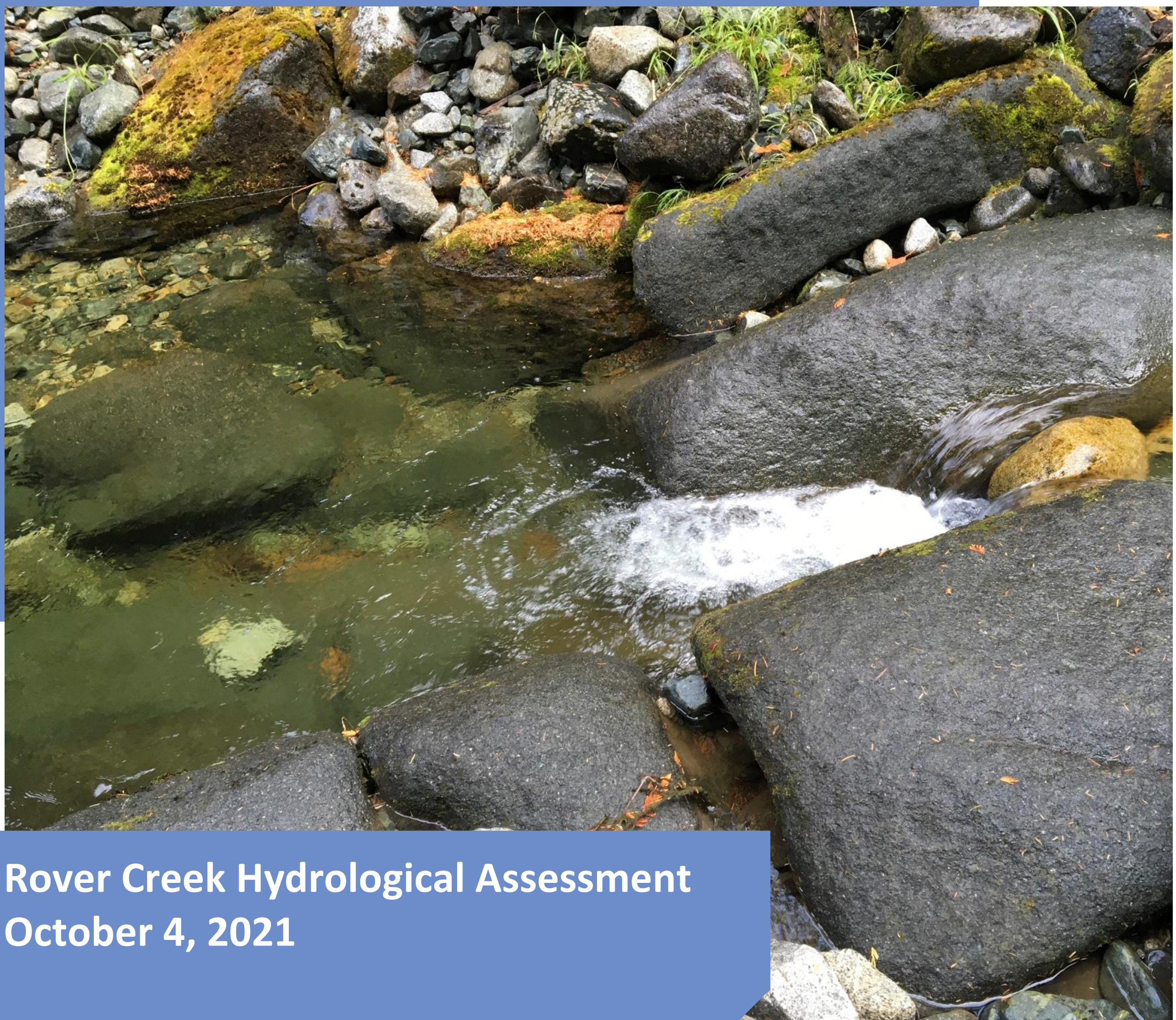

Rover Creek Hydrological Assessment
October 4, 2021

Prepared for
Gerald Cordeiro, Forestry Manager
Kalesnikoff Lumber Co. Ltd
P.O. Box 3000, Thrums, BC

Pex Geoscience Consultants Ltd.

MacHydro

TABLE OF CONTENTS

Introduction

In response to concerns regarding the impact of planned salvage harvest on peak flow magnitude and timing of flows along lower Rover Creek, you requested a more detailed, hydrological investigation to determine the potential for changes to peak flow magnitude and timing of flows relative to current conditions in Rover Creek. In order to investigate this question I was assisted by Matthew Chernos, MSc, P.Geo with MacDonald Hydrological Consultants Ltd. (MacHydro) who undertook the development of a hydrological model for Rover Creek. Information on existing cut blocks as well as stand height and level of hydrological recovery incorporated into the model was gained from the recent equivalent clearcut area assessment undertaken as part of the 2020 Watershed Assessment. This letter provides a summary of the development and outcomes of the Rover Creek hydrological model.

Model Objectives

The hydrological model applied in this project was developed for the West Kootenay area to simulate streamflow and driving hydroclimatic processes to produce estimates of stream flow for watersheds of interest such as Rover Creek. The model incorporates elevation, land cover, aspect, and slope information for Rover Creek together with nearby weather observations from Nelson and Castlegar. Results from the model provide an estimate of the change in hydrologic indicators due to planned development of K090 cutblocks in Rover Creek, British Columbia.

