Hydrological Modelling as an Improvement on ECA-Based Methods for Informing Risk-Based Forest Management

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Abstract

Forest disturbance can alter the hydrologic conditions of a watershed, including the frequency, magnitude, and timing of peak and low flows. Equivalent Clearcut Area (ECA) has been routinely used in watershed assessments to estimate hydrologic alteration due to forest disturbance. ECA analyses typically rely on broad regional assumptions, qualitative observations, and/or expert judgement, making it difficult to provide accurate quantitative estimates of hydrologic change. Process-based hydrological models offer an improved approach since they replicate watershed processes, can simulate land cover and climate change scenarios, and provide quantitative estimates of hydrologic change, including at ungauged points of interest. A workflow using a regionally calibrated hydrological model to investigate forest disturbance and future climate change scenarios is demonstrated. Results are contrasted with ECA-based outputs and emphasize that in addition to the amount of forest disturbance, watershed physical characteristics and the location of disturbance within a watershed influence the hydrologic response. This approach provides forest managers with quantitative outputs that support risk-based forest management decisions and presents a substantial improvement over ECA-based methods.

Keywords: hydrological modelling, ECA-based analysis, watershed assessment, forest disturbance, cumulative effects, risk-based forest management

Introduction

Vegetation can exert hydrological control on runoff processes in forested snowmelt-dominated landscapes, most notably by intercepting a fraction of incoming precipitation and by providing shade, which slows spring snowmelt (Winkler et al., 2005; Pomeroy et al., 2012). At the stand level, removal of trees leads to increased snow accumulation and higher melt rates (Winkler et al., 2010; Ellis et al., 2010; Pomeroy et al., 2012; Goodbrand et al., 2022) and to an advance in the timing of snowmelt compared with the forested stand (Winkler et al., 2005; Ellis et al., 2010). At hillslope to watershed scales, removal of forest cover can alter the timing and quantity of streamflow generated from these systems (Moore & Scott, 2005). While forest cover change can affect streamflow throughout the year (Moore & Wondzell, 2005; Moore et al., 2020; Winkler et al., 2015), it can have particularly consequential effects on the frequency and magnitude of peak streamflow events (Alila et al., 2009, Green & Alila, 2012; Kuraś et al., 2012; Schnorbus & Alila, 2013; McEachran et al., 2021). Changes in the frequency, magnitude, and timing of peak streamflow can alter stream channel morphology, sediment transport characteristics (Troendle & Olsen, 1994; Montgomery & Buffington, 1997), ultimately affecting downstream communities, water users, and aquatic ecosystems (Tollan, 2002; Poff & Zimmerman, 2010; Webb et al., 2013).

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Recent studies in mountainous regions have determined that the influence of forest removal on streamflow depends in part on where the forest disturbance is situated in the watershed (Schnorbus & Alila; 2004; Kuraś et al., 2012; Pomeroy et al., 2012; Schnorbus & Alila, 2013; Ellis et al., 2013). Lower elevation areas typically contribute less total runoff, and this runoff primarily occurs prior to freshet (Gluns, 2001; Whitaker et al., 2002; Pomeroy et al., 2012). By comparison, mid and upper elevation areas receive more precipitation and generate substantially greater runoff. Spring peak flows are typically generated by snowmelt in these elevation zones (Gluns, 2001; Schnorbus & Alila, 2004; Smith et al., 2008; Whitaker et al., 2002; Pomeroy et al., 2012; Mahat & Anderson, 2013; Goodbrand et al., 2022). Studies have also shown that the slope and aspect of forest disturbance impacts the timing of snowmelt, with steep south-facing openings advancing melt timing while steep north-facing openings delay melt timing relative to the adjacent forested stands, which can alter streamflow at the watershed scale (Jost et al., 2007; Ellis et al., 2010, Ellis et al., 2013). Forest disturbance within hydrologically "sensitive" areas associated with elevation and slope-aspect in a watershed can alter the quantity and timing of streamflow due to synchronization with runoff from other areas during the period when peak flows are occurring (Pomeroy et al., 2012; Green & Alila, 2012; Johnson & Alilia, 2023). Because of this dynamic, the accurate identification of hydrologically sensitive areas is integral in evaluating the likelihood of change in water yields, timing of flows, and peak flows related to forest disturbance.

Forest managers in British Columbia and Alberta often require watershed assessments to provide information on how forestry activities could affect water quality, quantity, or aquatic values in a watershed where development is proposed. To meet these requirements, risk-based management decision frameworks are now commonly used by resource managers to guide forest management decisions (e.g., ABCFP & EGBC, 2020). These frameworks require information on the possible effects of existing or proposed forestry activities that may generate a potentially harmful hydrological response (or event) in a watershed. For example, where the value of concern in a watershed is residential land on a fan, one harmful hydrological response/event may be an increase in the frequency of damaging floods, or, if the value of concern is water for irrigation, the harmful response/event could be increases in the duration of summer low flows. Providing an assessment of the change in the likelihood of a harmful hydrological response requires knowledge of how forest disturbance could alter the timing and magnitude of runoff generation and ultimately streamflow in a watershed.

Equivalent Clearcut Area (ECA) approach is used throughout British Columbia and Alberta to assess the potential effects of forest harvest on the likelihood of harmful hydrological response in a watershed, such as changes in annual or seasonal water yield or increases in the frequency and magnitude of peak flows. The ECA approach is a proxy-type indicator that relates a single calculated value, adjusted for forest recovery, and, at times weighted by elevation, to the hydrological response of the entire watershed (Winkler & Boon, 2017). In general, the ECA concept has been used as a cumulative effects assessment tool in the United States (Reid, 1993) and in Western Canada (Silins, 2000; Zhang & Wei, 2012; Provincial Aquatic Ecosystems Technical Working Group, 2016; Winkler & Boon, 2017). In British Columbia, the *Interior Watershed Assessment Procedure* (BCMoF, 1999) and the *Watershed Assessment and Management of Hydrologic and Geomorphic Risk in the Forest Sector* (ABCFP & EGBC, 2020) support the use of ECA-type calculations to evaluate the level of hydrological disturbance and the potential impacts of forest management on hydrological response.

Equivalent Clearcut Area calculations rely on knowledge of rates of forest stand recovery with respect to processes of snow accumulation and snowmelt but few studies have investigated the process of hydrological recovery in clearcut forest stands across western Canada (Hudson, 2000; Winkler, 2001; Winkler et al., 2005) and none have investigated recovery in partial retention stands (Moore et al., 2016). In the absence of studies relating metrics of mean or median forest stand height, canopy closure, and/or canopy height to a level of hydrological recovery relative to a mature forest stand, most assessments resort to expert judgement to assign a level of recovery (i.e., from 0% to 100%) of a regenerating stand. Aside from the subjective element of assigning a recovery value, a further issue is that this approach assumes a single value adequately represents the recovery of several distinct hydrological processes including vegetation interception, snowmelt, and evapotranspiration, all of which may have variable recovery rates (Moore et al., 2016). This subjective approach to estimating hydrological recovery creates discrepancies between assessments and uncertainty in the resulting determination of likelihood of change in hydrologic response due to forest disturbance.

Additional uncertainty in ECA-based assessments stem from the few studies that have attempted to relate a single watershed ECA value to a level of hydrological response within a watershed (King, 1989; Winkler et al., 2015, Winkler & Boon, 2017). Meta-analyses intended to gain general insight into forest effects on streamflow show inconsistent outcomes; while some found that low levels of forest disturbance resulted in a measurable hydrologic response, others found that high levels of forest disturbance had no (or only a short-term) detectable response (Scherer & Pike, 2003; Goeking & Tarboton, 2020).

These uncertainties and the sparsity of scientific studies underpinning the ECA approach create challenges when forest managers are faced with a demand for a higher level of certainty with respect to forest management impacts on a potentially harmful hydrological response in a watershed. Additionally, as inputs to a risk management framework, forest managers need quantitative estimates on the potential for change in the likelihood of occurrence of a harmful hydrological response. Process-based hydrological models that simulate the rate and volume of runoff through a watershed provide this needed quantification and can be integrated into established watershed assessment methods to provide improved estimates of hydrologic response due to forest disturbance (e.g., Schnorbus & Alila, 2004; Kuraś et al., 2012; Schnorbus & Alila, 2013).

The application of process-based hydrological models for forest management has been limited due to complexity and the lack of the necessary hydrological and climate data for most watersheds. Data requirements generally scale with model complexity, where simple, single watershed/lumped models often have few data requirements (e.g., Sando et al., 2018), and more complex, spatially distributed, physical- or process-based models may require detailed model inputs with additional meteorological data or further estimation of these inputs (Finger et al., 2015; Clark et al., 2017, Pomeroy et al., 2007; Wigmosta et al., 1994). In recent years, there has been notable development in more robust and easily appliable process-based modelling frameworks and platforms (i.e., Craig et al., 2020; Clark et al., 2017, Pomeroy et al., 2022) as well as improvements in spatially interpolated meteorological datasets (e.g., Thornton et al., 2020; Mai et al., 2020) and remotely sensed land cover and vegetation products (i.e., Hermosilla et al., 2018). These advances have improved the ability of the hydrology community to apply process-based hydrological models for data sparse watersheds. This study presents a process-based hydrological modelling workflow for the purpose of informing watershed forest management that leverages these rapidly developing resources. The modelling workflow explicitly accounts for the underlying hydrologic processes driving streamflow, incorporates climate and land cover, and has relatively modest data requirements. The model was regionally calibrated, making it well suited for applications in data sparse environments, including ungauged watersheds, where many forestry decisions are made in Western Canada. Here we simulate the effects of forest disturbance and climate change on the hydrology of Little Cayuse Creek, an ungauged watershed in the south Selkirk region of British Columbia. Results from this study provide a hydrological model that can reliably simulate streamflow and hydroclimatic processes for watersheds throughout the south Selkirk region and estimate the hydrologic response due to forest disturbance and climate change.

