CITY OF CRANBROOK

Hydrological Modeling for Climate Adaptation

APPLIED RESEARCH & INNOVATION
Selkirk College

COLUMBIA BASIN RDI RURAL DEVELOPMENT INSTITUTE
Selkirk College

CONTENTS

Publication Details

Project Team: Selkirk College Department of Applied Research and Innovation (Kim Green, Ian Dennis, Ines Schrottenbaum, Lauren Rethoret); City of Cranbrook (Katelyn Pocha)

Publication Date: May 25, 2021

The preparation of this study was carried out with assistance from the Government of Canada, the Federation of Canadian Municipalities, and the Natural Sciences and Engineering Research Council. Notwithstanding this support, the views expressed are the personal views of the author(s)

FCM FEDERATION OF CANADIAN MUNICIPALITIES FÉDÉRATION CANADIENNE DES MUNICIPALITÉS

Natural Sciences and Engineering Research Council of Canada Conseil de recherches en sciences naturelles et en génie du Canada

Canada

INTRODUCTION

PURPOSE

This report summarizes the results of a hydrological modeling investigation undertaken for the City of Cranbrook to investigate the potential for the impact of climate change and wildfire on the volume and timing of flows and the frequency of floods in Gold Creek and Joseph Creek.

The City of Cranbrook relies on Joseph and Gold creeks for its main water supply and supplements from three groundwater wells to meet higher summer water demand. Surface runoff from Joseph Creek and the upper portion of Gold Creek are captured by the City's water works and fed into a storage reservoir (northernmost POD, **Figure 1**). Below this point the overflow continues through the City of Cranbrook in the Joseph Creek channel.

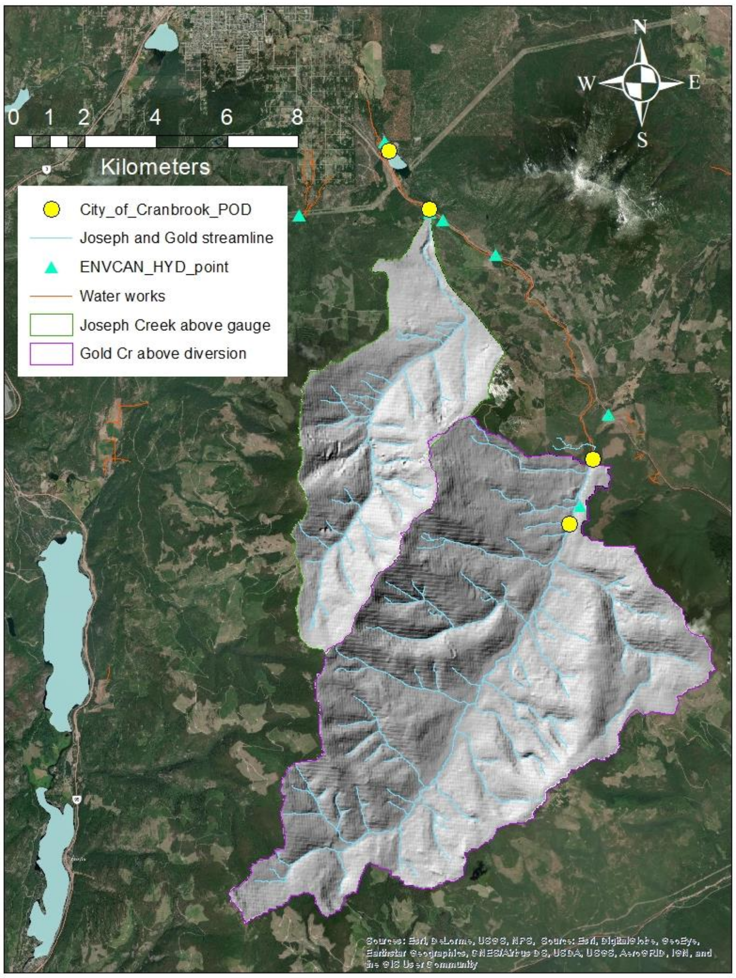

Figure 1: *Joseph Creek and Gold Creek catchment areas that contribute to the City of Cranbrook water supply.*

Climate-related events like flooding, drought and high temperatures can be critical events for communities and are examples of events that are projected to occur with greater frequency and/or intensity as the climate gets warmer. Flooding poses a risk to water infrastructure, public safety, and contributes to turbidity in surface sources. Drought has implications for water supply, local food production and increasing wildfire risk. Higher temperatures can impact vulnerable populations, including the elderly, socially isolated, chronically ill and infants.

The information presented in this report is intended to investigate potential trends and impacts related to the scenario of a changing climate and wildfire on flooding, flow volume and timing in order to inform local planning and decision-making.

STUDY AREA

Gold and Joseph creeks are located roughly 10 kilometers south of the City of Cranbrook. For this study the physical attributes of these watersheds are defined on the basis of the location of the City of Cranbrook's water discharge gauging sites. Joseph Creek has a catchment area of 50.7 Km^2 and an elevation range between 1116 meters and 2137 meters while Gold has a catchment area of 94.1Km^2 and ranges in elevation from 1300 to 2166 meters (**Figure 2**).

A comparison of the hypsometric curves for these watersheds in Figure 2 shows that Joseph Creek has a broader elevation range but overall, the contributing area is substantially lower in elevation than Gold Creek.

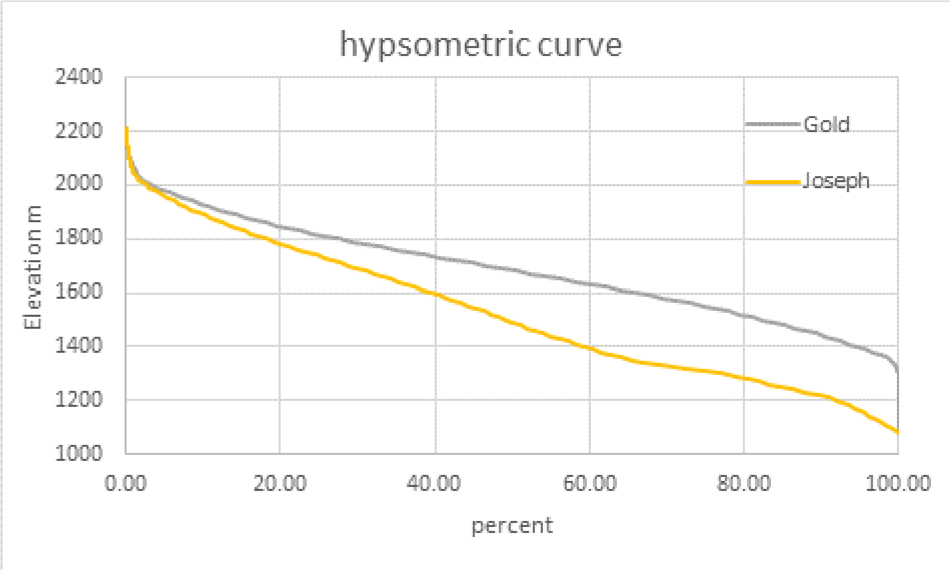

Figure 2: *Hypsometric curves for Joseph Creek and Gold Creek showing the distribution of watershed area in percent by elevation*

Both watersheds flow northeastward and the aspect distribution of slopes is predominantly northwest to west and southeast to east (**Figure 3**).

