A GIS Indicator-Based Protocol for Assessing Cumulative Watershed Effects: Procedures Adapted for the Kootenay Boundary Region

British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development – Kootenay Boundary Region

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Cover photo: Granby River north of Grand Forks, looking upstream (N. Neumann).

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This report is largely consistent with the protocol developed for the Thompson Okanagan Region, as reported by Lewis et al. (2016). The authors would like to express their appreciation for the support provided by staff in the Thompson Okanagan Region.

Version History:

Version	Authors	Date
1.0	Cassidy van Rensen, Natasha Neumann, Vicky Young	December 2020

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List of Acronyms

AU	Assessment unit
AW	Assessment watershed
BEC	Biogeoclimatic ecosystem classification
DDR	Drainage density ruggedness
DEM	Digital elevation model
DRA	B.C. Digital Roads Atlas
ECA	Equivalent clearcut area
FLNRORD	B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development
FSW	Fish Sensitive Watersheds
FTEN	B.C. Forest Tenures
FWA	B.C. Freshwater Atlas
KBR	Kootenay Boundary Region of FLNRORD
TRIM	Terrain Resource Information Management
TSA	Timber Supply Area
VRI	Vegetation Resource Inventory

1.0 Introduction

In the B.C. Cumulative Effects Framework (CEF), cumulative effects are defined as changes to "environmental, social and economic values caused by the combined effect of past, present and potential future human activities and natural processes". As resource extraction activities expand across the landscape (e.g. forestry, mining, agriculture and windpower) and the scale of natural disturbances increases (e.g. Mountain Pine Beetle outbreaks and wildfires), there is a need to assess the accumulated effects of these multiple activities so that they can be managed in a way that avoids negative consequences on the values that British Columbians hold dear. The assessment and management of these combined activities has led to implementation of the CEF in B.C.[1]

Changes in hydrologic, geomorphic and biological processes at the watershed scale due to natural and anthropogenic disturbance are referred to here as cumulative watershed effects, including changes to streamflow quantity and patterns, water quality, channel dynamics and riparian ecosystem functions. The downstream effects of these changes can impact aquatic habitat, public safety and infrastructure, or water supply and quality (Scherer 2011). As referred to in the definition of cumulative effects, the impacts can be environmental, social or economic.

Cumulative effects analysis by the Province of B.C. has adopted methods that use Geographic Information System (GIS) indicators to assess the potential impacts of natural and anthropogenic disturbance in a spatial way. GIS indicator-based approaches integrate research and field experience to identify characteristics of a watershed that are known to influence the hydrologic, geomorphic and biological processes of interest (e.g. the steepness of a watershed is known to influence how quickly precipitation makes its way to stream channels, and therefore is related to peak flow). Both the natural characteristics of watersheds and the types and extent of land cover and use are derived from GIS data and combined to estimate potential cumulative effects. The results can be used to inform a range of strategic-level planning activities, such as resource management (e.g. Water Sustainability Plans) and habitat restoration and conservation efforts (e.g. road rehabilitation projects).

The Kootenay Boundary Region Cumulative Effects Team has adopted the watershed assessment methods used in the Thompson Okanagan Region (described in the report "A GIS Indicator-Based Watershed Assessment Procedure for Assessing Cumulative Watershed Effects" by Lewis, Grainger and Milne 2016), adapted for the Kootenay Boundary region. The protocol is based on the framework presented by Carver (2001) and incorporates indicators and considerations described in other procedures (e.g. B.C. Ministry of Forests and B.C. Ministry of Environment 1999, Carver and Utzig 2000, Green 2005).

2.0 Assessment Approach

Risk is the product of hazard and consequence (**Risk = Hazard x Consequence**) (Wise et al. 2004, Canadian Standards Association 1997). This document describes the determination of hazards related to watershed processes, where a hazard is defined as the potential for human injury or damage to property, the environment or other things of value. Hazard ratings provide an estimate of the likelihood of a hazard occurring. The 5-class hazard rating scheme adopted here uses the qualitative terms *Very Low, Low, Moderate, High and Very High* to express the likelihood of a harmful event occurring (hazard) as a result of land use activities (Table 1). The 5-class rating scheme can be adapted to a 3-class rating scheme (*Low,*

[1] For more information on the BC CEF, visit https://www2.gov.bc.ca/gov/content?id=57D4625607564CED96C9C9EAF2E91ACA

Moderate, High) by combining *Very Low* and *Low* into a single *Low* rating, and *High* and *Very High* into a single *High* rating.

Table 1. *Terminology used to describe hazard ratings. Adapted from Carver (2001).*

Rating	Definition	Probability % of occurring
Very Low	highly unlikely	<10%
Low	unlikely	<33%
Moderate	may	33-66%
High	likely	>66%
Very High	very likely	>90%

Consequence refers to the "change, loss, or damage to a value(s) (e.g. human life, private or public property, water intakes, infrastructure, fish habitat, etc.) that may result from hazardous occurrences" (Lewis et al. 2016). Consequence ratings are not included in this cumulative watershed effects protocol because they are determined by how the hazard ratings will be used. For example, the hazard results may be used to assess the risk of scour in salmon spawning habitat at a specific location where flow above a certain threshold is known to remove gravels. Because (a) the number of combinations of hazards and consequences is immense, (b) the presence and vulnerability of downstream elements are quite dynamic, and (c) there is considerable variability in how things are valued, consequence ratings must be conducted on a case-by-case basis.

The following three hazards are the current focus of cumulative watershed effects analysis in the Kootenay Boundary Region:

1. **Streamflow Hazard** – increased frequency and magnitude of hydrogeomorphic events (floods, bank erosion, channel instability, debris floods and debris flows);
2. **Sedimentation Hazard** – reduced water quality and channel geomorphological effects as a result of sediment or other deleterious material input to streams from roads, landslides or other upslope sources, and the transport of these sediments by the stream or river system; and
3. **Riparian Function Hazard** - reduced channel bank stability, stream shading, nutrient cycling, habitat and inputs of large woody debris.

Note that the riparian hazard indicators are in development and riparian hazard will not be reported on until complete.

It is important to emphasize that while the GIS indicator-based results are useful for strategic-level planning decisions (e.g. at the scale of Timber Supply Areas and Resource Districts), they should not be used for operational decisions or to set management targets at the individual watershed level without field or expert verification as part of a multi-step process (Figure 1).

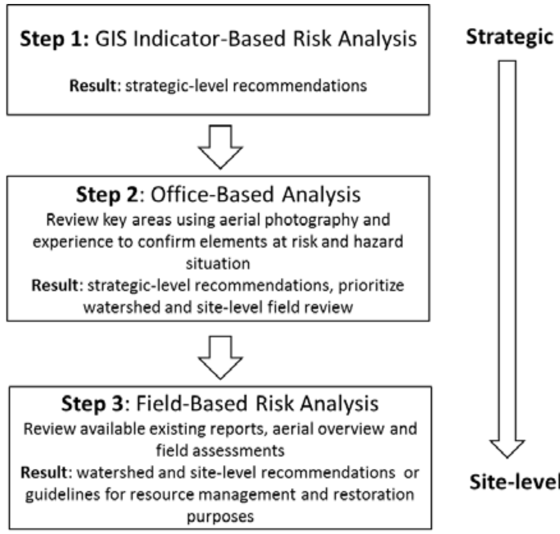

Figure 1. *Three step approach recommended for moving from strategic-level watershed risk analysis to site-level operational assessment and recommendations. From Lewis et al. (2016), adapted from Forsite Consultants Ltd. et al. (2012). From Lewis et al. 2016.*

2.1 Certainty and Confidence in Assessment Results

The selected indicators and how they are combined to determine hazard ratings were based on our best understanding of the effects of watershed characteristics and land use on hydrologic and geomorphic processes, which gives us confidence that the hazard rating results will be good first approximations of the effects of human and natural disturbances on peak flow and sedimentation processes. Because the same relationships are applied across a relatively wide range of conditions, some location-specific information or details can be lost; these may be best represented using hydrologic modeling approaches, which are outside the scope of this work. The GIS indicator-based approach, however, provides an efficient way to assess a large number of watersheds that span a wide geographic area.

