, so a high proportion of potential evapotranspiration is actually achieved in the forest. Effects may persist for more than 25 years but in some studies they have disappeared sooner. Reduced leaf or needle area during early succession accounts for the persistence of total or mean runoff effects, but changes in plant species composition may complicate the response. Beaudry and Sagar (1995) report an interesting variation of this theme from a study site on the northern British Columbia outer coast (north of Prince Rupert) where changes in physical evaporation are apt to dominate the adjustment of the water balance, but the summary effect is the same.
- Late summer low flows increase in magnitude following harvest, but may decrease (in comparison with pre-harvest flows) after 5 or 10 years, probably due to the establishment of different tree species, especially in the riparian zone.
- Clearcutting (including patch clearcuts of modest area) increases storm runoff volumes but storm peak flow response is complex. These effects have been observed to disappear after about 10 years in the absence of roads. Effects appear to become notable where more than about 20% of the watershed is cleared within a decade or two; that is, when the rate of clearance exceeds about 1% per year, on average. However, the apparent threshold of 1% per year may reflect the small number of appropriate studies, the precision of measurements, and the particular analyses that have been undertaken more than a real lower bound for significant response. The clearest evidence for the threshold is the apparent persistence after 25 years, identified by Jones and Grant (1996), of stormflow effects modestly greater than those

⁷ The hydriparian ecosystem consists of the aquatic ecosystem of streams and lakes plus those of the immediately adjacent terrestrial environment, the latter occupying all land adjacent to water bodies that is both influenced by and influences the aquatic ecosystem and its associated biota (Scientific Panel, 1995. Report 5: 280).

produced just by the roads in the 6% roaded and 25% patch-cleared HJA3 experimental basin.

- The most prominent stormflow increases occur in small and moderate, early autumn storms. This effect most likely is due to increased late summer soil moisture levels, possibly augmented by hydrophobic soil conditions. In these circumstances, less water is absorbed in soil moisture recharge. When major midwinter storms occur in already saturated watersheds, forest cover does not appear to influence the stormflow response notably.
- Roads increase storm runoff and advance storm runoff timing. These effects are caused by the extension of the surface drainage network produced by road ditchlines, and by the increase in the essentially impervious surface area. Effects are particularly marked on slopes where roadcuts intercept downslope subsurface drainage and the compact road berm itself acts as a dam against reinfiltration. Road effects appear to be permanent and they affect storms at all times of the year.
- Road extent and layout influence the severity of storm runoff response. Contrary to early reports, there appears to be no finite threshold for the appearance of effects, but the resolution of field measurements and the analytical methods employed may make it appear as if there is such a threshold.
- Rain on snow may produce increased storm runoff following forest harvest due to the snow surface area in clearings being exposed to accompanying warm air advection in high winds. However, the effects of rain on snow are complex. A warm storm on a mature forest canopy carrying a high snow load may create similar effects because of the high snow surface area on the trees.
- Clearcutting advances the timing of spring melt at intermediate to high elevations on the coast, where the snowpack may be deep and may persist until late spring.
- In coastal temperate rain forests, cloud and fog condensation provide considerable amounts of water. Tall old-growth canopies are effective at capturing this moisture and thus play a role in the natural hydrological regime on the exposed west coast. Old-growth forests might increase the net precipitation in regions with frequent low clouds and fog because of the large volume of space occupied by the canopy and the high surface area of foliage, branches, stems, and mosses. These structures are condensing surfaces which create “fog drip”.

The foregoing summary gives a concise, qualitative view of the pattern of hydrological response that has been associated with forest harvesting, including roadbuilding. It is constructed from the preponderance of observations over the available studies and it is consistent with physical hydrological theory and with the experience of local observers in the region. The summary represents, therefore, a reasonable scientific generalisation about hydrological response even though specific observations in individual studies may remain at variance with it. It is supposed that those observations might be traced to particular circumstances which would reconcile them with the general view. Generalisations in complex sciences, such as ecology and environmental science, are usually of this nature. Extracted from the particular circumstances of individual sites and events, conclusions commonly can be offered only in qualitative terms.

For the same reasons, the summary does not provide adequate basis for quantitative prescriptions to mitigate forest harvest effects at specific sites. With respect to hydrological impacts of forest harvest, the following are reasons which constrain interpretation of the overall body of observations in Pacific Northwest forests to remain qualitative.