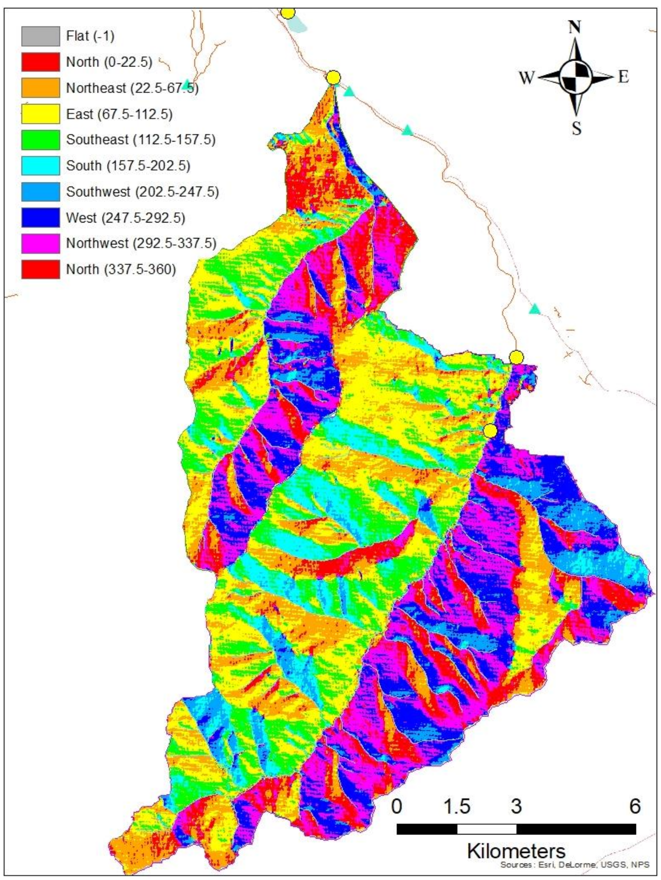

Figure 3: *Aspect distribution of Joseph and Gold Creek shows that slopes are predominantly northwest to west (pink to blue) and southeast to east (green/yellow)*

Annual precipitation in Joseph and Gold creeks estimated from climate normal (1981 – 2010) ranges from just over 600mm at the lower elevations of Joseph Creek to just over 1000mm at the upper elevations of Gold Creek[i].

According to long term meteorological data from the Cranbrook Airport weather station[ii], the wettest months of the year are May and June when the majority of precipitation falls as rain while the driest months are February and October (**Figure 4**).

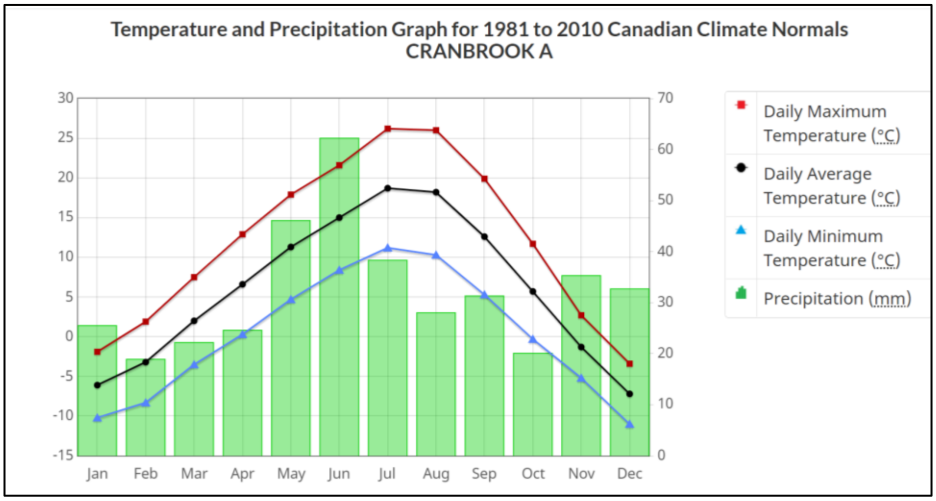

***Figure 4**. Temperature and precipitation normal for 1981 to 2010 for Cranbrook Airport weather station (https://climate.weather.gc.ca/climate_normals/)*

METHODS

Hydrological Modeling

The hydrological model used in this study is referred to as a lumped hydrological model and is an adapted version of the HBV-EC model, emulated within the Raven Hydrological Modelling Framework version 3.0 (Craig et al., 2020). The HBV-EC model simulates streamflow and other hydro-climatic variables (i.e. snowmelt, evaporation, etc.) at a daily timestep from 2001-2020. The model creates a virtual watershed and spatially distributes daily minimum and maximum air temperature and precipitation from the nearby Environment Canada Cranbrook Airport weather station (Station 1152105, Latitude 49.61° N | Longitude 115.78° W). The model accounts for water storage in the form of snow or rain, and simulates major hydrological processes including canopy interception, snow accumulation and melt, evaporation, soil infiltration, percolation, interflow, baseflow, as well as runoff (see Craig et al., 2020).

Data

We delineated the Gold Creek and Joseph Creek watersheds upstream from the City of Cranbrook's hydrometric station locations (**Figure 1**) using a digital elevation model. For input to the hydrological model, the two watersheds were discretized into hydrological response units (HRUs) based on overlaying elevation bands, aspect, and land cover (**Figure 5**). Specifically, the watersheds were divided into three elevation bands (<1589m, 1589 – 1879m and >1879m) using the 20-meter BC provincial digital elevation model (DEM). Land cover information was obtained from the B.C. provincial Vegetation Resource Inventory (VRI) database and reclassified into 3 classes based on years since harvest which included clearcut (<20 years), young forest (20 – 60 years) and mature forest (>60 years).

