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HYDROLOGIC DECISION MAKING TOOLS FOR SUSTAINABLE FOREST MANAGEMENT IN RAIN DOMINATED COASTAL BC WATERSHEDS

Operational Summary:
Effects of Forest Removal

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Introduction

Forest harvesting practices, including both forest removal and road construction, in the coastal mountains of British Columbia (BC) have the potential to alter the streamflow regime by increasing the magnitude, duration, and frequency of peak flow events. Such shifts in the regime of what could be geomorphically and ecologically significant events can have substantial consequences arising from changes to the distribution of water, energy, sediment, and nutrients within the channel and its associated riparian area [Ziemer and Lisle 1998]. Over time, the altered trajectory of channel development may seriously jeopardize the availability and quality of stream-associated resources. As a result, forest planners require knowledge of how forest operations may affect streamflow regime of coastal rain-dominated watersheds. This note provides a summary research investigating the impacts of forest removal alone upon the peak flow regime of Carnation Creek, a small rain-dominated coastal BC watershed. The effects of road construction are addressed in an accompanying operational summary Alila and Schnorbus [2005a]. The information presented herein is condensed from the work of Alila and Schnorbus [2005b].

Study Area

Carnation Creek watershed is located on the west coast of Vancouver Island and drains into Barkley sound, near the town of Bamfield, British Columbia (see Inset, Figure 1). The basin area of 9.8 km² contains rugged topography with elevation ranging from sea...
level to 900 m and basin slopes as steep as 40 to over 80%; although the lower 3 km of Carnation Creek flows through a relatively wide (50 to 200 m) valley bottom (Figure 1). Slope soils, which are underlain by watertight bedrock of volcanic origin, are derived from colluvial materials and are of gravely sandy-loam and loamy-sand texture. Soils are generally shallow, with a mean depth of 0.75 m, and are highly permeable.

The watershed lies entirely within the Coastal Western Hemlock (CWH) biogeoclimatic zone and prior to management was covered by climax forest composed primarily of western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and amabilis fir (*Abies amabilis*), with some Douglas fir (*Pseudotsuga menziesii*) in drier sites, Sitka spruce (*Picea sitchensis*) in the valley bottom, and red alder (*Alnus rubra*) along the stream margins. About 50% of the basin was clearcut logged in various stages between 1971 and 1990. The original climax forest has dominant overstory tree heights ranging from 23 to 43 m, and canopy density that ranges from 50 to 75%.

Annual precipitation ranges from 2100 mm at sea level to over 4800 mm at high elevation, with 95% falling as rain. Over 75% of precipitation falls during October through March during frequent frontal storms. Some snow occurs at high elevations in most years, but typically disappears quickly. For the most part, Carnation Creek lies below the transient snow zone and streamflow closely follows rainfall patterns, exhibiting flashy runoff.

**Method**

Streamflow in Carnation Creek was simulated for a variety of hypothetical clearcut harvesting scenarios using the distributed hydrology-soil-vegetation model (DHSVM) of Wigmosta et al. [1994]. This is a physically based distributed parameter model that explicitly estimates the spatial distribution of water fluxes by subdividing the model domain into small computational grid elements using the spatial resolution of an underlying 10-m digital elevation model (DEM). The digital elevation data are used to model topographic controls on meteorology, energy, and water movement. Water balance equations are solved simultaneously in each grid cell, accounting for evaporation, transpiration, snow accumulation and melt, and soil moisture storage. Vegetation influences on water and energy fluxes modelled explicitly. Grid cells exchange water with adjacent cells, resulting in a downslope distribution of surface and subsurface water across the watershed. Subsurface hillslope runoff is modelled as both matrix and/or preferential flow (i.e. via macropore channels), depending on rainfall intensity. Hillslope runoff eventually collects in the channel network and routed to the basin outlet as streamflow. The DHSVM was calibrated and validated for the study area by Beckers and Alila [2004].