Study area

The hydrological model applied in this study was developed for use in watersheds across the south Selkirk region between Kootenay Lake and Arrow Lake in British Columbia. The region is characterized by steep, forested mountain watersheds that feed the Kootenay and Columbia rivers. The region is classified as a humid continental climate (Köppen climate classification Dfb). Valley-bottom average air temperatures in the region (from Castlegar, B.C., ECCC, 2023) range from -2ºC in December to 20ºC in July and August. Precipitation averages 750 mm/year and is greatest during the winter months (Nov.-Jan.) and lowest during the summer months. In valley-bottoms, approximately 25 percent of precipitation falls as snow, while this snow fraction would be expected to be substantially greater at higher elevations. Model development considered long-term streamflow records for three relatively diverse watersheds within the region (Deer Creek, Duhamel Creek, and Coffee Creek; see Figure 1).

This study reports on the application of the hydrological modelling workflow for Little Cayuse Creek, an ungauged 27 km^2 watershed in the region. Little Cayuse Creek is in the Valkyr Range of the Selkirk Mountains of Southern British Columbia and flows south to Lower Arrow Lake

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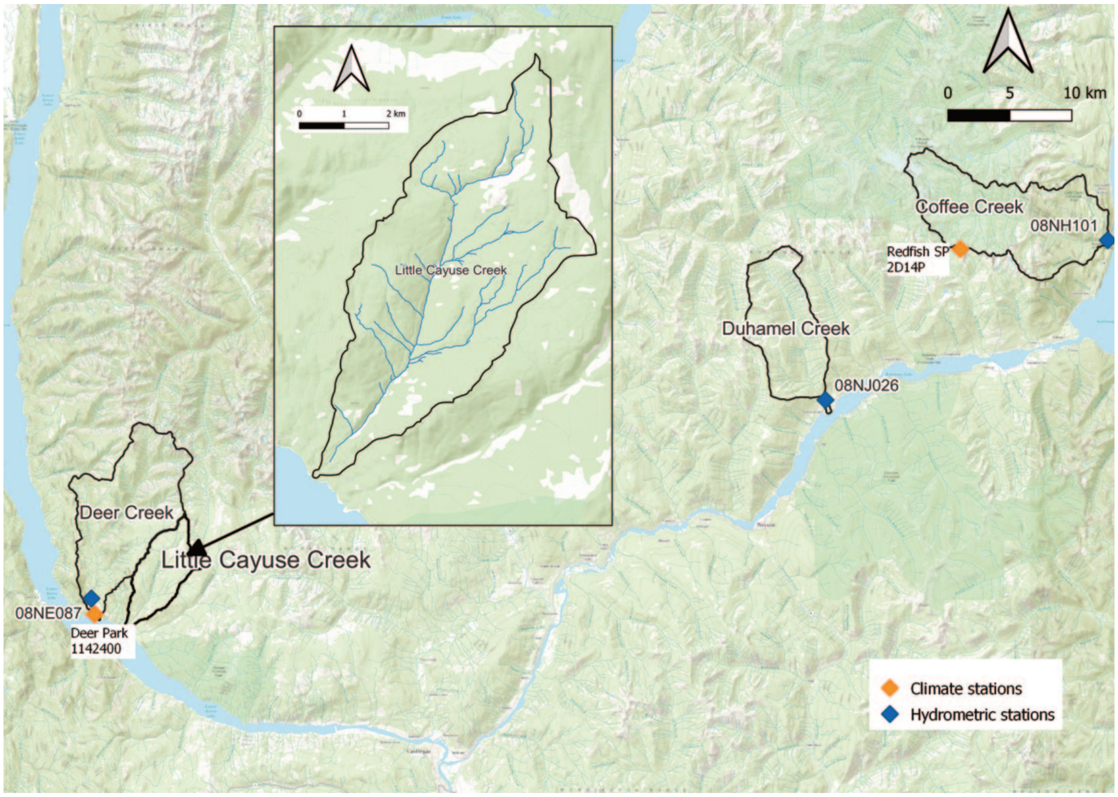

Figure 1. Regional study map showing the watersheds used in regional model development (blue diamonds), climate stations (orange diamonds), and the Little Cayuse Creek study watershed.

Reservoir, west of the community of Robson, B.C., from an upper elevation of 2100 meters (Figure 1). The watershed displays a dendritic drainage pattern with an array of small headwater tributaries flowing into the mainstem channel along its length. Slopes display predominantly southeast to southwest aspects and are mostly moderate gradient ranging from less than 30 percent at the upper elevations to near vertical bedrock and colluvium cliffs below about 700 meters above sea level (Figure 2).

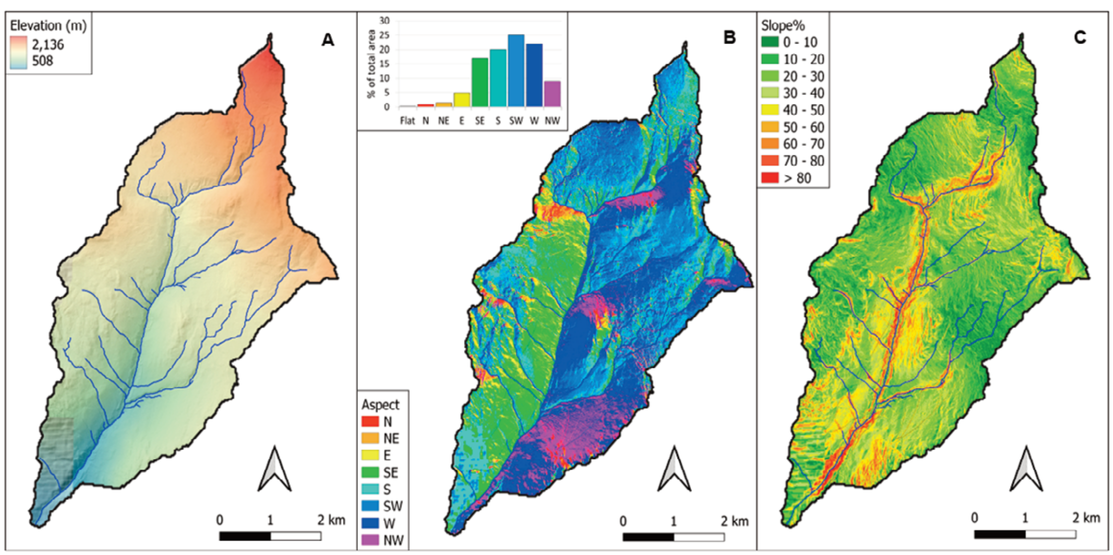

Figure 2. Elevation, aspect, and slope gradient distribution in Little Cayuse Creek.

Methods

Hydrological model

The semi-distributed process-based hydrological model used in this study is an adapted version of the HBV-EC model, emulated within the Raven Hydrological Modelling Framework version 3.5 (Craig et al., 2020; Craig & Raven Development Team, 2022). The model was calibrated to several gauged watersheds in the region, enabling it to produce useful outputs for ungauged watersheds across the south Selkirk region. The model spatially distributes the input forcing data (daily minimum and maximum air temperature, precipitation, and relative humidity) across the south Selkirk region and simulates major hydrological processes including canopy interception, snow accumulation and melt, glacier ice melt, evapotranspiration, soil infiltration, percolation, baseflow, and surface runoff. Primary processes are described below, while a comprehensive discussion of model algorithms can be found in Bergström (1995), Hamilton et al. (2000), Stahl et al. (2008), Chernos et al. (2020), and the Raven user manual (Craig & Raven Development Team, 2022).

Water input to the hydrological model occurs as precipitation, which is 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), which varies seasonally for deciduous forest classes, and interception is scaled by the forest cover fraction (also referred to as crown closure). Rainfall is intercepted following an exponential relationship (Craig et al., 2020), while snowfall is intercepted following the algorithm presented in Hedstrom and Pomeroy (1998). For both rain and snow, a maximum canopy storage value is applied to reflect the differing branch strength of vegetation types, with higher storage capacity in mature forests and lower values in regenerating vegetation. Snow and rain in the forest canopy can be removed by evaporation, preceded by melt in the case of snow.

Snowmelt is calculated using a spatially corrected temperature index model, which accounts for aspect, slope, and day length (Jost et al., 2012). The global snowmelt factor for open areas is scaled by vegetation type, reflecting the greater shading (and subsequently lower snowmelt rate) in mature forest stands. Potential evapotranspiration is calculated using the Priestley-Taylor equation and varies between vegetation types, with higher values in open areas. Once water infiltrates the three-layer soil, it moves downwards through percolation and upwards through capillary rise. Soil water is routed to streamflow through interflow (faster/shorter) and baseflow (slower/longer) pathways.

Model forcing data

Daily air temperature (maximum and minimum, °C) and precipitation (mm/day) are required to run the hydrological model with the configuration used in this study. These input data, along with relative humidity, were obtained from Daymet (Thornton et al., 2020) using the Single Pixel Extraction Tool to obtain observations from 1980 to 2020 at a 0.15-degree resolution over the study area. Daymet provides air temperature, precipitation, shortwave radiation, vapour pressure, snow water equivalent, and day length by interpolating and extrapolating ground-based observations through statistical modeling techniques (Thornton et al., 2021). Daymet was selected since it is of relatively high spatial resolution, is serially complete, and provides complete coverage across North America. Since Daymet data are based on a 1 x 1 km grid cell, reference elevations were obtained for each weather station used in the model and were used to correct observations to hydrological response units (HRUs) elevations using specified lapse rates within the hydrological model. Since HRUs are at much higher resolution, inverse distance weighting was used to spatially interpolate between weather stations.

