A GIS INDICATOR-BASED WATERSHED ASSESSMENT PROCEDURE FOR ASSESSING CUMULATIVE WATERSHED EFFECTS

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Table of Contents

1.0 Introduction

Cumulative effects have emerged as an area of increasing management concern in British Columbia (B.C.) over the last decade, particularly with the onset of large-scale natural disturbances (e.g. Mountain Pine Beetle outbreak, wildfire) and the expansion other natural resource sector activity (e.g. mining, windpower and natural gas). In parts of B.C., as much as 400% of the publicly owned or Crown land-base may be authorized for 70 or more different types of overlapping tenured land use activities. The concern is for managing the often unintended consequences of these overlapping activities on public land, combined with the consequences of other land uses on both public and private land, and natural disturbances (BC Forest Practices Board, 2010). The assessment and management of these multiple effects is at the forefront of the implementation of the Province of B.C.'s Cumulative Effects Framework[1].

Cumulative watershed effects are a specific type of cumulative effect. They result from changes in watershed processes, such as runoff regimes, riparian function, water quality and channel morphology as a result of land use activities and/or natural processes (Scherer 2011). Changes in watershed processes can have environmental effects on fish or aquatic ecosystems, result in damage to private land, public safety or infrastructure, or impact water quality and quantity (Scherer 2011). The effects are not only environmental, but may also be perceived by those with existing cultural and/or tenure rights as compromising their ability to exercise those rights (Forest Practices Board, 2012), such as water storage and withdrawal for domestic or agricultural purposes or traditional food fisheries.

While various tools exist to assess cumulative watershed effects (Pike et al. 2010), Geographic Information System (GIS) indicator-based watershed assessment procedures offer a useful tool for assessing potential cumulative watershed effects in a regional to sub-regional management unit, such as a Resource District or Timber Supply Area (TSA). GIS indicators can be used to broadly characterize the type and extent of both land use activities and watershed characteristics that influence watershed processes and contribute to cumulative watershed effects. They provide a relatively efficient, cost-effective and repeatable approach to assess numerous (10^2 to 10^3) watersheds over broad geographic areas (up to millions of hectares). As such, they can be used to inform a variety of strategic-level applications where broad-scale considerations are involved, such as resource allocation decisions (e.g. Annual Allowable Cut (AAC) determinations), conservation designations (e.g. Fisheries Sensitive Watershed Designation), or prioritizing watershed restoration or rehabilitation activities with limited budgets (e.g. road rehabilitation or bridge replacements).

This report presents a GIS indicator-based watershed risk assessment procedure applicable for broad-scale assessment of cumulative watershed effects in the snowmelt-dominated hydrologic regime of the southern interior of British Columbia. The procedure is built off the framework presented by Carver (2001) and incorporates indicators and considerations described in other procedures (e.g. B.C. Ministry of Forests 1999, Carver and Utzig 2000, Green 2005).

2.0 Assessment Approach

The full Watershed Assessment Procedure follows a risk-based approach as described in Wise et al. (2004) and Canadian Standards Association (1997), where risk is the product of hazard and consequence defined by the risk equation; **Risk = Hazard x Consequence**. In this report, we present only the indicators and rating used to derive the hazard side of the risk equation. Indicators and ratings of consequence will

[1] http://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/cumulative-effects-framework

be described in a subsequent report (See Conclusions and Next Steps section). *Hazards* in this case are a source of potential harm, or a situation with a potential for causing harm in terms of human injury, damage to property, the environment, and other things of value, or some combination of these[2]. Hazard ratings are the measurement or expression of the likelihood of hazard occurrence. In watershed management hazards can include:

1) **Streamflow effects** – increased frequency and magnitude of hydro-geomorphic events (floods, bank erosion, channel instability, debris floods and debris flows),
2) **Sediment** generation and delivery – 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
3) **Riparian Function** – reduced channel bank stability, stream shading and large woody debris inputs.

We use a five-class hazard rating scheme by using the qualitative terms (*Very Low, Low, Moderate, High, Very High*) to express the likelihood of a harmful event occurring (hazard) as a result of land use activities (Table 1). The five-class rating scheme can be adapted to a three-class rating scheme (*Low, Moderate, High*) by combining *Very Low* and *Low* into a single *Low* rating , and *High* and *Very High* in to a single *High* rating as applied in Figure 1.

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%

Hazard ratings are intended to be used with consequence ratings derived for downstream ecological and socio-economic values to derive risk ratings (Figure 1). *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. Consequence ratings are the measurement or expression of the potential loss or damage to downstream values, and the specific elements at risk comprising those values. The relative consequence resulting from any specific hydrologic hazard depends on the vulnerability and worth of downstream value being considered. Thus, combining hazard and consequence ratings to develop risk ratings requires careful consideration of the best available information regarding the presence and vulnerability of downstream elements to specific hydrologic hazards.

[2] Adapted from definitions provided in Land Management Handbook #56 (Wise et. al. 2004).

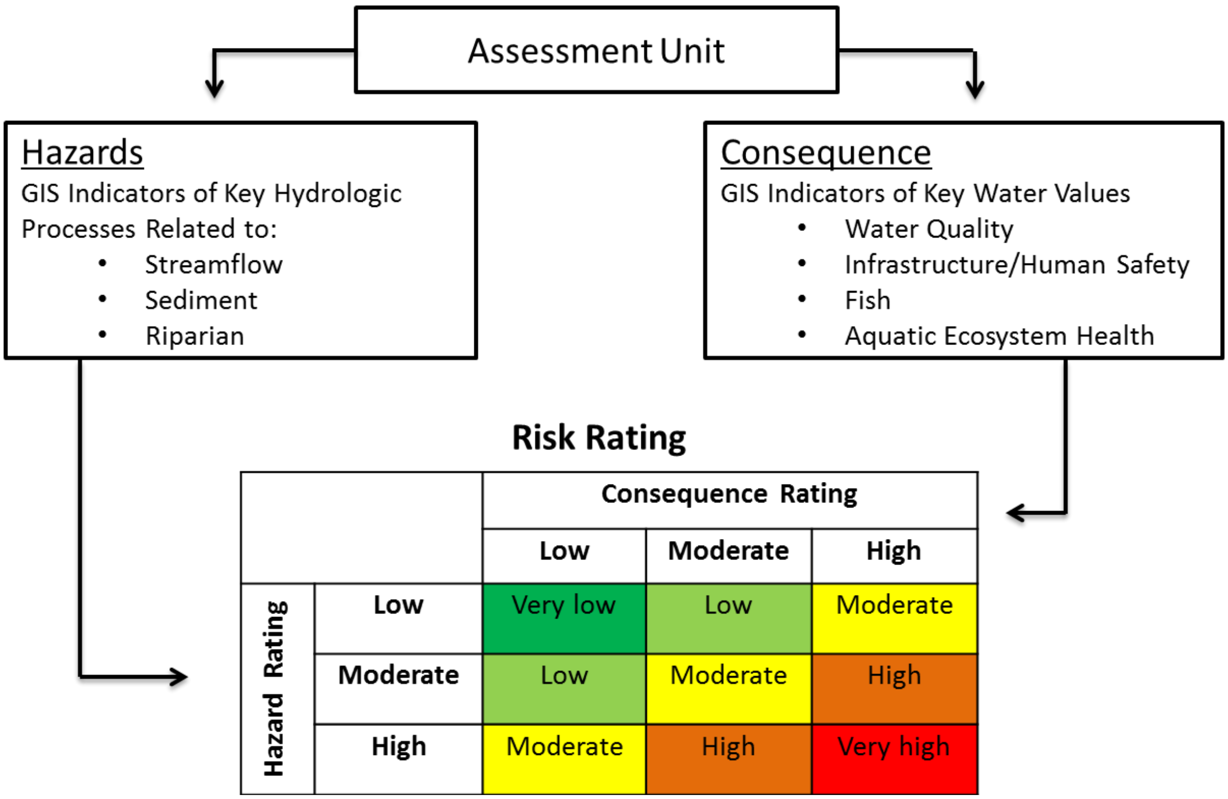


Figure 1. A qualitative risk matrix illustrating how hazard ratings from this assessment can be used with consequence ratings for both ecological and socio-economic values.