- The experimental studies which provide the most clearly interpretable evidence necessarily are long-term and are expensive to conduct. Therefore, the total number of studies remains few, yet forest terrain is remarkably variable. The quantitative extrapolation of results from the experimental sites to other sites would be potentially misleading because new sites probably encompass terrain conditions and historical circumstances not experienced at the experimental sites.
- It is clear, as well, that certain hydrological effects may be very long term ones, covering a substantial portion of the succeeding forest succession time, or longer. No experimental studies in the Pacific Northwest have yet been continued for that length of time (40 years is our current time horizon for well-quantified observations), so there may yet remain unanticipated consequences of forest land management.
- Within the experimental studies, treatments vary from study to study and are confounded with terrain variations. There are no studies that have been controlled to separate treatment effects from terrain variations (cf. Hewlett and Hibbert, 1961).
- Various treatment effects, especially roads and forest removal, have consistently been confounded since forest harvest has always followed shortly after road construction.
- Few of the experimental trials approximate the land management procedures of operational logging. In particular, most of the experimentally studied openings remain relatively small in relation to the scale of past clearcuts (though probably not in relation to future ones); nonetheless they usually represent unreasonably large proportions of the immediate drainage area (not uncommonly 100%). Hence, they represent realistic trials only in respect of small headward tributaries (where they commonly are located), where the cumulative cut over a few years might approach the relatively large proportional clearances that have been undertaken.
- Some of the trials have used special harvesting methods or post-harvest treatments that do not reflect the conditions of operational logging. In this respect, it is noteworthy that at Carnation Creek planning and operations attempted to replicate a range of operational conditions.
- Many of the experimental studies have been inadequately controlled, particularly with respect to the length of the “pre-harvest” calibration period. The result is that calibration relations often incorporate the particular effects of weather regimes which may occur for only a few years. (This may be a particularly important artifact on the west coast, where weather patterns are strongly modulated over periods of several years by the adjacent Pacific Ocean; cf. Bowling et al., 2000.) This effect may bias subsequent quantitative predictions and the magnitude of the bias might easily approach that of the incremental effects one seeks to resolve.
- Almost no study has been adequately analysed. The dominant method of analysis has been regression, which estimates the average effect over a range of events. In fact, it appears that significant response to changes in land surface condition may be expressed mainly through particular events with specific antecedent conditions. Certainly, to identify the physical processes responsible for particular hydrological behaviour, it is necessary to analyse individual events in detail.
- Analytical methods, particularly statistical methods, generally have not been critically considered for their suitability in relation to the questions that are being asked of the data.

A special circumstance which affects the interpretation of observations in the Pacific Northwest is that most of them are derived from unglaciated terrain in Washington and Oregon, with more or less deeply weathered soils and relatively short slopes. The shallow, glaciated soils and long slopes in coastal British Columbia probably create a hydrological system considerably different - and likely more sensitive to environmental disturbance -- than has been analysed in most experimental studies. Carnation Creek, the most closely studied site in British Columbia, does not escape from this stricture because it is a drainage basin with somewhat limited relief. Further-more, the unusual arrangement of the control sub-basin at Carnation Creek and the short calibration period -- which appears to have been influenced by a particular weather regime -- both remain constraints to interpretation.

Hydrological recommendations for the British Columbia coast

The limit rate at which a forest may be harvested -- expressed as area per unit time at which land may be cleared relative to the total forest area in a drainage basin -- in order to avoid significant changes to the subsequent runoff regime, has been a prominent and controversial criterion for forest management in British Columbia. It is apparent from the observations reviewed above that, at some rate of forest removal, significant changes certainly do occur. The Scientific Panel for Sustainable Forest Practices in Clayoquot Sound (1995) recommended a rate-of-cut not to exceed 1% of watershed area in each year, on average. The recommendation was based on watershed area (rather than forested area) because the entire drainage basin forms the hydrological response to water inputs. This rate is not unequivocally supported by data, but it appears to be appropriate on the basis of the hydrological experience reviewed above. The small number of studies which have examined progressive cut and sequential hydrological response do not detect a lower bound of the cut rate before hydrological response occurs. Those studies exhibit large variance in hydrological response, though, and could not detect small initial responses. Physical principles dictate that any level of cut must have some effect. The selected rate-of-cut recognises the need to find a compromise amongst several criteria for land management: it is consistent with needs for a temporal distribution of seral stages for biological diversity and with a temporal distribution of wood supply which will both be reasonably stable and will allow a range of rotation times to be selected for various sites and conditions.

