Hydrologic Analysis and Decision-Support Tool for Cumulative Effects Assessment in the BC Northwest

Draft for Review

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1.0 INTRODUCTION

The BC Ministry of Forests, Lands & Natural Resource Operations (MFLNRO) and Ministry of Environment (MoE) are developing a process for assessing the cumulative effects (CEs) of existing and proposed development. As a contribution to that effort, this report summarizes a proposal for a hydrologic decision-support tool for the Northwest Cumulative Effects Pilot Project.

2.0 BACKGROUND

The approach proposed in this report builds on conceptual work by the authors and other collaborators dating back to the 1990s. The original hydrologic analysis framework was developed for the Arrow Forest District in southern BC as a decision-support tool for strategic forest planning and estimating hydrologic constraints as an input to timber supply analysis (Carver and Utzig 2000).

Further development of these concepts was undertaken for the Water Stewardship Division of the BC Ministry of Environment. This work included the development of an assessment framework for hydrologic hazards, with a focus on the impacts of the mountain pine beetle epidemic (Carver *et al.* 2009a, Carver *et al.* 2009b, Sulyma *et al.* 2009, Utzig *et al.* 2009).

Whereas our previous work focused on impacts resulting from forest management, the present work is intended to include a wider range of potential development, including mining, renewable energy projects, dams and infrastructure such as transmission corridors, pipelines and highways. Given that the hydrologic interactions between development and aquatic systems result largely from soil disturbance, direct channel disturbance, and changes in vegetative cover, the general principles of cumulative effects remain consistent from forestry to many other types of development. To cover other types of disturbance, two addition hazards have been introduced in this report: changes in water chemistry and temperature. Water storage, release and removals (including water piracy where water is rerouted from one drainage to another) can also create significant hydrologic impacts, however, these mechanisms are only considered to a limited extent in the present framework.

3.0 THEORETICAL BASIS

This section discusses the physical basis for an analysis of the effects of development on watershed hydrology.

3.1 Watershed Characteristics

Inherent watershed characteristics determine a watershedõs relative sensitivity to development. Independent of the development activities themselves. The risk to resource values varies with watershed characteristics because the physical watershed characteristics shape the associated inherent hazards. Table 3.1 distinguishes these characteristics in terms of flow, water quality and channel stability hazards.The determination of inherent hazards essentially serves as a base case for further assessment of cumulative effects. Traditionally the base has assumed climatic conditions consistent with the ñrange of natural variabilityò(RONV ï e.g. Salasan Consulting Ltd. et al. 1999). With the increasing impacts of climate change, this concept becomes more complicated. Rather than having a single base case, projections of future hazard levels associated with proposed development, future projections also have to include the projected changes and associated uncertainty associated with climate change.

Table 3.1. Watershed characteristics which shape background hydrologic hazards.

Flow Hazards	Sediment Hazards

Peak Flow Regime
• extent of natural forest cover (ECA buffers)
• soil moisture storage
• low-elevation lakes/wetlands (flow buffers)
• basin morphology:
    • hypsometry
    • aspect/elevation complexity
    • basin shape and orientation
• climatic influences
    • precipitation amount/distribution (rain/snow)
    • intensity/duration/frequency of storm events
Low Flow Regime
• climate ï seasonal drought
• glaciers and long-duration snow fields
• wetlands, high-elevation lakes
• subsurface water storage
• elevational distribution
• precipitation amount/distribution (rain/snow)
	Sediment Regime
	• terrain stability (bedload)
	• soil erodibility (suspended sediment)
	• channel stability (see below)
	• glaciers
	• sediment traps (e.g., lakes)
	Water Chemistry
	• contamination sources
	Channel Stability
	• channel type
	• peak-flow regime
	• terrain stability (bedload inputs)
	• upstream hazards/ coupling
	Water Temperature
	• riparian forest cover
	• low flow regime

3.2 Mechanisms Linking Development to Hydrologic Response

Development can alter hydrologic and geomorphic responses through specific mechanisms of change. Identification of the resource values of importance implies which aspects of watershed hydrologic behaviour should be considered and which mechanisms are most important. In the present framework, the resource values under consideration are aquatic habitat, domestic/irrigation water sources, and downstream/downslope property values. In addition to the direct influence on background hazards, the inherent character of a watershed also shapes the extent to which development-related impacts increase or reduce the inherent levels of hazard. If these interactions are understood, they can be modeled in a risk-rating system.

The primary consequences that occur as a result of development activities, and which can cause impacts to the resources identified in section 3 are:

- altered water chemistry,
- altered water temperature,
- altered suspended sediment,
- altered bedload,
- increased peak flows,
- altered channel stability, and
- reduced low flows.

The types of mechanisms through which development can affect the resource values of concern are briefly described below. Some of the discussion in this section follows Church (1996).

3.2.1 Soil Exposure, Compaction and Displacement

Roads increase sediment production through waterborne erosion and mass wasting. Active surfaces of forest roads, mining roads, skid trails and other surface disturbances represent exposed areas where sediment is produced due to abrasion, rilling, and in some cases, gully erosion. These effects can be mitigated with surface materials, road deactivation, revegetation, and disuse. Mass wasting can result directly from road construction ï for instance, where a fillslope fails. Cutbanks can be undermined with the potential to cause chronic sediment sources contributing directly to ditch lines. Enhanced production of fine sediment increases suspended sediment concentrations especially during significant freshet rain-on-snow events. Enhanced delivery of coarse sediment to streams can destabilize channels resulting in, among other outcomes, a further increase in recruitment of fine sediment due to streambank erosion. Soil disturbance in materials that contain sulphide-rich minerals (e.g., gossan deposits) can also contribute to water quality deterioration as the released elements are leached or washed directly into surface waters.

3.2.2 Surface Flow Diversion

The drainage system associated with a road network or mining excavation can significantly modify the natural drainage pattern. Water can be routed to drainage features and hillslopes that otherwise would not experience the flow. These new flows can initiate landslides or gullying, delivering sediment to streams. In addition, diverted drainage can advance the timing of runoff increasing peak flows and potentially decreasing late-season low flows.

3.2.3 Subsurface Flow Interception

Roads and other excavations can bring subsurface flows to the surface, routing them to the drainage network. In addition, the road network acts as an extension to the drainage network, efficiently routing runoff to the natural drainage network (Wemple 1996). Both of these have the effect of advancing the timing of runoff serving to potentially increase peak flows and decrease late-season low flows. This mechanism is most likely to occur when roads pass through wet sites and/or require deep cuts (slopes with gradient over 40%).

3.2.4 Riparian Disturbance

Harvesting in the riparian zone may reduce bank stability through direct disturbance and loss of root strength as a result of forest removal. Riparian harvest may remove sources of coarse-woody debris that may be necessary for channel stability. In some stream reaches, increased water temperature can also result from the removal of riparian vegetation and loss of shade.

3.2.5 Increased Rate of Snowmelt

Openings in the forest (e.g., from harvesting, roads, utility corridors) increase the melt rate of the snowpack through greater exposure to solar radiation. Similar to the effect of flow interception, the faster melt rate serves to increase peak flows and potentially decrease late-season low flows, depending on distribution by aspect and elevation. Small openings may experience an intermediate melt rate in relation to their size and orientation.

3.2.6 Modified Sediment Capture and Removal

The movement of sediment through aquatic pathways can be altered by in-channel activities such as aggregate extraction, construction of dams for hydroelectric power, flood control, and water abstraction, and other activities such as the modification of wetlands and lakes that may serve to moderate the pace of sediment transport. This capture and removal of sediment modifies the substrate that is available to move downstream and form the channel bed and can disrupt bed stability. Excessive removals lead to channel degradation, while loss of sediment-trapping opportunities lead to aggradation. The altered substrate available for sediment transport can result in changes to channel stability and the loss and/or damage of aquatic habitat.

3.2.7 Increased Snowpack & Decreased Evapotranspiration

Openings in the forest ï resulting from whatever disturbance (e.g. harvesting, fire, mining exploration) ï generally increase winter snow accumulation through the loss of canopy snow interception and sublimation. The enhanced snow pack results in higher total basin runoff which can increase peak flows. The effect of harvesting is temporary ï as the trees grow and canopy closure occurs, hydrologic recovery takes place resulting in a gradually-diminished effect. In contrast, the effects of roads or utility corridors are permanent unless site rehabilitation/revegetation is accomplished. In general, enhanced snowpacks increase low flows but it is suspected that 5 to 10 years after initial harvest, depending on the type of new vegetation, reduced low flows can occur if water-uptake behaviour has changed.

Small openings (less than 5 tree heights in diameter) can yield a snowpack different from that of large openings due to wind effects, and in some colder climates, sublimation from the ground. In combination with the intermediate melt rate of small openings, it is generally expected that openings under 5 tree heights in diameter result overall in a potential for affecting peak flows which is intermediate between full canopy closure and large openings. The snowpack in very small openings (less than one tree height in diameter) may differ from that of small/large openings due to the higher relative significance of edge effects. Note that the enhanced-snowpack effect can be mitigated by the use of single-tree selection.

3.2.8 Surface Water Storage, Withdrawal and Release

Construction of dams, reservoirs and penstocks can result in sediment capture and alterations to flow regimes. Depending on the timing and magnitude of water storage and release, dams can increase or decrease peak and low flows downstream. Penstocks can remove significant flow from stream reaches, and depending on their operation, can also affect peak and low flows. Water withdrawals for industrial, agricultural and domestic uses will also impact downstream flows, and can be critical during seasonal low flow periods.

3.2.9 Pollution

The direct discharge of organic and inorganic materials into surface waters has an immediate impact on water chemistry. Processes associated with dam operations can also have impacts on water chemistry through changes in oxygen content.

3.3 Pathways of Hydrologic Cause and Effect

The mechanisms and hydrologic consequences introduced in section 3.2 cause impacts to aquatic values as illustrated in Figure 3.1. Reduced low flows affect only water quantity for consumption/irrigation and fish habitat. In contrast, increased peak flows can affect property directly through flooding and can also indirectly affect domestic water quality and fish habitat through channel destabilization. The degree to which these effects occur as a result of management will vary depending on the relative intensity, duration, and extent of the impacts resulting from the development activities applied.

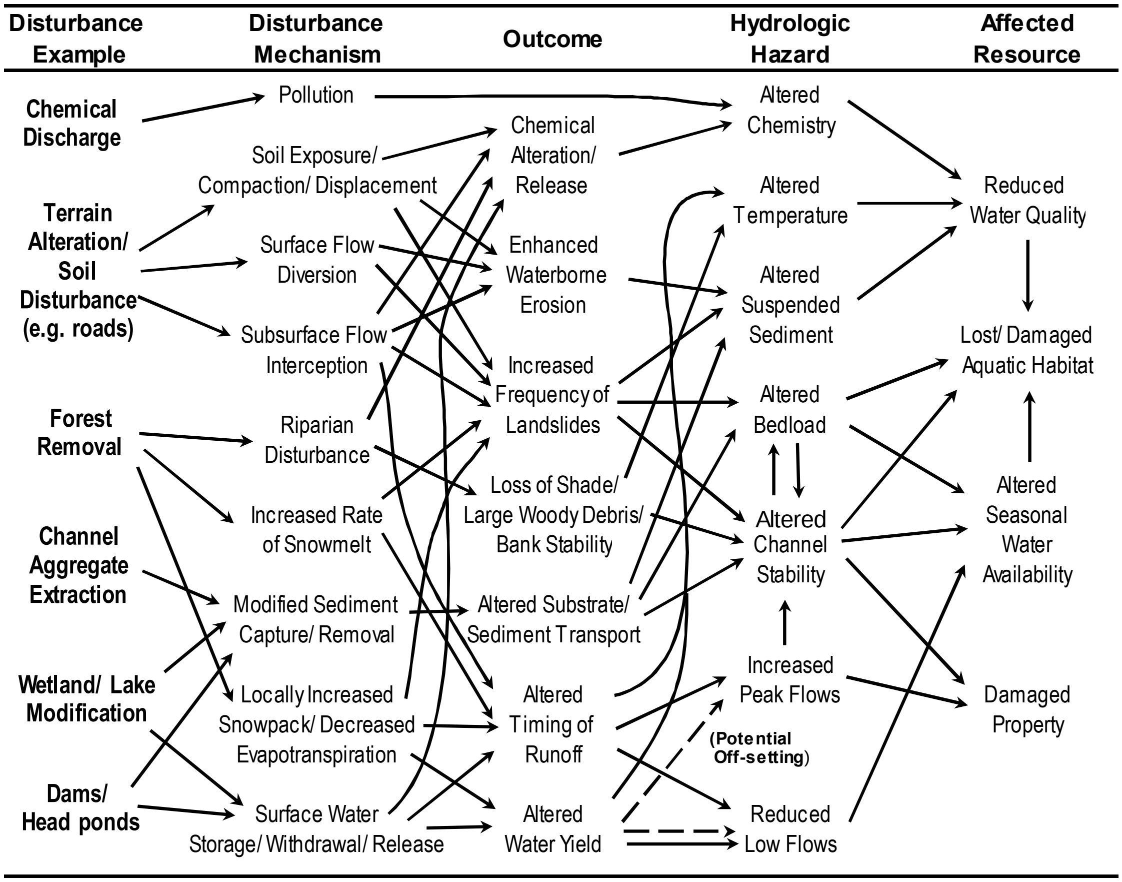

Figure 3.1. Mechanisms for hydrologic resource impact from forest development.