We stress that GIS-based indicators and ratings, while useful for strategic level planning decisions in large management units (TSA's, Resource Districts), should not be used alone to make operational decisions or set management targets at the individual watershed level. GIS indicator-based watershed risk assessments can be useful to 'flag' potentially high risk watersheds to assist in directing limited resources (e.g. riparian restoration, road rehabilitation efforts) or to focus conservation efforts (e.g. Fisheries Sensitive Watershed designations) but they must be followed up by further investigations by qualified professionals, including field work, as part of a multi-step process as shown in Figure 2.

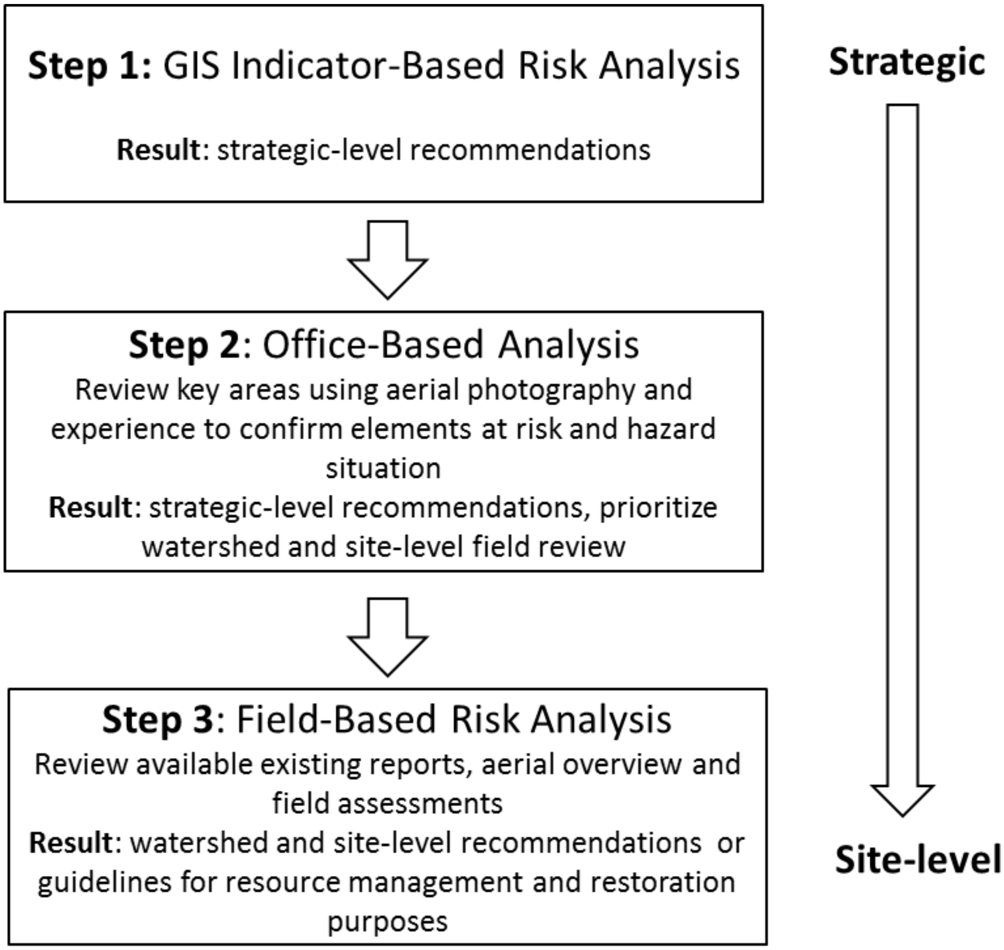


Figure 2. Three-step approach recommended for moving from strategic-level watershed risk analysis to site-level operational assessment and recommendations. Adapted from Forsite Consultants Ltd. and M.J. Milne & Associated Ltd. (2012).

3.0 Certainty and Confidence in Assessment Results

We are confident that the indicators and their application in the approach described herein will give a useful first approximation of the key hydrologic processes and watershed characteristics affecting streamflow, sediment and riparian function in a watershed. Nonetheless, we recognize the indicator scores and weightings used in this procedure relies strongly on expert judgement and may lack the certainty and confidence of data driven models or site-level field assessments. Throughout this document we attempt to be explicit in how indicator outputs are used to derive scores and ratings including key assumptions used. We avoid hidden, subjective weightings applied to indicators so the approach is transparent and repeatable and can be improved with new information. Therefore, we strongly recommend that whenever possible, model outcomes are validated by additional analyses as shown in Figure 2 and where necessary the results of those analyses, used to adjust indicators, scores and hazard ratings accordingly.

Throughout the document, we describe key sources of uncertainty in the indicator scores and hazard and risk ratings. All forms of assessment, particularly those analysing complex systems and unpredictable human behaviours, involve uncertainty (Table 2). Strategic-level GIS indicator-based assessments such as this, have particular uncertainties inherent with human behaviour, the broad-scale of application, the generalizations and assumptions used to characterize the complex systems involved, and information and data limitations.

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

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, clearly stating 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

To describe confidence in the indicators and ratings we adopted guidance developed for the Intergovernmental Panel on Climate Change vulnerability assessments[3] (Table 3). We accompany confidence ratings with descriptions of key types and sources of uncertainty that affect our confidence.

Table 3. Terminology and descriptions of confidence used to assign confidence ratings.

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

[3] Confidence statements follow recommended terminology from Table 2 in the Intergovernmental Panel on Climate Change (IPCC) Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties, July 2005

4.0 Assessment Units

We built a hierarchical structure of watershed units using BC Freshwater Atlas (FWA; https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/freshwater) 1:20,000 Watershed Assessment Unit boundaries (Carver and Gray, 2010) as the base units. The hierarchical structure consists of Super Watersheds, Large Watersheds, Watersheds, Basins, Sub-Basins and Residual Units, hereafter collectively referred to Assessment Units (AUs); see Figure 3. We determined the AU hierarchy by using the stream order ranking in the 1:20,000 FWA stream network to identify major drainage networks (Large or Super-watersheds) that flow into major southern interior B.C. river systems (e.g. Thompson or Fraser Rivers). We then delineated smaller units nested within the larger units.

