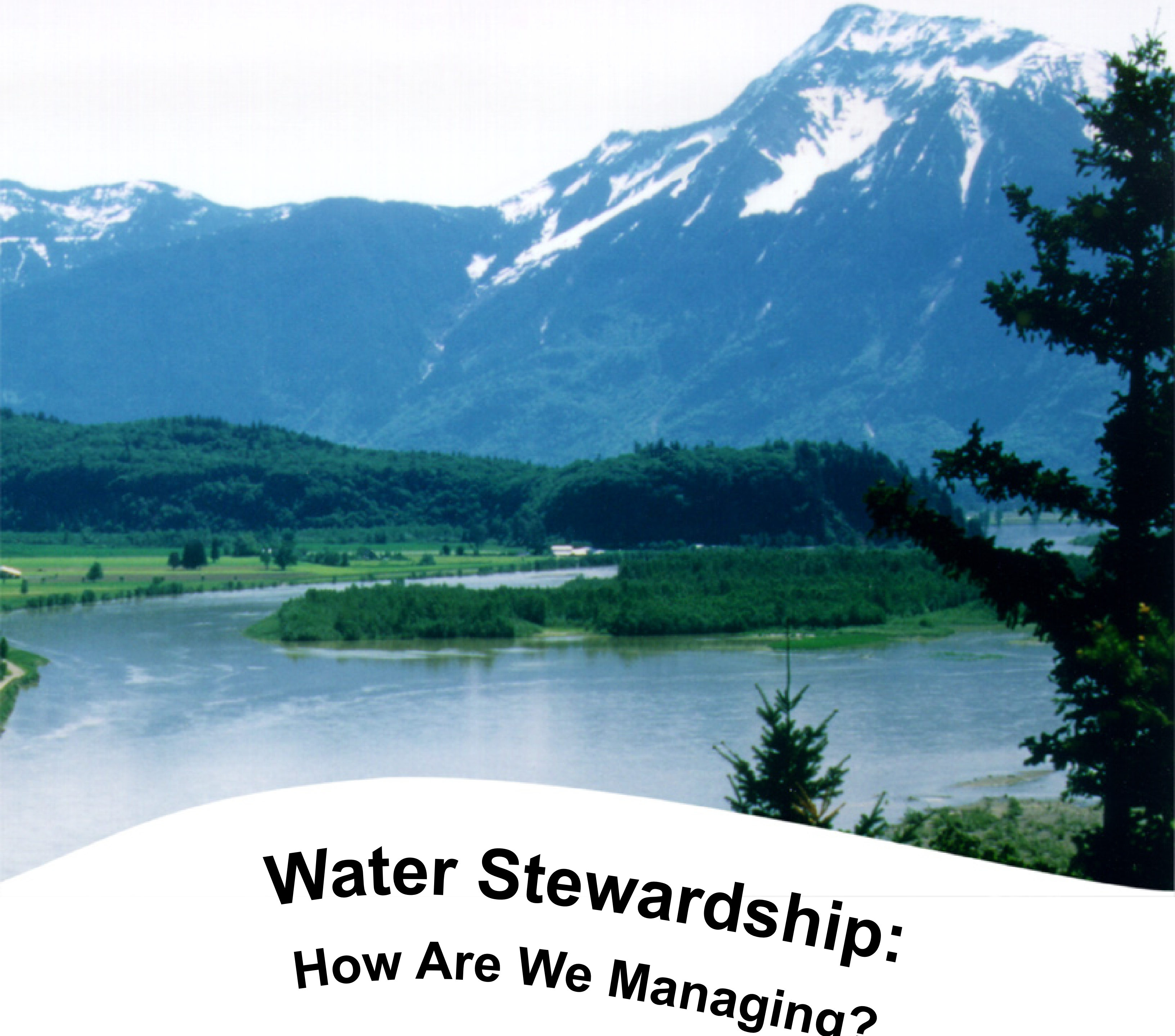

Water Stewardship:

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Peak Flow Effects in BC Forests: Real, Significant and Manageable

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Abstract

This review demonstrates the considerable body of data that now shows, despite substantial and expected variation, that forest clearing and road building are having significant effects on both annual yield and peak flows in the Pacific Northwest. It argues that in the general sense, at least as minima, those responses are predictable. Further, that increases in peak flows have the potential to impact channel shape, function and design, and may act synergistically with other processes, potentially increasing catastrophic effects. Lastly, this paper offers management considerations to help protect streams that would be otherwise sensitive to changes in channel forming flows.