3.4 Potential Impact to Resource Values

As introduced above, the three resources are of concern in this analysis are drinking/irrigation water, aquatic habitat, and downstream property values. Four potential impacts on these resources due to development are considered here:

Reduced Water Quality (for domestic consumption and irrigation)

All types of development can alter the physical, chemical, and biological makeup of the water resource. It is widely accepted that the most widespread water-quality concern is associated with increased sediment delivery to water courses. Other changes can be significant but often they stem from this fundamental physical change.

Loss/Damaged Aquatic Habitat

In addition to maintaining water quality, including specific temperature regimes, fish habitat often requires steady recruitment of gravels and a balance of inputs and outputs. In addition, maintenance of channel structure and stability are also concerns.

Damaged Property (and Structures)

Flooding and channel change are natural processes which can be exacerbated by some impacts of development activities.

Reduced Seasonal Water Availability (for irrigation, domestic consumption, and fish habitat)

Late-season low flows are important for the maintenance of water quantity for domestic consumption and fish habitat.

Each of these has the potential to occur as a result of development. The mechanisms for their occurrence can be complex, often with multiple simultaneous effects as discussed below.

4.0 ASSESSMENT APPROACHES

Cumulative effects assessment (CEA) has been defined as the process of systematically assessing the effects resulting from incremental, accumulating, and interacting stressors (Reid 1993). Cumulative effects are not generally well addressed in environmental assessments (Burris and Canter 1997). System complexity, management diversity, lack of knowledge about interactions through space and time, and political resistance all contribute to an inadequate state of knowledge to appropriately address the issue. There is even a lack of consensus on what constitutes a definition of cumulative effects (Reid 1993). Environmental assessment has generally focused on a proposed stressor, examined with limited baseline, unknown or poorly known stressor-effect linkages, and spatially and temporally restricted boundaries. Dubé et al (2013) propose an effects-based framework specifically structured to address impacts to aquatic ecosystems. They explain that the deficiencies in EIA practice stem from an overemphasis on stressor-based assessments and advocate for stronger effects-based watershed approaches. Although effects-based approaches are conducted at larger scales, and can be effective for determining system "health", development of predictive models to understand how the system may respond to future pressures, by linking effects to the stressors responsible for them, is much more difficult to accomplish, and thus far has not occurred (Squires and Dubé 2013). Over the past twenty years, there has been much written on deficiencies of CEA within Canada's regulatory framework of Environmental Impact Assessment. Examining cumulative effects (CEs) within this context has generally focused on water quality and end-point ecological outcomes, rather than the hydrologic and geomorphic processes that mediate much of the cumulative change. The causes for this include the lack of process-related models capable of handling spatially and temporally diverse stressors, the inadequacy of most monitoring networks to support effective CEA, and a regulatory system that limits the meaningful development of CEA within resource planning. For an understanding of these broader issues associated with CEA, the reader is directed to Connelly (2011), Gibson (2012), Gunn (2009), McDonald (2000), Noble (2008), Squires and Dubé (2013), and Tennoy et al (2006).

Concurrently, over the past 25 years, a broad community of modelers, earth scientists, and ecologists have been developing predictive tools for quantifying the hydrologic and geomorphic impacts of development, somewhat centred upon the forested regions of western North America. Although this work has emphasized impacts on forested watersheds (mostly due to widespread forestry activities), the approaches used and the mechanisms considered are largely transferrable to hydrologic and geomorphic assessment of impacts due to other resource developments. Hence, although the present review emphasizes approaches developed for use in forest planning, the techniques are more broadly applicable wherever forest cover is removed and roads constructed. Overviews exist of approaches available for assessing cumulative hydrologic and geomorphic effects on forested watersheds (e.g., Megahan 1992; Reid 1993; Beschta et al. 1995; Pike et al. 2010) and generally identify three types of approaches ï checklists, indicator models, and process models. The present review characterizes the range of existing approaches in terms of process-based models and indicator approaches linked to system response. Some more recent hybrid approaches are also discussed. Checklist approaches exist (e.g., Canter and Kamath 1997), but these are considered too subjective to be of use in the current situation. A discussion of some key issues follows the model descriptions.

4.1 Process-Based Models

Process-based models begin from a theoretical understanding of system behaviour. Given the diversity of natural systems and the complex interactions which are being modeled, they are generally complex with high data requirements and typically emerge from a research environment. However, they provide greater accuracy and have broad application across different landscapes and management regimes. Spatially-explicit process-based sediment transport models are less available than hydrologic models. This is due to a weaker scientific basis for simulating the processes and timescales involved in sediment production and delivery from the hillslope through to watershed discharge, and due to the stochastic nature of sediment production. The authors are unaware of available spatially-explicit process-based models that predict the combined hydrologic and geomorphic outcome of forest removal, road construction and related industrial disturbance activities (e.g., chemical discharges). Instead, spatially-explicit models are only available to address a limited number of component-specific hydrologic and geomorphic hazards. One example is provided below from British Columbia.

Where resources and data allow, detailed process-based models can be calibrated for specific basins of interest to estimate hydrologic changes that may result from modification of surface condition and surface vegetation. DHSVM is a distributed hydrologic model developed at the University of Washington that explicitly represents the effects of topography and vegetation on water fluxes through the landscape. This model has been used to examine the effects of forest management on flow parameters such as peak streamflow. For example, the BC Forest Practices Board (2007) describes the results of a DHSVM hydrologic simulation of Baker Creek in response to extreme loss of forest cover due to the Mountain Pine Beetle. The modelling predicts changes in water yield, peak flows, and flood timing resulting from forest death and salvage. With salvage of all pine-leading stands, this detailed spatially-explicit model predicts increases in peak flow by up to 92% with a 20-year flood frequency reduced to a three-year frequency. These complex detailed models necessarily focus on single hazards (e.g., changes in the hydrograph) due to the complexity of processes being modeled. Beckers et al (2009) provide a review of hydrologic models that may be used for modelling the effects of forest cover changes and climate change.

Existing predictive process-based models are useful in providing understanding, but in general, are challenged by data limitations, particularly in the present study area. Hence in general, existing process-based models cannot be usefully applied in the present context to resolve the suite of hazards of concern. Configuring them for the landscape under consideration would be onerous in data requirements and calibration difficult or impossible. As a result, indicator models are considered. Progress has been made in the context of forest management in the USA Pacific Northwest, and to a lesser degree in British Columbia, where public outcry combined with new legislation has initiated the development of assessment approaches in many jurisdictions (Ellefson et al. 1997).

4.2 Indicator Models

The second grouping of approaches uses indicators which correlate, to some degree, with resource degradation. As explained in Salasan Consulting Ltd. et al. (1999), this approach seeks to select indicators that link environmental pressures to changes in environmental values. See for example Westland Resource Group (1995, p 24). These simplified approaches using empirically-derived relations tend to be easy to apply but narrow in scope, requiring recalibration if applied to a different landscape and/or management regime. Their strength lies in their simplicity (relative to detailed process-based modeling) through an inherent focus on the key impact mechanisms. Several examples of this type of approach are reviewed here and address aspects of hydrologic change related to forest development. Most of the developmental work resulting from forestry research dates back to the 1980s and 1990s.

The Equivalent Clearcut Model (USFS 1974; Galbraith 1975) is perhaps the most widely known in British Columbia. This model considers only a change in peak flow and only in relation to its potential to cause channel disruption. In its original design, all forest management activities were rated (including roads) according to their equivalent effect as a clearcut in contributing to an increase in peak flow. Coefficients were determined through local calibration and professional judgment as to the increase in water yield of management activities in relation to vegetation type, elevation, and age of the activity (Reid 1993). Equivalent Clearcut Area (ECA) is often used in forest management in British Columbia as a single index to represent the combined impact of all forest development. The ECA concept was never intended to be used in this way, nor does ECA represent all mechanisms of resource degradation (see Figure 3.1 and section 5.1).

In its initial form, and like the ECA Model, the Equivalent Roaded Area (ERA) Model calculates a single index of forest-development impact, assuming channel destabilization to be the hydrologic response of greatest concern (e.g., Haskins 1986). In contrast to the ECA Model, the initial ERA approach assumed that resource degradation primarily occurs from increased peak flows due to soil compaction (reflecting the importance of this mechanism in California where it was developed). As explained by Reid (1993), this procedure has changed substantially since its conception (USFS 1988, Cobourn 1989a) to address downstream impact generated by several mechanisms. Impact potential is indexed by relating, through extensive calibration, the effects expected from each activity to that expected from roads (including openings created by forest harvesting). ERA has become more an index of land-use intensity through what can be described as a locally-calibrated accounting of past, present, and future activities. Accounts of its application suggest that there may be thresholds that crudely relate to impact on hydrology or ecosystem behaviour (Cobourn 1989b; McGurk and Fong 1995). Other examples exist of ECA and ERA used more on a site-specific basis (e.g., Athman and McCammon 1989).

The Washington Forest Practices Board (1997) provide a multidisciplinary watershed approach to ñwatershed analysisò that includes assessment, prescription, and evaluation. Its strengths are seen to lie in identifying and reducing the dominant, direct physical effects of forest-land uses on salmonid habitat (Collins and Pess 1997). It is weaker in integrating changes from more than one type of input. It relies heavily on field work and uses a range of tools including empirical relations developed in the USA Pacific Northwest. It is useful to the present study in terms of its consideration of factors which affect watershed hydrology; it is less useful in integrating these into risk ratings in relation to potential detrimental hydrologic response.

Between the mid-1980s and the present, ñwatershed assessmentò approaches have been developed in BC to address the cumulative hydrologic and geomorphic effects of forest development in Crown forests, including the Watershed Workbook (Wilford 1987), and various iterations of the Interior and Coastal Watershed Assessment Procedures (IWAP/CWAP; Anon. 1995, 1998, 1999). The Watershed Workbook asks a series of questions about past and present conditions. Using scoring in a flowchart, it provides recommendations for management based on sensitivity indices for a variety of hazard classes. Although this approach was developed for coastal watersheds, it formed the conceptual basis for the IWAP. The initial IWAP/CWAP (Level 1) provided the first formal consideration of cumulative hydrologic effects in the management of BCôs Crown forests. Its scoring and algorithms were based largely on collective professional experience and opinion, in addition to limited calibration. The other three WAP approaches have emerged from the experience provided by the initial IWAP. Additional indicator approaches used in watershed assessment and developed in the USA are reviewed in Pike et al (2010).

More recently, expert-system approaches have been developed in British Columbia to estimate hydro-geomorphic hazards resulting from forest development (Brown et al 2007; Beaudry 2011; Forsite Consultants 2011). These approaches rely on indicators interpreted using professional judgment to yield relative risk ratings by assessment unit. The reliance on "local calibration" makes it difficult to extrapolate these approaches to other areas. Their simplicity and attempt to integrate multiple hydrologic and geomorphic hazards make them attractive in decision support. Their vulnerability to differences in professional opinion may be problematic.

4.3 Hybrid Approaches

Given that process-based and indicator approaches each have drawbacks, hybrid approaches to estimating hydrologic hazards have been developed that model selected dominant processes in a spatially-explicit manner, and use empirical relations to address components that can't feasibly be modeled explicitly. See also MacDonald 2004 for further discussion. Several examples are discussed below.

Carver et al (2009a) describe their approach to estimating increases in peak flows resulting from forest loss by focusing on the spatial distribution of the runoff processes that may contribute to changes in peak flows. Although their model was developed in response to the Mountain Pine Beetle epidemic, and makes use of stand-level understanding of changes in snow accumulation and melt (e.g., Winkler et al. 2012), it can be readily adapted to any situation where forest cover is lost. Its success relies on the fundamental understanding that peak flow changes are most influenced by the areas in the watershed that actually generate most of the runoff. Changes in land-cover modification in these areas are assumed to drive changes in peak flows. The approach determines the location of dominant runoff processes through interpretation of a digital elevation model, using a collection of relations taken from published scientific studies. Additionally, empirically-derived relations are developed to determine selected model inputs. In a similar way, Carver et al (2009b) propose a low-flow hazard model built upon the analysis of streamflow recession in relation to basin characteristics that shape recession behaviour. The proposed approach would regionalize recession behavior data from gauged basins, and then extend the relations to other (ungauged) basins based on these basin characteristics.