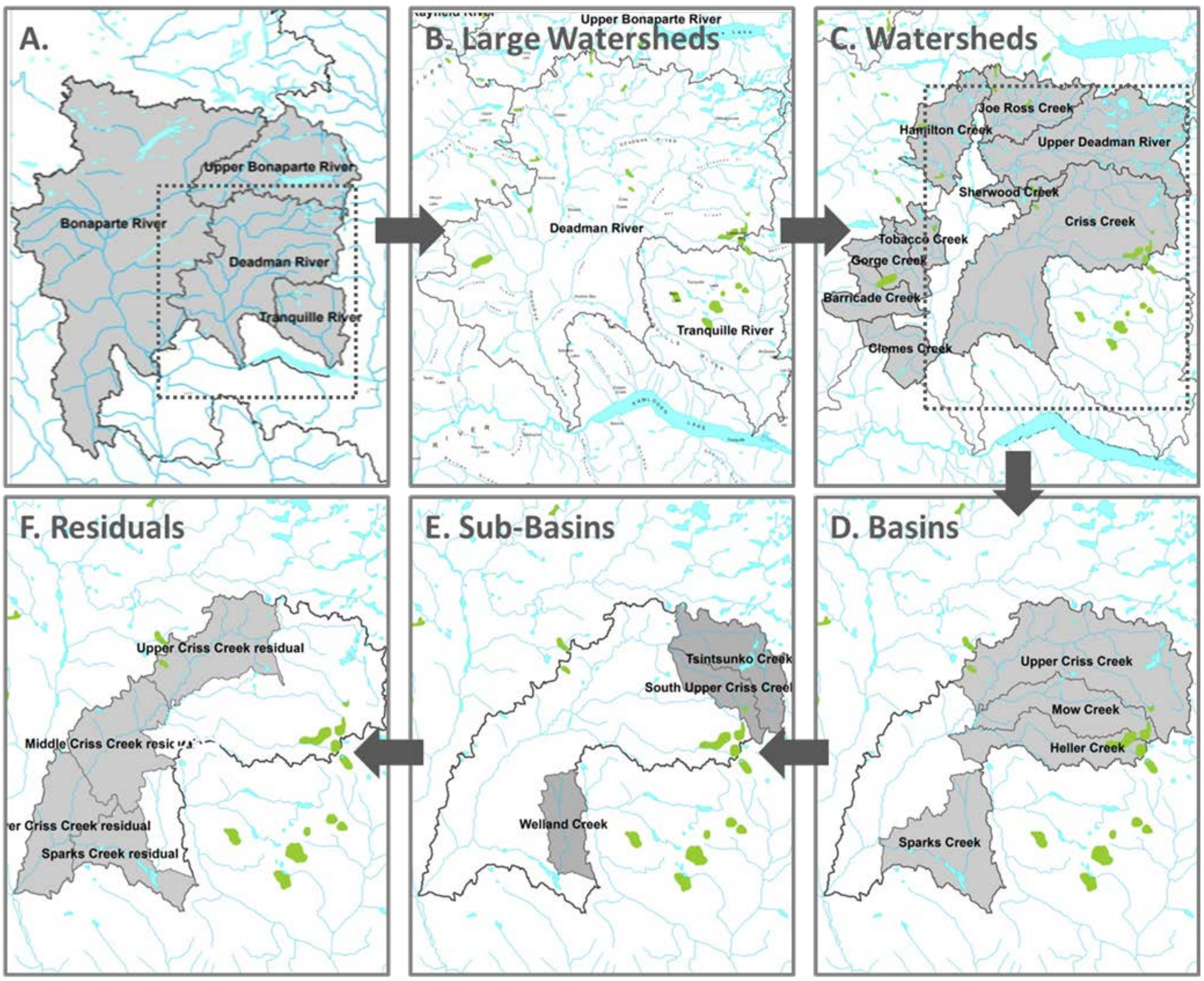


Figure 3. An example of the hierarchical structure used in the assessment. Fig 3A shows several large drainages (5th order or greater) that flow into the Thompson River west of Kamloops, B.C. Figures 2B-F, following the arrows, shows the progression from larger to smaller AU delineation, from: B) The 6th order Deadman River Large Watershed. C) Watersheds within the Deadman River Large Watershed. D) Basins within the Criss Creek watershed, southeast portion of Deadman River large watershed. E) sub-basins and F) residual units within the Criss Creek watershed.

5.0 Indicators and Ratings

Within each hazard category (streamflow, sediment and riparian), we selected indicators to represent watershed characteristics and land use activities that affect key hydrologic and geomorphic processes (Figure 4). Several indicators describe watershed characteristics associated with climate, geography and AU morphology; reflecting the inherent hydrologic or geomorphic sensitivity of each AU to land use and disturbance. Land use disturbance indicators reflect the various types and extent of land use activity and natural disturbances that may alter or impair key hydrologic and geomorphic processes.

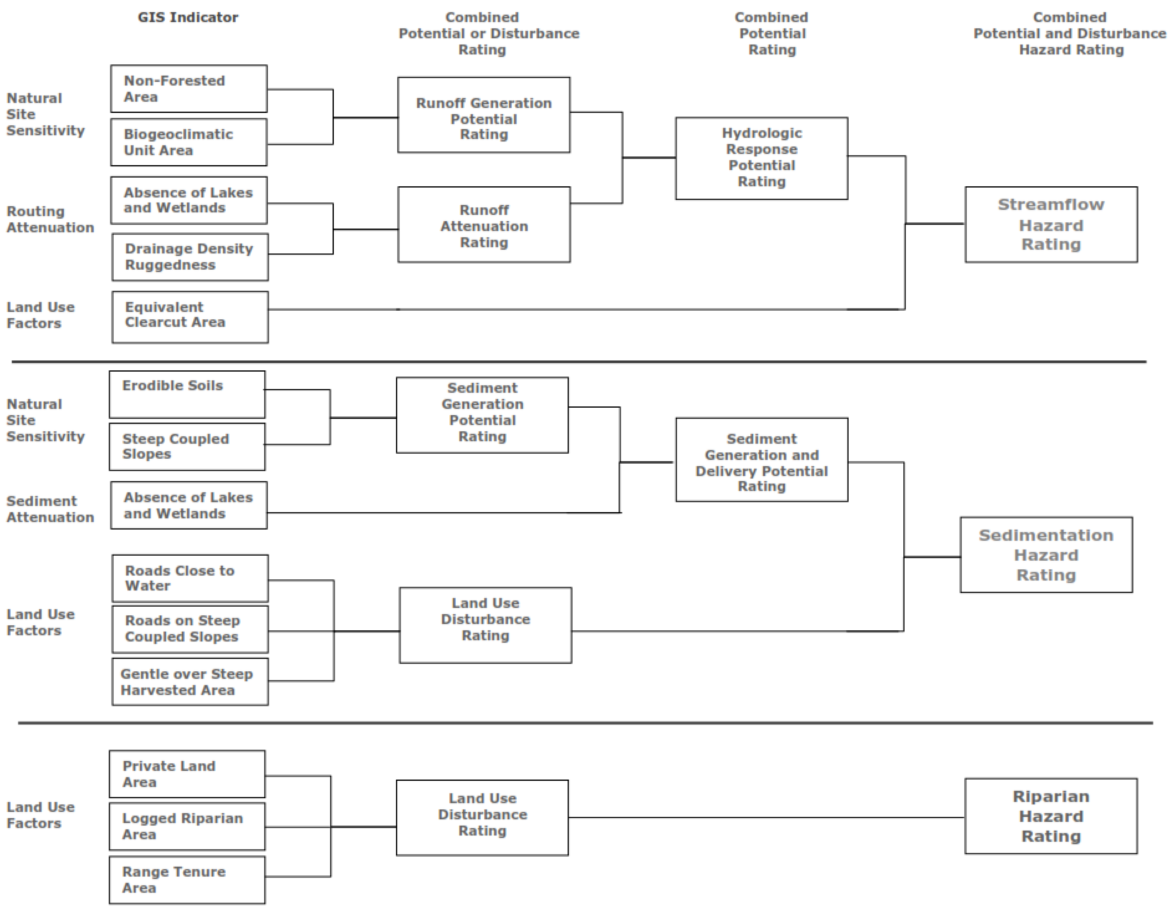


Figure 4. Flowchart illustrating the relationship of combined indicators to form ratings that are output from the assessment procedure.

