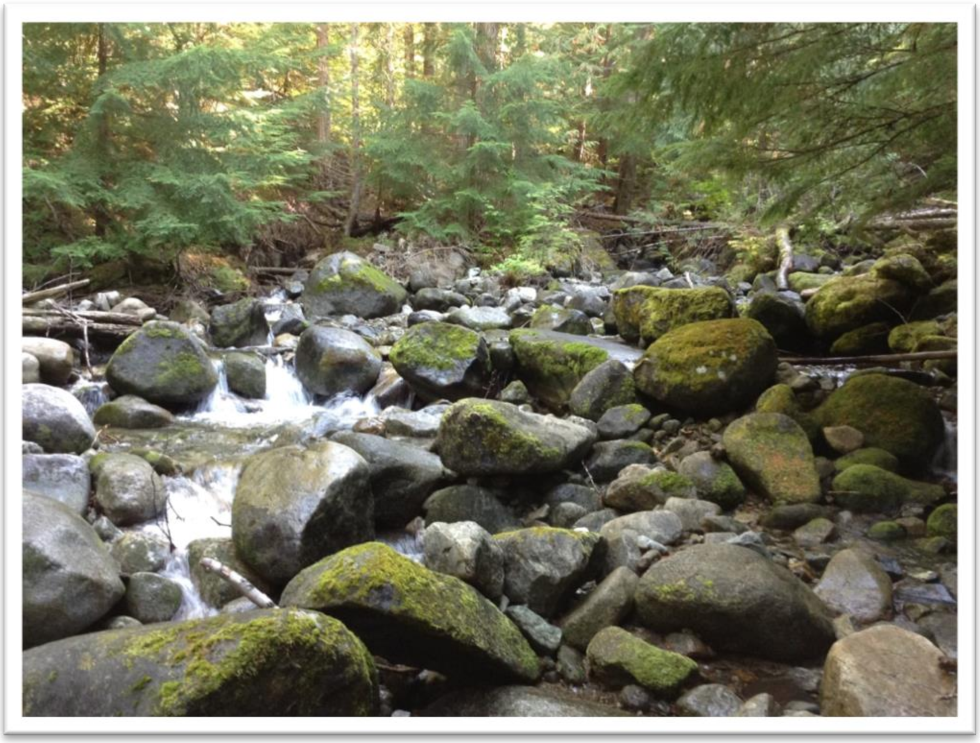
Glade Creek Hydrogeomorphic Assessment

Apex File HA-15-KL-02



Glade Creek near confluence of north and south forks

Prepared for: Tyler Hodgkinson, RPF, Woodlands Manager
Kalesnikoff Lumber Co. Ltd
Thrums, BC

And

Ron Ozanne, RPF, Forestry Manager
Atco Wood Products Ltd
Fruitvale, BC

Prepared by: Kim Green, PGeo., PhD.
Apex Geoscience Consultants Ltd
Nelson, BC

January 20, 2016

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PHOTOGRAPHS

Introduction

Mr. Tyler Hodgkinson R.P.F., Woodlands Manager for Kalesnikoff Lumber Co. Ltd., Thrums, BC, and Mr. Ron Ozanne, RPF, Forestry Manager for Atco Wood Products Ltd, Fruitvale requested that Kim Green P.Geo., PhD of Apex Geoscience Consultants Ltd. (Apex) undertake a hydrogeomorphic assessment of the Glade Creek watershed to provide guidance for forest management. Glade Creek is listed as a community watershed and supplies water to the lower Glade community.

According to BC's Forest Planning and Practices Regulation,

> "The objective set by government for water being diverted for human consumption through a licensed waterworks in a community watershed is to prevent … the cumulative hydrological effects of primary forest activities within the community watershed from resulting in
>
> (a) a material adverse impact on the quantity of water or the timing of the flow of the water to the waterworks, or
>
> (b) the water from the waterworks having a material adverse impact on human health that cannot be addressed by water treatment …"

This investigation is intended to assess the likelihood of adverse cumulative impacts to water quantity, quality and timing of flows at the Glade Irrigation District intake and to provide guidance for forest development to limit the risk of such impacts occurring.

Methods

The method used in this assessment is generally consistent with that described in Land Management Handbook 61 Managing Forested Watersheds for Hydrogeomorphic Risks on Fans (Wilford et al., 2009) (http://www.for.gov.bc.ca/hfd/pubs/docs/lmh/Lmh61.htm, downloaded May 2013). Glade Creek is the community waters supply for the Glade Irrigation District which services 100 households. The assessment in Glade Creek is intended to determine hydrogeomorphic risk to water quality, quantity and timing of flows at the intake in Reach 1 associated with existing and proposed forest development. The components of the hydrogeomorphic risk analysis include;

1. Watershed delineation and characterization
2. Identification of elements at risk,
3. Identification of channel processes,
4. Linking watershed processes and channel processes,
5. Risk analysis.

As part of this assessment a reconnaissance level channel survey of Glade Creek was conducted on September 28th and October 1st and 2nd, 2015 by Kim Green (P.Geo, PhD) and Will Halleran (P.Geo., L.Eng). During the field survey, information on channel morphology and disturbance history was collected at 30 sites throughout the watershed (Figure 1).

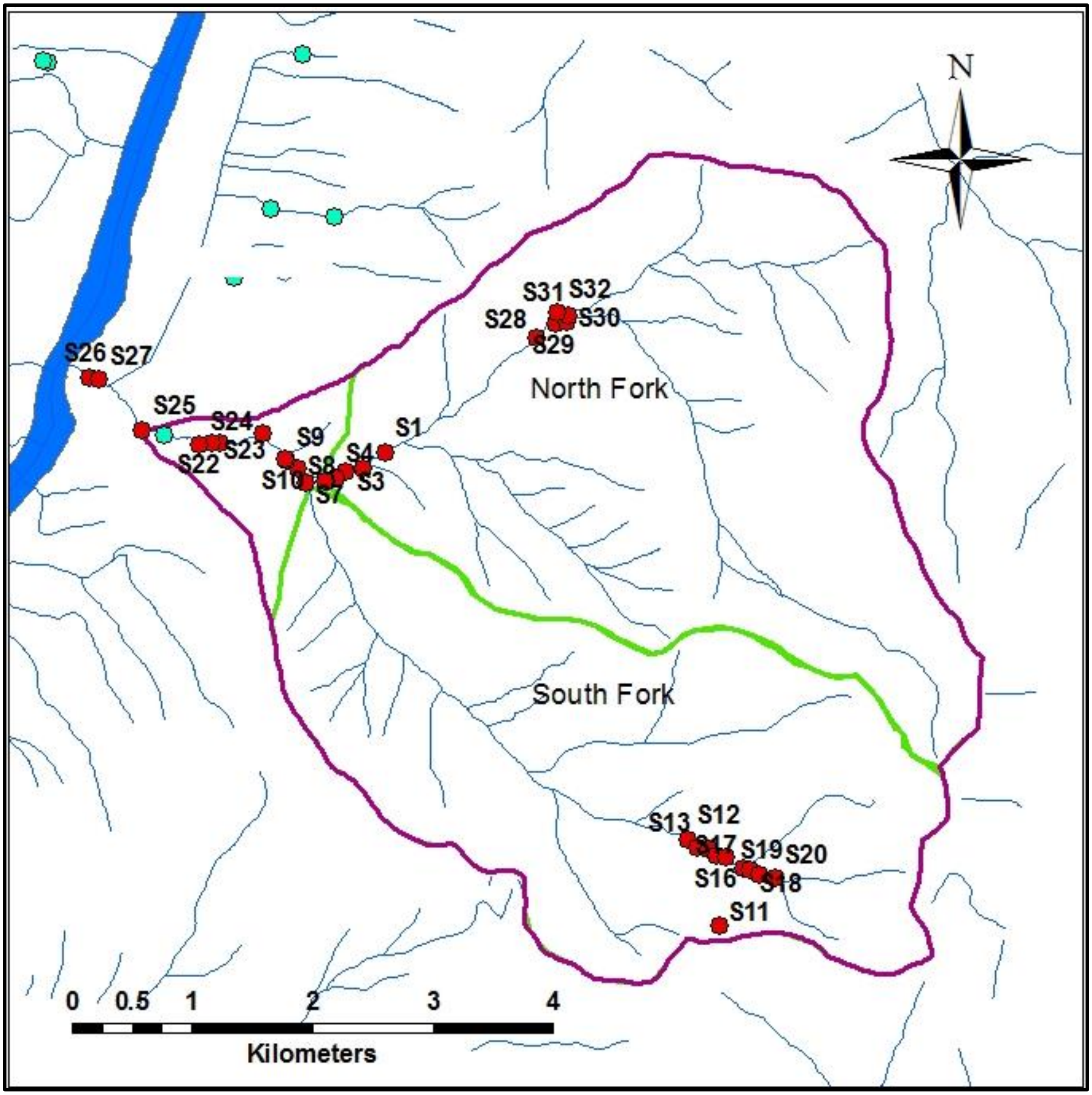


Figure 1. Glade Creek survey site locations. Blue dot marks Glade Irrigation District intake.

Data collected during the channel survey is used to characterize current channel condition and, as well, to assess the level and history of channel disturbance in Glade Creek. GIS is used In addition to the field-based geomorphic analysis to assist in the physical characterization of the watershed and provide an indication of the existing level of forest disturbance in the watershed. The 2013 VRI database and the Province of BC's Silviculture and Land Status Tracking dataset were used in the GIS analysis to quantify the current state of forest cover and are assumed to be representative of actual forest conditions. Google earth images were also used to investigate hillslope processes and the degree of hillslope – channel coupling throughout the watershed.

Background

Water use

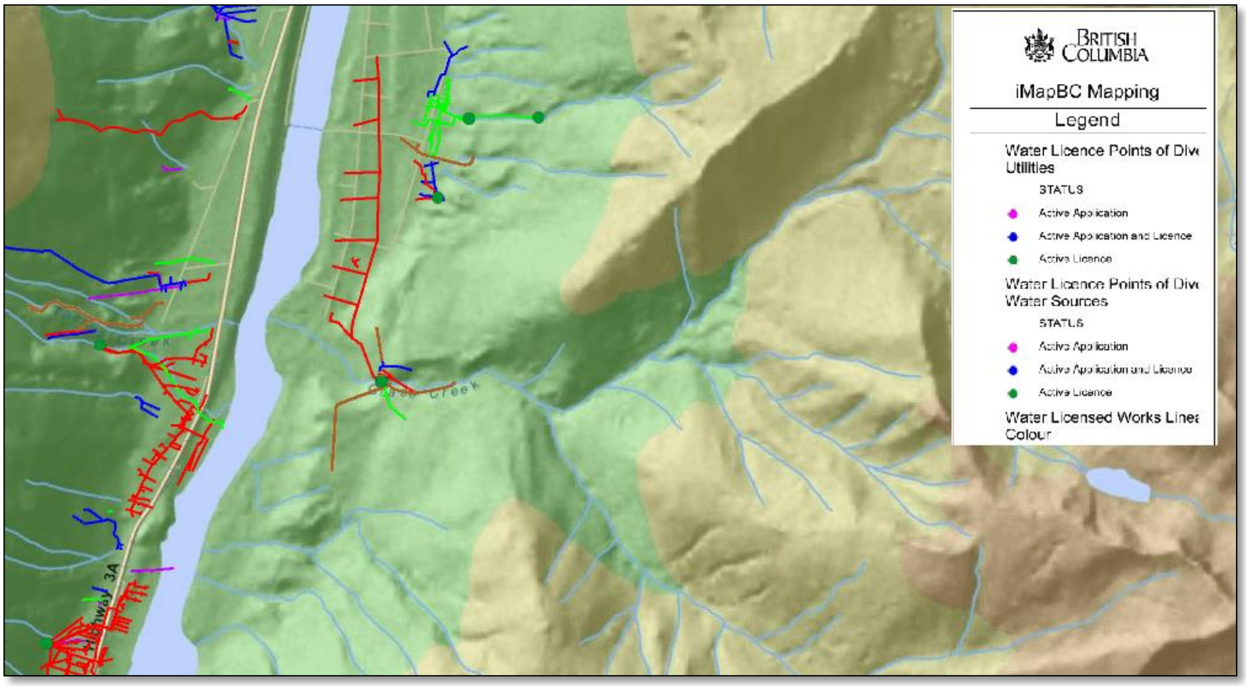


Figure 2. Water intake locations. Location of intakes (green dots) and water distributions systems (red) for Glade Creek.

Currently there are two licences and one water intake on Glade Creek with both registered to Glade Irrigation District (http://a100.gov.bc.ca/pub/wtrwhse/water_licences.input, June 2015 download).

The Glade intake and distribution system has been active since 1974. This intake supplies water to about 100 households in the lower Glade area (Carver, 2001)

Table 1. Water license information from BC water license website.

Licence No	Purpose	Quantity	Licensee	Licence Status	Priority Date
C044909	Irrigation Local Auth	370044	GLADE IRRIGATION DISTRICT 2222 GLADE ROAD CASTLEGAR BC V1N4R4	Current	19080901
"	Waterworks Local Auth	18252.551	GLADE IRRIGATION DISTRICT 2222 GLADE ROAD CASTLEGAR BC V1N4R4	Current	19080901
C048637	Waterworks Local Auth	116152.6	GLADE IRRIGATION DISTRICT 2222 GLADE ROAD CASTLEGAR BC V1N4R4	Current	19750724

Existing studies

The last hydrological assessment of Glade Creek was undertaken in 2001 by Carver Consulting (available online at: http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=8767). Terrain and terrain stability mapping has been undertaken in Glade Creek (Apex, 2000). This mapping identified surficial materials and areas of potential terrain instability related to forest development. Turbidity data has been recorded for on Glade Creek since 2012 with continuous daily monitoring starting in April 2014 (http://gladewater.weebly.com/, Figure 3).