A future climate change scenario was generated from statistically downscaled climate scenarios obtained from Environment and Climate Change Canada (ECCC, 2022) under the representative concentration pathway (RCP) 4.5. This RCP was chosen since it represents a relatively middle-of-the-road scenario where carbon emissions stabilize by 2040; other scenarios could be applied using this same workflow to explore additional future scenarios. The scenario applied the median projection from an equal-weighting ensemble of 24 General Circulation Models (GCM) from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) from 2021 to 2100. Projections among climate models can vary because of differences in their underlying representation of earth system processes. Thus, the use of a multi-model ensemble approach has been demonstrated in recent scientific literature to be more likely to provide better projected climate change information (Zhang et al., 2019; ECCC, 2022).

Daily future weather inputs were generated by first bias-correcting projected climate values by calculating the change between simulated future air temperature and precipitation and historical (simulated). Each future month and year were then matched with a proxy month from the baseline (observed/Daymet) period. These scaling factors for each month and year (i.e., fractional difference in precipitation and absolute difference in air temperature between the proxy and scenario) were then used these to correct the daily observed record for each climate scenario.

Model calibration/validation data

Regional weather/climate and hydrometric observations were gathered from publicly available data sources to calibrate and verify the hydrological model. This process is essential to ensure that the regional model is providing accurate results, to constrain uncertainty, and to ensure proper process representation. Streamflow (m^3/s) data were obtained from the HYDAT database using the R tidyhydat package (Albers, 2017) for three regional Water Survey of Canada (WSC) hydrometric stations: Deer Creek and Duhamel Creek had long-term streamflow records, while Coffee Creek had several years of daily streamflow available (Table 1). In addition, daily air temperature and precipitation observations were available from regional weather stations at Redfish and Deer Park (LaZerte & Albers, 2018), and snow water equivalent observations were obtained from the snow pillow site at Redfish Creek (Table 2). These data are useful to further constrain model parameters such as lapse rates and snowmelt variables.

Table 1. Water Survey of Canada hydrometric stations used to calibrate the regional hydrological model.

Station name	Station ID	Period	Drainage area (km^2)
Duhamel Creek above diversions	08NJ026	1996-2021	52.9
Deer Creek at Deer Park	08NE087	1980-2021	81.6
Coffee Creek near Ainsworth	08NH101	1988-1992	87.3

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

Station name	Station ID	Longitude	Latitude	Elevation (m)	Network	Data type
Deer Park	1142400	-118.05	49.42	485	EC	Weather station
Redfish Creek	2D14P	-117.08	49.68	2,104	FLNRO-WMB	Snow pillow

Spatial discretization

The study watersheds were discretized using HRUs based on the overlay of elevation bands, slope-aspect class, land cover, and sub-basin. Since this method primarily relies on vector-based geospatial data, it is scalable, allowing it to be used at a coarse scale over large areas or to provide very high resolution HRUs based on study objectives. We derived 100 m elevation bands using the 25 m resolution Canadian Digital Elevation Data digital elevation model (CDEM; 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 and was binned into three groups to represent steep south-facing, steep north-facing, and low-angle (or east–west) slopes. Watersheds were delineated based on hydrometric stations and/or sub-basin outlets, using routines in the R "whitebox" package (Lindsay, 2016) and a workflow adapted from the "CSHShydRology" R package (Shook et al., 2022).

Land cover was obtained from Baseline Thematic Mapping (BTM) Present Land Use, Version 1 (FLNRORD, 2011). Land cover was aggregated into the following classes: Agriculture, Alpine, Shrub, Burn, Disturbed Forest, Young Forest, Mature Forest, Lake, Wetlands, Developed. Roads were not considered in the delineation of HRUs due to their small spatial footprint within the watershed. Mature Forest was divided into the two prevalent biogeoclimatic (BEC) zones in the region—Interior Cedar Hemlock (ICH) and Engelmann Spruce Subalpine Fir (ESSF)—to allow for adjustment of snow interception and shading associated with different forest species. Finally, historical vegetation disturbance was accounted for using the Government of British Columbia's Fire Perimeter and Consolidated Cutblocks data layers, accessed, along with BTM, through the "bcdata" R package (Teucher et al., 2021). Areas within 25 years of the disturbance date were classified as Disturbed Forest while forest more than 25 but less than 50 years since disturbance were classified as Young Forest.

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Model parameterization, calibration, and validation

Model parameters were calibrated in a stepwise manner following Chernos et al. (2017) and originally adapted from Stahl et al. (2008). Initial parameters were selected using published values from similar environments and/or judgement based on expected and physically realistic values. First, air temperature and precipitation lapse rates were calibrated to regional weather stations, then snowmelt parameters were adjusted to represent the timing and rate of snowmelt at regional snow pillows and snow survey sites. Finally, vegetation interception and soil routing parameters were calibrated to streamflow observations. Final calibrations were completed by a combination of manual methods and automated calibration. Automated calibration of model parameters that could not be independently constrained by weather and snowpack data (i.e., vegetation interception and soil water routing parameters) was undertaken using OSTRICH calibration software (Matott, 2017), using the Dynamically Dimensioned Search (DDS) algorithm to maximize the Nash-Sutcliffe Efficiency (NSE). Model parameters were calibrated to the most recent decade (2010–2019) using the Duhamel Creek and Deer Creek hydrometric stations. Model performance was verified over the remaining record (prior to 2010) for Duhamel and Deer creeks as well as the short available record (1988–1992) for Coffee Creek.

Given the large number of potential parameters, calibration of all model parameters is computationally intensive and inefficient. It also increases the likelihood of over-fitting the model and equifinality, the concept that many possible parameter combinations can lead to similar model performance, but poor or inaccurate process representation. To mitigate this, when possible, parameters are best constrained or assigned values through independent data sources (i.e., Seibert et al., 2019). This is possible for some meteorological parameters, such as lapse rates and snow melt rates, which can be calibrated from weather stations and snow pillows/surveys from regional monitoring networks. In addition, in this model, leaf area index was constrained using remotely sensed products for land cover types in the model. Leaf area index (LAI300) was obtained from Copernicus Global Land Service for 2019-07-31 (Summer) and 2019-03-10 (Winter) and extracted for each HRU (Fuster et al., 2020). These values were then grouped by land cover class to constrain LAI by land cover type. This method gives a range of potential values as well as the relative differences between types, allowing for a more efficient calibration and/or imposing values in cases when the parameter is relatively insensitive to calibration.

Model parameterization

Model parameterization relied on a combination of calibration using independent weather, remotely sensed products, and snowpack data as well as a conceptual understanding of the dynamics of vegetation regrowth. A comprehensive list of model parameters is provided in Table 5. Notable parameter values include that snow in Mature Forest is assumed to melt at a slower rate than open areas (0.70 in ICH, 0.75 in ESSF), while this difference is less pronounced in Young Forest (0.85). Likewise, forest cover fractions are higher in Mature Forest, relative to Young and Disturbed Forest. Leaf area index (LAI) values extracted from remotely sensed imagery found that values are similar between mature forest classes, with slightly higher LAI in ICH forests relative to ESSF forests. Leaf area index in Disturbed Forest and Young Forest varies seasonally with winter values measuring 50 percent less than summer values, reflecting that much of recently disturbed forests consist of deciduous shrubs. This dynamic is corroborated by the LAI values extracted from remotely sensed imagery for various land cover types in the region.

Table 3. Parameters description and values used in the regional hydrological model applied in this study.

Process	**Description**	**Parameter**	**Value**	**Units**
Orographic corrections	Adiabatic lapse rate	Alapse	7.5	ºC/km
	Precipitation lapse rate	Plapse	6	mm/day/km
Rain-snow partitioning	Transition temperature	Snw1	1	ºC
	Mixed-range	Snw2	2	ºC
Snowmelt	Global snowmelt factor	K_factor	2.75	mm/ ºC /day
	Mature forest correction (ICH)	Forest_corr	0.70	fraction
	Mature forest correction (ESSF)	Forest_corr	0.75	fraction

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Table 3. (continued)

Process	Description	Parameter	Value	Units
Snowmelt	Young forest correction	Leaf_corr	0.85	fraction
	Aspect/slope correction	Acor	0.2	fraction
	Minimum melt (winter)	Min_melt	0	mm/ °C/day
	Refreeze factor	Refreeze	2	mm/ °C/day
Leaf Area Index*	Disturbed forest (summer)	Cut_LAI	4.0	unitless
	Disturbed forest (winter)	Cut_LAI	2.0	unitless
	Young forest	ForestY_LAI	4.5	unitless
	Mature forest (ICH)	Forest_LAI	4.5	unitless
	Mature forest (ESSF)	Forest_LAI	4.0	unitless
Vegetation/ canopy coverage	Disturbed forest	Cut_Cov	0.50	fraction
	Young forest	ForestY_Cov	0.60	fraction
	Mature forest (ICH)	Forest_Cov	0.85	fraction
	Mature forest (ESSF)	Decid_Cov	0.75	fraction
Infiltration	HBV beta	^HBV_B0	0.05	unitless
Percolation	Surface soil	^Perc0	4	mm/day
	Soil layer 1	^Perc1	4	mm/day
Capillary rise	Surface soil	^Cap0	4	mm/day
Baseflow	Soil 1 K	^Base_K1	0.05	unitless
	Soil 1 N	^Base_N1	1.12	unitless
	Soil 2 N	^Base_N2	1.12	unitless
	Soil 2 max rate	^Base_MAX2	7	mm/day

Notes: *Indicates maximum annual LAI value; Shrub/Wetland, Disturbed Forest, and Grassland values vary seasonally with lower values during the winter. ^ Indicates parameter was included in automatic calibration.

