A Qualitative Hydro-Geomorphic Risk Analysis for British Columbia's Interior Watersheds: A Discussion Paper

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Editor's Notes:

A preliminary version of this article was published in ASPECT, May 2004. Since then, the article has been revised, based on numerous technical reviews. This article is intended to stimulate discussion among forest hydrologists about the development of a qualitative hydro-geomorphic risk analysis for B.C. watersheds. As a discussion paper, the author acknowledges some limitations in the material presented below in attempting to develop the framework.

Introduction

Under British Columbia's new *Forest and Range Practices Act*, forest management is moving towards risk management and professional reliance. In this new regime, forest managers must understand potential risks to aquatic values associated with existing or proposed development in a watershed.

To date, industry and government professionals have had minimal discussions about a standard approach to hydrological risk analysis. Inconsistencies in methods, terminology, and elements being considered in hydrological risk analyses are causing significant differences in the way professionals estimate risk (e.g., Carver 2001; B.C. Ministry of Forests 2001; Uunila 2004).

Recently, the Association of Professional Engineers and Geoscientists of B.C. (2003) and the B.C. Ministry of Forests (Wise *et al.* [editors] 2004) have developed provincial standards for landslide risk analysis. These efforts have given professionals an understanding of the terms and methods of risk analysis needed for detailed terrain stability mapping. Similar efforts to standardize methods and terminology are needed if hydrologic risk analyses are to become a widely accepted and valued component of forest management in British Columbia.

The author developed this hydro-geomorphic risk analysis for use in Southern Interior B.C. watersheds and presents it to open discussion regarding a consistent methodology for risk analysis. Terminology used in this risk analysis is generally consistent with definitions in *Risk Management: Guideline for Decision-Makers* (CSA 1997) and *Landslide Risk Case Studies in Forest Development Planning and Operations* (Wise *et al.* [editors] 2004).

> *Under British Columbia's new* Forest and Range Practices Act, *forest managers must understand potential risks to aquatic values associated with existing or proposed development in a watershed.*

Natural Variability and Channel Response

Low-order watersheds (<100 km²) in British Columbia's Southern Interior have been shaped by their geology, glacial history, and climate over the past 10 000 years (Clague [compiler] 1989). The physical, chemical, and biological characteristics of low-order streams are closely linked to hillslope (hydro-geomorphic) processes and riparian function (Montgomery and Buffington 1998; Gomi *et al.* 2002).

Natural disturbance events such as wildfire, pest epidemics, and floods routinely affect watersheds and constitute an intricate part of the dynamic and evolving landscape of the Southern Interior (Bragg 2000; Benda *et al.* 2003; Gayton 2003). Changes to streamflow, sediment delivery rates, and riparian function (collectively referred to as *watershed processes*) following natural disturbance define the natural variability of a watershed over time (Gomi *et al.* 2002; Miller *et al.* 2003). While natural disturbance events typically have substantial, immediate impacts on channel structure and aquatic values such as water quality and aquatic habitat (Rinne 1996), the influx of nutrients, sediment, and woody debris in the decades following the event can play a vital role in maintaining the aquatic ecosystem of a watershed (Benda *et al.* 2003; Figure 1).

A channel's response to disturbance events (i.e., the variability of channel morphology in time and space) depends on the disturbance regime of a watershed, which is a function of its geographic location (i.e., within British Columbia's hydro-climatic and physiographic regions) and physical attributes including bedrock geology and glacial/paraglacial history (B.C. Ministry of Transportation and Highways 1996; Montgomery and Buffington 1998; Hallett and Walker 2000; Obedkoff 2002; Miller *et al.* 2003).

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Figure 1. Woody debris recruitment and sediment influx following fire are key factors in maintaining aquatic ecosystems in many Southern Interior watersheds. Photos are from similar low-order streams in Caven Creek, southeastern British Columbia. Stream (A) burned during the 2003 Plumbob fire. Stream (B) experienced a similar fire about 70 years ago.