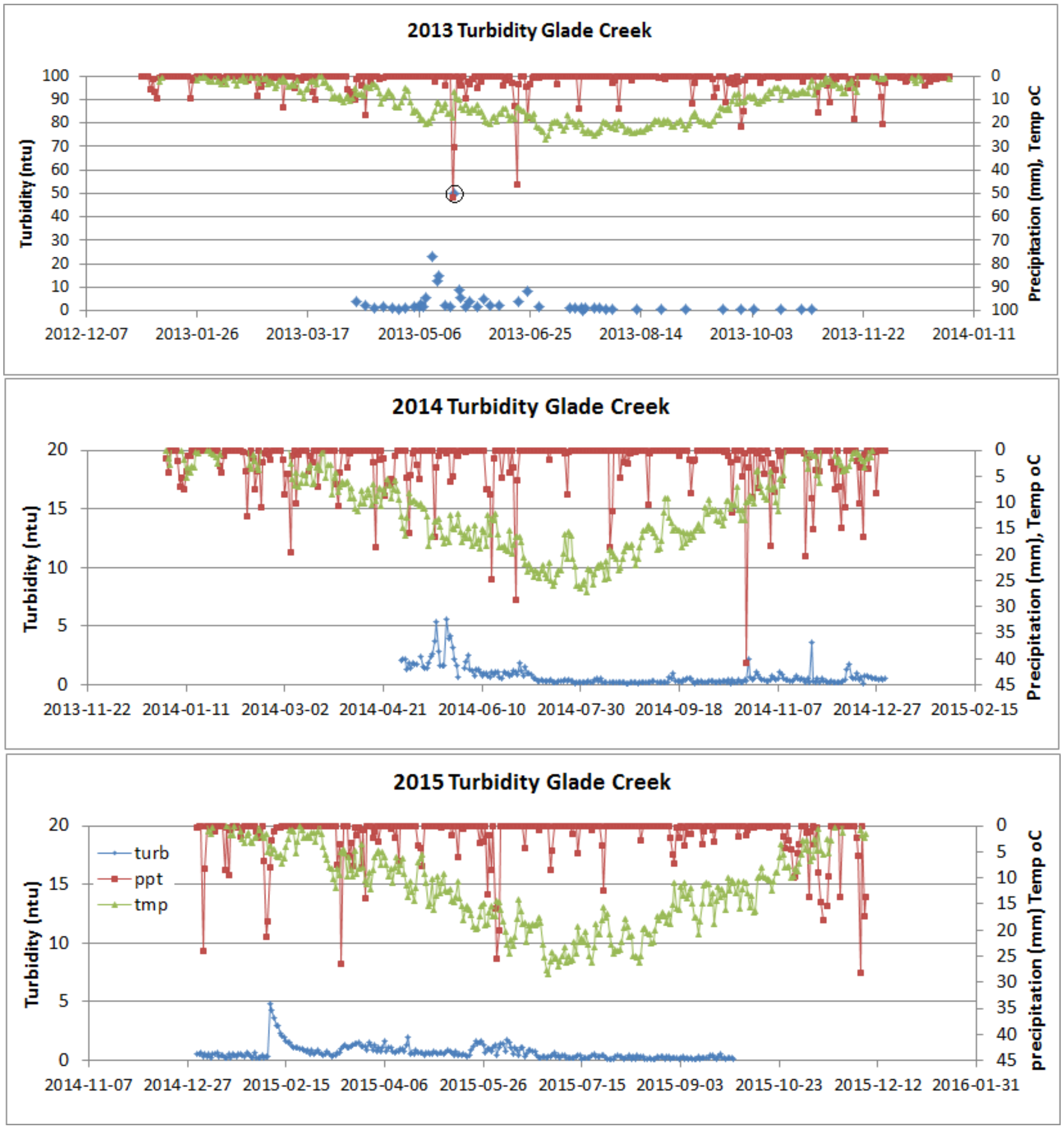


Figure 3. Turbidity data 2013 to 2015 from Glade Irrigation district website plotted with daily temperature and precipitation recorded at the Castlegar weather station. May 22 2013 data listed as 'off chart' is assigned 50 NTUs to represent an extreme reading for this day.

When turbidity data is plotted with the temperature and precipitation time series for the same period of time (Figure 3) it shows that high turbidity events are limited in occurrence in Glade Creek and correspond to periods of heavy precipitation during winter months (February, 2015) or rainfall combined with rapid warming (June 2012 (not shown), May, 2013 and 2014) during spring months. It is notable that large magnitude rainfall events during summer and fall months do not trigger substantial increases in turbidity.

Physiography

Glade Creek is a 2977 hectare watershed that flows westward from Siwash Mountain (2307m elevation) in the Bonnington Range to the Kootenay River (450 m elevation). The watershed includes two subbasins referred to here as the north fork (1561 ha) and south fork (1286 ha) tributaries (Figure 4). The two subbasins converge at an elevation of 780 meters.

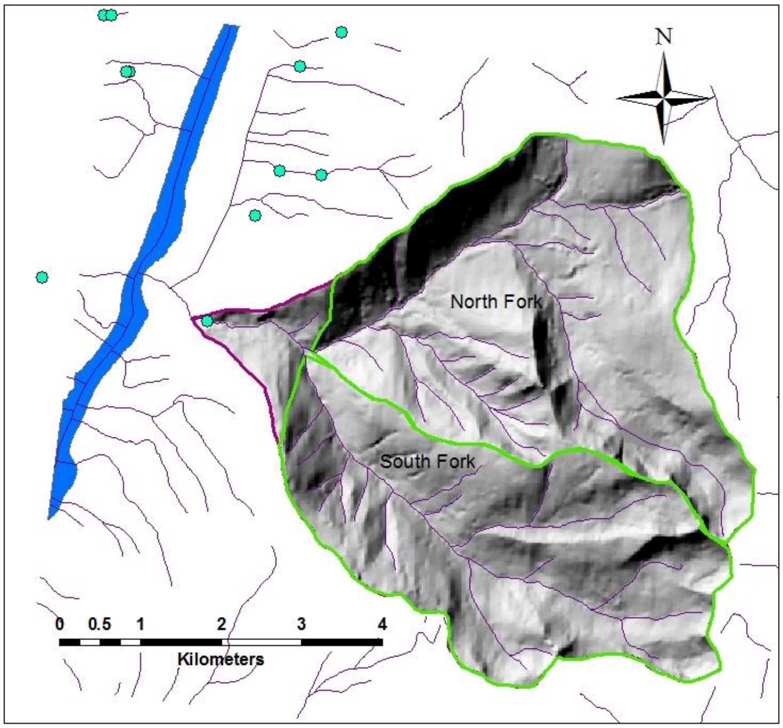


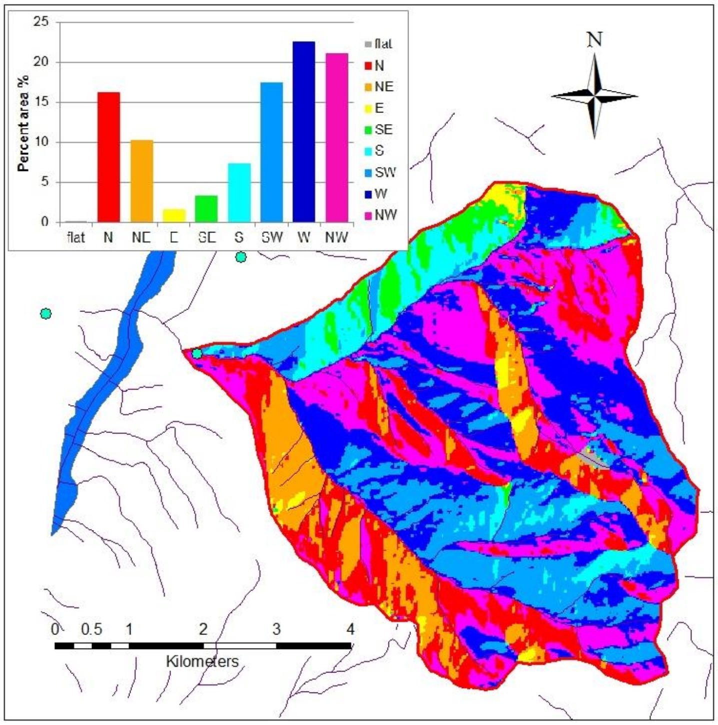
Figure 4. Relief map of Glade Watershed showing the north and south fork tributaries and the location of the Glade Irrigation District intake (blue dot).

Geology and Soils

Geology underlying the watershed is predominantly coarse grained granodioritic rock of the Nelson intrusive complex. Soils derived from the intrusive rock are generally well drained sandy gravels although highly erodible silty-sandy saprolitic soil derived from the granitic rock is present in some areas in the upper elevations (Apex, 2000). The north side of the north fork tributary is underlain by fine grained meta-sedimentary rocks of the Ymir Group. Soils derived from these rocks have a higher silt component. Surficial deposits include coarse colluvium and thin veneers of coarse textured ablation till. Thick deposits of glaciofluvial silts and fine sand occur at lower elevations along the western and northwestern boundaries of the watershed facing the Kootenay River valley. These thick, fine grained deposits display a substantial amount of instability (landslides and debris flows) and erosion associated with historical road development. Large boulders (glacial erratics) are scattered through the watershed. The sandy nature of the surficial materials and the soils derived from them make them particularly susceptible to erosion.

Aspect, Slope and Elevation Distribution

A GIS analysis of slope distribution in Glade Creek indicates that, over the entire watershed, slopes have predominantly west, southwest to northwest aspects. Western aspect slopes (W, NW, SW) account for over 60% of the aspect distribution in the watershed (Figure 5). When the two tributaries are considered separately the south fork tributary includes relatively more southwest and northeast aspect slopes while the north fork displays a greater amount of west and northwest aspect slopes.



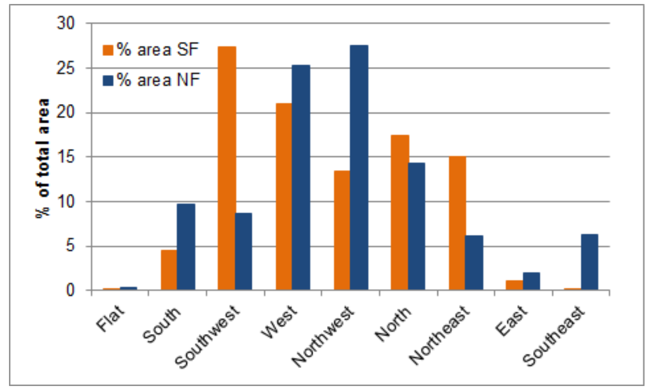


Figure 5. Aspect distribution of Glade Creek and the two forks.

An analysis of slope gradient reveals that the majority of the watershed has moderate to gentle gradient slopes that are generally less than 50 percent (Figure 6). This figure shows that the headwaters of the north and south forks tributaries consist of low gradient bowls. A region of flat-over steep terrain is present along the western and southwestern boundary of the watershed and along the ridge between the north fork and south fork tributaries. Slopes greater than about 60% are generally limited to the upper elevation ridges and locally on the north side of the north fork and southwest side of the south fork tributaries.

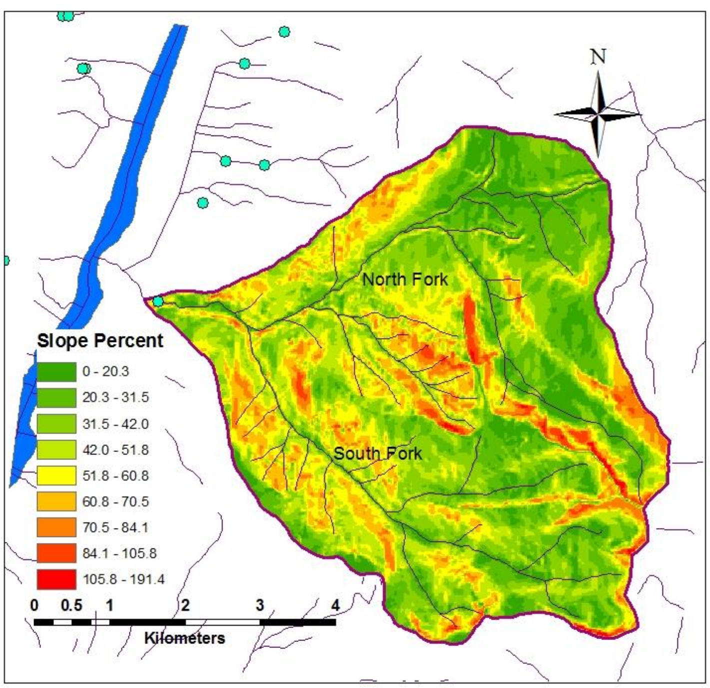


Figure 6. Slope distribution of Glade Creek. Slope gradients range from 0 to over 100 % but the majority of slopes are less than about 60%. Headwaters are comprised of low gradient basins.