Land cover scenarios

To demonstrate the hydrological modelling workflow, land cover disturbance scenarios were investigated in Little Cayuse Creek. In total, four land cover configurations were run (Figure 3):

- **Baseline (2000)**: A land cover configuration as of the year 2000, where 15 percent of the forest has been disturbed. This scenario is treated as the baseline forest condition against which to measure hydrologic change.
- **Current**: A land cover configuration as of the year 2020, where 8 percent of the forest has been disturbed. This scenario was selected to provide additional context on recent forest disturbance and regrowth.
- **Scenario A**: A conceptual land cover scenario where approximately 25 percent of the watershed is disturbed, concentrated in the lower elevations of the watershed.
- **Scenario B**: A conceptual land cover scenario where approximately 25 percent of the watershed is disturbed, concentrated in the higher elevations of the watershed.

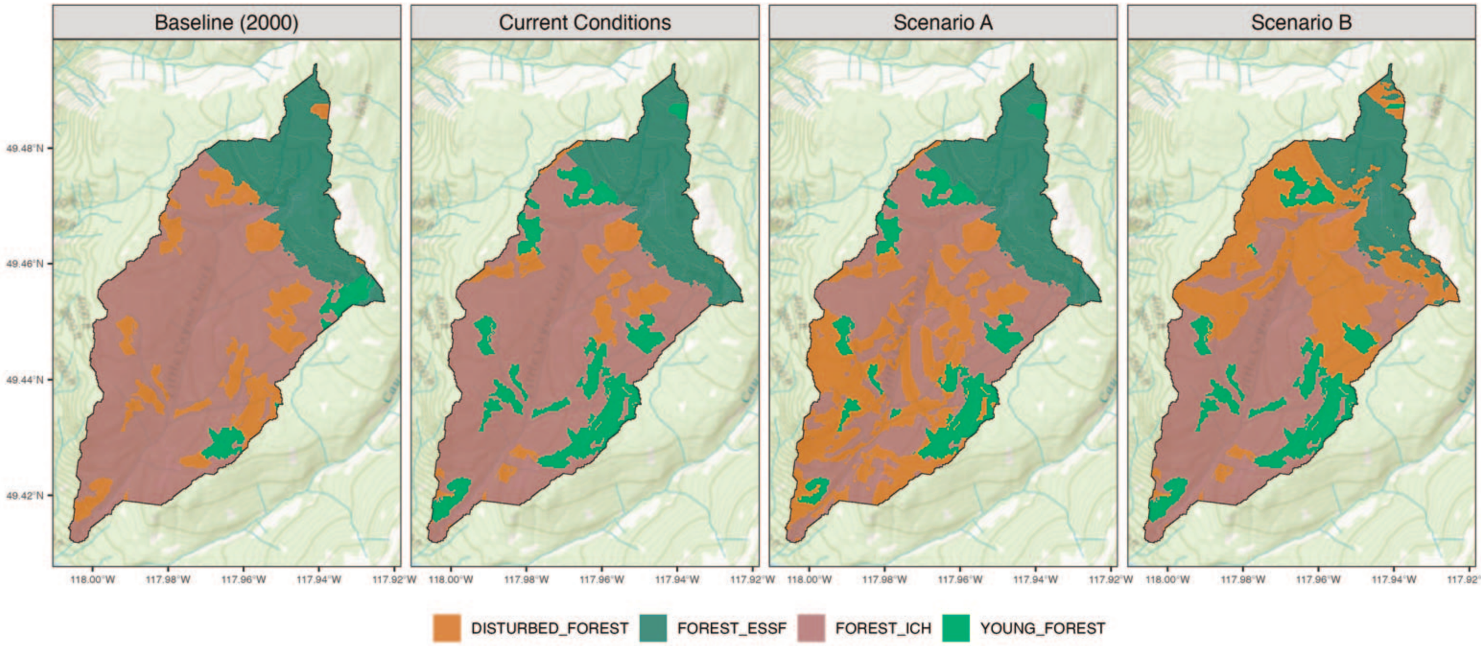

Figure 3. Land cover for all scenarios considered in this study.

Scenarios A and B represent relatively severe forest disturbance scenarios that are unlikely to occur through forest harvest but could occur as a result of wildfire. In this study, the scenarios were selected to provide a conceptual assessment of sensitivity to land cover change. In all cases, disturbed forest represents clearcut or fully open blocks.

Hydrologic indicators

To investigate the watershed hydrological response for land cover and climate scenarios, several hydrologic indicators were selected that affect important ecological, environmental, and/or economic functions. These indicators were all calculated annually and averaged over a 30-year period (1991–2020, 2021–2050, 2051–2080):

- **Mean Annual Flow**: The average annual streamflow, representative of the volume of water passing through this point in a calendar year.
- **Aug.–Sept. Low Flow**: The average August–September streamflow, representative of the period following snowmelt, which has historically coincided with summer low flows and heightened risk of droughts, degraded water quality, and is a critical period for aquatic ecosystems.
- **2-year Peak Flow:** The median annual peak flow (annual exceedance probability of 50%). This peak flow is typically a bank-full streamflow and associated with maintaining sediment transport processes and channel morphology.
- **20-year Peak Flow:** The flood magnitude that has an annual exceedance probability of 5 percent. This hydrologic metric provides insight regarding the influence of land cover and climate disturbance on extreme floods that can harm property and human life.
- **Peak Flow Timing:** The average Julian day of peak daily streamflow in a calendar year, representative of the timing of spring snowmelt-driven runoff which is important to aquatic ecosystems.

The 2-year and 20-year return period flood magnitudes are estimated by fitting the 30-year time series of annual peak flow using a log-normal distribution in the "fitdistrplus" package in R (Delignette-Muller & Dutang, 2015).

Equivalent Clearcut Area calculation

The ECA for Little Cayuse Creek was estimated using the methods described in Winkler and Boon (2017). For each disturbed stand, ECA is calculated as ECA = $A \times (1 - HR)$, where A is the original cut-block or disturbed area (ha) and HR is hydrological recovery (fraction). A single ECA level (%) for the watershed is determined by summing the ECA-adjusted disturbed areas and dividing by the

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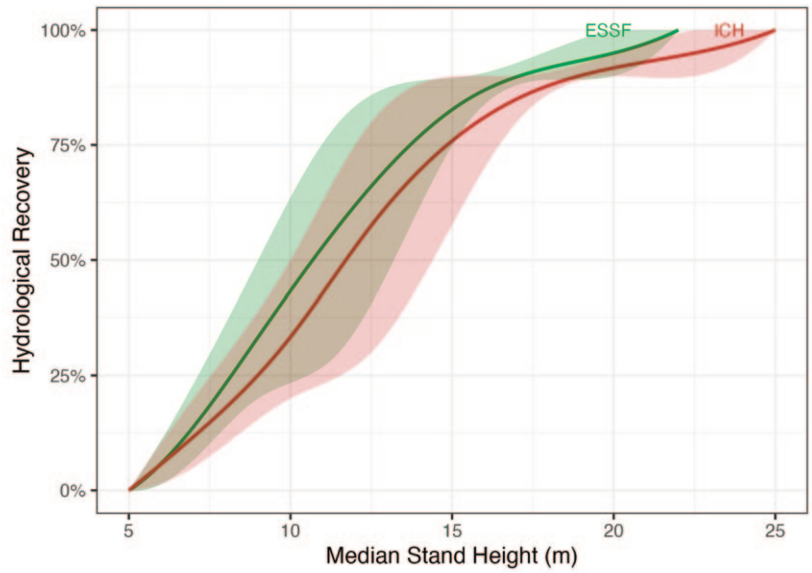

Figure 4. Hydrological recovery values applied to stands for each BEC zone in Little Cayuse Creek. Shaded areas correspond to corrections based on stand crown closure.