The following sections describe data sources and assumptions used to generate indicators and derive the hazard ratings used in the assessment.

5.1 Streamflow Hazard

Streamflow[4] in the southern interior of B.C. is characterized by a snowmelt dominated or 'nival' hydrologic regime, with a distinctive 'peak' in the spring months (May-June) resulting from snowmelt-generated runoff (Eaton and Moore, 2010). A large proportion (up to 80%) of total annual water yield is discharged in the peak flow[5] period. The peak flow and peak flow period are of considerable management concern as they can result in channel forming events important when considering the design of stream crossings, in-stream structures or the effects of flooding on downstream values. Snowmelt dominated hydrologic regimes are also characterized by a growing season low flow period (July-October).The growing season low flow period is also of significant management concern when considering instream flow requirements for fish and water availability for drinking water, irrigation and other uses. The focus of this assessment is on harmful peak flows, albeit several streamflow indicators and ratings related to watershed characteristics are relevant to the assessment of changes in growing season low flows. We intend to consider additional land use indicators and modifications for low flow hazard assessment in a subsequent version of this procedure (see Conclusions and Next Steps sections).

Forests can play a significant role in affecting peak flows in snowmelt dominated hydrologic regimes (Winkler et al. 2008, 2010a, 2015). Loss or alteration of the forest canopy can reduce the amount of precipitation that is intercepted and evaporated (Winkler et al. 2010a). In snowmelt dominated regimes, forest canopy loss leads to increased snow accumulation and melt rates (Winkler et al. 2012). Forest canopy loss has been shown to increase the potential frequency of more extreme peak flow events that can significantly impact downstream values (Forest Practices Board 2007, Alila et al. 2009, Grainger and Bates 2010, Green and Alila 2012).

We also recognize that the magnitude, duration and timing of the peak flow in a given year are controlled by a number of factors including (From Winkler et al. 2010a):

1. The duration and intensity of 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, and
3. Watershed characteristics affecting precipitation, watershed response and synchronization of runoff including drainage area, elevation, aspect, topography, physiography and storage (i.e. lakes, reservoirs and wetlands).

In this procedure, we include only factors affecting hydrologic and geomorphic processes for which readily available GIS datasets exist. We did not include factors associated with weather, and antecedent moisture conditions as these are outside the scope of GIS-based indicators, and are best considered through process-based models (See Beckers et al., 2009 and Pike et al. 2010 for reviews). Thus, Streamflow Hazard is derived in three stages based on considerations of:

1. The natural potential to generate increased runoff[6] due to man-made and natural forest canopy disturbances , referred to as *Runoff Generation Potential*,
2. How efficiently runoff is slowed as it is transferred downslope and downstream, referred to as *Runoff Attenuation,* and

[4] Streamflow is defined as water flowing in, or discharging from a natural surface stream (Winkler et al. 2010a).
[5] Peak flow is referred to here as the greatest instantaneous discharge occurring in a year (Pike et al. 2010). The peak flow period is the several weeks to months during which snowmelt runoff results in elevated streamflows, and in which the maximum annual peak flow usually occurs.
[6] 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)

3. The extent and severity of forest canopy disturbances and the degree of hydrologic recovery of disturbed forest as measured by the indicator *Equivalent Clearcut Area (ECA)*.

5.1.1 Runoff Generation Potential

Runoff Generation Potential refers to the potential for additional runoff to be generated due to forest cover loss or alteration. The Runoff Generation Potential Rating considers the type and amount of precipitation, when precipitation falls or melts, and how widespread and dense forest cover is to intercept, sublimate and/or evapotranspire incoming precipitation. We represent these factors using two metrics having readily available GIS data covering most of BC: Biogeoclimatic (BEC) Unit and Non-forested Area.

5.1.1.1 Biogeoclimatic Unit Area

In BC, the Biogeoclimatic Ecosystem Classification (BEC) system is used to delineate areas with relatively homogeneous climate and vegetation cover (Meidinger and Pojar 1991). We use provincial BEC units to as an indicator of average annual precipitation, average snowpack accumulation and persistence, and forest cover density; all factors that influence the potential for a watershed to generate runoff and forest cover loss to affect that situation. 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. Increases in water yield following a reduction in vegetation cover have been shown to be greatest in coniferous forests in areas with more precipitation (Best et al. 2003, Bosch and Hewlett 1982).

To generate the *BEC Unit* indicator, we assigned values between 0 and 3 for each BEC unit considering average annual precipitation, snowpack accumulation and persistence, and forest density and continuity (Table 4). We then calculated an area-weighted average BEC Unit score to derive a single BEC Unit Score for each AU.

Table 4. Biogeoclimatic (BEC) units and the associated BEC unit score assigned in the assessment procedure.

Biogeoclimatic (BEC) Units	BEC Unit Score
BAFAun, BGxh1,xh2,xh3,xw1,xw2, CMAun,unp CWHun, ESSFdcp, ESSFdvp, ESSFmmp, ESSFmvp, ESSFmwp, ESSFvcp, ESSFwcp, ESSFxcp, ESSFxvp, IDFdc, IDFdk1,1a,1b,2,2a,2b,3,4, IDFdm1, IDFdw, IDFmw1,mw2,mw2b, IDFww, ww1, IDFxc, IDFxh1, 1a, 2, 2a, IDFxm, IDFxw, IMAun, IMAunp, PPxh1,xh1a, xh2,xh2a	**0**
CWHms1, MSxk3, xv, SBPSxc, SBPSdh1	**0.5**
CWHds1, ESSFmm1, ESSFxv1,xv2, ICHdk, ICGHdw3,ICHmw2, MSdc2, MSdv, MSxk1, xk2, SBPSdc, SBPSdk,SBPSdw1, dw3, SBSmh, SBSmw	**1.0**
ICHmm,ICHmw3,SBPSmk, SBPSdw2	**1.25**
ESSFdv1, dv2,dvw,ESSFmmw,ESSFmww, ESSFxc1,xc2,xc3, xcw, ESSFxvw, ICHmk1, mk2, mk3, MSdm1, dm2, dm3, dm3w, MSmw1, SBPSmc,SBSmc2, mc3, SBSmk1, SBSmm,	**1.5**
SBSmc1	**1.75**
ESSFc1, dc2,dc3, ESSFdcw, ESSFmv1, ESSFmw, mw1, mw2, ICHwk1, wk1c, wk2, wk4, MSdc1, dc3, MSmw2,	**2.0**
ICHvk1, vk1c,	**2.25**
MHmm2, SBSvk, SBSwk1	**2.5**
ESSFvc, vcw, ESSFwc2, wc2w, wc3, wcw	**3.0**

5.1.1.2 Non-Forested Area

We used the *Non-Forested Area* indicator to estimate the amount of naturally non-forested area. While precipitation in non-forested areas contributes to runoff, watersheds with a large proportion of naturally non-forested area will generate less additional runoff with forest canopy loss or alteration (Winkler et al. 2010a).