It was proposed that the rate-of-cut be applied on a five-year average basis in drainage basin units of greater than 500 ha. In units of area 200 to 500 hectares, it was proposed that the rate-of-cut be applied on a ten-year average basis. These recommendations are for operational flexibility in forest harvest. Available studies do not discriminate whether they will lead to singular effects, but it appears, in general, doubtful. In any case, watershed assessment procedures should be applied to constrain the rate-of-cut whenever any indication of undesirable effects appears.

No specific, hydrologically based constraint to the rate of forest harvest was recommended for drainage basins of less than 200 ha area. Activity in most such units will be constrained by their position as tributary units within larger basins, and by other criteria. However, there is, then, no hydrological recommendation for small basins which drain directly to the sea. Many of them have fish habitat in their lowermost reaches. In such drainage basins, harvesting either could not proceed very quickly, or it could not be sustained for more than a short time. Where such basins

are steep, they may be subject to severe disturbance, including debris flows running the full length of the channel (e.g., Tripp and Poulin, 1986), if slope stability problems ensue. Most experimental studies have been conducted on land units in this size range but the experimental treatments have been substantially more severe than any envisaged for future operations in British Columbia forests. As a general guideline, it is proposed that the 1% guideline be applied over a 20-year averaging period in such basins (to permit a worthwhile harvest to be obtained upon an individual entry), down to 20 ha total area, and that no specific guideline be applied in the smallest basins. In the last analysis, it appears important to use good judgement on such small land units -- each of which will present particular constraints -- in order to avoid the excessive costs and damages that might otherwise become associated with planning and operations there.

It appears that a high proportion of hydrological and soil disturbance derives from roads and road construction. The Scientific Panel recommended that permanent access (roads and landings) should occupy no more than 5 per cent of the *harvestable* area of a watershed, and that road engineering should include improved standards for construction and maintenance of drainage structures, including design measures to permit the passage of shallow groundwater draining downslope. The Panel recognised that research would be required into how to effect the latter recommendation.

All of the foregoing recommendations appear to be sound ones for the Coast, but they should be subject to revision for local practice as deliberately planned local experience is gained. Eventually, one expects there to be a patchwork of local variations on these recommendations, adapted to local terrain conditions. But such variations can usefully be developed only as deliberately recorded experience is gained to provide a basis in experience for such variations.

Interpretation of Sedimentation Studies in the Pacific Northwest

Experimental treatments do not reveal so much about sedimentation as they do about hydrology, even though this factor is probably the more important in respect of maintaining resource values in aquatic ecosystems. Most experiments have not covered sufficient area to reveal the effect of episodic, major slope failures. Fine sediment yield has been studied, but in many cases road and land surface treatment effects have been confounded. Major conclusions which can be drawn from the available studies, most of which have been either regional surveys or studies of processes on a very local scale, are as follows:

- The major sources of sediment in steepland drainage basins in the Pacific Northwest are landslides and streambank erosion. "Landslides" here include both shallow debris slides which originate on hillslopes and debris flows which start in stream channels (possibly when a landslide enters the channel). Rock slope failures and deep-seated earth movements are difficult to relate to land use, and almost always occur where there are prior signs of instability.
- These processes occur naturally in the landscape, and the maintenance of a modest yield of sediments, particularly of gravels, is essential for the maintenance and renewal of high quality aquatic habitat. The hydriparian ecosystem is adapted to sediment transfer.