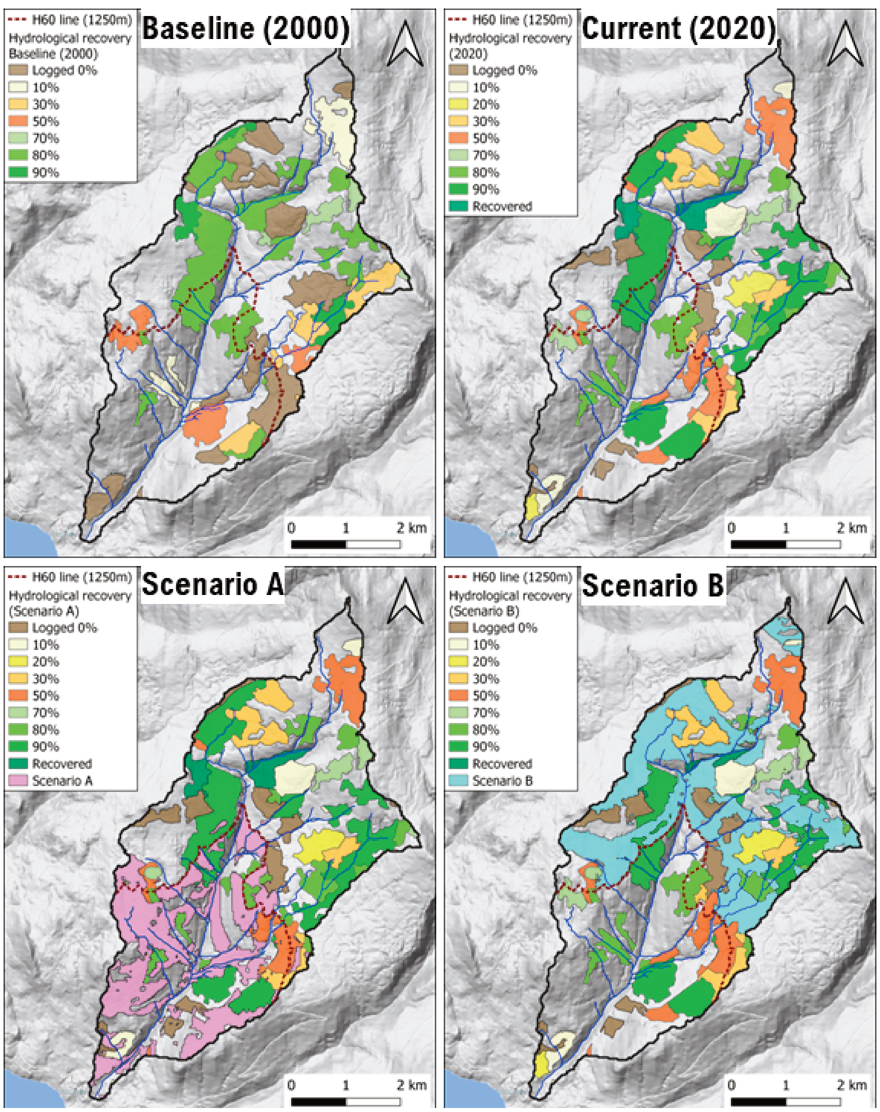

Figure 5. Graphical representation of hydrological recovery in Little Cayuse Creek for the land cover conditions investigated in this study.

total watershed area (Winkler & Boon, 2017). A 2018 LiDAR canopy height model (CHM) supplied by industry partner Interfor Corp. was used to assign the median tree height and crown cover percent for each 2021-Vegetation Resource Inventory (VRI) polygon (BCMoF, 2022b). The relationship between stand age and LiDAR-derived median tree height was assessed for forest stands within each biogeoclimatic subzone represented in Little Cayuse Creek and compared with a sample of stand characteristics identified from the LiDAR for nearby stands. This relationship was used to develop growth curves for juvenile and recovering stands in each Biogeoclimatic Ecosystem Classification (BEC) zone (BCMoF, 2021). The resulting growth curves were used to project the original 2018 LiDAR heights to current conditions, as well as to estimate (i.e., un-grow) baseline (2000) harvested stand conditions together with information on harvest date included in the VRI.

Projections of crown cover percent (%) have greater uncertainty than projected heights since the projection is dependent on the stem/restocking density in addition to tree maturity. Baseline (2000) crown cover (%) estimates are based on comparisons with similarly aged, nearby undisturbed stands identified in the 2018 LiDAR. Juvenile and recovering stands not included in the Results—Provincial Silviculture (BCMoF, 2022a) or consolidated cutblocks datasets and without harvest dates recorded in the VRI database were identified through visual inspection of recent satellite imagery, VRI reported stand ages, and LiDAR tree heights.

Hydrological recovery percent (%) (calculated as 100 – ECA%) was applied to each disturbed polygon to account for recovery of the juvenile forest stands based on median stand height and canopy cover (%) according to the recovery curve presented in Winkler and Boon (2015). The Winkler and Boon curve, which was developed for Thompson–Okanagan stands, was adjusted to the forest stands in the study region using the mature stand median height and canopy cover percent characteristics. The resulting recovery curves apply to stands in the Interior Cedar Hemlock (ICH) BEC zone, and the Engelmann Spruce Subalpine Fir (ESSF) zones (BCMoF, 2021). Hydrological recovery is adjusted upwards (downwards) by up to 20 percent for stands with crown closure values higher (lower) than the median canopy closure value for stands of a given height. This adjustment is represented as the shaded area bounding the recovery curves in Figure 4. The resulting hydrological recovery values applied to stands in Little Cayuse Creek is shown graphically in Figure 5.

Results

Equivalent Clearcut Area analysis

The outcomes of the ECA analysis for Little Cayuse Creek are presented in Table 4 for the entire watershed (2608 ha) as well as only areas above the H60 elevation (1250 m asl; 1567 ha). The analysis indicates the baseline (2000) condition represents an ECA of 621 ha or 24 percent, with most of this ECA (427 ha) located above the H60 elevation. For Current Conditions, the ECA is estimated at 19 percent, with 363 ha of the ECA situated above the H60 elevation. The Current Condition ECA is lower than the baseline (2000) ECA because of the limited development (131 ha) in the watershed between the two periods and the amount of regrowth in the previously harvested stands that is accounted for with increased amounts of hydrological recovery. The two scenarios (A and B) result in ECAs of 38 percent and 41 percent, respectively. In Scenario A, most of the additional disturbance is situated below the H60 elevation, while in Scenario B, all but 124 hectares of the ECA is situated above the H60 elevation.

Table 4. Equivalent Clearcut Area (ECA) with applied recovery for all land cover scenarios considered in this study.

	Baseline (2000)		Current Conditions		Scenario A		Scenario B	
	Little Cayuse	above 1250m H60	Little Cayuse	above 1250m H60	Little Cayuse	above 1250m H60	Little Cayuse	above 1250m H60
ECA (ha)	621	427	485	363	989	408	1075	951
ECA (%)	24	27	19	23	38	26	41	61

Regional model performance

Simulated daily maximum air temperature, total monthly precipitation, and daily snow water equivalent (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 may not be fully independent since some are likely inputs into the Daymet grid (Thornton et al., 2020) used in this study. Daily total SWE was well simulated at Redfish Creek snow pillow (r^2 = 0.94, percent bias [PBIAS] = -16%).

Streamflow simulations demonstrated strong performance in reproducing observations from the Duhamel and Deer WSC hydrometric stations (Figure 6). Performance was similar between the calibration period (2010–2019) and validation period (1988–2009). Nash-Sutcliffe Efficiency (NSE of 1 indicates a perfect simulation) was between 0.72 and 0.84 at all hydrometric gauges (Table 5). Overall, the model displays minimal bias between simulated and observed streamflow, with a small positive bias (i.e., over-simulation) at Deer Creek and a negative bias at Duhamel Creek and Coffee Creek. Performance was more modest for peak flows, with r^2 values of 0.27 at Deer Creek and 0.50 at Duhamel Creek and underestimates (PBIAS) of approximately 30 percent at both sites.

Table 5. Hydrological model performance statistics for calibration and validation periods.

Site	Period	NSE	PBIAS
Coffee Creek near Ainsworth	Validation	0.79	-12%
Deer Creek at Deer Park	Calibration	0.80	13%
Deer Creek at Deer Park	Validation	0.72	5%
Duhamel Creek above diversions	Calibration	0.84	-19%
Duhamel Creek above diversions	Validation	0.79	-21%

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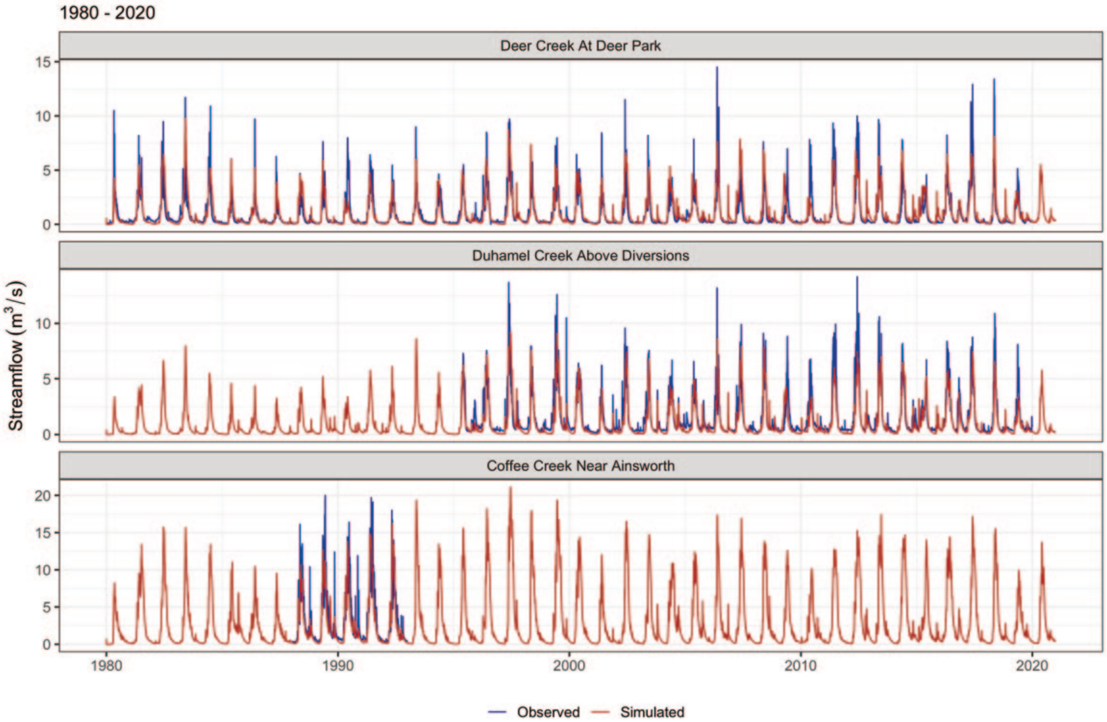

Figure 6. Daily hydrographs for three regional hydrometric stations used to calibrate and verify model performance.