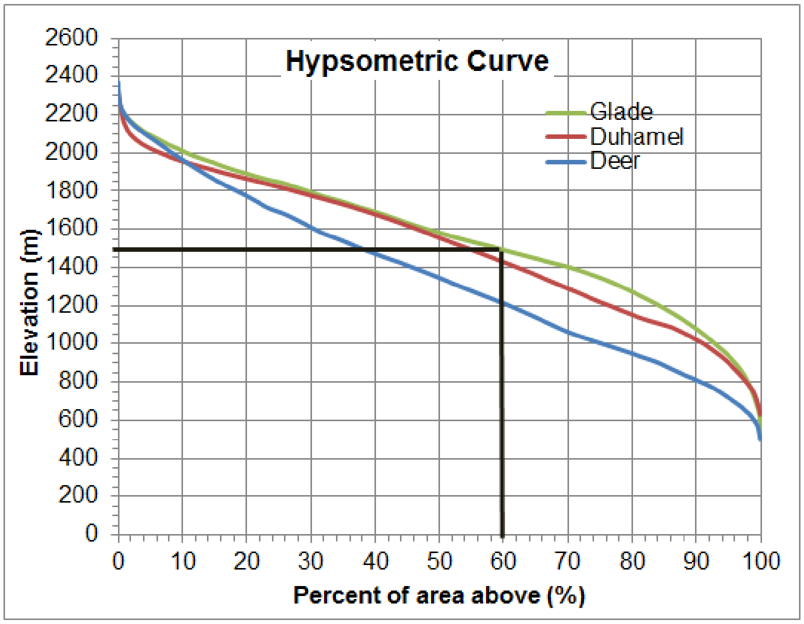


Figure 7. Elevation distribution (hypsometric curve) for Glade Creek. The curves for Duhamel and Deer Creeks are provided for comparison.

The elevation distribution of Glade Creek is investigated by plotting the hypsometric curve which shows the amount (in percent) of watershed area above a given elevation. A comparison with the hypsometric curves from some nearby watersheds shows that Glade Creek is a relatively high elevation watershed (Figure 7). The upper 50% of the watershed displays a similar elevation distribution to Duhamel Creek but the lower 50% is roughly 100 meters, on average, higher than Duhamel Creek. The H60 (60% of watershed are above this elevation) elevation in Glade Creek is 1500 meters.

Climate and Hydrology

Discharge was gauged on Glade Creek during the spring freshet in 1968. A graphical investigation of the climatic controls on discharge is possible using daily precipitation and average daily temperature data for 1968 recorded at the Castlegar Airport just over 10 kilometers west of Glade Creek (Figure 8).

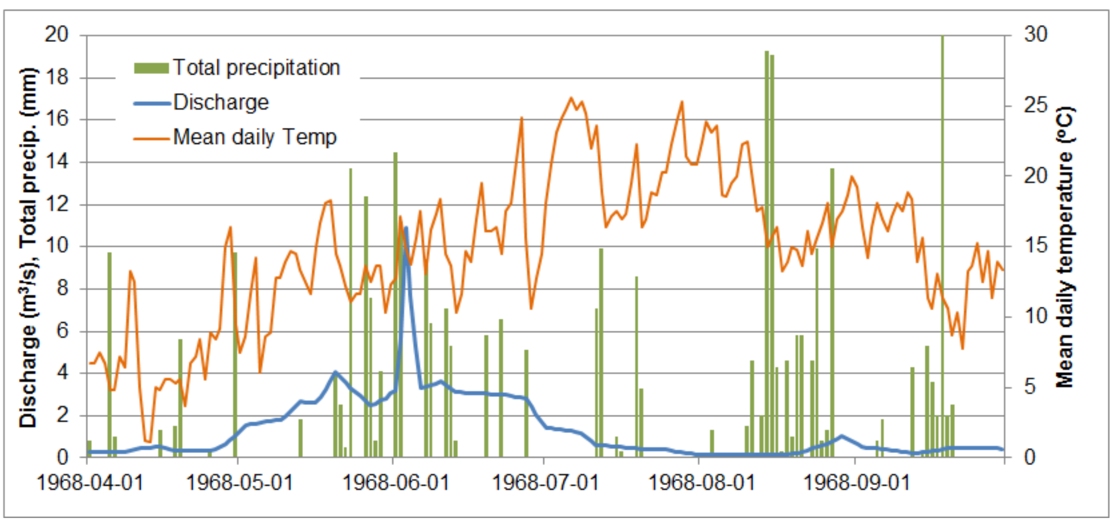


Figure 8. Discharge for Glade and daily precipitation and daily average temperature recorded at the Castlegar Airport for April 1st to September 30th 1968.

Although one year's worth of data provides a limited amount of information it appears that flows began to increase in early May in response to a rise in daily temperature and continued to rise relatively gradually over a couple of weeks of warm and dry conditions. The peak discharge event of just under

11m^3/s also corresponds to a period of increased daily temperature but occurs after about a week of cool wet weather and immediately following a large precipitation event of over 14mm of rainfall in a 24 hr period. Following the peak event discharge drops rapidly to below 4m^3/s despite temperatures remaining elevated. It is also interesting to note a small increase in low-flow discharge in late August following roughly two weeks of rainfall.

Forest Development/Disturbance

Forest harvesting in Glade Creek dates to the early 1900's. The oldest disturbance that is recorded in the Province's VRI data base shows openings dating back to 1934. Some remnants of the old roads exist on the flats of the two main tributaries but there is minimal visual evidence of old blocks on the Google Earth images. Historical information contained in Carver (2001) indicates the watershed was logged in the 1920's according to Glade resident Bill Shlakoss. The 1920's logging involved the establishment of several logging camps as well as a system of flumes for transporting the logs out of the watershed. Remnants of a flume and a check dam were noted during the field investigation for this study in the north fork approximately below the point where the upper power line crosses through the watershed (Photo 1)

Photo 1. Looking upstream at a remnant of a log crib structure that spanned the north fork valley bottom. This structure appears to have been used as a retention dam to supply water to the flume system.

Carver (2001) also records that a large forest fire occurred in Glade Creek in 1934 (apparently human caused and originating near the mouth of the Slocan River). According to Bill Shlakoss the fire put an end to this earliest logging due to high discharges which impacted the ability to flume logs (Carver, 2001). Data from the VRI database indicates the total watershed area disturbed by the 1934 fire was 1136 hectares or 38% assuming that the stands regenerating from the fire have all been assigned a projected age of 77 years in the VRI database.

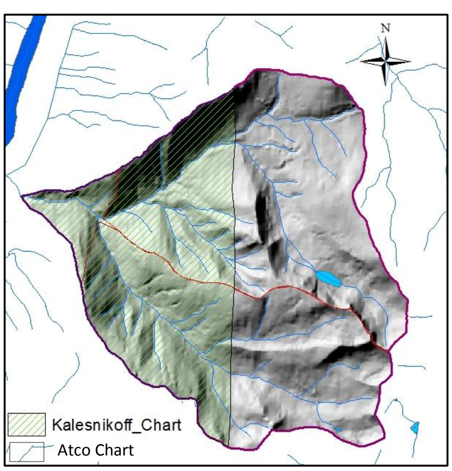


Figure 9. Current licensed chart areas in Glade Creek.

Currently Atco Wood Products Ltd and Kalesnikoff Logging Company Ltd hold licenses to harvest forests in Glade Creek. The licenced chart area for the two logging companies is shown in Figure 9. Kalesnikoff holds the license to harvest wood from crown land in the lower half of the watershed while Atco holds the license for the upper half of the watershed.

Hydrological Recovery

In snowmelt-dominated regions like the Kootenays, forest removal affects the hydrological response of a watershed because it can alter (1) the amount of snow that accumulates on the ground and (2) the rate and timing of snowmelt during the spring freshet (Winkler et al., 2010). As the forest stand regenerates in the years following removal an amount of hydrological recovery can be applied to the stand reflecting the recovery of the processes of snow accumulation and snowmelt. Currently there is very limited data on hydrological recovery in forest stands of the West Kootenay area. Ongoing studies of the recovery of snow accumulation and melt processes in the Thompson – Okanagan region by Dr. Rita Winkler have been used to develop a preliminary hydrological recovery curve applicable to that region (Figure 10, from Winkler and Boon, 2015).

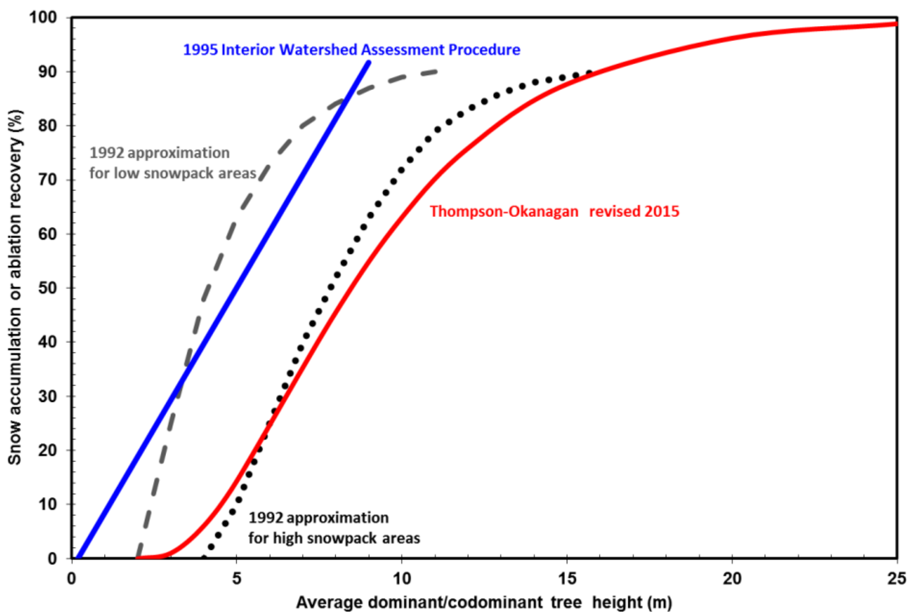


Figure 10. Recently developed hydrological recovery curve based on Rita Winkler's stand level studies in the Thompson and Okanagan Region.

Winkler and Boon (2015) determined that the amount of hydrological recovery depends on the stand height as well as the canopy density. The red curve shown in Figure 10 which is based on Winkler's research is applicable to stands that have a stem density consistent with the pre-harvest condition. The recovery curve is not applicable to stands where the regenerating stand has a substantially lower stocking density than the undisturbed forest. In addition the recovery curve is developed for lodgepole pine and spruce – pine forest types typical of the Thompson-Okanagan.

Despite the lack of locally-relevant hydrological recovery studies, an estimate of the current hydrological recovery in Glade Creek is provided here by using the recovery curve of Winkler and Boon (2015) together with available literature on forest harvesting effects on snow accumulation and melt (Appendix 3). Forest stand information including stand height and canopy closure is determined from the VRI database (downloaded from BC data warehouse, November, 2015), limited field observations and Google earth imagery.

Glade Creek has experienced extensive forest disturbance over the past century. Mature forest stands of greater than 100 years old in the upper portion of the watershed have stand heights in excess of 23 meters and crown closures ranging from 50% to 60%. For the purpose of estimating hydrological recovery of the current disturbed area in Glade Creek, a stand is considered fully recovered once it reaches 23 meters in height and has a crown closure of at least 55%. Stands greater than 15 meters but less than 23 meters are also considered fully recovered if they have a crown closure of 60% or greater. The assignment of hydrological recovery values for regenerating stands less than 100 years in age is provided in Table 2.

Table 2. Hydrological recovery values for given stand characteristics

Stand height (m) of primary strata	Canopy closure (%)	Hydrological recovery (%)
15 to 23 meters	45 to 60%	90
10 to 15 meters	45 to 60%	70
5 to 10 meters	45 to 60%	40
Greater than 15m	Greater than 60%	100
10 to 15 meters	Greater than 60%	90
10 meters or more	30 to 45%	60
Less than 10 meters (and/or)	Less than 30%	0

The VRI database indicates that a substantial amount of disturbed forest is either 77 years or 82 years old. These dates correspond well to disturbance associated with 1920's logging and the 1934 forest fire. Together the disturbed stands correspond to 2013 hectares of Glade Creek (67% of the watershed) which would have been essentially in a clearcut condition following the 1934 fire. Based on information on stand composition, height and canopy closure provided in the VRI database 201 hectares is estimated to be still in a hydrologically unrecovered (0% recovery) state (Figure 11) with crown closures less than 20% and vegetation consisting of predominantly deciduous stands. In addition, 283 hectares of forested area disturbed during the past 100 years has not achieved full hydrological recovery due to low stand height or low canopy closure compared to the fully forested condition (Table 3).

The most recent logging consisting of four small blocks totaling 45.3 hectares in the upper portion of the south fork tributary was undertaken in the 1990's by Atco Lumber Ltd. One of the blocks was cut using a high retention system where only 50% (approximately) of the forest within the block boundaries was harvested (i.e. 5.2 hectares of the 10.4 hectare block is counted as clearcut).

Table 3. Equivalent Clearcut Area (ECA) estimation for Glade Creek.