Streams draining steep mountain slopes in the interior wet belt of British Columbia have larger peak discharges per unit area and experience a higher frequency of channel-forming events (e.g., debris flows, snow avalanches) than watersheds in arid, lowland regions (Jakob and Jordan 2001; Obedkoff 2002). As a result, the morphology of channels in the interior wet belt typically have greater natural spatial and temporal variability than channels in arid and semi-arid regions where less frequent events such as wildfire and floods define the disturbance regime.

Forest development in a watershed can cause changes to watershed processes including increased hillslope runoff and stream discharge (Troendle *et al*. 2001; Wemple and Jones 2003; Schnorbus and Alila 2004); increased rate of sediment delivery to streams (Roberts and Church 1986; Gomi and Sidle 2003); and reduced riparian function through removal of streamside vegetation and direct impacts to channel bed and banks (Bragg 2000; Faustini and Jones 2003). The potential for significant (observable, long-term) change to aquatic values in a watershed due to changes in watershed processes associated with forest development will be greater in channels that have less natural variability in channel morphology.[1]

Maintaining or improving aquatic values of watersheds while maximizing harvesting opportunities is a primary management objective of forest development in British Columbia. Understanding watershed processes and the natural variability in channel condition and aquatic values allows forest managers to apply management practices to reduce the risk of direct negative impacts to low-order streams. In turn, this reduces the risk for cumulative impacts in higher-order streams.

Hydro-geomorphic Risk Analysis

A qualitative risk analysis offers (1) a framework for forest hydrologists and geomorphologists to document critical watershed processes (i.e., stream discharge, rate of sediment delivery, and riparian function) that are linked to aquatic values; and (2) recommendations for sustaining or improving aquatic values within a watershed. This reconnaissance-level analysis is intended to help forest managers identify areas where a more detailed level of assessment is required.

Simply stated, estimation of risk to aquatic values from forest development considers two independent factors: the potential response of the channel to changes in watershed processes and the potential impact of forest development on watershed processes. It is expressed as the product of two components: *channel sensitivity* (C) and *hydrologic hazard* (H).

$$Risk = C \times H$$

Hydro-geomorphic risk is determined for the main stem and significant tributary channels upstream of a point of interest (POI), such as a water intake structure or a specific fish habitat (elements at risk) for each watershed process or, where appropriate, for each identified aquatic value at the point of interest (e.g., water quality at the intake, channel stability on the fan). A simple matrix such as shown in Table 1 can be used to determine risk in this qualitative analysis.

Channel sensitivity, a measure of the vulnerability (robustness or fragility) of the channel given changes to watershed processes, depends on the physical attributes of the channel. Channel sensitivity is equivalent to consequence in the conventional equation of Risk = Hazard × Consequence.[2] The ratings of “low”, “moderate” and “high” sensitivity express the potential size of change to

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[1] In general, channel types associated with transport-limited, alluvial valley segments (e.g., step–pool or riffle–pool channels) or those in supply-limited colluvial valleys dominated by forced alluvial reaches (LWD step–pool or step–bed channels) will have a greater potential for change than channel types in colluvial or bedrock valley segments (Montgomery and Buffington 1998).

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Table 1. Hydro-geomorphic risk matrix (B.C. Ministry of Forests 2002)

Hydro-geomorphic risk [a]		Likelihood of a hydrologic hazard		
		Low	Moderate	High
Channel sensitivity	Low	Very low	Low	Moderate
	Moderate	Low	Moderate	High
	High	Moderate	High	Very high

[a] A rating of "negligible" can also be added to the matrix if channel condition is independent of a watershed process, or forest development does not affect watershed process.

the channel structure and associated aquatic values (collectively referred to as channel condition) and are assessed for each of the watershed processes separately. What each sensitivity rating implies in terms of probable level of impact to the channel/aquatic values is specific to a watershed and should be defined in the report. Example definitions are in the footnotes to Table 2.