This document is intended to provide transparency on the cumulative watershed effects analysis conducted by the Ministry of Forests, Lands, Natural Resource Operations and Rural Development by providing details on input data and how they are used to derive the hazard ratings, including the key assumptions used. This approach avoids the use of hidden, subjective ratings and relies on publicly available input data as much as possible so that the results can be duplicated by other groups, and so that methods can be improved as new information becomes available. Before results are used for operational applications, they should be validated by additional analysis, field work and/or expert knowledge where possible, and that information should then be fed back into the process to adjust indicators, scores and hazard ratings.

As the GIS indicators and ratings are described in the rest of this document, key sources of uncertainty will be described. All models of complex systems must simplify processes and relationships and therefore have inherent uncertainty. These include data errors and limitations, the generalization of relationships, assumptions made about representations and associations and uncertainties related to human behaviour (Table 2).

Table 2. A typology of uncertainties, sources, and considerations to reduce uncertainty. Adapted from IPCC (2005). From Lewis et al. (2016).

Type	Examples of sources	Considerations to reduce uncertainty
Unpredictability	Projections of human behaviours; chaotic components (e.g. natural disturbances) of complex systems	Use of scenarios spanning a plausible range; clear statements of assumptions; limits considered
Structural uncertainty	Inadequate model; lack of agreement on model structure; ambiguous system boundaries or definitions; significant processes wrongly specified or not considered	Specify assumptions and system definitions clearly; compare models with observations for a range of conditions; assess maturity of the underlying science and degree to which understanding is based on fundamental concepts tested in other areas
Value uncertainty	Missing, inaccurate or non-representative data; inappropriate spatial or temporal resolution; poorly known or changing model parameters	Analysis of statistical properties of sets of values (observations, model ensemble results, etc.); bootstrap and hierarchical statistical tests; comparison of models with observations

For each hazard rating and indicator used, a level of confidence is provided for some of the key elements along with a description of how that level was derived. Definitions of confidence developed for the Intergovernmental Panel on Climate Change vulnerability assessments have been adopted (Table 3).

Table 3. Terminology and descriptions of confidence used to assign confidence ratings (IPCC, 2005). From Lewis et al. (2016).

Terminology	Degree of confidence in being correct
Very High Confidence	At least 9 out of 10 chance of being correct
High Confidence	About 8 out of 10 chance
Moderate Confidence	About 5 out of 10
Low Confidence	About 2 out of 10
Very Low Confidence	Less than 1 out of 10 chance

2.2 Assessment Units

Assessment units are areas that range in spatial scale from major watersheds to smaller areas of interest defined using drainage patterns in the B.C. Freshwater Atlas Watershed Groups (FWA; https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-watershed-groups). A hierarchical grouping structure of watershed assessment units (AUs) was designed using FWA Assessment Watershed (AW) boundaries as the base units (Carver and Gray, 2010; https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-assessment-watersheds). AWs were grouped in a nested hierarchy following the FWA stream network to create larger AUs based on drainage patterns, and were named based on the number of AWs that were joined to create the AU.

The smallest AUs are base AWs that do not receive water from an adjacent AW, and are considered headwater basins. These are identified as Level 1 AUs (L1) since they only include one AW (Figure 2). From there, increasingly larger hydrologic groups were created by combining AUs with adjacent AWs or AUs that drain into each other or connect at a stream confluence (Figures 3). The AU grouping continued in this nested fashion until it represented the entire major watershed area of interest (Figure 3). This nesting allows results to be analyzed in a cumulative manner. Results can be evaluated at any scale, from the smallest L1 AU unit to the largest watershed, to help inform decision making across different scales. To use the results, a user first identifies the point of interest (e.g. a bridge or culvert that may be damaged by peak flow); the relevant AU will be the drainage area upstream of that point.

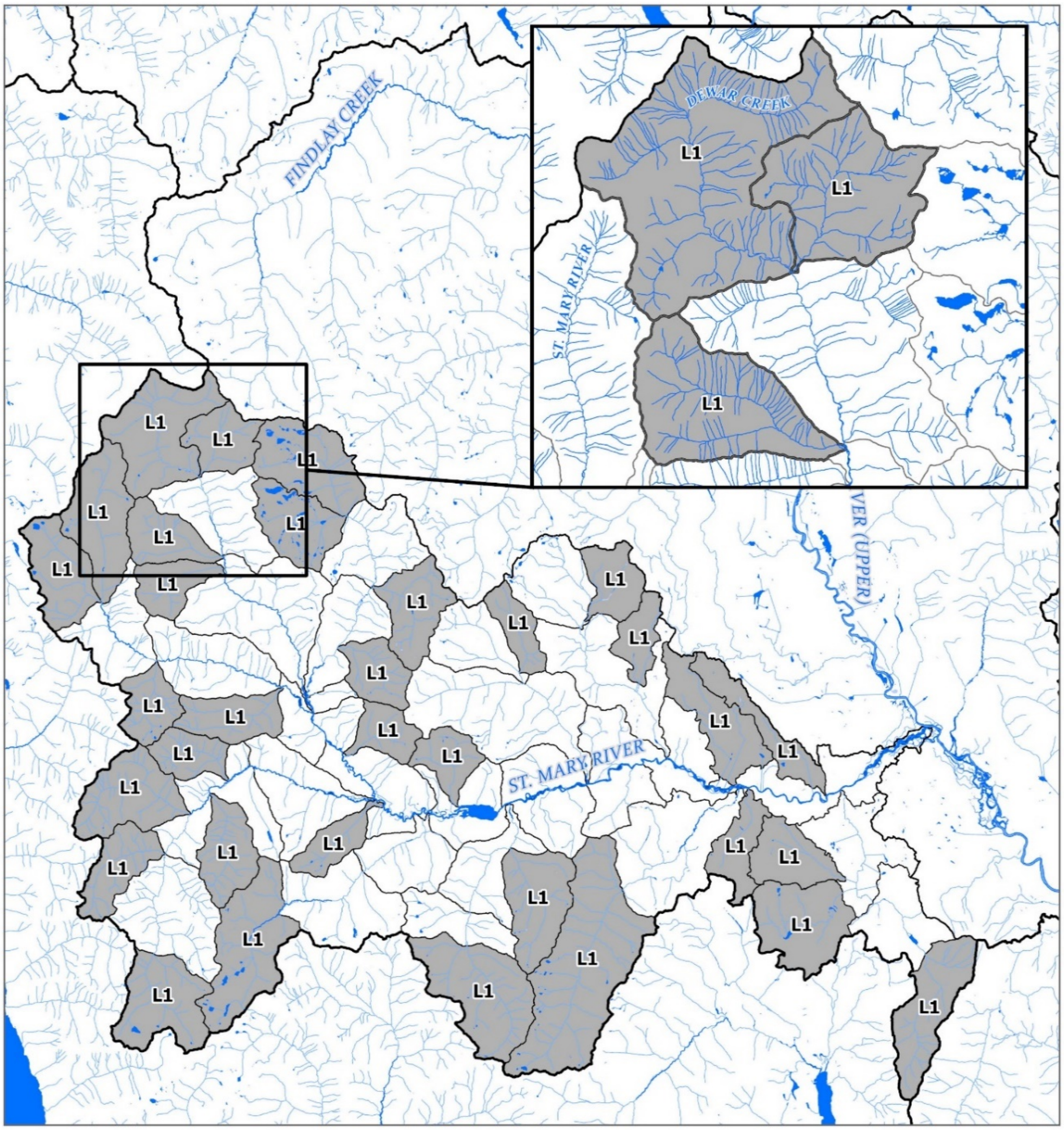

Figure 2*. Example of Level 1 AUs in the watershed delineation process for St. Mary River. Level 1 AUs are headwater basins because they do not receive inflows from adjacent units. Only AWs in the St. Mary River watershed are shown in this figure.*