Methods

The semi-distributed hydrological model used in this study is an adapted version of the HBV-EC model, emulated within the Raven Hydrological Modelling Framework version 3.0 (Craig et al., 2020). The model simulates streamflow and other hydro-climatic variables (i.e. snowmelt, evaporation, etc.) at a daily timestep from 1980-2019. The model spatially distributes daily minimum and maximum air temperature and precipitation from weather stations across the study region. The model simulates major hydrological processes including canopy interception, snow accumulation and melt, glacier melt, evaporation, soil infiltration, percolation, and baseflow, as well as surface runoff. Major processes are described below, while a comprehensive discussion of model algorithms can be found in Bergström (1992), Jost et al. (2012), and Chernos et al. (2020).

In the hydrological model, water inputs occur as precipitation, which are partitioned into rain or snow following the HBV linear transition based on air temperature. Precipitation interception by the forest canopy is estimated as a function of Leaf-Area Index (LAI; Craig et al., 2020; Hedstrom and Pomeroy, 1998). Snowmelt is calculated using a spatially corrected temperature index model, which accounts for aspect, slope, and day length (Jost et al., 2012, Craig et al, 2020). Potential evapotranspiration is calculated using the Priestley–Taylor equation. Once water infiltrates the three-layer soil, it moves downwards through percolation and upwards through capillary rise. Soil water becomes surface runoff (i.e. streamflow) through (faster) interflow and (slower) baseflow pathways. Technical details on model data sources, calibration and verification, and parameters are provided as an appendix to this letter.

Hydrologic Indicators

Five hydrologic indicators were used to capture the effect of a changing landscape on water resources in the watershed. These indicators are used to identify changes in streamflow during key periods of the year and are summarized in Table 1.

Table 1. Hydrologic indicators used to identify changes in hydrologic regime and function

Variable	Description
Day of Peak Flow	The average Julian day of peak daily streamflow in a calendar year, representative of the timing of spring snowmelt-driven runoff.
Annual Flow	The average annual streamflow, representative of the amount of water passing through this point in a calendar year.
Summer Flow	The average August-September streamflow, representative of conditions following snowmelt, which has historically coincided with summer low flows and heightened risk of droughts, degraded water quality, and water scarcity.
Winter Flow	The average January-March streamflow, representative of conditions prior to snowmelt, which has historically coincided with the lowest flows of the year.
Peak Flow	The maximum daily streamflow in a calendar year, representative of the potential magnitude of large flood and/or erosion events in the watershed.

Land Cover Scenarios

Since the hydrological model uses land cover and weather data as inputs to simulate streamflow (and other hydroclimatic variables), modifying these input data can be used to investigate how those changes will impact hydrological response in the watershed. The possibilities for scenario analysis are essentially limitless, and could include specific management plans or configurations, weather or climate patterns, or combinations of both.

This study investigates the effect of a forest harvest scenario (K090), as well as a conceptual no forest disturbance scenario (Mature), compared against current forest disturbance conditions (Current Conditions). Land cover scenarios are described in Table 2 and shown spatially in Figure 1.

Table 2. Land cover scenario descriptions.

Name	Treatment
Current Conditions	Current (2020) level of forest disturbance, held constant.
Annual Flow	Mature All forest regenerates to fully mature (no forest disturbance).
Summer Flow	K090 A harvest plan, which additionally disturbs approximately 2% (0.88 km^2) of Rover Creek.

