Modelling the Effects of Forest Roads and Harvesting in a Snow-Dominated Interior Catchment in South Eastern British Columbia

-Fiscal Year Report-

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INTRODUCTION

A. Overview

1. The Effects of Forest Roads and Harvesting

Following road construction and forest harvesting, the hydrograph in a watershed can be expected to change through four mechanisms: an increase in snow accumulation and melt, decrease in evapotranspiration, and decrease in channel roughness from large woody debris removal, and extension of the channel network by roads [Jones & Grant, 1996]. An increase in snow accumulation and melt combined with a decrease in evapotranspiration can affect the hillslope water balance by increasing peak discharge and storm flow. A decrease in channel roughness with extension of the channel network can affect flow routing by speeding stormflow, and advancing the peak discharge without a change in volume.

In snow-dominated watersheds, the interception of flows by roads, as well as the increased snowpack and snowmelt from forest canopy removal leads to increasing the water yield and advancing the timing of runoff, which increases peak flows and reduces late-season low flows. The Interior Watershed Assessment Procedure (IWAP) [British Columbia Ministry of Forests, 2001] includes a peak flow hazard index score calculation which is used to express the susceptibility of a watershed to increased snowmelt peaks due to roads and harvesting. This is based on the Equivalent Clearcut Area (ECA), and the extent to which the ECA lies above the H60 elevation. Roads are assumed to hasten surface runoff and reduce groundwater recharge, so road densities above and below the H60 contour are used in combination with ECA to rate the peak flow hazard.

Roads interact positively with clearcutting by modifying flowpaths and speeding the delivery of water to stream channels during storm events; the combination of the two produces greater changes in peaks than either alone. Jones and Grant (1996) found that there was an increase in peak discharge due to clearcutting and roads, independent of return period; clearcutting and roads increased peaks by as much as 50% in small (less than 101 hectare) basins and 100% in large (60-600 square kilometre) basins over 50 to 55 year return periods. The authors also found similar percent increases in peak discharge due to roads and harvesting during the largest storm events. Roads and
clearcutting interacted to produce larger peaks, and shorter lag to the peak, the major mechanism being the connectivity of the road system to the channel network. These increases were attributed to changes in flow routing by roads and an increase in the water balance from forest removal.

The location of forest removal relative to roads is important in determining their combined impact the hydrology of a watershed. Road segments located below areas of forest removal will have a greater contribution to subsurface interception as long as road cuts intercept the soil profile. This is due to the increase in soil moisture above the road as a result of a reduction in evapotranspiration. On the other hand, harvesting below roads increases soil moisture in the lower area, which counteracts the loss of moisture from runoff diverted by the road network [Bowling & Lettenmaier, 1997].

It is difficult to separate the effects of forest harvesting and roads, because many of the hydrological processes from the two treatment types can occur simultaneously and their individual effects are obscured or mitigated by other processes. For instance, Tague and Band (2001) found with numerical modelling that the individual effects of roads diminished slightly post-harvest as opposed to pre-harvest, due to higher flow volumes after harvesting. Due to the integrative nature of the two, many studies investigated the combined effects of forest removal and roads on watershed hydrology [refer to: Beckers & Alila, 2004a; Beschta, 1978; Bowling & Lettenmaier, 2001; Harr et al., 1975; Jones, 2000; Jones & Grant, 1996; Tague & Band, 2001; Thomas & Megahan, 1998; Ziemer, 1981].

Bowling and Lettenmaier (2001) found that roads and harvesting increased peak flows more than either alone, but the effects were additive rather than synergistic. The increase in peak flows due to roads alone was approximately equal to that of harvesting alone. Contrary to this, Jones and Grant (1996) found that the combined effect of roads and harvesting can be greater than their additive effect.

In general, hydrologic recovery of a watershed after road building takes much longer than harvesting due to the modification of physical hydrologic pathways, in which roads have a more persistent and pervasive effect; harvesting principally effects evapotranspiration which recovers over time [La Marche & Lettenmaier, 2001; Gucinski et al., 2001].
2. Objectives

The purpose of this research is to apply a physically-based, spatially distributed hydrological model in combination with long-term synthetic meteorological data to examine the simulated effects of harvesting and roads on streamflows in 241 Creek, a snow-dominated watershed located in the Okanagan area of south-eastern British Columbia. The specific objectives were to look at the sensitivity of streamflow metrics to hypothetical and existing operational harvesting scenarios, with and without roads. The hydrologic model is used in combination with long-term synthetic meteorological data, to generate streamflows that can be quantified with peakflow discharges of increasing return period. The effects of roads were of particular interest, and this report focuses on the central hypothesis that avenues exist through which road networks can increase streamflows by replacing subsurface flow paths with surface flow paths, and that these avenues can be represented by a spatially distributed hydrological model.

B. Hydrological Significance of Forest Roads

1. Overview

Forest roads can play a major role in altering the hydrological processes of a forested landscape. The quantitative and qualitative effects of forest roads on hydrology are more evident at the catchment or watershed scale, and most studies of roads are performed at this level. The primary purpose of forest roads is for access to natural resources for extraction. Forest roads are most often developed by the timber, energy, and mining industries, but also end up serving as access routes for wildland fires, non-timber forest products, grazing, and outdoor recreation [Gucinski et al., 2001]. This report deals exclusively with forest roads developed for timber extraction.

Forest engineers in British Columbia (BC) design forest roads for timber extraction with three main simultaneous considerations in mind:

1. Selection of the route with minimal travel distance
2. Observation of maximum road grades and curve radii
3. Reducing the impact of roads on the landscape and environment, by meeting the requirements of the *Forest Practices Code of British Columbia Act* (Act), and all associated regulations [British Columbia Ministry of Forests, 2002]

It is the first two considerations in road design that create the potential for forest roads to have a great impact on the hydrological processes of a watershed. The first consideration reduces the travel distance and minimizes the amount of land designated to road networks; thereby reducing vehicle travel time, road construction costs, and environmental disturbance. The second consideration caters to the needs of the larger vehicles required for timber extraction. The combination of the two design considerations results in the incision of forest roads into topography of the landscape. The environmental impacts of forest road design are strongly related to the design elements of the road cross-sectional width: cutslope, road surface, and fillslope; which are largely controlled by the topography of the landscape, soils and intended traffic [Gardner, 1979]. Road prism incision can be in two forms: one required when the route is along a hillslope steep enough, so that the road bed needs to be cut into the hillslope to create a generally horizontal cross-sectional surface; and the other that is required to reduce the gradient of a road, when the route approaches a rise in the landscape.

In the following section, an explanation is made of the hydrological processes altered and created by forest roads, followed by a section on the implications of such processes.

2. Processes

Forest roads intercept water directly in the form of precipitation on the road surface and right-of-way, and by road cuts intercepting water moving in subsurface layers down the hillslope. The two forms of water interception by roads combined can constitute a significant proportion of the water balance in a watershed. Water intercepted by roads is channeled into adjacent ditches or streams, being diverted from its natural paths of flow. Most hydrologic and geomorphic consequences of roads are a result of one or more of these processes.

Subsurface flows intercepted by roads can be in the form of deep groundwater flow or subsurface stormflow. Subsurface stormflow is water that infiltrates the surface
during and shortly after a storm, and moves laterally through upper soil layers as unsaturated flow or as shallow, perched saturated flow above the main groundwater table. Groundwater flow occurs from the deep percolation of infiltrated water that enters the saturated groundwater flow system [Bowling & Lettenmaier, 1997].

Incision of the landscape by forest roads can result in the interception of subsurface flows that would normally continue to flow below ground, had the roads not been constructed. The maximum depth of subsurface flow interception by a road segment can be determined by the perpendicular depth of a road segment’s cutbank in reference to the hillslope. This can easily be calculated by:

\[
H = h \times \sin(\gamma - \theta)
\]

Where:
- \(H\) = maximum depth of road interception
- \(h\) = cutbank slope length
- \(\gamma\) = cutbank slope (in degrees)
- \(\theta\) = hillslope slope (in degrees)

For road subsurface flow interception to occur, the water table has to raise high enough to be intercepted by the road cut, in which case subsurface flows are diverted into road side ditches. However, in cases where the road prism is cut right into the bedrock, all subsurface flows will be intercepted, regardless of the height of the water table. Subsurface flow interception is most likely to occur in watersheds with steep slopes over 40% [Carver, 2001], where the deep incision of the road prism into the hillslope, results in deep road cuts. However, La Marche and Lettenmaier (2001) found that road cut height did not seem to affect subsurface flow interception, which is contrary to what is expected. This could be due to the findings of Megahan (1972), who estimated that 65% of subsurface flow passes below road cuts, probably occurring in rock joints and fractures. In cases where the bedrock lies below the road cut, quite often in watersheds with subdued topography, the water table first has to rise above the road cut to be intercepted; usually only occurring after a substantial amount of rainfall or snowmelt has recharged the groundwater table. Wemple and Jones (2003) found that on steep slopes,
the surface area occupied by road surfaces is small in comparison to the hillslope areas intercepted by road cuts, and road segments whose road cuts intersected the entire soil profile were most likely to produce runoff from subsurface flow interception; hillslope length, soil depth, and cutbank depth explained much of the variation of road segment runoff during storm events.

Subsurface flow interception may not be the dominant source of runoff for roads in watersheds where the bedrock/regolith is deep. Ziegler et al. (2001) found that Horton Overland Flow (HOF) [Horton, 1945] is the dominant source of observed road runoff in deep soils, where it is uncommon for the water table to raise above the road surface and for subsurface flow interception to occur. Roads have a decreased infiltration capacity due to compaction, which is why they produce HOF soon following the initiation of precipitation. However, it is not appropriate to assume the same reduced infiltration capacity for the entire road right-of-way, because cuts and fills are not as compacted as the road surface. Wemple and Jones (2003) found that the magnitude of road-induced overland flow can be 1-7% of total runoff; however, road surface runoff is a minor component in catchments where runoff generated by roads is dominated by subsurface flow interception. The road gradient, surface area and aspect (in the case of road runoff generation by snowmelt on roads) influence the timing and volume of surface runoff from road networks. During small storms, the proportion of HOF generated by roads is greater than all other land surfaces in a watershed [Ziegler & Giambelluca, 1997; Ziegler et al., 2001]. HOF also occurs on roads in snow dominated watersheds, but only once the rate of snowmelt exceeds infiltration [Bowling & Lettenmaier, 1997]. Precipitation intercepted by the road surface and right-of-way has several possible routes: it may be directly intercepted by a road side ditch or cutbank; flow off the road surface and into a road side ditch, or back onto the hillslope where it infiltrates; infiltrate the surface of the road or right-of-way; or continue to flow on the road surface as overland flow until it is intercepted by a waterbar and channeled into a road side ditch.

The proportion of intercepted rainwater that is channeled into a road side ditch may be combined with subsurface flows that have been intercepted by the road cut. Water in a road side ditch may take two paths: either infiltrating into the ditch bed or being channeled further down the ditch system until it is released by a relief or stream crossing culvert. As water continues down a ditch system, it has more opportunity to
infiltrate into the ditch bed. The roughness coefficient of ditches is generally higher than streams since water does not generally cover roughness elements completely [Bowling & Lettenmaier, 1997]; infiltration into the ditch surface is more likely, particularly in ones with low gradients [La Marche & Lettenmaier, 2001]. However, even if water infiltrates into the ditch bed at a high rate, this is minor compared to the total volume of water accumulating in the ditch, as more subsurface flow and rainwater is channeled into the ditch system.

Relief culverts are installed under roads to drain the water from road side ditches. These culverts may dispense water onto the hillslope where water re-infiltrates, or if higher volumes of flow permit channeling, water may be transported further to join a stream. The drainage area required to support channel head is smaller for road runoff than for undisturbed slopes [Montgomery, 1994], and gulley incision below relief culverts is a common occurrence. For instance, Wemple et al. (1996) found that in slopes greater than 40%, 25% of culverts emptied into channelized flowpaths that were not pre-existing streams. Coe and MacDonald (2001), reported that the contributing road length and hillslope gradient were significant factors in predicting channelized versus non-channelized flows from culverts draining onto the hillslope, and that the upslope contributing area of the culverts yielded similar results. Contrary to these findings, La Marche and Lettenmaier (2001) found that neither slope, road, nor culvert drainage areas were significant in determining gullyng.

Stream culverts are installed under roads to allow water flow from streams to pass under the surface of a road, and it is quite common for streams to have ditch system flows channeled directly into them. It is also possible for a stream to be diverted down a ditch system for some distance before it is channeled under the road via a culvert.

3. Implications

The uniqueness of the hydrological processes created by forest roads has led to the study of, “Forest Road Hydrology” [Stevens, 2001; Toman, 2004]. At the scale of individual road segments, roads are designed to drain or channel water away from the road surface. The surface and subsurface interception of water by roads and resultant channeling via road ditch systems alters the natural path that water would normally take
without the presence of roads. The effect of road networks on hydrological response depends on how significantly road segments modify the capture and routing of flow to stream channels [Wemple & Jones, 2003]. This is of great interest to forest hydrologists, especially during flood periods when roads have a higher potential for impact on streamflow hydrographs. Subsurface flow paths, road position, construction technique, and culvert spacing all interact to determine road effect on a watershed’s hydrograph [Bowling & Lettenmaier, 1997]. The impact of forest roads on the hydrology of a watershed depends on: soil profile characteristics, location of roads on the hillslope, amount of subsurface water flow interception by roads, road surface runoff generation, the design of the road drainage system that affects water routing (culverts and ditch systems), stream network connectivity, and the proportion of the watershed occupied by roads [Bowling & Lettenmaier, 1997; Gucinski et al., 2001]. Road configuration along slopes can influence the magnitude of the subsurface interception effects. Jones (2000) found that midslope road segments “…perpendicular to subsurface flowpaths, midway between ridges and major stream channels, who’s cuts intercepted most of the soil profile” had the greatest impact on increasing peak discharge.

Horton (1945) used drainage density to describe the degree of drainage in a watershed. Drainage density is defined as the ratio of total length of streams within a watershed to total area of the watershed. Road networks can extend the natural drainage network of a watershed into previously unchanneled portions of the hillslope, thereby increasing the watershed’s drainage density. The density of streams is increased by roads intercepting surface and subsurface flows, and routing such flows to stream channels via ditch systems and culvert gullies.

By converting subsurface flows to surface runoff, roads decrease the length of subsurface pathways [Bowling & Lettenmaier, 1997]. The extent to which this changes the travel time of water depends on whether subsurface water follows Darcian or preferential flow. Roads intercepting subsurface water that follows Darcian flow will substantially decrease travel time more significantly than they would in the case of preferential flow. Road cuts collect water that is moving slowly in subsurface layers and rapidly channel it through ditches and culverts. This changes the amount of time that it takes water to enter a stream, which alters peak flows and hydrograph shape [Bowling and Lettenmaier, 1997; Wemple et al., 1996a]. The integration of the road and channel
network can change the controlling runoff mechanism to one dominated by channel flow. The length of roads that convert subsurface flows to surface flow indicates the extent to which the natural drainage pathway is altered, but it is not proportional to the increase in peak flows [Bowling & Lettenmaier, 1997]. Subsurface flow interception by roads occurs during large events when the water table is high enough to be intercepted by the road cut. To affect peak discharge during large events, the influence of road interception must be large relative to other components of the water balance [Jones, 2000]. A particular road segment may act differently during storms of varying magnitude, and some road segments can contribute more flow to channels than others, depending on how much subsurface stormflow is intercepted [Beckers & Alila, 2004a; Bowling & Lettenmaier, 1997; Wemple et al. 1996b]. As soils become more saturated with increasingly larger storms, or increased rates of snowmelt in snow-dominated watersheds, roads will contribute more flows to the streams that they are connected to. The hydrological connectivity between roads and streams is most significantly predicted by hillslope curvature and the downslope distance from roads to natural channels [La Marche & Lettenmaier, 2001].