Introduction

Forest removal and its subsequent impact on the hydrologic response of watersheds has been investigated for the last century in North America. As early as 1909, experimental watersheds were designed to determine the type and level of impact from logging practices (Hewlett *et al.,* 1969). Globally, including in North America, the majority of studies have occurred in the last 30 years. Jones and Swanson (2001) suggest that we are currently at a critical threshold in the understanding of watershed hydrology as long–term records of paired basin studies worldwide are dissected to reveal linkages to the physical world. That being said, relatively little work has been completed to date in British Columbia, and one is forced to rely largely on work done in Washington and Oregon.

The issue of hydrologic response to logging is of critical importance to the management of forest lands in coastal British Columbia. Coastal British Columbia encompasses a massive expanse of land of dense forest cover where logging is the major extractive industry. Physiographic and climatic differences mean that hydrologic effects will vary locally; precipitation for example may vary from 1 to 6 m per annum depending on location. These differences correctly give cause for concern about the applicability of broad results, or the applicability of results from the US. However, sustainable management of forest lands requires a threshold level of understanding and acceptance of the effects of harvest and road building on stream hydrology.

This paper summarizes the current state of the art, reviewing in particular, advances in the last decade. It argues that despite variation in the data, increased peak flows and annual yield due to logging and road building are real, predictable in the general case, and relevant to changes in stream morphology. Lastly, it provides general recommendations based on those results.

Annual Yield

Annual yield is the total volume of water leaving a watershed in a given year. It is clear from the last 50 years of data using paired watershed studies that clearcutting results in significant measurable increases to total runoff. The increase in annual yield is primarily a result of changes in evapotranspiration amounts with reduced forest cover. For example,

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mature (100 years old) coniferous forests typical of coastal British Columbia have been shown to intercept about 30% of rainfall (based on 100 mm storm event) and young forests (20 years old) about half of that (Spittlehouse, 1998). Interception and evapotranspiration processes are well documented in the literature and the reader is referred to Bosch and Hewlett, 1982; Hudson, 2000a; McNay *et al.,* 1988; among others.

With rare exceptions, where no changes in annual yield were detected (Harr, 1980; Bosch and Hewlett, 1982), increases in annual yield have been reported across North America from as little as 6% to almost 300% (Bosch and Hewlett, 1982). Local variations are considerably smaller, and may be attributable to several factors including short calibration periods, growth of vegetation following treatment in some studies and not in others, sensitivity to scale effects and short post–logging time frames. The latter is problematic, because effects to annual yield appear to be most prominent in the period immediately following treatment, and are reduced rapidly with afforestation. Thus for many studies, there may never be a long post–treatment period showing measurable effects, and the mean effect of the treatment is subsequently reduced.

The effects of afforestation reducing annual yield are equally well known, and also studied in paired basin studies worldwide (Bosch and Hewlett, 1982).

Regionally, variations in annual yield increases may be the result of many more factors, including the ones mentioned above. Differences in snow accumulation, total annual precipitation, type of vegetative cover (and evapotranspiration potential), precipitation patterns, type of forest clearing, mean annual albedo, geology and soil type, watershed aspect, elevation and slope are among the many factors that make it difficult to relate studies across a large area.

Figure 1 shows the results of 54 studies on changes to mean annual yield following 100% loss of vegetation from paired watershed studies in North America. As suggested previously, the results vary, however, they are all positive, and the lowest mean difference is an increase of 25%. Several individual studies show fairly large increases, up to 109% over the pre–treatment state (Bosch and Hewlett, 1982).

Studies from Oregon and Washington are expected to be the most applicable to the Coastal British Columbia case and several studies in the H.J. Andrews research forest and in Coyote Creek research forest, both in Oregon, present an average increase in annual yield of about 32% (the range being from 15% to 53% increases). Washington's are higher with two studies showing yields increasing 48% and 81%, respectively.