Opening description	Area (ha)	Applied Recovery (%)	Unrecovered area (ha)		
			total (2977 ha)	South Fork (1286 ha)	North Fork (1561 ha)
Recent Blocks and powerline (2000/2011 harvest year)	65.4	0	65.4	46	3.9
1934 burn still unrecovered (deciduous leading)	201	0	201	0	180.5
Recovered early 1900s disturbed forest	868	100%	0	0	0
Disturbed forest 90% recovered	740	90%	74	28.1	44.6
Disturbed forest 70% recovered	102	70%	30.6	6.1	24.5
Disturbed forest 60% recovered	64	60%	25.6	5.2	19.6
Disturbed forest 40% recovered	37.8	40%	22.7	0	22.7
Total current ECA			**419.3 (14.1%)**	**85.4 (6.6%)**	**295.8 ha (19%)**
Proposed ECA with Atco block (Figure 10)	29.7		29.7 (15.1%)	na	325.7 ha (20%)

Based on the assumptions of hydrological recovery the current ECA of Glade Creek is estimated at 419.3 ha or 14% of the 2977 ha watershed area. 296 hectares (19%) of ECA are in the north fork tributary and 85.4 hectares (6.6%) of ECA are in the south fork tributary.

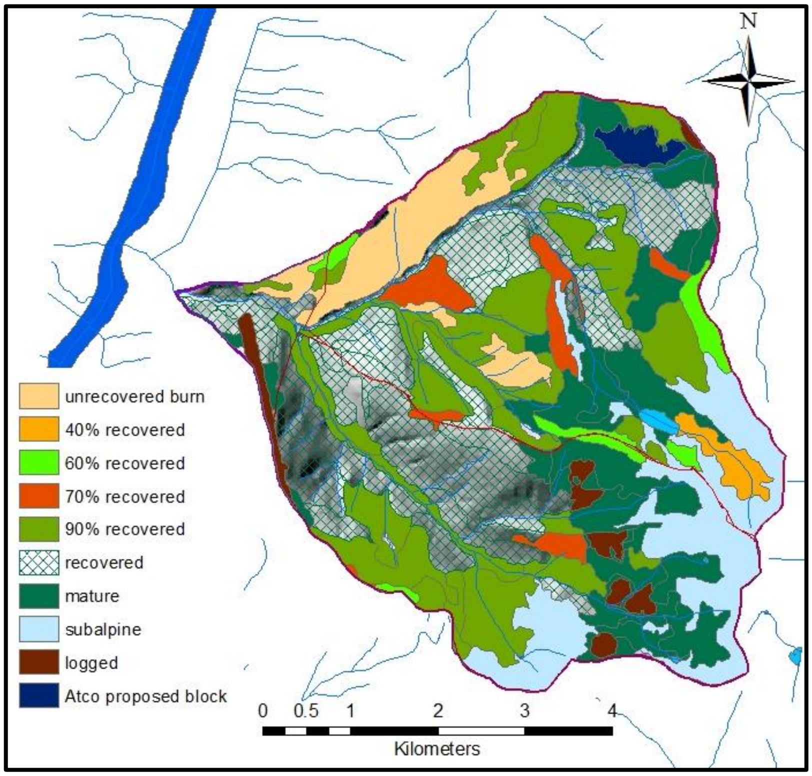


Figure 11. Existing cutblocks (brown) and partially recovered (green and orange) or unrecovered (buff) burned areas in Glade Creek. Proposed block of Atco is dark blue. Subalpine/alpine area is light blue.

Atco is proposing one block of 29.7 hectares along the northern boundary of the map area (blue block Figure 11). The proposed logging will increase the existing ECA to 449 hectares or 15.1% of the total watershed area and will increase the ECA in the north fork to 325.7 ha or 20% of the 1561 ha subbasin.

Hydraulic Geometry

Survey data of channel bankfull width, bankfull depth and stream gradient is used to characterize the relationship between channel structure and watershed area (a proxy for discharge). As watershed area increases discharge also increases. Well-defined relationships between channel geometry and watershed area implies a strong connectivity between the contemporary flow regime and the channel form. Well defined relationships between channel form and watershed area also indicate a potentially high sensitivity of a channel to changes in the flow regime. Additionally, well-defined relationships between grainsize and the stream power which is a function of the product of discharge and channel gradient also indicates the degree of sensitivity of the stream bed to changes in discharge.

In Glade Creek both channel width and depth and the derivative (flow cross-sectional area) display a positive trend with watershed area but there is a relatively high degree of scatter in the data especially through the lower reaches of the watershed (beyond 2800 ha) where the channel is either confined by bedrock or is unconfined on the alluvial fan (Figure 12a-c). When the data from the two tributaries are considered separately it is apparent that the channel in the north fork is wider and deeper than that of the south fork for the same watershed area. Although it could be that unit discharge (i.e. discharge divided by watershed area) is higher in the north fork, it is also likely that the extensive riparian disturbance from past logging activities has contributed to channel degradation. Observations made during the field investigation support the latter cause. The lack of mature riparian vegetation has made the channel banks on the north fork tributary more vulnerable to erosion.

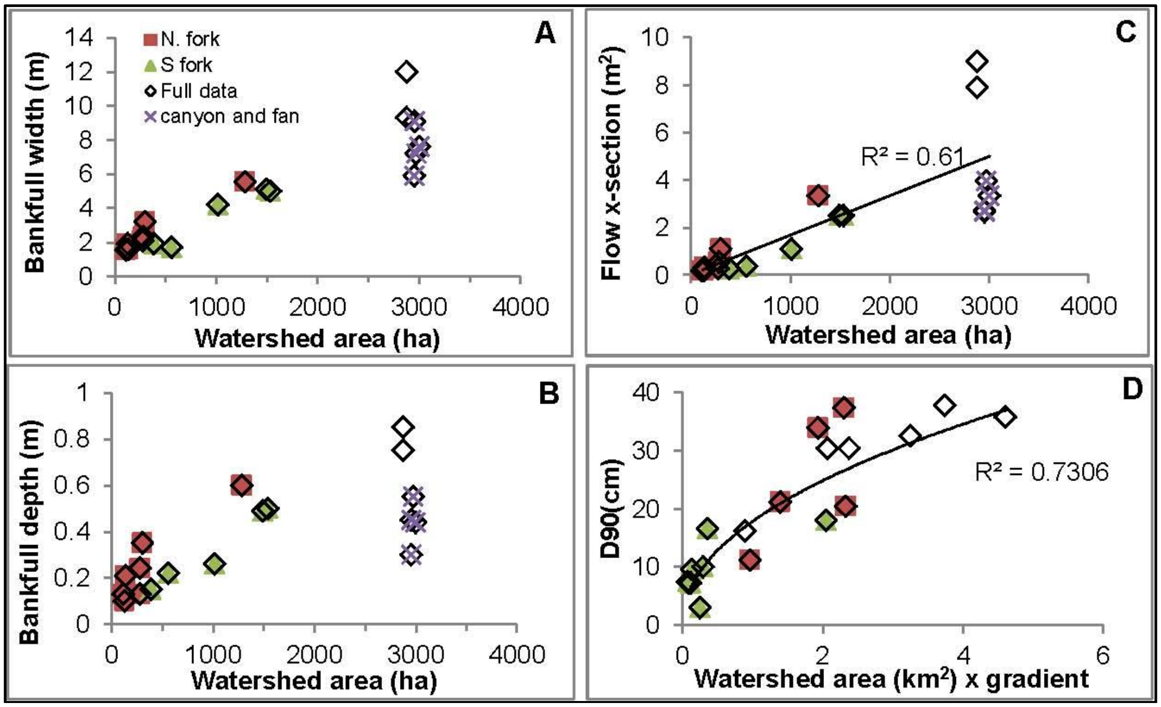


Figure 12. Hydraulic Geometry and maximum mobile grainsize relationships for Glade Creek.

The dynamics of sediment transport in Glade Creek is investigated using the trends between the largest frequently mobile grain (i.e. the largest bed material that is likely mobile during the bankfull flood), and stream power, which is the product of watershed area and channel gradient. The largest mobile grain is referred to as the D90 (the diameter of the grain is in the 90th percentile of obviously mobile grains at the sampling site). In Glade Creek there is an obvious increase in the size of the maximum mobile sediment with increasing stream power but there is a substantial amount of scatter to the data (Figure 12d). Additionally it appears that the maximum mobile grain for a given stream power is larger in the north fork tributary than the south fork tributary.

Field Observations

The objective of the field survey is to gain a general understanding of the existing channel morphology and controls on the spatial variability of the morphology with increasing scale as well as changes in gradient, confinement, aspect and elevation. To achieve this objective survey sites are selected to provide a representative sample of channel morphologies with increasing scale and a range of elevation and aspects (Figure 1). Due to the limited road access only portions of the upper reaches of the north and south fork tributaries and the lower mainstem channel below the confluence of the two tributaries was surveyed as part of the field investigation.

North fork

Photo 2. looking upstream in channel from Siwash lake. The deciduous riparian vegetation and the abundance of cut logs in the channel are the legacy of early 1900's logging.

The channel below Siwash Lake is the main headwater tributary of the north fork of Glade Creek. Only the lower two hundred meters of this headwater tributary were observed in the field.

The lower reach has a forced step pool to cascade morphology with broken and cut wood jams and colluvial boulders forming the steps. The channel in this area has an average bankfull width of 1.7 metres and an average bankfull depth of 0.22 meters. Channel gradient average 25%.

Photo 3. looking upstream on North Fork headwater below Siwash lake. Channel shows indications of very large debris flood that occurred roughly 50 years ago as well as extensive disturbance from logging.

The channel shows indicators of a large debris flood that is at least 50 years old as well as a smaller recent flood that has mobilized material up to large cobble size and formed cobble deposits behind woody debris.

Riparian vegetation consists of alder and shrubs. The disturbance to the channel and riparian area from the 1920s logging is still very evident as piles of cut wood and boards in and along the channel and old trails on the valley bottom that have disturbed channel banks.

Photo 4. Northern branch of north fork tributary is smaller than the tributary from Siwash Lake. There is an extensive amount of disturbance in this tributary from past logging. The channel appears to have been skidded through during the 1920's logging.

The northern branch of the north fork tributary is smaller and carries lower flows than the branch from Siwash Lake. Channel disturbance is very extensive in this tributary. There is almost a complete lack of channel structure. On average the active channel width is about 1.9 metres and the depth averages about 0.15 meters. Channel gradient average 25%. Very little bed material in this channel appears mobile. Most of the cobbles and boulders are moss covered and do not appear to have moved since they were disturbed by logging in the 1920s. There is a large volume of old cut and burned vegetation in the channel and wood from the regenerating stand (birch) is also starting to fall in to the channel.

Riparian vegetation includes alder, birch, fir, larch, poplar and cedar. All of the regenerating conifers are less than about 30 cm diameter at breast height.

Photo 5. Looking upstream 700 meters upstream from the north and south fork tributary confluence. North fork channel shows recent disturbance from large flood as well as very extensive disturbance from 50 year old debris flood and the 1920's logging.

Further downstream the tributary of the north fork displays extensive disturbance from the old (1948) debris flood and from the 1920s logging.

Through the lower reaches the north fork channel has a forced step to cascade/step pool morphology with boulders and broken woody debris forming the steps and cascades. Channel banks are eroded and laid-back to vertical but mostly mossy. There is a lack of mature coniferous vegetation in the riparian area. Riparian vegetation includes cottonwood, cedar, hemlock and alder all less than 30 cm. Old cut stumps that have been burnt consistent with historical information that indicates the fire (1934) post-dated the logging

(1920's). The bankfull channel width average 5 meters and the bankfull depth averages 0.5 meters. The channel gradient averages 13%.

Photo 6. Large old woody debris jam from 1948 debris flood.

The large debris flood that occurred in 1948 caused the majority of the north fork channel to become mobile including the large boulders, pieces of woody debris and cut lumber. Large levees and debris deposits from this major debris flood occur along the length of the north fork tributary. Observations made during the field investigation suggest that failure of valley-spanning retention dams used for fluming logs in the 1920's in the vicinity of the confluence of the two north fork headwater tributaries (Survey site 29) may have played a role in the extensive flood disturbance downstream from this point in the north fork channel.

South Fork

Photo 7. Looking upstream at survey site 20 in headwaters of south fork tributary.

Compared to the north fork, the headwaters of the south fork tributary display few indications of past channel disturbance. The channel alternates between a colluvial channel where the stream is flowing over large granitic boulders to a forced step-pool channel with large, old (mossy) woody debris forming steps. In the semi-alluvial step-pool reaches the channel has an average bankfull width ranging from 3 meters at site 12 to 1.5 meters at site 20 while bankfull depth ranges from 0.35 to 0.13 meters over this same area. Channel gradient ranges from 5% through step pool segments to over 20% in the colluvial cascade segments.

Riparian vegetation is a mixed age stand of Englemann spruce and subalpine fir. Channel banks are overhanging, mossy and vegetated with mature coniferous trees and shrub alder.

A recent large flood event has mobilized some smaller wood and caused local scour and deposition of small cobble to gravel sized material in the channel bed.

Photo 8. Looking downstream at site 12. Banks and larger colluvial blocks are mossy. Very old woody debris is functioning in the channel to retain sediment.

The lower reaches of the south fork channel above the confluence with the north fork are much different in appearance than the lower reaches of the north fork. The south fork channel has a high percentage of large, mossy lag boulders and channel banks are mostly mossy and overhanging to vertical. The lag boulders are mostly granitic in composition and appear to have entered the channel from the valley side slopes after the glacial ice retreated.

Photo 9. Looking upstream on the south fork at survey site 7 above north fork confluence. Channel is mossy, with a lag boulder cascade morphology.