[i] https://data.pacificclimate.org/portal/bc_prism/map/
[ii] https://climate.weather.gc.ca/climate_normals/

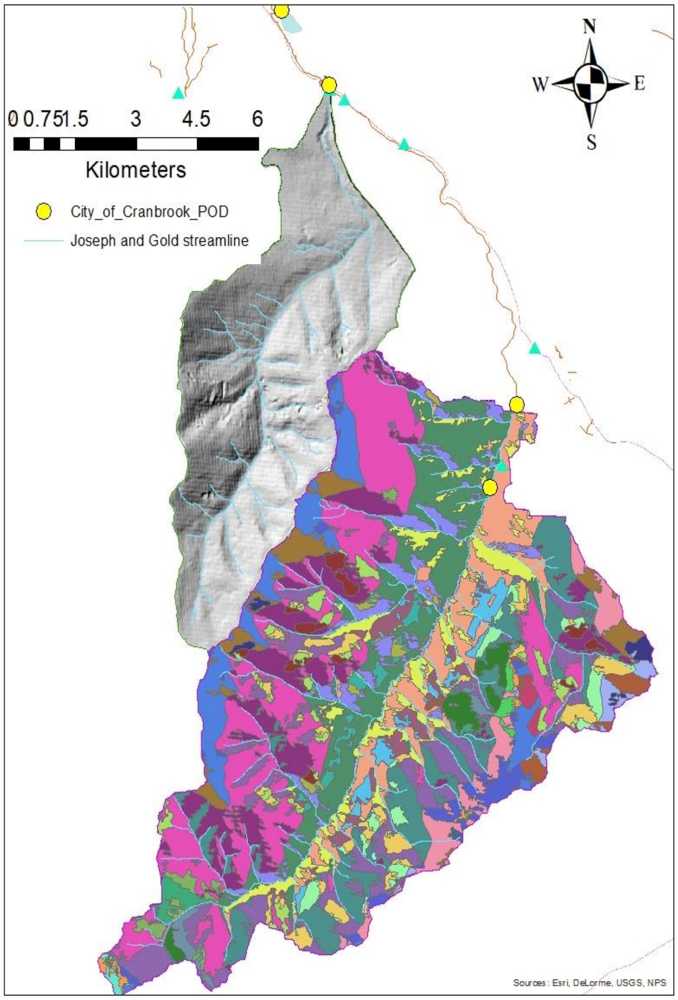

Figure 5: *Gold Creek showing delineation of hydrological response units (HRUs)*

Daily mean streamflow (m^3/s) data from 2001 to 2020 for both Joseph Creek and Gold Creek were obtained from the City of Cranbrook hydrometric stations. The model was calibrated and verified using daily air temperature and precipitation observations from the Cranbrook Airport weather station and snow water equivalent observations were obtained from the Moyie Mountain snow pillow site. The climate data from several nearby stations were also used to improve temperature and precipitation lapse rate estimates.

Model Formulation

The model spatially distributed daily minimum and maximum air temperature and precipitation across the catchment using inverse-distance weighting. Water, delivered as precipitation is intercepted by and/or passed through the forest canopy to the soil surface as rain or snow depending on the temperature.

Snow accumulated in the HRUs during the winter months and then melted according to a spatially corrected temperature index model, which has been shown to perform well over a variety of regions and environments at a daily time step (Hock, 2003; Jost et al., 2012). Rain and snowmelt then infiltrated into the three-layer soil model, where it was able to move upward by capillary rise and downward by percolation. Water returned to the surface (in the stream channel) via interflow from the middle soil layer which had a faster response and from the deepest soil layer, which had much slower baseflow response. The model algorithms are listed in **Table 1**.

Table 1: *Algorithms used to represent hydrologic processes in the model. All algorithms are documented in the Raven User's Manual (Craig et al., 2020)*

Process	Model Algorithm
Potential Melt	HBV
Rain-Snow Partitioning	HBV
Evaporation	Priestley-Taylor
Orographic Corrections	HBV, Simple Lapse
Snow and Rain Interception	Hedstrom and Pomeroy (1998), Exponential LAI
Canopy Evaporation	Maximum
Snow Refreeze	Degree Day
Snow Balance	HBV (Snowbal Simple Melt)
Infiltration	HBV
Soil Evaporation	HBV
Capillary Rise	HBV
Percolation	Constant
Interflow (Soil Layer 1)	Power Law
Baseflow (Soil Layer 2)	Variable Infiltration Capacity

Model Calibration

To best represent key hydrologic processes and streamflow, model parameters were calibrated in a stepwise manner following Chernos et al. (2017). First, air temperature and precipitation lapse rates were calibrated to regional weather stations, and further fine tuned to balance the water output from the system. Then snow melt parameters are modified to follow empirical values obtained from regional snow survey and pillow observations. Finally, vegetation interception and soil routing parameters are calibrated to streamflow observations. Calibrations were completed by a combination of manual methods and automated calibration. Automated calibration of parameters was completed using OSTRICH calibration software (Matott, 2005), using the Dynamically Dimensioned Search (DDS) algorithm. Model parameters were calibrated to the 2001-2010 period. Model performance was verified over the remaining record (2001-2020) for the Gold Creek hydrometric station.

Model Scenarios

The calibrated hydrological model was used to investigate the relative impact and sensitivity of watershed hydrology to forest disturbance compared to the 2001 - 2010 'baseline' condition. The calibrated hydrological model was used to run two scenarios with fire related forest disturbance and one scenario with the 'worst-case' climate change scenario. The forest disturbance scenarios were run over the 20-year (2001 -2020) simulation period while the climate change scenario was run using 80-year of simulated climate data with temperature and precipitation projected for RCP 4.5 and RCP 8.5.

These scenarios are meant to inform the City of Cranbrook regarding potential changes in flooding and water yield and timing of runoff associated with possible future landcover and climate change. The two landcover disturbance scenarios included the 30% disbursed burn where forest cover was removed across the full range of elevations and aspects and the 30% concentrated burn where a large patch of forest in a potentially hydrologically sensitive area was burned off (**Figure 6**). These burned scenarios also included conversion of the soil surface to impermeable which is consistent with the hydrophobic soil conditions that occur for several years following a forest fire.