- Forest land use has typically accelerated sediment mobilisation and delivery to the stream system by factors of order 2x to 10x. Roadbuilding and use are disproportionately important in achieving these changes.
- The incidence of fine sediments in channels varies seasonally (with increased quantities present on the bed during summer low flows), but fine material is highly mobile in vigorously flowing coastal streams so that isolated additions of fines persist in the channel for a relatively short time.
- In developed basins, fine sediment is mobilised from road surfaces and roadsides and from other sites with exposed mineral soil. Considerably increased quantities of material can have strong impacts on the aquatic ecosystem. Chronic sources, of which roads are an outstanding example, are particularly problematic since it is continually operating sources that perpetuate the presence of fine material in stream channels.
- Operational experience and contrived studies both show that where streambanks are disturbed, sharply increased erosion and sedimentation occur.
- The lower banks of many channels are composed of material similar to that which forms the bed of the contemporary channel: they are formerly deposited alluvium. After remobilisation, the material comes to rest within the channel. This deflects flows against the banks and creates much more erosion. A modest initial disturbance is capable of propagating into major bank erosion and morphological change along the stream with consequent reduction in aquatic habitat quality.
- Debris jams are of major significance in intermediate order channels both for modulating the transfer rate of sediments through the stream system, and for initiating the renovation of the channel and aquatic habitat.
- Maintenance of water quality requires maintenance of surface and subsurface conditions throughout the drainage system.

Because the hydriparian system is adapted to sediment transfers, maintenance of the system entails maintaining processes of sediment mobilisation, transfer and deposition at rates that do not depart dramatically from established long-term rates. Control of sediment mobilisation and delivery to the stream system is largely a matter of appropriate treatment of hillslopes. However, transfer and sedimentation in stream channels requires that fluvial processes also not be strongly perturbed. For these reasons, it is important to leave streambanks undisturbed. The importance of maintaining stream banks has been recognised for many years and there is substantial experience with streamside forest “leave strips”. In many cases, the typically 5 to 20 metre strips have not survived well.

There are other reasons to preserve the forest environment along streambanks, as well. Sedimentation plays a role in normal shifting of channels which renews aquatic and riparian habitats. The valley floor is the area within which this activity occurs. When the majority of the valley floor is preempted for other activities, the intermediate to long-term renewal and maintenance of hydriparian habitat is placed at risk since the elements of streamside and floodplain environments away from the current channel are removed. Furthermore, valley floor forests serve to create a particular microclimate around stream systems and act as an important source of food material for aquatic organisms. Neither of these functions is adequately served by maintaining only narrow gallery forests along stream channels. It is evident that the entire

hydroriparian zone⁸ is important for these processes. Within this zone, all natural processes -- including normal sedimentation and channel shifting -- should be maintained so far as possible.

Valley bottoms are preferred and often the only routes for road access. Many roads have been built along valleys adjacent to streams. Road berms often interfere with drainage within the floodplain, with seepage from slope base into the floodplain, or with the stream channel itself. To achieve minimum disturbance of hydroriparian ecosystem functions, roads should be eliminated from hydroriparian zones so far as is practical. Otherwise, they need to be constructed with special care to ensure that the disturbance remains minor.

Hydroriparian recommendations for the British Columbia coast⁹

Forest management in British Columbia has for some time included some form of special management or protection for stream channels, streamside habitat and shore zones. The principal basis for specifying management procedures along streams is a simple classification of the stream channel and characteristics of fish populations in the streams (cf. *Forest Practices Code of British Columbia*). In an ecosystem-based approach to land management these criteria are neither sufficient nor logical as a basis for managing aquatic and riparian ecosystems because they do not recognise the essential connectivity of the entire drainage system, hydrologically, sediment-ologically, and ecologically. A classification and operational rules that recognise the ecosystem units themselves, including the stream channel and the adjacent terrestrial surface to the limit of riparian influence, is more appropriate. Such a classification was developed by the Clayoquot Sound Scientific Panel (Report 5, 1995; Appendix II).

The Scientific Panel recommended that the entire hydroriparian zone be designated a special management zone. A special management zone (in Panel recommendations) is an area to which particular land management rules or constraints apply that are the direct consequence of the quality of the terrain features found in the area.

Within the special management zone, it is recommended that the entire “*active floodplain*” be a reserve. For streams that do not have an active floodplain, it is recommended that reserves be extended for 20 to 50 m horizontal distance into the forest from each channel bank, according to the size of the channel. These recommendations, which are intended to apply to all perennially flowing channels, are to secure the ecological function of the hydroriparian system in the following respects:

⁸ The hydroriparian zone consists of the entire floodplain of the stream, alluvial fan surfaces and, where channels are entrenched, the entire slope that rises immediately from the channel, even though the latter may contain dominantly upland forest types.

⁹ Parts of this section closely paraphrase Report 5 of the Scientific Panel, pp.175-183.