Channel sensitivity to increases in peak discharge considers the potential for increased bedload transport, which is estimated by considering mean grain size, grain size distribution, channel gradient, and hydraulic roughness (O'Connor and Harr 1994; Buffington and Montgomery 1999; Church 2002). For example, a stream that has a cobble–boulder cascade morphology will have a smaller change to channel condition due to a given increase in peak discharge than a low-gradient, gravel, riffle–pool channel.

Channel sensitivity to increases in sediment delivery considers the capacity of the channel to transport sediment as determined by channel gradient and sediment storage opportunities. Due to increases in sediment delivery in the headwater reaches, a low-gradient (<5%) meandering channel with intervening wetland segments will have a smaller change to channel condition over the length of the channel network than a moderate gradient (5–15%) channel with limited sediment storage opportunities (Lisle 2000).

Channel sensitivity to disturbances of riparian function considers the past, present, and future dependence of channel condition on riparian vegetation (Montgomery 2003). A channel with deciduous riparian species such as alder and willow, which are indicative of frequent flooding and snow avalanches, will be less sensitive to disturbance of riparian function than a channel with mature coniferous riparian species supplying large woody debris that contributes to channel bed and bank stability. Where stream temperature is a concern, the dependence of a channel on riparian function considers channel orientation, hillslope gradient, and riparian species (Brown 1980).

Channel sensitivity is estimated for the main stem channel and larger tributary channels through a combination of field assessment, interpretation of current and historical air photos, and analysis of regional hydrometric and climate information. Montgomery and MacDonald (2002) describe in detail a similar approach to assessment of channel condition and sensitivity.

Key channel attributes that contribute to the estimation of channel sensitivity for the three watershed processes are summarized in Table 2.

A *hydrologic hazard* is a harmful sustained change to a watershed process. The hydrologic hazards considered in this analysis are increased peak discharge (H_p), increased rate of sediment delivery (H_s), and decreased riparian function (H_f) associated with proposed and existing development. The variability of watershed processes resulting from past natural disturbance in a watershed forms a baseline for the assessment of hydrologic hazard.[3] In this assessment the likelihood of a hydrological hazard is expressed qualitatively as "low," "moderate," and "high." These ratings indicate that the likelihood of a harmful or potentially harmful change to a watershed process occurring within the time span of the development is "negligible," "not likely but possible," and "probable," respectively.

When detailed information such as flood frequency, annual sediment budgets, and the frequency of disturbance to riparian function is available, the risk analysis can be adapted to be more quantitative. This is done by expressing and contrasting the likelihood of a hydrologic hazard in the undeveloped (baseline) condition and developed (disturbed) condition as the annual probability (P_a) and the long-term probability (P_x) for the lifespan of the proposed development.

For example, a stream that experiences a major channel-forming flood event once every 50 years (1:50) has an annual probability of 0.02 (2%). If the development in question has a lifespan of 20 years the long-term probability (P_{20}) of a channel-forming flood event is

$$P_x = 1 - (1-(P_a))^x$$

so

$$P_{20} = 1 - (1-(1/50))^{20} = 0.33\ (33\%).$$[4]

If development is estimated as potentially increasing the annual probability of a major channel-forming flood from a 1:50 to 1:20 return period (e.g., Schnorbus and Alila 2004, scenario 2/3U, Table 3) the long-term probability (P_{20}) of a major channel-forming flood is increased to 0.64 (64%). In this case the proposed development increases the probability of a channel-forming flood event from 33 to 64% (Δ31 percentage points). Professionals

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[2] In this case, channel sensitivity (consequence) equals vulnerability because the spatial and temporal probabilities of the elements being considered (channel structure and aquatic values) are both equal to 1 (e.g., Wise *et al.* [editors] 2004, p. 16).

[3] For example, the frequency of channel-forming floods, return period of fire or forest health epidemics, distribution and frequency of occurrence of mass wasting or erosion events.

[4] See Wise *et al.* (editors, 2004), pp. 13–14, and Table, A4.2.