Cline et al. (1981) describe the model used in the R-1 and R-4 Regions of the US Forest Service. Sediment yield is predicted using relations and coefficients developed form extensive research in the Idaho Batholith. It is linked to another model (Stowell et al. 1983) to describe the effect on fish survival with changes in sediment yield. The procedure is well founded in research but looks only at one effect of one mechanism (increased sediment yield) and is calibrated only for the Idaho Batholith. This model has been combined with the ECA procedure described below and termed WATSED (USFS 1991 in Megahan 1992).

WRENSS (USFS 1980) consists of a series of procedures to evaluate forest-development impacts including changes in flow, sediment, and temperature regimes, in addition to changes in nutrients and dissolved oxygen. The basis of the hydrologic component is computer simulation of water budgets. According to Reid (1993), WRENSS is a collection of tools useful for impact evaluation - some of the methods contained in it have been intensively tested while others have not been validated at all. Its use in cumulative-effects assessment would necessitate additional methods and demand extensive calibration.

Sulyma et al (2009) and Utzig et al (2009) describe the development of a pair of models created to determine the geomorphic hazards associated with fine-sediment and coarse-sediment hazard, respectively. These spatially-explicit approaches use Bayesian (probabilistic) relations based on expert opinion to quantify changes in sediment production and delivery due to changes in forest cover and road construction over mountainous terrain. These models follow the middle road (MacDonald 2004) – simultaneously utilizing the capability of spatially-explicit models, recognizing data limitations and creating a model that can easily be applied over large areas (see Section 6 for more details).

4.4 Selected Discussion

4.4.1 Integrated Assessment of Hydrologic Hazard

Modeling platforms providing an integrated assessment of multiple hydrologic hazards would be very attractive within the context of examining cumulative effects. Unfortunately, such models appear to be uncommon. One example that integrates low-flow hazard with peak-flow hazard is given in Mohamoud (2004). This study describes a hybrid modelling approach developed for USA mid-Atlantic watersheds that determines landscape and climate controls on watershed hydrologic response over widely contrasting temporal scales and including flow duration indices ranging from low flows (Q95) to peak flows (Q1).

Carver et al (2007) describe the results of several hazard models developed for the same area that used a collection of hybrid approaches. The approach combines spatially-explicit modeling with lumped relations based on synthesis of current knowledge, and is easily updated as scientific knowledge improves. The preliminary approach described integrates the hybrid method of Carver et al. (2009a, described above) to estimate peak-flow hazard with the hybrid approach of Utzig et al. (2009) to determine coarse-sediment hazard. An additional model has been developed by the Ministry of Environment to determine fine-sediment hazard (Sulyma et al. 2009) and can be integrated with the others. These models use similar data inputs and identical assessment units to facilitate integration of model outputs for improved decision support. These modelling efforts signal an attempt by the Province of British Columbia to determine a more complete range of hydrologic and geomorphic effects resulting from changes in surface condition and surface vegetation. This integration provides an ideal basis for CEA where forest removal and surface disturbance are the typical mechanisms of impact. This move toward recognizing the full range of hydrologic hazards, including closely-related geomorphic hazards, but also other consequent hazards focused on water quality and ecological communities, is consistent with progressive landscape industrialization and its consequences for cumulative effects. The present study is an attempt to broaden assessment capabilities to cover a greater range of hydrologic and aquatic hazards, and a wider range of stressor types, while still recognizing data deficiencies over the spatial scales under consideration.

4.4.2 Flow Changes

The concern for increased peak flow from removal of forest vegetation and the construction of road systems has garnered considerable attention over many decades, and remains a central hydrologic issue in hydrologic CEA. Grant et al (2008) conducted a synthesis of research on this question. In examining the results of paired watershed studies, and other work, they conclude that effects of forest removal on peak flows diminish with increased basin size and event return period. They also find that watersheds in the pluvial regions are less sensitive to forest cover removal than in the transient snow region. More recently, Alila et al (2009) have challenged these well established conclusions by pointing out that they are based on a flawed approach that has focused on changes in magnitude of peak flows without invoking changes in frequency. They point out that small changes in flood magnitude can be difficult or impossible to detect and yet can lead to surprisingly large differences in flood return period. These ideas are further explored in Green and Alila (2012) and Kuras et al (2012).

In comparison, only a small number of studies has looked at changes in low flows in response to changes in forest vegetation and/or roads. Studies are reviewed by Winkler et al (2010) who find that available research is inconclusive due to limitations of the design of low-flow studies.

4.4.3 ECA

A basin ECA of 20% is often used in BC as a threshold to guide management decisions. For instance, this formed the basis of a recommendation for Clayoquot Sound of 1% basin harvest per year to a maximum of 20% ECA (Clayoquot Sound Scientific Panel, 1995). Church (1996) and others have found from detailed reviews of the literature that a trend of measurable increased peak flows occurs for basins with over 20% ECA. This observation does not mean that an ECA of 20% is a physical threshold of watershed response. Further, it does not imply that above an ECA of 20% channels will be destabilized by forest development, nor remain stable below 20%. The consequence of the change depends on a number of additional factors including the magnitude of the change in peak flow, changes in the regimes of sediment and coarse woody debris which may occur simultaneously, and many channel-related characteristics. Church (1996) has pointed out that an increase in peak flows likely occurs at lower levels of ECA (below the level at which it becomes measurable) ï the inability to detect the change is a reflection of the large synoptic and landscape variability and implies a natural range of variability. It may be technically justified on other physical grounds to support an increase in peak flows; however, in the absence of the more detailed analysis that would be required, it is prudent to maintain the flow regime within the natural range of variability.

4.4.4 Roads

It has become increasingly accepted that roads contribute to changes in peak flow (Burroughs et al. 1972; Harr et al. 1975; Zeimer 1981; King and Tennyson 1984; Wright 1990; Jones and Grant 1996 - in Ziegler and Giambelluca 1997). Wemple (1996) identified one mechanism in demonstrating how roads extend the natural drainage network by up to 40%, routing runoff and subsurface flow at a faster rate to the basin outlet. This hypothesis is also consistent with basic theory. What is less clear is the extent of road contribution to increased peak flows, especially in relation to other changes such as higher basin water yield. Jones and Grant (1996) examined long-term records of streamflow in the H.J. Andrews experimental watersheds using categorical analysis and analysis of variance, approaches which appear to be much more sensitive than standard regression techniques (Church 1996). Their findings caused them to suggest that the increased efficiency with which roads deliver water to channels is the most significant factor responsible for increased peak flows. However, Thomas and Megahan (1998) disputed the findings of Jones and Grant (1996) by suggesting that their conclusions cannot reasonably be drawn due to flaws in their analysis of the data.

5.0 SUPPORT TOOL DEVELOPMENT

5.1 General Considerations

The experience described above suggests the general content and structure of what is needed in the present work. Ideally, the rating system will have a strong theoretical basis, focused on the landscape and management regime under consideration. It will address both singular and cumulative effects (including interactions) to the extent that they are understood. While it is not feasible to use only a physical model at this time, the approach should be grounded in the understanding that research and detailed modeling can provide. The approach should be based on measurable, spatially definable, physical components that are combined in a transparent manner.

In developing management indices, these studies make it clear that hydrologic response is too complex to be adequately represented by one index. Bettinger and Johnson (1998) reached this same conclusion in comparing indices of habitat quality with various indices of forest development including Equivalent Clearcut Area (ECA). This was recognized in BC in the development of the Interior Watershed Assessment Procedure which assesses five hazard indices. However, if the indices are poorly formulated or lack data or a physical basis, it may be more appropriate to acknowledge the lack of understanding and simply use crude ñback of the envelopeò calculations based on general indicators like basin ECA and road density.

The management context constrains the approach to be a tool simple in application exploiting GIS capabilities and available data. It is likely that an indicator approach will be most feasible; however, those indicators selected should be tied to relevant physical processes which correlate with impact (recall Figure 3.1). The structure should be established so that the results are amenable to interpretation in a risk-assessment context. It is suggested that the proposal would be best implemented in terms of an adaptive-management framework. Ongoing evaluation as knowledge and data improve would give the rating system the capacity to evolve thereby improving the precision and accuracy of its indications.

5.2 Framework

The approach proposes the recognition of seven potential hazards (see Figure 3.1):

- Altered water chemistry
- Altered temperature
- Altered suspended sediment (fine sediment)
- Altered bedload (coarse sediment)
- Increased peak flow
- Decreased low flow
- Altered channel stability

These seven hazards act separately and cumulatively to change the condition of aquatic values. To quantify these changes for decision support, the factors that shape the hazards are assessed at a consistent spatial scale and integrated using the understanding of hydrologic cause and effect presented in section 3 above.

5.3 Assessment Units

British Columbia's Assessment Watersheds (Carver and Gray 2010) are used as the basic assessment unit for the analyses. The Assessment Watersheds (AWs) provide a standardized division of the entire province into aquatic units of similar size, based on stream mapping and watershed boundaries taken from BC Freshwater Atlas. Provincially, these units were created to have a mean size of 50 km^2 (range of 10 to 100 km^2) and emphasize polygons as complete watersheds, minimizing the areal extent of units that are residual areas. There are three types of polygons within the AW coverage: complete watersheds, incomplete watersheds and large lakes. A complete watershed is an area drained by a locally connected network of streams that drain to a single point; it has no additional streams draining into it (i.e., a typical basin, or the headwaters of a moderate-size basin). Terrestrial units that do not fit this definition are residual areas or incomplete watersheds. These can consist of "face units" that occur along the coastline, lakeshores, and the banks of large rivers where the land is not drained by a mapped stream or small basins too small to be recognized as individual AWs. Some face units are discontinuous multi-part polygons. Other incomplete watersheds are the lower reaches and tributaries of moderate-size basins that are too large to be an individual complete AW.

There are 1381 assessment watersheds within the study area with a size distribution as summarized in Table 6.1. The larger units that exceed the 100-km^2 threshold are generally basins with extensive glacial area and/or are adjacent to the Alaska border.

The assessment of the potential for altered channel stability and stream temperature requires a different assessment unit than the other hazards. While the other hazards can be reported by AW, channel stability and stream temperature are more suited to reporting by stream reach, and generally the reaches that are of most interest are reaches of streams of a higher stream order than those contained within a single AW. To facilitate this type of analysis, the hierarchical coding included with BC's AWs provides the opportunity to roll up the assessment units into larger basins more appropriate for reach analysis of higher-order streams (see discussion of channel stability in section 6.5). This also allows for investigation of hydrologic and geomorphic processes operating at larger spatial scales.

Table 5.1. Size distribution of the assessment units upon which the analysis is performed.

Grouping or Type	No.	Area (km^2)			Stream Order		
		Mean	Min	Max	Mean	Min	Max
Watersheds	758	44.4	20.0	455.2	4.1	1	6
Residual Areas	623	56.7	7.5	362.6	5.9	1	9
Lakes	4	33.1	27.9	36.7	5.8	4	7
All	1385	49.9	7.5	455.2	-	-	-

5.4 Data Inputs

5.4.1 Factor Selection and Modeling

The selection of factors used in the hazard rating system considers:

- level of understanding of system complexity (Figure 3.1),
- extent and quality of available data, and
- present knowledge of hydrologic outcome in relation to mechanisms under consideration.

The proposed approach possesses a moderate degree of complexity. A highly simplified system could be considered ï for example, one that involves limited factors such as Equivalent Clearcut Area (ECA) and total road density - however, such a system would limit permanently the accuracy of assessed ratings. We know with confidence that these simple surrogate variables correlate only weakly with hydrologic outcome. In contrast, a highly-complex assessment may be inappropriate where there is a lack of quantitative understanding of the effect of some mechanisms on hydrologic outcome, or there is insufficient watershed data for its application. The selection of factors in the tables presented provide a reasonable balance between the level of knowledge, the present availability of data, and data that can be generated with a modest amount of additional work.

A general summary of the factors which have been selected for inclusion in the rating system for both inherent- and development-related hazard ratings is provided in Table 5.2 along with data sources generally available across the province. Table 5.3 summarizes the disturbance activities to be considered in assessing potential development effects in relation to the various hazards (X ï principal factor, (X) ï secondary or indirect factor).

Many of the proposed input data layers are modeled from Digital Elevation Models (DEMs). Previous work on landform, terrain and soil modeling from DEMs has established that the accuracy of terrain and soil modeling requires a relatively detailed DEM (e.g., Pack et al. 2005, MacMillan et al 2000, MacMillan 2004), preferably with a pixel size of 5-15 m and vertical resolution of <1 m. Unfortunately the resolution readily available for most of BC is a 25 or 30 m DEM. The assessment procedures presented here would greatly benefit from higher resolution DEMs.

Table 5.2. Assessment factors and their associated data sources (more details in Section 6.0).