- to assure the stability of streambanks and the undisturbed continuation of normal sedimentation processes in stream channels;
- to assure the stability of soils adjacent to streambanks so that stream channels will not be disturbed and so that adequate filtration of seepage waters entering the stream channel from adjacent hillslopes will be maintained;

- to assure maintenance of a long-term source of large woody debris to the stream channel;
- to maintain the microclimate of the stream and streambank zones;
- to secure areas into which channels may shift by normal fluvial processes without loss of ecological function of the riparian edges;
- to maintain supplies of carbonaceous material and nutrients that enter the stream from the streambanks and overhanging vegetation;
- to maintain sheltered animal routeways and the diverse local habitats along stream courses.

Riparian reserves serve a range of functions in the landscape, including provision of connections in a forest ecosystem network.

The active floodplain is defined as that part of the contemporary floodplain subject to occupation by standing or flowing water more frequently than once in five years, on average (see the Appendix of this report for a presentation of the statistical basis of this definition). These are the lowest lying parts of the floodplain, into which stream channels are most likely to shift as the result of channel avulsion or rapid lateral erosion.

“*Dry floodplain*” is that part of the contemporary floodplain subject to only occasional inundation. Areas of dry floodplain may be subjected to special land use management if certain other conditions are met. The object of this proposal is to avoid tying up what could be considerable areas in some valleys that are relatively remote from stream channels or other wetlands, where other land uses may be compatible with maintaining the hydroriparian ecosystem. “Other conditions” may consist principally of ensuring that access may be arranged without unreasonable incursion into the wet floodplain, and ensuring that no other significant ecological values associated with the area will be compromised.

A different management regime must be applied to small, steep, hillside channels that do not flow permanently¹⁰. Reserve zones cannot practically be associated with such channels except where special ecological features have been identified along them. More than half of the entire length of the drainage system may fall into this class of channels. Systematically applying reserves along them would fragment the landscape to the point that forest harvest could not economically be

¹⁰ The recommendation of the Clayoquot Scientific Panel states that this group comprises “*ephemeral*” channels -- ones that flow only after a storm, or for some days after a prolonged wet period. “*Seasonal*” channels -- ones that flow continuously for several months of the year -- are grouped with perennial ones for mandatory reserves. On the British Columbia coast, seasonal channels are ones that flow throughout the winter and into the following spring, say from October through the following June. In many places it will be practically difficult to distinguish seasonal and ephemeral channels.

undertaken. But from the perspective of water quality, this situation appears like a major departure from the intention to protect all of the hydroriparian system. In fact, hydrological rate-of-cut constraints, the requirement to reserve very steep and potentially unstable slopes, and to designate several other classes of reserve land, will ensure that no more than a fraction of these headward channels is recently cleared within a short period, and within one drainage basin larger than 200 ha. Some hydroriparian reserves should extend to the drainage divide to form part of

the forest ecosystem network. The occurrence of unstable terrain will effectively ensure that this happens on many slopes.

A complete set of hydriparian proposals must also contain recommendations for road construction in hydriparian zones. The fundamental recommendation is to avoid it, but where there is no practical alternative (such as direct crossing) activities must be supervised by professional engineering personnel at all stages. Major design attention must be given to runoff management and sediment control during both the construction and operational periods. Road berms and bridges should not impede drainage. These provisions represent recognition that a significant portion of the interference which land use provides to normal hydriparian function has been associated with engineering activities at specific places in the landscape. Recognition opens the possibility to eliminate the problems by taking appropriate action.

This is also true of many of the sedimentation problems in the larger landscape which, on the whole, are very local in occurrence, easily recognised, and often associated with specific land management decisions. This means that there is a good prospect to eliminate them.

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Appendix: Bankfull Discharge Return Period

Introduction

Some criterion is required to identify valley bottom areas the ecological function of which is significantly influenced by more or less frequent inundation. This is not a straightforward matter since streams are well known to reach successively higher elevations (stages) on successively less frequent occasions. It does seem reasonable to suppose that there is some level beyond which the frequency of inundation is insufficient to sustain ecological functions that depend on episodic inundation. We therefore require some specification of a limit frequency (or of its reciprocal, return period) for definition of what is termed the active or “wet” floodplain (to distinguish such areas from higher levels, subject more rarely to inundation, which may be termed “dry” floodplain). Another sort of limit is specified by the requirement that the floodplain be distinct from the stream channel, so flows must occur overbank; that is, the stream must exceed bankfull stage. So the specification of some critical return period for bankfull stage becomes the necessary criterion to determine whether there is valley bottom area subject to ecologically significant inundation.