Increases in annual yield recorded in Arizona are substantially higher on average and overall, ranging from 107% to 272% increase over six different experimental watersheds (Hibbert, 1971; Hibbert, *et al.,* 1975; Bosch and Hewlett, 1982). However, annual runoff is low in these dry climates, and even small changes to evapotranspiration have a relatively large effect.

Similar increases are shown worldwide. In Japan, across five watersheds increases are an average of 39%, they are an average of 45% in New Zealand studies, 62% in Kenya and so on (Bosch and Hewlett, 1982). Bosch and Hewlett (1982) looked at 94 cases of vegetation change (either regrowth or removal) worldwide and determined that, in absolute terms, yield changes are greatest in high rainfall areas, however, that those areas are also the quickest to recover (by being revegetated).

In an examination of 25 cases of 100% clearcutting in coniferous forest, Bosch and Hewlett (1982) showed increases in annual yield of more than 15% in 96% of cases. Looking at the data for the Pacific Northwest (Figure 1), one might reasonably conclude that on average, at least 30% increase in annual yield should be expected following removal of 100% of the vegetation.

Peak Flows

The relationship between land clearing and peak flows is more fundamental and, in British Columbia at least, more contested. More fundamental because peak flows of sufficient size are generally considered

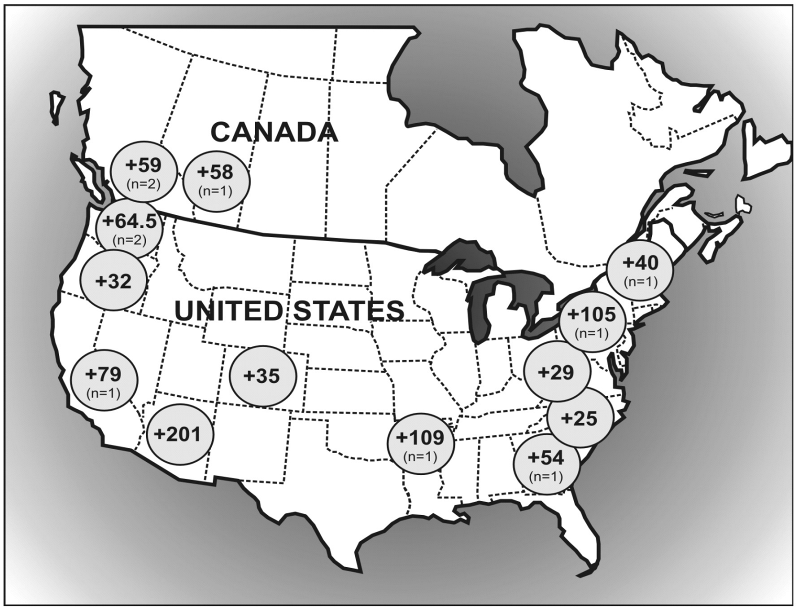

Figure 1. Mean increase in annual yields following 100% vegetation removal in 54 paired basin catchment studies in North America (based on data from Bosch and Hewlett, 1982; Cheng, 1989; Harr et al., 1982; Hibbert, 1971; Hibbert et al., 1975). Results based on two or fewer studies are indicated. There are several studies reported here from the Pacific Northwest, primarily from Oregon and Washington.

to be channel forming, thus strengthening the linkage between channel changes and landuse practices. More contested because it is difficult to separate peak flow effects from natural variability, particularly as those effects are sensitive to a myriad of physiographic inputs. While, for rain and rain–on–snow dominated watersheds, it intuitively makes sense that increased annual yields equate to increased storm runoffs, the economics of landuse decisions require more than intuition alone. Regression statistics are the general tools used to show that empirical observations of change have not occurred merely by chance. Statistical comparisons, however, are fettered by the 'noise' of low flows, the accuracy of measurements, and the power and suitability of tests applied. In addition, the physical parameters in the watershed complicate the data sets. Snow and elevation differences affect the amount of water that is available to runoff from one season to the next, and as with annual yield, precipitation patterns (strength of storm cells), antecedent moisture, geology and soil type, watershed aspect, elevation and slope are among the complicating factors. Unlike measurements of annual yield, however, these complications are enhanced by the limited time to peak following a storm.