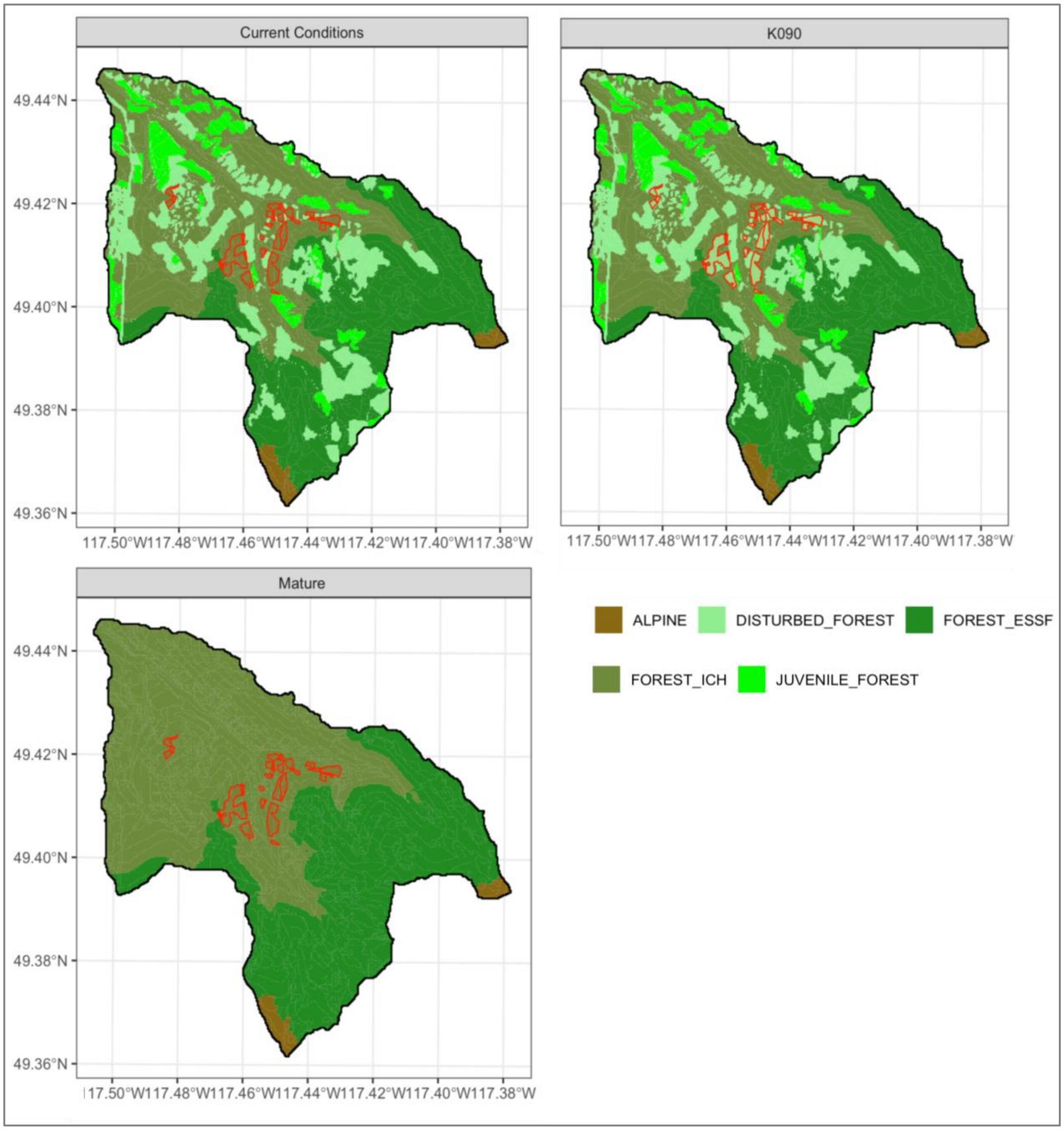

Figure 1: Landcover scenarios investigated in Rover Creek. Shaded red outline corresponds to proposed K090 blocks.

Results

Hydrological Baseline Conditions

Streamflow in the study area follows a strongly snowmelt driven pattern. Flows are low during the winter months as snow accumulates, and increases sharply during the spring, coinciding with snowmelt, particularly at upper elevations. Streamflow decreases into July, with only small spikes in flow coinciding with large rainfall events. Spatially, runoff is greater at higher elevations, with ridgetops and alpine areas supplying over 1500 mm of runoff annually (Figure 2). Conversely, lower elevations and valley bottoms produce runoff under 500 mm per year on average. This dynamic reflects the relatively steep precipitation gradient in the region, where upper elevations receive substantially more precipitation (estimated at 3.5 mm/day/km in the model) and greater evaporation at lower elevations and southern aspects due to warmer air temperatures and greater solar radiation. Runoff is highest in alpine areas without substantial forest cover, which are found at the highest elevations in the south of the watershed. Runoff is relatively lower in mature forest than in juvenile and disturbed forest areas, with greater absolute differences in forests at higher elevations.

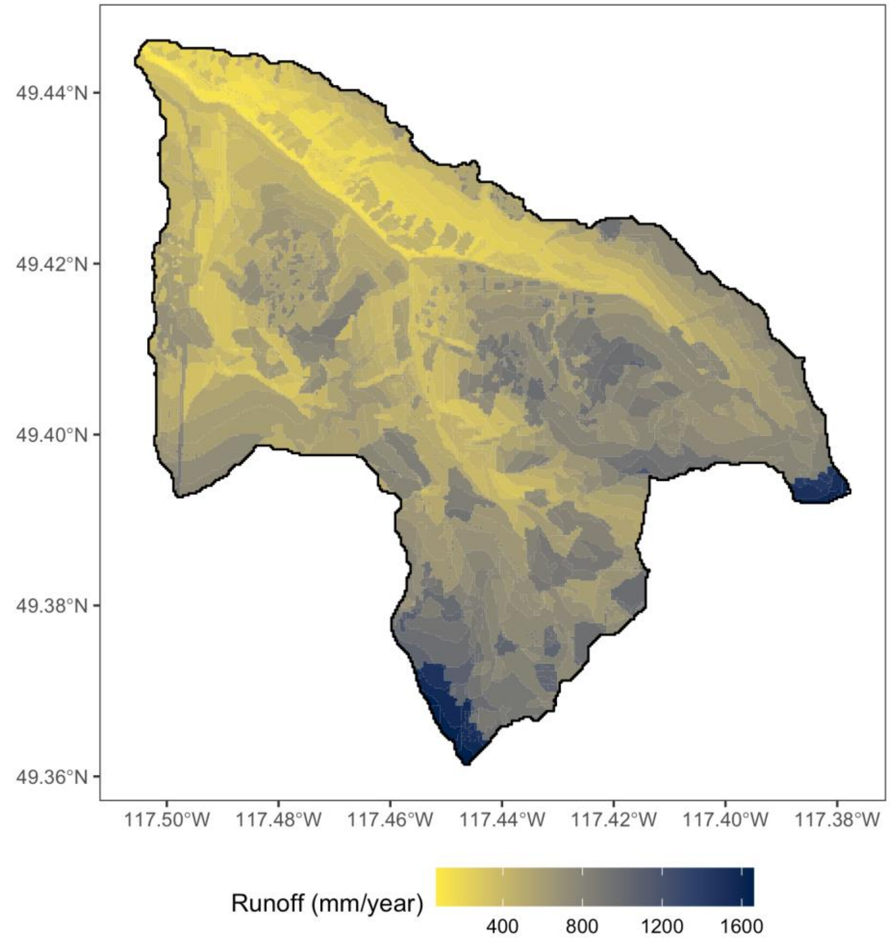

Figure 2. Runoff in mm/year simulated by the model for current conditions. Existing cutblocks show higher annual runoff which is consistent with observed effects of forest removal. Runoff also increases with increasing elevation.