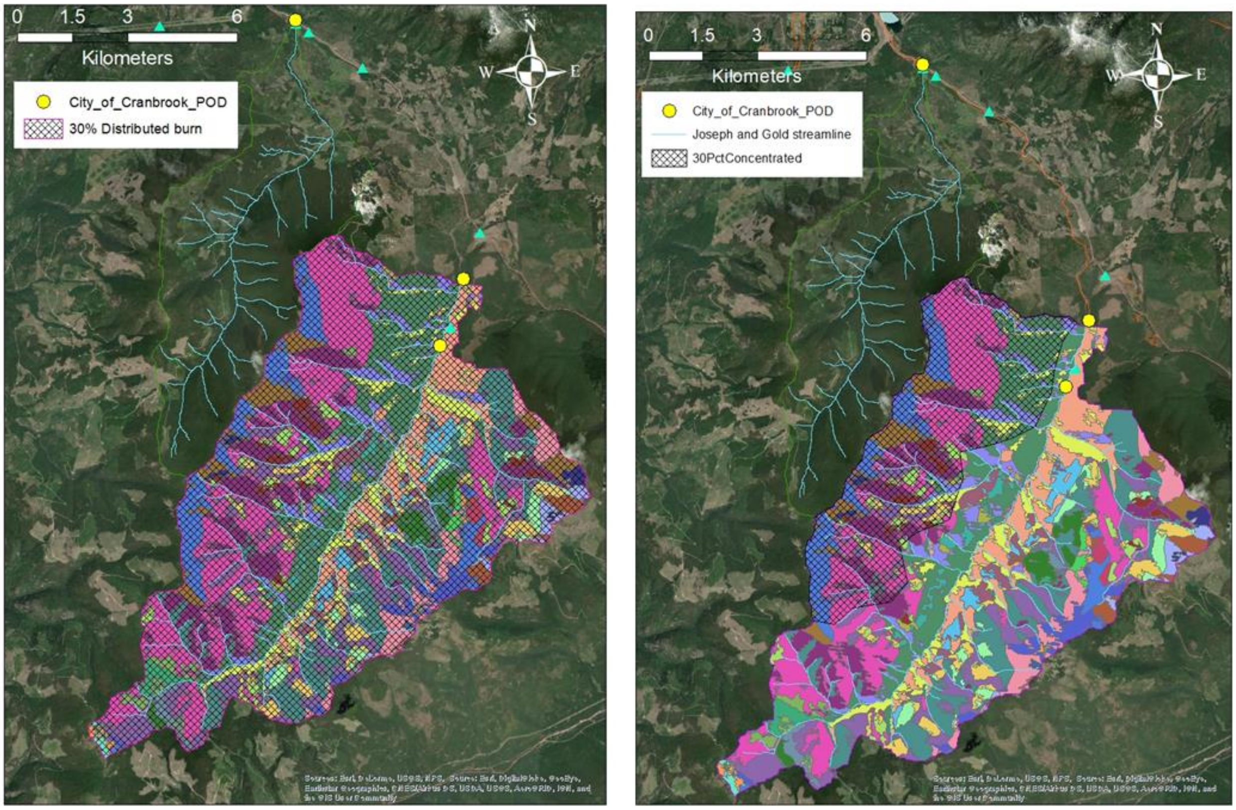

Figure 6: *Land cover disturbance scenarios from forest fire with HRU base*

Data Issues

As a result of initial difficulties with model calibration for Joseph Creek, a comparison of annual water yield per unit area (i.e., normalized by watershed area) with Gold Creek and other nearby watersheds revealed substantially lower-than-expected water yields in Joseph Creek (**Figure 7**).

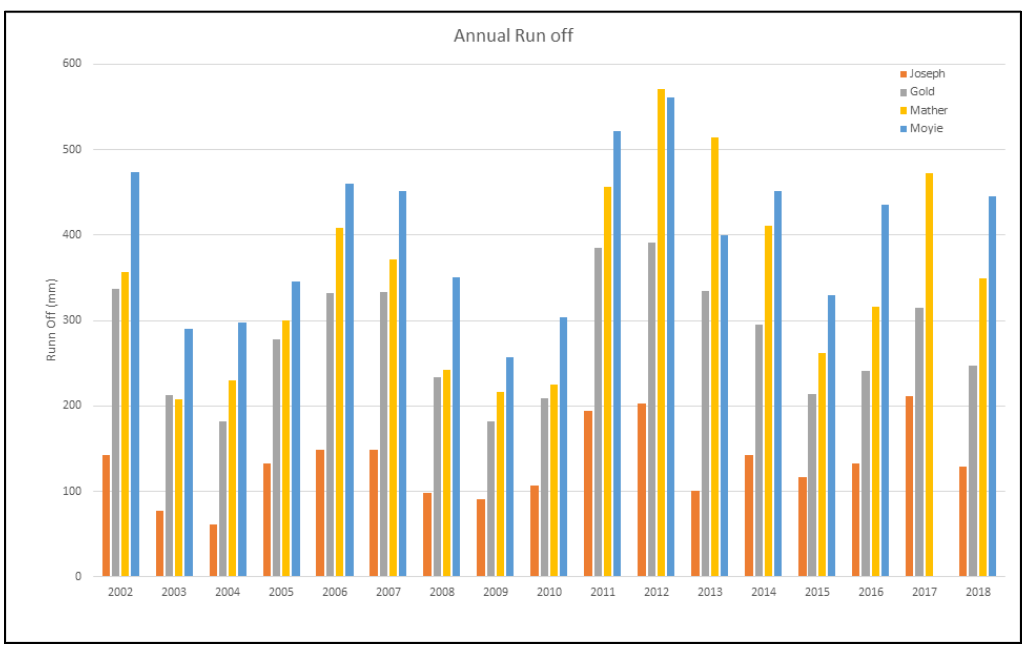

Figure 7*. Annual runoff (per km^2) for Joseph Creek and nearby watersheds.*

The comparison of annual unit water yield (mm^3/km^2 or mm) reveals that Joseph Creek discharge (orange bars, **Figure 7**) is a fraction of the volume (~ ½ to ¼ the volume) of water per unit area compare to nearby watersheds including Gold Creek and Mather Creek. It is not clear whether there is an error in the stage to discharge relationship being used to convert water depth to discharge or, if a large volume of water is being lost from the channel – possibly disappearing into a karsted limestone within the Kitchener Formation upstream from the discharge gauging site. Regardless of the cause of the water loss, it is not possible to accurately model the flows in Joseph Creek without manually adjusting inputs to reflect physically impossible conditions.

Lower-than-predicted discharges were not encountered in Gold Creek and good agreement between modeled and observed discharge was achieved during model calibration. Consequently, this project has focussed on model development and calibration in Gold Creek to provide information on likely watershed response for land cover and climate change scenarios.

Climate Change Modeling

The impact of climate change is assessed by feeding the HBV-EC model climate data including precipitation and temperature (maximum and minimum) projected to account for climate change scenarios. The projected climate data were generated with LARS_WG6, a stochastic Climate generator. The LARS_WG6, climate model was calibrated to the 2001-2020 baseline period using data from the Environment Canada Cranbrook Airport weather station. In addition to the 80-year baseline climate, the climate emission scenarios RCP45 and RCP85 are generated using the CNRM-CM5 Climate model. The stochastic model produced climate data with adjusted statistics resulting in increasing average of the maximum and minimum temperature (**Figure 8**) from baseline to high emission scenario, but with no change in standard deviation, which is probably not a realistic scenario but was the only option for the LARS_WG6 climate generator.