Empirically, on the west coast, there should be some cases where peak flow decreases following harvest, and others where it remains undistinguishable. A reduction in fog drip, for example, could result in reduced moisture reaching the ground. Changes in subsurface conditions such as reported by Cheng *et al.* (1975) might do the same. Harr and McCorison (1979) attributed a reduction in peak flows following harvesting to differences in short–term accumulation and melting of snow. Cheng *et al.* (1975) argued a case where logging disrupted subsurface channel networks, effectively sealing them and therefore reducing peak flows. Jones (2000) discusses many of the processes that may account for peak flow reductions or an apparent lack of response, as well as those that result in a measured increase following harvesting. Those discussions are not repeated here. Despite several legitimate exceptions, the majority of data gathered for coastal watersheds and analyzed over the last decade, particularly longer term data, demonstrate strong positive relationships between increased peak flows and logging (Beschta *et al.*, 2000; Jones, 2000; Jones and Grant, 1996, 2001a, and 2001b; Thomas and Megahan, 1998; Wright *et al.*, 1990). These studies also suggest that the proportional increase in peak flow drops as the storm magnitude increases.

Unfortunately, until the last few years, coastal British Columbia has suffered a dearth of information on peak flows. The exception was data from Carnation Creek, however, analysis of this data has been largely unattended. Hetherington (1982, 1998) did report increased peak flows in Carnation Creek at two sites (J weir and H weir) during the first few years following logging, but was unable to measure increases at a third (B weir). Recent long–term analysis has now shown increases at the third site (B weir) as well (Chapman, in review; Chapman *et al.*, 2001).

The focus to date then, has been primarily on the results from the U.S. studies. Two studies in particular have become landmark papers. Jones and Grant (1996) determined the long–term changes in streamflows associated with clearcutting and road construction, stating maximum increases in peak flows from 50–100%. Thomas and Megahan using the same data reported maximum increases in peak flows from 40–90%. Thomas and Megahan, however, applied a further statistical test, termed the maximum detectable flow increase, for flows greater than about 1.8 years, and concluded that the results were not statistically significant. Jones and Grant (2001a) contend that this additional test required that the results be significant to $p < 0.0001$, and Thomas and Megahan (2001) contend that it speaks to the difficulty of predicting peak flow changes given large variability. Often lost in subsequent discussions is the fact that Thomas and Megahan did in fact detect and demonstrate peak flow changes from storms up to and exceeding 10–year return intervals. What they have added with their additional test, is a measure of their uncertainty about the potential variability of data after about 1.8 years.

Additional analysis of several more paired basin studies in the western Cascades (Beschta *et al.*, 2000; Chapman, in review; Chapman *et al.*, 2001; Harr *et al.*, 1979; Jones, 2000; Jones and Grant, 1996, 2001a; and Thomas and Megahan, 1998) helps to resolve a picture of increased peak flows (Figure 2). This includes long–term data analyzed for coastal British Columbia at Carnation Creek (Chapman, in review; Chapman *et al.*, 2001), where increases in peak flows were determined by the statistical techniques used in Jones and Grant (1996) and those used in Thomas and Megahan (1998). Statistically significant increases in peak flows were found in both cases for 10–year return events in two different watersheds. In Figure 2, flow increases from the several studies in the Pacific Northwest were plotted against storm return periods for basins at a 100% logged state. The plots show that there is, as expected, considerable variability in even the long–term data and an average line would not account for much of the data presented.

An exception to the data presented in Figure 2 is a small (10 ha) watershed in Oregon (Andrews 10) where despite a long–term record, a reduction in peak flows of about 8% following logging (Jones, 2000). This is the same watershed noted by Harr and McCorison (1979) and explained by differences in short–term accumulation and melting of snow.

The general case, however, is clear. Based on the majority of long–term data sets in the Pacific Northwest, including British Columbia, increases in peak flows following harvesting are both expected and predictable. The two lines in Figure 2 represent minimum thresholds, beyond which, despite variability, all of the increases in peak flows are captured in these studies. While it under–represents the potential effects of most of the data, it could be used to predict the minimum expected increases to peak flows at various return intervals should logging occur. Therefore, at a minimum, with 100% harvesting in a watershed with roads, peak flows could be expected to increase about 50% for the one–year event, about 35% for the two–year event and so on with the 10–year event still exceeding an increase of 10%.