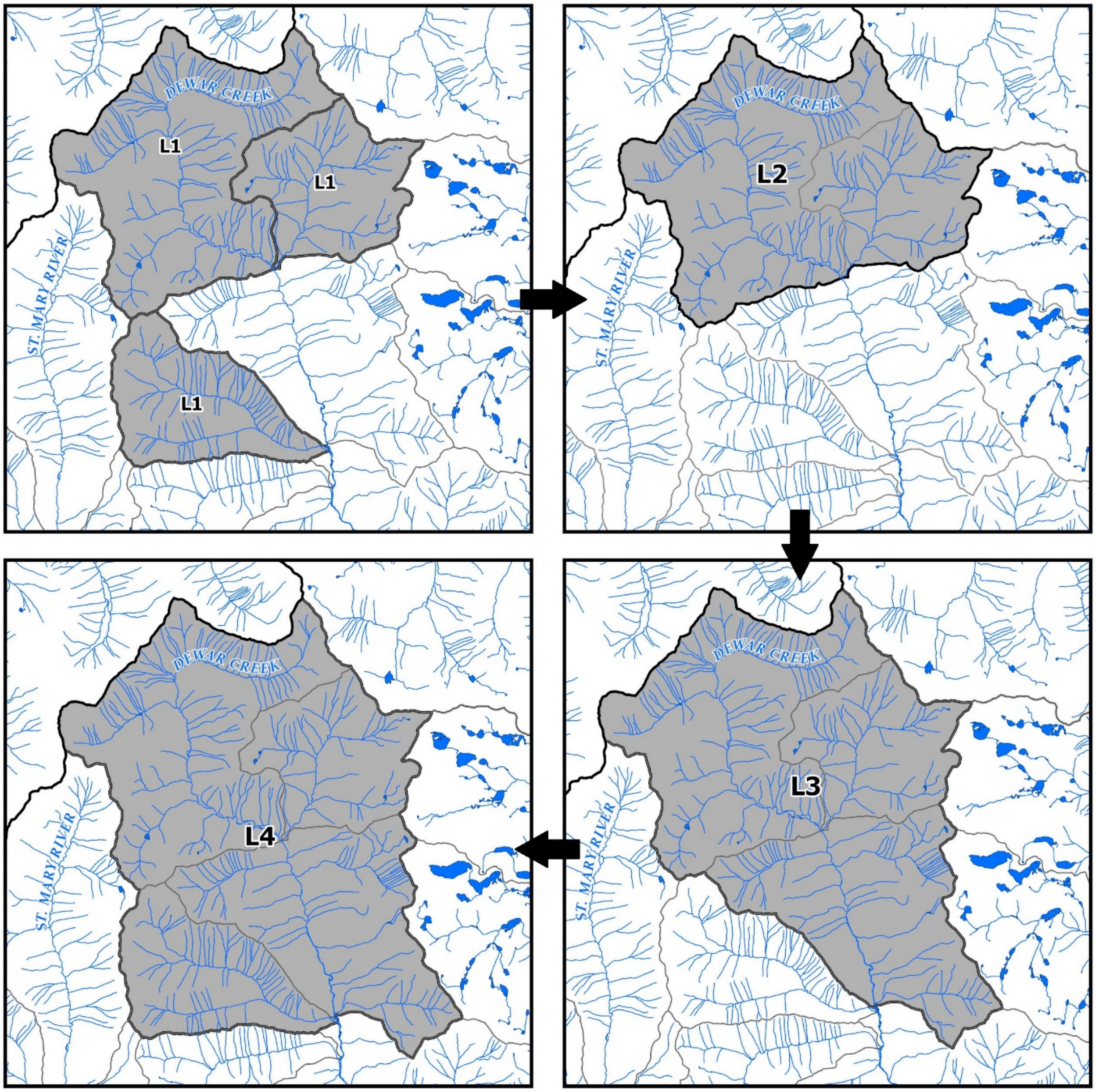

Figure 3*. AU grouping based on Freshwater Atlas AWs (outlined in grey) and drainage patterns for the subsetted area in Figure 3 (stream channels and lakes/ponds are shown in blue). The map in the upper left shows the L1 (headwater) AUs in this tributary; in the upper right, the two AWs with stream channels that meet were combined to create an L2 AU. In the lower right, the AW that receives water from the L2 unit was added to create an L3 AU, and in the lower left a tributary that joins the main stream channel was added to create an L4 AU. This nested hierarchical method of grouping continues up to the major watershed or area of interest.*

Due to data and analysis constraints the current assessments were conducted for only the Canadian portion of the drainages. AWs and AUs that had only a small proportion of their area within the United States were still assessed. For assessment units (watersheds) that had considerable proportions of their area in the U.S., the assessment was not completed.

3.0 Indicators and Ratings

Within each hazard category (streamflow and sedimentation), GIS indicators were selected to represent watershed characteristics and land cover properties that are related to the hydrologic and geomorphic processes of concern (Figure 4). For each hazard, one set of indicators was used to assess the natural sensitivity of a watershed (a) for increased peak streamflow generation following forest disturbance and (b) to introduce sediment to stream channels and transport those sediments downstream. The indicators represent relevant aspects of climate, watershed geography and the stream network. Another set of GIS indicators were used to assess the extent of land disturbance (natural and anthropogenic), focusing on the primary types of disturbances that occur in the southern interior of B.C. that are known to alter or impair important hydrologic and geomorphic processes. The indicators were combined to create intermediate ratings, which in turn were combined to generate the final hazard ratings.