Little Cayuse Creek hydroclimatic conditions

Spatially, hydroclimatic conditions follow a steep elevational gradient. Runoff in Little Cayuse Creek was substantially greater at higher elevations, with some subalpine areas approaching 1000 mm of runoff annually (Figure 7). Conversely, lower elevations, south aspect slopes, and valley bottoms were estimated to produce less than 100 mm/year on average. This dynamic reflects the relatively steep precipitation gradient in the region, where upper elevations receive substantially more precipitation (estimated at 6.0 mm/day/km in the model) and greater evapotranspiration at lower elevations due to warmer air temperatures. In addition, higher annual runoff occurs in areas of recent forest disturbance, most notably in cut blocks along the south face of Little Cayuse Creek.

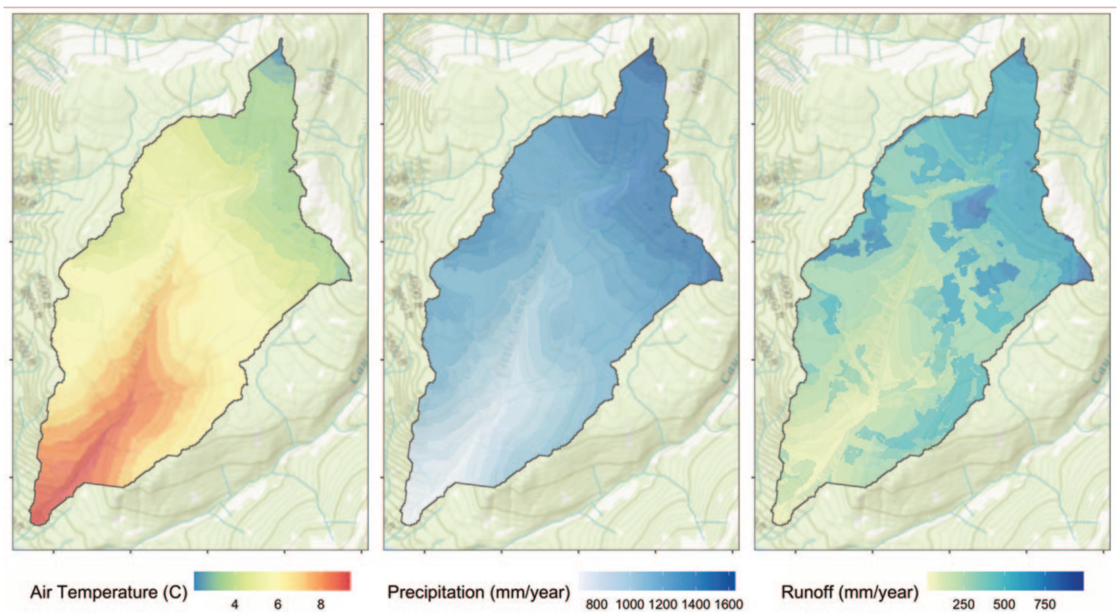

Figure 7. Average annual air temperature, precipitation, and runoff in Little Cayuse Creek over the 1990–2019 historical period, under the current conditions land cover scenario.

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Scenario analysis

Streamflow in Little Cayuse Creek follows a nival (snowmelt-driven) pattern, with flows increasing in April, peaking in late May and early June, and decreasing into the summer, with only small increases in the late summer and fall flow coinciding with larger rainfall events (Figure 8). Low flows persist throughout the winter months. Under the land cover scenarios, increases in simulated streamflow coincide with increased levels of forest disturbance. Hydrologic effects are most notable during freshet; an earlier onset of freshet and higher peak flows under the two harvest scenarios relative to baseline (2000) and current conditions. Under the future climate change scenarios, the hydrograph maintains a strongly nival pattern, but with increased variability, particularly in the 2051–2080 period. In addition, spring freshet tends to occur earlier in the season under both future scenarios, and subsequently low flows occur earlier in the summer.

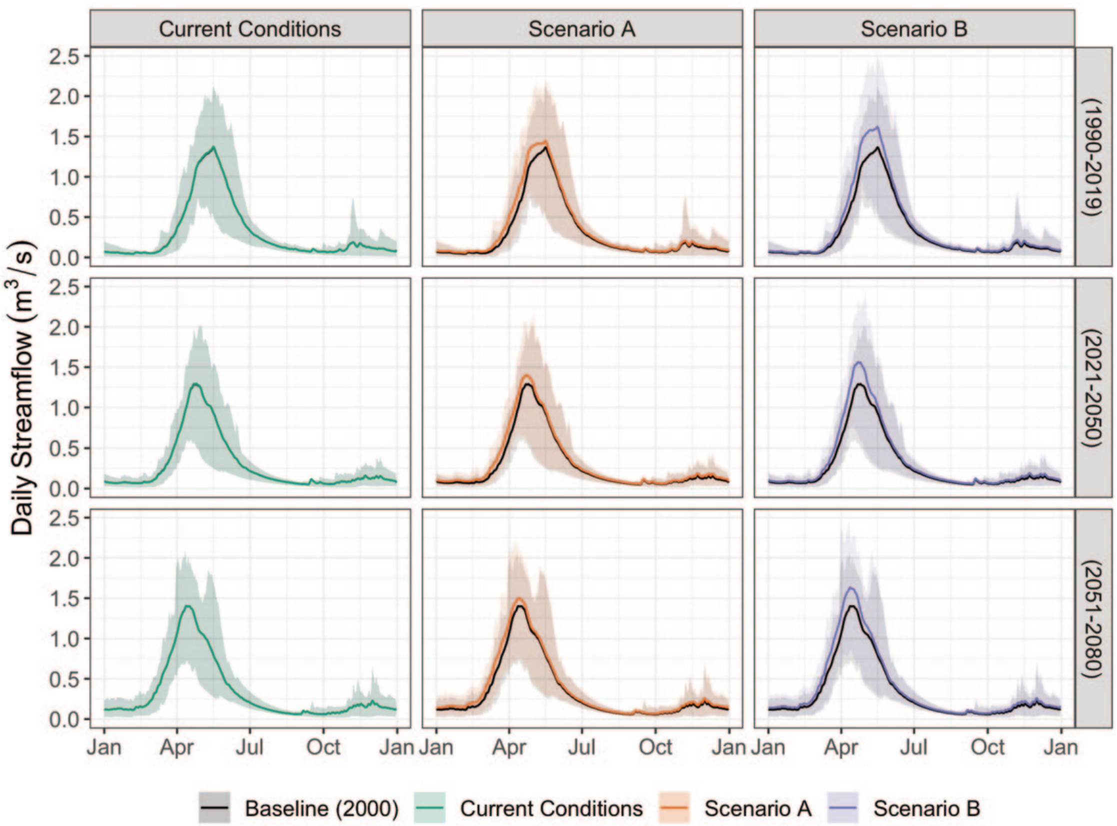

Figure 8. Mean daily streamflow in Little Cayuse Creek under all land cover scenarios and historical and future periods.

Notes: The solid line corresponds to the mean daily streamflow, while the shaded areas correspond to the 10–90% quantiles. Baseline (2000) and Current Conditions average hydrographs are nearly identical resulting in overlap of the two hydrographs; however, differences are apparent between the hydrographs in Scenarios A (low elevation harvest) and B (high elevation harvest).

Hydrologic indicators were derived from daily simulated streamflow for Little Cayuse Creek and are summarized in a hydrologic change summary table. For illustrative purposes, values are colour-coded to flag the relative magnitude of change ranging from 0 to 5 percent, >5 to 10 percent, >10 to 20 percent, and >20 percent for each indicator (Table 6). Little Cayuse Creek displays negligible (i.e., <5%) differences in all hydrologic indicators between baseline (2000) and current conditions. Conversely, under Scenario A and Scenario B, more substantial increases in streamflow were simulated as well as a marginally earlier freshet (0.9 and 2.5 days). Changes in all hydrologic indicators were greater under Scenario B (high elevation forest disturbance), most notably a 22 percent increase in the 2-year Peak Flow versus a 7 percent increase under Scenario A, and a 16 percent increase in the 20-year Peak Flow versus a 5 percent increase under Scenario A.

In Little Cayuse Creek, the changes in hydrologic indicators due to the climate change scenario were, for the most part, greater than those due to the land cover scenarios. Relative to the historical (1990–2019)

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Table 6. Hydrologic change summary table for Little Cayuse Creek, showing change in hydrologic indicators for Current Conditions and Scenarios A (low elevation harvest) and B (high elevation harvest) relative to the Baseline (2000) land cover and current 1990–2019 climate period.

Little Cayuse Creek Near Deer Park

Land Cover Scenario	Mean Annual Flow	Aug-Sept Low Flow	2-year Peak Flow	20-year Peak Flow	Peak Flow Timing
1990-2019					
Current Conditions	−0%	−0%	1%	1%	0.0 days
Scenario A	13%	9%	7%	5%	-0.9 days
Scenario B	18%	12%	22%	16%	-2.5 days
2021-2050					
Baseline (2000)	−7%	−25%	−13%	6%	-14.9 days
Current Conditions	−7%	−25%	−13%	6%	-14.9 days
Scenario A	5%	−18%	−7%	10%	-17.0 days
Scenario B	10%	−14%	5%	19%	-18.0 days
2051-2080					
Baseline (2000)	9%	−25%	−3%	1%	-16.2 days
Current Conditions	9%	−26%	−2%	1%	-16.3 days
Scenario A	22%	−19%	3%	4%	-19.2 days
Scenario B	27%	−16%	13%	12%	-19.2 days

Note: Colour coded thresholds of change (i.e., 5%, 10%, etc.) are for illustrative purposes only and not based on the actual potential for a negative response.

period, the Baseline (2000) land cover scenario results in a decrease of 7 percent in Mean Annual Flow over the short-term climate projections (2021–2050) but an increase of 9 percent over the long-term (2051–2080). Under both future periods, peak flows were projected to occur on average 15 to 16 days earlier in the spring. Aug.–Sept. Low Flow was projected to decrease by 25 percent under both future periods. The 2-year Peak Flow was projected to decrease by 13 percent in the 2021 to 2050 period and by 3 percent over the latter half of the century. Conversely, the 20-year Peak Flow was projected to increase by 6 percent over the near term, with negligible changes in the 2051–2080 period relative to 1990–2019.