Several studies have suggested that roads effectively increase the drainage network in a watershed, intercepting, collecting and rerouting water into streams and consequently increasing the timing and magnitude of peak flows (Harr *et al.*, 1975; Jones and Grant, 1996; Reid, 1981; Reid and Dunne, 1984; Wemple *et al.*, 1996; Ziemer, 1981, among others). The data summarized in Figure 2 suggest a visible road effect, however, there remain unanswered questions such as why those effects would not persist beyond the 10–year period. It is difficult to answer the question without knowing the particular case histories of various paired basin studies. Jones (2000) detected increases of 13–36% in peak flow events greater than one year for several paired basin studies, and stated that the effects did in fact persist for decades. Jones (2000) stated further, however, that road effects on subsurface flow interception varied according to design and position of each.

In either case, the current information allows us to generally predict the effects of logging (without roads) on peak flows in a watershed. At a minimum, with 100% harvesting in a watershed with no roads, peak flows could be expected to increase about 16% for the one–year event, about 11% for the two–year event and

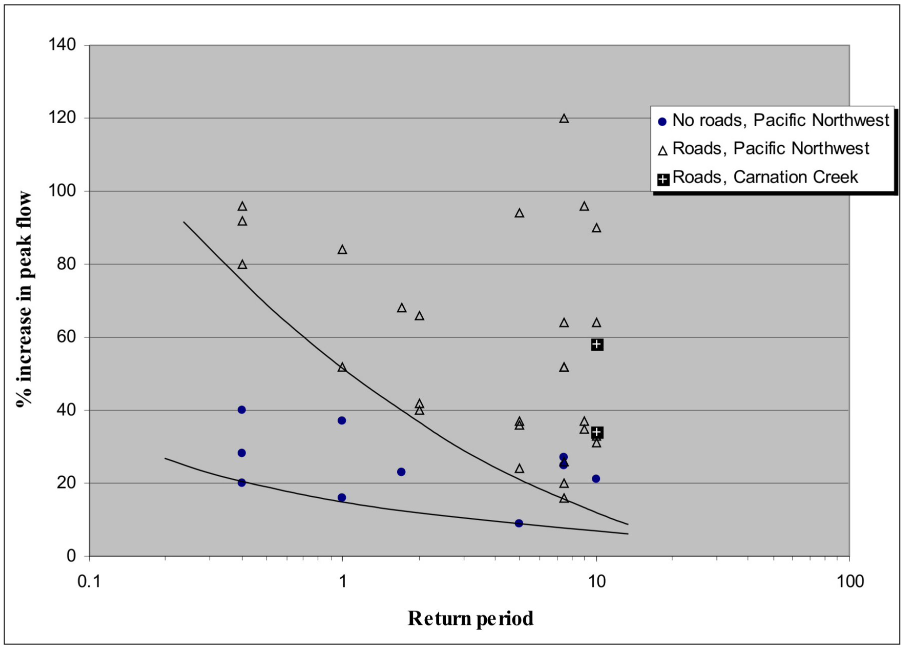

Figure 2. Peak flow increases calculated based on 100% clearcutting in 10 research watersheds in the Pacific Northwest (derived from data in Beschta et al., 2000; Chapman, in review; Chapman et al., 2001; Harr et al., 1979; Jones, 2000; Jones and Grant, 1996, 2001a; Thomas and Megahan, 1998). Lines represent minimum increases in peak flows (in percent) that capture all the data for a given return interval. Note: In order to compare studies against one another, peak flows have been increased linearly with harvesting when total harvested area was less than 100% similar to extrapolations by previous authors (Beschta et al., 2000; Jones and Grant, 1996, 2001a; Thomas and Megahan, 1998).

so on with the 10–year event still showing measurable increases. Again, this will likely underestimate the actual impact of harvesting on peak flow effects.