Regime			Factor of Interest	Surrogate for Modeling Purposes	Data Source	
					Full & Available Coverage	Partial and/or Potential Coverage/ Comments
site factors	flow		climatic regime (precipitation, ET, storm frequency, etc.)	Regional Landscapes based on current biogeoclimatic subzone mapping	BEC mapping	AES, ClimateWNA and other data; Regional Landscape mapping
			snowmelt patterns	index of aspect/ elevation complexity	DEM	GIS analysis
			vulnerability to ECA/ riparian disturbance	% naturally forested	Forest Cover/ VRI, BTM, imagery	analysis of FC data
			subsurface storage and discharge rate	material depth /texture; infiltration rates, bedrock	terrain and bedrock mapping	terrain mapping and modeling; includes karst
			seepage interception/ likelihood of saturation	soil wetness/ flow accumulation	DEM	
		sediment/ chemistry	low flow/ sediment buffering	lakes and wetlands, glaciers	Freshwater Atlas	
			sulfide-rich deposits	bedrock lithology	bedrock mapping	Gossan deposits
			channel vulnerability	channel index based on type and gradient	DEM, Freshwater Atlas; Reports	airphotos; assessments; flood disturbance history
			coarse sediment yield	Class III, IV, and V terrain stability (and delivery)	DEM, bedrock, terrain	modeling; terrain mapping
			fine sediment yield	waterborne-erosion potential and delivery, glaciers	DEM, terrain, Freshwater Atlas	modeling; terrain mapping
			channel continuity/ connectivity	debris-torrent and debris flood potential	DEM/ Freshwater Atlas	modeling; terrain mapping
development factors	soil disturbance		existing and potential inputs of coarse and fine sediment	types and locations of existing and proposed soil disturbance in relation to unstable/ erodible soils	Development Plans; land use maps, road inventories	GIS overlays; consideration *of quality* of road construction or other activities
	vegetation change		existing and potential changes to vegetation cover	types and locations of existing and proposed changes to vegetation cover	Development Plans; FC/ VRI, imagery	includes concepts such as ECA and riparian disturbance
	pollution		existing and potential chemical discharges/ leaching	types/ locations of existing/ proposed discharges and disturbance of sulfide-rich deposits	Development Plans; bedrock mapping	
	flow changes		existing and potential impacts on infiltration/ soil storage	types and locations of existing and proposed soil disturbance in relation to seepage; changes to vegetation cover	Development Plans; see sediment and vegetation entries	
			storage/ release/ diversions of water from channels/ watersheds	existing and potential flow diversions	Development Plans; water licenses	

Table 5.3. Summary of disturbance activities, mechanisms and hydrologic-hazard interactions (x – principle factor, (x) potential secondary or indirect factor).

Disturbance Activity	Mechanism	Hazards						
		Bedload	Suspended Sediment	Water Chemistry	Peak Flow	Low Flow	Channel Stability	Temperature
Excavations and sidecasting on slopes	Soil displacement	X	X				X	(X)
Excavations on Slopes	Subsurface flow interception; altered timing of runoff	X	X		X	(X)	X	(X)
Alteration of surface drainage pattern	Surface flow diversion; loss of wetland/ lake buffers	X	X		X	X	X	(X)
Creation of bare soil	Soil exposure	(X)	X	X			(X)	(X)
Creation of impervious surfaces (including compacted soil)	Soil compaction; runoff generation	(X)	(X)		X	(X)	(X)	(X)
Forest removal	Locally increased snowpack and melt rate; altered yield and timing of runoff	X	(X)		X	(X)	X	(X)
Forest canopy removal in the riparian area	Riparian disturbance			(X)			X	X
Disturbance of sulfide-rich materials	Chemical alteration/ release			X				
Chemical discharge	Direct impact			X				
Reservoir impoundment	Water storage flow buffers; capture of bedload and suspended sediment	X	X		X	X	X	X
Reservoir/ Spillway Operation	Direct impact on timing of flow; chemical alteration			X	X	X	X	(X)
Water Withdrawals	Direct impact on water yield/ timing of flow				X	X		X

Work is underway to compile and develop data layers for implementation of the hazard assessment procedures. Existing terrain mapping has been examined and found to cover less than half the study area, and to be of marginal quality. The potential for modeling broad classes of terrain types and textures is being explored as an alternative. Preliminary analysis of bedrock geology for estimating soil texture has been completed, and analysis for deep subsurface water storage capacity and sulphide-rich materials are in progress.

The following section describes ongoing work on the establishment of Regional Landscapes for use as hydrologic zones for the estimation of hydrologic flows in unguaged basins. Hydrologic flow data and climate data are presently being compiled for each of the Regional Landscapes.

5.4.2 Regional Landscapes – Hydrologic Zones

Given the lack of widespread detailed hydrologic and climatic information, it is necessary to extrapolate from areas where data are available and utilize modeling to fill in data gaps. The development of ClimateWNA (Wang et al. 2012), a spatial database of numerous climatic variables for Western North America, provides a useful tool for extrapolating climate information. One approach for filling data gaps in streamflow data has been to define hydrologic zones, areas with similar streamflow characteristics. Various attempts have been made to define hydrologic zones for BC, but none is sufficiently detailed for this scale of analysis (e.g., Coulson and Obedkoff 1998).

An approach that has recently been developed for defining areas of similar ecological response to climate change potentially offers a simple method for defining detailed hydrologic zones (Holt et al. 2012, Utzig 2013). This approach establishes units called Regional Landscapes (RLs), where each RL is defined to represent a geographic area of relatively similar climate (see Figure 5.1). Consistent elevational sequences of currently defined Biogeoclimatic units are used as indicators of climatic similarity.

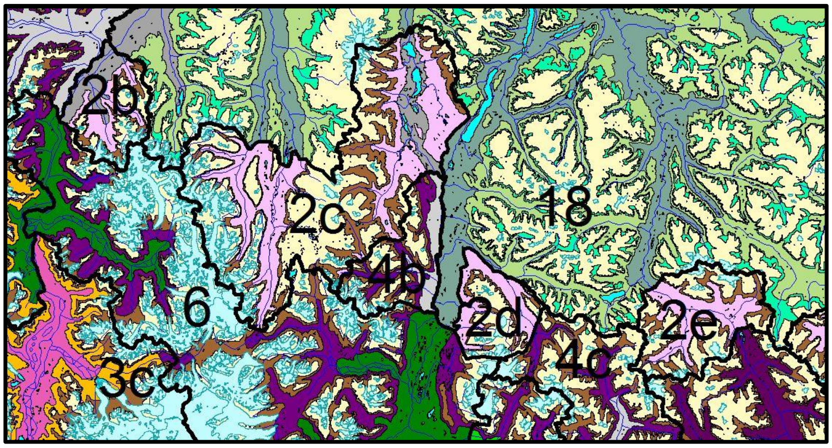

Figure 5.1 Mapping Regional Landscape hydrologic zones with BEC unit sequences.

Because the macroclimate is relatively similar within each RL, they also define zones where streamflow characteristics are similar. Differences in streamflow between basins within a single RL will be the result of difference in other basin-specific factors such as topography, bedrock, terrain and vegetation distribution. RLs for the study area are depicted in Figure 5.2.

Climatic variability within the RLs is primarily determined by aspect and elevation, with some contributions of meso- and micro-topographic elements. For ecological purposes, RLs have been split into elevation bands (e.g., <1000m, 1000-1500m, etc.). For more detailed work, the units can be further subdivided based on aspect, finer topographic subdivisions, landforms/terrain units and/or moisture regime. The RLs can also be grouped into subregional and regional climatic units (Utzig 2013).

Table 5.3. Summary of biogeoclimatic elevational sequences for Regional Landscapes.

BEC Units	Regional Landscapes/ Hydrologic Zones																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
BAFAun	X	X		X		X	X					X	X	X	X		X
CMAun			X		X			X	X	X	X					X	
CWHwm			X						X								
CWHws1										X							
CWHws2										X	X	X					
MHmm1									X								
MHmm2			X		X			X		X	X					X	
Mhunp			X		X			X	X	X	X					X	
ICHmc1													X		X	X	
ICHmc2											X	X	X				
ICHwc					X	X											
ICHvc							X	X									
ESSFmc		X															
ESSFmcp		X															
ESSFwv												X	X	X	X		
ESSFwvp												X	X	X	X		
ESSFun				X		X	X										
ESSFunp				X		X	X										
SBSmc2		X												X			
SBSun				X													
BWBSdk	X																X
SWBmk																	X
SWBmks																	X
SWBun	X																
SWBuns	X																

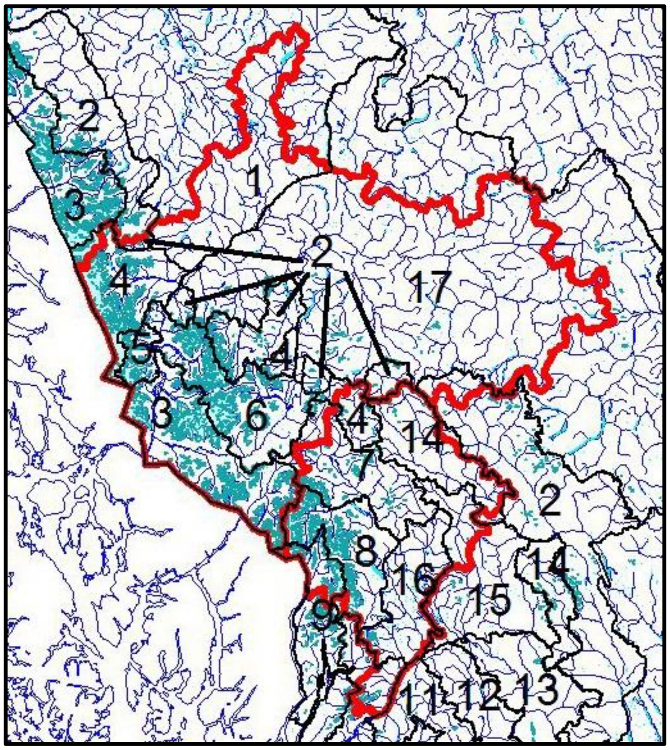

Figure 5.2. Regional Landscapes/ hydrologic zones (black lines) for the study area (red lines).

The climatic variation between RLs is assumed to result principally from macro-topography interacting with weather systems. Because macro-topography is stable in the face of climate change, it is assumed that the climate within individual RLs will likely remain relatively homogeneous, even as climate change proceeds[1]. Preliminary modeling results in the West Kootenay appear to be consistent with that assumption (Utzig 2012).

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[1] This assumption would be less valid under a severe climate change scenario where there may be significant shifts in the patterns of weather systems. For example, if there is a significant shift in continental vs. maritime influences, or in the long-term seasonal patterns of the jet stream.

6.0 HAZARD RATING TOOLS

6.1 Altered Bedload (Coarse Sediment, adapted from Utzig et al. 2009)

Coarse sediment, for the purposes of this modelling, is defined as unconsolidated geologic material greater than 2 mm in diameter that is generally expected to move as bedload rather than suspended sediment. The modelling in this section focuses on predicting coarse sediment produced by open-slope landslides. Although large organic debris (trees and stumps) often accompanies coarse sediment in landslide materials, it is not addressed in this model. Although coarse sediment inputs to water bodies occur through natural hydrologic processes, increased rates of input above background levels occur from non-equilibrium disturbances and can have significant impacts on stream channel stability (e.g., NHC 1994, Hartman et al. 1996). Large inputs can result in channel infilling, channel avulsion, bank erosion, channelized debris flows (debris torrents) and debris floods (e.g., Hogan et al. 1998, Swanson et al. 1998). The resulting channel changes can have significant negative impacts on aquatic habitat, riparian values and water quality. The most common human causes for increases in coarse sediment inputs are landslides initiated by failure of road construction materials directly, drainage diversions resulting from improper drainage management associated with roads, and exacerbated by or occasionally caused by forest harvesting. Tables 6.1 and 6.2 provide a summary of variables utilized in the determination of the inherent hazards, and development activities considered in the determination of potential development impacts.

Previous modelling of landslide occurrence and consequent stream sedimentation in BC has largely used simple techniques, often restricted to using only slope as an indicator to landslide potential (e.g., BC MoF 1995). In recent years there have been various efforts to investigate multi-factorial approaches (e.g., Miller and Burnett 2007). A more complex model to identify potential landslide initiation zones for terrain stability mapping has been developed by Robert Pack (Pack 1997 and Pack et al. 2005), and a portion of his modelling approach has been adapted for this model. Channelized debris flow modelling has also received significant attention (e.g., Millar et al. 2002, Miller and Burnett 2008). There does not appear to be any previous modelling of landslide delivery potential (i.e. hillslope-to-channel coupling). Therefore the combination of flow algorithms and barriers used to model coupling in this project may offer a new approach to representing the relationship between landslide potential and actual impacts on hydrologic features.