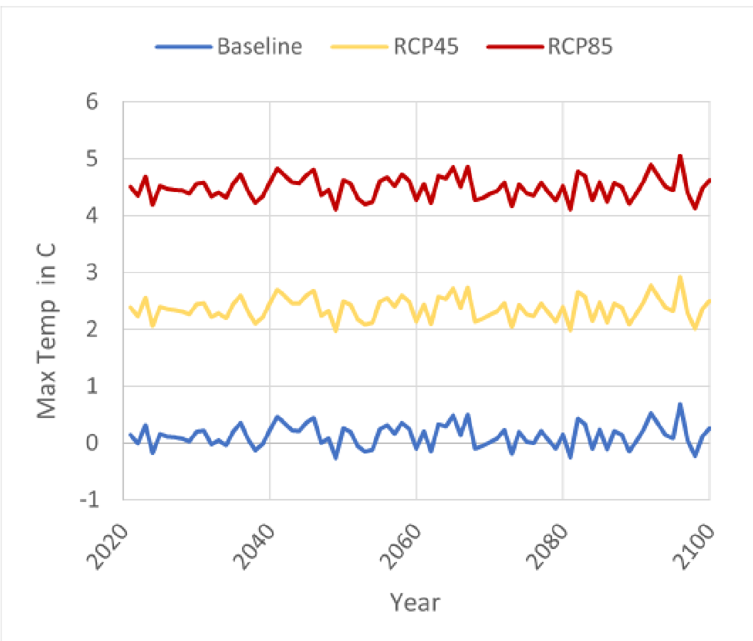

Figure 8: *Maximum temperature timeseries generated for the baseline, RCP45 and RCP85 climate change scenarios*

The RCP 8.5 Precipitation data (**Figure 9**) show an increase in precipitation for portions of the year compared to the baseline data as well as a 3% decrease in variability compared to the baseline. The RCP 4.5 scenario shows similar increases in precipitation but marks a 1% decrease in variability. Again, the minimal change in variability for daily precipitation data given the RCP 4.5 and RCP 8.5 climate change scenarios is probably unlikely but it is a limitation of the projection tool.

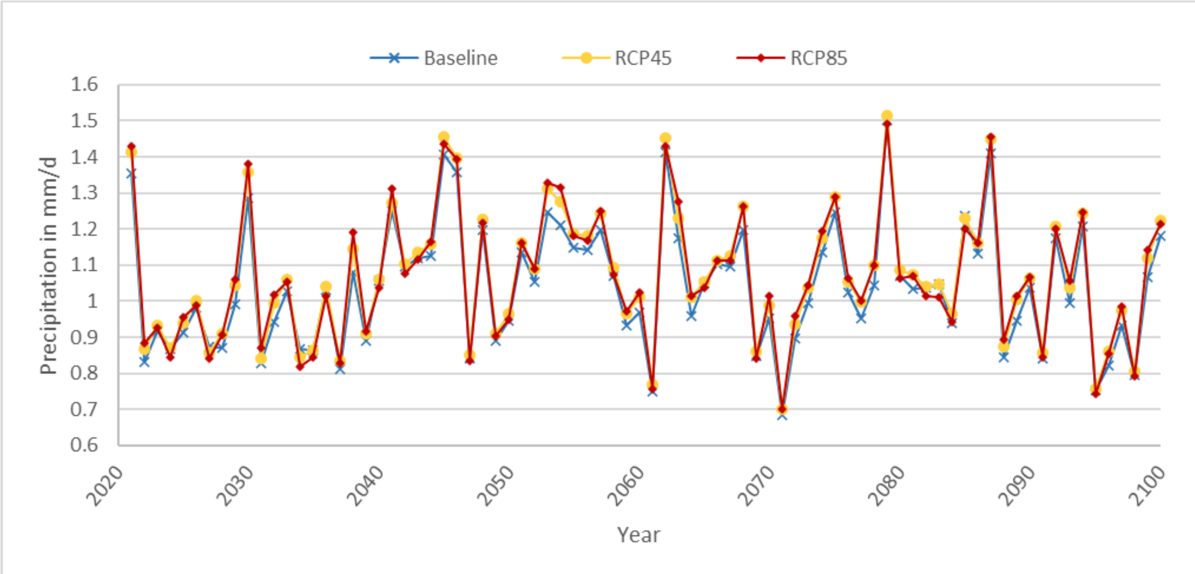

Figure 9: *Climate scenarios for precipitation*

Forest Disturbance

Both Joseph Creek and Gold Creek are forested watersheds on crown land and lie within the harvestable land base of the Province of BC under forest license #847632 currently held by Galloway Lumber Company Ltd. (Tenure license A19042). The Provincial VRI database indicates that harvesting has occurred in both watersheds dating back to the 1980s.

Harvesting began in the southern region of Gold Creek in 1992 and continued through to 2005. Additional harvesting was undertaken in 2011 and has been occurring every year since to 2020. During the period of model calibration (2001 to 2010) the area of forest disturbance associated with past logging totalled 1245 hectares or 13% of the 9410ha watershed (all colours except purple in **Figure 10**). The 1992 to 2010 logging is distributed across aspects and elevations and is unlikely to have had a measurable effect on the discharge of Gold Creek.

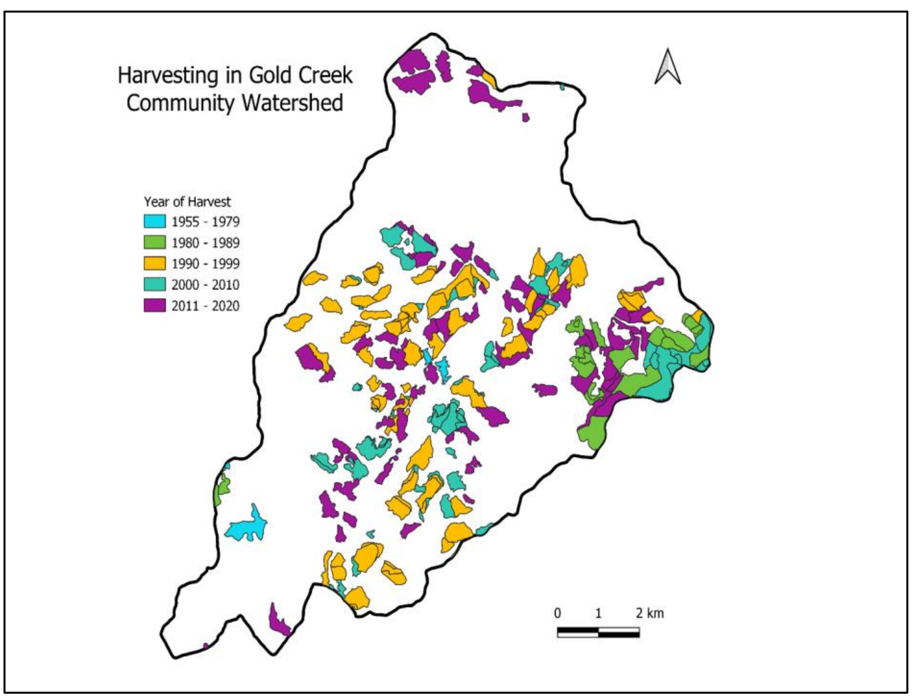

Figure 10: *Age and extent of forest disturbance in Gold Creek to 2020*

The current level of forest disturbance in Gold Creek is 2154.3 ha or 23% of the watershed area. Some of the older harvested stands will have some level of forest recovery so are likely no longer acting as clearcuts.