The response of the peak flow regime to forest removal was investigated using 30 scenarios based on hypothetical clearcut harvesting with rate-of-cut (*ROC*) varying from 0 to 100%. Scenarios were designed using two different approaches. Firstly, eleven scenarios were constructed based on the point-of-interest (POI) located at the basin outlet.
(upstream drainage area fixed at 9.8 km²). The ROC was adjusted from 0 to 100% (in increments of roughly 10%) by changing the size of the total harvest area within the basin, using randomly generated cut blocks. Secondly, nineteen scenarios were constructed by using a single fixed harvest block located in the headwaters of either C- (7 scenarios) or E-tributary (12 scenarios). The ROC was adjusted from 100 to 0% by progressively moving the POI downstream from just below the harvest area (ROC = 100%; upstream drainage area of 0.88 or 0.96 km²) to the basin outlet (ROC ≈ 9 or 10%; upstream drainage area of 9.8 km²).

Streamflow was simulated using 18 years of meteorological data collected at various climate stations within the study area (Figure 1) between 1972 and 1990. An 18-year hourly streamflow series was generated for each harvest scenario and a control scenario (original pre-management forest cover). A partial duration series (PDS) (all peak flows above a certain threshold value) of peak flows was subsequently extracted from each generated 18-year streamflow series. The PDS data were then used to estimate hourly peak flow magnitudes using flood frequency analysis for partial-duration return periods ($T_p$) ranging from 0.17 to 20 years (2 to 240 months). Relative changes in peak flow were assessed by comparing the control to the harvest peak discharge for each $T_p$ for a given ROC. As the initial concern is with the detection of the immediate impact of forest harvesting, scenarios did not incorporate vegetation recovery (i.e. clearcuts remained clearcuts throughout the simulation). The possible effect of soil compaction due to skidding was also ignored.

**Results and Discussion**

The flood frequency analysis approach of comparing flood quantiles estimated from the simulated flood peaks is shown graphically in Figure 2, which compares flood quantiles for 100% ROC for the entire 9.8-km² basin to those for the control scenario. Due to increased sampling variance for less frequent flood events the estimated 95% confidence interval increases with increasing $T_p$ (dashed lines in Figure 2) from 1.4 to 11.4 m³/s for $T_p$ ranging from 0.17 to 20 years, respectively. In this extreme harvesting case the discharge following forest harvesting is consistently increased for all $T_p$. However, the absolute increase in peak discharge generally decreases with increasing $T_p$ and is only significant (i.e. where post-harvest discharge exceeds upper confidence limit) for very small return periods ($T_p < 1$ year). Taken over all scenarios, the flood frequency analysis confirms that hourly peak discharge is increased following forest removal. However, the increase in peak discharge is not generic and follows two trends: the relative increase of peak discharge a) increases with increasing ROC (for a given $T_p$), and b) decreases with increasing $T_p$ (for a given ROC). Statistically significant ($\alpha = 0.05$) increases in hourly peak discharge are restricted to $ROC > 30\%$ for $T_p = 0.17$ years, $ROC > 60\%$ for $T_p = 0.5$ years, $ROC > 80\%$ for $T_p = 0.75$ years and $ROC > 90\%$ for $T_p = 1$ year. Relative increases in hourly peak discharge are statistically insignificant for $T_p \geq 2$ years for all ROC.
The trend of relative peak discharge increase with $ROC$ for return periods of 0.17, 0.5, 1.0 and 20 years for all 30 scenarios is shown in Figure 3; relative increases in peak discharge range from -4 to 30%. From this figure it is also apparent that the relative increase in hourly peak discharge displays a linear relationship with $ROC$. Linear regressions of the form