6.1.1 Objectives

The objective of the coarse sediment model is to predict the amount of coarse sediment delivered to stream channels, lakes and wetlands by landslide activity. The intent is not to predict individual landslides, but instead to provide information suitable for estimating coarse sediment inputs at the mesoscale watershed level (2,000-20,000 ha). Output is the estimated average annual volume (m^3) of coarse sediment delivered to the hydrologic network within a watershed.

Table 6.1. Components and indices for assessing inherent hazard to Altered Bedload.

Component	Index	Specific Variables	Rationale	Data Source	Comments
Stability Mapping	Terrain Stability	Stability Rating	Detailed terrain mapping with stability ratings provides landslide hazard information for specific areas	Terrain stability mapping	Preferred source of information
Where stability mapping is unavailable **Stability Modelling Inputs**	Soil Cohesion/ Angle of Repose	Fine fraction texture/ coarse fragments	In cohesive soils, the relative mix of sands, silts and clays (i.e., fine fraction texture) are primary factors in determining soil strength; in non-cohesive soils the size and angularity of coarse fragments are important factors	Terrain/ soil mapping; estimated from bedrock mapping and landform modeling	Alt. info.; based on broad scale terrain/soil maps and/or bedrock lithology
	Saturation Likelihood	Accumulated soil moisture	Saturation reduces soil cohesion and is a primary contributing factor to landslides in finer materials on steep slopes	Modelled from DEM	Presence of melting permafrost may also have to be considered
		Precipitation Inputs	Where study area includes wide variation in precipitation, this may be an additional factor to include	Climate WNA	
	Slope	% Slope	Increased slope angle increases landslide risk	DEM	Alt. info.; from DEM
	Coupling to stream network	Barriers to coupling	Presence of areas of low slope between the landslide site and the nearest downslope stream segment decrease the likelihood of transport of sediment to a stream	Modelled from DEM	Based on DEM modelling

Table 6.2. Potential disturbance activities utilized for the assessment of development interactions with Altered Bedload Hazard.

Disturbance Activity	Mechanism	Disturbance Types	Rationale	Comments
Excavations and sidecasting on slopes	Soil displacement	Roads and other terrain alteration (e.g., mining, pipelines)	Cuts and fills may increase the risk of landslides by removing support, increasing slope angle and/or adding weight	
Excavations on Slopes	Subsurface flow interception	Roads and other terrain alteration (e.g., mining, pipelines)	Interception, redistribution and concentration of subsurface flow is a common contributor to landslide occurrence, especially in gentle-over-steep situations	
Alteration of surface drainage pattern	Surface flow diversion	Roads, mines and other disturbances with stream crossings	Diversion and concentration of surface flows is a common contributor to landslide occurrence	
Reservoir impoundments	Bedload capture	Reservoirs and headponds	Dams do not allow passage of bedload	
Forest removal	Locally increased snowpack and melt rate	Forest harvesting, land clearing (agriculture, pipelines, mining, etc.), fire, insect/ pathogen infestations, windthrow	Removal of forest cover can increase melt rates, decrease interception, reduce evapotranspiration, and eliminate root systems, all of which can contribute to increased landslide risk due to increased saturation and/or decrease soil strength	

6.1.2 Model Description

6.1.2.1 Structure

The model design is based on the following basic assumptions:

- the main sources for coarse sediment deposition to streams channels and other hydrologic features are open-slope debris-avalanche/debris-flow landslides originating upslope of these features[2],
- the main contributing factors to landslide occurrence are: slope, soil moisture levels and terrain/soil type, and
- stream coupling is mainly controlled by the occurrence of areas of gently sloping terrain downslope of the landslide starting zone.

As shown in Figure 6.1, the model consists of four main components:

- an estimate of the likelihood that a landslide will originate in a given pixel,
- an estimate of the likelihood of a landslide originating in that pixel depositing material in a hydrologic feature (i.e. coupling),
- potential increases in landslide likelihood due to activities on pixels upslope from an unstable pixel (upslope induced hazard), and
- disturbance scenario inputs indicating the location and type of disturbance present in each scenario, on or upslope of potentially unstable pixels.

The determination of the likelihood of landslide initiation is either based on terrain stability mapping or a sub-model that estimates terrain stability based on slope, soil type and likelihood of saturation (adapted from Pack 1997, see Figure 6.2). The likelihood of saturation is determined from the application of a slope accumulation model to the DEM (Infinite slope method ï Tarboton 1997).

Slope coupling is estimated by first identifying potential barriers to coupling ï i.e. areas with sufficiently gentle slopes and width to contain the runout zones of potential landslides, and then using a flow accumulation model to identify all pixels upslope of such barriers (see Figure 6.3). Barriers are defined based on literature review and expert opinion (e.g., Horel 2006). Major barriers were defined as areas with <30% slopes and >200m wide, and moderate partial barriers as areas <40% slope and >100m wide.

Interactions between disturbance resulting from changes to forest cover and road construction and the likelihood for landslide initiation are modelled in two ways. Disturbance occurring on a given pixel increases the likelihood of landslide initiation by a specified factor, with the level of the factor depending on the type of disturbance (e.g., road construction has a greater influence than tree death). Factors are based on a review of the literature and expert opinion (e.g. Schwab 1998; Jordan 2002). In addition, disturbance that occurs upslope of pixel ñxòwill also increase the likelihood of landslide initiation at pixel ñxòdue to the potential for increased downslope drainage accumulation and/or drainage diversion (i.e. the ñgentle-over-steepòphenomenon, see Figure 6.3).

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[2] Deep-seated rotational landslides and in-channel debris torrents are not accounted for in the model. These landslide types may be significant sources of coarse sediment in some watersheds.

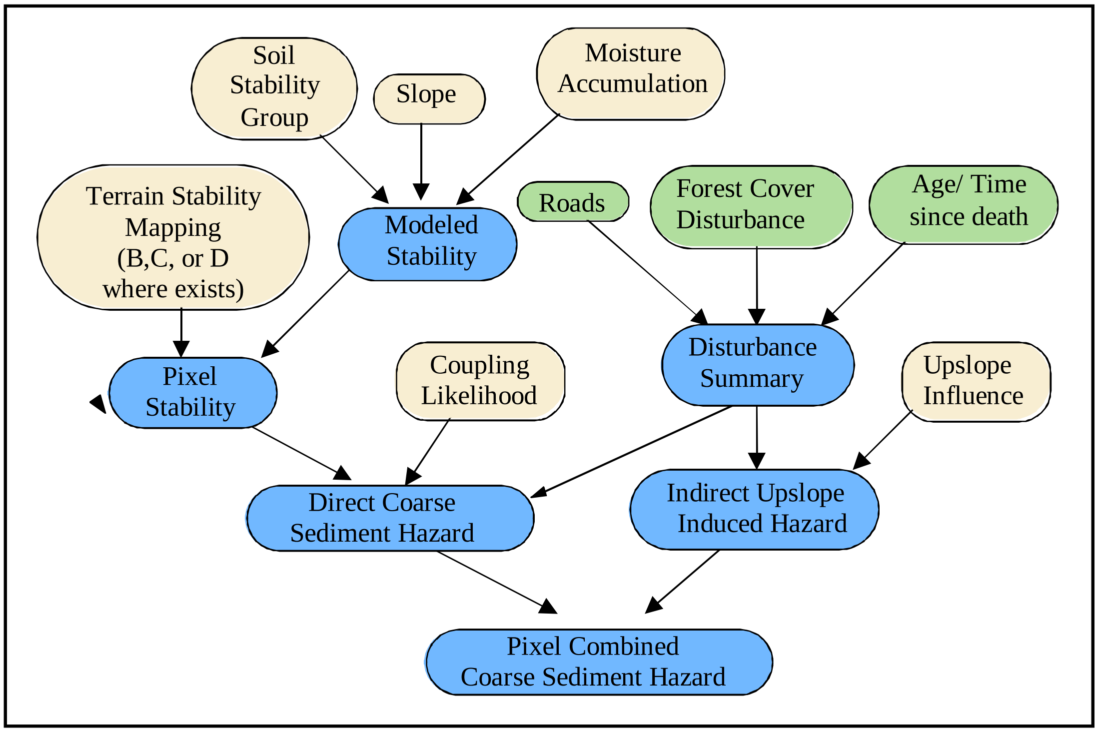

Figure 6.1. Structure of coarse sediment model. Tan coloured boxes indicate basic input nodes, green boxes are disturbance scenario input nodes, and blue nodes are computational nodes.

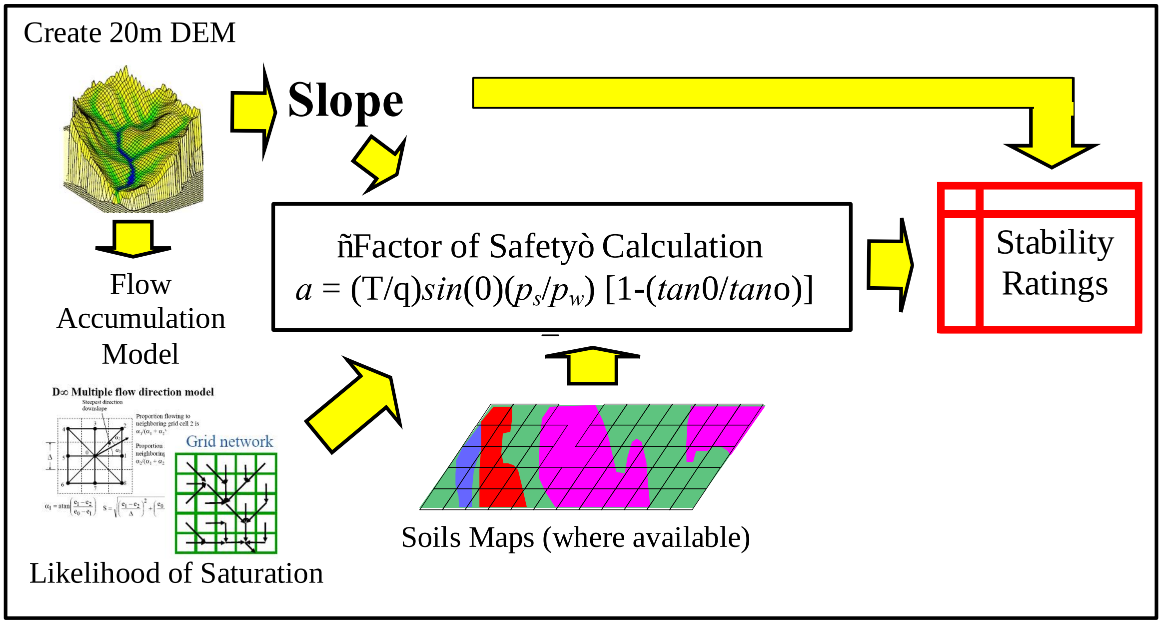

Figure 6.2. A generalized diagram of the terrain stability submodel.

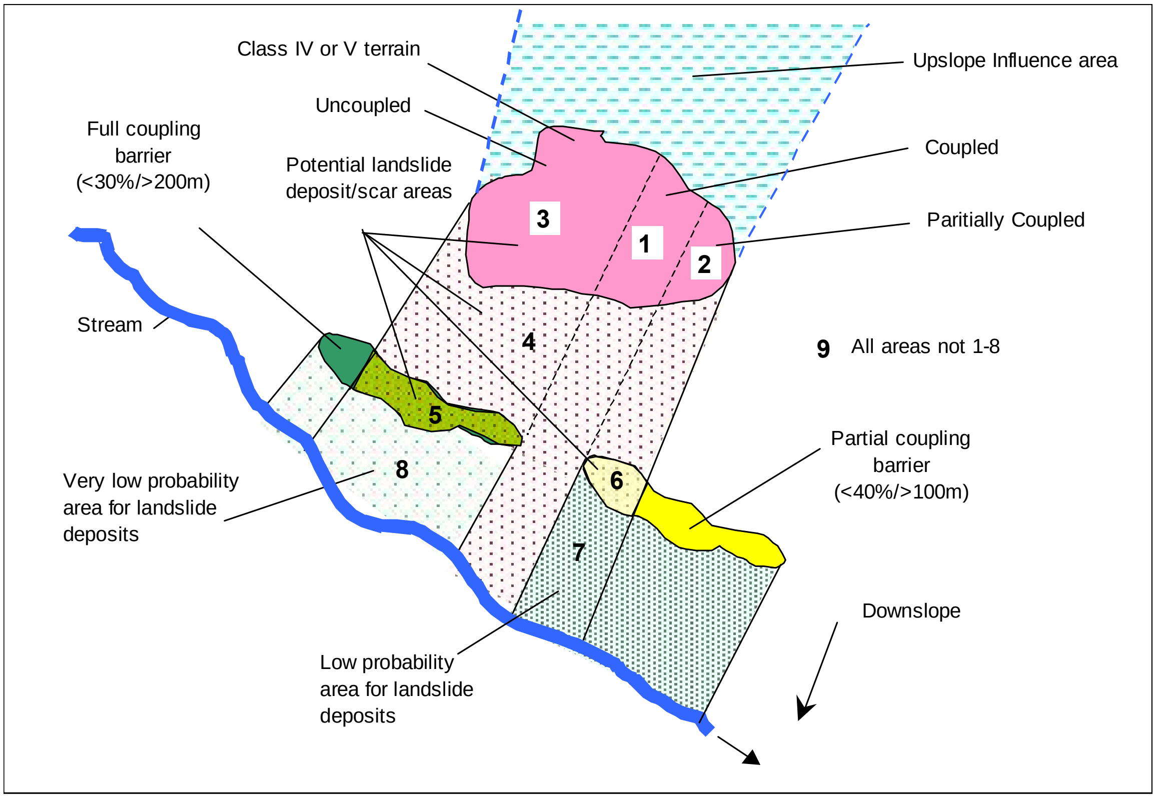

Figure 6.3. Conceptual diagram illustrating the conceptual framework for determining coupling and upslope influence contributions to the coarse sediment model. Zones 1, 2 and 3 are potential landslide initiation areas determined by terrain stability mapping or the terrain stability submodel. Zones 5 and 6 are potential barriers to landslide deposits entering the stream (zone 5 a major barrier and 6 a partial barrier). The blue stippled area above the initiation zones is the potential upslope influence area, where drainage diversions may increase the likelihood of landslide initiation downslope.