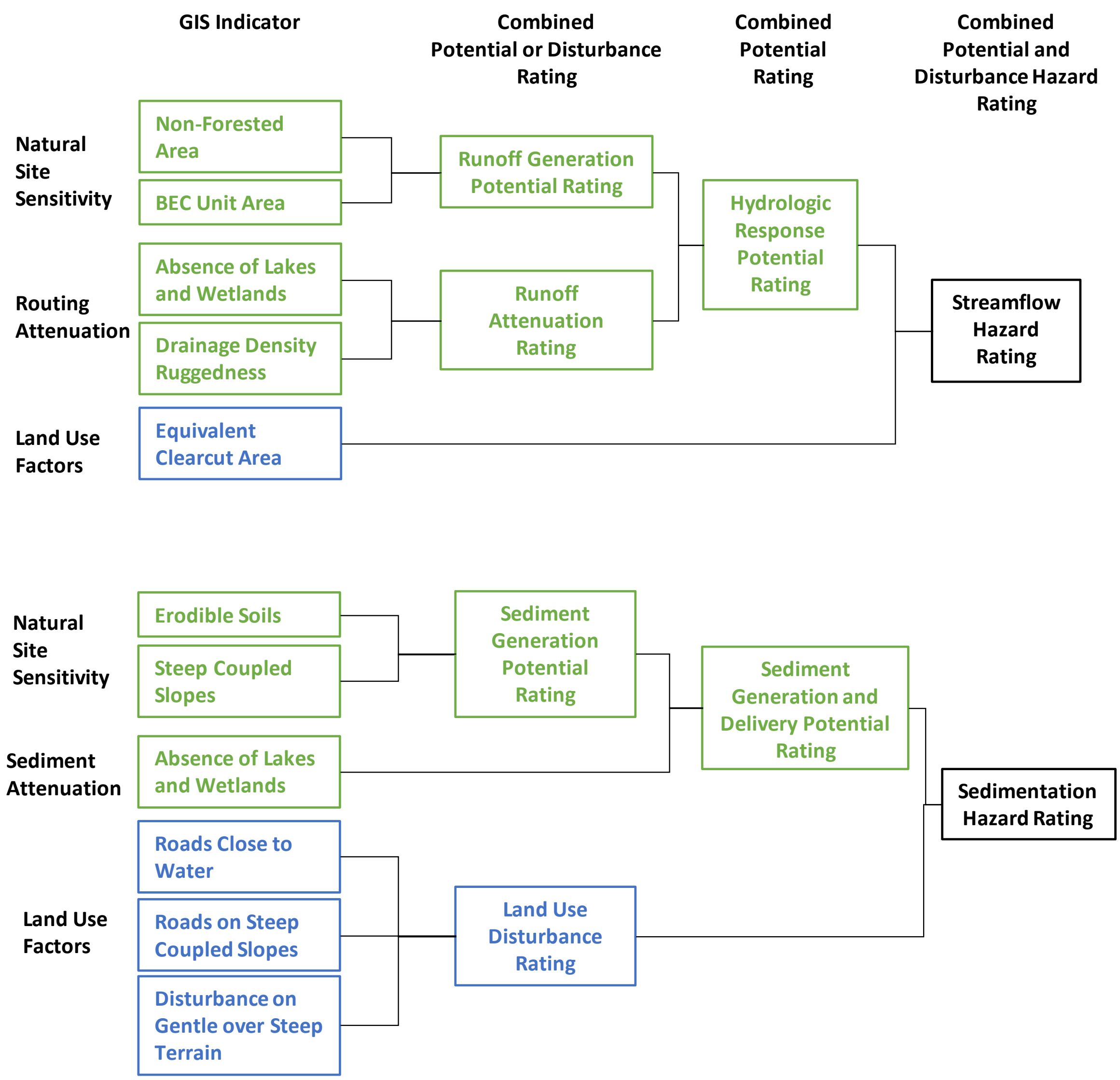

Figure 4. Flow chart diagrams showing the GIS Indicators used to qualitatively describe the natural sensitivity of watersheds (in green) and land use disturbance factors (in blue), and how they were combined to derive the Streamflow (upper) and Sedimentation (lower) Hazard ratings. Adapted from Lewis et al., 2016.

This step-wise process facilitates interpretation of the final results by providing the user with insight into the main drivers for the final hazard ratings. The following sections describe how each of the *Streamflow* and *Sedimentation Hazard* ratings were generated, including the data sources and assumptions used. Much of the content comes from Lewis et al. (2016) who applied the same method in the Thompson Okanagan Region. Some modifications were made for application to the Kootenay Boundary Region.

4.0 Streamflow Hazard

The streamflow regime in the Kootenay Boundary Region is characterized by a snowmelt-driven peak flow season in the spring and early summer, followed by declining flows in late summer through winter (Eaton and Moore 2010). Most streams are at their lowest in the fall or winter, when flow is primarily due to groundwater inputs. The cumulative watershed effects analysis for the Kootenay Boundary Region focusses on snowmelt-generated peak flows, though a low flow hazard assessment may be included in future work. The peak flow period[2], when up to 80% of the total water yield from a watershed may occur, is significant to both human activities and environmental processes. Spring flooding is a significant public safety concern, affecting lives and livelihoods, and critical infrastructure (e.g. roads and bridges). Important channel forming processes and floodplain connections also occur that affect aquatic habitat characteristics and functions.

The magnitude, duration and timing of peak flow in a given year are controlled by several factors, including (Winkler et al. 2010a):

1. the duration, intensity and timing of snow- and rainstorm events, and snowmelt rates and runoff volumes, which are affected by seasonal, annual or longer-term variations in weather and climate;
2. antecedent moisture conditions, especially in soils, ponds, wetlands and lakes; and
3. watershed characteristics that affect precipitation, watershed response and synchronization of runoff, and include drainage area, elevation, aspect, topography, physiography, land cover and storage (i.e. lakes, reservoirs, wetlands and aquifers).

This analysis is limited to factors that can be represented using GIS datasets. Weather and antecedent moisture conditions are beyond the scope of GIS-based indicators and are best represented using process-based hydrologic models (see Beckers et al. 2009 and Pike et al. 2010 for reviews). The effects of interannual variability in these factors are also better addressed through hydrological modelling. One such model has already been completed for the Kettle River watershed (Chernos et al. 2020a, 2020b).

With regards to land cover factors, forests and forest disturbance have significant influence on snowmelt-driven peak flows (Winkler et al. 2008, 2010a, Winkler and Boon 2015). Removal or loss of the forest canopy increases the amount of snow that accumulates on the ground (through decreasing interception losses to the atmosphere) and increases snowmelt rates (by reducing shading) (Winkler et al. 2012). These effects have been found to increase the potential frequency of more extreme peak flow events, which has downstream consequences (Forest Practices Board 2007, Alila et al. 2009, Grainger and Bates 2010, Green and Alila 2012).

[2] Peak flow is referred to here as the greatest instantaneous discharge occurring in a year (Pike et al. 2010). During the peak flow period, which lasts several weeks to months, spring snowmelt is the primary driver of elevated streamflows and is when the largest annual flow usually occurs.

The *Streamflow Hazard Rating* is derived in three steps based on indicators of:

1. The natural potential of a watershed to generate increased runoff[3] if the forest cover is altered, referred to as the *Runoff Generation Potential*;
2. How efficiently runoff is slowed as it is moves downslope and downstream, referred to as *Runoff Attenuation;* and
3. The extent and severity of natural or anthropogenic forest canopy disturbances and the degree of hydrologic recovery of disturbed forest stands, as measured by the *Equivalent Clearcut Area (ECA)* indicator.

Each of these ratings, the GIS indicators used to generate them, and how the three ratings are combined in the final Streamflow Hazard rating are described in the following sections.

4.1 Runoff Generation Potential

Runoff Generation Potential refers to the inherent sensitivity of a watershed to generate higher peak flows following forest cover loss or alteration. The *Runoff Generation Potential* rating considers the climatic conditions of a watershed (the type and amount of precipitation, and when precipitation falls or snow melts) and forest cover characteristics (how widespread and dense forest cover is), which affects the interception, sublimation and/or evapotranspiration of precipitation. These factors are represented using two metrics having readily available GIS data covering most of B.C.: *Biogeoclimatic Ecosystem Classification (BEC) Unit Area* and *Non-Forested Area*.

4.1.1 BEC Unit Area Indicator

In B.C., the BEC system is used to delineate areas with relatively homogeneous climate and climax vegetation cover (Meidinger and Pojar 1991). Provincial BEC subzone units were adopted in this protocol as indicators of average annual precipitation, average snowpack accumulation and melt timing, and forest cover density, factors that influence the potential for a watershed to generate runoff and for forest cover loss to affect that condition. Total annual precipitation and vegetation cover type (e.g. grassland, shrub, deciduous, different types of conifer forests) are key variables related to increases in annual water yield due to reductions in vegetation cover. Increased water yield following a reduction in vegetation cover has been shown to be greatest in coniferous forests in areas with higher precipitation (Best et al. 2003, Bosch and Hewlett 1982).

To generate the *BEC Unit Area* indicator, each BEC subzone was assigned a score between 0 and 3 reflecting average annual precipitation, snowpack accumulation and persistence, and forest density and continuity based on expert knowledge (Table 4). Higher scores were assigned to BEC subzones that were associated with higher precipitation and snow accumulation, and higher forest density. For each area of interest, the area-weighted average BEC unit score was calculated to obtain a single *BEC Unit Area* indicator value. Results were then categorized as low (<1.0), moderate (1.0-2.0) or high (2.0-3.0).

[3] Runoff is defined as the portion of precipitation that moves from land to surface water bodies either as surface or sub-surface flow (Pike et al. 2010).