Scenario Analysis

Under the three land cover scenarios run, the hydrological model shows modest changes in the timing and magnitude of streamflow in Rover Creek (Figure 3). Most notably, streamflow is projected to be lower under the Mature scenario relative to Current Conditions and K090. In absolute terms, this difference in streamflow is greatest during the spring snowmelt runoff period (April-May). Additional differences in streamflow are simulated during the fall and winter periods, coinciding with increased runoff during rainfall events due to lack of forest canopy interception. A slight increase in streamflow is simulated under the K090 scenario, relative to Current Conditions.

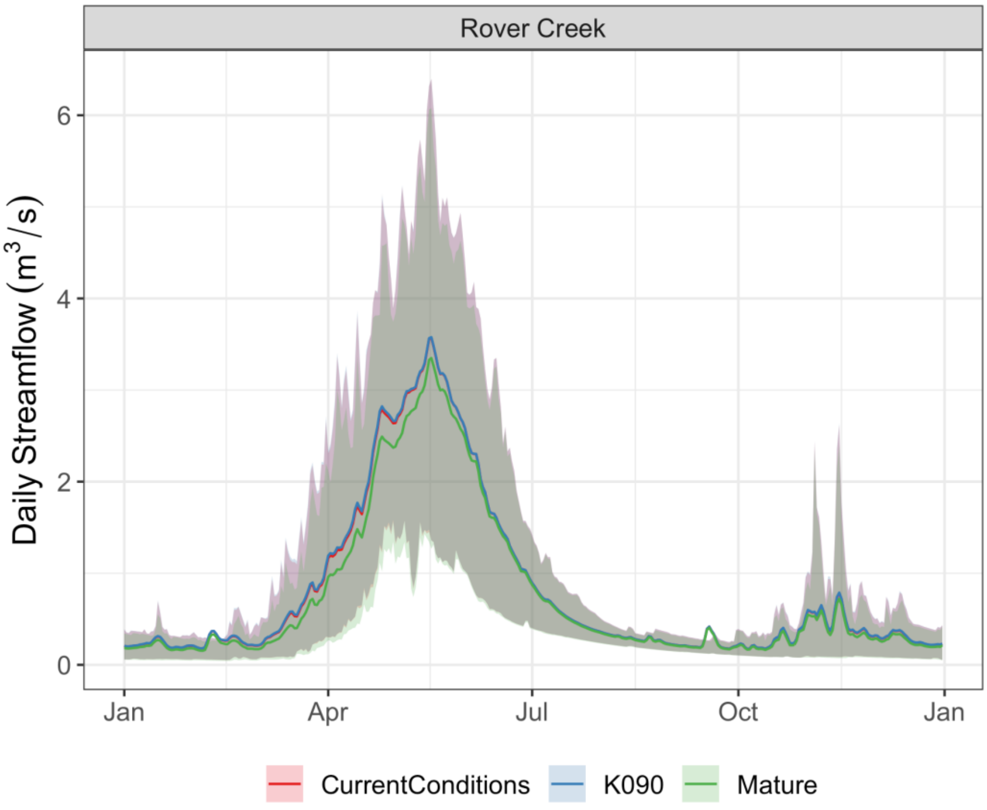

Figure 3. Average 30-year hydrographs for all three land cover scenarios under historical (1990- 2019) climate. Shaded areas correspond to 10-90% quantiles, while the solid lines correspond to average conditions.

Changes in hydrologic conditions relative to Current Conditions are summarized in hydrologic indicators in Table 3. Under the K090 scenario, no change in the average day of peak flow is projected, relative to Current Conditions. Mean annual flow is projected to increase by 0.7% on average under K090 relative to current conditions, while winter flows are projected to increase by 1.9%. Increases in mean summer flow and median peak flow are estimated at 0.2%.

While changes in hydrologic indicators under the K090 scenario are relatively minor and not substantially detectable relative to current conditions, greater changes are indicated under the Mature scenario. The model indicates that in undisturbed 'Mature' watershed, the day of peak flow is on average 5.6 days later and the median peak flow is 5.3% lower than current conditions. Additionally, mean summer flow is estimated to be 3% lower under the Mature scenario, while mean winter flow is 16.9% lower when compared to current conditions (Table 3).

Table 3. Change in hydrologic indicator relative to the Current Conditions (1990-2019) scenario for Rover Creek.

Scenario	Day of Peak Flow	Mean Annual Flow	Mean Summer Flow	Mean Winter Flow	Median Peak Flow
K090 (1990 – 2019)	0	0.7%	0.2%	1.9%	0.2%
Mature (1990 – 2019)	5.6	-8.2%	-3.0%	-16.9%	-5.3%

Notably, the distribution of peak flows shows little difference between Current Conditions and K090 but shows a larger shift towards lower magnitude peak flows under the Mature scenario (Figure 4). Changes in the 1:2, 1:10, and 1:100-year peak flows under K090 are well within the margin of error of the Current Conditions scenario (approximately an 0.1% increase under K090). Conversely, under the Mature scenario, the 1:2-year peak flow is 6.1% lower, the 1:10 year peak flow is 4.4% lower, and the 1:100 year peak flow is 3.1% lower.