Table 2. Channel sensitivity

Watershed process	Channel sensitivity[a]	Typical channel attributes that contribute to channel sensitivity[b]
Increased peak discharge	Low	• Experiences frequent large, rapid peak flows: banks and floodplain vegetated with alder and willow, bright, scoured channel bed and banks, historically active fan; typical of channels draining watersheds with steep alpine headwaters • Coarse-textured bedload, not the result of a single anomalous flood event or an anthropogenic disturbance; numerous boulder cascade or bedrock reaches • Well-vegetated, overhanging banks (e.g., mature coniferous species with well-developed root system) and abundant functioning large woody debris (LWD) and debris jams that provide channel and bank stability • Often includes channels in supply-limited, colluvial, or bedrock valley segments
	Moderate	• Experienced larger flood events in the past, indicated by numerous, multi-aged vegetated bank sloughs, levees, or old woody debris jams at obstructions with minimal long-term changes to channel stability • Some inherent capacity to withstand higher flows, such as overflow channels or an entrenched channel with resilient banks or non-alluvial segments • Banks and riparian area vegetated with species that have well-developed root systems that protect the banks and forest floor from erosion • Often includes forced alluvial channels in colluvial or bedrock valley segments or transitional morphologies in alluvial valley segments
	High	• Does not experience frequent flood events; bed is dark and mossy, banks are overhanging, vegetated to bankfull, and show no or little evidence of old scour or overbank deposits • Contains fine-textured bedload that is susceptible to erosion • Partially or entirely confined and lacks structures, such as overflow channels, low gradient marshy reaches, and abundant functioning LWD that help reduce flow velocity • Generally includes fine-textured, transport-limited plane–bed to riffle–pool channels or forced alluvial channels
Increased sediment[c] delivery	Low	• Abundant locations for sediment storage, such as frequent functioning LWD jams or frequent low gradient unconfined sections (e.g., alluvial valley segments with riffle–pool channels) • Contains slow-flowing, meandering stream (e.g., flows through marsh or wetland segments) and lacks the power to transport bedload (i.e., decoupled systems where source areas are isolated from downstream channels) • Headwaters are steep snow avalanche and (or) debris flow gullies that deliver large volumes of sediment annually
	Moderate	• Colluvial valley segments with some storage capacity, such as some long (>100–200 m), low gradient sections (<15%) that allow bedload sediment to settle out • Bordered by currently inactive, but relatively numerous natural landslide scars or debris flow gullies
	High	• Laterally confined, forced alluvial and riffle–pool to cascade–pool systems that will become aggraded • Channel has little or no storage capacity so that increases in sediment delivery are likely to cause lateral avulsion or channel aggradation • Additional sediment input will be rapidly transported through system to P.O.I. due to steep headwater tributaries and ephemeral channels (>10%) with minimal opportunity for storage of sediment
Decreased riparian function	Low	• Not dependent on LWD to control rate of sediment transport, such as a steep colluvial or bedrock channels or snow avalanche chutes • Low gradient, braided, or anastomosing channels, situated on a wide valley bottom vegetated with shrubs
	Moderate	• Requires some LWD in a number of reaches to offer long-term storage, moderate bedload transport rate, or shade and cover for aquatic habitat (e.g., forced alluvial, LWD step–pool, or step–bed channels in colluvial valley segments) • Has tendency to migrate laterally across valley bottom and is unentrenched so that migration could be accelerated if valley bottom is disturbed and banks destabilized (e.g., meandering step–pool to riffle–pool channel in alluvial valley segment) • Some reaches are oriented such that the riparian canopy produces shade and moderates water temperatures
	High	• Entirely dependent on LWD to control bedload transport rates and maintain bank integrity • Appears to migrate over floodplain/valley bottom frequently and requires a wide effective riparian area for long-term stability (typically LWD forced alluvial step–pool to cascade pool channels in colluvial valley segments) • Dependent on riparian canopy to maintain water temperature and habitat values

Notes:

[a] "High," "moderate," or "low" channel sensitivity is a measure of the size of observable, sustained impacts to channel morphology/aquatic values in response to a change in a watershed process. "High" implies extensive observable sustained negative impacts. "Moderate" implies local extensive or widespread moderate negative impacts. "Low" implies local moderate to no observable negative impacts.