Table 4. *Biogeoclimatic Ecosystem Classification (BEC) subzone units within the Kootenay Boundary Region and the associated BEC unit scores assigned in the assessment procedure.*

Biogeoclimatic Ecosystem Classification (BEC) Subzones	BEC Unit Score
BGxh1, ESSFdcp, ESSFdkp, ESSFmmp, ESSFvcp, ESSFwcp, ESSFwmp, IDFxh1, IDFxh4, IDFxk, IDFxx2, IMAun, PPxh1, PPxh3	0
ICHmk5, ICHxw, ICHxwa, IDFdk5, IDFdm1, IDFdm2, MSdm1	0.5
ESSFdk1, ESSFmh, ICHdm, ICHmk1, ICHmk4, ICHmw1, ICHmw3, ICHmw5	1
ESSFdc2, ESSFdk2, ESSFxc2, ICHdw1, ICHmw2, ICHwk1, MSdk, MSdw	1.5
ESSFdc1, ESSFdkw, ESSFmm1, ESSFmm2, ESSFmm3, ESSFwh1, ESSFwh2, ESSFwm1, ICHmw4	2
ESSFdcw, ESSFmmw, ESSFvcw, ESSFwc2, ESSFwc4, ESSFwh3, ESSFwm2, ESSFwm4, ESSFwmw, ICHvk1	2.5
ESSFvc, ESSFwcw, ESSFwm3	3

4.1.2 Non-Forested Area Indicator

A *Non–Forested Area* indicator was used to estimate the amount of naturally non-forested area in each assessed area. Because these areas are not forested, the runoff generated in non-forested areas cannot be altered due to canopy loss or alteration (Winkler et al. 2010a).

The natural non-forested area was classified using the Non-Forest Land label in the Vegetation Resource Inventory (VRI; https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory). These areas included alpine regions, rock, swamp and non-productive brush. The indicator score was calculated as the proportion (%) of non-forested area relative to total area. Results were then categorized as low (<30%), moderate (31-70%) or high (>70%).

4.1.3 Runoff Generation Potential Rating

The *Runoff Generation Potential Rating* is a qualitative expression of the natural sensitivity of an area to generate higher peak flows following forest cover loss. It combines the *BEC Unit Area* and *Non-Forested Area* indicator scores in a ratings matrix (Table 5) such that densely forested areas with little non-forested area, relatively high precipitation and deep and persistent snowpacks are rated highest.

Table 5. *Runoff Generation Potential Rating matrix based on binned BEC Unit Area and Non-Forested Area indicator scores. Ratings indicate level of hazard from very low to very high.*

		BEC Unit Score		
		<1.0	>1.0-2.0	>2.0-3.0
Proportion of Non-Forested Area (%)	<30	Mod	High	V. High
	31-70	Low	Mod	High
	>70	V. Low	Low	Mod

4.2 Runoff Attenuation

Runoff attenuation refers to how efficiently hillslope and stream runoff is slowed, captured and/or stored as it is routed through a watershed. Runoff attenuation was calculated using two indicators that can be determined from readily available GIS data: *Drainage Density Ruggedness* and *Absence of Lakes and Wetlands.*

4.2.1 Drainage Density Ruggedness Indicator

The Drainage Density Ruggedness (DDR) indicator represents the potential for rapid runoff delivery to and through streams, which may contribute to harmful flood events (Patton and Baker 1976). DDR is the dimensionless product of drainage density (stream length per unit area - km/km^2) and total elevation relief (the difference between the highest and lowest elevation, km) (Schumm 1956, Melton 1957). Drainage density has been shown to reflect important natural factors influencing runoff storage and routing such as soil type, permeability and depth, overall hillslope gradient and the distance water must travel before reaching the mainstem (Horton 1932, 1945). With increasing relief and steeper hillslopes and stream gradients, water velocities increase. These factors increase runoff routing efficiency and reduce the time it takes for runoff to be transferred downstream.

The 1:20,000 FWA stream network was used to determine total stream length. Elevation relief was calculated using the 25m resolution Terrain Resource Information Management (TRIM) Digital Elevation Model (DEM) (https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/elevation/digital-elevation-model). Although roads can expand the stream drainage network by intercepting subsurface hillslope runoff (Wemple et al. 1996, Gucinski et al. 2001), these were not included in the calculation of drainage density because the *Drainage Density Ruggedness* indicator is intended to reflect the inherent runoff routing efficiency regardless of land use activity.

Results were categorized as low (<2000), moderate (2001-4000) or high (>4000).

4.2.2 Absence of Lakes and Wetlands Indicator

The presence of lakes, ponds, wetlands and anthropogenic reservoirs in a watershed can have an attenuating influence on peak flow discharge (Acreman and Holden 2013, Woltenmade and Potter 1994, Taylor and Pierson 1985). Flood flows have been shown to be reduced as the percent of lake and wetland area increases (Conger 1971, Verry 1988 cited in Brooks et al. 1997). The size and placement of wetlands within a watershed has also shown to influence attenuation, with larger lakes and wetlands located on the main-stem channel lower in a watershed being more effective at reducing downstream flooding (Acreman and Holden 2013, Delaney 1995, Ogawa and Male 1986).

The *Absence of Lakes and Wetlands* indicator reflects the attenuating capacity of lakes, reservoirs and wetlands to buffer peak flow response. The indicator was calculated using the 1:20,000 FWA lakes (natural and manmade) and wetlands layers to measure the area of lakes and wetlands within the lower 30%, middle 30% and upper 40% of each area of interest. The area-weighted proportion (%) of lakes and wetlands was calculated by weighting the lake/wetland area in the lower 30% by 100%, in the middle 30% by 75% and in the upper 40% by 25%. This gave greater weight to larger lakes and wetlands situated at lower elevations which are more likely to attenuate runoff from a larger area; higher indicator values indicate greater attenuation. Results were categorized as low (0-2), moderate (2.1-6.0) or high (>6.1).

4.2.3 Runoff Attenuation Rating

The *Runoff Attenuation Rating* is a qualitative expression of how effectively hillslope runoff may be slowed, captured and stored, as derived by combining the *Drainage Density Ruggedness* and *Absence of Lakes and Wetlands* indicators in the *Runoff Attenuation Rating* matrix (Table 6). A Very Low rating results in higher risk of peak streamflow, which is reflected in the colour scheme used in the *Runoff Attenuation Rating* matrix (Table 6).

***Table 6**. Runoff Attenuation Rating matrix based on binned scores for DDR and Absence of Lakes and Wetlands indicators. Ratings indicate level of hazard from very low to very high, and the colour scheme reflects the resulting influence on peak flow generation (e.g. a very low attenuation rating indicates higher sensitivity to increase peak flow).*

		Drainage Density Ruggedness		
		<2000	2001-4000	>4000
Location - Weighted Percent Area of Lakes/ Wetlands	0-2	Mod	Low	V. Low
	2.1-6.0	High	Mod	Low
	>6.1	V. High	High	Mod

4.3 Hydrologic Response Potential Rating

The *Hydrologic Response Potential* rating is a qualitative expression of the natural sensitivity of an area to generate higher peak flows following forest disturbance (Figure 4). The rating is derived by combining the *Runoff Generation Potential* and *Runoff Attenuation* ratings (Table 7). Wetter and more densely forested areas that are steep and have little runoff attenuation are more likely to respond hydrologically to forest cover loss and have a higher *Hydrologic Response Potential* rating.