Additional work in coastal British Columbia watersheds suggests that these numbers may be too conservative (Hudson, 2001 and 2002). In a classic paired basin approach in the Roberts Creek Study Forest (Hudson, 2001), peak flows were increased 77% to 194% (at about 10% to 40% harvest, respectively) for events greater than 0.5–year return. This may be the result of a very short data set (about three years), as well as a small sensitive study area (a total of 116 ha over three watersheds). However, the results are similar to his analysis of 10 years of data at Russell Creek (Hudson, 2002). Here, he concludes that mean response to a change in Equivalent Clearcut Area (ECA is a model that accounts for forest and hydrologic regeneration, equating the landscape to a clearcut of equivalent size) is, at 10% ECA an increase in peak flows of 50%, and at 17.5% ECA an increase in peak flows of 70%. Both of these studies suggested that the increases were not related to road development which remained largely unchanged for the period of record. Chapman[2] (in review) has compiled and analyzed 30 years of data at Carnation Creek and found mean peak flows increased of 45% for the two–year return event following 50% clearcutting with roads in a 930–ha basin. Similarly, in a smaller, 12–ha basin within Carnation Creek, he found mean peak flows increased of 37% for the two–year return event following 90% clearcutting with roads. For both basins, statistically significant increases in peak flows were detected for events as large as 10–year return period (Chapman *et al.*, 2001). Mean 10–year increases are displayed in Figure 2. Both authors show that the results are significant beyond the two–year limit determined by the maximum detectable flow increase used by Thomas and Megahan (1998).

The recent results from coastal British Columbia suggest that for the highly responsive streams that comprise our landscape, the effect of clearcutting on peak flows is large. It is likely that the U.S. studies, which occur below the glacial limit and therefore have

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[2] Author's note, March 2003: Carnation Creek may have some significant inherent study design problems. Consequently, as of this date, these numbers are under review and may be reduced.

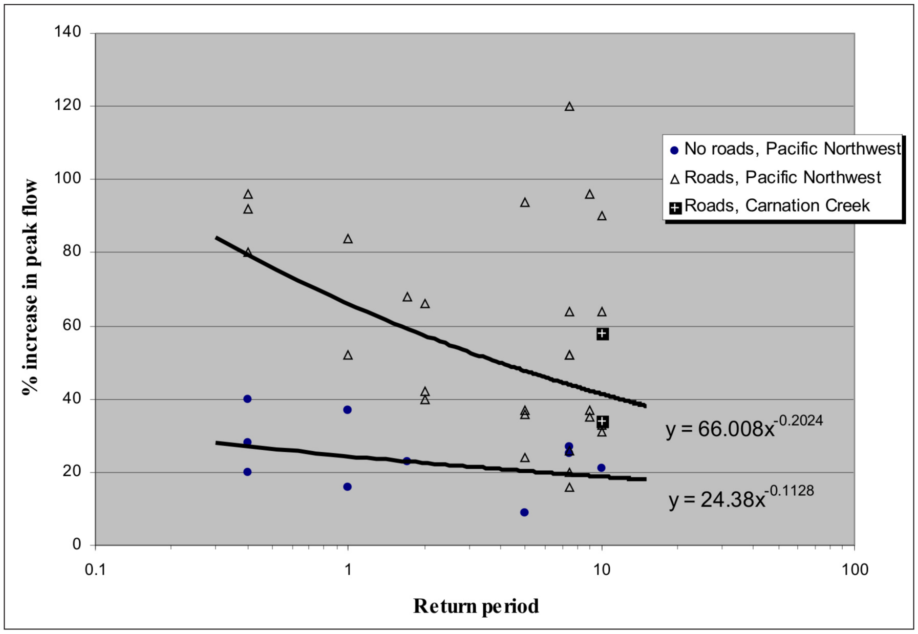

Figure 3. Peak flow increases calculated based on 100% clearcutting in 10 research watersheds in the Pacific Northwest (derived from data in Beschta et al., 2000; Chapman, in review; Chapman et al., 2001; Harr et al., 1979; Jones, 2000; Jones and Grant, 1996, 2001a; Thomas and Megahan, 1998). Lines represent best fit power curves. These capture little of the overall variability, however, may be used as an alternative to predicting effects of peak flow increases in coastal BC, whose streams appear to be highly responsive to changes in forest cover. Note: In order to compare studies against one another, peak flows have been increased linearly with harvesting when total harvested area was less than 100% similar to extrapolations by previous authors (Beschta et al., 2000; Jones and Grant, 1996, 2001a; Thomas and Megahan, 1998).