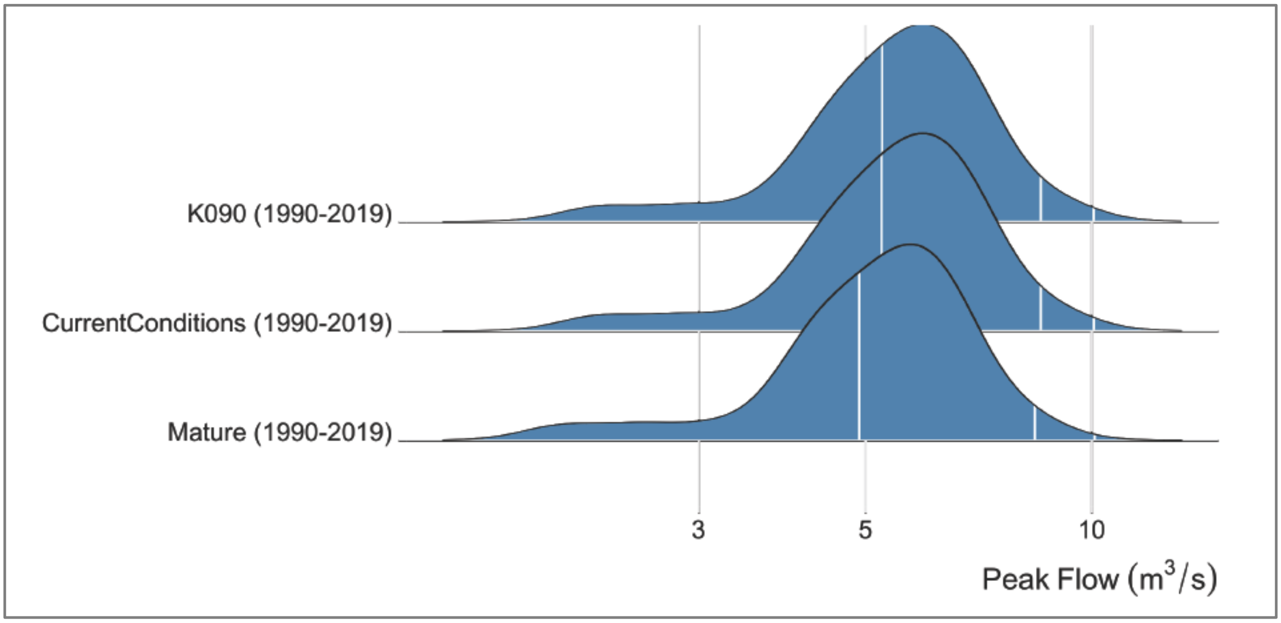

Figure 4. Frequency of Annual Peak Daily Flow over the 1990 – 2019 period under each land cover scenario. Vertical lines show 1:2, 1:10 and 1:20-year peak flow magnitude. The 1:100 year peak flow values are 10.2 – 10.6 m3/s and therefore not visible on the far right of the plot.

Discussion

The hydrological model was applied to Rover Creek to gain a greater understanding of the potential for alteration to the flow regime associated with harvest of K090. The model outcomes indicate that harvest of planned blocks K090 will not substantially alter the magnitude of peak flows that could substantially affect water quality in Rover Creek relative to current conditions. The risk analysis undertaken in the Rover Creek Watershed Assessment (Apex, 2020) assessed the current likelihood of detectable (defined as changes greater than 10% relative to pre-development conditions) alterations to peak flow magnitude as ‘low’ given the ECA of just under 23% based on studies of watershed response in nearby Redfish Creek. The hydrological modelling undertaken here estimates that, relative to undisturbed (Mature) conditions, the median peak has increased by just over 5% while the 2-year and 10-year peak flow magnitudes have increased by just over 4% and 3% respectively. These estimates are consistent with the original estimated ‘low’ likelihood in the 2020 assessment. While peak flow timing is revealed to not change relative to current conditions it is worth considering that peak flow timing has advanced on average by 5.6 days relative to Mature conditions. Further consideration on what is considered an unacceptable shift in peak flow timing may be warranted.

Limitations

The hydrological assessment is a novel approach that uses a process-based hydrological model to simulate the hydrologic effects of forest disturbance. This approach allows a quantification of the projected hydrologic change to better inform management decisions. The scenarios presented here made several assumptions that should be noted. First, this analysis does not take climate change into account. Changes in air temperature and precipitation in the watershed are likely to alter the timing and magnitude of streamflow in Rover Creek. These changes are subsequently likely to alter the hydrologic regime and impact hydrologic indicators beyond what is simulated here. In addition, the cumulative effects of forest disturbance and climate change could be additive, particularly with respect to peak flow magnitude and timing. For a more comprehensive risk analysis for medium-to-long term management decisions (i.e. 30-50 year time periods), we recommend further analysis to investigate the individual and cumulative effects of climate change and forest disturbance in Rover Creek.

The hydrological model also simulates land cover scenarios assuming a static landscape with varying configurations of forest disturbance. While forests are dynamic and begin to regrow following disturbance, research suggests that this regrowth is relatively slow, taking many decades before it is hydrologically recovered. However, this rate of regrowth is also geographically variable and further research into the rate of this regrowth will allow future modelling exercises to better incorporate this into the hydrological assessment. Finally, these land cover scenarios do not account for the potential for future natural forest disturbance. Specifically, the Mature land cover scenario is not likely to occur in Rover Creek due to natural disturbance regimes, such as forest fires and insect outbreaks, and should be treated as a conceptual scenario rather than a potential land cover configuration. However, we note that natural forest disturbances could interact with forestry scenarios, either through increased forest disturbance beyond what is estimated here or reducing the harvestable forest available.