Based on assumptions described below, estimated volumes of coarse sediment delivered to hydrologic features were assigned to pixels with varying conditions related to instability. These assumptions and values will be reviewed and updated during the calibration process in the next phase of the project. Examples of the estimated volumes of coarse sediment generated under various conditions are also provided below.

Pixels: 20 x 20 m, or 400m2, or 0.0004 km2

Class V: A Class V pixel generates one landslide 1 m in depth once every 1000 years; 50% of the material generated is coarse sediment, the other 50% is fine sediment and organic material

20 x 20 x 1 x 0.5 = 200 m3 / 1000 yrs = 0.2 m3/400m2/yr = 500m3/km2/yr

Class IV: A Class IV pixel generates one landslide 0.5 m in depth once every 5000 years; 50% of the material generated is coarse sediment, other 50% is fine sediment and organic material

20 x 20 x 0.5 x 0.5 = 100 m3 / 5000 yrs = 0.02 m3/400m2/yr = 50m3/km2/yr

Coupling Influence: The following are the factors applied for each of the three states of coupling:

- Fully Coupled ï 90% deposited in hydrologic feature (80-100%)
- Partially Coupled ï 50% deposited in hydrologic feature (40-60%)
- Uncoupled ï 10% deposited in hydrologic feature (0-20%)

Table 6.3. Factors applied to increase the likelihood of landslide occurrence when disturbance activities occur on, or upslope of an unstable or potentially unstable pixel.

Class	Disturbance Type	Factor	
		Disturbance On Pixel	Disturbance Upslope
VH	Road-poor	2	1.1
H	Road-good	1.5	1.05
M	Cutblock	1.25	1.025
L	Dead Hi Pl	1.10	1.01
VL	Dead Low Pl	1.05	1.005
None	None	1	1

Disturbance Impacts: The following table summarizes the factors applied to unstable or potentially unstable coarse sediment volumes for various disturbances. The influence of disturbance upslope of unstable areas are estimated to increase sediment delivered by 10% of the volumes of coarse sediment estimated for sediment produced with similar disturbance on the pixel itself. (e.g., a road on coupled Class V estimated at 675 ï 1000 m3/km2/yr, road above coupled class V is 67-100).

6.1.2.2 Range of Outcomes

The following table provides selected examples of estimated coarse sediment outcomes for selected combinations of unstable terrain, coupling and disturbance. See Appendices in the original report for detailed descriptions of modeled relationships between disturbance and coarse sediment generation.

More detail on all aspects of the model is provided in the Appendices of the original report.

6.1.3 Tools

Modelling activities are completed with a combination of software tools using ArcGIS ® (ESRI), MS Access and Netica ® (Norsys - Bayesian modelling software), involving a four-step process. First, input data is combined in a GIS to export a table of unique combinations of input data and their location. Second, a spatially referenced case file containing all of the attributes necessary for running the model was built in MS Access. The third step involves processing the case file in Netica according to probability tables defined within the Bayesian model (Bayesian Belief Network ï BBN). The resultant from the model is then used in the fourth step of presenting spatially referenced outputs with ArcGIS.

Table 6.4. Examples of potential outcomes for selected combinations of factors.

Case	m3 / km2/ yr	Comments
Stable / any disturbance	0	
V / road / coupled	600 ï 1000	Highest of all
V / no disturbance / coupled	400 ï 500	
V / cutblock / partially coupled	250 ï 375	
V / dead hi Pl / uncoupled	0 ï 110	
IV / road / coupled	60 ï 100	Highest IV
IV / dead low Pl upslope / uncoupled	0 ï 10.1	
IV / no disturbance / uncoupled	0 ï 10	Lowest of all

BBNs are used to predict outcomes from a variety of input factors. They are probabilistic graphical models that represent a set of variables and their interdependencies and the expected outcomes based on the relationships defined in the network structure. A number of tools are available for construction of Bayesian nets (Marcot et al. 2006); however, we have chosen Netica as it is one of the more commonly applied ones in British Columbia. A BBN is a particularly useful tool in this type of situation because it allows the use of empirically defined relationships, as well as expert judgement where data gaps exist (Nyberg et al. 2006). Netica utilizes a series of conditional probability tables, or ñCPTsò to incorporate those relationships into the overall model structure.

Modelling ecological systems is carried out generally for one of two purposes: predictive modelling or descriptive modelling (Bunnell 1989). Predictive models tend to be used by resource managers to help direct decisions and implement policy; whereas, descriptive models are commonly used by researchers to provide answers associated with why or how systems work. Bayesian models provide utility to both managers and researchers simultaneously because they offer the ability to interpret interim processing stages, and because of their graphical nature aiding in presentation of model relationships.

6.1.4 Data Inputs

The coarse sediment model incorporates data from the following sources:

- Detailed terrain stability mapping (where available, Level B, C or D)
- Digital elevation model (DEM with 20m pixel, 10 or 15m pixel is preferred)
- Soil and terrain mapping (where available, generally 1:50,000, 1:20,000 is desirable)
- Hydrologic feature coverage, including streams, lakes, wetlands and watershed boundaries
- Forest Cover (disturbance component, can include disturbances ï e.g. beetle attack), and
- Road and Cutblock (disturbance component, could include existing and/or proposed; possible to add other disturbances).

Data preparation and pre-processing includes:

- where necessary, combining existing Terrain Stability mapping into a continuous rasterized coverage for the study area; combining Levels B, C and D Terrain Stability mapping into a common four-class rating system: stable (S and I, II and III), class 5 (V and U), class 4 (IV and P), unmapped;
- combining existing soil and/or terrain mapping into a continuous rasterized coverage where existing soil mapping units have been grouped into a three-class ĩSoil Stability Groupingsòmap layer;
- utilising the DEM and Soil Stability Grouping layers, running a terrain stability hazard submodel to determine stability ratings for areas without Terrain Stability Mapping;
- utilising the DEM, hydrologic feature coverage, existing Terrain Stability Mapping and the resultant of terrain stability hazard modelling, running a coupling submodel to determine the likelihood of unstable areas depositing landslides into hydrologic features
- utilising the DEM, hydrologic feature coverage, existing Terrain Stability Mapping and the resultant of terrain stability hazard modelling, running an upslope influence submodel to determine areas where disturbance may affect unstable areas downslope of those areas; and,
- preparation of layers depicting disturbance scenarios (e.g., rasterized coverages of changes in forest cover and road locations).

Data preparation and pre-processing requirements are described in more detail in the Appendices of the original report.

6.1.5 Data Outputs

Outputs are provided at two scales. Resultant files from the BBNs for each disturbance scenario are converted into spatialized GIS raster files indicating relative likelihood of each pixel for directly or indirectly supplying coarse sediment to hydrologic features. In addition the pixel values are summed for each assessment watershed to provide an overall predicted coarse sediment hazard for the watershed as a whole.

Interim outputs include GIS files showing the spatial distribution of inherent likelihood of landslide initiation, changes to the inherent likelihood for each disturbance scenario, the location of barriers to slope coupling, and couple/uncoupled slopes.

6.2 Altered Suspended Sediment (Fine Sediment from Sulyma *et al*. 2009)

Fine sediment[3] caught in water transport results in a number of adverse impacts including a reduction in the quality of water for domestic consumption, damage to the food web in aquatic systems, and deleterious impacts to stream bed characteristics. Multiple factors influence the levels of fine sediment input to a stream network (Liden *et al*. 2001). These range from the characteristics of a geographic region, including bedrock, soil types, terrain features, climate and vegetative cover, to the effects of both natural and anthropogenic related disturbances. Examples of natural disturbances resulting in fine sediments include wildfire, landslides or other events that create exposed mineral soil. Human induced disturbances resulting in fine sediments include forestry activities, roads and agriculture. Tables 6.5 and 6.6 provide a summary of variables utilized in the determination of the inherent hazards, and development activities considered in the determination of potential development impacts.

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[3] In this documents our reference to fine sediment, or fines, is consistent with the term suspended sediments and refers to soil particles of sand and finer (< 2.0 mm diameter).

Table 6.5. Components and indices for assessing inherent hazard to Altered Suspended Sediment.

Index	Specific Variables	Rationale	Data Source	Comments
Soil erodibility	Fine fraction texture/ coarse fragments	Detachability and ease of sediment transport are related to soil texture	Terrain/ soil mapping; estimated from bedrock mapping and landform modeling	
Soil exposure	Exposed mineral soil	Presence of soil organic layers (LFH) significantly reduces the potential for waterborne surface erosion	VRI/ FC mapping; BTM; remote sensing	
Runoff availability	Accumulated soil moisture	Increased surface water flows increase detachment and the capacity to move fine sediment; surface waters result directly from precipitation and snowmelt, and indirectly from emerging subsurface flows	Modelled from DEM	Presence of melting permafrost may also have to be considered
	Precipitation inputs	Where study area includes wide variation in precipitation, this may be an additional factor to include	Climate WNA	
Slope		Increased slope angle increases detachability and flow rates	DEM	
Landslide potential	Terrain stability	Landslide potentially deposit fine sediment directly into streams, as well as providing bare soils subject to surface soil erosion on scarps, transport zones and depositional areas	Stability mapping or modeling (see Bedload Hazard)	
Coupling to stream network	Barriers to coupling	Presence of areas of low slope between the erosion site and the nearest downslope stream segment decreases the likelihood of transport of sediment to a stream	Modelled from DEM	

Table 6.6. Potential disturbance activities utilized for the assessment of development interactions with Suspended Sediment Hazard.

Disturbance Activity	Mechanism	Disturbance Types	Rationale	Comments
Creation of bare soil	Soil exposure	Roads (could include skid trails, seismic lines, etc.), severe fire, landslides and other soil disturbances (e.g., mining, urbanization, agriculture, site preparation)	Bare soil has higher waterborne surface erosion rates, due to being exposed to raindrop energy and increased ease of particle detachment	
Excavations on slopes	Subsurface flow interception	Roads and other terrain alteration (e.g., mining, pipelines)	Subsurface flow interception makes more water available for waterborne surface erosion	
Alteration of surface drainage pattern	Surface flow diversion	Roads, mines and other disturbances with stream crossings	Water diversions often move water into areas with no previous water activity where surface erosion removes fines until a new channel is established	
Reservoir impoundment	Fine sediment capture	Reservoirs with sufficient residence time and surface water withdrawals may reduce fine-sediment loads	Depending on residence time, reservoirs may capture significant suspended sediment	

Using a Bayesian modeling platform we identify the likelihood of any given point in a watershed contributing fine sediments to a stream network. To accomplish this, we compartmentalize three primary sources of fine sediments into individual sub-models. In each sub-model the likelihood of fine sediment generation is modified by the likelihood that sediment will be transported to a stream network to determine the final hazard.

The three primary sources of fine sediments considered were:

- dispersed disturbance resulting from both natural (e.g. beetle attack) and anthropogenic events (e.g. forestry activities);
- roads; and,
- disturbance resulting from mass wasting events.

We recognize that there are many sources of fine sediment, however, we believe we have captured the most significant with the three selected (Jordan 2006), except where glaciers are present (Church and Day 1989). The process of modeling the likelihood of coupling between a source and a stream network was likewise considered a critical issue necessary to address fine sediment inputs to hydrologic features (Luce 2002; Macdonald et al. 2003; Reid et al. 2007). The resulting hydrologic hazard will be incorporated with outputs from four other hydrologic hazard models to help identify which water values are at risk and what potential consequences may result from a variety of potential disturbance scenarios.