The problem of specifying return periods for stream flows, and critical return periods for certain index stream flows, has been extensively considered by hydrologists and river engineers. Geomorphologists have been particularly interested in the return period for bankfull stage, since they have supposed it defines the most effective flow, or “dominant discharge”, in forming the stream channel.

Prior proposals

The concept of a dominant discharge in rivers has been thoroughly examined. Several discharges have been defined on the basis of frequency of recurrence which appear to represent well some dominant discharge for a majority of rivers. However, the most commonly encountered “dominant” discharge is that associated with bankfull stage, the stage at which the channel banks only just contain the flow, and above which overbank flooding occurs. ‘Bankfull’ is not a frequency of recurrence criterion. It has been proposed that the return period for bankfull flows, based upon the annual maximum flood series, is between 1 and 2 years for most rivers. Wolman and Leopold (1957) claimed that “studies of a number of flood plains in both the eastern and western United States and in India indicate...the frequency of overbank flow is remarkably uniform in many rivers flowing in diverse climatic and physiographic regions” (p.88). Wolman and Miller (1959) inferred from the relatively uniform return periods of bankfull floods that these discharges are responsible for maintaining the channel morphology. That is, that bankfull floods are the dominant discharge. They attributed a great deal of the scatter within the data to the difficulty in determining the bankfull stage, which is especially problematic in narrow, mountain valleys.

This position has been critically examined by other workers. Dury (1973) examined data contained in several United States Geological Survey Water Supply Papers and concluded that they “strongly support the proposition that natural bankfull discharge can be specified by $Q_{1.58}$ on the annual series” (p.113). $Q_{1.58}$ is the median flood in the annual maximum flood sequence. Nixon (1959) examined bankfull discharges in rivers in England and Wales and found that

bankfull discharges have what he called a standard frequency. He identified a bankfull stage for each river. He then determined from his data, which were mean daily flows measured over a period of 5 years, the percentage of time during which his study rivers had flows equal to or above the bankfull level. While he also reported a fair amount of scatter in his data, he estimated that the standard frequency for such flows is 0.6%, or roughly 2 days/yr. This value cannot be transformed to give a return period for a mean annual maximum flood series, but it seems to agree with the range of 1 to 2 years given by Wolman and Leopold. However, it is worth emphasis that the period of record was only 5 years, which is not really sufficient to adequately characterize the typical flows that occur in a given system, nor to characterize the frequency of bankfull flows. Thus while Nixon's work seems to suggest that a standard frequency exists, his results must be interpreted with reservations.

An analysis by Williams (1978) cast some doubt upon the consistency of return periods for bankfull discharges. Williams reiterated the problem of identifying the bankfull stage and the compounding problem of calculating the bankfull discharge. He identified 11 different definitions for bankfull (p.1141-42) and he specified four methods which may be used to calculate discharge once the stage has been identified. For his analysis, however, Williams restricted his attention to rivers for which the bankfull stage has been determined by the elevation of the "valley flat" or by the active floodplain elevation, and he used only established rating curves to calculate the discharge at the specified stage. He used a total of 36 observations for the active floodplain, and 28 for the valley flat, both from data he provided and data of other workers. He presented the results in a histogram which revealed, for the active floodplain, a median return period of 1.5 years but a range from 1.01 to 32 years. Results for the valley flat were indeterminate, in part because of the possibility that the rivers have become entrenched (that is, that they have eroded downward into valleyfill sediments or rock).

From his histogram Williams concluded that "because of this wide range in recurrence intervals and the considerable spread and skewness of the distribution an average recurrence interval has little meaning for these active floodplains and valley flats and is a poor estimate of bankfull discharge" (p. 1152). He reported that only 1/3 of the observations have values near the median value of 1.5 years, but did not report the proportion of observations between 1.01 and 2.23, which is as close as one can get to the aforementioned 1 to 2 year interval, given Williams' histogram classes. One should also consider the small number of observations used in this analysis. By limiting himself to studies for which the active floodplain or the valley flat are used to define bankfull, Williams may have preferentially selected rivers with common features, existing in similar physiographic regions, thus limiting the range of rivers to which his conclusions apply. It also seems that, given the scatter that can be expected in the data, and the difficulty of establishing the bankfull stage, the conclusion that return period is a poor estimate of bankfull may be premature. Because the amount of scatter produced by estimating bankfull stage is unknown, it is not appropriate to infer that bankfull frequencies are themselves subject to a large amount of scatter. The skewness mentioned by Williams can also be addressed. Given that the sequence used for analysis is the annual maximum sequence, which is necessarily limited to return periods of 1.0 years or more, a skewed distribution for return periods close to 1 should be expected.