We classified the natural non-forested area in any catchment as that area assigned a 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), such as alpine, rock, swamp or non-productive brush. We calculated the indicator score as the proportion (%) of non-forested area relative to total AU area.

5.1.1.3 Runoff Generation Potential Rating

The *Runoff Generation Potential Rating* is an expression of the potential to generate additional runoff due to forest canopy loss. It combines the *BEC Unit* and *Non-Forested Area* indicator scores in a ratings matrix (Table 5) such that densely forested AUs with little non-forested area, relatively higher precipitation and deeper and persistent snowpacks are rated highest.

Table 5. A Runoff Generation Potential Rating matrix based on binned BEC Unit and non-forested area indicator scores.

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

5.1.2 Runoff Attenuation

Runoff Attenuation refers to how efficiently hillslope and stream runoff is slowed, captured and stored as it is routed through the watershed. We represent Runoff Attenuation using two indicators that can be determined from readily available GIS data covering most of B.C.: 1) *Drainage Density Ruggedness* and 2) *Absence of Lakes and Wetlands.*

5.1.2.1 Drainage Density Ruggedness

Drainage Density Ruggedness (DDR) indicates the potential for rapid runoff delivery to and through streams, which may contribute to harmful flood events (Patton and Baker, 1976). DDR (Melton, 1957) 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 points in the AU relative to AU length - Km (Schumm 1956). Drainage density (Horton 1932, 1945) has been shown to reflect important natural factors influencing runoff storage and routing such as soil type, permeability, depth, overall hillslope gradient and the distance water has to travel before reaching the mainstem. With increasing relief, 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.

To calculate drainage density (km/km^2) we use the 1:20,000 FWA stream network to determine total stream length (km), and divide this by total AU area (km^2). We calculate elevation relief by using 1:20,000 TRIM elevation contours to measure the elevation difference between the lowest and highest point in each AU (km), divided by the distance between those points (km). Although roads can expand the stream drainage network by intercepting subsurface hillslope runoff (Wemple et al.1996, Gucinski et al. 2001), we did not include roads in the calculation of drainage density. Our drainage density indicator is intended to reflect the inherent runoff routing efficiency of each AU regardless of land use activity. Since road density is generally correlated with the amount of forest harvesting, we consider the effects of roads on drainage density (which has been decreasing over the last several decades with better road drainage management) are captured by the ECA indicator when calculating the Streamflow Hazard Rating.

5.1.2.2 Absence of Lakes and Wetlands

The presence of lakes, ponds, wetlands and man-made reservoirs in a watershed can have an attenuating influence on peak flow discharges (Acreman and Holden 2013, Woltenmade and Potter 1994, Taylor and Pierson 1985). Flood levels have been shown to be reduced as the percent of watershed area in lakes and wetlands 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 natural and man-made lakes and wetlands to buffer peak flow response. To calculate the indicator we use the 1:20,000 FWA lakes and wetlands layers to measure the area of lakes and wetlands within the lower 30%, mid 30% and upper 40% of each AU. We then calculated the area-weighted proportion (%) covered by lakes and wetlands by weighting the lower 30% of the AU area by 100%, the middle 30% of the AU by 75% and the upper 40% by 25%. This gives greater weight to larger lakes and wetlands situated lower in an AU, which are more likely to attenuate runoff from a larger proportion of the AU.

5.1.2.3 Runoff Attenuation Rating

A *Runoff Attenuation Rating* is a qualitative expression of how effectively hillslope runoff will be slowed, captured and stored. We derived the rating by combining the *Drainage Density Ruggedness* and *Absence of Lakes and Wetlands* indicators in the Runoff Attenuation Rating matrix (Table 6). For the Absence of Lakes and Wetlands indicator the weighted area of lakes and wetlands was inversely scored such that AUs with more location-weighted area of lakes and wetlands have a higher runoff attenuation rating.

Table6. Runoff Attenuation matrix based on binned scores for DDR and Absence of Lakes and Wetlands indicators.

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

5.1.2.4 Hydrologic Response Potential Rating

The *Hydrologic Response Potential Rating* is a qualitative expression of the potential for increased runoff to be generated as a result of reductions in forest cover, and how efficiently runoff is delivered downstream. We derived the rating by combining the *Runoff Generation Potential* and *Runoff Attenuation* ratings in the following matrix (Table 7). Wetter and more densely forested AUs that are steep and have little runoff attenuation are more likely to respond hydrologically to forest cover loss, and will have a higher *Hydrologic Response Potential Rating*.

Table7 . Hydrologic Response Potential Rating matrix based on combined Runoff Generation Potential and Runoff Attenuation Ratings.

		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

5.1.3 Equivalent Clearcut Area

Land Use Disturbance is a function of the single indicator, Equivalent Clearcut Area (ECA). We use ECA to determine the area of an AU over which a reduction in forest cover has occurred that is hydrologically equivalent to a recent clearcut. ECA is intended to be a reflection of the relative hydrologic function of disturbed compared to mature forests. ECA estimates are based on existing research in nival (snow-melt dominated) environments documenting differences in snow accumulation, energy fluxes and melt rates between clearcut openings, mature, regenerating, and insect attacked forests (Winker et al. 2012, Winkler et al. 2010b, Winkler and Boon 2010, 2015).

ECA is calculated for each opening by applying a net-down of the total disturbed area, based on tree height as an index of relative hydrologic recovery in the regenerating forest (BC Ministry of Forests and BC Ministry of Environment 1999, Winkler and Boon 2015). We use VRI information to identify projected tree heights and calculate ECA using published hydrologic recovery rates (Winkler and Boon, 2015). We assigned perpetually de-forested areas (urban, agricultural, highways, transmission right of ways) an ECA of 100%. Recent wildfires are modelled the same as clearcuts assuming these have limited residual structure[7] to influence hydrologic function. For partial forest disturbances (i.e. partial cuts, un-harvested insect attacked stands) ECA values are net-down by factoring in the relative hydrologic function contributed by residual forest cover and forest re-growth in the time since disturbance. For partial cut forests, we followed estimates provided in the Interior Watershed Assessment Guidebook (B.C. Ministry of Forests and B.C. Ministry of Environment 1999). We applied ECA net-downs for un-harvested Mountain Pine Beetle (MPB)-attacked forests for different BEC subzones using predicted pine mortality (Walton, 2010) with modelled ECA estimates from Lewis and Huggard (2010) to incorporate the hydrologic function of non-affected pine and non-pine overstory and understory trees.