It is the general consensus that road segments draining directly into streams will speed catchment response time and contribute more to the rising limb of hydrographs, potentially increasing peak discharge [Beckers & Alila, 2004a]. Roads alter routing to streams and can influence the height, but not volume of peak discharge, and this varies seasonably depending on the configuration of roads relative to water flow paths [Jones, 2000]. Studies have found that due to roads, the average time to storm peak advanced, and that the average peak may increase for at least some storm sizes [Harr et al., 1975; Jones & Grant, 1996; Thomas & Megahan, 1998]. However, others have found that there is no detectable change in the timing and magnitude of peak flow discharge due to roads [Rothacher, 1965; Wright et al., 1990; Ziemer, 1981], and there are still others that have found that roads can actually decrease peak flows due to altering the natural drainage patterns of a watershed. Roads can divert runoff to areas that contribute less directly to streamflow, desynchronizing runoff with peak flow, or even divert it across basin divides [Calvert, 2003; Hart, 1997; King & Tennyson, 1984; Wigmosta & Perkins, 2001].

The effect of roads on peak discharge depends on whether road runoff generation is synchronized with the normal peak of the watershed [Megahan, 1972]. Roads may
decrease the peak flow depending on the time between water pulses generated by watershed source areas, and pulses generated by roads. Wigmosta & Perkins (2001) found that the impact of roads occurs early if roads divert flows into the drainage rather than out. By diverting flows into stream channels, roads increase the contributing area of a channel and result in increasing the discharge. However, the road network may increase the contributing area of some stream segments and decrease the area draining to others. When road segments direct flows out of the natural drainage in a watershed, the impact is not felt until the channel contributing area extends upslope to the road system, as the hillslope water table rises. Such flows diverted by the road drainage will not appear until the falling limb of the hydrograph, resulting in reducing the normal peak discharge. To complicate this even further, some road segments that divert flows may only respond to larger events [Bowling & Lettenmaier, 2001], and the effects of such roads may not be apparent during smaller storms. Tague and Band (2001) found that roads can reduce subsurface recharge to areas below roads if there is significant rerouting of subsurface flows by road networks. As a result, these downslope areas will contribute less to the outflow of adjacent streams.

Forest roads can have a significant contribution to the sediment budget of a watershed, especially over shorter time scales [Luce & Black, 2001]. Beschta (1978) found that suspended sediment production significantly increased after road construction and logging directly resulting from these activities; sediment is still produced from these disturbed areas even following the deactivation and removal of roads [Madej, 2001]. The exposure of soil from road cuts and fills increases sedimentation through erosion and mass wasting [Wemple et al., 2001]. Roads can also divert water to portions of hillslopes that do not normally experience flows, where excess soil water raises pore water pressure and reduces the shear strength of the soil. As a result, mass erosion can occur in the form of landslides and gullying [Megahan, 1972]. For instance, Reid and Dunne (1984) found that a heavily used gravel road segment contributes 130 times as much sediment as an abandoned road. The increase in streamflows often resulting from roads increases channel destabilization and stream bank erosion, which increases the fine sediment in streams [Carver, 2001]. Sediment increase in small mountain streams can be detrimental to fisheries by clogging gravels and reducing survival rates following spawning. In addition to affecting the biological component of stream systems, sediment increases
affect downstream water quality; the sediment eroded by roads is less than two millimetres, the size most harmful to fish and water quality. However the effect of roads on sediment budgets is beyond the scope of this report, which looks at the quantitative effects of forest roads on streamflows.

The effects of roads on watershed hydrology are hard to determine exclusively, because most studies on forest roads are in watersheds that have also been harvested. In the Pacific Northwest, the maximum measurement period for which roads are the only treatment ranges from one to four years [Wemple, 1994]. In addition, it is difficult to evaluate the effects of roads during the largest floods due to an insufficient length of data collection. This has led to increasing reliance on hydrological numerical simulations generated with synthetic long-term meteorological data, to distinguish the effects of forest road on watershed hydrology.

C. Hydrological Effects of Forest Harvesting

1. Processes & Implications

Forest cover removal has a direct impact on the canopy interception and evapotranspiration components of the hydrologic cycle. In addition, where snowmelt is a major factor in generating peak flows, forest canopy removal has a significant effect on snow accumulation, and the timing and rate of snowmelt.

The peak discharge and annual water yield of a watershed is expected to increase following forest removal, due to a decrease in evapotranspiration, which increase soil moisture [Jones & Grant, 1996]. The change in evapotranspiration following forest harvesting is dependant on vegetation quantity, distribution, rooting depth, and health [Bowling & Lettenmaier, 1997]. It is the general consensus that increases in peak flows and water yields from forest harvesting are inversely related to drainage area, i.e. the smaller the watershed, the larger the detected increase in streamflow at a certain level of forest harvest [Scheres, 2001]. In the Pacific Northwest, evapotranspiration may account for 40% of the annual precipitation, whereas in the interior of BC, it is slightly lower. In order for evapotranspiration to have a significant affect on peak discharge, it must be relatively large in comparison to the other components of the water balance. Therefore, the effect of reducing evapotranspiration through forest canopy removal is low when
precipitation is high, there is large soil moisture storage, or large snowmelt inputs. For instance, the higher the role of cloud water interception prior to forest harvesting (fog drip), the greater the reduction in soil moisture inputs following forest removal, which can offset the increase in moisture from a reduction in evapotranspiration, particularly for small fall events [Jones, 2000].

Jones and Grant (1996) found that clearcutting resulted in an increase in peak flow discharge and storm volumes, later peak times and earlier hydrograph start times for the first five years following treatment. In another study, Jones (2000) found that the peak discharge significantly increased following harvesting (31-116%), but only in small events (<0.22 or 0.28 return periods) that occurred in the fall (when the soil moisture is in deficit) rather than in the spring (when soil moisture is in surplus). Forest canopy removal decreases evapotranspiration, which increases soil moisture at the end of the season, thereby increasing the volume of late season stormflows. Such increases in fall peaks are greater in drier than wetter basins, where an increase in low flows is noticeable from a reduction in evapotranspiration [Scheres, 2001].

In snow-dominated watersheds where spring snowmelt is the dominant process contributing to the freshet peak, late season stormflow volumes are reduced following forest removal. The reduction in late-season low flows in a snow-dominated watershed is not attributable to one process alone. The increase in snowmelt following canopy removal is mitigated by an increase in snow accumulation and a decrease in transpiration. Removal of the forest canopy creates changes in snowpack dynamics, and results in increased snow accumulation and greater rain-on-snow events. The snowpack is increased due to a loss of canopy interception and sublimation. If snowmelt from an increased snowpack coincides with peak rainfall (rain-on-snow event) an increase in peak discharge can result. However, if snowmelt is not synchronized with rainfall, but delayed, then precipitation will be absorbed by the snow, decreasing the peak discharge.

Snow accumulation and melt dominate the hydrology of most interior BC watersheds, where melting snow generates the spring hydrograph [Winkler, 2001]. Snowmelt in the interior is very dependant on solar radiation, and rainfall plays a minor role in increasing the peak discharge. Forest canopy removal creates large open areas with increased snowpack, which are exposed to solar radiation from the sun. The snow
in these areas melts more quickly than snow covered by the forest canopy, and the volume of melt is higher than normal from an increase in snowpack. The increased rate of snowmelt due to solar radiation exposure is dependant on the aspect and elevation of openings [Carver, 2001].

Harvesting in snow-dominated watersheds increases the peak discharge, and reduces the time to peak. Rainfall plays a minor role, but if synchronized with peak snowmelt, then peak discharge will increased even more. Rainfall can also prime the hard upper layer of the snowpack and make it more susceptible to radiation melt earlier in the freshet. The greater the role of snowmelt in a watershed, the greater the effect that forest harvesting will have on snowpack dynamics [Jones, 2000].

**D. Numerical Modelling of Forest Roads and Harvesting**

1. **Paired Watershed Studies**

   The purpose of paired watershed studies is to investigate the influence of different patterns of, and often deliberate land-use change on the hydrologic cycle. Paired watershed studies are a form of Before-After-Control-Impact (BACI) analysis. These are commonly applied to a time series of response measurements obtained from two units, one of which is subjected to intervention at some intermediate time. The pair of units is monitored over time with measurement of some response of interest, which is streamflow in paired watershed studies. The post intervention responses in the disturbed unit (one with intervention applied), is compared to pre-intervention in that unit and/or in the undisturbed (control) unit. Significant differences imply an effect from intervention [Murtaugh, 2002]. Paired watershed experiments can consist of one or more watersheds where streamflow at the watershed outlet(s) is/are monitored before and after treatment. A paired watershed study may also be applied to only one watershed, where control and treatment streamflow data corresponds to before and after treatment, respectively.

   Paired watershed studies are often used to predict the effects of treatment on the hydrology of a catchment for larger return period events. There are three main problems with prediction in hydrology, associated with the time variability of watersheds resulting from: geomorphological evolution; uncertainty of space and time distribution of input, output, and the state of the system; and non-linearity of mass and energy transfer.
processes in the hydrologic cycle [Amorocho, 1967]. Murtaugh (2002) found that, due to temporal variability, BACI analysis greatly overstates the evidence for associations of interventions with ecological responses. In addition, no matter how sophisticated the statistical technique used in analyzing treatment effect is, it is useless if data are deficient in any way, regardless of the length of the data collection period [Kazmann, 1965]. Incomplete streamflow data is a common occurrence in paired watershed studies, due to the technical difficulties associated with field data collection.

There are complications in the statistical analysis of paired watershed studies due to natural variability, climate, and vegetation regrowth. Evaluating longterm trends in streamflow for paired watershed studies first requires an analytical procedure to remove the natural variability of data between watersheds. Using a single watershed for a paired watershed study will exclude the complications of natural variability, but then there is also a lack of control for climate due to climate change following treatment and climate variability between observation years. It is entirely possible for post- and pre-treatment streamflows to be found to be significantly different as a result of highs and lows in the climate during the time interval of study, and studies employing a control watershed throughout the period of study can at least identify such a cause. The regrowth of vegetation in a treatment watershed also creates problems because the state of the system is changing due to changes in evapotranspiration. The regrowth of vegetation plays such a major role in the hydrologic cycle of a watershed, that only the first year following treatment is truly representative of the effects of treatment [Ward, 1971]. A key question in paired watershed studies is how peak discharges are affected by treatment for events of increasing return period. This can only be accomplished by monitoring streamflows for a period of time following treatment, the effects of which are diminished as vegetation regrows.

Paired watershed studies are often on a rainfall-runoff basis, which is only an input-output approach to analyzing treatment effects on the hydrologic cycle of a watershed. This sheds little light on the hydrological complexities of internal catchment processes, and has led hydrologists to the utilization of hydrologic numerical modelling to aid in explaining such intricacies.
2. Hydrologic Numerical Simulation & The Distributed Hydrology Soil Vegetation Model

One of the problems with studying the effects of forest roads and harvesting on the hydrology of a watershed is that climate and vegetation are not stationary in the natural system. Hydrologic models act as a control to filter out climatic variability [Beckers & Alila, 2004a], and keep the application of a treatment such as forest removal at a constant throughout the period of simulation. Many longterm hydrological simulations of watersheds utilize generated synthetic meteorological data as input [Schnorbus & Alila, 2004a & 2004b], which removes the problem of climate variability occurring in the natural scenario. There is slight bias in this method because the synthetic data is generated based only on a number of years of meteorological observation, which generates a stationary representation of the current climate period. However, this does disrepute such studies, because hydrologists do not use longterm numerical modelling to see the effects of treatment in the long run; such is the objective of paired watershed studies in the natural scenario, where the hydrologic system is recovering with time. Longterm simulations are used to assess the effects of treatment with increasing event size, which corresponds to larger return periods. Once a hydrologic model is calibrated for a watershed, a series of hypothetical scenarios can be assessed with numerical simulation. Hydrologic numerical simulations provide hydrologists with the freedom to analyze the effects of treatments individually or in combination, a common example being forest harvesting and roads. Natural variability is removed because one watershed is used, and the effects of hypothetical treatments are compared to a control scenario, which is based on the watershed’s pristine condition prior to any anthropogenic activities. The sensitivity of streamflow metrics to treatment can be assessed with external variability removed, where land-use change is the most likely explanation. By controlling for climate and vegetation, as well as natural variability, models allow hydrologists to analyze the effects of treatment on catchment processes over a range of event return periods.

One of the benefits of numerical simulation with hydrologic models is the ability to analyze streamflow response to variations in the application of treatments. For example, Whitaker et al. (2002) and Schnorbus and Alila (2004b) looked at the
sensitivity of streamflow peak discharges to harvesting in various elevation bands. Models can also help to assess how road effect is related to segment positioning relative to the hillslope and stream network [Bowling & Lettenmaier, 2001; Tague & Band, 2001; Wemple & Jones, 2003]. Hydrologic numerical models such as the Distributed Hydrology Soil Vegetation Model (DHSVM) [Wigmosta et al., 1994] also provide the opportunity to analyze more than just the changes in streamflows as a result of treatments, and offer a closer look into internal catchment processes.

DHSVM is a physically based hydrologic model, which explicitly solves the water and energy balance for each cell of a digital elevation model (DEM) (see section: Digital Elevation Model & Cover Types). DHSVM is topographically explicit and is more sensitive to land-cover changes than other models [VanShaar et al., 2002]. The spatial distribution of soil moisture, snow cover, evaporation and runoff production can be simulated at the hourly time step. The model uses a two layer canopy representation for interception and evaporation, a two layer energy balance model for snow accumulation and melt, a multi-layer unsaturated soil model, and a saturated subsurface flow model. For details on how these processes are simulated by DHSVM, the reader is referred to Wigmosta et al. (2002).

In DHSVM, roads can intercept overland flow and precipitation when these are present in a road grid cell. Road subsurface flow interception occurs when the water table rises above road cuts. Runoff is routed through the road network using a linear reservoir scheme and explicit information on the location of roads (Wigmosta & Perkins, 2001). The ability of the model to predict the quantity of flow intercepted by a road depends on whether runoff is generated through the correct overland and/or subsurface flow mechanisms, and the depth of the water table compared to the depth of the road cut [Alila & Beckers, 2001].