***Table 7**. Hydrologic Response Potential Rating matrix based on combined Runoff Generation Potential and Runoff Attenuation Ratings. Ratings indicate level of hazard from very low to very high.*

		Runoff Attenuation				
		Very High	High	Mod	Low	Very Low
Runoff Generation Potential	Very Low	V. Low	V. Low	Low	Low	Mod
	Low	V. Low	Low	Low	Mod	High
	Mod	Low	Low	Mod	High	High
	High	Low	Mod	High	High	V. High
	Very High	Mod	High	High	V. High	V. High

4.4 Equivalent Clearcut Area

Land use disturbance in this protocol is a function of a single indicator, *Equivalent Clearcut Area* (ECA, %). ECA is used to determine the area over which a reduction in forest cover has occurred, expressed relative to the hydrologic impact of a recent clearcut. ECA is intended to be a reflection of the hydrologic function of disturbed relative to mature forests. ECA calculations are based on existing research in nival (snow-melt dominated) environments documenting differences in snow accumulation and melt rates between clearcuts, openings, mature, regenerating and insect attacked forests (Winkler et al. 2010b, 2012, Winkler and Boon 2010, 2015, Lewis and Huggard 2010).

An ECA value is calculated for each relatively homogeneous disturbed forest stand area as the product of the disturbed area (A, km^2) and a hydrologic recovery factor (HR) assigned based on tree height (B.C. Ministry of Forests and B.C. Ministry of Environment 1999, Winkler and Boon 2015, 2017):

$$ECA = A \times (1 - HR)$$

Higher recovery rates are applied as the mean tree height increases, with the assumption that the growing stands begins to act hydrologically more similar to a mature forest stand than a recent clearcut (Table 8). Tree heights from VRI data (which are projected heights) are cross-referenced with published hydrologic recovery rates (Winkler and Boon 2015) (summarized in Table 8) to calculate ECA. Specific ECA calculation considerations included:

- Perpetually de-forested areas (e.g. urban, agricultural, transmission right of ways) were assigned a hydrologic recovery of 0%;
- Recent wildfires were dealt with in the same way as clearcuts, assuming that they had limited residual structure to influence hydrologic function;
- The stand structures of partial forest treatments (e.g. the remaining basal area of trees in partial cuts and thinned forests) were assumed to be represented in the VRI data and no ECA adjustments were made; and
- Hydrologic recovery factors were estimated for unharvested stands following attack by Mountain Pine Beetle (MPB) in different BEC subzones using predicted pine mortality rates (Walton 2010) and modelled ECA estimates from Lewis and Huggard (2010) to incorporate the hydrologic function of non-affected pine and non-pine overstory and understory trees.

A final ECA indicator value for each area of interest was calculated as the sum of the values for each disturbed area divided by total area (%).

Table 8. *Hydrologic recovery factors applied for different minimum and maximum tree height classes. Based on Winkler and Boon (2015) for pine-dominated forests in the B.C. southern interior.*

Minimum Tree Height (m)	Maximum Tree Height (m)	Hydrologic Recovery (%)
0	2	0
2	3	0.2
3	4	3.1
4	5	9.9
5	6	19.3
6	7	29.9
7	8	40.5
8	9	50.3
9	10	59.1
10	11	66.7
11	12	73.1
12	13	78.3
13	14	82.7
14	15	86.2
15	16	89.0
16	17	91.3
17	18	93.1
18	19	94.6
>19	NA	100

4.5 Streamflow Hazard Rating

The *Streamflow Hazard Rating* is a qualitative estimate of the likelihood that harmful increases in streamflow will result from the patterns in forest cover disturbance reflected by the ECA indicator. In particular, an increase in peak flow frequency and magnitude may result in harmful hydrogeomorphic events (floods, bank erosion, channel instability, debris floods and debris flows). The *Hydrologic Response Potential* rating and land use disturbance *ECA* values were combined to generate a *Streamflow Hazard* rating (Figure 4 and Table 9).

Table 9. *Streamflow Hazard Rating matrix based on Hydrologic Response Potential Rating and the ECA Indicator. Ratings indicate level of hazard from very low to very high.*

		Equivalent Clearcut Area (%)									
		0	10	20	30	40	50	60	70	80	90
Hydrologic Response Potential	VH	V.Low	Low	Mod	High	V. High					
	H										
	M										
	L										
	VL										

There is a higher likelihood of peak flow increases and streamflow hazards with increased *Hydrologic Response Potential* and reduced forest cover. To generate the relative rating scale, a moderate *Hydrologic Response Potential* rating was combined with ECA values between 30 and 40% to yield a moderate *Streamflow Hazard* rating; this approach was consistent with published findings showing increased frequency and magnitude of peak flows at moderate (33-40%) harvest levels (Green and Alila 2012, Winkler and Boon 2015). A moderate *Hydrologic Response Potential* rating combined with ECA levels <20% yields low to very low *Streamflow Hazard* ratings (a significant increase in peak flow is unlikely to occur) as changes in streamflow are generally not detected when vegetation cover reduction is less than 20% (Best et al. 2003). The remaining *Streamflow Hazard* ratings were then extrapolated from lower and higher *Hydrologic Response Potential* ratings and *ECA* values.

4.5.1 Confidence in the Streamflow Hazard Rating and Component Indicators

Based on the indicators and ratings used, we have *Moderate* confidence that the *Streamflow Hazard* ratings adequately estimate the likelihood of increased frequency and magnitude of snowmelt-generated peak flows following forest cover disturbance, for strategic level applications. This confidence level is supported by:

- *High* confidence that the GIS data layers and indicators associated with watershed morphology used in this procedure adequately capture relative differences in watershed characteristics used to describe complex hydrologic and geomorphic processes that affect streamflow response;
- *Moderate* confidence that the land use disturbance indicator (*ECA*) adequately captures the effects of human and natural disturbances on forest cover, and that the generalized stand growth models used to produce the VRI data represent field conditions;
- *High* confidence in pine dominated stands that the ECA indicator and scores are supported by considerable published literature on the effects of reduced forest cover and forest regrowth on snow accumulation and ablation affecting runoff and streamflow response;

- *Moderate* confidence in areas that receive higher snowfall and where pine is not the dominant tree species because there is limited understanding of hydrologic recovery rates in these settings; and
- *Low* confidence that the potential for snowmelt synchronization between forests and disturbed areas at different elevations, which is known to increase peak flows, is represented in the ECA calculations. In the past the H60 elevation (the elevation above which 60% of the basin area lies) has been used in harvest planning as a threshold above which logging activities should be carefully managed for potential synchronization, but this concept has not been widely verified; while the H60 was validated for adjacent watersheds in the West Kootenays (Gluns, 2001), analysis in parts of the Okanagan River watershed has suggested an elevation threshold at the H40 may be more appropriate (Dobson Engineering Ltd., 2004; Smith et al., 2008). In the watershed assessment protocol used in this analysis of the Kettle River watershed, the *BEC Unit Area* indicator somewhat reflects elevation effects. However, research is currently underway to determine the best way to incorporate the potential for melt synchronization.

5.0 Sedimentation Hazard

In this protocol, a sedimentation hazard has been developed to represent the potential for an increase in the amount, frequency and/or duration of sediment generated from non-natural sources entering a stream channel and being transported downstream. Increased sedimentation in stream channels can affect aquatic life and habitat (especially fish) as well as water quality (Reid and Dunne 1984, Gucinski et al. 2001), so management of both chronic inputs and conditions that may lead to spontaneous inputs (e.g. landslides) is essential for protection of downstream communities, aquatic ecosystems and infrastructure.

Most forested headwater streams in the Kootenay Boundary Region have relatively low sediment budgets (Slaymaker 1987, Church et al. 1989, Jordan 2006) which make them more sensitive when human activities increase sediment supply (e.g. roads and logging) (Jordan et al. 2010). Mass wasting events such as landslides can occur due to road cut or fill failures or inadequate road drainage, as well as from road surface erosion where there is poorly designed or failed drainage controls (Jordan et al. 2010). While there have been significant improvements in road design and construction since the 1980's, roads still represent risks for sedimentation, especially as a source of fine sediments (Carson et al. 2009, Jordan et al. 2010).