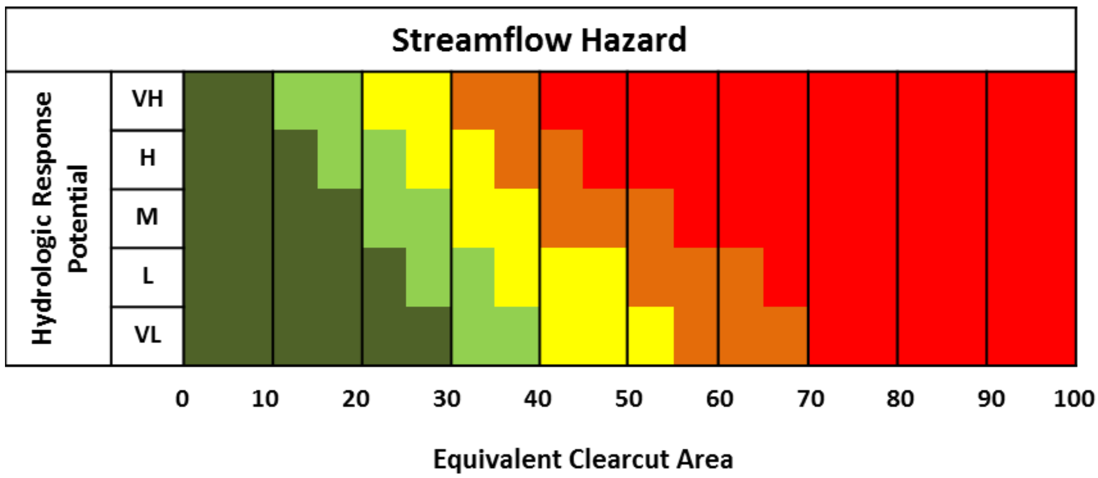
5.1.4 Streamflow Hazard Ratings

The *Streamflow Hazard rating* is a qualitative estimate of the likelihood of harmful changes in streamflow will result from current land use activities. In particular, an increase in peak flow frequency and magnitude may result in harmful hydro-geomorphic events (floods, bank erosion, channel instability, debris floods, and debris flows). We combined the *Hydrologic Response Potential Rating* and

[7] Includes within-stand residual structure such as individual retained trees or clumps outside of reserves (wildlife tree patches) or fires skips that were large enough to be identified as a forested polygon (ECA=0%).

Land Use Disturbance ECA values to generate a *Streamflow Hazard Rating* using the following matrix (Table 8).

Table 8. Streamflow Hazard Rating matrix based on Hydrologic Response Potential Rating and ECA values.



The matrix shows an increased likelihood of peak flow increases and streamflow hazards with increased hydrologic response rating and reduced forest cover. To generate the ratings, we assign a *Moderate* Hydrologic Response Rating combined with ECA values 30 to 40% to yield a *Moderate* Streamflow Hazard; consistent with published findings showing increased frequency and magnitude of peak flows at moderate (33-40%) harvest levels (Green and Alila 2012, Winkler et al. 2015). A *Moderate* Hydrologic Response Rating combined with ECA levels <20% yields a *Low - Very Low* Streamflow Hazards (a significant increase in runoff generated is *Unlikely* to occur) as changes in streamflow are not detected when vegetation cover reduction is <20% (Best et al. 2003). We then extrapolate to get other Streamflow Hazard ratings from lower and higher Hydrologic Response ratings and ECA values.

Confidence in the Streamflow Hazard Rating and Indicators

Based on the indicators and ratings used, we have *High* confidence that the Streamflow Hazard ratings adequately estimate the likelihood of increased frequency and magnitude of peak flows following forest cover disturbances, for the strategic level application it is intended for. Our confidence level in these ratings 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.
- *High* confidence that the indicator (ECA) adequately captures the effects of human and natural disturbances on forest cover.
- *High* confidence that the above indicators and their scores are supported by considerable published literature on the effects of reduced forest cover and recovery on snow accumulation and ablation affecting runoff and streamflow response.
- *High* confidence that the resulting ratings are consistent with experience and observations derived from field-based watershed risk assessments completed throughout southern interior B.C.

5.2 Sediment Hazard

Sediment hazard refers to harm or the potential for harm to elements at risk from increase in the amount, frequency and/or duration of sediment generated from non-natural sources entering a stream and being delivered downstream. In the interior of B.C., streams in many forested mountain and plateau-type watersheds have relatively low sediment budgets given the relatively low levels of geomorphic activity (Slaymaker 1987, Church et al. 1989, Jordan 2006). Thus, road-related sediment sources can have significant impacts on watershed sediment budgets (Jordan et al., 2010). Forest road-related sediment can be generated through mass wasting events (i.e. landslides) from road cut or fill failures or inadequate or poor road drainage, and from road surface erosion resulting from inadequate drainage control and failure of road drainage structures (Jordan et al,2010). Given a general improvement in road-building practices since the 1980's, road-related landslides have decreased in significance (Carson et al. 2009), but where they occur can dominate the sediment budgets for many years (Jordan et al. 2010). Surface erosion due to resource road construction and use is considered the most significant and chronic source of fine sediment to streams (Jordan et al. 2010). Increased sediment inputs from both landslides and chronic inputs from surface erosion can have harmful effects on downstream elements such as water quality, fish and fish habitat (Reid and Dunne 1984, Gucinski et al 2001).

The Sediment Hazard Rating is derived in three stages based on considerations:

1) The natural potential to generate increased levels of sediment from road and land use disturbances or 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 affecting *Sediment Generation and Delivery Potential*, and
3) Estimates of the likelihood that the extent of road-related sediment sources that are hydrologically connected to water bodies will generate and deliver harmful sediment levels.

<u>5.2.1 Sediment Generation Potential</u>

Sediment generation potential refers to the potential for sediment to be generated when affected by land use activities. We based estimates of sediment generation potential on two indicators that can be determined from readily available GIS data covering most of BC; 1) erodible soils, and 2) steep coupled slopes.

5.2.1.1 Erodible Soils

We used the *Erodible Soils* indicator to estimate the potential for soil erosion to occur. Since B.C. lacks comprehensive finer scale (e.g. 1:20,000 – 1:100,000) soil data layer that can be used in a GIS-based approach to identify the extent and location of erodible surficial and sub-surface material, we used the provincial 1:2m Quaternary Deposit layer (https://www2.gov.bc.ca/gov/content/data/geographic-data-services) to identify the extent of erodible soils as a percentage of watershed area (see Table 8). Quaternary deposits are often glacio-fluvial or glacio-lacustrine sedimentary deposits that lack cohesion and are highly prone to erosion. Field experience has shown that quaternary deposits are a continuous and problematic source of sediment generation and delivery where they occur in the southern interior.

5.2.1.2 Steep Coupled Slopes

We use the *Steep Coupled Slopes* indicator to estimate the potential for sediment to be generated from land use on potentially unstable terrain and enter a stream. To derive the indicator, we used the B.C.

Digital Elevation Model (DEM; https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/elevation/digital-elevation-model) to identify the extent of steep (>50% gradient) slopes 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.

5.2.1.3 Sediment Generation Potential Rating

We assigned a *Sediment Generation Potential Rating* by combining the *Steep Coupled Slopes* and *Erodible Soils* indicators using the following matrix (Table 8).

Table 8. Sediment Generation Potential Rating matrix based on percent (%) Erodible Soils and Steep Coupled Slopes indicators

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

5.2.2 Sediment Generation and Delivery Potential Rating

The *Sediment Generation and Delivery Potential Rating* uses the *Sediment Generation Potential Rating*, modified by the *Absence of Lakes and Wetlands* indicator to provide a qualitative estimate of the watershed potential for increased sediment to be generated from non-natural sources and to be delivered downstream (Table 9). As with runoff attenuation, sediment transfer in streams can be attenuated by lakes, ponds, wetlands and man-made reservoirs. We used the same Absence of Lakes and Wetlands indicator values as in the Streamflow Hazard section, to reflect the sediment attenuating characteristics of a watershed.