This report uses the version of DHSVM developed by Thyer et al. (2004) to look at the sensitivity of streamflow metrics to hypothetical and existing operational harvesting scenarios, with and without roads. This model version was calibrated by Thyer et al. (2004) to the streamflows in 240 Creek, which is the control watershed in the paired watershed study involving 241 Creek as the treatment (see section: Description of 241 Creek). Due to the completeness of its streamflow record, 240 Creek was used for
calibration of the model version rather than 241 Creek. The streamflows of 241 Creek were only used to assess the transferability of the model version parameters between the two basins, and results were found to be good. DHSVM was successful in simulating slight differences between the two watersheds; for example, the earlier and more pronounced peaks of 241, due to its higher stream network density and slightly more southerly aspect.

Thyer et al. (2004) developed three forest radiation schemes for the model version, and this report utilizes Scheme 2. The shortwave radiation balance for this scheme is calculated on an alternate approach to DHSVM’s original formulation by Wigmosta et al. (1994), and is based on fractional forest cover rather than leaf area index (LAI). Fractional forest cover was used instead of LAI because higher resolution forest cover maps are available for the two watersheds, and LAI is only an estimator. Longwave radiation exchange at the snow surface is also an alternate to original formulation, and utilizes the canopy view factor, which is the proportion of the canopy “seen” by the snow pack.

In this report, the longterm synthetic meteorological data used for input into DHSVM was developed by Markus Schnorbus using methods described by Schnorbus and Alila (2004a). Short-duration meteorological records were extended by using a combined stochastic-empirical technique, to generate synthetic meteorological data in three steps: hourly precipitation was generated using a rectangular pulses point process; daily meteorological data was generated using a multivariate, first-order, autoregressive process; and final hourly non-precipitation meteorological data was derived by disaggregating daily meteorology. The long-term meteorological data was generated from the P1 climate station (see Figure 1), based on observations collected from August 1997 to December 2001, and is a reproduction of the current climate period.

E. Study Area

1. Description of 241 Creek

The numerical simulations in this report examine 241 Creek, one of three watersheds included in the Upper Penticton Creek Watershed Experiment, located 26 kilometres northeast of Penticton, BC. 241 Creek is a headwater tributary to Penticton
Creek, and drains an area of approximately 5 km², ranging in elevation from 1602 to 2024 metres. The watershed is the treatment in a paired watershed study and is currently 30% clearcut harvested. The physiographic details of 241 Creek are presented in Table 1, with a detailed map and the study area’s location displayed in Figure 1.

The 241 Creek watershed is situated in the dry Engelmann Spruce Subalpine Fir (ESSF) biogeoclimatic subzone. The predominant forest cover type in the watershed is lodgepole pine (*Pinus contorta* Dougl.), with small amounts of Engelmann spruce (*Picea engelmannii* Parry) and sub-alpine fir (*Abies lasiocarpa* (Hook.) Nutt). The trees in the study site are over one hundred years old and reach a maximum height of 20 to 26 metres [Winkler et al., 2003].

Table 1. Physiographic Characteristics of 241 Creeka.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>241 Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Area, $A_D$ (ha)</td>
<td>474.3</td>
</tr>
<tr>
<td>Minimum Elevation, $Z_N$ (m)</td>
<td>1602</td>
</tr>
<tr>
<td>Maximum Elevation, $Z_M$ (m)</td>
<td>2024</td>
</tr>
<tr>
<td>Relief, $Z_M - Z_N$ (m)</td>
<td>422</td>
</tr>
<tr>
<td>Mean Elevation (m)</td>
<td>1758</td>
</tr>
<tr>
<td>Mean Aspect (degrees clockwise from North)</td>
<td>197</td>
</tr>
<tr>
<td>Mean Slope (%)</td>
<td>21</td>
</tr>
<tr>
<td>Total Stream Channel Length, $L_S$ (km)</td>
<td>12.6</td>
</tr>
<tr>
<td>Drainage Density, $L_S/A_D$ (km/km²)</td>
<td>2.7</td>
</tr>
</tbody>
</table>

aData derived from 30-m digital elevation model

The mean summer (June to August) and winter (November to March) air temperatures are 11 and -5 °C, respectively with an average temperature of 2 °C over the entire year [Spittlehouse, 2001]. The mean annual precipitation is 750 millimetres, approximately half of which falls as snow, and permanent snow cover generally lasts from late October until early June [Spittlehouse, 2001]. The late winter snowpack is normally 1 to 1.5 metres deep, with snow water equivalents measured on April 1st averaging 265 millimetres [Winkler et al., 2003]. The watershed is snow-dominated and
the annual hydrograph is dominated by snowmelt; the timing and duration of which depends on forest cover, aspect and elevation. The freshet peak typically occurs in late spring to early summer, and approximately 0.8 to 3 million cubic metres of water flow from the watershed annually [Winkler et al., 2003].

The soil textures in the study area are predominantly coarse sandy-loams and loamy-sands, derived from glacial-tills and coarse-grained granitic rocks. The soil horizons are low in clay and high in coarse fragment content [Winkler et al., 2003]. The soils are generally well-drained and have a low water holding capacity, but late summer field observations have verified hydrophobicity in upper soil layers.
Figure 1. Detailed map of 241 Creek and location of study area in south-central BC.
2. Road Network & Treatments

The road network in 241 Creek is divided into two sections: the east and west roads (see Figure 2). The total length of roads in the watershed is 4.7 kilometres, with a total of 0.9 kilometres of road draining directly into streams. The proportion of road segments directly draining into streams has increased the drainage density of the watershed by at least 7%, while the entire road network has the potential to increase this figure to 37% (see Table 2 for details). The road network surface and right-of-way, accounts for 4% of the area in the watershed, which is the harvest rate for the Control with Roads scenario. The road network segments were divided into 45 classes describing: road width, ditch depth and width, cutbank slope and height, drainage type (crowned, in-sloped, out-sloped) and coefficient of roughness (Manning’s n). The details of each class are shown in Table 11B, with the class assigned to each road segment in Figure 21A.

Table 2. Summary of Road Implications in 241 Creek\textsuperscript{b}.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>241 Creek</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Stream Channel Length, $L_S$ (km)</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>Drainage Density, $L_S/A_D$ (km/km\textsuperscript{2})</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Length of Roads, $L_R$ (km)</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>Length of Roads Connected to Streams, $L_{RS}$ (km)</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Length of Roads Draining to the Hillslope (km)</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>Extended Drainage Density Due to Stream Connected Roads, $(L_{RS} + L_S)/A_D$ (km/km\textsuperscript{2})</td>
<td>2.8</td>
<td>7%</td>
</tr>
<tr>
<td>Potential Extended Drainage Density Due to Entire Road Network, $(L_R + L_S)/A_D$ (km/km\textsuperscript{2})</td>
<td>3.6</td>
<td>37%</td>
</tr>
<tr>
<td>Area Cut for Road Construction (ha)</td>
<td>19.0</td>
<td>4%\textsuperscript{c}</td>
</tr>
</tbody>
</table>

\textsuperscript{b} Data derived from 30-m digital elevation model

\textsuperscript{c} As a percent of total watershed area
Figure 2. Location of roads in 241 Creek.

Three operational scenarios were developed representing 20%, 30% and 50% rates of harvest in 241 Creek, which in Figure 3, correspond to “Op2”, “Op3”, and “Op5”, respectively. The simulations in this report involved these scenarios with and without roads and the addition of roads to each scenario is represented by the suffix “R” (i.e. Op2R, Op3R, Op5R); however, for clarity the road networks are not included in
Figure 3. The Op3 scenario is a representation of the current state of 241 Creek. The Control scenario represents the pristine condition of the watershed, prior to any anthropogenic activities (“Control” in Figure 3). To isolate the hydrological effects of roads in the watershed, the Control with Roads scenario was created, and is a combination of the road network and control (“Control with Roads” in Figure 3). The structural properties of vegetation classes found in 241 Creek are presented in Table 3.
Figure 3. Spatial Distribution of vegetation classes for each scenario in 241 Creek.

Table 3. Structural Properties of Vegetation Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Overstory Description</th>
<th>Dominant Height (m)</th>
<th>Canopy Closure (0.0 – 1.0)</th>
<th>LAI (m²/m²)</th>
<th>Understory Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rock</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Lodgepole Pine</td>
<td>19</td>
<td>0.5</td>
<td>4.0</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Lodgepole Pine</td>
<td>25</td>
<td>0.5</td>
<td>4.0</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>Engelmann Spruce</td>
<td>23</td>
<td>0.2</td>
<td>2.4</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>Engelmann Spruce</td>
<td>28</td>
<td>0.4</td>
<td>3.8</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>Clearcut</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
</tr>
</tbody>
</table>

Source: Thyer et al., 2004
METHODS

A. Data Preparation

1. DHSVM Data Requirements

The DHSVM application requires a number of input files, and these are briefly described below; for a more detailed description of input parameters, the reader is referred to the University of Washington Hydrology Group’s website:

http://www.hydro.washington.edu/.

The DHSVM model version utilized required the following inputs: a configuration file, DEM, mask, soils, vegetation, shading, meteorological data, roads, and streams. The configuration file contains model settings, input file names and paths, vegetation and soil attributes, and information on what output files to produce and at what time step in the simulation. The DEM is point elevation data corresponding to each individual grid cell. The model’s pixel size is limited by the spatial resolution of the DEM’s grid cells, which in this case is 30 metres. The mask indicates which cells in the other terrain, soil and vegetation files are inside the basin, and defines the boundaries of the terrain output data reported by DHSVM. This includes: precipitation, evapotranspiration, and sublimation (a separate entity from evapotranspiration in DHSVM). Normally, the mask should delineate the drainage basin as determined by the underlying DEM; however, the boundaries (mask) of the 241 Creek DEM were modified by Thyer et al. (2004) to better conform to the field surveyed boundary of the watershed [personal communication, Jos Beckers]. The details and implications of this are described in the following section: Digital Elevation Model & Cover Types. The soil input parameters define the soil type and depth of each pixel, where maximum soil depth is considered to meet with the bedrock of the watershed. The vegetation file defines the spatial distribution of forest cover types (which can combine overstory and understory layers), as well as the distribution of rock and clearcut. The shading parameter is separated into two factors for each individual cell in the basin: one is a shading factor for each month, and the other a sky-view factor year-round. The meteorological input contains meteorological conditions for each time step of model simulation, which consists of: air temperature, precipitation, wind speed, relative humidity, and incoming
shortwave and longwave radiation. Temperature and precipitation lapse rates were not considered, due to the small elevation range and gentle topography in 241 Creek, where variations in temperature and precipitation are most likely a function of site exposure [personal communication, Markus Schnorbus]. The road and stream networks are separately defined by three inputs: classes, networking, and maps. The class file defines the range of classes that are assigned to each road/stream channel segment, which in the case of roads describes: the road surface width, hydraulic width and depth of the ditch, cut bank slope, and friction coefficient (Manning’s n). For stream segments, the class file describes: the hydraulic width and depth of the channel, and friction coefficient. The networking file for both networks contains the routing parameters common to the classes of stream/road segments. The mapping files assign segments defined in the networking files to individual DHSVM cells.

2. Data Collection

The road input files for the DHSVM application in 241 Creek were originally developed by Thyer et al. (2004). However, it was recommended by the primary author that the field measurements for roads be confirmed, due to the uncertainty of measurements and culvert/waterbar locations as a result of snow cover during the time of field data collection (October 11-12, 2001) [personal communication, Mark Thyer].

The field work in 241 Creek consisted of several trips which involved: field reconnaissance of potential flow routings through the watershed and separation of flows on road networks, soil type and depth measurements, streamflow measurements using a salt dilution technique, and road network measurements for input into DHSVM. The road input data for DHSVM was collected on two separate occasions: September 11-12 and September 17-18, 2004. A Trimble GeoExplorer I handheld Global Positioning System (GPS) was used for collecting road network details at a five-second sampling interval. The location of many culverts and waterbars has changed since the time of original data collection, and these are presented in Figure 2. The two branch roads first encountered when heading north on the east road have also since been deactivated, and only the road surface remains on these segments. The road network segments in 241 Creek have been separated into forty-five road classes as required for input into DHSVM.
The details of these classes are shown in Table 11B, with segment locations by class in Figure 21A. Each road class indicates segment: road width, ditch depth and width (if ditches are present), cutbank slope and height, and road drainage type (crowned, in-sloped, and out-sloped). The cutbank height is not required for DHSVM, because the calculation for it is developed later with the cutbank slope in reference to the DEM, and it has only been provided for detail. The road drainage type is also currently not used by the DHSVM application.

3. Digital Elevation Model & Cover Types

The DEM for 241 Creek is derived from a 1:20,000 digital map series developed by the Terrain Resource Information Management (TRIM) program for the province of BC (available from Geographic Data BC, Ministry of Environment, Land & Parks).

As mentioned earlier, Thyer et al. (2004) modified the boundary of the mask in the 241 Creek DHSVM application to better match the field surveyed boundary of the watershed. Normally, the mask is developed in a Geographical Information System (GIS) application and is based on the DEM, where the boundary of the mask coincides with the watershed boundary as delineated by the DEM. Since downslope water movement in DHSVM is dictated by the DEM, the mask should coincide with the boundaries of the DEM to avoid problems such as water being transported outside of the drainage basin (and off the edge of the model mask) [personal communication, Laura Bowling]. In GIS applications, a watershed is the upslope area contributing flow to a given location. Delineation of a watershed can be accomplished by computing the flow direction of all raster points in a DEM, and using this to determine contributing area. The difference between the watershed boundary modified to match field surveys of 241 Creek and the boundary determined in GIS based on the DEM is presented in Figure 22A. It was absolutely necessary for Thyer et al. (2004) to modify the boundary of 241 Creek, not only to match the boundary in the field, but to ensure that the outlet of the watershed in the DHSVM model coincided with the outlet in the field. In order to calibrate the model to the watershed, the virtual and real-world outlets must coincide; calibration based on two distanced points on the main channel would not make sense. The modification of the watershed boundary did not affect the water balance, which was
based on streamflows in 241 Creek during the calibration/verification period, averaging a zero percent bias [Thyer et al., 2004]. The larger watershed boundary as delineated by the DEM is an example of the limited accuracy of DEM in areas with gentle topography, such as the lower portion of 241 Creek.

Each treatment scenario used in the simulations of 241 Creek had to have forest cover types or classes defined in the vegetation input file for DHSVM. The vegetation file describes the spatial distribution of forest cover types, which combines the overstory and understory layers, and defines areas of clearcut and rock. The forest cover maps which are based on 241 Creek’s pristine condition, were edited accordingly for each scenario using the ArcMap (Environmental Systems Research Institute (ESRI), 1999-2004) GIS application. A separate vegetation raster coverage file was created for each scenario, by changing the areas assigned to harvest blocks to a clearcut vegetation class. The raster coverage was then converted into a DHSVM vegetation input file, using a conversion application specific to the model.