The *Sedimentation Hazard* rating is derived in three steps based on indicators of:

1. The natural potential to generate increased levels of sediment from road and land use disturbances expressed through a *Sediment Generation Potential* rating, based on the amount of erodible soils and steep slopes;
2. The attenuating capacity of lakes and wetlands to facilitate sediment deposition and limit downstream delivery of sediment, expressed using a *Sediment Generation and Delivery Potential* rating; and
3. Estimates of the likelihood that the extent of road- and logging-related sediment sources that are hydrologically connected to water bodies will generate and deliver harmful sediment levels, as indicated by a *Land Use Disturbance* rating.

5.1 Sediment Generation Potential

The *Sediment Generation Potential* rating is a qualitative measure of the potential for sediment to be generated when affected by land use activities. Estimates of sediment generation potential were based on two indicators that can be determined from readily available GIS data: *Erodible Soils* and *Steep Coupled Slopes*.

5.1.1 Erodible Soils Indicator

The Erodible Soils indicator was used to estimate the potential for soil or sediment erosion to occur. B.C. has a soil survey dataset that contains data from various projects (https://catalogue.data.gov.bc.ca/dataset/soil-survey-spatial-view). Within this dataset, the KBR research team identified glaciofluvial and glaciolacustrine type parent materials because they lack cohesion and are highly prone to erosion. The soil survey dataset does not cover the entire Kootenay Boundary Region; as a surrogate to erodible soils for areas that lacked soil survey data, the Quaternary alluvium deposits dataset was used (https://catalogue.data.gov.bc.ca/dataset/geology-quaternary-alluvium-and-cover). Field experience has shown that these types of Quaternary deposits are a continuous and problematic source of sediment generation and delivery where they occur.

The extent of these readily erodible sediments was expressed as a percentage of the area of interest (see Table 8). The results were categorized as low (<10%), moderate (11-20%) or high (>20%).

5.1.2 Steep Coupled Slopes Indicator

The *Steep Coupled Slopes* indicator was used to estimate the potential for sediment to be generated from land use activities on potentially unstable terrain and for that sediment to enter a stream. The TRIM DEM was used to identify the extent of steep slopes (>50% gradient) that are hydrologically connected or 'coupled' to streams by calculating the percentage of watershed area of steep slopes where the base of the slope is within 50m of a stream. The results were categorized as low (<10%), moderate (11-20%) or high (>20%).

5.1.3 Sediment Generation Potential Rating

Sediment Generation Potential ratings were assigned by combining the *Steep Coupled Slopes* and *Erodible Soils* indicators (Figure 4 and Table 10).

Table 10. *Sediment Generation Potential Rating matrix based on the proportion of the area with Erodible Soils and Steep Coupled Slopes. Ratings indicate level of hazard from very low to very high.*

		Erodible Soils		
		<10%	11-20%	>20%
Steep Coupled Slopes	<10 %	V. Low	Low	Mod
	11-20%	Low	Mod	High
	>20%	Mod	High	V. High

5.2 Sediment Generation and Delivery Potential Rating

The *Sediment Generation and Delivery Potential* rating combines the *Sediment Generation Potential* rating with the *Absence of Lakes and Wetlands* indicator to provide a qualitative estimate of the potential for increased sediment to be generated from non-natural sources and to be delivered downstream (Figure 4 and Table 11). As with runoff attenuation, sediment transfer in streams can be attenuated by lakes, ponds, wetlands and anthropogenic reservoirs. The same *Absence of Lakes and Wetlands* indicator values that were used in the *Streamflow Hazard* rating were adopted here, categorized as low (0-2), moderate (2.1-6.0) or high (>6.1).

Table 11. *Sediment Generation and Delivery Potential Rating based on the Sediment Generation Potential rating and Absence of Lakes and Wetlands indicator. Ratings indicate level of hazard from very low to very high. A low attenuation score indicates a higher potential for sediment to be transported downstream.*

		Location -Weighted Percent Area of Lakes/ Wetlands		
		0-2 (Low)	2.1-6.0 (Moderate)	>6.1 (High)
Sediment Generation Potential	VH	V. High	High	Mod
	H	High	Mod	Low
	M	Mod	Low	V. Low
	L	Low	V. Low	V. Low
	VL	V. Low	V. Low	V. Low

5.3 Land Use Disturbance

Three indicators were used to represent the potential impacts of roads and logging activities on sedimentation. Some approaches focus on the points where roads and stream channels intersect, representing known point sources of sediment introduction to streams (Carson et al. 2009). Other methods include measures of road density without considering whether or not roads are adjacent to streams and can therefore realistically be expected to be a sediment source (Carver and Teti 1998, Carver 2001). In the approach adopted here, three indicators were used to reflect the potential for roads and land use activities to generate and deliver sediments directly into streams: *Roads Close to Water*, *Roads on Steep Coupled Slopes* and *Disturbance on Gentle over Steep Terrain* adjacent to streams.

5.3.1 Roads Close to Water Indicator

Roads that are hydrologically connected to streams can be a chronic source of sediment through:

- Sediment deposited directly during road construction;
- Continuous ditchline and road surface erosion, particularly during wet periods; and
- Cutbank and hillslope failures.

The *Roads Close to Water* indicator is used to estimate the potential for increased sediment generated from surface erosion or mass wasting events to enter a stream. It uses a consolidated roads dataset that combines roads from the B.C. Digital Road Atlas layer (DRA; https://catalogue.data.gov.bc.ca/dataset/digital-road-atlas-dra-master-partially-attributed-roads), the Forest Tenure road sections (FTEN; https://catalogue.data.gov.bc.ca/dataset/forest-tenure-road-section-lines) and the TRIM roads (https://catalogue.data.gov.bc.ca/dataset/trim-transportation-lines). Trails identified through the DRA were also included in the road dataset. Since available data sources had limited information on factors that influence sediment generation and delivery, we assumed all roads had equal construction and maintenance practices and use. The indicator was calculated as the road length within 50m of a stream per unit watershed area (km/km^2).

5.3.2 Roads on Steep Coupled Slopes Indicator

Roads on steep coupled slopes are a primary cause of forest development-related landslides delivering sediment to streams (Jordan 2002, Jordan et al. 2010). Long road segments on steep slopes also have the potential for running surface erosion; as road segment length and road grade are key factors shown to increase road sediment yields (Luce and Black 1999). The *Roads on Steep Coupled Slopes* indicator was calculated by measuring the total road length on the area of steep slopes (>50% gradient) where the base of the slope is within 50m of a stream per unit watershed area (km/km^2) (see also the *Steep Coupled Slopes* indicator description used for the *Sediment Generation Potential* rating).

5.3.3 Disturbance on Gentle over Steep Terrain Indicator

Poor road drainage (i.e. plugged, undersized or improperly located drainage) is closely linked with the occurrence of road-related landslides in southern interior of B.C. (Jordan et al. 2010). Runoff from harvested areas may concentrate along roads on gentle gradient terrain positioned immediately over steep slopes. The water can saturate the road prism or be diverted onto the steep slope below, triggering mass wasting events (Jordan 2002, Grainger 2002, Jordan et al. 2010). The *Disturbance on Gentle Over Steep Terrain* indicator is used to estimate the area with logging on gentle slopes (<50% gradient) immediately above steep slopes (>50% gradient) where the base of the slope is within 50m of a stream. Gentle slopes above steep coupled slopes were identified using the provincial TRIM-derived DEM. Because the drainage patterns that are implemented at the time of logging are rarely remediated, these disturbances persist into the future. A consolidated harvest layer was used to identify all polygons with a history of harvest to calculate the harvested area within gentle terrain adjacent to steep coupled terrain (expressed as a percentage of the total area of interest).

5.3.4 Land Use Disturbance Rating

To generate a combined land use disturbance rating with the two road-related and one logging related indicators, a score (1-3) was first assigned for each indicator following the criteria adopted for the Thompson Okanagan Region cumulative watershed effects analysis (Lewis et al. 2016) (Table 12). Scores for the road density indicator were assigned based on expert advice and available studies (e.g. Bradford and Irvine 2000; Thompson and Lee 2000; Valdal and Quinn 2011), and for the roads on steep slopes and disturbance on gentle over steep slopes based on expert advice (Doug Lewis, pers. comm., 4 November 2020).