Table 9. Sediment Generation and Delivery Potential Rating based on the Sediment Generation Potential and Runoff Attenuation Ratings.

		Lakes and Wetlands		
		L	M	H
Sediment Hazard Rating	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

5.2.3 Land Use Disturbance

Most sediment sources associated with roads are associated with easy to identify point sources that occur wherever disturbed terrain comes in close hydrologic proximity with natural water bodies (Carson et al. 2009). However, single GIS-based indicators of road-related impacts that don't consider proximity (e.g. road density) are not well correlated with field-based estimates of sediment hazard (Carver and Teti, 1998), and often do not adequately capture sediment impacts on underlying hydrologic or geomorphic processes (Carver 2001). We use three indicators to reflect the potential for roads and land use activities to generate and deliver sediment directly into streams including: *Roads Close to Water*, *Roads on Steep Coupled Slopes* and *Disturbance on Gentle over Steep Terrain coupled to streams*.

5.2.3.1 Roads Close to Water

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

- Sediment deposited directly during road construction,
- Continuous ditchline and running surface erosion, particularly during wet seasons, and
- Cutbank and fillslope failures.

We used the *Roads Close to Water* indicator to estimate the potential for increased sediment generated from surface erosion or mass wasting events to enter a stream. We used the B.C. Digital Road Atlas (DRA; https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/roads) layer to identify all roads. 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. We then calculate the indicator as the road length within 50m of a stream per unit watershed area (km/km^2).

5.2.3.2 Roads on Steep Coupled Slopes

Roads on steep coupled slopes are a primary source 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). We use the *Roads on Steep Coupled Slopes* indicator to capture the potential for increased sediment to be generated and delivered to streams. We calculated the indicator by measuring the percent total road length (Km) on steep coupled slopes (km/km^2; See Steep Coupled Slopes Indicator description).

5.2.3.3 Disturbance on Gentle over Steep Terrain

Poor road drainage (i.e. plugged, undersize 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 mast wasting events (Jordan 2002, Grainger 2002, Jordan et al., 2010).We use the *Disturbance on Gentle Over Steep Terrain* indicator to estimate the area with logging on gentle slopes (<50%) immediately above steep slopes (>50%) coupled to streams. We identify gentle slopes above steep coupled slopes using the provincial DEM. We then use the provincial VRI layer to identify all polygons with a harvest history and calculate the harvested area within gentle terrain adjacent to steep coupled terrain as a percentage of watershed area.

5.2.3.4 Land Use Disturbance Rating

To generate a combined land use disturbance rating with the three road-related sediment indicators, we first assign a score (1-3) for each indicator based on relative road length or logged area in a watershed (Table 10). We then summed individual indicator scores to derive an overall Land Use Disturbance Rating. Combined scores of 3, 4, 5, 6 and 7 or greater are assigned a Very Low, Low, Moderate, High and Very High rating respectively.

Table 10. Scoring matrix for land-use indicators.

Indicator	Score			Indicator measurement
	1	2	3	
Roads Close to water	<.1	.1 -.3	>.3	length of roads within 50m of stream per unit watershed area (Km/Km^2)
Roads on Steep Coupled Slopes	<0.005	0.005-0.010	>0.010	Length of roads on steep coupled slopes per unit watershed area(Km/Km^2)
Disturbance on Gentle Over Steep	<5%	5.1-10%	>10%	Percentage of watershed area with logged gentle terrain area above steep coupled slope

5.2.3 Sediment Hazard Rating

A *Sediment Hazard Rating* is a qualitative expression of the likelihood that harmful levels of sediment will be generated from existing land use activities, enter into a stream and be delivered downstream. We derive a *Sediment Hazard Rating* by combining the *Sediment Generation and Delivery Potential* and *Land Use Disturbance Ratings* in the following matrix (Table 11).

Table 11. Sediment Hazard Rating matrix based on Sediment Generation and Delivery Potential and Land Use Disturbance Rating.

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

Confidence in the Sediment Hazard Rating and Indicators

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

- *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),
- *Moderate* confidence that assumptions regarding human behaviour (road construction and maintenance practices, patterns of use) that influence road-related sediment generation and delivery reflect actual conditions in any given area. 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 estimates and associated hazard 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 reflect the extent of erodible soils in a watershed. Although our experience has shown the presence of Quaternary deposits often results in sediment delivery to streams, the coarse spatial resolution of input data can only be used, at best, to inform relative differences between AUs over large areas. Our confidence in this indicator would increase with improved soils data.

5.3 Riparian Function Hazard

Riparian Function Hazard refers to the loss and/or alteration of riparian vegetation causing reduced function of the riparian area.[8] Within the riparian area a wide variety of hydrologic, geomorphic, and biotic processes interact and exert an influence on the adjacent aquatic and terrestrial environment (Richardson and Moore, 2010). These processes result in a distinct vegetative community that support riparian functions, including maintaining soil and stream bank stability, filtering sediment and nutrients to maintain water quality, and providing habitat structures for aquatic or terrestrial organisms (Richardson and Moore, 2010). In this assessment procedure, we define riparian function more narrowly by referring to three key ecological functions of riparian vegetation in the aquatic environment, including:

1) The provision of stream bank stability (Eaton et al., 2004), particularly where alluvial materials are involved,
2) The recruitment of large woody debris (LWD) to aquatic systems. In-stream wood plays a role in the regulation of sediment in channels, creation of fish habitat, and dissipation of energy and sediment in alluvial fan and floodplain environments (Hogan and Luzi 2010, Smith et. al. 1993, Robison and Beschta 1990), and

[8] Riparian zones are defined as the portion of the terrestrial environment that exerts influence on a stream and/or that is influenced by the water body (Gregory et al.1991, Richardson and Moore 2010).

3) The provision of shade to aquatic systems. Riparian vegetation may intercept as much as 95% of light depending on a variety of factors, can alter microclimate and directly affect primary biotic production in the stream (Richardson and Moore 2010, Rex et al. 2013).

Riparian Function Hazard is derived using three indicators that measure the extent of land use activity that has the potential to affect riparian function: *1) Private Land, 2) Logged Riparian*, *and 3) Range Use*.

For all riparian function hazard indicators, we weighted the potential effects of land use activities on riparian function by stream size. Notwithstanding the many important ecological functions of riparian vegetation in small streams (Richardson and Moore 2010, Rex et al. 2012), the role of riparian vegetation in bank stability and LWD recruitment is less important in small stream channels with insufficient power to rework their beds and banks (generally <1.5 metres bank-full width). The banks and channel beds of these small streams most often remains stable despite removal of riparian vegetation. The role of riparian vegetation, particularly mature trees, in providing bank stability and LWD is greatest in mid-sized streams (1.5-20+ metres) wide.

To capture these effects, we applied a weighting factor to the total length of stream affected by each land use activity based on stream size, where: small streams (first order generally <1.5m wide) are weighted by 0.5; small to mid-sized streams (approx. 1.5-3 m. wide) by 0.75, and mid-sized streams (approx. 3-20+m wide) by 1.0. Major rivers (>30m wide) are not a part of the AU hierarchy.