[b] The list of channel attributes here is incomplete and is only for illustration. The attributes must be considered and interpreted in a temporal, spatial, and cumulative context, not in isolation.

[c] The sensitivity of the channel to increases in bedload sediment and increases in suspended sediment should be considered separately. In small headwater streams, suspended sediment is typically transported through the system rapidly, resulting in short-term negative changes to water quality.

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undertaking the analysis must use their judgment to define the hazard ratings in terms of change in probability (see Wise *et al.* [editors] 2004, Chapter 3, Table 2).

The likelihood of a hydrologic hazard is estimated by considering the extent and location of existing or proposed development in a watershed with respect to elevation, aspect, hillslope gradient, and hillslope–channel connectivity. The biophysical conditions of the watershed, including forest canopy and terrain characteristics are also considered.

The likelihood of occurrence of increased peak discharge (H_p) associated with existing or proposed development depends on the amount and distribution of the development; the current and historical forest cover characteristics; and the extent that basin physiography, such as the amount of alpine area or the variation of elevations and aspects, allows for de-synchronization of snowmelt runoff and controls streamflow (Schnorbus and Alila 2004). A low level of development (<20%) that is distributed over a range of different elevations and aspects in a forested watershed has a low likelihood of increasing peak discharge. A moderate level of development (20–40%) in a watershed that has an alpine-dominated peak discharge will also have a low likelihood of increasing peak discharge (Schnorbus and Alila 2004).

The likelihood of occurrence of increased sediment delivery (H_s) in a watershed associated with development considers the location of existing or proposed development with respect to unstable or potentially unstable slopes, the connectivity of hillslopes and channels, and the mechanism and frequency of natural sediment delivery events. Proposed development on or above unstable or potentially unstable slopes adjacent to the channel in a watershed with few natural sediment sources could have a high likelihood of increasing sediment delivery if roads or trails are proposed (Jordan 2002).

A qualitative approach to hydro-geomorphologic risk analysis is an effective tool to identify the key processes affecting aquatic values within a watershed and develop practical recommendations to minimize risks to aquatic values from forest development.

The likelihood of occurrence of harmful changes to riparian function (H_f) considers the location of existing or proposed development with respect to the functioning riparian area and the degree of natural variability (both spatial and temporal) in riparian function through the watershed. A moderate amount of development in a riparian area where immature coniferous and deciduous species offer limited riparian function will have a lower likelihood of development-related impacts than a similar level of development in a riparian area with a climax stand of mature coniferous species providing channel bed and bank stability.

The likelihood of occurrence of a hydrological hazard is determined through field assessment (focusing on observations that give information on past disturbance history of the watershed); observations of historical and recent air photos; and information from terrain stability, soil erosion, forest cover, and development maps. Examples of watershed attributes and development factors that contribute to the qualitative assessment of hydrologic hazard are presented in Table 3.

Summary

Under British Columbia's new *Forest and Range Practices Act,* forest management is moving towards risk analysis and professional reliance. In this new regime, forest managers must thoroughly understand potential risks to aquatic values associated with existing or proposed development. Results of a hydro-geomorphic risk analysis can guide new forest development, identify areas where more detailed assessments are required, or direct mitigative work. The results can also be used to identify aquatic values and locations in the watershed that are suitable for monitoring.

The hydrologic risk analysis suggested here is ideally suited for low-order watersheds (<50 km²) but can be adapted for use in smaller first-order watersheds (<100 ha) as well as larger landscape-level watersheds (≥500 km²). In a detailed analysis, watershed processes are adjusted to reflect hillslope processes and more detailed, site-specific information is required such as likelihood of landslides, terrain and soil information, the nature of surface and subsurface runoff, slope gradient and aspect, and forest canopy characteristics. The potential for cumulative hydro-geomorphic impacts can be estimated in larger watersheds by dividing the landscape into smaller, hydrologically meaningful sub-basins and determining risk at each fan or confluence along the main stem channel. Applying this risk analysis to watersheds larger than about 50 km² could result in meaningless risk ratings due to the increased variability in basin response at large scales (Bunte and MacDonald 1999; Miller *et al.* 2003).