4. Road Input File Creation

The road network GPS data collected in the field was first differentially corrected and then transformed into shapefiles using Pathfinder Office 2.51. The new road network segments were compared to the originals developed by Thyer et al. (2004), which overlapped perfectly when superimposed. As mentioned earlier, the only differences between the two are locations of culverts and waterbars, and the two newly deactivated road branches on the east road. Even though the differences are seemingly minimal, it is not possible to simply edit the road input files for DHSVM, and these had to be re-created. It is critical that the proper method be used when creating road network inputs that contain the high amount of road prism detail as in this report (it is also possible to incorporate road networks into DHSVM without specifications on ditches and cutbanks). It is also necessary to thoroughly inspect intermediate files that are created at certain checkpoints in road input file development, to avoid problems such as water recycling in the road network. The steps used in creating road input files for DHSVM are described in the following paragraphs.
The road input files for DHSVM were developed using the ArcInfo Workstation GIS platform (ESRI, 1999-2004), in combination with the platform’s ArcMap and ArcCatalog levels. The creation of road input files was through the application of a series of Arc Macro Language (AML) scripts developed by Perkins (1995-1996). The AML scripts require the input of road and stream arc coverages, culvert/waterbar point coverages, and raster coverage of the DEM. The coverages were projected on a datum based on the Universal Transverse Mercator System (UTM), which divides the globe into sixty zones. 241 Creek falls into Zone 11N, and all coverages were projected onto the UTM North American Datum 1983 (NAD 1983) coordinate system (based on the NAD 1983 geographic coordinate system (GCS) spheroid).

In DHSVM, culverts and waterbars are considered to be the same, and function as “sinks” in the road network. As such, culverts do not have dimensions defined for them, and high volume flows cannot backup culverts as in the real-world scenario. The application of road networks in DHSVM requires that each stream crossing has a sink assigned to it. This was accomplished by superimposing the stream and road network coverages and assigning sinks at intersections. The road network coverages were then checked for any inconsistencies that may have occurred when transforming the GPS’d data into GIS coverage, by ensuring that the entire network was connected, and that appropriate nodes were assigned at arc endpoints. In GIS, coverages such as road and stream networks consist of arcs which are connected by nodes. For example, the sinks that were applied to the road network at stream crossings formed new nodes by splitting arcs at these locations. The next step was to add the culvert and waterbar locations obtained from the field as sinks to the road network. Any overlapping locations, for instance at road and stream crossings, were first removed. Even after differential correction, there is always an error associated with a GPS device, and culverts and waterbars did not necessarily overlap perfectly onto the road network centerlines. Therefore, the culverts and waterbars had to first be assigned to their nearest road arc neighbour using a specified search radius. Once this was accomplished, the culvert and waterbar (sinks) locations were appended to the sinks that are required by DHSVM. The road network was already checked for connectivity; however, some arcs within the network may be misoriented and need to be flipped. To find these misoriented arcs, it is necessary to run a trace through the road networks, which is a GIS method similar to the
one used in identifying low points restricting flow in municipal sewage systems. The roads in 241 Creek were separated into two networks, consisting of the east and west roads, and a trace was run with the road outlets specified at the points where both roads meet the watershed boundary. Any problem segments within either of the road networks were then corrected.

The elevations of road segments in the road network are sampled from the underlying DEM and assigned accordingly. Using this information, slopes are found for each arc in the road network and applied to the road coverage. The new elevation and slope data for the road networks might identify new sinks (where flows converge) or divides (where flows diverge) resulting from the sampling of the DEM. These new points need to be accounted for, and any new sinks are appended to the already existing sinks, while the locations of new divide points are used to assign new nodes to the road network. The road segments in DHSVM correspond to individual arcs in GIS, and each has a particular slope assigned that is later used to determine flow routing in the network. When a new divide is identified in an arc, it has to be split with a node, and new slopes are calculated and assigned to each of the two new arcs.

The drainage direction for each road segment in the road network is verified with field observations. The road drainage order is then found by assigning each individual road segment an order in flow routing. This is analogous to stream channel ordering, with the exception that roads contain many dips and rises along their route, and ordering will not simply be based on hillslope positioning. The order of road segment drainage in 241 Creek is presented in Figure 23A, note that opposite to stream channel ordering, lower order segments drain to higher order segments. Using this information, a series of computations are made to develop the road network, map, and class files as required for DHSVM.

B. Numerical Simulations

1. Simulation of Treatment & Road Network Effects

The sensitivity of streamflow metrics to hypothetical and existing harvesting scenarios, with and without roads are assessed using long-term numerical simulation with DHSVM. The effects of forest roads are of particular concern, a key question being how
the hillslope responds during rare events compared with more common events, and how this changes with roads [Luce, 2002].

The DHSVM application was powered by a Pentium III processor (1.00 GHz) with 1.00 GB of memory (RAM). There were a total of eight simulation types, corresponding to no harvesting (control), and 20%, 30% and 50% harvest rates, all with and without roads. Several of these simulations had to be re-run to query DHSVM for certain internal catchment processes, and additional experimental simulations were made, which are described in the following section. At the start of each simulation, DHSVM was run for a “warm-up” period for 10 months, necessary so that the initial specified distribution of soil moisture over the watershed does not bias results [Stork et al., 1998]. This short time period is not included in the simulated streamflow metrics used in analysis. Each longterm simulation was initiated at January 1, 2000 and ended on December 31, 2089, with simulated streamflows prior to Oct 1, 2000 being part of the warm-up period.

2. Experimental Simulations

Further investigation was necessary upon noticing that the application of roads in 241 Creek mitigated hydrograph peaks in comparison to the Control scenario. It was hypothesized that this mitigation could be a result of flow diversion, where roads divert runoff to areas contributing less directly to streamflow [Wigmosta & Perkins, 2001]. The alteration of the natural drainage can desynchronize road runoff with the normal peak of the watershed, and result in reducing the peak discharge [Megahan, 1972]. The volume of runoff generated by roads would appear later in the freshet, occurring in the falling limb of the hydrograph. This investigation considered only roads, so the Control with roads scenario was simulated again, but with changes to culvert spacing in the road network. It was expected that applying the road network, with the minimum number of culverts possible, would mitigate peak flows even more than in the original Control with roads scenario, due to greater runoff diversion. This is based on the assumption that a road network with an absolute minimum culvert spacing (i.e. one culvert after the other), would have the least impact on diverting runoff since flows from the hillslope would pass under the road upon encountering it. A minimum number of culverts had to be used
rather than none, because of the sinks (culverts) required by DHSVM at stream crossings, and at topographic conversions along the road network.

Upon closer investigation of the differences between the Control with roads and Control hydrographs, it was noticed that the volume of flow from road runoff was not being recuperated later in the hydrograph. Development of hourly hydrographs for the two scenarios confirmed this observation, and it was found that differences in water yield between the two scenarios indicated that water was being lost from the watershed in the Control with roads scenario. It was very possible that roads could be diverting runoff out of the watershed and across basin divides [Calvert, 2003; Hart, 1997; King & Tennyson, 1984; Wigmosta & Perkins, 2001]. In order to rule out this possibility, an attempt was made to alter the DEM and make it impossible for water to leave the watershed through any other path other than the basin outlet. The DEM was edited along the lower portion of the watershed’s boundary, ranging from the east road to the west point of boundary modification by Thyer et al. (2004) (see Figure 22A). The grid cells along and outside of this boundary were raised by ten metres to create a wall around this zone of uncertainty, where it was suspected that water routed by roads to the area was transported out of the boundaries of the watershed. The synthetic “ridge” was continuous along the lower boundary except at the outlet of the watershed, where the main channel was allowed to drain. The success of this alteration to the DEM was tested by delineating the watershed in GIS, based on the newly developed DEM. Unfortunately, the attempt was not successful and the boundary was not entirely adjusted as planned. Editing the DEM is a more difficult task than was expected, and subsequent attempts were also unsuccessful. Future work may involve a more in depth process for editing the DEM for 241 Creek.

C. Data Analysis

1. Simulated Hydrograph Analysis

It is important to analyze hydrological data purely based on the observations of freshet hydrographs. The hourly streamflows simulated for each scenario were converted to average daily flow and used to develop yearly freshet hydrographs. Each of these hydrographs had the control and treatment with roads hydrographs superimposed on them so that any changes in streamflows could be easily identified. Temperature and
precipitation was also plotted on each hydrograph by first being converted to daily values from the synthetic hourly meteorological data used by DHSVM. The hourly temperature data was averaged for each day, while precipitation was totaled. The hydrographs developed for each scenario are interactive, and with the click of a button either the precipitation or temperature graphs can be viewed in combination with the three superimposed hydrographs (control, treatment, and treatment with roads). Any changes in the hydrographs following treatment and treatment with roads can be related to the potential effects of solar radiation and precipitation. The full range of simulation years can be “jumped through”, and particular years of interest can be quickly identified. The hydrographs can also be zoomed in and out, to have a closer at points along the hydrograph, which is particularly useful for cluttered hourly data. Daily hydrographs were developed from hourly simulated data, because hourly hydrographs were too cluttered and changes were hard to identify unless the view was constantly zoomed in. However, hourly hydrographs were also used in cases when simulated streamflow data needed to be viewed at a greater time step resolution.

In addition to simulated streamflow, DHSVM has the capability to report flows for individual road and stream segments, the number and length of which correspond to the arcs created for these networks in ArcInfo. Prior to running a simulation, the user has to edit the stream or road input files for DHSVM, and query for the model to report flows for segments of interest. Road networks in DHSVM can have certain glitches, such as recycling of flows within the road network. This can happen if water is intercepted by a road in one pixel (Pixel A), flows along the road side ditch to a sink in another pixel (Pixel B), but the elevation of Pixel B happens to be higher than the elevation of Pixel A. The water will be deposited onto Pixel B through the sink, but then travels downslope via overland flow to Pixel A, where it is intercepted by the same road segment in the next time step [personal communication, Laura Bowling]. This would result in the road segment accumulating flows for the entire duration of the simulation, resulting in a large water balance error. Due to such concerns, DHSVM was queried to report flows for the entire road. Using the simulated road flow data output by DHSVM, hydrographs were constructed that were similar to the ones described for each treatment. However, these were constructed at the hourly time step since road flows can be miniscule and flashy, and averaging daily flows may mask small events. The road hydrographs developed have
the capability of jumping between individual road segments, to see how the road flows vary as one moves downslope along the road network. The hydrograph for the Control with roads scenario is superimposed on each road segment hydrograph, in order to see the interactions between the timing of peaks, and duration of hydrographs.

After comparing the hydrographs for each scenario, it was noticed that roads mitigated peaks without recuperation in the hydrographs later in the freshet. The magnitude of these differences was found by calculating the water yields for the Control and Control with roads scenarios for each year. Certain years (2025, 2029, 2030, 2031, 2037) in the Control with roads scenario had high road mitigation during peak discharge (see Figure 26A, Figure 12, Figure 27A, Figure 28A, and Figure 29A, respectively), and these were the years for which the road segment hydrographs were created. The year 2010 also had a road segment hydrograph constructed, because this year had the highest difference in total water yield between the Control and Control with road scenarios (see Figure 25A and Table 4). Upon further investigation, it was noticed that the road segment hydrograph for the southerly most segment on the west road (Road Segment 18, see Figure 24A), plateaued for a time interval that coincided with the Control with roads scenario peak discharge. It was suspected that the area may be susceptible to flooding during the peak discharge period of the watershed, and that the addition of road networks made this process more apparent. The Control with roads scenario was simulated once more, with a query for DHSVM to produce GIS compatible snow water equivalent (SWE) and water table maps for instantaneous times of interest. The water table maps indicate the depth of the water table below the surface, but will not report depths of water above the surface. At present, DHSVM does not have the capability to produce maps which indicate the depths of water above ground, and flooding may only be hypothesized for areas where the depth of the water table is equal to zero. This hypothesis is supported by the fact that the road segment hydrograph in this area plateaus for some time, which indicates inundation. The same maps were also produced for the Control scenario in the same manner, because it was suspected that flooding and loss of water from the watershed may occur even without the presence of roads.

DHSVM produces a mass balance file with each simulation that reports the various water balance components and water balance error for each model time step. The watershed was assumed to have a tight water balance, and the stream runoff for the
Control and Control with roads scenarios was calculated from the mass balance file by subtracting the evapotranspiration, ground sublimation, canopy sublimation, and mass balance error components of the water balance from precipitation. In DHSVM, the ground and canopy sublimation components of the water balance (termed vapour mass flux) are independent values from evapotranspiration, because the two processes types are calculated by separate models [Wigmosta et al., 2002]. Unfortunately, calculating the runoff from the mass balance file does not work on a yearly basis. The water balance processes for the watershed are not synchronized at each hourly time step, or for each year, so it is only possible to make sense of the water balance reported by the mass balance file at the end of each simulation. As a result, the calculated stream runoff was determined from the totals of each of these components, and this was compared to the total streamflow reported by DHSVM at the outlet of the watershed, in order to determine how much water was lost from the watershed during simulation.

2. Annual Maximum Series

The numerically simulated flows for each treatment scenario were transformed into streamflow metrics corresponding to hourly, daily, and weekly peak discharges. Following treatment, the effect of peak flow discharges can only truly be interpreted by separating flow regimes into class measurements (streamflow metrics) that describe peak flows in a range from the instantaneous (hourly peak flows) to sustained (daily and weekly). Only reporting a single streamflow metric may not represent the full range of hydrologic, geomorphic and ecological consequences of peak annual discharge [Schnorbus & Alila, 2004b]. Numerical simulation with DHSVM was done at the hourly time step, and the algorithm reported streamflows for every hour of simulation. The annual maximum series (AMS) for each streamflow metric was sampled based on the technique described in the following paragraph.

The hourly peak discharge for a particular year is equal to the maximum flow recorded by the algorithm for that year. Hourly peak discharge is used to describe the effects of treatment on instantaneous or “flashy” flows, which is important in engineering design that is based on such flows. The daily peak discharge is calculated by averaging the hourly flows for each individual day in a year, and selecting the day with the highest
average flow for that year. In turn, the weekly peak discharge is calculated by averaging the hourly flows for each week in a year, and selecting the week with the highest average flow for that year. Weekly peak discharges are used to describe the effects of treatment on more sustained lower flows, with daily peak discharges falling into a class somewhere in between instantaneous (hourly) and sustained (weekly). Sustained flows are more geomorphologically significant and better describe the effects of treatment on processes such as channel formation.

3. Ranking Techniques

Several ranking techniques were employed in an effort to display, in a comprehensive manner, the various effects of simulated treatments on peak discharge. Ranking is a method used by hydrologists to compare events of equivalent return period. The sequence of yearly peak discharge values or AMS for a particular scenario are ranked from low to high magnitudes, where smaller peak events have lower ranks, and the higher the rank, the larger the magnitude in peak flow event. The size of the peak flow event, and therefore the rank, is a surrogate of the return period. The return period of each individual event can be determined by its rank, where:

\[
\text{Return Period} = \left[ \frac{(\text{Rank of Event in the AMS} + 1)}{\text{Total Number of Events in the AMS}} \right]
\]

The simplest of ranking techniques is to plot the peak discharge value of each event versus its rank in the AMS (see Figure 36A). The ranked treatment events are superimposed onto the ranked control events, which indicates how a particular rank event discharge has changed as a result of treatment. However, it is important to make the distinction between comparing ranked events and events in the AMS. Comparing two events of equal rank, in both the treatment and control AMS for instance, is not necessarily a comparison of the same events (i.e. the events may not be occurring in equivalent years). The comparison of two equally ranked events only indicates the difference between two events of equal return period.
An alternative to Figure 36A is paired rank analysis, where the treatment ranks are plotted versus control ranks, with relative discharge quantiles on both axes (see Figure 37A). A forty-five degree line is added for reference, and if treatment had no changes with respect to control, all points would lie on this line. Points above the line indicate that treatment has increased peak discharges with reference to the control, and certain trends may be apparent with increasing event magnitude (and therefore increasing return period events). This plot can also be modified to show the change in the treatment peak discharge relative to the control peak discharge, which is a more comprehensive display of any trends that may be present (see Figure 38A). The change in treatment peak discharge relative to the control is found by:

\[
\Delta Q_p (\%) = \left[ \frac{(Treatment \ Discharge \ - \ Control \ Discharge)}{Control \ Discharge} \right] \]

In this case it was found that the trends in Figure 37A and Figure 38A were not easily explained, so a variation of paired rank analysis was applied. The treatment peak discharge events were plotted versus the control peak discharge events without ranking these values in the AMS of either scenario. This is known as paired event peak discharge analysis, and is a similar concept to the paired rank analysis, except that the paired events of the treatment and control are occurring in equivalent years. This analysis is presented in Figure 39A, with the variation of this plot indicating \( \Delta Q_p \) versus the control peak discharge shown in Figure 40A. These figures did not provide any more incite than paired rank analysis, and it was necessary to find a new ranking technique to analyze the simulated data.