5.3.1 Private Land

Urban and agriculture development in the riparian area of streams on private land can contribute a variety of negative effects on riparian and stream channel habitat and water quality, including (after Allan 2004):

- A chronic source of non-point source pollutants in runoff,
- Altered flows or erratic hydrology through re-direction of water off impervious surfaces and/or channelization of streams,
- Increased sediment delivery and bank de-stabilization through livestock trampling, and
- Increased water temperature with reduced riparian cover.

The *Private Land* indicator estimates the potential loss of riparian function associated with private land by measuring the proportion (%) of total stream length that is overlapped by private land. We used the 1:20,000 provincial Integrated Cadastral Fabric (https://catalogue.data.gov.bc.ca/dataset/cbm-integrated-cadastral-fabric-public-view) to identify private land including; urban, agricultural and federal Indian Reserve lands.

5.3.2 Logged Riparian

Forest harvesting and road-building activities in riparian areas can result in a number of direct physical alterations including (after Tschaplinski and Pike 2010):

- Input of fine sediments through loss of root strength following tree harvest and/or exposure of bare soil from machinery,
- Channel disturbances from cross stream falling and yarding,
- Channel bank erosion through de-stabilization of LWD, and
- Changes in stream temperature with removal of overstory vegetation.

Historic practices that removed riparian vegetation on channel morphology can persist for decades (Hogan and Luzi 2010). Even recent forest harvesting practices have been shown to have impacts, such as along small streams that have reduced riparian buffers (Tschaplinski 2010, Tschaplinski and Pike 2010). These site-level impacts can accumulate as the proportion of total stream length affected by logging increases (Jones et al. 1999, Nordin et al. 2009).

The *Logged Riparian* indicator estimates the effects of historic and current logging by measuring the proportion (%) of total stream length with harvesting within 30m of a stream. The logging history information in the most recent VRI layer with updated depletions is used to identify all harvested stands within a 30m buffer of 1:20,000 FWA stream network.

5.3.3 Range Use

A wide body of literature exists on the subject of livestock related impacts on riparian function and resulting impact to water quality and aquatic ecosystems (Fleischner 1994, Armour et al. 1991, Belsky et al. 1999, Agourdis et al. 2005), including:

- Removal or alteration of riparian vegetation through grazing,
- Streambank erosion and collapse of overhanging banks through tramping and shearing,
- Addition of fine sediment through bank degradation and off-site soil erosion,
- Soil compaction, and
- Deposition of fecal material.

In many parts of B.C., grazing tenures and leases on public land are granted to livestock owners providing relatively unrestricted access to streams and wetlands without natural or man-made barriers to prevent access. The *Range Use* indicator estimates the potential effects of livestock in riparian areas on the publicly owned or Crown land-base, using provincial range tenure data (https://catalogue.data.gov.bc.ca/dataset/range-tenure) to determine range tenure overlap with the 1:20,000 FWA stream network.

5.3.4 Riparian Hazard Rating

To generate a Riparian Hazard Rating from the three riparian indicators, we assign a score (1-3) based on the extent of stream affected by each land use impact (Table 12). For each AU, the hazard scoring assumes an increased total stream length exposed to one or more of the land use indicators has a greater potential to result in reduced riparian function. Combined scores of 3, 4, 5, 6 and 7 or greater are assigned a Very Low, Low, Moderate, High and Very High rating respectively.

Table 12. Scoring of indicator metrics for the riparian hazard rating

Indicator	Score			Indicator measurement
	1	2	3	
Private Land	<20%	21-40%	>40%	Percent stream length within or adjacent to private land
Logged Riparian	<20%	21-40%	>40%	Percent total stream length within or adjacent to cutblocks
Range Use	<30%	31-60%	>60%	Percent total stream length within active range tenures.

Confidence in the Riparian Hard Rating and Indicators

We have *Moderate to High* confidence that the Riparian Hazard Ratings reflect the likely extent and severity impacts to riparian function from various land use activity. Our confidence in the ratings and indicators is based on:

- *High* confidence that the Private Land indicator reflects the impacts of private land on riparian function. This is based on extensive field experience and observation of the extent and severity pf private land impacts on riparian vegetation in the southern interior of B.C. The effects of reduced riparian function on channel stability and associated processes are well described in published research,
- *Moderate-High* confidence that the Logged Riparian indicator reflects the accumulated effect of forest harvesting in riparian areas. While the effects s of riparian forest harvesting is well understood and documented in the published literature, all logging near streams may not have an equal impact. The data does not capture riparian reserves that may exist within the 30m buffer around streams and so the potential mitigating effects of riparian reserves, particularly regulated riparian buffers on larger streams (>5m), are unaccounted for, and

- *Moderate* confidence that the Range Use indicator reflects potential range use impacts on riparian function. Livestock-related effects can be significant in the interior of BC based on our own field experience and observation; as well as reported by others (Forest Practice Board, 2002, 2012). Unrestricted livestock grazing may result in more damage to riparian zones than the small numbers of animals would suggest, as cattle avoid hot dry environments and congregate in wet areas for water and forage (Belsky et al.1999). However, current data sources do not contain reliable information on cattle use, nor is the efficacy of stewardship practices or extent of range barriers impeding cattle access to streams known.

6.0 Conclusions and Next Steps

We present here a GIS indicator-based watershed risk assessment procedure applicable for strategic-level applications in snowmelt dominated watersheds of the southern interior of B.C. We have made a first approximation to classify watersheds based on potential to respond to land use, and the likelihood of changes in watershed processes based on the type and extent of land uses. Thus, we believe this procedure is useful for cumulative effects assessments that support various strategic-level decisions where considerations of multiple land uses over broad and diverse geographic areas is required. With this in mind, we also recognize that actual hazard conditions in any watershed may vary from those derived from this procedure when considering site-level factors that cannot be accurately accounted for using GIS-based indicators. Thus, this approach should not replace the use of qualified professionals and field-based assessments of individual watersheds for operational-level decisions.

A key next step in ongoing development of the procedure is to ensure the full range of land use activities that affect hydrologic processes are considered. The assessment procedure originated from a largely forest-sector specific application, so further work is ongoing to capture indictors of non-forest sector land use factors. Future work is specifically focussed on including additional indicators and ratings that account for:

- Low flow hazards – include or revise indicators to reflect watershed conditions susceptible to growing season low flows and land use activities that may affect growing season streamflow levels (e.g. industrial and domestic water withdrawals), and

- Water quality – include point sources of pollution such as; mining sector, agricultural or other industrial discharges.

Further work is also ongoing to support use of the described hazard ratings with GIS indicator-based consequence ratings as intended in a risk-based assessment approach. Important resource values that may be affected include:

- Drinking water intakes considering vulnerability of changes in water quality based on water treatment,
- Fisheries values – based on the distribution of sensitive species and the economic/cultural importance of the fishery to local and provincial economies, and
- Public and private property, infrastructure or human health and safety vulnerable to changes in peak flow.

As with any strategic-level GIS indicator-based assessment procedure, we also recommend that ongoing validation of indicators and ratings using consistent measures of impact, is required to improve confidence in assessment procedure outcomes (Carver, 2001). Work is underway to validate indicators and ratings by applying existing monitoring protocols such as:

- The Forest and Range Evaluation Program (FREP) Routine Riparian Effectiveness Evaluation (RREE) protocol and Water Quality Effectiveness Evaluation (WQEE) monitoring data, and
- Water quality and Benthic Index of Biotic integrity results from Ministry of Environment and federal CABIN (Canadian Benthic Invertebrate Index Network) monitoring data.

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