Hydrological Modeling Parameterization and Performance

Parameterization of the HBV-EC Model is provided in **Table 2**.

Table 2: *Final model parameters used in the hydrological model.*

Process	Description	Parameter	Value	Units
Orographic Corrections	Adiabatic Lapse Rate	Alapse	7.0	°C/km
	Precipitation Lapse Rate	Plapse	2.4	mm/day/km
Rain-Snow Partitioning	Transition Temperature	Snw1	2.0	°C
	Mixed-Range	Snw2	2.0	°C
Snowmelt	Global Snowmelt Factor	K_factor	3.5	mm/ °C /day
	Forest correction	Forest_corr	0.75	fraction
	Young_Forest correction	ForestY_corr	0.85	fraction
	Aspect/Slope correction	Acor	0.2	fraction
	Minimum Melt (winter)	Min_melt	0.0	mm/ °C/day
	Refreeze factor	Refreeze	1.0	mm/ °C/day
Leaf Area Index*	Cutblock	Cut_LAI	2.5	unitless
	Young_Forest	ForestY_LAI	3.5	unitless
	Forest	Forest_LAI	3.5	unitless
Vegetation/Canopy Coverage	Cutblock	Cut_Cov	0.50	fraction
	Young Forest	ForestY_Cov	0.60	fraction
	Forest	Forest_Cov	0.75	fraction
Infiltration	HBV Beta	HBV_B0	0.025	unitless
Percolation	Soil Layer 1	Perc1	4.0	mm/day
Capillary Rise	Surface Soil	Cap0	2.0	mm/day
Baseflow	Soil 1 K	Base_K1	0.33	unitless
	Soil 1 N	Base_N1	0.66	unitless
	Soil 2 N	Base_N2	2.0	unitless
	Soil 2 Max Rate	Base_MAX2	22	mm/day

**Indicates maximum annual LAI value; Cutblock values vary seasonally with lower values during the winter.*

Simulated snow water equivalent showed relatively good performance when compared to observations at the Moyie Mounatain snow pillow. Snow water equivalent is under-estimated at all three survey/pillow sites, with bias ranging from -10 to - 21%, but displays a good correlation with observations (r^2 = 0.81 to 0.0.9, **Table 3**). These meteorological verification statistics suggest that snow accumulation is well represented by the model.

Table 3**:** *Meteorological verification statistics for the full simulation period (1990-2019).*

Site	Period	Years	N	PBIAS	r2
Gold	Calibration	2001-2010	2648	-21	0.9
Gold	Verififcation	2011-2020	3500	-11.9	0.81
Gold	All	2001_2020	6148	-15.8	0.84

Note: N is the number of observations evaluated, PBIAS is the percent bias, and r^2 is the Pearson correlation coefficient

The model displays good performance at reproducing daily streamflow for hydrometric gauge used in this study (**Table 4**, **Figure 11**). Performance is best for the calibration period with daily Nash Sutcliffe Efficiency (NSE) and Kling Gupta Efficiency (KGE) values in the range of 0.73 to 0.84, performance is marginally worse over the verification period with NSE and KGE values in the range 0.56 – 0.78. In all sites, simulated streamflow displayed a minimal bias, ranging from 0.5 to 7.5%.

__Table 4:__ Daily streamflow performance statistics for the calibration period (2001-2010)

Site	Period	Years	NSE	KGE	PBIAS
Gold	Calibration	2001-2010	0.73	0.84	7.5
Gold	Verififcation	2011-2020	0.56	0.78	0.45
Gold	All	2001_2020	0.67	0.82	6.2

Note: NSE is the Nash-Sutcliffe Efficiency, KGE is the Kling-Gupta Efficiency, and PBIAS is the percent bias

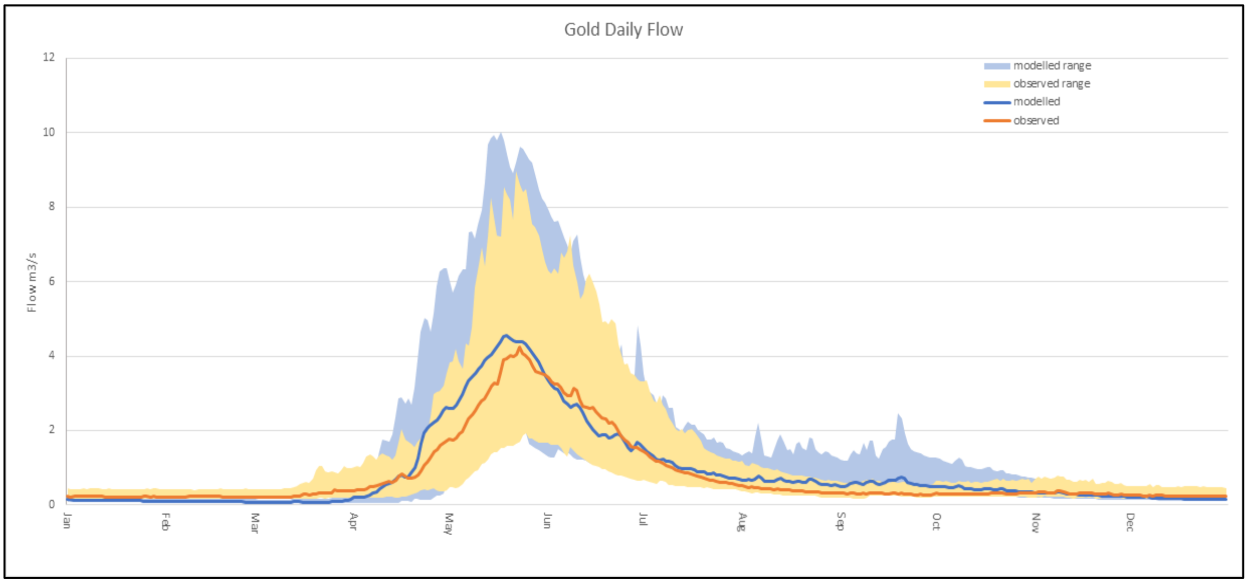

***Figure 11:** Average daily streamflow for Gold Creek used in model evaluation over the study period (2001-2020). The solid line corresponds to the average streamflow, while the shaded areas correspond to the 10 and 90% quantiles.*

Qualitatively, the model does a reasonable job at reproducing the timing and magnitude of spring runoff. Although snowmelt timing is slightly advanced the rate of runoff is generally well reproduced. In addition, low streamflow is well reproduced. Streamflow during the late summer and fall period (August – October) is somewhat over-estimated while winter streamflow (November -March) is somewhat under-estimated. Overall, the inter-annual and daily variability in flow is well reproduced, following the character of the observed hydrographs.