The new ranking technique combined the paired event (by year) and paired rank (by return period) methods of analysis to create a comprehensive plot of treatment versus control peak discharge events (see Figure 16). The treatment and control scenario AMS were ranked independently, with reference to the year of each individual rank separately for the treatment and the control. Each treatment rank event was then paired with a control rank event based on the control rank event’s year of occurrence. This pairing technique indicated, relative to the control, how the event for a particular year changed in
rank following application of the treatment. The difference between the two ranks (treatment rank – control rank) was plotted versus the control ranks, to show if the rank change was positive, negative or nil, with reference to increasing return period events (i.e. increasing control ranks). To make this plot more comprehensive, two variations were created where the points were replaced with labels indicating the treatment rank, and $\Delta Q_p$ (see Figure 18).

4. Flow Duration Curves

Flow duration curves (FDC) are the cumulative distribution function of streamflow for some given time interval (daily, weekly, monthly, etc.). FDC are a simple, yet comprehensive graphical picture of the overall historical variability associated with streamflow for a watershed. An FDC is essentially a cumulative distribution function of daily streamflow, and each value of discharge along the curve corresponds to an exceedance probability. FDCs have long been used in the field of hydrology, but are often criticized because, traditionally, their interpretation depends on the particular period of record for which they are based. Vogel and Fennessey (1994) have overcome this uncertainty by considering individual FDCs corresponding to each year of a particular record, treating these as one treats a sequence of annual maximum or minimum streamflows. This new way for interpreting FDCs allows for statistical analysis of pre- and post-treatment streamflows through the construction of confidence intervals.

Using the techniques described by Vogel and Fennessey (1994), median annual FDCs were constructed with corresponding confidence intervals for each scenario based on the eighty-nine years of each scenario’s simulated streamflows (October 1, 2000 to September 31, 2089). The technique is described in detail by Vogel and Fennessey (1994), and is briefly described here. The daily discharge for each year is calculated by averaging the hourly flows for every individual day in a year. The daily streamflow values are then sorted in ascending order for every individual year. Estimates are made of flow durations for each year for probability ranging from zero to one hundred. The maximum streamflow value in a particular year is assigned a probability of zero, while the minimum is assigned a probability of one hundred. Estimates are made for the remaining quantiles, which correspond to probabilities lying in between zero and one.
hundred, through calculations based on Equation (3) of Vogel and Fennessey (1994). To clarify, at this point in the calculation there is a matrix of calculated quantiles with eighty-nine columns (each column representing a particular year) and 101 rows (the range of rows corresponding to probability from zero to one hundred). For each given probability, the years are then sorted in ascending order. The median, upper, and lower flow percentiles are then calculated for a given probability of exceedance using Equation (10) of Vogel and Fennessey (1994). The upper and lower flow percentiles are the ninety-five percent confidence limits of the fiftieth percentile (the median flow percentile), calculated using an alpha level of 0.05.

FDCs were also developed for individual years with a large increase in peak flow discharge following treatment. These were compared with the FDCs developed for the entire streamflow regime for each scenario. While flow duration curves for individual years cannot be compared statistically, the changes between treatment and control may be more visually apparent for a particular year, than when these changes are averaged across years. A FDC for an individual year is calculated by sorting the year’s streamflows from largest to smallest and assigning a rank to each, with the maximum streamflow corresponding to the highest rank. The probability of exceedance for each streamflow quantile is then calculated by:

\[
\text{Probability of Exceedance} = 1 - \frac{\text{Rank}}{(\text{Total Ranks} + 1)}
\]

The FDC is then developed by plotting streamflows on the y-axis with corresponding probabilities of exceedance on the x-axis (see Figure 19 & Figure 20).

5. **Flood Frequency Analysis**

The generated peakflow regime for each scenario and streamflow metric was quantified using flood frequency analysis of the annual maximum flood series using the generalized extreme values (GEV) distribution [Stedinger et al., 1993]. Flood frequency analysis involves the choice of a frequency distribution to describe a sample AMS, and
the estimation of the parameters of that distribution, so as to estimate flood flow discharges for different recurrence intervals (i.e. return periods).

The sample AMS extracted from each scenario (see section Annual Maximum Series) was used to estimate the frequency distribution of the annual maximum peak for each streamflow metric. The frequency distribution for each scenario consisted of eight-nine sample points corresponding to eight-nine years of streamflow data (from October 1, 2000 to September 31, 2089). However, the two years (2022 & 2031, see Figure 35A) where peak discharges corresponded to rainfall were removed from the distribution, since there was only an interest in peak events resulting from snowmelt. GEV parameters were estimated using the method of L-moments as described in detail by Stedinger et al. (1993), and which is only briefly summarized here. L-moments are a way to describe the statistical properties of hydrologic data, and are linear combinations (i.e. no squaring or cubing) of ranked observations. The alternative to L-moments is product-moments, but product-moment estimators have highly biased and highly variable coefficients of skewness and variation in small samples. L-moment estimators are linear functions of estimators of probability-weighted moments (PWMs). The GEV distribution is a mathematical form that incorporates Gumbel’s type I, II and III extreme value distributions for maxima. The GEV distribution uses three parameters in terms of L-moments, which are calculated based on the frequency distribution of the annual maximum peak individually for each of the streamflow metrics for a particular scenario: a location parameter, a scale parameter, and a shape parameter. Using Monte Carlo simulation with 10,000 runs, the flood quantiles for a range of return periods (1.03, 1.25, 2, 5, 10, 20, 50, and 100 years) are estimated for each streamflow metric. The quantiles of the GEV distribution are based on the cumulative probability of each return period, which is found using the empirical probability calculation for return period:

\[
\text{Probability} = 1 - \left[ \frac{1}{\text{Return Period}} \right]
\]

The GEV fit for each scenario was used to compare treatment and control flood quantiles for the range of return periods. Each treatment was tested using a statistical
significance at an alpha level of 0.05, with confidence limits constructed based on the variance of the control quantile estimator, which is assumed to be asymptotically normally distributed [Stedinger et al., 1993]. The variance of the control quantile estimator was found using Monte Carlo simulation with 10,000 runs (M = 10,000). The variance increases with a decrease in sample size and with increasing return period [Schnorbus & Alila, 2004b].
RESULTS

A. Hydrographs

1. Effects of Harvesting & Roads

The simulated streamflows from the operational 50% harvest scenario (Op5, Figure 3), with and without roads, is used to assess the effects of harvesting on peak flow discharge in 241 Creek. The 20% and 30% operational harvest scenarios (Op2 and Op3 scenarios, respectively) experience identical trends in simulated streamflow hydrographs following treatment (with and without roads) as Op5, but with lesser magnitude. As a result, only the Op5 and Op5R scenarios have been presented to provide a clearer representation of streamflow and process changes following treatment.

Figure 4 shows simulation year (2057), where the maximum peakflow discharge decreases following treatment ($\Delta Q_p = -36\%$), with no change in the timing to peak.

Figure 5 shows an example of two simulation years (2076 & 2086) where maximum peakflow discharge increased following treatment. In 2076, the maximum treatment peakflow discharge occurs slightly earlier than the control. In 2086, there are two peaks, and following treatment the first peak increases over the control and becomes the largest peak flow discharge for the year, while the second peak is lowered. Combining roads with harvesting reduces peak flow discharges in both simulation years in comparison to harvesting alone.

Figure 6 is an example of a simulation year (2049) where there is an increase in peak flow discharge following treatment, without a change in the timing to peak.

In simulation year 2060 (Figure 7), the treatment maximum peak flow discharge increases over the control, without a change in the timing to peak. The mitigating effect of roads on treatment discharges is most apparent at the time of the maximum peak.

Simulation years 2030 and 2032 (Figure 8) are an example of large treatment maximum peakflow discharge increases over the control ($\Delta Q_p = 40\%$ and 124\%, respectively) with a reduction in timing to peaks (June 13$^{th}$ to May 15$^{th}$, and April 30$^{th}$ to April 20$^{th}$, respectively). 2030 exhibits a strong mitigating effect of roads on treatment
maximum peakflow discharge, while the treatment in 2032 experienced a minor effect from roads at the time of the maximum peak.

Figure 9 and Figure 10 show simulation years (2010 and 2043, respectively) where the maximum peakflow discharge experienced a large decrease following treatment ($\Delta Q_p = -37\%$ and -36\%, respectively ). In 2010, the maximum peakflow discharge in the treatment is reduced without a change in the timing to peak. In 2043 the maximum peakflow discharge in the treatment occurs earlier in the season than in the control (April 21st compared to May 4th).

**Figure 4.** Comparison of simulated streamflow hydrographs for the Op5, Op5R, and Control scenarios, for simulation year 2057.
Figure 5. Comparison of simulated streamflow hydrographs for the Op5, Op5R, and Control scenarios, for simulation years 2076 and 2086.
Figure 6. Comparison of simulated streamflow hydrographs for the Op5, Op5R, and Control scenarios, for simulation year 2049.
Figure 7. Comparison of simulated streamflow hydrographs for the Op5, Op5R, and Control scenarios, for simulation year 2060.
Figure 8. Comparison of simulated streamflow hydrographs for the Op5, Op5R, and Control scenarios, for simulation years 2030 and 2032.
Figure 9. Comparison of simulated streamflow hydrographs for the Op5, Op5R, and Control scenarios, for simulation year 2010.
Figure 10. Comparison of simulated streamflow hydrographs for the Op5, Op5R, and Control scenarios, for simulation year 2043.
2. Effects of Roads

Combining road networks in 241 Creek with any of the scenarios (Control, Op2, Op3, or Op5) resulted in reducing simulated streamflows reported at the outlet of the watershed. The mitigating effect of roads on simulated streamflow hydrographs is analyzed with the Control with Roads scenario. The effects of roads on streamflows can be distinguished in this scenario, as only 4% of forest cover is removed for the road network right-of-way (see Figure 3 & Table 2), and the effects of harvesting are considered to be negligible.

The mitigating effect of roads on peakflows in comparison to the control, is most apparent around the time of maximum peakflow discharge for freshets peaks dominated by snowmelt, and this occurs for simulation years 2010, 2025, 2029, 2030, 2031, and 2037 (Figure 25A, Figure 26A, Figure 12, Figure 27A, Figure 28A, and Figure 29A, respectively). The largest mitigating effect by roads at the time of maximum peakflow discharge occurred in 2029, and this year is more thoroughly investigated.

The water table maps in Figure 11 are a snapshot of May 8th, 2029 at 4:00 PM, which is the time of the maximum hourly peak discharge for this year. Flooding may only be inferred from areas where the water table depth is equal to zero (areas of red), and the level of water is either at the surface or above.

Figure 13 shows road runoff hydrographs for road segments 17 and 18, which are located on the west road of the watershed (just before and adjacent to the watershed boundary, respectively; see Figure 24A).

Figure 14 and Figure 15 show road runoff hydrographs for road segments 52, 8, 50, and 63, which are located on the east road of the watershed (segments around the road intersection of the first branch road encountered while heading north on the east road; see Figure 24A).
Figure 11. Water table depths for the Control with Roads (right panel) and Control (left panel) scenarios at the time of maximum hourly peak discharge for simulation year 2029 (May 5th at 16:00 hrs).
Figure 12. Comparison of simulation year 2029 streamflow hydrographs for the Control with Roads and Control scenarios, with total daily precipitation and average daily temperature.
Figure 13. Road segment 17 & 18 hydrographs for simulation year 2029 from the Control with Roads scenario.
Figure 14. Road segment 52 & 8 hydrographs for simulation year 2029 from the Control with Roads scenario.
Figure 15. Road segment 50 & 63 hydrographs for simulation year 2029 from the Control with Roads scenario.


3. Water Balance Implications

The difference between simulated water yields reported by DHSVM at the outlet of 241 Creek for the Control with Roads and Control scenarios are presented in Table 4. On average, the application of roads in 241 Creek reduced the annual water yield in the control by 2.3% (48,040 m$^3$).

Table 4. Difference in simulated annual water yields reported at the outlet of 241 Creek between the Control with Roads and Control scenarios$^d$.

<table>
<thead>
<tr>
<th>Simulation Year</th>
<th>Annual Water Yield Difference (Treatment-Control) (m$^3$)</th>
<th>Change Relative to Control (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>- 105,654</td>
<td>- 3.2</td>
</tr>
<tr>
<td>2025</td>
<td>- 47,355</td>
<td>- 2.4</td>
</tr>
<tr>
<td>2029</td>
<td>- 39,331</td>
<td>- 2.4</td>
</tr>
<tr>
<td>2030</td>
<td>- 65,201</td>
<td>- 2.6</td>
</tr>
<tr>
<td>2031</td>
<td>- 63,708</td>
<td>- 2.6</td>
</tr>
<tr>
<td>2037</td>
<td>- 34,494</td>
<td>- 2.1</td>
</tr>
<tr>
<td>Yearly Simulation Average</td>
<td>- 48,040</td>
<td>- 2.3</td>
</tr>
</tbody>
</table>

$^d$ Calculated based on simulated streamflows reported by DHSVM at the outlet of 241 Creek

Average annual water yield changes in the Control with Roads and Control scenarios resulting from the modification of the watershed boundary (see Figure 22A and section Digital Elevation Model & Cover Types) are presented in Table 5. On average, 0.85% of the annual water yield in the control is transported out of the watershed through flow paths other than the outlet. With the addition of roads this figure increases to 3.35%, which is an increase of 293% over the control.
Table 5. Average annual difference between simulated water yields reported by the mass balance file and at the outlet of 241 Creek, for the Control and Control with Roads scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average Yearly Difference in Water Yield (Mass Balance-Outlet) (m³)</th>
<th>Change Relative to Mass Balance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control, $WY_C$</td>
<td>17,888</td>
<td>0.85</td>
</tr>
<tr>
<td>Control with Roads, $WY_{CR}$</td>
<td>70,362</td>
<td>3.35</td>
</tr>
<tr>
<td>Difference, $WY_{CR}-WY_C$</td>
<td>52,474</td>
<td>293$^e$</td>
</tr>
</tbody>
</table>

$^e$ Relative to the Control scenario average yearly difference in water yield

The average annual changes relative to control in simulated hydrological processes following the application of roads to the control in 241 Creek are presented in Table 6. On average per year, roads intercept 458,192 m³ of water and increase the total surface runoff in the watershed by 55% relative to control.