The cumulative effects of land cover and climate change displayed some offsetting changes, as well as some additive effects. Overall, the simulated increases in Mean Annual Flow and 2-year Peak Flow due to the harvest scenarios (scenarios A and B) were offset in part by climate change driven decreases. The offsetting effects of high elevation harvesting did not extend to the 20-year Peak Flow, which displayed the largest increases for high elevation harvest in Scenario B. This increase reflects the additive effects of higher precipitation during the spring freshet, particularly for the 2021–2050 period, as well as forest disturbance leading to decreased interception of both the snowpack and a more rapid spring snowmelt. The decrease in peak snowpack projected in the long-term (2051–2080) has a dampening influence on the 20-year Peak Flow response for that period. For both the short- and long-term time periods, the advance in the Peak Flow Timing is exacerbated by increased levels of forest disturbance.

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Discussion

ECA assessment

The ECA-based assessment is limited to the estimation of the percentage of the watershed acting as a clear cut. In Little Cayuse Creek, the Current Conditions ECA is lower than Baseline (2000) ECA, suggesting that relative to the Baseline (2000) period, the effect of forest disturbance on streamflow response may have decreased over the past 20 years. Scenarios A and B both result in substantially increased ECA levels, with Scenario B representing a slightly higher total ECA but a much higher ECA above the H60 elevation compared with Scenario A. Using the information from an ECA calculation to assess the change in likelihood of a harmful event requires the use of a qualitative assessment method. One such method modified from Wise et al. (2004) assigns a rating based on the qualitative likelihood of a harmful event occurring, ranging from negligible (no change in likelihood is expected) to very high (a change in likelihood is certain to occur).

In Little Cayuse Creek, the assessment of the change in likelihood of a harmful event (e.g., the 20-year Peak Flow) for a land cover scenario relative to baseline (2000) may be guided by the outcomes of published studies in nearby watersheds such as Redfish Creek (Schnorbus & Alila, 2004) or Upper Penticton (241) Creek (Kuraś et al., 2012). These studies indicate that harvest levels of around 20 percent have a small but insignificant effect on larger-than-average peak flows but higher levels of harvest or harvest at upper elevations can have much larger impacts on changes in the magnitude and frequency of peak flows. However, since no perfect proxy watershed is likely to be exist, further consideration is required to determine how Little Cayuse Creek streamflow response may differ from that of Redfish Creek or 241 Creek due to its differences in physical and hydroclimate characteristics. Little Cayuse Creek is roughly the same size as Redfish Creek but contains less alpine area. Likewise, Little Cayuse Creek shares similarities in aspect distribution, elevation, and slope gradient with 241 Creek, but is an order of magnitude larger and lacks the lodgepole pine stands that cover much of 241 Creek. In cases where the physical characteristics of the watershed are substantially different than those investigated in published studies, the qualitative assessment of the change in likelihood of a harmful event becomes even more subjective as it requires the assessor to weigh the differences in relevant hydrologic processes between the watersheds to determine the qualitative likelihood.

When watershed process understanding is absent, the assessment of likelihood may be assigned solely by ECA thresholds (e.g., Low < 25%, Moderate > 25% to < 35%, and High > 35% ECA) or ECA thresholds by elevation band (e.g., ECA thresholds for below H80, between H80 and H40, and above H40), and may be combined with other assigned thresholds based on geospatially determined proxy indicators such as road density, stream crossings, and amount of riparian area disturbed. In this proxy-based approach, the qualitative assessment of likelihood in change of a harmful event becomes strictly a GIS-based analysis with no watershed specific knowledge and all watersheds are assumed to respond in a similar way to a given level of disturbance.

In all cases, the qualitative assessment of likelihood does not provide the forest manager with information on the specific change in the frequency or magnitude of a harmful event for a current or proposed forest disturbance relative to a baseline forest condition. Further challenges exist when the assessment of likelihood must incorporate the combined effects of land cover and climate change (ABCFP & EGBC, 2020). Without a clear process understanding of the hydroclimatic conditions in a watershed that trigger a harmful event and a structured process-based approach to weighing the projected changes in land cover and climate, the estimate of hydrologic response is speculative.

Hydrological modelling assessment

Unlike an ECA-based assessment, the presented hydrological modelling workflow provides the assessor with quantitative estimates of hydrologic indicators for individual scenarios. Since the model incorporates land cover and climate, scenarios can be developed to evaluate the isolated and cumulative impacts of these components. In addition, it allows the assessor to evaluate individual components of streamflow, which is necessary to link changes in land cover and climate to a specific harmful event of concern in the area of interest. Finally, hydrologic indicators can be compared against a baseline condition, ultimately providing the assessor with a quantitative measure of change that is necessary for risk-based management decision making.

The hydrological model identifies what negligible hydrologic changes have occurred between Baseline (2000) and current conditions in Little Cayuse Creek. However, substantial hydrologic changes are

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projected under Scenarios A and B. Notably, both scenarios increase the magnitude of peak flow events as well as earlier freshet. Importantly, although the model identifies that Scenario B presents more change in hydrologic indicators relative to Scenario A, it also reveals that the changes to some of the indicators including Aug.–Sept. Low Flows associated with Scenario A are not negligible. If the value of concern in the risk analysis is low flows for agricultural purposes, this knowledge may require the forest planner to redesign a proposed block lay-out to minimize this response. Additionally, the model identifies a substantial change in the timing to an earlier freshet and subsequently reduced summer flows under all future climate scenarios. The magnitude of change in the hydrological indicators associated with climate change is greater than what could be offset under the forest disturbance scenarios. This information allows forest planners to explore best forest management scenarios under a changing climate to reduce the potential for long-term impacts to water resources and aquatic habitat under projected climate change.

Changes in the 2-year and 20-year Peak Flow hydrologic indicators are reported as a percent change in magnitude. To satisfy the requirements of the risk management framework, hydrologic indicators can also be reported in terms of the change in the annual exceedance probability (i.e., inverse of the return period) allowing direct input to the risk management framework. Additionally, the probability density function or cumulative frequency distribution of the annual flood frequency curve can be developed as an output to the model which allows for a more comprehensive understanding of how the full distribution of the annual maximum peak flow regime of the watershed is likely to change.

The model outputs emphasize that the cumulative effects of land cover and climate change on hydrological indicators are not straightforward and are influenced by the location of the disturbance in the watershed as well as changing hydroclimatic conditions. In some cases, hydrometric indicator response is mitigated by climate change (e.g., 2-year Peak Flow change for Scenario B) while for other indicators the change is amplified relative to current climate conditions (e.g., Peak Flow Timing). The complex interactions between changes in land cover and climate, as well as their varying response depending on location, highlights the importance of a process-based hydrological modelling workflow that can accurately simulate these processes directly to provide quantitative estimates of change.

The absence of a comprehensive understanding of watershed response for selected hydrological indicators makes the assessment of likelihood of change in an indicator using the ECA-based approach difficult. Additionally, even with the consideration of the outcomes of published studies in nearby catchments, the information from an ECA-based assessment does not allow for an accurate assessment of the potential for change in an indicator such as Aug.–Sept. Low Flows or Day of Peak. Nor is it possible to accurately assess for differences in outcomes between multiple forest disturbance scenarios.

Process understanding

In addition to providing quantitative inputs to a more robust risk-based framework, another advantage of this workflow is that it provides the assessor with a heuristic tool to better understand the hydrologic regime of the watershed of interest and provide context on the projected hydroclimatic changes between scenarios. For instance, the two land cover scenarios evaluated in Little Cayuse Creek are conceptual demonstrations of the effect of a relatively large level of disturbance that is concentrated at high or low elevations. Simulated model outputs demonstrate that forest disturbance at higher elevations in Little Cayuse Creek leads to a disproportionately greater change in hydrologic indicators. This dynamic is driven by a steep precipitation gradient in the watershed, where the removal of forest canopy at higher elevations leads to greater snow accumulation and subsequently a more sustained spring freshet.

The greatest changes in hydrologic indicators due to climate change in Little Cayuse Creek are related to streamflow timing and late-summer streamflow. This climate change analysis highlights that with warming air temperatures, the winter snowpack begins melting earlier in the spring. This earlier melt onset subsequently leads to an earlier freshet, captured in the Peak Flow Timing hydrologic indicator. This change has implications later in the summer, since the winter snowpack is depleted earlier in the summer, late summer flows show substantial decreases, which could have profound impacts on aquatic habitat in the watershed.

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While the 2-year Peak Flow is projected to decrease in the coming decades, the 20-year Peak Flow is projected to increase. This difference in response suggests that future conditions are likely to have a more variable peak flow regime. In most years, peak flows should be expected to be lower, due to warming air temperatures leading to a combination of more precipitation falling as rain, a lesser snowpack (particularly at lower elevations), and consequently a lower spring freshet. However, extreme peak flows become larger in the future; or conversely, high-magnitude peak flows are projected to occur more frequently. This dynamic reflects that climatic conditions in the future are likely to be more volatile and will increase the "tail-risk" of rapid spring snowmelt coinciding with higher rates of precipitation during the springtime, leading to severe flooding (i.e., Musselman et al., 2018). Furthermore, this may indicate more substantial shifts in the hydrologic regime, such as a transition to a more rainfall-dominated hydrograph.