The average bankfull width is 5.5 meters and the average bankfull depth is 0.6 meters. The channel gradient averages 16%.

Along this portion of the channel the riparian consists of immature cedar and hemlock with a mix of deciduous trees including alder, cottonwood and birch. Due to the coarse texture of the channel bed there is no woody debris functioning in the channel.

Observations of flood impacts are much fewer in this tributary. The banks appear to have been scoured during the 1948 debris flood and it appears that the lag boulder stone lines have been in place for at least several decades. However, there is a lack of debris levees along the channel margins and a lack of debris flood deposits on valley bottom associated with the 1948 flood. Some brighter cobble – gravel deposits along channel margins that were likely the result of the recent (2012 or 2013) large flood but the maximum mobile sediment is generally less than 20cm.

Glade Creek below North – South fork confluence

Photo 10. Looking downstream at recent debris flood deposit below confluence of north and south forks at survey site 9.

Approximately 300 meters of Glade Creek in the vicinity of survey site 9 the channel displays the impacts of a recent (2012 or 2013) very large flood/debris flood. Large, bright boulder levees occur along channel margins and banks are eroded and vertical. The channel appears to have flowed in multiple branches eroding new channels on the valley bottom. In some locations riparian vegetation along the margins of the channel has been buried by over 2 meters of cobbles and woody debris. It is not clear why this portion of the Glade channel was so severely impacted but it may have resulted from the failure of an old debris jam in the lower reach of the north fork tributary. Boulders up to approximately 40 centimeter diameter were mobile during this recent large flood and mid channel levees are up to 2 meters high.

Photo 11. Survey site 10 shows much less recent flood disturbance than at site 9.

At survey site 10 the channel gradient decreases to an average of 12% and flood disturbance associated with the 2012 or 2013 flood is limited to localized bank erosion and deposits of gravel and cobbles.

Riparian vegetation along this portion of Glade Creek consists of a mixed age stand of cedar and hemlock with diameters up to about 40 cm (abh). Channel banks are scoured and vertical. The channel bankfull width averages 12 meters and the bankfull depth averages 0.8 meters. Channel gradient averages 16 percent.

Bedrock canyon and falls

Photo 12. Panorama looking upstream at site 21. Mossy boulder levee on right is from 1948 flood.

From Survey site 21 to survey site 25 the channel of Glade Creek flows in a steep-sided canyon with bedrock or large lag boulders confining the channel and banks. The channel has a cascade morphology with channel gradient ranging between 7 and 20 percent and bankfull width varying from 9 to 12 meters

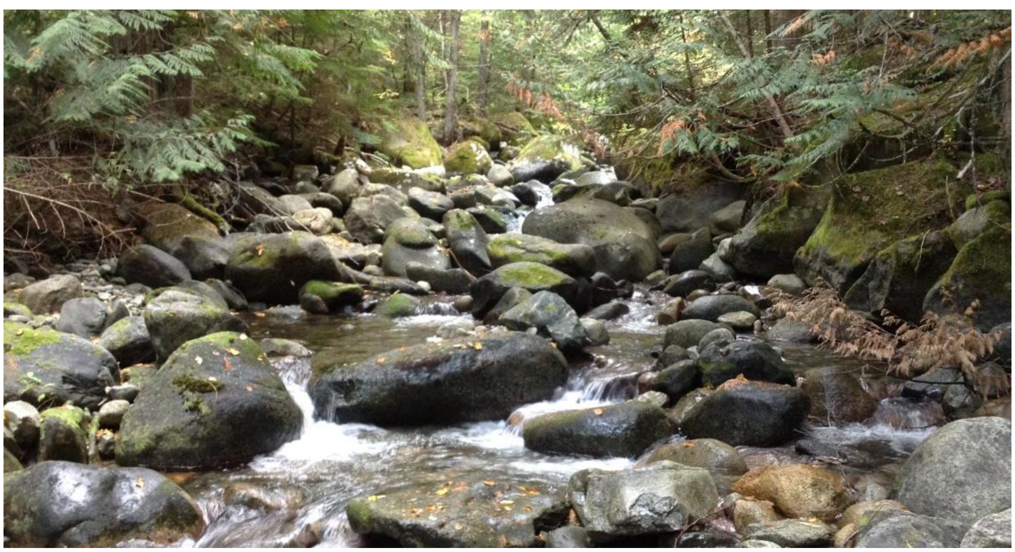


Photo 13. Looking upstream at site 23. Lag boulders in channel and along banks are from glacial moraine features that are present throughout the south fork and lower reaches of Glade Creek.

The channel through this section varies from dark, mossy boulder cascade sections showing a limited amount of bank scour and bed mobility to sections where the channel appears to have been almost fully mobilized with debris levees and channel avulsions as a result of the 2012 or 2013 flood event. Mossy, vegetated debris levees from the 1948 debris flood occur along much of this lower portion of Glade Creek

Photo 14. Looking upstream at recent debris flood deposits at site 24. This section of channel is about 100 meters downstream from site 23 (above) which displays little disturbance as a result of 2012 or 2013 flood.

Summary of watershed hydrogeomophic processes

Glade Creek consists of two tributaries with different hydrogeomorphology that can be related to differences in disturbance history, geology and aspect distributions.

Hydrology

The combination of slope aspect, slope gradient and elevation distribution controls the hydrological response of a snowmelt watershed (Romshoo et al., 2012). In the northern hemisphere, watersheds with predominantly south aspect slopes have greater exposure to incoming solar radiation which results in greater responsiveness and variability in daily stream flows during the snowmelt freshet period (Hendrick et al., 1971). In addition steeper slopes in a watershed result in faster, more effective delivery of runoff to the mainstem channel (Romshoo et al., 2012; Schnorbus and Alila, 2013).

The investigation undertaken in this study provides some information on the hydrological processes and responses in Glade Creek. Firstly Glade Creek appears to be relatively slow to respond to warming weather in the spring. Early April warm temperatures did not result in a discharge response in 1968. Turbidity data for 2015 support this observation; April warming and precipitation events did not trigger substantial increases in turbidity which suggests that discharge is not increasing in response to these early spring meteorological events. Secondly, discharge does not appear to fluctuate substantially with daily temperature. In 1968 there is one large magnitude but short duration peak event that appears to be the result of warm temperatures and a fully saturated snowpack following a period of rainfall (i.e. rain-on-snow event), however individual peaks in temperature do not result in corresponding increases in discharge. Finally, there is a gradual decrease in discharge following the main, early June peak despite the continued increase in daily temperature.

If the historical data is accurate, these observations suggest that discharge on Glade Creek is not particularly sensitive to direct solar radiation inputs. In addition Glade watershed does not have much soil water storage available to contribute to successive peak events. Once the snowmelt is finished water levels drop quickly and stay low except for periods of very wet weather. The limited soil water storage capacity is consistent with the condition of shallow soils over bedrock which has been documented in the terrain mapping (Apex, 2000). Turbidity data for 2013 to 2015 also support these conclusions. In 2014 there are few rises in turbidity following the main peak in turbidity that occurs with a mid-May rainfall/rapid warming event. Similarly, following the 2015 February peak in turbidity (likely associated with an ice jam flood event that occurred in many streams in the west Kootenay region) turbidity increases only a small amount in late May in response to rapid warming and precipitation and then remains low for the remainder of the late spring and early summer months.

The aspect distribution of the south fork basin which has over 30% south to southwest aspect slopes and 32% north to northeast aspect slopes results in this tributary having naturally desynchronized snowmelt runoff. It is likely that the southern aspect slopes are mostly snow-free by the time the north aspect slopes begin to melt. Natural desynchronization of runoff likely results in lower unit discharges (discharge per unit area) in this tributary compared to those with a wider aspect distribution. The relatively lower unit discharge is supported by the hydraulic geometry data which shows smaller channel geometry in the south fork compared to the north fork.

The predominance of northwest and north aspect slopes in the north fork tributary (Figure 5) south of the stream channel that account for 41% of the basin area results in much more synchronized snowmelt runoff to the stream network compared to the south fork. In addition, it is likely that the burned and sparsely vegetated south aspect slopes on the north side of the north fork channel melt off much earlier than the north-aspect slopes so that the main peak event in the north fork is driven almost entirely by late-season longwave driven snowmelt from the naturally shaded northwest to north aspect slopes. This mechanism of snowmelt (indirect longwave versus direct shortwave radiation) makes the north fork tributary less sensitive to harvesting related openings in the forest, but only for years where the snowmelt is driven by warm dry weather. For extreme events (such as 1948, 2012, 2013) where the snowmelt is driven by rain-on-snow events, the additional snow (upwards of 50% more) in the harvested openings will increase the magnitude and duration of these late season rain-on-snow peak flows.

The observed similarity in flood disturbance histories for the lower reaches of Glade Creek and north fork channels suggests that the major floods (i.e. rain-on-snow floods) in the watershed are controlled by runoff in the north fork tributary.

Geomorphology

The north fork channel and riparian area has been severely impacted by the 1920's logging and a large forest fire in 1934. The channel of the north fork has been directly impacted by log hauling and roads to the point that none of the surveyed reaches was in a natural condition. The channel of the north fork also showed extensive bed mobility and bank erosion disturbance associated with the recent (2012 or 2013) large flood event. In addition, large debris lobes and levees from the 1948 flood are present from the lower reaches of the Siwash Lake headwater channel down to the confluence with the south fork. In contrast the south fork channel, where it was observed in the field, does not show extensive disturbance from past logging activities or major floods. Evidence of recent high flows is limited to mobilization of small woody debris and gravel in the headwater reaches and bright deposits of cobbles and gravel in the lower reaches.

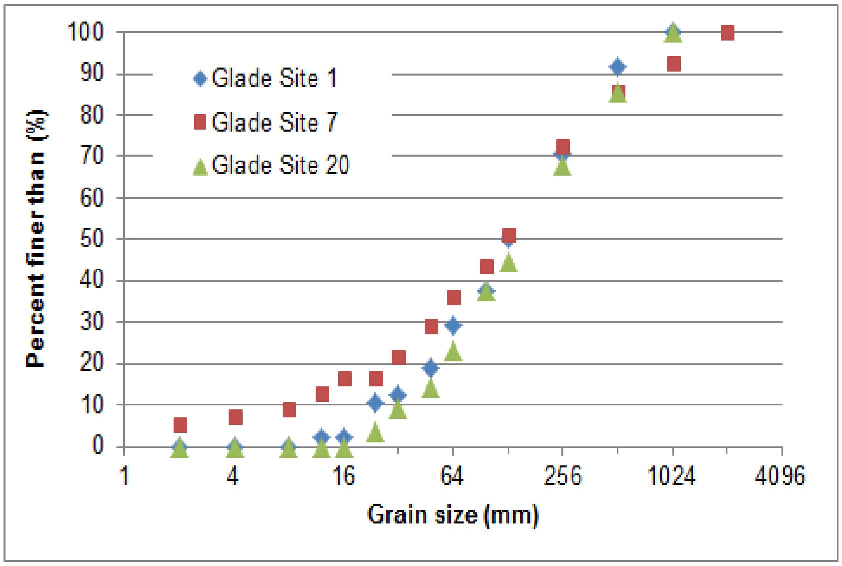


Figure 13. Grain size distribution for Survey site 1 (north fork), site 7 (lower south fork) and site 20 (upper south fork).

These observations indicate that the north fork tributary experiences more flood disturbance than the south fork tributary. The greater incidence of flood disturbance in the north fork contributes to differences in riparian integrity, channel bed grain size distribution and a greater degree of synchronization of snowmelt runoff from the upper elevations compared to the south fork. The channel of the south fork has a coarser bed grain size distribution and contains a larger percentage of lag boulders compared to the north fork channel (Figure 12, red squares – south fork, blue diamonds – north fork). The presence of lag boulders increases channel bed roughness which decreases the flow velocity and, as well, armours the channel bed and bank reducing the potential for erosion and grain mobility during high flows. In addition, the mixed-age cedar-hemlock riparian stand along the south fork tributary also contributes to channel bank stability.

The variability in the extent of flood disturbance observed along the lower reaches of Glade Creek reflects the influence of bedrock and lag boulders on stabilizing the stream channel. The extensive impact from the 1948 flood suggests that for some extreme conditions, which likely include high snowpacks, delayed spring snowmelt and large rain-on-snow events (conditions that occurred in 1948), debris floods are capable of traveling through the lower reaches of Glade Creek and impacting the water intake at the falls and the fan below the falls. The 1948 debris floods that appears to have initiated in Glade Creek (north fork) as a result of prolonged high discharge and, possibly, the failure of a valley-spanning water retention dam that had been used to supply water to the flume system. The 2012 flood, which triggered a debris flood in portions of the north fork and Glade Creek, occurred following 42mm of rain (Castlegar weather station) falling on a saturated snowpack. The 2012 flood, estimated as having a return period of between 30 and 70 years in other nearby gauged watersheds (Redfish and Duhamel Creek), was not of sufficient duration and/or magnitude to have a major physical impact on the lower reaches of Glade Creek although it created the some of the highest turbidity readings since recording began in 2012 (only May 22, 2013 rain-on-snow event exceeded the 2012 turbidity levels).

Risk analysis for existing conditions and proposed development

Risk is assessed as the product of the probability of a hazardous event and the consequence of the hazardous event on the element at risk. The chance of a hazardous event occurring is assigned a quantitative probability or qualitative likelihood according to the following criteria (Table 3).