deeper soils, are less sensitive to increased peak flows than coastal British Columbia. With this in mind, an alternative to managing for the minimum expected increases is to use a best fit line through the long–term data. Figure 3 shows two such power curves through that data in the Pacific Northwest. It is recognized that the fit accounts for little of the variability, however, it remains substantially lower than much of the recent coastal British Columbia research results. Hudson's (2001 and 2002) work was not included on the graph because the paired basin study was very short, and the Russell Creek study used an alternative method of analysis based on a rainfall intensity model. The results may, however, be rapidly extrapolated from the above text, and the reader will note that they would fall well above the curves.

Linking Peak Flows and Channel Morphology

Recently, the importance of increased peak flows has been questioned. The question draws perhaps from the debate around the significance of 'large' events, following the Thomas and Megahan (1998) paper. At what point do peak flows substantially affect the morphology of the stream channel, and how does that compare with other channel forming processes?

Other disturbances affecting stream morphology have been highlighted correctly as being orders of magnitude more damaging (Jakob and Jordan, 2001; Millar and Quick, 1993; Millar, 2000; among others). For example, Jakob and Jordan (2001) point out that many mountainous streams in British Columbia suffer from periodic debris flows. The peak flow as measured during these events may range from 2 to 200 times more than the 200–year maximum determined through typical precipitation and runoff analysis. Hogan and Schwab (1991) and Hogan *et al.* (1998) have observed that the geomorphic effects of landslides on a stream persist from 5–60 years in the channel. Millar (2000) showed that streamside logging (a common practice under previous logging regimes in British Columbia) could result in channel widening more than three times the original width due to a loss in bank strength. Again, the effects to stream morphology would be expected to persist over decades.

Analogs to both examples of processes that may impact stream channel morphology are readily found in coastal British Columbia. At the same time, they are not ubiquitous. Since 1995, streams have been afforded a protective buffer, and many older streams that were logged to the banks are beginning to recover. Landslides are intermittent and debris flows do not occur in all streams, or may be separated by decades. We have stated previously that peak flows of a given size are expected to be channel forming, and that changing those will likely result in morphological changes. The question remains, however, peak flows of what size?

Despite the aforementioned debate about whether peak flows are increased in large storms (Jones and Grant, 2001; Thomas and Megahan, 1998, 2001; among others) the return period for the main channel forming event is actually low and within the range of agreement of most authors. As early as 1960, Wolman and Miller (1960) determined that bankfull discharge had sufficient power and consistency to be the main channel forming flow. They further stated that for large alluvial rivers, this event occurred every one to two years. They acknowledged that higher magnitude events including landslides, new gully formation, massive floods and avulsions had enduring impacts on the channel, but noted that those events were spatially and temporally capricious and dropped in frequency as they increased with magnitude. Leopold *et al.* (1964) went on to refine the bankfull definition as occurring on average once every 1.5 years.

Castro and Jackson (2001) recently re–evaluated the bankfull discharge relationship for the Pacific Northwest in the United States, and determined the mean return value to be 1.4 years. For the wetter west coast regions, it was reduced to 1.2 years. Faustini (2000) looked at mountain stream channels estimated to include non–fluvial landforms and determined that peak flows with return intervals of 1.7–3 years produced detectable changes at 25% of sites. Faustini and Jones (2001) similarly determined that 2–3 year return intervals resulted in detectable channel changes at 50% of sites and the mobilization of D_{50} sized material. Measurable changes in smaller streams (third order tributaries) were detected at return intervals of 4–6 years. Faustini (2000) estimated that if peak flows were increased 10% across the range of sizes, there would be 30–60% more peak flows of a magnitude large enough to produce measurable channel changes.

In British Columbia, Hudson (2002) determined the bankfull event at almost 1.4 years in Russell Creek. Given peak flow changes, that return interval was reduced to 0.78 years and Hudson (2002) suggested that sediment transport processes now operate 74% more frequently than prior to harvesting. Hudson (2002) observed physical indications of channel degradation to corroborate his hypotheses. Therefore, channel forming flows are occurring more frequently following harvesting, and with greater magnitude. Further, despite potential order of magnitude impacts from other processes to a stream, the increased flows will produce measurable changes in morphology that cannot be ignored. Thirdly, the increased flows will likely act synergistically with other processes, such as erosion of less stable banks and debris flow potentials, to increase the likelihood of sudden catastrophic changes.