Conclusions

A hydrological model was used to evaluate the effects of current and projected forest disturbance in the Rover Creek watershed. The model demonstrates that more runoff occurs at higher elevations and in open areas as well as areas with recent forest disturbance. The K090 scenario is projected to have minimal differences on hydrologic indicators relative to current conditions in Rover Creek. Conversely, the current degree of forest disturbance in the watershed (i.e. Current Conditions) is estimated to have led to a departure from the hydrologic conditions in the watershed relative to a fully mature (i.e. Mature) forest. While the fully mature condition is an unlikely baseline condition it is worth recognizing that the current level of development may be contributing to earlier peak flows, higher magnitude peak flows, and greater flows during the winter months relative to natural conditions.

Closing

Thank you for the opportunity to complete this work. Please do not hesitate to contact us if you have additional questions or concerns.

Kim Green, PhD., P.Geo
Apex Geoscience Consultants Ltd

Matthew Chernos, MSc., P.Geo.
MacDonald Hydrological Cnslt Ltd.

References

Apex Geoscience Consultants Ltd (2021). Rover Creek Watershed Assessment. Prepared for Gerald Cordeiro, Forestry Manager, Kalesnikoff Lumber Co. Ltd., 26p.

Bergström, S. (1995). The HBV model. Computer models of watershed hydrology., 443-476.

Chernos, M., MacDonald, R. J., Nemeth, M. W., & Craig, J. R. (2020). Current and future projections of glacier contribution to streamflow in the upper Athabasca River Basin. Canadian Water Resources Journal/Revue canadienne des ressources hydriques, 45(4), 324-344.

Chernos, M., MacDonald, R., & Craig, J. (2017). Efficient semi-distributed hydrological modelling workflow for simulating streamflow and characterizing hydrologic processes. Confluence: Journal of Watershed Science and Management, 1(3).

Craig, J.R., Brown, G., Chlumsky, R., Jenkinson, W., Jost, G., Lee, K., Mai, J., Serrer, M., Snowdon, A.P., Sgro, N. and Shafii, M., (2020). Flexible watershed simulation with the Raven hydrological modelling framework.

Environmental Modelling & Software, p.104728. Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. Hydrological Processes, 12(10-11), 1611-1625.

Jost, G., Moore, R. D., Menounos, B., & Wheate, R. (2012). Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada. Hydrology and Earth System Sciences, 16(3), 849- 860.

LaZerte, Stefanie E and Sam Albers. (2018). weathercan: Download and format weather data from Environment and Climate Change Canada. The Journal of Open Source Software 3(22):571. doi:10.21105/joss.00571.

Ministry of Forests, Lands, Natural Resource Operations and Rural Development. (2011). Baseline Thematic Mapping Present Land Use Version 1. Government of British Columbia.

Natural Resources Canada (NRCAN). (2016). Canadian Digital Elevation Model. 2016-10-21. Government of Canada. Sherbrooke, Quebec.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Teucher, A., Albers, S., Hazlitt, S., & Province of British Columbia. (2021). bcdata: An R package for searching and retrieving data from the B.C. Data Catalogue. Journal of Open Source Software, 6(61), 2927, https://doi.org/10.21105/joss.02927

Appendix A: Hydrological Modelling Methods

Data

To run the hydrological model configurations used in this study, daily air temperature (maximum and minimum, °C) and precipitation (mm/day) are required. These data were collected from DayMet (Thornton et al., 2018) using the Single Pixel Extraction Tool to obtain observations from 1980- 2019 for at a 0.15 degree resolution over the study area. Since DayMet data are based on a 1x1 km grid cell, reference elevations are obtained for each data point and are used to correct observations to HRU elevations using specified lapse rates within the hydrological model. Streamflow (m3/s) data were obtained from all Water Survey of Canada (WSC) hydrometric stations in the study area with long-term records. In addition, community monitoring has collected streamflow observations from both Harrop Creek and Narrows Creek. In total, 3 hydrometric sites which were used in model calibration and verification (Table 4). In addition, the model was further calibrated and verified using daily air temperature and precipitation observations from regional weather stations and snow water equivalent observations were obtained snow pillow and snow survey sites (Table 5).

Table 1. Hydrometric stations/sites used in this study. WSC corresponds to the Water Survey of Canada, while HPCF corresponds to Harrop-Procter Community Forest monitoring program.

Name	Station ID	Source	Period	Drainage Area (km^2)
Anderson Creek Near Nelson	08NJ130	WSC	1980-2020	9.1
Five Mile Creek Above City Intake	08NJ168	WSC	1980-2015	47.7
Lasca Creek at The Mouth				66.4
Harrop Creek Near Harrop	08NJ027	WSC, HPCF	1984-1994, 2002-2021	42.2
Narrows Creek Near Procter	08NJ020	HPCF	1999-2018	22.3
Procter Creek at Procter	08NJ021	WSC	<1980	7.8

Table 2. All weather and snow stations used for model verification in this study.