6.2.1 Objectives

The objective of the fine sediment model is to articulate the relationship of the key factors influencing the input of fine sediment to a stream network. The model has three distinct components (sub-models) each evaluating one primary sources of potential fine sediment contribution. The raw output of each sub-model provides a predicted amount of fines, originating from each 0.04 ha (20m x 20m) pixel. Raw values are summarized over an entire watershed assessment unit to produce a watershed level hazard rating.

6.2.2 Model Description

6.2.2.1 Structure

Three sub-models, representing dispersed disturbance, roads, and potential disturbance resulting from mass wasting events, were used to predict the total contribution of fine sediment input to a stream network. Each sub-model produced a pixel-based prediction that represented an annual contribution of fine sediments. The results of the sub-models were summed to provide the overall hazard for a watershed assessment unit. Model development was undertaken with consideration of validation tools such as the BC Ministry of Forests and Range, Forest and Range Evaluation Program water quality assessment (Carson 2006), and detailed watershed sediment budget monitoring (e.g., Jordan 2006, Church et al. 1989).

For each of the sub-models the contribution of fine sediments at the pixel level was based on:

- amount and type of soil exposure;
- erosion potential (soil type and estimated surface runoff); and,
- connectivity between transported fines and the stream network.

An influence diagram, presented in Figure 1, identifies the relationships among factors used for **modeling each primary source of sediment.**

The basis for the delivery of fine sediments to a stream network in each sub-model was determined by inferring a level of exposed soil that resulted from site disturbances. This value was subsequently modified by three factors that were considered to influence the erosion potential of a pixel: a precipitation index, soil erodibility factor, and an index representing surface water availability (based on pixel upslope catchment area). Once the amount of potentially erodible soil was determined for each pixel, the connectivity to a stream network, also referred to as coupling likelihood, was used to determine the fine sediment portion of that soil that could enter the hydrologic system. Not all factors on the left side of the tree in Figure 1 equally influence the prediction of sediment contribution relative to the process defined in each of the three sub-models; thus, variation, or refinements from the influence diagram in Figure 6.4 can be seen in each of the individual BBNs which are presented as influence diagrams in Figures 3.2, 3.3, and 3.4. The specific relationships between individual factors are summarized in the conditional probability tables (CPT) for each summary node for each sub-model. These CPTs for all the sub-models are provided in Appendix A1. Technical details specific to the application of the model and requirements for pre-processing are also provided in Appendices A1 and A2.

Preliminary calibration of the model output has been partially based on the results of source and sediment budget research in Redfish Creek of the Kootenay Lake study area (Jordan 2006). A case example representing an extreme situation would be a pixel (400 m2) located on section of a heavily used road that is built on a highly erodible material with extensive exposed cuts and fills, with high precipitation/snowmelt and seepage water availability, and located in closely coupled proximity to a stream. In this case, the model predicts >100 kg/yr of fine sediment delivered to the stream from this pixel. This is equivalent to an average of about 0.25 mm/yr of erosion depth across the entire pixel. Jordan (2006) reports average values ranging from 39 kg/yr per 400m2 to 325 kg/yr per 400m2 for roads in the Redfish area. At present the model is likely underestimating sediment delivery from roads, and the process of model calibration requires further work. Sediment delivery outputs for pixels with other combinations of disturbance, erosion and coupling factors are assessed according to the relationships defined in the CPTs, and all have values less than the extreme case example described above.

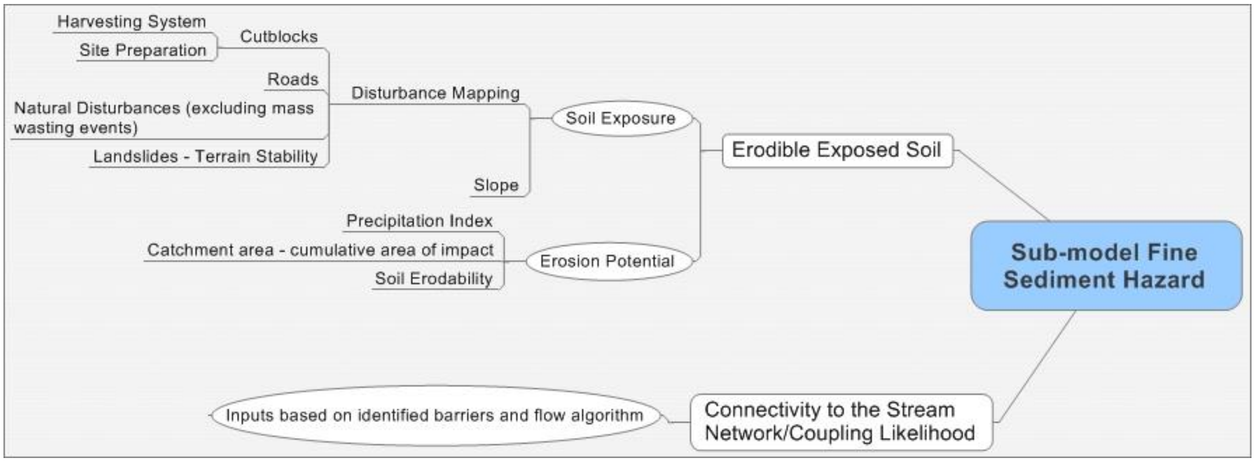

Figure 6.4. General structure of the factors considered in each of the sub-models used to determine the fine sediment hazard.

6.2.2.2 Soil Exposure

Dispersed Disturbance Sub-model: the prediction of soil exposure in the dispersed disturbance sub-model was based on predicting the likelihood that organic matter had been removed from a pixel as a result of a disturbance event (*Organic Matter Disturbance* ï Figure 3.2). Two disturbance classes were considered: anthropogenic, including different forest harvesting and site preparation methods; and, natural, which considered different intensities of wildfire, blowdown and forest pests. The resulting soil exposure of anthropogenic disturbance events, such as harvesting and site preparation were also considered to be affected by the slope of the terrain. The disturbance and slope factors were combined relative to a function of time (time was used as a correlate to express revegetation and re-establishment of the forest floor ï *Age* node[4] figure 6.5) to predict the value of *Estimated Dispersed Soil Exposure* (Figure 6.5).

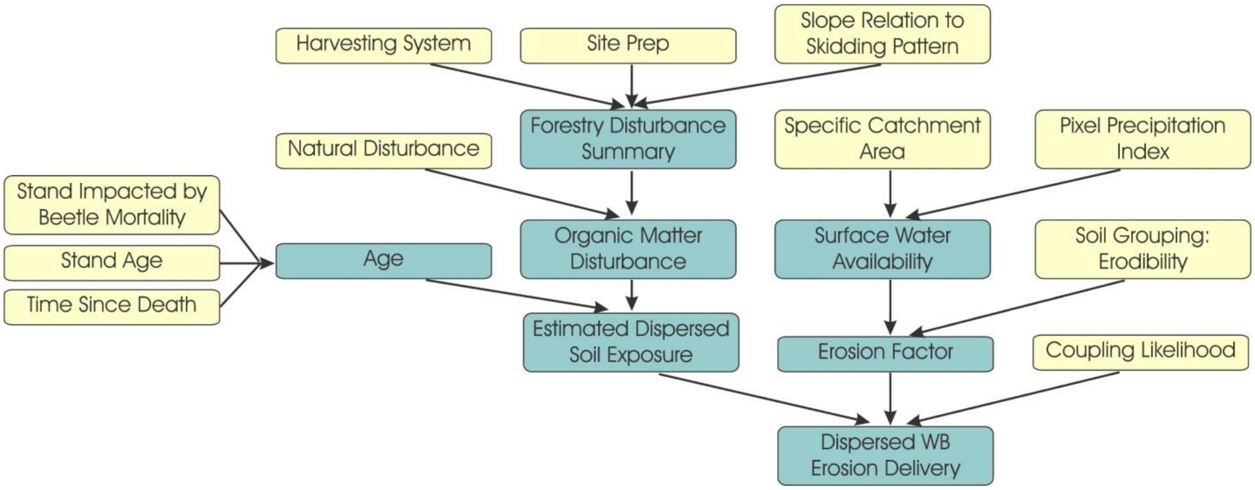

Figure 6.5. Dispersed Fine Sediment BBN/Influence Diagram where yellow nodes represent input values and blue are summary nodes.

Mass Wasting Events Sub-model: Mass wasting can result in fine sediment reaching hydrologic features in two ways:

- Landslides result in the deposition of landslide materials directly into a hydrologic feature (usually a combination of coarse sediment, fine sediment and organic debris).
- Landslides result in deposits of material on the hillslope or benches downslope of the landslide initiation zone, and subsequent waterborne erosion by runoff results in transportation of fine sediment derived from the landslide deposits being transported and deposited in a hydrologic feature.

Both pathways were incorporated into the Mass Wasting Events sub-model (Figure 6.6). Fine sediment resulting from landslide material being directly deposited into a hydrologic feature was determined by evaluating terrain stability hazard on a pixel and the likelihood that that the pixel was coupled with the hydrologic feature.

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[4] Ideally the age node should be an input node, but unfortunately the VRI data we were using to account for time since disturbance does not account for mountain pine beetle-caused forest mortality. When a stand is attacked it continues to age such that a 100 year old stand that was killed 10 years ago is now 110 not 10. So the input nodes to age simply allow for an accurate determination of age since beetle mortality.

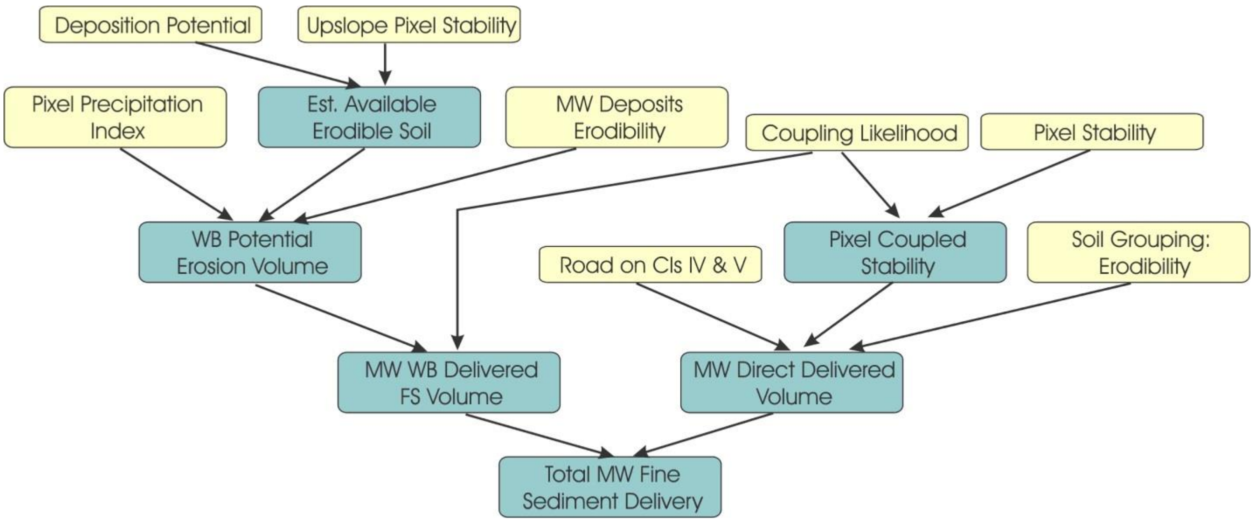

Figure 6.6. Mass Wasting Events Fine Sediment BBN/Influence Diagram where yellow nodes represent input values and blue are summary nodes and where Est. = Established, WB = Waterborne, and MW = Mass Wasting.

Predicting the amount of fine sediment resulting from landslide materials that were deposited on hillslopes relied on a series of overlays identifying deposition areas and the availability of surface water to erode the deposits. An input layer depicting various zones (Figure 6.8) where landslide materials would be deposited had to be developed (*Deposition Potential* - Figure 6.7) using identified landslide barriers and flow algorithms. Relationships between zones of potential deposits with the terrain hazard class of the landslide source pixels (*Upslope Pixel Stability*) were used to model the potential amount of exposed soil that would be subject to erosion processes (*Est. Available Exposed Soil* ï Figure 6.7).

Road Sub-model: Within the road sub-model, exposure was a direct determination based on the road class, which represented the road type, size and amount of use, and the slope of the pixel that a road was built on (Figure 6.7).