Management of Peak Flow Effects

Harr *et al.* (1979) determined that peak flow increases could be managed and minimized in a watershed using a 100–year rotation at a rate of cut equal to 1% per annum. He showed that each year, the previous years' harvests recovered somewhat until the peak flow effect becomes negligible after about 30 years from the cut date. This principle is the same as that of ECA used in British Columbia where hydrologic recovery is matched with stand height (Hudson, 2000a, 2000b; Ministry of Forests and Ministry of Environment, Lands and Parks, 1995). A hydrologic recovery rate of 30 years is a reasonable fit to coastal British Columbia forests where full recovery generally occurs between 9 m and 12 m forest stand height (Hudson, 2000a, 2000b; Ministry of Forests and Ministry of Environment, Lands and Parks, 1995). At a rate of cut of 1% per year with hydrologic recovery in 30 years, the ECA may be determined by the following formula:

$$ECA = \sum_{n=1}^{t} a\,(1-\frac{nR}{100})$$

where ECA = Equivalent clearcut area
t = the number of years to hydrologic recovery (30 in this example)
a = 1% of total area
R = a recovery constant defined by: the total area A, divided by t.

Expressed as a percentage of the total area, a 1% rate of cut yields 14.5% ECA over the 30–year recovery period and perpetually thereafter. This is equivalent to saying that there is only 14.5% of the watershed clearcut at any given time. While there are several indications that sensitive streams would still be affected by peak flows, Harr *et al.* (1979) pointed out that the effects would be considerably reduced, and more within the range of stream variability. In British Columbia, the Coastal Watershed Assessment Procedure (Ministry of Forests and Ministry of Environment, Lands and Parks, 1995) recommended limiting harvest to 20% ECA in several cases where increased peak flows could impact streams, surface erosion or result in landslides. In practice, an ECA limit of 30% is commonly used and recently, recommendations around ECA have been removed in the second edition of the guidebook (Ministry of Forests and Ministry of Environment, Lands and Parks, 1999). Based on data from the last decade, however, it would seem that ECA or some equivalent measure is valuable, and that the guidebook was on the right track with management recommendations.

In 1995, the Clayoquot Sound Scientific Panel independently determined that a 1% rate of cut was appropriate with regard to hydrology and long–term sustainable wood supply (Clayoquot Sound Scientific Panel, 1995). They proposed that rate of cut be applied by watershed area whereby watersheds greater than 500 ha meet the 1% rate of cut over five years and watersheds 200–500 ha meet it over 10 years. This was done to lend flexibility to cutting plans in changing markets. Watersheds less than 200 ha were not addressed, however, management policy could be extrapolated from the above numbers.

While not definitive, the 1% rate of cut appears reasonable based on the limited information available to date. The variability in data means that some sites may be more sensitive to peak flow changes, and others more robust. This will affect actual on the ground decisions, however, should not greatly affect the general management plan.

Conclusions

Determining the hydrologic response of watersheds to logging activities is not a simple task. It is complicated by many systems interacting, all having the potential to affect the outcome. Despite a hundred years of concern, the majority of quantifiable work in this area of study has been done in the last three decades. Long–term data and better use of statistical techniques have only been employed for half that time. Early information generally determined that logging was increasing total annual yields, but until recently, the effects from peak flows remained elusive.

That is no longer the case. There is a considerable body of data now showing that despite substantial but expected variation, logging practices are having significant effects on peak flows and the hydrologic response of watersheds. What is more, in the general sense at least as minima, those responses are predictable.

Further, increases in peak flows will impact channel shape, function and design, and may act synergistically with other processes, potentially increasing catastrophic effects. The effects of peak flows cannot be dismissed despite the existence of other channel impacting mechanisms.

Lastly, this paper argues that peak flows are a manageable concern, and that standards such as a 1% rate of cut or a relatively low equivalent clearcut area will help protect streams that would be otherwise sensitive to changes in channel forming flows.

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