Station Name	Station ID	Longitude	Latitude	Elevation (m)	Network	Data Type
Nelson CS	1160	-117.31	49.49	535	EC	Weather Station
Harrop	5194	-117.04	49.60	535	ARDA	Weather Station
Nelson NE	1154	-117.21	49.59	570	EC	Weather Station
Nelson	2D04	-117.23	49.42	930	FLNRO-WMB	Snow Survey
Whitewater	2745	-117.15	49.44	1,640	MoTIm	Weather Station
Glory Basin	2744	-117.16	49.44	1,920	MoTIm	Weather Station
Southridge	2746	-117.16	49.42	1,990	MoTIe	Weather Station
Redfish Creek	2D14P	-117.08	49.68	2,104	FLNRO-WMB	Snow Pillow

The study area was discretized using hydrological response units (HRUs) based on the unique overlay of elevation bands, hillshade, land cover, and sub-basin. We derived 100 m elevation bands using the Canadian Digital Elevation Data digital elevation model (DEM; Natural Resources Canada, 2016). Hillshade is calculated using the `hillshade` function in the R `raster` package (Hijmans, 2020), which incorporates the slope and aspect of each grid cell. Watersheds were delineated based on hydrometric stations, using routines in the RSAGA package (Brenning et al., 2018). Land cover was obtained from Baseline Thematic Mapping Present Land Use Version 1 (FLNRORD, 2011). We further aggregated land cover into the following classes: Agriculture, Alpine, Shrub, Burn, Disturbed Forest, Juvenile Forest, Mature Forest, Lake, Wetlands, Developed. In addition, Mature Forest was divided into the two prevalent Biogeoclimatic (BEC) zones in the region: Interior Cedar Hemlock (ICH) and Engleman Spruce Subalpine Fir (ESSF). Finally historical vegetation disturbance was accounted for using a VRI dataset provided by the client. Areas with less than 40% recovery were classified as “Disturbed Forest” while forest with 40-75% recovery were classified as “Juvenile Forest”.

Model Calibration

To optimize model representation of key hydrologic processes and streamflow, model parameters were calibrated in a stepwise manner following Chernos et al. (2017) and originally adapted from Stahl et al. (2008). First, air temperature and precipitation lapse rates were calibrated to regional weather stations, then snowmelt parameters are modified to follow empirical values obtained from regional snowmelt and glacier mass balance observations. Finally, vegetation interception and soil routing parameters are calibrated to streamflow observations. Final calibrations were completed by a combination of manual methods and automated calibration. Automated calibration of parameters will be completed using OSTRICH calibration software (Matott, 2017), using the Dynamically Dimensioned Search (DDS) algorithm to finalize parameter values. Model parameters were calibrated to the 2010-2018 period using the Five Mile Creek Above City Intake hydrometric station. Model performance was verified over the remaining record (1987-2009) for sub-basins used in model calibration, and for the complete record for sites not used in calibration.

While calibration was able to constrain the value of most model parameters, some parameters are relatively insensitive, such that changing their value does not substantially alter streamflow simulations. In some cases, this is because the model parameter does not affect a dominant hydrologic process in the watershed (for example, capillary rise). In other cases, particularly, for land cover specific model parameters, the parameter is insensitivity because little of that land cover type exists in the sub-basin. For example, since Five Mile Creek contains minimal Juvenile Forest over the calibration period, it is difficult to calibrate the interception parameters for this land cover class. In these cases, model parameters were finalized to ensure conceptual and physical realism (i.e. to ensure Juvenile stands intercept more precipitation than Disturbed stands, but less than Mature forest).

Model Parameterization

Model parameterization relied on a combination of calibration using independent weather and snowpack data and conceptual understanding of the dynamics of vegetation regrowth. A comprehensive list of model parameters is provided in Table 3. Notable parameter values include that snow in Mature Forest is assumed to melt at a slower rate than open areas (0.80 in ICH, 0.85 in ESSF), while this difference is less pronounced in Juvenile Forest. Likewise, forest cover fractions are higher in mature forest classes, relative to juvenile and disturbed forest. Finally, although maximum annual leaf-area-index (LAI) values are the same between forest age classes, Disturbed Forest varies seasonally with winter values half their summer value, reflecting that much of recently disturbed forests consist of deciduous plants.

Table 3. Final model parameters used in the hydrological model.

Process	Description	Parameter	Value	Units
Orographic Corrections	Adiabatic Lapse Rate	Alapse	6.5	°C/km
	Precipitation Lapse Rate	Plapse	3.5	mm/day/km
Rain-Snow Partitioning	Transition Temperature	Snw1	1.0	°C
	Mixed-Range	Snw2	2.0	°C
Snowmelt	Global Snowmelt Factor	K_factor	2.75	mm/°C /day
	Mature Forest correction (ICH)	Forest_corr	0.80	fraction
	Mature Forest correction (ESSF)	Forest_corr	0.85	fraction
	Juvenile Forest correction	Leaf_corr	0.90	fraction
	Aspect/Slope correction	Acor	0.2	fraction
	Minimum Melt (winter)	Min_melt	0.5	mm/°C/day
	Refreeze factor	Refreeze	2.0	mm/°C/day
Leaf Area Index*	Disturbed Forest	Cut_LAI	4.5	unitless
	Juvenile Forest	ForestY_LAI	4.5	unitless
	Mature Forest	Forest_LAI	4.5	unitless
Vegetation/Canopy Coverage	Disturbed Forest	Cut_Cov	0.60	fraction
	Juvenile Forest	ForestY_Cov	0.80	fraction
	Mature Forest (ICH)	Forest_Cov	0.90	fraction
	Mature Forest (ESSF)	Decid_Cov	0.85	fraction
Infiltration	HBV Beta	HBV_B0	0.5	unitless
Percolation	Surface Soil	Perc0	4.0	mm/day
	Soil Layer 1	Perc1	4.0	mm/day

Capillary Rise	Surface Soil	Cap0	4.0	mm/day
Baseflow	Soil 1 K	Base_K1	0.16	unitless
	Soil 1 N	Base_N1	1.12	unitless
	Soil 2 N	Base_N2	1.25	unitless
	Soil 2 Max Rate	Base_MAX2	5.0	mm/day