Table 4. Quantitative and qualitative frequency definitions for a hazard adapted from LMH 61.

Quantitative frequency (annual probability)	Qualitative likelihood	Description
≥ 0.19 (1:5.26 yrs)	Very high	An event will occur frequently within a human lifespan
0.05, <0.19 (1:5.26 to 1:20)	High	An event will occur several times within a human lifespan
0.02, <0.05 (1:20 to 1:50)	Moderate	An event is possible within a human life span
0.005, <0.02 (1:50 to 1:200)	Low	There is a small likelihood of an event occurring within a human lifespan
≤0.005 (1:200 yrs)	Very Low	There is a very remote likelihood of an event occurring within a human lifespan

Consequence is assessed qualitatively as the extent of impact to the element at risk. Given quantitative information about the vulnerability of the water intake to sedimentation or infrastructure damage, it is possible to assign a consequence rating such as shown in the example in Table 4.

Table 5. Example consequence assignment.

Consequence	Water Quality/Channel Stability
High	On-going deleterious impacts to water quality causing water to be non-potable for several weeks or more annually or destruction of intakes due to channel avulsion or mobilization large cobbles, boulders and debris.
Moderate	Short term impacts to water quality requiring temporary measures (less than several weeks) to improve potability, or requiring minor repairs to intake structures.
Low	No substantial change in management protocols for maintaining water quality, no change in maintenance regime for intakes.

The risk is determined using a qualitative risk analysis matrix such as the one shown below in Table 5.

Table 6. A qualitative risk matrix adapted from Wise et al., 2004.

	Consequence		
Hazard	**High**	**Moderate**	**Low**
Very high	Very high	Very high	High
High	Very high	High	Moderate
Moderate	High	Moderate	Low
Low	Moderate	Low	Very low
Very low	Low	Very low	Very low

Definition of Element at Risk

The Glade Creek assessment considers that (1) the water quality and (2) the timing of flows at the water intake are elements at risk, as well as (3) the water intake itself are elements at risk.

Assessment of Hazardous events in Glade Creek

This assessment considers four hazardous events; (1) a flood in Glade Creek below the north – south fork confluence that could damage the water intake, (2) a flood capable of substantially increasing sedimentation at the intakes (i.e. above the normal range of variability), (3) a change in the timing of runoff that could create water supply problems during low flow months and (4) a landslide that could impact the water intake and/or cause long term impacts to water quality on Glade Creek.

Damaging Flood

Current hazard

The channel of Glade Creek above the falls where the water intake is located is generally resilient to larger than average flood events due to the presence of glacial lag boulders and bedrock in the channel and along the banks. The channel and intake structure observed during the field survey were not substantially affected by the 2012 flood event which had an average return period (based on nearby watersheds) of about 1:50 years (or an average annual probability of 0.02). Field observations indicate that the 1948 flood was the last large flood event that had sufficient magnitude and/or duration to impact the lower reaches of Glade Creek. Although the local annual probability of occurrence of the 1948 flood is not known it had a regional return period of 1:200 years which corresponds to a **Very Low** likelihood of occurrence according to Table 3. The current low level of forest disturbance of 14.1% ECA, will not increase the probability of a damaging flood event above the fully forested condition. This disturbance level has dropped substantially over the past 77 years as the forests have regenerated from early 1900's logging and forest fire impacts that originally accounted for an ECA of 67% (2013ha) over all of Glade Creek and 64% (997ha) in the north fork basin.

Future conditions – Effects of additional forest removal

Modeling of harvesting scenarios in Redfish Creek (Schnorbus and Alila, 2004) determined that harvest levels below approximately 20% when distributed across aspects in the lower third of the watershed will not result in detectable changes in the frequency distribution of floods (i.e. have a low likelihood for increasing the existing frequency of the hazardous event). However, Redfish Creek is predominantly south aspect and has roughly 40% subalpine/alpine area while Glade Creek is predominantly west to northwest aspect and has only 12% subalpine/alpine area. Consequently the two watersheds are likely to have much different hydrological responses to forest harvesting. To determine how Glade Creek is likely to respond to harvesting it is necessary to consider stand level studies that investigate the effects of aspect and elevation on harvesting related changes to snow accumulation and melt.

As discussed previously Glade Creek consists of two headwater tributaries. The south fork tributary, which has roughly equal amounts of southern and northern aspect slopes has naturally desynchronized snowmelt runoff and therefor is likely to be less sensitive to forest harvesting if openings are located across a range of elevations and aspects so as to maintain the desynchronized melt. In the south fork subbasin, a level of harvest of up to 20% is unlikely to affect flood frequency or magnitude in Glade Creek (i.e. represents a **low** hazard or **low** likelihood of changing the frequency/magnitude of damaging floods) at the intake given well distributed arrangement of cutblocks.

The north fork tributary is likely to have a greater response to forest harvesting for extreme (damaging) flood events due to the limited aspect distribution that is controlling peak flows. Stand level studies show that forest openings with northern aspects accumulate upwards of 50% or more snow but have little change, or even reduced rates of snow melt compared to the forest stand (Ellis et al., 2010). These studies relate only to snowmelt driven by solar radiation and not to rain-on-snow. Studies in the rain-on-snow zone (Hudson, in press) show that north aspect openings are much more sensitive to harvesting than south aspect openings when peak flows are driven by rain-on-snow events because they retain snow longer into the freshet period. Hudson (in press) shows that snowmelt in north-aspect cutblocks is more than three times faster than the adjacent forest stand. For this reason development concentrated on north and northwest aspect slopes is likely to result in much larger runoff (peak flows) during late season rain-on-snowmelt driven flood events. The concentration of forest fire and logging disturbance on these slopes in the early 1900's which totaled 508 ha of the 1224 ha peak flow generating area south of the channel (41.5%) likely caused the very large peak flows reported by the old loggers following the 1934 fire. In contrast, forest openings on south aspect slopes on the north side of the north fork stream channel are unlikely to have any impact on the flood regime in the north fork tributary because these slopes, especially following harvesting, melt off much earlier (possibly a month or more earlier) than the slopes on the south side which are contributing to peak flows.

Currently 136 ha of the 1224 ha area (11%) south of the north fork channel and approximately 160 ha of the 337 ha area north of the north fork tributary is considered ECA. Based on the rational provided above, Atco's 29.7 hectare proposed block situated below 1600 meters on south aspect slopes will **not affect** the existing hazard of a damaging flood event in Glade Creek. This block increases the ECA in the north fork tributary to 325.7 ha (20%) of the total area. Harvest levels for the north fork tributary of less than 25% overall and less than 15% (or less than about 184 ha of the 1224 hectare area) of the area south of the north fork channel, represent a **low** likelihood of increasing the hazard of damaging flood events **if** openings are situated primarily on southern to western aspect slopes and encompass a range of elevations.

Cut blocks that are situated at the lower elevations directly above the channel above the falls also pose **no change** to the existing likelihood of damaging flood events. This area will be snow free well before Glade Creek annual peak flows occur.

Flood – sedimentation

Current hazard

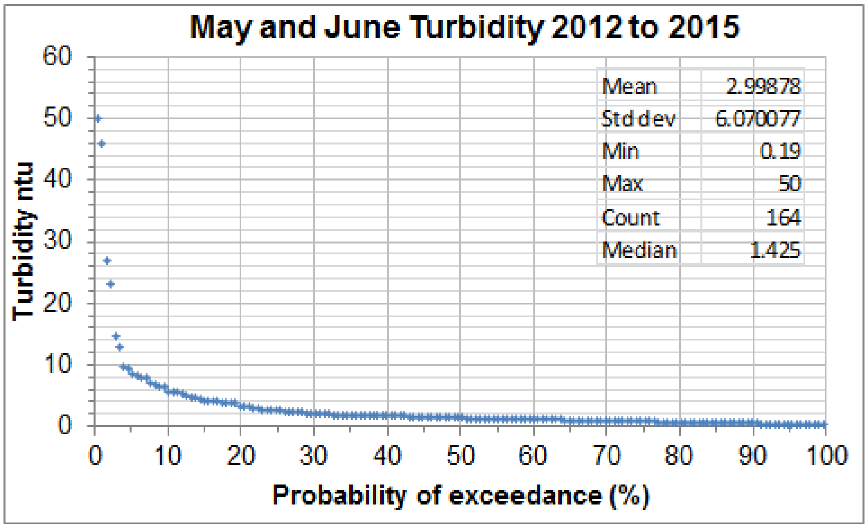


Figure 14. Turbidity data collected during the freshet period by Glade Irrigation District between 2012 and 2015

Turbidity data for Glade Creek indicates that the May to June freshet period average turbidity for the 2012 to 2015 gauging period is 3 NTU's based on 164 samples (double samples collected in 2014 have been averaged, Figure 13).

For the 4 year freshet period the turbidity exceeded the BC water quality guidelines of 1 NTU for 65% of the samples. A total of 5% of the samples exceeded 8 NTU's and 4 events in 4 years or 2% of the samples, had turbidity in excess of 25 NTUs. Due to the lack of discharge gauging on Glade Creek it is not possible to relate variability in water quality to the flow regime. For this reason the hazard of flood related impacts to water quality at the intake cannot be quantified.

Information collected from field investigation determined that bank erosion along the north fork tributary is a major source of fine grained sediment to the lower reaches of Glade Creek. There are also a number of bank failures and small debris slides located in the canyon area upstream from the intake that likely produce sediment during high flows. Besides these relatively minor sediment sources no large, active landslides were identified.

Flow timing

Current hazard

The lack of discharge gauging on Glade Creek makes it impossible to quantify the hazard of runoff timing changes. However, the information from the analysis of hydrological processes undertaken in this study suggests that changes in the timing of flows in Glade Creek are unlikely given existing or proposed forest harvesting. Field observations indicate that peak flows in Glade Creek are controlled by snowmelt from high elevation, north to west aspect slopes in the north fork tributary. In general, flood regimes controlled by snowmelt from north aspect slopes will not experience advances in the timing of peak flows following forest harvesting that have been documented in some studies (Moore and Scott, 2005). Stand level studies in snowmelt regions show that harvesting on north aspect slopes actually delays snowmelt compared to the unharvested stand (Ellis et al., 2010). The relative delay in snowmelt following harvesting on north aspect slopes occurs due to the increased snow accumulation in openings and the reduction in longwave (reflected) radiation from the forest that is the primary driver of snowmelt on shaded, north-aspect slopes.

Landslide impacts to water intake

Current hazard

Although a large landslide capable of causing long-term impacts to water quality at the intake is identified as a hazardous event a rigorous assessment of the likelihood of such event is beyond the scope of this assessment. Such an analysis would require extensive field investigation of slope stability which is typically done once a cutblock is proposed on or above terrain mapped as potentially unstable or unstable. Observations of the effects of past development can provide a less rigorous quantification of the likelihood of this hazard. Several landslides have occurred above the intake off of roads associated with the power line development. The slides off of the power line road above the intake occurred over the past several decades since the road was constructed (1974, information from Carver, 2001) indicating there is a **high** likelihood of development related landslides according to Table 2 (~4/40 years = 0.1 annual probability). However, none of these existing landslides has been sufficiently large to result in substantial, long-term impacts to the intake. Based on this knowledge the historical likelihood of a large slide capable of causing long-term impacts to the intake is less than at least 1:40 years (<0.025 annual probability) which corresponds to a **Moderate** or lower likelihood.

Future condition

Landslides (at least four of them) related to the 1970's power line road development appear to have occurred as a result of inadequate drainage control on gentle-over-steep terrain. Steep, potentially unstable and highly erodible glaciofluvial sands and silts are present as veneers and blankets over bedrock in this portion of the watershed that is directly above the water intake. Currently there is no development proposed on the gentle-over-steep areas adjacent to the intake. To prevent development related increases in the hazard (likelihood) of a large, damaging landslide a Landslide Risk Assessment and a Gentle-Over-Steep terrain assessment would be required if cutblocks or roads are proposed on or above potentially unstable or unstable terrain. Assessments that 1) identify and provide prescriptions to maintain surface drainage patterns and 2) provide an assessment of and prescriptions to mitigate for the increase in landslide hazard associated with increased slope runoff following logging can reduce the hazard of development related landslides.

Assessment of Consequence

The intake on Glade Creek is a concrete diversion structure that is well designed to manage larger than average floods (Clearwater floods), however, it is unlikely that it has been designed to withstand a debris flood. According to the ratings given in Table 4, the occurrence of a landslide or debris flood represents a **high** consequence to the Glade Irrigation District waterworks structure.

Assessment of Risk

Risk Matrices

Table 7. Risk Matrix for Water Intake

Hazard	Consequence		
Debris flood	High	Moderate	Low
Very High	Very High	Very High	High
High	Very High	High	Moderate
Moderate	High	Moderate	Low
Low	**Moderate**	Low	Very Low
Damaging landslide	High	Moderate	Low
Very High	Very High	Very High	High
High	Very High	High	Moderate
Moderate	**High**	Moderate	Low
Low	Moderate	Low	Very Low

The existing risk of a damaging flood event is determined to be **Moderate** (Low hazard x High consequence). Proposed harvesting of Atco in the north fork tributary represents **no change** to the existing risk of a damaging flood event. The existing risk of a landslide that could impact the water intake is currently assessed as **High** (Moderate hazard x High consequence). There is currently no development proposed on gentle-over-steep (potentially unstable) terrain directly upslope from the water intake. Should development be proposed in the area directly above the intake the risk of a damaging landslide could increase if measures are not taken to identify and control surface drainage. Atco's proposed block which is situated on south aspect slopes along the northern boundary of the watershed represents **no change** to the current risk of a damaging landslide.