Table 6. Average annual changes in simulated hydrological processes, resulting from the application of road networks in 241 Creek$^f$.

<table>
<thead>
<tr>
<th>Process</th>
<th>Average Annual Difference (Treatment-Control) (m³)</th>
<th>Change Relative to Control (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evapotranspiration</td>
<td>8,995</td>
<td>0.8</td>
</tr>
<tr>
<td>Vapour Mass Flux (Ground and Canopy Sublimation)</td>
<td>13,428</td>
<td>- 4.3</td>
</tr>
<tr>
<td>Surface Runoff</td>
<td>359,969</td>
<td>55</td>
</tr>
<tr>
<td>Water intercepted by Roads</td>
<td>458,192</td>
<td></td>
</tr>
</tbody>
</table>

$^f$ Based on the mass balance files of the Control with Roads and Control scenarios

The average annual road runoff processes in the Control with Roads scenario are summarized in Table 7. The total amount of water intercepted by roads accounts for 22% of the water yield; 81% of the intercepted water is discharged back onto the hillslope through relief culverts, while 8% is discharged directly into streams. The remaining 9% (52,644 m³) of water intercepted by roads is unaccounted for by culvert flows.
Table 7. Average annual road runoff processes in the Control with Roads scenario of 241 Creek\textsuperscript{g}.

<table>
<thead>
<tr>
<th>Process</th>
<th>Average Annual Volume (m\textsuperscript{3})</th>
<th>Relative to Average Annual Water Yield (%)</th>
<th>Relative to Total Water Intercepted by Roads (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water intercepted by Roads, $W_R$</td>
<td>458,192</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Culvert Discharge to Streams, $C_S$</td>
<td>36,240</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Culvert Discharge to the Hillslope, $C_H$</td>
<td>369,308</td>
<td>18</td>
<td>81</td>
</tr>
<tr>
<td>Excess, $W_R - C_S - C_H$</td>
<td>52,644</td>
<td>2</td>
<td>11</td>
</tr>
</tbody>
</table>

\textsuperscript{g} Based on the mass balance file of the Control with Roads scenario

### B. Rank Plots

Figure 16 shows the treatment rank change relative to the control rank, occurring in equivalent simulation years, of maximum hourly peakflow discharge events in the Op5 scenario. The red line indicates a trend of decreasing treatment rank change relative to control, with increasing control ranks that are a surrogate of return period. 38% of events lowered rank as a result of treatment in the Op5 scenario. Figure 17 indicates the year of each rank change. In Figure 18, the first panel indicates the new ranks of events following treatment and the second panel indicates $\Delta Q_p$.

Some of the highest peak events on record in the control became much lower in rank as a result of treatment, and the trend line indicates that the larger the peak flow event, the more likely it is for the event to rank lower after treatment.

Events that had a positive change in rank following treatment are mostly in the middle of the frequency distribution, i.e. medium sized magnitude peak flows that are not too large or too small. In all cases, if $\Delta Q_p$ is negative, there is a negative change in rank as a result of treatment. If $\Delta Q_p$ is greater than 20% there tends to be a positive change in rank, and if $\Delta Q_p$ ranges from 0-20% than there is very little change in rank as a result of treatment.
Figure 16. Treatment rank change as a function of control rank year versus control ranks, with the Op5 scenario as the treatment; the trend with increasing control rank is indicated by the red line.

Figure 17. Rank change following treatment as a function of control rank year versus control ranks; the Op5 scenario is the treatment. Data point labels indicate simulation year of rank.
Figure 18. Rank change following treatment as a function of control rank year versus control ranks; the Op5 scenario is the treatment. Data point labels in the first and second scatter plots indicate treatment rank and $\Delta Q_p$, respectively.
C. Flow Duration Curves

The median annual flow duration curves for the Op5, Op5R and Control scenarios are presented in Figure 19. The 95% confidence bands are based on the variance of the Control scenario. Following treatment, the change in the median annual FDC was found to not be statistically significant at an alpha level of 0.05, for both the Op5 and Op5R scenarios.

Figure 20 shows annual daily FDCs for simulation years 2030, 2032 and 2086, for the Op5, Op5R, and Control scenarios. 2030 experiences increases in peak flows for larger events following treatment, with a decrease in some of the largest events. 2032 exhibits decreases in peak flows for all events following treatment, except for an increase in the largest of events. 2086 shows increases in some of the largest events, and also an increase in some of the smaller events. For all three simulation years, the addition of roads to the Op5 scenario slightly decreased peakflows throughout all events.
Figure 20. Flow duration curves of the Op5, Op5R, and Control scenarios, for simulation years 2030, 2032, and 2086.
**D. Flood Frequency Analysis**

The relative change in hourly flood quantiles based on the GEV distribution are presented in Table 8 for a range of return periods (1.003, 1.05, 1.25, 2, 5, 10, 20, 50, and 100 years) for all scenarios, with and without roads.

Table 9 and Table 10 correspond to daily and weekly GEV flood quantiles, respectively. The tables presented here are a summary of GEV flood quantiles for each scenario, by streamflow metric. The graphical representation of the fitted GEV line to the frequency distribution of events for each streamflow metric, with 95% confidence bands based on the Control variance, are displayed for all scenarios in Figure 41A through to Figure 48A.

For the hourly streamflow metric (Table 8), the GEV flood quantiles in the Op5 scenario were significantly increased from the control (alpha = 0.05) for return periods ranging from 1.05 to 100 years. The addition of roads to the Op5 scenario, lowered the GEV line, which resulted in less significant increases in flood quantiles following treatment, and only flood quantiles for return periods ranging from 5 to 100 years in Op5R were found to be significantly different from the control.

**Table 8. 241 Creek hourly control quantile magnitude and relative change in hourly flood quantile magnitude by scenario (harvest area, with and without roads) and return period**

<table>
<thead>
<tr>
<th>Return Period T (Years)</th>
<th>Control Q&lt;sub&gt;C&lt;/sub&gt; (m&lt;sup&gt;3&lt;/sup&gt;/s)</th>
<th>CR</th>
<th>OP2</th>
<th>OP2R</th>
<th>OP3</th>
<th>OP3R</th>
<th>OP5</th>
<th>OP5R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.003</td>
<td>0.35</td>
<td>1</td>
<td>0</td>
<td>10</td>
<td>8</td>
<td>43</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>1.05</td>
<td>0.61</td>
<td>-3</td>
<td>0</td>
<td>-3</td>
<td>4</td>
<td>0</td>
<td>21&lt;sup&gt;a&lt;/sup&gt;</td>
<td>15</td>
</tr>
<tr>
<td>1.25</td>
<td>0.85</td>
<td>-4</td>
<td>0</td>
<td>-4</td>
<td>3</td>
<td>-2</td>
<td>15&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>1.14</td>
<td>-5</td>
<td>1</td>
<td>-4</td>
<td>3</td>
<td>-2</td>
<td>14&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>1.49</td>
<td>-5</td>
<td>2</td>
<td>-3</td>
<td>5</td>
<td>0</td>
<td>16&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>10</td>
<td>1.70</td>
<td>-5</td>
<td>3</td>
<td>-2</td>
<td>6</td>
<td>1</td>
<td>19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>12&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>20</td>
<td>1.88</td>
<td>-5</td>
<td>4</td>
<td>-1</td>
<td>8</td>
<td>3</td>
<td>23&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>50</td>
<td>2.11</td>
<td>-5</td>
<td>5</td>
<td>0</td>
<td>11</td>
<td>5</td>
<td>28&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100</td>
<td>2.26</td>
<td>-4</td>
<td>6</td>
<td>1</td>
<td>12</td>
<td>6</td>
<td>33&lt;sup&gt;a&lt;/sup&gt;</td>
<td>25&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Two-tailed Z-test P(Q<sub>T</sub> < Q<sub>C</sub> or Q<sub>T</sub> > Q<sub>C</sub>) is significant at α = 0.05
For the daily streamflow metric (Table 9), the GEV flood quantiles in the Op5 scenario were significantly increased from the control (alpha = 0.05) for return periods ranging from 1.25 to 100 years. The addition of roads to the Op5 scenario, lowered the GEV line, which resulted in less significant increases in flood quantiles following treatment, and only flood quantiles for return periods ranging from 10 to 100 years in Op5R were found to be significantly different from the control. The GEV flood quantiles in the Op3 scenario were significantly increased from the control (alpha = 0.05) for return periods ranging from 20 to 100 years. The addition of roads to the Op3 scenario lowered the GEV line, which resulted in no significant changes in flood quantiles following treatment.

Table 9. 241 Creek daily control quantile magnitude and relative change in daily flood quantile magnitude by scenario (harvest area, with and without roads) and return period

| Return Period T (Years) | Control QC (m³/s) | ΔQP (%) by Treatment Scenario CR OP2 OP2R OP3 OP3R OP5 OP5R |
|-------------------------|-------------------|-------------------------------------------------|-------|-------|-------|-------|-------|-------|
| 1.003                   | 0.27              | 1 4 4 13 10 39 33                               |
| 1.05                    | 0.50              | -3 -2 -5 1 -2 15 9                             |
| 1.25                    | 0.70              | -5 -2 -6 -1 -5 9 a 3                          |
| 2                       | 0.93              | -5 -1 -6 0 -5 9 a 2                          |
| 5                       | 1.20              | -5 1 -3 4 -2 12 a 5                          |
| 10                      | 1.35              | -5 4 -1 7 1 16 a 9 a                       |
| 20                      | 1.48              | -5 6 1 10 a 3 21 a 13 a                    |
| 50                      | 1.63              | -4 8 3 14 a 7 28 a 19 a                   |
| 100                     | 1.73              | -4 11 5 18 a 10 33 a 25 a                  |

Two-tailed Z-test P(Q_T < Q_C or Q_T > Q_C) is significant at α = 0.05
For the weekly streamflow metric (Table 10), the GEV flood quantiles in the Op5 scenario were significantly increased from the control (alpha = 0.05) for return periods ranging from 1.05 to 100 years. The addition of roads to the Op5 scenario, lowered the GEV line, which resulted in less significant increases in flood quantiles following treatment, and only flood quantiles for return periods ranging from 5 to 100 years in Op5R were found to be significantly different from the control. The GEV flood quantiles in the Op3 scenario were significantly increased from the control (alpha = 0.05) for return periods ranging from 10 to 100 years. The addition of roads to the Op5 scenario lowered the GEV line, which resulted in no significant changes in flood quantiles following treatment.

Table 10. 241 Creek weekly control quantile magnitude and relative change in weekly flood quantile magnitude by scenario (harvest area, with and without roads) and return period

<table>
<thead>
<tr>
<th>Return Period T (Years)</th>
<th>Control Qc (m³/s)</th>
<th>∆Qp (%) by Treatment Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR QP2 OP2R OP3 OP3R OP5 OP5R</td>
<td></td>
</tr>
<tr>
<td>1.003</td>
<td>0.24</td>
<td>-1 -3 1 -3 28 22</td>
</tr>
<tr>
<td>1.05</td>
<td>0.40</td>
<td>-3 -5 1 -4 15a 9</td>
</tr>
<tr>
<td>1.25</td>
<td>0.54</td>
<td>-4 -4 1 -3 11a 5</td>
</tr>
<tr>
<td>2</td>
<td>0.70</td>
<td>-4 3 -1 6 15a 8a</td>
</tr>
<tr>
<td>5</td>
<td>0.88</td>
<td>-4 5 -1 8a 18a 10a</td>
</tr>
<tr>
<td>10</td>
<td>0.98</td>
<td>-4 6 0 8a 2 18a 10a</td>
</tr>
<tr>
<td>20</td>
<td>1.06</td>
<td>-4 8 1 10a 4 21a 13a</td>
</tr>
<tr>
<td>50</td>
<td>1.15</td>
<td>-4 9 3 12a 6 25a 17a</td>
</tr>
<tr>
<td>100</td>
<td>1.22</td>
<td>-4 4 14a 7 29a 20a</td>
</tr>
</tbody>
</table>

* Two-tailed Z-test P(QT < QC or QT > QC) is significant at α = 0.05
DISCUSSION

A. Overview

Hydrological numerical simulation was used to assess the impacts of harvesting and roads on the simulated streamflow metrics of 241 Creek, for a range of harvesting scenarios. Several techniques were used to analyze the changes in simulated streamflows following treatment, and the results from each particular technique offers unique insight into the consequences of forest harvesting and roads on watershed streamflows. In addition to reporting simulated streamflows, DHSVM provides the capability to investigate internal catchment processes, which corroborates the rationale for streamflow change following treatment.

B. Effect of Roads & Harvesting in 241 Creek

The sensitivity of hourly, daily, and weekly streamflow metrics to harvesting and roads is discussed, followed by a look at the overall simulation period variability associated with pre- and post-treatment streamflows. The magnitude of change in peak flow event discharges following treatment are then examined, relative to their change in rank in the annual maximum series. Several years that are representative of the trend in rank changes following treatment are chosen for closer examination of streamflow hydrographs.

GEV hourly, daily and weekly flood quantiles for the Op5 scenario were found to have significantly increased over the control for return periods ranging from 1.05 to 100 years (excluding the 1.05 year return quantile in the daily streamflow metric) (see Table 9 to Table 10). Significant $\Delta Q_P$ in the Op5 scenario ranged from 21 to 33% for hourly, 9 to 33% for daily, and 15 to 29% for weekly discharge. The increasing range of $\Delta Q_P$ with increasing return period in each streamflow metric indicates that larger return period events responded more substantially to treatment than did smaller return period events.

The relative increase in Op5 flood quantile magnitudes was larger for smaller events (smaller return periods) and larger events (greater return periods), with moderate changes in medium sized events. The frequency distribution of the annual maximum series is also tighter to the GEV fit for these moderate events (with return periods ranging
from 1.25 to 5 years), and this is observed in all streamflow metrics for each scenario (see Figure 41A to Figure 48A). The variance of the control quantile estimator is larger with decreasing sample size and with increasing return period [Schnorbus & Alila, 2004b]. As a result, the confidence bands used to test the statistical significance of the GEV quantile estimators following treatment are narrower for medium sized return periods, broadening out towards larger and smaller return periods. Consequently, it is harder to reject the null hypothesis that quantile estimators are equal following treatment for the largest and smallest return period quantiles. For example, the smallest of return period (1.03 years) Op 5 flood quantiles had the greatest increase in relative magnitude, but were not found to have significantly increased.

The frequency distribution of the annual maximum series exhibits a wave-like trend towards larger events (greater than 5 year returns) and smaller events (less than 1.25 year returns) for all streamflow metrics in each scenario (see Figure 41A to Figure 48A). As a result of this, the hourly Op5 flood quantiles for returns of 20 to 50 years are underestimated, as the GEV fit lies below simulated points from the AMS. A small watershed such as 241 Creek does not produce volumetric flows large enough to potentially damage engineered structures, but flood quantile estimators that underestimate flows are a good example of problems that could exist in engineering design. For instance, if 241 Creek was a large enough watershed with magnitudes of streamflow that justified a large bridge crossing, then the engineering design for such a structure would be based on estimates of the instantaneous (hourly) flows for a given return period event. Underestimating the magnitude of this flood quantile would produce a structure that is inadequate in flood design, and would not meet required factors of safety. If the structure failed during an event for which it was designed as a result of underestimation, than the engineer who designed it could be held legally accountable.