A new analysis

To further study this issue, the data provided in most of the papers cited above were combined and reanalyzed to assess whether or not bankfull discharges can be characterized by a given return period or range of return periods. There are no British Columbia data in a format suitable for incorporation into this analysis. Data from Bray (1972), which focuses on rivers in Alberta, have also been examined and compared with the data from the above papers. This should allow some insight into whether or not floods with return periods of 1 to 2 years are apt to have any morphological significance for rivers within British Columbia. In the Bray data, two definitions of bankfull are specified according to the lower limit of occurrence of perennial terrestrial vegetation and according to the valley flat level.

One of the most easily examined problems is whether or not the frequency of bankfull discharges is related to the size of that discharge. Data from Leopold and Wolman (1957), Leopold Wolman and Miller (1964), Dury (1973), and Williams (1978) are combined with the data from Bray (1973) in figure 1. This plot illustrates two things. First, it is evident that, within the data sets employed, no relation exists between the magnitude of the bankfull flood and its return period. Second, while there is considerable scatter in the data (return periods of from 1 to more than 200 years), most of the observations have return periods between 1 and 5 years, with a concentration of observations between 1 and 2 years. This plot also illustrates that the data from the Alberta rivers scatter between return periods of 1 and 6 years, and seem to be concentrated between values of 1 and 3 years. These data also exhibit a smaller range of return periods, extending from 1 to about 22 years, probably because Bray used the low level vegetation trim line as a basis for defining the bankfull discharge, and one might reasonably expect shoreline terrestrial vegetation to become established within 1 to 5 years on sites that are not inundated within that period.

Histograms based on the individual data sets were constructed (figure 2). The most obvious point is that the data based on the valley flat are not at all similar to the other data sets. Bray noted that most of the Albertan rivers are entrenched to some degree so, in Alberta, the use of the valley flat to define the bankfull stage is not appropriate. Indeed, fully 30% of the rivers in Bray's study for which the valley flat criterion was used have bankfull return periods in excess of 100 years. The other 70% have return periods that are widely spread between 1.5 and 31 years. Mild entrenchment is a frequent consequence of glacial and early postglacial sedimentary history along river valleys in Alberta and leads to unrealistically inflated estimates of "bankfull" return periods. Similar circumstances might reasonably be expected in British Columbia. Certain valley flats will be terraces in the present day, and not form part of the hydriparian zone.

A Chi squared test reveals that the trim line data from Alberta are also different from the combined data ($p < 0.0005$). The results remain unchanged when return periods in excess of 20 years are removed from the data. But the median values of the untruncated distributions are 1.48 years (combined data) and 2.4 years (Alberta trim line data). These values change only slightly for the truncated distributions. The median is the best measure to describe skewed distributions and the large, anomalous return periods have little effect on this measure. When cumulative percent of observations below a given return period is plotted against return period (figure 3) one sees that for both the combined data and for the Alberta trim line data, more than 80% of the observations have return periods less than or equal to 5 years. From these results, one can conclude that scatter within the data is a significant problem, but that the median frequency is quite consistent at about 1.5 to 2.5 years. The scatter may be due in part to the difficulty of identifying bankfull stage, and to inaccurate discharge estimation once the stage is known. The

amount of scatter due to actual differences between rivers is therefore uncertain. Thus it seems reasonable to assert that a return period near 2 years in the annual maximum series does in general indicate the bankfull discharge of rivers of the general size and character represented in the sample data (there are good reasons to expect that systematic scale effects influence the result, and such effects may be responsible for some of the scatter in the data presented here).