Individual indicator scores were then summed to derive an overall *Land Use Disturbance* rating for the area of interest. Combined scores of 3, 4, 5, 6 and 7 or greater were assigned Very Low, Low, Moderate, High and Very High ratings, respectively.

Table 12. *Scoring matrix for land use disturbance indicators (from Lewis et al. 2016).*

Indicator	Score			Indicator Measurement
	1	2	3	
Roads Close to Water	<0.1	0.1 -0.3	> 0.3	Length of roads within 50m of stream per unit watershed area (km/km^2)
Roads on Steep Coupled Slopes	< 0.1	0.1-0.2	> 0.2	Length of roads on steep coupled slopes per unit watershed area (km/km^2)
Disturbance on Gentle Over Steep Terrain	< 10%	10-20%	>20%	Percentage of watershed area with logged gentle terrain area above steep coupled slope

5.4 Sedimentation Hazard Rating

The *Sedimentation Hazard* rating is a qualitative expression of the likelihood that harmful levels of sediment, generated through the *Land Use Disturbance* indicators, will enter a stream channel and be delivered downstream. The *Sedimentation Hazard* rating was derived by combining the *Sediment Generation and Delivery Potential* and *Land Use Disturbance* ratings (Figure 4 and Table 13).

Table 13. *Sedimentation Hazard rating matrix based on Sediment Generation and Delivery Potential and Land Use Disturbance ratings. Ratings indicate level of hazard from very low to very high.*

		Land Use Disturbance Rating				
		Very Low	Low	Moderate	High	Very High
Sediment Generation and Delivery Potential Rating	VH	Mod	High	V. High	V. High	V. High
	H	Low	Mod	High	V. High	V. High
	M	V. Low	Low	Mod	High	V. High
	L	V. Low	V. Low	Low	Mod	High
	VL	V. Low	V. Low	V. Low	Low	Mod

5.4.1 Confidence in the Sedimentation Hazard Rating and Indicators

Based on the indicators and ratings used, we have *Moderate* confidence that the *Sedimentation Hazard* rating reflects likely increases in harmful levels of sediment from non-natural sources. This confidence level is based on:

- *Moderate-High* confidence that the land use disturbance indicators accurately identify the extent of potential sediment sources hydrologically connected to streams. This is supported by the published literature, experience in completing watershed-level road risk assessments, and ground-truthing of GIS-identified contributing road segments showing high-levels of congruence with field-identified sediment sources (Lewis, D., unpublished data). Other potential in-stream sources of sediment, for example placer mining and agricultural activities, are not currently represented in the *Land Use Disturbance* indicator; more information is needed to include these activities in the land use indicator.
- *Moderate* confidence that the assumptions regarding the human behaviours that influence road-related sediment generation and delivery reflect actual conditions in any given area (e.g. road construction and maintenance practices, patterns of use). Actual amounts of sediment generated from landslides or surface erosion vary depending on road location, construction methods, surface material type, amount and timing of use, maintenance regimes, and weather-related considerations (Gucinski et al. 2001). Actual sediment production estimates and associated hazards require field-based assessments from qualified professionals. For the purposes of strategic-level assessments, better data on road status and use would improve confidence in sediment hazard ratings.
- *Low-Moderate* confidence that the *Erodible Soils* indicator adequately reflects the extent of erodible soils and sediments in a watershed. Although our experience has shown that unconsolidated Quaternary deposits are vulnerable to erosion and are the most common sources of sediment in streams, the coarse spatial resolution of the input data can only be used, at best, to represent relative differences between AUs over large areas. Our confidence in this indicator would increase with improved soils/sediment data.

6.0 Conclusion and Next Steps

The GIS indicator-based approach for cumulative watershed effects assessment that was developed for the Thompson Okanagan Region of FLNRORD (Lewis et al. 2016) was adapted for use in the Kootenay Boundary Region. As the number and scale of human activities (e.g. forestry, mining, agriculture and renewable energy projects) and natural disturbances (e.g. insect outbreaks and wildfires) increase in the Province, there is a need to assess their cumulative effects on hydrologic and geomorphic processes. The protocol described in this report assesses the potential for changes to snowmelt generated peak flows and sediment introduction to and transport through stream channels following natural and anthropogenic land cover disturbance.

The protocol uses readily available GIS data which allows for consistent and transparent assessment across the region; however, the accuracy, resolution and relevance of the results depends on the quality of the input data and the frequency at which the GIS data are updated. Because of this, the results should be applied at a strategic level to inform stewardship and resource management planning and require verification through field work or expert knowledge before being used at an operational level.

The indicators and ratings selected for this protocol and how they are combined to generate the final *Streamflow* and *Sedimentation Hazard* ratings were based on (a) identification of forest disturbance and forestry related activities as the predominant types of land use activities and land cover changes that affect peak streamflow and sedimentation processes, and (b) our best understanding of the effects of watershed characteristics and the identified land cover changes on hydrologic and geomorphic processes. Establishing a direct cause-and-effect link between land use and cover changes on these processes can be challenging (Carver 2001), and the protocol will continue to be refined as our knowledge improves. Indicators and rating procedures for other land use activities (e.g. mining, agriculture, water diversions) and other cumulative watershed effects (e.g. pollution, low flows, fisheries values) will be added as they are developed, and methods will be developed to accurately represent activities on private lands. Currently, indigenous knowledge is not incorporated into the assessment protocol, but we plan to build appropriate relationships in order to reflect indigenous values and ways of understanding, and to collaborate on the development of management activities.

The current assessment does not consider areas in the U.S. although many watersheds in the Kootenay Boundary Region extend across the international border. This decision was made because of incompatibilities between available GIS datasets; the current protocol was developed to use data available for B.C. Including these areas in the future will depend on finding appropriate surrogate GIS datasets as well as the feasibility of incorporating and aligning these datasets into the assessment protocol.

Assessment of cumulative effects on riparian ecosystem health is an important aspect that is currently not included in this protocol. Although the procedures described by Lewis et al. (2016) that this assessment is adapted from included a *Riparian Function Hazard* component, it was determined that it required a review to better align with available research. Once these new measures have been established the Kootenay Boundary Region intends to include a *Riparian Function Hazard* rating.

Efforts are underway to use existing monitoring and modeling projects as means to validate the indicators and ratings. Field based monitoring programs such as the Forest and Range Evaluation Program (FREP) and hydrologic models are two potential sources of information to help confirm or refine the protocols.

The protocols could also be used with modelled or simulated landcover maps to identify how future harvest plans, natural disturbances, wildfire mitigation treatments and/or climate change may impact hazard ratings. The current assessment protocols do not explicitly consider climate change; however, the indicators could be derived using a modelled 'future' landcover. The hydrologic and geomorphic processes represented in the watershed assessment protocols can be assumed to operate in the future, though there may be changes in such things as the timing and duration of peak flow or storm events that saturate unstable sediments. If peak flow transitions from snowmelt- to rainfall-driven, however, a new assessment protocol would be needed. The input data layers are publicly available, and it is the intent that the scripts used to generate the results can eventually be shared so that this work can be conducted on an as-need basis to inform natural resource management and will depend on technical capacity.

Similarly, the protocols could be used with data layers representing past conditions to assess changes in indicators and hazards over time due to different management practises or natural disturbance regimes.

It is the intent of the Kootenay Boundary Region Cumulative Effects Team to make the results of this assessment publicly available so the information can be viewed and used by decision-makers and the public at large. There are plans to launch an online and interactive mapping application that will allow users to select and view results and statistics for areas or watersheds of interest. This approach will also help present the nested watershed results in an easy to read manner. Release of the application is planned for 2021.

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