In snow-dominated watersheds such as 241 Creek, it is important to look at instantaneous (hourly) flows, since these are the flows that are most likely to experience the combined effect of rainfall and snowmelt, which is masked by daily and weekly flows. In addition, the runoff generated by the lower elevation roads of 241 Creek will reach streams within hours, and the hourly streamflow metric will better describe this process than the daily metric, as the response time of roads is less than one day.
Adding roads to the Op5 scenario mitigated peak flows following treatment, and resulted in reducing the GEV quantile estimators for all return periods in each streamflow metric. The mitigating effect of roads lowered the GEV fit low enough to narrow the return period range of quantile estimators that were found to be significant following treatment, and only the GEV flood quantile estimates corresponding to 5 to 100 year returns were found to be significantly increased (excluding the 5 year return quantile in the daily streamflow metric). Significant $\Delta Q_p$ ranged from 9 to 25% for both hourly and daily discharge, and 8 to 20% for weekly discharge. As in the Op5 scenario, larger return period events responded more substantially to treatment than smaller return period events, and roads simply decreased their magnitude. The relative decrease in Op5 flood quantiles with the addition of roads was equivalent for all return periods in each streamflow metric (7 to 9%); roads decreased peakflow discharges across the board. This is contrary to the findings of La Marche and Lettenmaier (2001), who modeled road effects and harvesting with DHSVM and found that road effects increased with increasing return period, while the effect of forest removal decreased. The mitigating effect of roads on peakflow discharge is made quite obvious through inspection of the relative change in magnitude of GEV flood quantiles in the Control with Roads scenario (“CR” column in Table 8 to Table 10). For each streamflow metric the relative change in CR flood quantiles is negative for all return periods, with the exception of a 1% increase for a 1.003 return, in the hourly and daily streamflow metrics, which results from the GEV fit overestimating the flood quantile for this return (see Figure 42A). The mitigating effect of roads on peakflow discharge was not expected, as it is the general consensus in forest road hydrology that roads tend to increase peakflows by routing water more quickly to streams [Bowling and Lettenmaier, 1997; Harr et al., 1975; Jones, 2000; Jones & Grant, 1996; Thomas & Megahan, 1998; Wemple et al., 1996a]. However, roads reducing peakflow discharges is not a novel concept [Calvert, 2003; Wigmosta & Perkins, 2001] and the rationale for this occurrence in 241 Creek is discussed in the following section.

Sustained flows (daily and weekly) are important to consider for snow-dominated watersheds, as these better describe the contribution of snowmelt to streamflows than the hourly metric. 241 Creek is an upper tributary to Penticton Creek, which supplies municipal water to the City of Penticton. Harvesting in 241 Creek has a direct impact on
downstream water quality, by increasing the amount of sediment in streams. These sediment increases are due to channel destabilization and stream bank erosion, which result from sustained increases in peakflow discharge events following forest harvesting. These channel forming events are an example of the geomorphological processes that are driven by sustained (daily and weekly) flows, and the daily and weekly streamflow metrics are better at describing the effects of treatment on such processes.

The GEV daily and weekly quantile estimates for the Op3 scenario were found to have significantly increased over the control for return periods ranging from 20 to 100 and 10 to 100, respectively. Significant $\Delta Q_P$ in the Op3 scenario ranged from 10 to 18% for daily, and 8 to 14% for weekly discharge. The small variation in $\Delta Q_P$ indicates that small and large discharge events responded similarly to forest harvesting in the Op3 scenario, which is contrary to what was found in the Op5 scenario.

The Op3 hourly quantile estimates did not experience a significant change, and this indicates that harvesting in 241 Creek has a greater impact on sustained (daily and weekly) flows than on the instantaneous (hourly). To corroborate this even further, the impact of harvesting appears to be greatest for the most sustained streamflow metric (weekly), due to the wider return period range of significantly increased weekly quantiles in comparison to daily quantiles (10 to 100, as opposed to 20 to 100, respectively). As observed in the Op5 scenario, the addition of roads to the treatment (Op3) decreases peakflow discharge quantiles across the board, and the Op3R flood quantiles were diminished enough, to no longer be significantly different from the control in either streamflow metric.

The Op5 and Op5R median annual flow duration curves (FDCs) were not significantly different from the control (see Figure 19), and the relative changes in these curves showed little variation, with treatments minutely increasing over control in the largest of events (flows occurring <10% of the time). These curves are a combination of daily FDCs for each year in the entire simulation (eighty-nine years), and conceal much of the interannual variability of individual FDCs for each simulation year. For example, Figure 20 shows three simulation years where there are clear changes in FDCs following treatment, but these changes cannot be proven statistically, and only inferences can be made on the effects of treatment. Median annual flow duration curves (Figure 19) permit
statistical analysis, but are inadequate in assessing interannual variability. These observations have strong implications for paired watershed studies that investigate the effects of treatment on short periods of record; while differences may be apparent in the short-term, the overall effects of treatment in the long-term may be insignificant. In addition, statistical analysis of short-term records is not representative of the overall perspective of treatment effects on streamflow.

In the Op5 scenario, the rank of hourly events relative to control events occurring in equivalent simulation years, tended to decrease with increasing return periods. The plot of rank change following treatment is plotted against the control rank on the x-axis, which is a surrogate of return period (Figure 16 to Figure 18). 38% of the events in the control changed to a lower rank following treatment, with the majority of events ranking higher as a result of treatment. Some of the largest events in the control became smaller in rank after treatment, and there is a tendency for larger peakflow events to rank lower following treatment.

The largest peakflow events in the control happened late in the melt season, and following harvesting, the snowpack in these event years melts earlier due to the removal of forest cover. By the time the normal peak (in the control) is reached, there is not enough SWE to raise the peak as high as it normally was in the control. As a result, harvesting has a mitigating effect on the magnitude of peakflow for this type of event, and instead of increasing the peakflow discharge, it decreases it. The only reason for this occurrence is that the control peaks later in the melt season, and the treatment causes snowmelt to advance in time, but not at a rate high enough to increase peakflow to pre-treatment levels. The timing of the treatment peak discharge depends on the rate of snowmelt earlier in the season, and the treatment peak discharge can either occur earlier than the control peak, or have no change in timing. Simulation years 2010 and 2043 (Figure 9 and Figure 10, respectively) are good examples of where the maximum peakflow discharge experienced a large decrease following treatment ($\Delta Q_p$ equals -37% and -36%, respectively). These two years were some of the largest ranked events in the control, and following treatment, 2010 and 2043 dropped by 60 and 50 ranks, respectively, to become some of the smallest events on record (see lower right corner of Figure 17 and Figure 18). In 2010, two temperature increases (April 12th to 14th, and April 21st to 25th) increased early season treatment peaks by increasing the rate of
snowmelt, which results in reducing the treatment’s maximum peakflow discharge occurring later in the season (May 16th), without changing the timing to peak. The maximum peakflow discharge in the treatment is still synchronized with the boosting effect of a rainfall event (May 15th), which raises it above early season peaks, but the lack of SWE later in the season does not raise the peak over pretreatment levels. 2043 experiences similar processes to 2010, but larger temperature increases (April 9th to 13th, and April 17th to 20th) create increased rates of snowmelt, causing the maximum peakflow discharge in the treatment to occur earlier in the season than in the control (April 21st compared to May 4th). The maximum peakflow discharge is desynchronized with a rainfall event (May 3rd) that would normally boost the peak (as in the control). Simulation year 2010 (Figure 9) is also a prime example of a reduction in late season flows (June 15th to 28th, and July 23rd to Aug 1st) following treatment, which results from the high rate of snowmelt earlier in the season reducing available water later in the season.

Note that in 2010 and 2043 (Figure 9 and Figure 10, respectively), the mitigating effect of roads when combined with treatment is most apparent during the first peaks in the freshet period, which are dominated by snowmelt rather than rainfall. Road mitigation does not necessarily occur during the largest peakflow discharge, and is more dependent on whether runoff generation is dominated by snowmelt or rainfall. For example, in 2010 the first large peak in the treatment (April 27th) purely results from snowmelt, and the mitigating effect of roads is very apparent at this time; on the other hand, the maximum peakflow discharge that occurs later in the season (May 16th) is more rainfall dominated, and the mitigating effect of roads is negligible. This observation is supported by later season flows when peaks (June 15th, June 19th, and July 26th) dominated purely by rainfall events (June 14th, 19th, and July 25th, respectively) indicate a negligible effect from roads. The similar case exists in 2043, where the maximum peakflow discharge (April 21st) is entirely snowmelt dominated, and the mitigating effect of roads is greatest at this time. The later season peak dominated by rainfall in this year (May 4), is close to the size of the maximum peakflow discharge, but does not experience a mitigating effect from roads.

2057 (Figure 4) is an example of a smaller return period event in the control that dropped 20 ranks following treatment (see lower left corner of Figure 17 and Figure 18).
The entire freshet period in 2057 is purely a function of radiation melt, as no rainfall occurs throughout this period. The maximum peakflow discharge decreases following treatment ($\Delta Q_p$ equals -36%), with no change in the timing to peak. Two temperature increases (April 11th to April 18th, and April 21st to May 3rd) melt the snowpack and increase early season peaks (April 19th and 29th), which reduces the maximum peak flow discharge later in the season (May 4th).

Figure 5 shows an example of two simulation years (2076 & 2086) where maximum peakflow discharge increased following treatment. These two events have low ranks in the control, but jumped up in rank to become moderate return period events following treatment (see Figure 17 and Figure 18). In 2076, the maximum treatment peakflow discharge occurs slightly earlier than the control, corresponding to a large increase in temperature (April 14th – 19th) which melts the snowpack rapidly. In 2086, there are two peaks that correspond to two large increases in temperature (April 10th - 12th, and May 2nd – 9th). Following treatment, the first peak increases over the control from a high rate of snowmelt, becoming the largest peak flow discharge for the year, while the second peak is lowered from less available SWE at this time. As a result, the maximum peak flow discharge following harvesting occurs 25 days earlier than in the control (April 14th compared to May 9th). Both years are a good example of maximum peak discharges resulting from snowmelt induced purely by solar radiation, where temperature increases jolt around the time of the maximum peak. Combining roads with harvesting reduces peak flow discharges in both simulation years in comparison to harvesting alone. The mitigating effect of roads on streamflows in 241 Creek occurs throughout the entire freshet, but is most apparent around the time of peak discharge.

Some of the highest peak flows occur later in the melt season, at a time when the snowpack is so ripe that a sudden increase in temperature produces the greatest peaks on record, providing there is enough SWE during this time. For this to occur, early season temperature increases must evolve in such a way as to permit snow to remain on the ground until the time of peak. The magnitude of increase in peakflows following harvesting may be more dependent on temperature during snowmelt, than the size of the snowpack [Whitaker et al., 2002]. 2049 (Figure 6) is an example of this type of occurrence, and experiences a large increase in peak flow discharge following treatment, without a change in the timing to peak. 2049 is a medium sized event in the control, and
following treatment, it moves up 40 ranks to become one of the largest ranked events (see center top, in Figure 17 and Figure 18). The peakflow discharge in this year receives a double “boost” from solar radiation and precipitation. Snow melts rapidly during a jolt in temperature (April 27th – May 2nd) and is combined with a rainfall event (May 1st), which results in increasing the maximum peak discharge (May 2nd) by 71% relative to the control.

2060 (Figure 7) is another example of a smaller sized event in the control, that becomes much larger following treatment (increases by 40 ranks, see upper left corner Figure 17 and Figure 18). The treatment maximum peak flow discharge increased over the control, without a change in the timing to peak. This year is a good example of where the maximum peakflow discharge (April 15th) following treatment increases, as a result of an early spring precipitation event (April 8th) that “ripens” the hard snowpack, in combination with a steady increase in temperature (April 3rd – 11th). The mitigating effect of roads on treatment discharges is most apparent at the time of the maximum peak.

Simulation years 2030 and 2032 (Figure 8) are an example of large treatment maximum peakflow discharge increases over the control ($\Delta Q_p$ equals 40% and 124%, respectively) with a reduction in timing to peaks (June 13th to May 15th, and April 30th to April 20th, respectively). 2032 is one of the smallest events in the control, but increases by 40 ranks following treatment (see left side of Figure 17 and Figure 18). 2030 is a medium sized event in the control, and increases by 15 ranks following treatment (see center of Figure 17 and Figure 18). The maximum peakflow discharge in 2030 results from snowmelt during a steadier increase in temperature (April 3rd to May 13th) than does 2032, which results from a more abrupt change (April 11th to 20th). 2030 exhibits a strong mitigating effect of roads on treatment maximum peakflow discharge, while the 2032 treatment has a minor effect from roads at the time of the maximum peak.

C. Roads in 241 Creek

The road networks in 241 Creek intercept a significant amount of water in the watershed, which averages 22% (458,192 m$^3$) of the annual water yield in the Control with Roads scenario (Table 7). Roads extended the stream channel network density in
241 Creek by 7% (Table 2), and on average only 8% of water intercepted by roads is
discharged directly into streams, corresponding to 2% (36,240 m$^3$) of the annual water
yield (Table 7). The total surface runoff in an average year was increased by 55%, which
reflects the amount of surface water that is transported by roads (Table 6). Some studies
have found that roads produce no effect when the area of the road right-of-way in a basin
is less than five percent [Wright et al., 1990; Ziemer, 1981]. It was expected that the
small area harvested for the road right-of-way (4%) in 241 Creek, would slightly decrease
the amount of evapotranspiration relative to control; however, the average annual
evapotranspiration increased by 0.8% (8,995 m$^3$), and total sublimation decreased by
4.3% (13,428 m$^3$) (Table 6). The sublimation component comprises of sublimation from
ground and canopy intercepted snow. The area designated to roads is proportional to the
loss of forest cover, and this reduces the amount of sublimation from canopy intercepted
snow. Road corridors act as a permanent clearcut, which increases snow accumulation
and melt in snow-dominated watersheds [Bowling & Lettenmaier, 1997]; snow on roads
melts more quickly than it sublimes under the canopy, resulting in a further reduction in
the sublimation component. While harvesting of vegetation in the small area designated
to roads reduces transpiration, the increased melt water from a greater snow pack on
roads contributes more to evaporation, resulting in a slight increase in the collective
evapotranspiration component.