Summary/Recommendations

Glade Creek is a high elevation watershed with two main subbasins that display different hydrogeomorphic characteristics. The north fork channel displays extensive disturbance from past flooding and direct impacts to the stream channel and riparian area from early 1900's logging and forest fire. The south fork channel appears to be more resilient to disturbance as a result of the high percentage of lag boulders, better preserved riparian area and possibly lower peak discharges.

The hydrogeomorphic risk assessment for Glade Creek has determined that the most sensitive portion of the watershed to hydrological impacts associated with forest development is the 1224 ha area south of the north fork stream channel. This area has predominantly west to north aspects and appears to be the source area for extreme floods that are triggered by late-season rain-on-snow events.

The Glade Irrigation District intake is the element at risk in this assessment. Currently there is a Moderate Risk (low hazard x high consequence) of a damaging flood event. Harvest levels of less than 20% in the south fork tributary when and balanced over a range of elevations and aspects represent a low likelihood of increasing in the existing hazards of a damaging flood (debris flood) at the intake. In the north fork subbasin, southern aspect slopes north of the north fork stream channel are likely not contributing runoff to the stream during peak flows. Harvesting in this area will not affect the risk of damaging floods in Glade Creek. A total ECA of less than 25% in total and 15% for the area south of the north fork channel, when situated on slopes with aspects other than north or northwest and over a range of elevations will not increase the existing risk of a damaging flood at the intake.

Currently there is a high risk to the intake from landslides off of gentle-over-steep, potentially unstable terrain and erodible glaciofluvial terrace slopes located upslope from the water intake. Any future development proposed in this area will require measures to identify and manage for this hazard. Drainage plans that identify and prescribe measures to maintain surface drainage patterns and avoid interception and concentration of subsurface water should be undertaken as part of all landslide risk assessments (DTSFA's).

Closure and limitations

The information in this hydrological assessment is for the exclusive use of Kalensikoff Lumber Company Ltd and Atco Wood Products Ltd and is intended to provide guidance for forest management in Glade Creek. The recommendations in this report are based on field observation of active hydrologic and geomorphologic processes in the watershed and on historical data collected from various sources. In addition, assessment of hazard presented in this report considers the results of numerous recent studies from BC and elsewhere that identifies the effects of harvesting on hydrologic response of snowmelt dominated mountainous watersheds.

Fluvial geomorphology data collected during this assessment quantify the existing channel conditions. This data can be used to compare against channel condition during future channel assessments to determine if there have been changes.

Literature Cited

Apex Geoscience, 2000. Detailed Terrain Stability Mapping of Glade Project Area (TSIL C). Prepared for Atco Lumber Ltd., April 2000. 17p plus appendices.

Carver Consulting, 2001. Watershed Assessment and Reconnaissance Stability Assessment of Structure Locations. Revised Final Report. Prepared for KRM Associates Inc. S31 C23 RR3 Nelson, BC. 36p plus appendices.

Ellis, C.R., Pomeroy, J.W., Essery, R.L.H., and Link, T.E., 2010. Effects of needle-leaf forest cover on radiation and snowmelt dynamics in the Canadian Rocky Mountains, Canadian Journal of Forest Research, 41, 608–620, doi:10.1139/X10-227.

Harr, R. D., and B. A. Coffin. 1992. Influence of timber harvesting on rain-on-snow: a mechanism for cumulative watershed effects. In: Interdisciplinary approaches in hydrology and hydrogeology, pp. 455-469. American Institute of Hydrology.

Hendrick R.L., and D. Filgate, 1971. Application of Environmental Analysis to Watershed Snowmelt. Journal of Applied Meterorology., Volume 10, 418-429.

Hudson, R., (In press). Hydrologic Recovery Revisited: a frequency-based re-evaluation of stand-level snow ablation and rainfall interception recovery in a high elevation coastal forest. To be published in Hydrological Processes.

Robert O. Hudson, Department of Forest Resources Management, Faculty of Forestry, UBC

Moore, R.D., and Scott, D.F., 2005. Camp Creek revisited: Streamflow changes following salvage harvesting in a medium-sized, snowmelt-dominated catchment, Canadian Water Resources Journal, 30, 331–344.

Romshoo, S.A., Bhat, S.A., and Rashid I. 2012. Geoinformatics for assessing the morphometric control on hydrological response at watershed scale in the Upper Indus Basin. J. Earth Syst. Sci. 121, No. 3, June 2012, pp. 659–686

Schnorbus, M., and Y. Alila (2004), Forest harvesting impacts on the peak flow regime in the Columbia Mountains of southeastern British Columbia: An investigation using long-term numerical modeling, Water Resour. Res., 40, W05205,doi:10.1029/2003WR002918

Schnorbus, M., and Y. Alila (2013), Peak flow regime changes following forest harvesting in a snow-dominated basin: Effects of harvest area, elevation, and channel connectivity, Water Resour. Res., 49, doi:10.1029/2012WR011901

Wilford, D.J., Sakals, ME., Grainger WW., Millard., TH, and TR Giles., 2009. Managing forested watersheds for hydrogeomorphic risk on fans. B.C., Min.For. Range., For. Sci. Prog. Victoria BD., Land Manag., Handb. 61. www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh61.htm

Winkler R.D., Moore R.D., Redding T.E., Spittlehouse D.L., Carlyle-Moses D.E., and B.D. Smerdon (2010). Hydrological Processes and Watershed Response. Chapter 6. *In* Pike, R.G., T.E. Redding, R.D. Moore, R.D. Winker and K.D. Bladon (editors). 2010. Compendium of forest hydrology and geomorphology in British Columbia. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Manag. Handb. 66. www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66.htm Forest Hydrology Compendium, Forrex

Winkler R.D. and S. Boon (In press), Revised Snow Recovery Estimates for Pine-Dominated Forests in Interior British Columbia. B.C. Ministry of Forests, Lands and Natural Resource Operations, Extension Note.

Appendix 1 - Climate Change, Flood Frequency in Glade Creek and implications for Forest Harvesting.

Without discharge gauging in Glade Creek it is not possible to make an informed comment on how climate change could affect flood frequency. Anecdotal information from residents suggests that the extreme floods in Glade Creek are triggered by rain-on-snow events. The field evidence collected during this study support this claim.

Recent publications by the Pacific Climate Impacts Consortium at the University of Victoria report the results of projected changes in a number of hydroclimate variables within the southern BC Columbia Basin based on the application of the Variable Infiltration Capacity Model. (Hamlet et al., 2012). The PCIC study found that;

> "Of all the metrics evaluated, hydrologic extremes, and particularly high flow extremes, showed the greatest inconsistencies between modeling approaches. Substantial differences were also found in the percent changes in cool and warm-season streamflow, and changes in the timing of peak flows..."

The PCIC modeling study projects that by 2050 in the Southern Kootenay region, summer months will experience higher temperatures on average while winter months will experience increased precipitation on average. The PCIC group suggests that for alpine-dominated watersheds increased precipitation could result in increased winter snow packs, while increased spring and summer temperatures could result in a shift to earlier peak flows. However, it is not clear how these changes will affect the magnitude or frequency of larger-than-average (i.e. extreme) flood events. It is possible that there will be an increase in the number of rain-on-snow peak events compared to solar radiation driven peaks particularly during the fall, late winter and early spring months. In Glade Creek this could mean that there will be more mid to late winter ice jam floods. It could also mean that the snowpack might decrease as a result of mid-winter melting.

The following excerpt is from APEGBC document *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC* (APEGBC, 2012).

> "Projections of future climate or runoff are best assessed in terms of the mean and range of outputs from an ensemble of model runs. Such results must be obtained from climatologists who specialize in model analysis, from the sources listed in section 3.6.2 or from specialized consultants. In the absence of applicable hydroclimate model results, magnitude-frequency analyses based on recent experience (approximately 30 years) may remain valid for short-term (<30 years) projections, provided no trend is evident in the historical sequence of flood flows."

The following excerpt is from the Columbia Basin Trust website (Water and Climate Change in the Canadian Columbia Basin, CBT website publication download October 2014)

"…cold winter temperatures will protect mountain snowpack from warming and capture water from wetter winters. Some high-elevation areas may even see increasing snowpack due to cold winter temperatures and increasing precipitation. "

For the purpose of the Glade Creek Hydrogeomorphic Risk analysis the projected change in climate could either increase or decrease the frequency of extreme rain-on-snow floods.

Some selected literature concerning climate change projections in the Columbia Basin:

Hamlet, A., M. Schnorbus, A. Werner, M. Stumbaugh, and I. Tohver. (2012). A Climate Change Scenario Intercomparison Study for the Canadian Columbia River Basin. Prepared for the Columbia Basin Trust

Murdock, T.Q. and A.T. Werner, 2011: Canadian Columbia Basin Climate Trends and Projections: 2007- 2010 Update. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 43 pp.

Murdock, T.Q., S.R. Sobie, 2013: Climate Extremes in the Canadian Columbia Basin: A Preliminary Assessment. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 52 pp.

Pike, R. G., K. E. R. Bennett, T.E., A. T. S. Werner, D.L., R. D. M. Moore, T.Q., J. S. Beckers, B.D.,, K. D. F. Bladon, V.N., and D. A. T. Campbell, P.J., 2010: Climate Change Effects on Watershed Processes in British Columbia, Chapter 19. Compendium of forest hydrology and geomorphology in British Columbia, R. G. Pike, T. E. Redding, R. D. Moore, R. D. Winkler, and K. D. Bladon, Eds., BC Ministry of Forests and Range with FORREX Forum for Research and Extension in Natural Resources, 699-747.

Appendix 2 Field data from Glade Creek survey

Site ID	Watershed area	Morphology	D90-1(cm)	D90-2	D90-3	D90-4	D90-5	Avg D90	Description	Riparian	Banks	Wb(m)	Dbf(m)	S%	Wd Function	Wd Density #/10m
Gld001	1492	Ca-b	32	32	33	36	37	34	Boulder step to cascade. Boulders up to about 60 cm forming steps. Mossy boulders above about 40 cm. old cobble boulder levee about 20 to 30 years. Channel is entrenched about 1.5 meters but has avulsed over valley flat which is 30 m wide.	Cottonwood cedar hemlock and alder all less than 30 cm. old cut stumps are burnt. Riparian logged about a century ago. Banks are scoured and verticle but conifr and dec roots holding.	Veg and vertical	5.1	0.49	13	Partial Broken Jams	2
Gld002		Ca-b	0	0	0	0	0		Abandoned channel but carries water in freshet	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld003	1540	Ca-b	40	42	36	39	30	37.4	Two channels converge. Brighter more mobile appearence. Still old cut wood in channel. Channel confined on north side. Frogs in stream.	N/A	Scoured vertical	0	0	0	Partial Broken Jams	0

Gld004		-None Selected-	0	0	0	0	0		Full debris flood deposit about 20 years old. Then recent flood that has moved boulders. Channel entrenched about 2 m	Cottonwood and cd hem alder maple	Scoured vertical	0	0	0	-None Selected-	0
Gld005	1561	Ca-c	0	0	0	0	0		Debris wedge from 20 yr debris flood with recent scour	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld006		-None Selected-	0	0	0	0	0		Photo	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld007	1285	Cv	13	10	24	21	22	18	Dark mossy lag boulder channel. Only cobbles less than 15 cm mobile.	Immature cedar hemlock. Lag boulders along banks	Veg and vertical	5.55	0.6	16	Suspended	2
Gld008	2880	Ca-b	37	41	35	40	36	37.8	Boulder cascade with lag boulders. Wolman	Cedar hemlock to about 35 cm. lag boulder banks. Lag boulders in channel are mossy.	Veg and vertical	9.3	0.85	13	//	0
Gld009	2881	Ca-b	27	36	37	39	40	35.8	Recent flood has moved cobbles and boulders to 40 cm. lag mossy but piled with debris. Banks scoured but roots still functioning.	Cw hem to 40 cm.	Scoured vertical	12	75	16	Partial Broken Jams	1
Gld010		-None Selected-	0	0	0	0	0		Photo	N/A	-None Selected-	0	0	0	-None Selected-	0

Gld011		-None Selected-	0	0	0	0	0		photo	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld012	301	Ca-b	13	8	9	10	10	10	Lag boulder cascade. Bedload is mostly sand with small cobbles less than 10cm. Lag all mossy. Appear to be terminal morain features.	Alder and subfir spruce along banks. Banks and lag boulders mossy. Vold burnt logs in stream.	Veg and overhanging	3.18	0.35	10	Single Funct Pieces	1
Gld013	280	Fsp	11	10	10	9	8	9.6	Old jam recently broken. Sand and cobbles mobilized 10 m downstream. Site above morain deposit so channel lower gradient. Funct wood is v old and burnt.	Alder and subfir spruce to 20 cm	Veg and overhanging	2.3	24	5	Partial Broken Jams	1
Gld014	275	Ca-b	16	15	16	18	18	16.6	Broken wd jam from recent flood. Lag boulder cascade.	Spruce balsam to 30cm	Veg and overhanging	2.1	0.13	13	Partial Broken Jams	1
Gld015		Fsp	0	0	0	0	0		Recent broken v old jam	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld016		Cv	0	0	0	0	0		N/A	N/A	-None Selected-	0	0	17	-None Selected-	0