Outcomes

Effects of Land Cover change scenarios (forest fire) on stream flow

Peak Flows

A dispersed 30% burn disturbance causes the average annual peak flow in Gold Creek to increase by 16%. In addition, the variability of the time series of annual peak flows changes (5%) so that lower than average peaks decrease slightly while larger than annual peak flows increase (**Figure 12**). In the scenario where a concentrated 30% of the watershed area (2890 ha) burn is situated at the upper elevations in a portion of the watershed there is a substantially larger change in both the mean and variability of annual maximum peak flows. In this scenario the model suggests an increase of 13% in the mean annual peak flow and an increase of 4% in the standard deviation. This change in the frequency distribution of floods results in a shift of the 4-year return period flood becoming the 2-year return period flood.

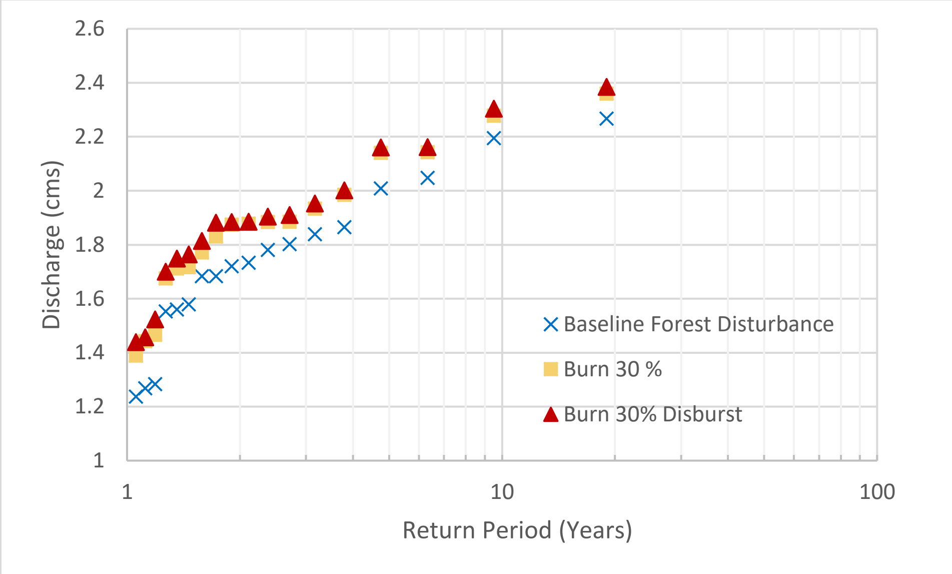

Figure 12: *Cumulative frequency distribution of annual peak flows given the baseline, 30% concentrated and 30% dispersed forest disturbance scenarios.*

Flow Timing

In the 30% disbursed burn scenario, the model predicts an average shift to 4 days earlier in the timing of peak flows and a return to base flows 1.5 days later than the 2010 baseline condition (**Figure 13**). Interestingly, according to the model output this shift is not observed every year but only for 2 of the 20-year time series. For the 30% concentrated burn the model predicts a shift to 1 day earlier in the timing of peak flows. Similar trends are also observed in the shift in the timing of half flow volume.

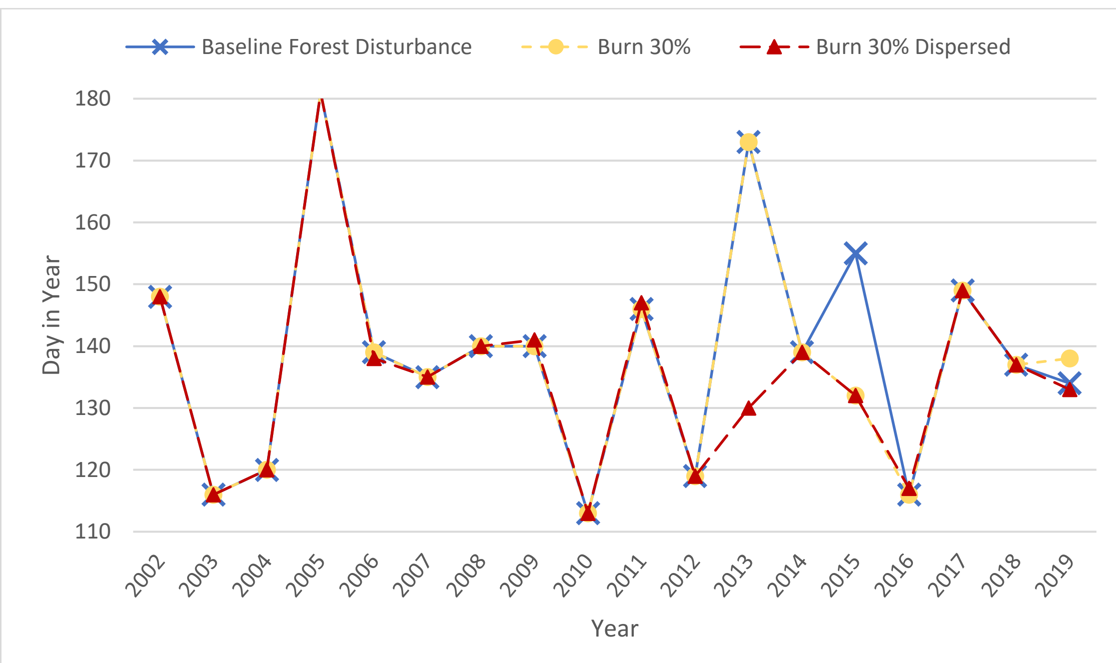

Figure 13*: Change in the timing of annual maximum peak flow for the forest burn scenarios.*

Effects of Climate Change Scenarios

Peak Flows

The RCP 4.5 Scenario causes the average annual peak flow in Gold Creek to decrease by 5%. In addition, the variability of the time series of annual peak flows increases slightly (7 %) (**Figure 14**). For the RCP 8.5 Climate scenario there is an even larger decrease in the mean (10%) with no difference in the variability of annual maximum peak flows. These changes in the frequency distribution of floods results in larger floods becoming less frequent than currently.