Risks to aquatic values exist regardless of forest development. Therefore, such development should not automatically be excluded from areas of higher risk. In these cases forest managers can adapt management practices to reduce the potential

Table 3. Hydrological hazard

Watershed process	Likelihood[a]	Watershed attributes and development factors contributing to hazard rating [b]
Increased peak discharge	**Low**	• Watershed has significant alpine area and peak flows dominated by alpine snowmelt • Watershed has wide elevation/aspect component and openings are appropriately distributed • Minimal existing/proposed development • Minimal road density and ditches are not concentrating runoff
	Moderate	• Moderate existing/proposed development in moderate to steep gradient, non-alpine watershed • Moderate road density and ditches are concentrating and delivering runoff to stream network • Development is limited in distribution and (or) focused on 1 or 2 elevation/aspect zones that could influence peak flows
	High	• Watershed is forested to the headwaters and has an upper broad basin or plateau where development is concentrated • Limited elevation/aspect distribution and development are concentrated in one or two areas that likely control peak flows • Extensive existing/proposed development • High road density and ditches are carrying intercepted and concentrated runoff to stream network.
Increased sediment delivery	**Low**	• Low connectivity (coupling) between hillsides and valley bottom • Large watershed with the capacity to dilute local forestry related sedimentation events • Stable and non-erodible terrain is adjacent to channel • Low road density and few stream crossings
	Moderate	• Some coupling between valley sides and stream channel with moderate density of roads/trails on or above unstable or potentially unstable slopes adjacent to channel • Moderate road density and number of stream crossing on steep slopes with erodible soils
	High	• Channels are directly coupled to valley sides with high road/trail density located on or above unstable terrain • Watershed is small with no opportunity for sediment dilution • High road density with numerous stream crossings on moderate to steep slopes with erodible soils
Decreased riparian function	**Low**	• No development in riparian zone • Appropriately sized riparian buffers in place • Few stream crossings by roads or trails
	Moderate	• Significant amount of riparian area directly impacted by development • Undersized riparian buffers along some of the channel resulting in a reduction of LWD recruitment or shade function of canopy • High density of stream crossings by roads or trails
	High	• Large amount of development/disturbance in riparian area • Undersized or no riparian buffers along more than half of channel • Main stem channel oriented east–west with moderate or low gradient hillsides. Development/disturbance has removed significant amount of riparian vegetation on south side of channel.

Notes:

[a] The ratings of “low,” “moderate,” and “high” indicate that the likelihood of a harmful or potentially harmful change to a watershed process occurring within the time span of the development is negligible, not likely but possible, and probable, respectively.

[b] The typical watershed attributes and development factors given for the “low,” “moderate,” and “high” hazard ratings are for discussion purposes only. Different watersheds will respond differently to similar levels of road development and harvesting.

hazards associated with development. Strategies to reduce the likelihood of occurrence of a hazard and thereby reduce development-related risk could include undertaking detailed drainage plans to maintain natural drainage patterns, conducting riparian assessments to ensure block boundaries do not impinge on riparian function, or adjusting the size or distribution of cutblocks to reduce the potential for increasing peak flows.

As with any analysis of qualitative risk, this analysis is subject to professional experience and judgment. Therefore, all observations, interpretations, and assumptions should be appropriately documented.

Eventually, with continued research initiatives directed at quantifying the effects of timber harvest and road development on watershed processes (e.g., Schnorbus and Alila 2004), the strength of risk analyses like the one presented here will improve. Until then, a qualitative approach to hydro-geomorphologic risk analysis is an effective tool to identify the key processes affecting aquatic values within a watershed and develop practical recommendations to minimize risks to aquatic values from forest development.

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