Gld017		Cv	0	0	0	0	0		Top of steep lag boulder cascade. Morain feature. Mossy	N/A	Veg and overhanging	0	0	0	Suspended	0
Gld018	135	Fsp	6	6	8	8	8	7.2	Fsp through mossy lag	Sprucr and fir to 50 cm . Lots of we suspended	Veg and overhanging	1.6	0.21	9	Suspended	2
Gld019	128	Cv	3.5	3.5	3	2	3	3	Cv mossy lag with sand and small cobbles. Some recent movement od sand ans swd.	Essf to 50 cm. lots of wd suspended. Also individual pieces.	Veg and overhanging	1.9	0.1	20	Suspended	2
Gld020	111	Fsp	6	6	8	9	8	7.4	Mossy fsp with lag cv. Unconfined over forest floor. Wd in channel very old likely more than 100 yrs. little disturbance indicators. Some recent sand and swd accumulations.	Mature sp fir to 60cm	Veg and overhanging	1.54	0.13	7.5	Single Funct Pieces	3
Gld021	2959	Ca-b	32	29	30	28	33	30.4	Bedrock confined on L looking up. Cv silty sandy slope from brk eroding during high flow. Bouldr levee on right from 50 yr event about 0.5m above bankfull. Mega levee to right of this 2 to 3 m higher. Channel is bolder cascade with	Deciduous and cedar to 20 cm	Scoured vertical	5.9	45	7	//	2

									lag up to a m forming cascades. Also brk in channel.							
Gld022	2959	Ca-b	28	33	37	35	30	32.6	Lag boulder cascade. Lag over 1 m here.	Decicuous cedar hem to 40 cm abh	Scoured vertical	9.1	30	11	//	0
Gld023		-None Selected-	0	0	0	0	0		Photo	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld024		Ca-b	0	0	0	0	0		Channel split through here with large amount of swd	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld025	2977	Ca-b	28	30	31	31	32	30.4	Scoured lag bld cascd. Recent bank scour. Lag to more than 1 m. Unconfind with abandoned channels below flls	Maple cedar hem cottonwood to 25 cm. cwd to 40 cm	Scoured vertical	7.2	55	8	//	0
Gld026	2977	Sp	15	14	15	19	18	16.2	Multi channel. 2012 flood moved 19, 22	Mixed decid and conifer. Banks mossy above scour	Scoured vertical	7.6	0.44	3	Single Funct Pieces	0
Gld027		Sp	0	0	0	0	0		N/A	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld028	1016	-None Selected-	22	21	18	23	18	20.4	Bedrock on west boulder levee on east recent high scour old wood broken	Cedar cotton wood alder	-None Selected-	4.2	26	23	-None Selected-	0

Gld029		-None Selected-	0	0	0	0	0		Photos of large structure may have orininally spanned valley may be jct	N/A	-None Selected-	0	0	0	-None Selected-	0
Gld030	561	-None Selected-	25	22	18	20	21	21.2	N/A	Alder	Veg and overhanging	1.7	22	25	-None Selected-	0
Gld031	387	-None Selected-	10	12	13	10	11	11.2	N/A	Alder birch fir larch poplar cedar	-None Selected-	1.9	15	25	Partial Broken Jams	0
Gld032		-None Selected-	0	0	0	0	0		Wallow	N/A	-None Selected-	0	0	0	-None Selected-	0

Appendix 3 - Background literature for hydrological recovery Estimate

All studies are from snowmelt dominated regions.

Winkler et al. 2005 (3 year study at two sites)

Site 1

Mayson Lake – 4 sites at 1250m elevation all within 1km.

- Mature Forest – 23 m 100 yr, multi-layer spruce, subalpine fir, pine, 54% crown closure and 4400 stems/ha
- Juvenile stand – 15 year, pine (spruce, fir) average height of 4.5m 28% cc and 2600 st/ha.
- Juvenile thinned – 15 yr, pine, avg height 6.4m, 21% cc and 1000 st/ha
- Clearcut – pine less than 1m

Accumulation

Study determined that clearcuts accumulated between 37 to 75% more snow than the forest stand and 11 to 40% more snow than the juvenile stands. The juvenile stands accumulated on average 27% more snow than the forest stand (measured during the peak accumulation around April 1st of each year). Results indicate that process of snow accumulation are beginning to recover in the 4.5 to 6.4 m juvenile stands.

Melt rate

Study determined that melt rate varies considerably from year to year (this is probably because melt rate is directly dependent on amount of solar radiation (temperatures) which vary from year to year). On average melt rate in the clearcut is 2.4 times that of the mature forest. The ratios of juvenile stand to clearcut melt rates were 0.8 to 0.9. In the juvenile stands, melt rates were reduced by less than 0.1 cm day^{-1} in the juvenile-thinned stand and by 0.17 cm day^{-1} in the juvenile unthinned stand (10% and 17% respectively), relative to the clearcuts. Winkler et al., (2005) conclude that “These results indicate that juvenile stands, such as those included in this investigation, have a small effect on snowmelt rates.”

Additional information from snowmelt lysimeters in the clearcut and juvenile stands indicated that melt rate early in the snowmelt period was actually higher in the juvenile thinned stand than in the clearcut. On average for the 3 years snowmelt ‘recovery’ is estimated as 13% and 23% in the juvenile-thinned and juvenile pine stands respectively.

Site 2

Upper Penticton Creek – 5 sites at 1600 to 1700 m

- Mature Pine approx 18m stand with 40% cc and 4000 st/ha
- Mature mixed spruce, subalpine fir, pine, approx 19m stand with 44% cc and 3800 st/ha.
- 2 -clear cut stands adjacent to these mature stands
- 4 meter juvenile stand mixed spruce, fir, pine with 3400 st/ha and 0%cc

Snow Accumulation

At Upper Penticton Creek, April 1st SWE in both mature stands was significantly different from that in adjacent clearcuts in all years. Differences in April 1st SWE varied from 27 to 35% higher in the clearcut than in the mature spruce-fir stand (Figure 4.2). but only 6 to 19% relative to the mature pine stand. SWE in the juvenile stand at Upper Penticton Creek was also significantly larger (26 to 42%) than that in the spruce-fir stand, but not larger than that in the clearcut. Since April 1st SWE in the juvenile stand was equal to or slightly greater than in the clearcut, depending on the year, these data suggested that there has been no reduction in peak snow accumulation as a result of forest regrowth in this juvenile stand.

Melt rate

At Upper Penticton Creek, the average snowmelt rate in the clearcut was 38% higher than in the pine stand and 62% higher than in the spruce-fir stand . Melt rates in the juvenile spruce-fir stand at Upper Penticton Creek were greater than those in the mature spruce-fir stand in all years, by 0.26 cm d^{-1} on average, but were not different from those measured in the clearcut, except in 1996 when they were 0.06 cm d^{-1} higher.

Buttle et al. 2005.

NE Ontario ten sites within 22 km on flat terrain. Snowmelt dominated (no rain) 1yr study

- Mature black spruce approx 7m with 73% cc and 5400 st/ha (s8)
- Mature balsam fir, black & white spruce 16m with 80% cc and 1529 st/ha (s9)
- Mature balsam fir and white spruce, 16.4 m with 82% cc and 1000 st/ha (s10)
- 2 clearcuts (sites 1 and 2)
- 1.7m white spruce juvenile stand, 9%cc and 1947 st/ha (site 3)
- 1.8m black spruce juvenile stand, 0%cc and 6421 s/ha (site 4)
- 2.4m black spruce (minor balsam) juvenile stand 3%cc and 1552 st/ha (site 5)
- 3.2m juvenile stand black/white spruce, balsam fir, 22% cc and 12400 st/ha (s6)
- 3.3m juvenile stand black/white spruce, balsam fir, 36% cc and 7316 st/ha (s7)

Snow Accumulation

Generally 20 to 40% less snow in the mature forest than in the clearcut sites at peak SWE, however, in the 15 yr, 3.2 meter juvenile stand with over 12000 stems/hectare (Site 6), peak SWE is approaching

80% that of the mature stand (only 20% greater accumulation than the mature stand). Note: It is probably important to consider that snow accumulation may evolve differently through the winter months in NE Ontario as compared to intermontane BC. This is possibly due to larger variability in mid-winter air temperatures (associated with mild gulf coast weather systems)

Melt Rate

Highest melt rate was observed at site 3 , a 14yr old 1.7m white sp with 1947 stems per hectare and lowest melt rate was observed at site 10 (Mature, 16.4 m average balsam fir/spruce stand). The relationship between mean melt rate (*MMR)* and canopy height and density showed an increase in *MMR* with initial regeneration, followed by a decrease in *MMR* to values equal to or less than those measured in the clearcut sites. Buttle et al., 2005 state: "Conversely, MMR values suggest that snowmelt rates may actually increase above melt rates in recent clearcuts during the initial stages of stand regeneration, and do not drop significantly below those observed for Site 3 (harvested in 1990) until at least 14 years after harvesting."

Hardy, Hansen-Bristow, 1990. Southwest Montana 2085m

<u>Lick Creek – 4 sites with similar aspect, elevation and slope characteristics – 1yr study</u>

- Mature Douglas fir 18 – 26m, 85% crown closure
- Juvenile pine stand (35yr) 10 to 14m, 56% cc.
- Clearcut (10-15yr - young pine stand) 0.5 to 4m, 6% cc
- Meadow

Snow Accumulation

Of the four sites the meadow accumulated the most snow and the mature forest accumulated the least. There is no significant difference in snow accumulation between the meadow and the young pine (clearcut) stand. The juvenile stand had roughly 12% less SWE at max SWE than the meadow and the mature stand accumulated roughly 26% less SWE than the meadow. They suggest that there is very little change in peak SWE relative to the meadow in stands with canopy closure between 0 and 55%.

Melt Rate

Melt rate was highest in the meadow early in the melt season. The young and juvenile stands prolonged the melt but the average melt rate in the young (clearcut) was not significantly different than the meadow. The avg. melt rate in the juvenile stand was roughly 38% faster than the forest. They suggest that there is a gradual change in melt rate until the canopy density reaches 70 to 75% of the mature stand.

Bewley et al., 2010 - plots on level ground at 990 and 1220 m

Baker Creek west of Quesnel

All plots on level ground (avg 3^o gradient) at either 990 or 1220 m Baker Creek west of Quesnel

- 2 Juvenile pine stands (25-50yr), 10-15m, 1700 – 2900 st/ha (green/red attack)
- 1 Juvenile pine (10-25yr), 1-5m, 2000 st/ha.
- 2 Clearcuts

Snow Accumulation

No significant difference in total SWE accumulation between sites at 990m elevation. Sites at 1220 meters showed some differences with the clearcut accumulating more SWE (175mm) than the forest (~157mm) or approximately 12% more SWE.

Melt Rate

The avg melt rate in the clearcut was significantly higher than the melt rate in the forest at 990 metres but not significantly higher than the melt rate in the (1-5m) regen stand at 990m. The average melt rate in the clearcut is higher than that of the forest at 1220 meters but the difference is not as great as at the lower elevations.

Ellis et al., 2010 – Plots on north versus south aspect in Marmot Creek Alberta

This study did not include an investigation of recovery in juvenile stands but does highlight the differences in snow accumulation and melt dynamics between north-aspect, south-aspect and flat ground clearcut/forest pairs. This investigation found that slope aspect plays a key role in determining differences in accumulation and melt dynamics. It follows that recovery of snow accumulation and melt processes will vary considerably depending on the slope aspect/gradient.

Summary of Snow Accumulation and Melt data from snowmelt dominated regions

Much more research is needed to fully understand the combined effects of watershed physiography and stand composition on the recovery of snow accumulation and melt in the Kootenay region. Most of the studies summarized above suggest that maximum snow accumulation begins to decrease in the young blocks (~15 yrs) relative to the clearcut but that there is no significant decrease in the rate of melt in these young stands relative to the clearcuts. Most studies found that more snow accumulates in the young regenerating stands relative to the forest and the melt rate varies from slightly slower to slightly faster than the clearcut. In terms of 'hydrological recovery' these young stands (that ranged in height from 1 to 6.4m depending on the study) are not showing significant recovery relative to the unharvested stands. An exception to this was observed by Buttle et al. (2005) that documented a much lower melt rate in the 3.3 meter regen stand that had a stem density of over 12000 st/ha.

Most studies agree that recovery of melt rate is dependent on an increase in crown closure (crown density). Hardy and Hansen-Bristow report recovery of melt rate relative to the forest of roughly 40% in a 35yr 10-14m (12m avg) juvenile stand. Canopy density of this juvenile stand had recovered to approximately 65% of the unharvested forest.

Conclusions interpreted from these studies:

Up to approximately 6 meters and less than 30% crown closure hydrological recovery is essentially 0%. Beyond 7 meters hydrological recovery increases gradually and depends on stem density. Once stand height exceeds roughly 12 meters and crown closure exceeds roughly 60% of the unharvested forest the stand is somewhere around 40% recovered. The rate of recovery likely increases slightly beyond this point as crown closure increases in the maturing stand. Once crown closure reaches roughly 75 to 80% or more of the unharvested stand hydrological recovery begins to approach 100%. Hardy and Hansen-Bristow suggest that complete hydrological recovery does not occur in the mixed species stands of southwestern Montana until upwards of 80 years. Regenerating stands of between 10 and 20 years old in central BC and northern Ontario show very minimal to no recovery, which is consistent with the Montana findings.