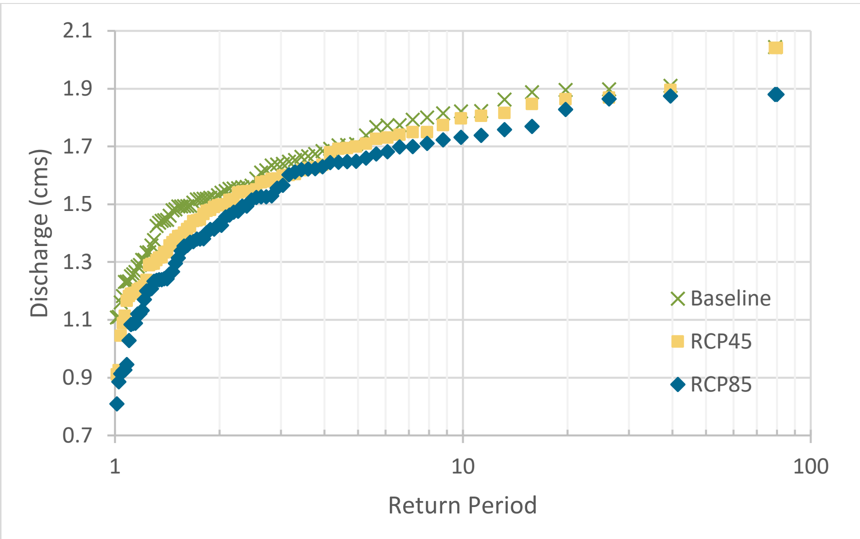

Figure 14: *Cumulative frequency distributions for Gold Creek for the RCP45 and RCP85 as well as baseline climate scenarios*

Flow Timing

Of all the metrics investigated changes in flow timing associated with climate changes scenarios yield the greatest changes. For the RCP 4.5 Climate Scenario the model predicts a shift to 7 days earlier in the timing of peak flows and a return to base flows 8 days later than the 2010 baseline condition (**Figure 15**). For the RCP 8.5 climate scenario the model predicts a shift of 12 days earlier in the timing of peak flows with some years up to 52 days earlier than the climate baseline scenario (with a range of 94 days, at a 34% range increase from the baseline) and a return to base flows 23 days later than baseline conditions (**Figure 15**). This trend is considered statistically significant at the 95% confidence limit. Similar trends are also observed in the shift in the timing of half flow volume – annual half flow is reached 7 days earlier for RCP 4.5 and for RCP 8.5 eleven days earlier compared to the baseline climate scenario.

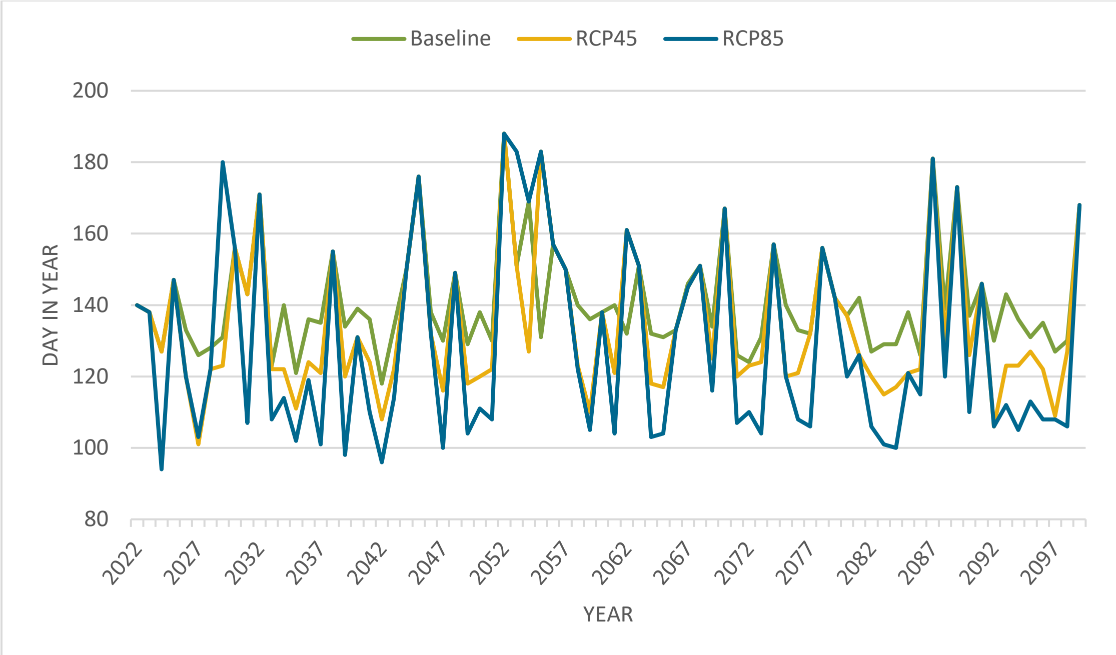

Figure 15*: Change in the timing of peak flows – relative to the baseline conditions for climate scenarios RCP 4.5 and RCP 8.5.*

DISCUSSION

The outputs of the HBV-EC model indicate that landcover disturbance from wildfire could have an immediate increase on the magnitude of peak flows from Gold Creek but that the timing of flows is unlikely to change substantially. Given changes in temperature and precipitation as projected with climate change within approximately the next 60 years, it is possible that there will be a decrease in the magnitude of floods across the full range of frequencies. In addition, the timing of peak flows and return to low flows is projected to occur substantially earlier in the year.

The modeled and projected changes in the timing and magnitude of flows from Gold Creek have uncertainties associated with both the HBV-EC model and the LARS_WG6 climate generator. Some of these uncertainties could be addressed give additional time to better calibrate the model. In addition, it is recommended to investigate the use of other climate generators that better model changes both the mean and the variability of daily temperature and precipitation time series given RCP 4.5 and RCP 8.5 climate projections.

REFERENCES

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, R. W., Jost, G., Lee, K., ... & Tolson, B. A. (2020). Flexible watershed simulation with the Raven hydrological modelling framework. *Environmental Modelling & Software*, *129*, 104728.

Hock, R.: Temperature index melt modelling in mountain areas, J. Hydrol., 282, 104–115, 2003.

Jost, G., Moore, R. D., Menounos, B., and Wheate, R.: Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada, Hydrol. Earth Syst. Sci., 16, 849–860, https://doi.org/10.5194/hess-16-849-2012, 2012.

Matott, L. S. (2005). OSTRICH: An Optimization Software Tool; Documentation and User's Guide. Version 1.8, http://www.civil.uwaterloo.ca/lsmatott/Ostrich/OstrichMain.html.