The Albertan data are significantly different from the combined data, yet we expect that they may best approximate what might be found within British Columbia, since these are the only data from a glaciated terrain, at comparably northern latitudes. The summary statistics for this data set were largely unchanged by the truncation at twenty years, and the histogram shows that a large portion of the observations are concentrated in the range from 1 to 6 years (over 90% from the cumulative plot). As a result, the data were further truncated to include only data within this range. The remaining data are best fit by a Log-normal distribution ($\chi^2 = 1.98$; $p = 0.74$) (figure 4). The log-normal distribution has its median value at about 1.9 years and from it the expected distribution of return periods about the median value can be estimated, providing a method for estimating appropriate degrees of uncertainty for individual estimates of return period.

Bray (1973) studied how best to represent dominant discharges in Albertan rivers. After considering various morphological definitions, such as bankfull discharge, and hydrological definitions, such as flows exceeded 0.5% of the time, he concluded that “considering all of the data, the 2 year flood (log-normal analysis) was adopted as the most acceptable representative discharge based on a hydrological definition.” Amongst the reasons he cited for this choice was that the bed, observed via hydrophone measurements, was found to be in motion or nearly in motion at this discharge level, so the flow was presumably competent to modify the channel, and that longer return periods produced a great increase in the number of stations for which the flow level was above bankfull.

Conclusions

It seems that the return periods for bankfull flows are log-normally distributed, and that for the data from Alberta, the median value is about 2.0 years. Bankfull flows for main valley rivers in British Columbia may likewise be distributed log-normally, with a median return period of roughly 2 yrs. The scatter that can be expected for return periods is typified by figure 1.

The 2 year flood (a hydrological definition) was advocated by Bray (1973), based on how well this discharge performed as a representation of the dominant discharge. His work was based on the same Albertan rivers studied here. We suppose, following the argument above, that the 2-year flood should provide a reasonable index in British Columbia for bankfull stage, at least for streams governed by purely fluvial processes (that is, ones in which debris flow is not a factor). Furthermore, the Albertan data show a rapid decline in numbers of rivers with bankfull stage recurrence greater than about 5 years, but the data extend out to very long return periods indicating mildly degraded or entrenched conditions. On this basis, 5 years has been selected as the limit return period for rivers to have a contemporaneously “active” floodplain, and inundation at least once in 5 years is accepted as the criterion for the “wet floodplain”. Rivers which do not achieve bankfull more frequently than once in 30 years are considered to be entrenched; that is, to have no active floodplain at all. Hence, the “dry floodplain” is that area in the valley flat that is apt to be inundated, on average, once in a period of between 5 and 30 years.

It should be emphasised that the foregoing results apply to rivers of intermediate to large size flowing in valleys with alluvial valley flats. It is known that small mountain streams experience “bankfull” or significant sediment transporting flows much more rarely. The reason for this is that headwater channels, which drain only a limited area, do not experience the relatively extreme inputs of water that create major floods very often, whereas larger channels, which combine water inputs from many headward tributaries, receive extreme contributions from some portion of the contributing watershed, or moderately extreme contributions from much of their drainage area, comparably frequently. Underlying this distinction is the sporadic and relatively rare occurrence of the extreme meteorological events (extreme rainfall, rain-on-snow, or snowmelt rate) that create extreme runoff at any particular place in the landscape. The consequence is that extreme flows typically occur only once in 10 to perhaps 100 years in mountain headwaters (Nolan et al., 1987).

In practice, relatively few rivers are gauged, so the determination of the stage (elevation) for floods with specific return periods (such as 5 or 30 years) is difficult. In the absence of gauging data, morphological evidence such as back-channel elevations, terrace or bank edges, alluvial deposits, cumulated soil development, and botanical evidence such as the presence of plant species that are tolerant (or intolerant) of inundation at specified frequencies and durations may have to be used to approximately identify flood limits. Hydraulic flow models may also be used to specify water levels associated with given flows, but these require extensive survey information and are unlikely to be applicable to most channels encountered in the usual course of forest land management.

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Figure captions

Figure 1. Discharge magnitude in relation to discharge frequency at bankfull: alluvial rivers in western North America (see text for sources).

Figure 2. Distribution of bankfull return periods for various data sets and bankfull definitions.

Figure 3. Cumulative percent distribution for two data compilations (data truncated at 30 years).

Figure 4. Lognormal approximation for bankfull return periods based on vegetation trimline in Albertan rivers: return periods of less than 6 years.