Rather than increasing peak flows, roads were found to have a mitigating effect,
which was most apparent at the time of maximum peakflow discharge. Some road
segments may only respond to larger events (increasing return period), and these may be
diverting flows out of the natural drainage [Bowling & Lettenmaier, 2001]. The best
example of this occurs in simulation year 2029 (Figure 12), and this year will be
discussed in detail. The reduction in streamflow volume during the freshet peak of 2029
resulting from roads is not recuperated later in the falling limb of the hydrograph, and
2.4% (39,331 m$^3$) of the year’s water yield is lost from the system (Table 4). The
reduction in water yield resulting from roads in the Control scenario is consistent for all
simulation years, with a simulation average of 2.3% (48,040 m$^3$). This implies that roads
transport water out of the watershed, either directly through roadside ditches, or through
culverts that discharge onto hillslope areas that further transport water out of the basin.
Upon closer investigation of the mass balance files for the Control with Roads and Control scenarios (see section Simulated Hydrograph Analysis), it was noticed that the watershed always loses water, with an average annual loss of 17,888 m³ (0.85% of the actual annual water yield) in the Control scenario (Table 5). This is due to the modification of the watershed boundary by Thyer et al. (2004) that was delineated by the DEM (see Figure 22A, and section Digital Elevation Model & Cover Types), and some water along the new boundary is able to leave the watershed, as the actual ridge of the DEM is not on the boundary. The addition of roads to the control increases the average annual loss of water from the watershed to 70,362 m³ (3.35% relative to control) (Table 5). The difference between the two scenarios (52,474 m³) is equivalent to the total simulated water yield difference between the two that is reported at the watershed’s outlet (48,040 m³, Table 4) in combination with the net loss of water collectively from the evapotranspiration and sublimation components (8,995 m³ – 13,428 m³ = - 4,433 m³; Table 6).

Simulation year 2029 road hydrographs for critical segments in the road network were evaluated to investigate whether roads directly or indirectly transported water out of the watershed. Figure 13 shows road runoff hydrographs for road segments 17 and 18, which are located on the west road of the watershed (before and adjacent to the watershed boundary, respectively; see Figure 24A).

Road segment 17 drains into the watershed, and the flows from this segment reach a relief culvert that discharges onto the hillslope (culvert first encountered when heading north on the west road, see Figure 2). This road segment closely follows the dynamics of streamflow throughout the freshet period, and while it does not directly transport water out of the watershed, it may contribute to diverting flows away from the outlet. Water diverted by the road may be discharged onto a portion of the hillslope that transports water out of the watershed through avenues other than the outlet.

Road segment 18 drains out of the watershed and the area under the segment hydrograph corresponds to the volume transported directly out of the watershed by the west road (via road surface runoff and ditch flow). The east road does not contribute to directly transporting water out of the watershed, as the lower 5 road segments on this road...
(segments 24, 53, 54, 56, and 60 in Figure 24A) experienced negligible flows throughout the freshet.

The volume of water transported out of the watershed by road segment 18 is miniscule and does not contribute significantly to the loss of water for this year; however, the shape of this road segment’s hydrograph suggests the types of processes that may be occurring in this area. The plateau of the hydrograph coincides with the peak discharge period of 2029, indicating that the area in this lower portion of the watershed may be flooding around the time of peak. The apparent flooding of road segment 18 is also present in the other simulation years (see Figure 30A, Figure 31A, Figure 32A, Figure 33A, and Figure 34A) that experience high road mitigation effect at the time of peakflow discharge, and is not restricted to peakflows dominated by snowmelt or rainfall, but is more a function of the outlet’s peakflow magnitude.

To investigate whether flooding occurred around the time of the peak discharge period in 2029, water table maps were produced for the Control and Control with Roads scenarios, and are presented in the left and right panels of Figure 11, respectively. Unfortunately, surface water depth could not be queried in DHSVM, and flooding may only be inferred from areas where the water table depth is equal to zero (areas of red in Figure 11), where the level of water is either at the surface or above. The water table maps in Figure 11 are a snapshot of May 8th, 2029 at 4:00 PM, which is the time of the maximum hourly peak discharge for this year. Maps were produced before and after the peak to investigate the dynamics of the water table over time, but the hour of the maximum hourly peak discharge was the most useful in assessing the effects of roads.

As expected, the area around the lower road segment on the west road experienced flows at the surface or above (area A, right panel of Figure 11), and these flows are most likely leaving the watershed through elevation points in the DEM close to the outlet, but not through it. These flows are consequently lost from the system, as they are not reported at the outlet.

The spatial distribution of the water table depth in area C (right panel of Figure 11) changed with the addition of roads (compare to control, left panel), and the overall level of the water table was reduced in this area. Road segments (52, 8, 50, and 63 in Figure 24A) may be diverting intercepted water into areas of the hillslope that do not
contribute to the stream network, such as the lower elevation area of the watershed along the boundary. The volume of water intercepted by these road segments is quite high (Figure 14 and Figure 15), but is not substantial enough to account for the magnitude of flows that are lost from the watershed. Regardless of this, these segments are a good example of how the spatial distribution of water in the watershed is altered by road runoff diversion, and the cumulative effect of this road segment diversion increases flows to hillslope areas that transport water out of the watershed. In Figure 11 (right panel), area B was suspected of being a route for water transport out of the watershed, especially since the level of the water table in this area increased following the addition of roads (compare to control, left panel). Of particular interest was the zone in this area that is adjacent to the watershed boundary, which had water levels raise to the surface or above (red coloured pixels), following the addition of roads. Viewing the DEM in a three-dimensional GIS environment revealed that the boundary in this red coloured area slopes outward from the watershed rather than inward, and this confirms that a good proportion of the water lost from the watershed as a result of roads leaves through this zone.
CONCLUSION

A. Summary of Main Findings

Numerical simulation with DHSVM for a series of operational harvesting scenarios, with and without road networks was used to assess the simulated impact of forest roads and harvesting on 241 Creek. It was found that following harvesting, peakflow discharge increased for all harvest scenario treatments with a tendency for larger return period events to respond more substantially than smaller return period events. The Op5 scenario was found to have increased with statistical significance over the control, for a wide range of return periods of the hourly, daily, and weekly GEV flood quantiles. The addition of roads to the Op5 scenario reduced this significance, and only the highest return period flood quantiles were found to be significantly different. The Op3 scenario was also found to have increased with a statistical significance over the control, but only in the largest of return period GEV flood quantiles, and only for the daily and weekly streamflow metrics. The addition of roads to the Op3 scenario reduced daily and weekly flood quantiles enough to no longer be statistically significant over the control.

The rank of treatment events relative to the control in equivalent simulation years, tended to decrease with increasing return period, but the majority of events increased in rank following treatment. Events that experienced a decrease in rank following treatment occurred in years were the control event peaked later in the season. Harvesting caused snowmelt to advance in time, which increased flow during the active melt period; however, by the time the peak was reached, there was not enough SWE to increase peakflow to pre-treatment levels.

The road networks in 241 Creek were found to reduce streamflows across the board, and the reduction in flow was most apparent during peakflow discharges that resulted from snowmelt. The application of roads in the watershed resulted in decreasing the average annual water yield, and roads were responsible for transporting water directly and indirectly out of the basin. Roads transported water directly out of the watershed through roadside ditches and surface runoff, but the volume transported via this route was
minimal. Roads had a more significant effect on diverting water to lower elevation areas close to the boundary of the watershed that further transported it out of the basin.

**B. Future Work**

1. **Overview**

   Extensive field measurements are necessary to determine whether the DHSVM application for 241 Creek is accurately representing the watershed’s surface and subsurface hydrological processes, in combination with road networks. For this purpose, field measurements will include: monitoring ground water table fluctuations, measurements of water flow in streams and road side ditches, and an investigation of the connectivity of roads to stream channels. Some of the input parameters for DHSVM also need to be verified in the field, especially for particular areas of the watershed.

   Simulations which included the road network were found to have substantial water loss from the watershed, and this will be investigated in the field and with further simulations.

2. **Piezometer Installations**

   Piezometers will be used to determine whether DHSVM is accurately simulating the subsurface processes of 241 Creek, with emphasis on how these processes are altered by roads. Groundwater table fluctuations need to be monitored in areas where incision into the hillslope by road cuts has a significant effect on subsurface flow interception. The subsurface flow mechanisms around such road segments may change throughout the freshest, dependant on the rate of snowmelt and infiltration into subsurface flow layers. The dynamics of the ground water table will be monitored with piezometer installations, strategically located to provide an accurate representation of the watershed’s subsurface processes.

   A total of ten piezometers will be installed in four locations in the watershed (see Figure 49A). At each location, piezometers are installed in a transect running perpendicular to hillslope contours, preferably so positioned as to have representations from: the riparian zone, riparian/hillslope interface, and hillslope. In locations where a road intersects the piezometer transect, one piezometer will be positioned on the hillslope
a distance above the road cut, while the other is located a distance below the road. The interval between two piezometers intersected by a road will be significant enough to avoid local variability of water table depth, in subsurface zones with close proximity to the road.

The four locations are split into two groups representing the lower and higher elevations of the watershed. In each of the two groups, one location is situated in a clearcut area, while the other is in a forested area. The “L1” transect is situated in a clearcut, with one piezometer in the riparian zone, and the other further upslope and across the road. “L2” is located in a forested area, but will cross the road possibly entering a clearcut. One piezometer is at the riparian zone, and the other two are situated above and below the road respectively. In the upper elevations of the watershed, “U1” is located in a forested area, with one piezometer at the riparian zone, and the other two located further upslope at equal intervals. It is likely that the large hillslope area above the riparian zone is regenerating the lower zone, and even at the time of low late summer flows, field observations verified that the water table in this riparian zone is very close to the surface. This indicates that high flows occurring during the melt season would produce much near surface flow. An investigation needs to be made of whether flow at the road culvert below the riparian zone accounts for the water draining from this area, or whether much of it moves subsurface below the road. “U2” is located in a clearcut area, with one piezometer in the riparian zone and the other further up the hillslope.

3. Road Runoff and Streamflow Measurements

Water flow in road side ditches and streams will be calculated using a salt dilution technique involving conductivity measurements [refer to: Østrem, 1964 & Church, 1975].

Synoptic flow measurements of ditch and culvert flows will be made throughout the freshet period, to develop an understanding of road runoff dynamics and how these compare to simulated road runoff by DHSVM. The extent to which roads directly transport water out of the watershed will also be verified in the field through measurements of ditch flow at road segments adjacent to the watershed boundary. Once climate data for the upcoming freshet (2005) is obtained from the P1 (see Figure 1) climate station, DHSVM will be used to simulate flows for the existing operational
scenario. The simulation of road runoff by DHSVM will then be compared to field observations to check for inconsistencies in the model’s road runoff flow routing.

The extent to which hillslope subsurface flows are contributing to streamflows or vice versa will be investigated using intermittent streamflow measurements along the stream network. The stream network is essentially gauged at multiple points along network segments to determine increases or decreases in discharge in the downstream direction that are unaccounted for by tributary sources. Downstream increases are a result of streams gaining water from the hillslope, while decreases result from water loss to the hillslope. The ideal scenario would involve gauging the entire stream network at a given spacing and monitoring the flows at each gauging station instantaneously, providing a “snapshot” of streamflows at points along the network. This would produce the most accurate information for calculating stream segments that are losing and gaining water; however, separating the network into multiple sections will also suffice. At each network section, flows are measured at equal intervals moving upstream. Since a salt dilution technique is used for measurement of streamflows, it is absolutely necessary to move upstream to avoid contaminating successive measurements. A small error will exist in streamflow measurements, associated with the time lag between each successive measurement. However, as successive measurements are taken at a good pace, the error will be insignificant.

The monitoring of subsurface flows with piezometer transects (see section Piezometer Installations) in combination with road runoff and streamflow measurements will also test the model’s assumption that the rise and fall of groundwater levels closely follows the dynamics of runoff.

4. Road to Stream Connectivity

The connectivity of the road network to streams in 241 Creek needs to be determined in the field and compared with what is simulated by DHSVM. Road segments draining to stream crossing culverts are not the only source of runoff increasing the contributing area of stream channels. If the volume dispensed by a relief culvert onto the hillslope is high enough, gully initiation may occur and flows may be channeled further down slope to join a stream channel. Croke and Mockler (2001) recommend field
investigation to confirm the possible occurrence of such culvert channelization. A greater drainage area is required to initiate channels on gentler slopes, such as ones in 241 Creek, but since roads create a surface with decreased infiltration capacity, channel initiation by runoff from roads requires less area the hillslope [Montgomery, 1994].

Road drainage direction was determined in DHSVM using AML scripts that sample the DEM, and create elevation and slope parameters. As a result, the ordering of drainage is constant throughout all events. However, field investigation could yield different results, due to the spatial resolution limitations of the DEM, and processes that the model may not capture. Montgomery (1994) recommends that road drainage flow directions, drainage divides, culverts, and other points of drainage concentration be mapped immediately after rainfall that produces copious runoff from road surfaces to reduce errors in contributing areas; there is a higher error when such reconnaissance is carried out during times with no runoff. Since 241 Creek experiences runoff due to snowmelt and rainfall, it will be necessary to map such processes during each type of event, as the drainage processes may vary between the two.

5. Confirmation of Model Input Parameters

In DHSVM, by default the maximum depth of road cut for a road segment is ninety-nine percent of the maximum soil depth at that location. If road input files contain segments where the road cut is lower than the soil depth, the application will automatically change the cut depth values to the default. A total of eighteen road segments in the road network encountered this problem, with an average difference of 0.9 metres between what was observed in the field and the default set by DHSVM. Field measurement of soil depths in these areas, and synoptically throughout the watershed, will need to be made to confirm that the average soil depths in 241 Creek are accurately represented in DHSVM. It is critical to confirm these input parameters, because the significance of subsurface flow interception by roads may be greater or less than what is simulated by DHSVM. For instance, if soil depths are found to be deeper than road cuts, than a significant proportion of subsurface flow will pass under roads; whereas road cuts that intersect the entire soil profile will be more likely to produce runoff from subsurface flow interception [Wemple & Jones, 2003]. The problem is that any significant changes
to existing soil depth inputs may result in voiding Thyer et al.’s (2004) calibration of the model to the watershed. However, it may be possible to change soil depth values only in soil zones with close proximity to road segments, which would accurately represent the interception effect of roads without significant affect on model calibration.

6. Further Investigation with Numerical Simulations

The extent to which roads transport water out of the watershed will be investigated with additional numerical simulations with DHSVM. The lower road segments adjacent to the watershed boundary may be responsible for water being diverted out of the natural drainage and across basin divides. To factor out the potential for this occurrence, simulations with roads will be re-run with road networks ending inside the watershed boundary. However, the connection to the actual watershed boundary is not the only possible area for water loss as a result of road runoff, and this loss may occur further up the road network. Water discharged onto the hillslope by road culverts close to, but not at the watershed boundary may also contribute to transporting water out of the watershed via overland flow. As previously mentioned, water loss due to the application of roads cannot be accounted for by the volume of runoff in road segments adjacent to the watershed boundary. The new simulations with DHSVM will include the same road networks, but the roads will end inside the watershed boundary at the last road/stream crossings for each respective road (east and west roads). As required by DHSVM, the last road/stream intersections will be assigned a sink or culvert. Any road runoff in the new lower segments of the roads will then be channeled directly into streams, and it is expected that water will no longer be lost from the watershed. Note that the road runoff channeled into the stream from each of the last road segments will not consist of the runoff volume for the entire road network, as relief and stream culverts will still be positioned along the rest of the road network as they currently are. The changes to the road networks will essentially involve clipping and removing lower segments below the last road/stream intersections. If it is found that water is still being lost from the system after such edits to the roads, then the process of roads diverting water out of the natural drainage and out of the basin is occurring further upslope the road network.
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APPENDIX A: APPENDED FIGURES

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### Table 11B. Road Class Details.

<table>
<thead>
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