$$\Delta \hat{Q}_{T_p} = b_0 + b_1 \cdot ROC$$  \hspace{1cm} (1)$$

have been fit for $T_p = 0.17, 0.5, 0.75, 1, 2, 5, 10, 15$ and 20 years; where $\Delta \hat{Q}_{T_p}$ is the estimated relative increase in hourly peak discharge for given $T_p$ and $b_0$ and $b_1$ are regression parameters (intercept and slope respectively). The regression results are summarized in Table 1. All regressions are significant at $p < 0.001$ and all slopes, $b_1$, are significant at $p < 0.001$. The regression relationship given by (1) has been plotted for $T_p = 0.17, 0.5, 1$ and 20 years in Figure 3. The slope of (1) decreases with increasing $T_p$, confirming the results of the flood frequency analysis that indicated that the sensitivity of peak discharge to forest harvesting decreases with increasing event magnitude. Additionally, the trend of the coefficient of determination, $R^2$, suggests that the relationship between $\Delta \hat{Q}_{T_p}$ and $ROC$ weakens with increasing $T_p$. The scatter about the relationship defined by (1), which is evident from Figure 3, is attributed to variations in the spatial distribution of cutblocks, and variations in upstream drainage length, structure and density for similar $ROC$. The statistical significance of the regression results (Table 1) should not be confused with the statistical significance associated with the flood frequency analysis. The regression results simply state that $\Delta \hat{Q}_{T_p}$ increases with increasing $ROC$ in a statistically significant fashion. The flood frequency analysis tells us...
As Table 1 illustrates more specifically (and more informatively) whether or not the relative increase in peak discharge at a given $T_p$ and $ROC$ is significant (in most cases it is not). Additionally, as $T_p$ increases the standard error of regression eventually takes the same order of magnitude as $\Delta \hat{Q}_{Tp}$, such that the predictive uncertainty of $\Delta \hat{Q}_{Tp}$ is almost as large as $\Delta \hat{Q}_{Tp}$ itself. In other words, the relative increase in hourly peak discharge for $T_p \geq 2$ years is so small to begin with that there is little utility in attempting to predict it with linear regression.

<table>
<thead>
<tr>
<th>$T_p$ (years)</th>
<th>Intercept, $b_0$ (%)</th>
<th>Slope, $b_1$ (-)</th>
<th>Standard Error (%)</th>
<th>$R^2$</th>
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<tbody>
<tr>
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<td>0.30</td>
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<tr>
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<td>-0.20</td>
<td>0.04</td>
<td>0.96</td>
<td>0.65</td>
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</table>

*All regressions significant at $p < 0.001$; all slopes ($b_1$) significant at $p < 0.001$.

In general, the relative change in peak discharge (as result of forest harvesting) with return period can be related to the physical process governing runoff production in low-elevation rainfall-dominated coastal watersheds. The strongest impact upon peak discharge occurs at return period equal to (and by extrapolation, less than) 0.17 years. This return period marks the transition from subsurface runoff dominated by matrix flow, which is sensitive to changes in runoff efficiency resulting from changes in antecedent moisture, to subsurface runoff dominated by preferential flow, which is already a highly efficient runoff mechanism and is generally insensitive to antecedent soil moisture [Alila and Schnorbus, 2005b]. At return periods greater than 0.17 years, changes in peak discharge are attributed to the reduction in rainfall interception; the relative increase in peak discharge decreases with increasing return period due to the decrease in interception efficiency with increasing storm size.

**Conclusion**

This report has presented the results of the use of a physically-based distributed parameter model to investigate the impacts for forest management on the rain-dominated 9.8 km$^2$ Carnation Creek watershed located on the west coast of Vancouver Island, British Columbia. The model used accounts explicitly for the effects of vegetation upon
runoff production and is also unique in its explicit portrayal of preferential subsurface runoff processes common to forested watersheds. The effects of forest harvesting upon the peak flow regime were investigated using 30 scenarios which specifically focussed on the effects of cut rate. Flood frequency analysis was used to quantify the relative change in peak discharge for return periods ranging from 0.17 to 20 years.

The results of this study are in general agreement with the results of Thomas and Megahan [1998] and Beschta et al. [2000], and show clearly that forest harvesting in rainfall-dominated watersheds in the Pacific Northwest has the largest impact on peak discharge at very low return period events, and that the effect of forest harvesting diminishes rapidly as return period increases. Additionally, statistically significant increases in peak discharge only manifest at the lowest return periods ($T_p \leq 1$ year in all cases), and then only when $ROC$ exceeds at least 30%. The simulation results also suggest that the relative change in peak discharge is linearly related to rate of cut and that this relationship is statistically significant at all return periods; implying that the potential impact of forest harvesting upon peak discharge can be estimated for any return period for cut rates ranging from 10 to 100%. However, as the standard error of the regression eventually approaches the same magnitude as relative peak discharge change as return

Figure 3. Relationship between percent increase in peak discharge and $ROC$ for all scenarios showing individual values and fitted linear regressions.
period increases, these relationships have questionable use for return periods greater than two years.

It must be reiterated that the effects analysed represent the maximum potential impacts that are expected to occur immediately following forest harvesting operations. Increases in peak discharge due to forest removal can be subject to reductions flowing regrowth [Thomas and Megahan, 1998], although the nature and extent of hydrologic recovery will likely depend to some degree upon the physiographic and structural properties of the recovering vegetation.

References