Informing risk-based forest management

In a risk management framework, the decision to proceed with a proposed development, to initiate a higher level of assessment, or to revise a development plan will generally be guided by a set threshold of change in the likelihood of a harmful response/event occurring (e.g., ABCFP & EGBC, 2020). For example, if the harmful event is a flood that has the potential to damage private land (e.g., a 20-year flood), the threshold for deciding to proceed or to re-evaluate the development plan may be set at less than or equal to 5 percent increase in the annual likelihood of occurrence of a damaging flood.

Equivalent Clearcut Area-based assessments provide a single ECA value (or ECA values by elevation band), which is related to a qualitative likelihood of change in a hydrological indicator of concern. The outcomes of the ECA-based assessment can, at best, infer a possible magnitude of change based on nearby published studies of forests effects on streamflow response. Predicting how hydrological indicators will respond to projected climate change becomes highly speculative in the absence of a process-based investigation. By comparison, a hydrological model that is grounded in reliable process representation, incorporates land cover and climate, and is regionally calibrated can be used as a tool to assess the quantitative hydrologic impact of changes in land cover and climate on a watershed of interest. In addition, model outputs provide a heuristic tool to understand changes in hydrologic processes and can be used to identify which areas can have disproportionate impacts on hydrologic indicators of concern to minimize forest development related disturbance in these more hydrologically sensitive areas. Information on changes in hydrological indicators, identified as a potentially harmful hydrological response, can be used by forest managers in a risk decision framework to guide forest management decisions.

Due to changing climatic conditions in the region, and across the globe, forest managers must be able to plan under future hydroclimatic conditions. With continued warming air temperatures and changing precipitation patterns and timing, the location and relative sensitivity of areas within a watershed, including the most sensitive elevation zones, should be expected to change. For instance, with warmer air temperatures, higher elevation areas are likely to experience earlier spring snowmelt, while low-elevation areas may accumulate less winter snowpack (Musselman et al., 2017; Marshall et al., 2019). Both factors are likely to alter the spatial pattern of hydrologic sensitivity and should be incorporated into future forest management plans.

Currently there are few studies undertaken in forested snowmelt regions to investigate the potential cumulative effects of climate change and land cover disturbance on watershed response (Giles-Hansen et al., 2019; Rasouli et al., 2019; Chernos et al., 2022; Goodbrand et al., 2022). The projected changes to hydrological indicators observed in this study are generally consistent with existing study outcomes as well as other model and empirical-based studies that have investigated changes in runoff alone (Milly & Dunne, 2020). An advantage of using a process-based hydrological model to evaluate these changes is that it accounts for watershed-scale differences in physical characteristics across a region of interest. For example, high elevation (and/or higher relief) watersheds may have a more predictable spring runoff period, whereas low elevation watersheds may exhibit a more variable summer runoff pattern driven by rainfall events. The spatial pattern of hydrologic sensitivity is likely to vary between watersheds, as will the expected change in response due to climate change. Equivalent clearcut area-based assessments, which lack a consideration of these watershed-specific characteristics and how they are expected to change in the coming decades, are prone to mis-evaluating the hydrologic effects of forest disturbance on the watershed of interest.

Limitations and future work

The magnitude and direction of alteration of hydrologic indicators predicted by the south Selkirk model are generally consistent with those identified in published scientific studies (Winkler et al., 2010; Moore & Scott, 2005), including the 2-year Peak Flow and 20-year Peak Flow (Winkler et al., 2015; Green & Alila, 2012; Schnorbus & Alila, 2004; Schnorbus & Alila, 2013). In addition, the influence of elevation and aspect distribution on mitigating or amplifying the hydrological response observed here is consistent with the conceptual understanding of these factors presented in Green and Alila (2012). Notably, the hydrological model predicts increases in flow during the late summer period in response to forest disturbance due to less rainfall interception and a higher winter snowpack leaving more soil water available as baseflow. Studies in watersheds in the Thompson-Okanagan region have found that in smaller watersheds, summer low flows decrease following harvest (Winkler et al., 2015) but this outcome is not consistent across studies (Winkler et al., 2010) and in some cases, is found to increase, while in other studies, is observed to decrease following harvest (Moore et al., 2020). This highlights the relative importance of local catchment-specific conditions such as the watershed's dependence on the winter snowpack, summer evapotranspiration rates, and vegetation regrowth, as well as scientific uncertainty in the underlying processes driving changes in low flow conditions in response to forest disturbance. Further work is required, both in modelling and in empirical studies, to better understand the importance and interaction of these factors in driving streamflow during the late summer months, which could ultimately lead to better process-representation and model parameterization.

Improvements could be made to better model watershed response to extreme peak flow events, which are currently under-estimated and display modest performance in this version of the model. This includes two major factors: process-representation and data inputs. Notably, the hydrological model likely underestimates surface runoff and snowmelt during rain-on-snow (and frozen soil) events since it does not account for the energy input of warm rain nor the decreased infiltration rate of frozen soils. In addition, extreme precipitation events are notoriously difficult to capture in weather station data, due to the relatively coarse network of available observations, variable spatial patterns, and a higher probability of sensor failure during extreme events (i.e., McMillan et al., 2011). These factors tend to lead to underestimates in model forcing data, which, combined with model process-weaknesses during these extreme events, tend to lead to model underestimates of extreme high flows. Future work in improved model forcing data as well as better process representation of these key extreme event periods is needed to reduce uncertainty and better constrain risk, particularly considering how these factors may change in response to climate change.

The process of hydrological recovery of forest stands following harvest or disturbance (i.e., burn) is coarsely represented as three age classes: Disturbed, Young Forest, and Mature Forest. Further improvements could be made in terms of representing forest interception, shading, and evapotranspiration in several stages of a Young Forest (i.e., Early, Young, and Advanced Young). In addition, this level of model parameterization does not explicitly consider disturbance severity, particularly for fire disturbance, nor does it account for variable rates of recovery between BEC zones/elevation bands or the level or type of forest disturbance. Improving this representation in the hydrological model is possible, but requires additional data, both in terms of historical disturbance severity and recovery and model parameterization. Further work is required to better understand the changes in stand-level interception, snow accumulation, and melt in the years following disturbance. Future work incorporating new and emerging remotely sensed products (i.e., White et al., 2022; Francini et al., 2022) could better constrain model parameter values and constrain how they change in the years following disturbance.

To improve the utility of this tool, the authors recommend additional work to better consider the implications and assumptions inherent in the selection of a baseline condition. This study considered current conditions and a baseline (2000) land cover configuration. While these historical land cover configurations offer a snapshot at the level of disturbance in the region, this baseline is somewhat arbitrary. Regardless of the year chosen, the hydrologic response of individual sub-basins to land cover change is dependent on the history of forest disturbance, both natural and anthropogenic. In addition, even excluding anthropogenic disturbance (i.e., forest harvest), this range of natural variability in forest disturbance is itself dynamic, where changes in climatic conditions could impact the size, frequency, intensity, and/or seasonality of forest disturbances such as fires and pests (Erni et al., 2020;

Axelson et al., 2018). Finally, disturbance and/or climate change impacts could modify forest species composition and subsequently stand characteristics, which could prevent the watershed from ever returning to a baseline condition (Moore et al., 2016).

Decision making for forestry activities in watersheds using a risk-based approach requires forest managers to establish thresholds of tolerance of change for a potentially "harmful" hydrological response of concern (ABCFP & EGBC, 2020). These thresholds should be based on a defendable (i.e., scientific) understanding on what constitutes a harmful level of change to water quality/quantity and aquatic habitat values. In this study, changes in hydrologic indicators are binned as < 5 percent, <10 percent, <20 percent, >20 percent; however, the selection of these thresholds is arbitrary and only done for illustrative purposes. Further conceptual work is needed to link percent change in an indicator with known physical impacts to aquatic values. It is probable that harmful changes in one indicator are not the same as for other indicators. For instance, a 5 percent reduction in Mean Annual Flow may have less of an impact on water supplies and aquatic habitat than a 5 percent reduction in Aug.–Sept. Low Flow. Likewise, increases in the variability of a hydrologic indicator may be obscured by average conditions, but could be an important part of a risk-based approach.

Conclusions

The development and application of a regionally calibrated process-based hydrological modelling workflow presented here provides a more rigorous approach to estimate the potential for watershed hydrological response to forest disturbance than traditional methods of Equivalent Clearcut Area calculations. The modelling workflow explicitly accounts for the underlying hydrologic processes driving streamflow, incorporates climate and land cover, and has relatively modest data requirements. A regionally calibrated model is well suited for applications in data sparse environments, including un-gauged watersheds, where many forestry decisions are made in Western Canada. The workflow documented here provides a template for similar work in other environments and illustrates a novel method for assessing the cumulative effects of land cover and climate change at ungauged watersheds in a scientifically rigorous and quantitative manner.

Results from this study emphasize that in addition to the amount of forest disturbance, the location and elevation of the disturbance are important considerations to evaluating the potential amount of hydrologic alteration in a watershed. In addition, due to changing climatic conditions in the region and across the globe, forest managers must be able to plan under future hydroclimatic conditions. Model outputs provide a heuristic tool to understand changes in hydrologic processes and can be used to identify which areas can have disproportionate impacts on hydrologic indicators of concern to minimize forest development related disturbance in these more hydrologically sensitive areas. The strength of this tool to support forest management decisions lies in the ability of the model to replicate physical watershed processes and, in doing so, to provide accurate quantitative estimates of the likelihood for hydrological change, which can be integrated by into a risk management framework to guide forest management decisions.

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