**Indicates maximum annual LAI value; Shrub/Wetland, Disturbed Forest, and Grassland values vary seasonally with lower values during the winter.*

Model Performance

Simulated daily air temperature, total monthly precipitation, and daily SWE closely followed observed values from independent weather stations throughout the study region. Daily maximum air temperatures had r^2 values ranging from 0.75 to 0.98. Monthly precipitation r^2 values ranged from 0.45 to 0.90 with four out of five sites over 0.70. It should be noted that these weather stations are likely not fully independent since some are likely are inputs into the DayMet grid used in this study. Daily total SWE was well simulated at Redfish Creek snow pillow (r^2 = 0.94, PBIAS = -16%). Streamflow simulations demonstrated strong performance in reproducing observations from at the Five Mile Creek Above City Intake WSC hydrometric stations (Figure 2). Performance was similar between the calibration period (2009-2019) and verification period (1990-2008). Nash-Sutcliffe Efficiency (NSE), ranging up to 1 (perfect simulation) was 0.84 for both periods at Five Mile Creek. Overall, the model displays minimal bias between simulated and observed streamflow, with a positive bias of 10% in the calibration period and 7% in the verification period for Five Mile Creek. At Anderson Creek Near Nelson, performance is more modest, with an r^2 of 0.71 for the entire period and a positive bias of 27%. At Harrop and Narrows Creek, only point measurements are available for much of the record and therefore error statistics should be treated with additional caution. However, model performance was relatively good at both sites. Over the entire record, the model simulates a positive bias of 27% at Harrop Creek and 15% at Narrows Creek, with r^2 values of 0.66 for Harrop Creek and 0.78 for Narrows Creek.

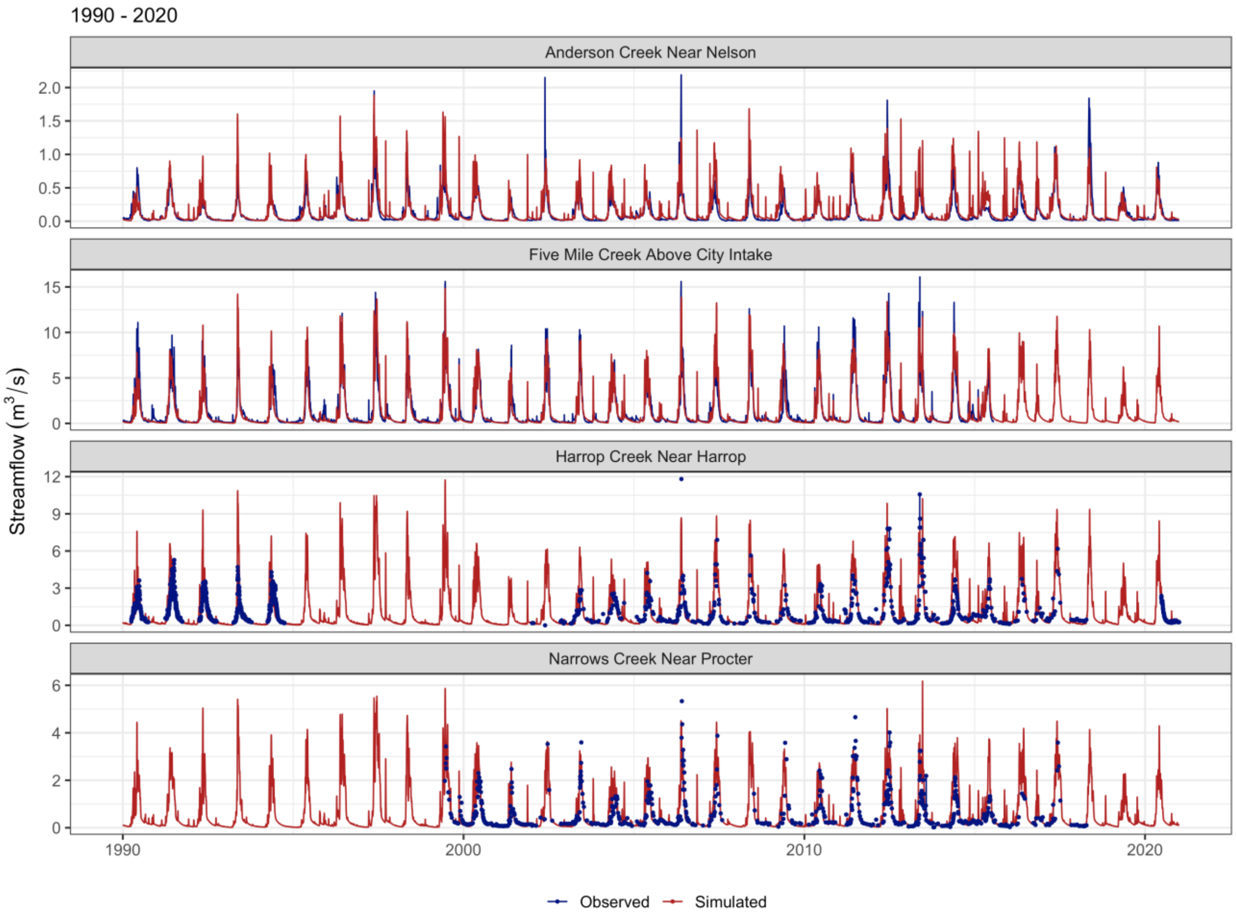

Figure 2. Daily hydrograph for three sites with hydrometric records. Continuous records shown as lines while point measurements are shown as dots.