6.2.2.3 Erosion Potential

In all sub-models the erosion potential of a pixel was influenced by precipitation rates (*Pixel Precipitation Index*), derived from downscaled climate data for British Columbia by Wang et al. (2006). Within the Mass Wasting Events sub-model (Figure 6.7) relationships between the *Pixel Precipitation Index* and the erodibility of landslide debris (*MW Deposits Erodibility*) were used to provide an indication of the erosion potential of landslide debris deposited on a pixel (summarized *WB Potential Erosion Volume*). For both the Dispersed Disturbance and the Road sub-models relationships between zones of water flow accumulation (*Specific Catchment Area* - Figures 6.5 and 6.7) derived from flow algorithms, and the *Pixel Precipitation Index* were defined to give an indication of the *Surface Water Availability*. The ratings of *Surface Water Availability* and the erodibility of the soils (*Soil Grouping: Erodiblity)* were then used to predict the *Erosion Factor* (Figures 6.5 and 6.7).

6.2.2.4 Connectivity to the Stream Network/Coupling

All three sub-models incorporated analysis of the DEM to express the connectivity of a pixel and the stream network. Flow directions were modeled using flow accumulation algorithms. The results of the flow algorithm analysis were subsequently modified to consider the influence of barriers and summarized as one of three classes: coupled, partially coupled and not coupled. Barriers were defined on the basis of slope gradient and width (not coupled <30% and >200m; part coupled <40% and >100m). The barriers provide zones where a portion of fine sediment may settle out of surface water flow, reducing the amount of fine sediment delivered to the steam network.

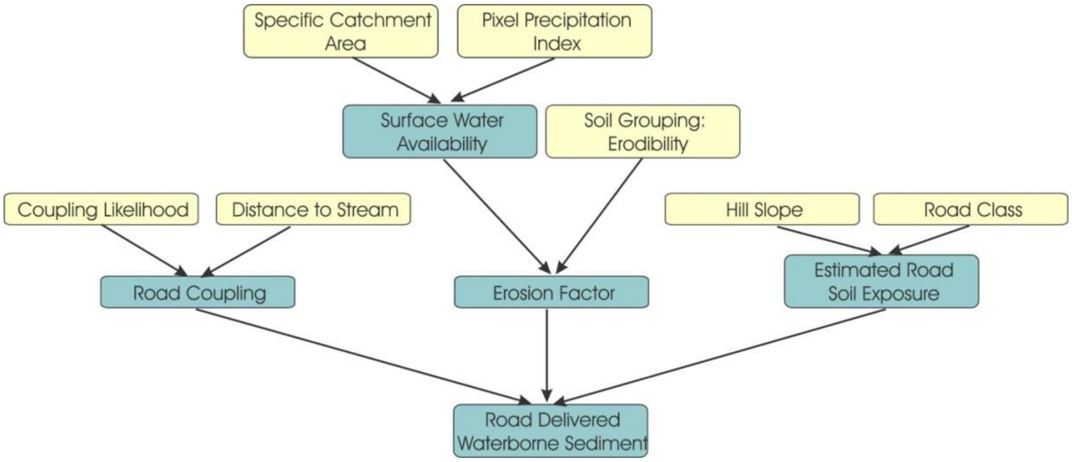

Figure 6.7. Roads Fine Sediment BBN/Influence Diagram where yellow nodes represent input values and blue are summary nodes.

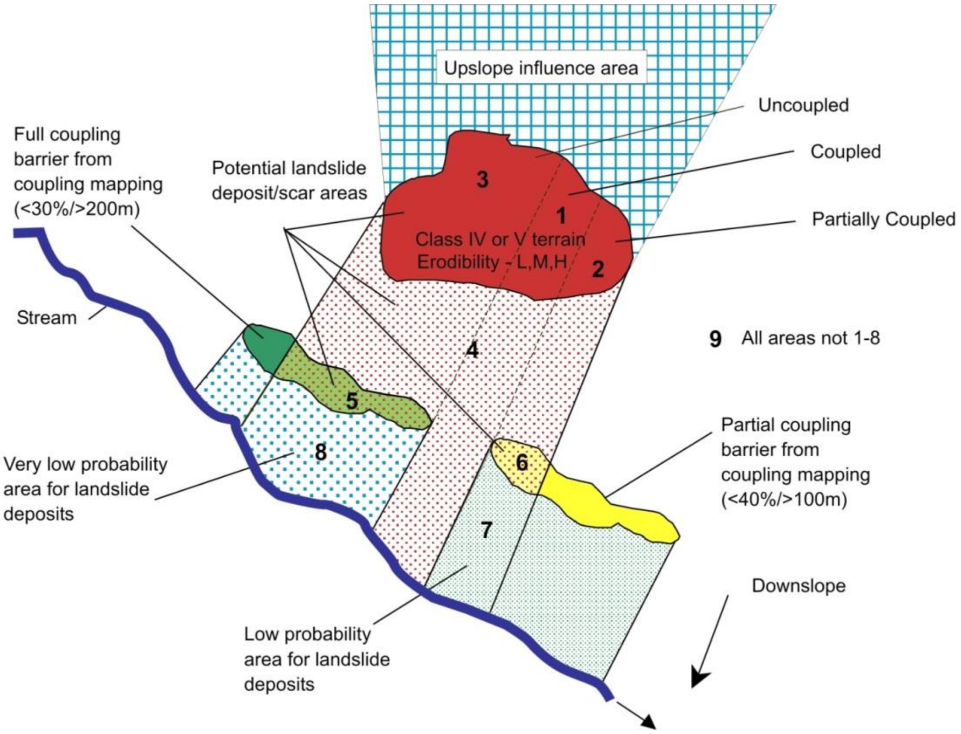

Figure 6.8. Conceptual diagram of the framework for determining coupling and upslope influence contributions to the mass wasting component of the fine sediment model. Zones 1, 2 and 3 are potential landslide initiation areas determined by terrain stability mapping or the terrain stability sub-model. Zone 2 has an increased likelihood for generating landslide deposits that may be directly deposited in a hydrologic feature (due to coupling). The red dotted area (Zones 4, 5 and 6) has a high potential for landslide deposits. Zones 5 and 6 are potential barriers to landslide deposits entering the stream (zone 5 a major barrier and 6 a partial barrier). The areas below the barriers have reduced likelihood of receiving landslide deposits, depending on barrier type. The blue crosshatched area above the initiation zones is the potential upslope influence area, where drainage diversions may increase the likelihood of landslide initiation downslope.

6.2.3 Tools

Many of the input layers used in each of the sub-models were derived from the digital elevation model (DEM) using a the ñTauDEM" software tool ñTerrain Analysis Using Digital Elevation Modelsò(Tarboton 2005). TauDEM is a set of tools that can manipulate the DEM, by filling depressions, and calculate flow direction and accumulation, and the influences of flow between adjacent pixels.

Modeling of the actual fine sediment hazard was completed in a four-step process with a combination of software tools using ESRIôs ArcGIS ® (Environmental Systems Research Institute, Redlands, California), Netica ® (Norsys ï Vancouver, British Columbia) and Microsoft Access® (Microsoft Corporation, Redmond, Washington). First, input data is combined in a GIS to export a table of all unique combinations of input data and their locations. Second, a spatially referenced case file containing all of the attributes necessary for running the model was built in MS Access. The third step involves processing the case file in Netica according to probability tables defined within the Bayesian model (Bayesian Belief Network ï BBN). The resultant from the model is then used in the fourth step of presenting spatially referenced outputs with ArcGIS.

BBNs are used to predict outcomes from a variety of input factors. They are probabilistic graphical models that represent a set of variables and their interdependencies and the expected outcomes based on the relationships defined in the network structure. A number of tools are available for construction of Bayesian nets (Marcot et al. 2006); however, we have chosen Netica as it is one of the more commonly applied ones in British Columbia. A BBN is a particularly useful tool in this type of situation because it allows the use of empirically defined relationships, as well as expert judgement where data gaps exist (Nyberg et al. 2006).

Modelling ecological systems is carried out generally for one of two purposes: predictive modelling or descriptive modelling (Bunnell 1989). Predictive models tend to be used by resource managers to help direct decisions and implement policy whereas descriptive models, are commonly used by researchers to provide answers associated with why or how systems work. Bayesian models provide utility to both managers and researchers simultaneously because they offer the ability to interpret interim processing stages and because of their graphical nature aiding in presentation of model relationships.

6.2.4 Data Inputs

The fine sediment sub-models incorporate the use of seven data sources. Data layers required include (Table 6.7):

- Soils mapping (where available, generally 1:50,000, but 1:20,000 desirable);
- Digital Elevation Model (DEM) (20 m resolution preferred);
- Precipitation ï based on climate data with 300 m resolution (Wang et al. 2006);
- Hydrologic feature coverage, including streams, lakes, wetlands and watershed boundaries (TRIM);
- Terrain Stability (terrain stability mapping and/or modeling);
- Roads and Cutblocks (disturbance component including beetle attack); and,
- Forest Cover (disturbance component, VRI).

Table 6.7. Summary of the BBN input nodes for each model and the data sources required for each.

BBN Input	Raw Data[1]	Input Pre-Processing	Sub-Model[2,]		
			D	R	MW[3]
Soils Erodibility Group	Soils	Classification	✓	✓	✓
Soils Stability Group	Soils	Classification			*
Coupled Likelihood	DEM	TauDEM algorithms	✓	✓	✓
Specific Catchment	DEM	TauDEM algorithms	✓	✓	*
Slope	DEM	Classification	✓	✓	*
Deposition Potential	DEM	TauDEM algorithms			✓
Pixel Precipitation Index	Interpreted PRISM[4]	Classification	✓	✓	✓
Distance to Stream	Hydrologic Features - TRIM	Buffering features		✓	
Terrain Stability[5]	Terrain Mapping/DEM	Project algorithms			✓
Roads on Pixel	FTA/ABR	Updates Required	✓	✓	✓
Harvesting System	VRI/FTA/RESULTS	Updates Required	✓		
Site Preparation	VRI/FTA/RESULTS	Updates Required	✓		
Natural Disturbance	VRI	Updates Required	✓		
Stand Age	VRI		✓		

[1] DEM = Digital Elevation Model, VRI = Vegetation Resources Inventory. FTA (Forest Tenure Application), ABR (As-Built Roads), and RESULTS (Reporting Silviculture Updates and Land status Tracking System) are BC Ministry of Forests and Range electronic data (including spatial data) management systems for tracking forestry disturbances.

[2] D = Dispersed Disturbance Sub-model (Figure 2), R = Roads Sub-model (Figure 3), MW = Mass Wasting Events sub-model (Figure 4).

[3] ✓ indicates the input is required and used in the designated sub-model, * indicates an indirect requirement where the input is used to model terrain stability in the coarse sediment model.

[4] The PRISM data set was developed by the Spatial Climate Analysis Service of Oregon State University for the Canadian and BC provincial governments using the 1961-1990 weather station normals (Wang et al. 2006).

[5] Terrain stability is modeled in the Coarse Sediment BBN. For more detail refer to documentation on the coarse sediment model.

Several of the raw data layers must undergo a classification prior to their use. Data preparation and pre-processing step, not including basic classifications were:

- where necessary, combining existing Terrain Stability mapping into a continuous rasterized coverage for the study area; combining Levels B, C and D Terrain Stability mapping into a common four-class rating system: stable (S and I, II and III), class 5 (V and U), class 4 (IV and P), unmapped;

- combining existing soil and/or terrain mapping into a continuous rasterized coverage where existing soil mapping units have been grouped into a three-class ñSoil Stability Groupingsòmap layer and a five-class ñSoil Erodibility Groupingsòmap layer;
- utilising the DEM and Soil Stability Grouping layers, running a terrain stability hazard sub-model to determine stability ratings for areas without Terrain Stability Mapping;
- utilising the DEM in and flow algorithms, modified by terrain breaks that act as barriers, delineating zones of a watershed assessment unit that are coupled with hydrologic features.
- utilising the DEM, zones of water/flow accumulation into ñSpecific Catchment Areasòare delineated,
- utilising the DEM, hydrologic feature coverage, existing Terrain Stability Mapping and the resultant of terrain stability hazard modelling, running an upslope influence sub-model to determine areas where deposits of landslide debris will occur that are subject to subsequent erosion; and,
- preparation of layers depicting disturbance scenarios (e.g., rasterized coverages of changes in forest cover and road locations).

6.2.5 Data Outputs

Raw sub-model outputs are produced for each individual pixel in the grid. The resultant values, also referred to ñexpected valueòof a BBN node, are the sum of the products between the likelihood of each individual state multiplied by the state mid-point value. We interpret the expected value to be a prediction of the kilograms of sediment per pixel per year.

An expected value is calculated for every pixel using each of the three fine sediment sub-models and summed to provide a total hazard fine sediment pixel value (i.e. combined dispersed, roads, and mass wasting). This summarized pixel value represents site level hazards when real values are used for all inputs. Under certain scenarios, however, some input layers are modeled at a lower precision and accuracy resulting in products that are only suitable for strategic level planning. An example of this is with the salvage scenario (described below) where we model roads to access future blocks. The roads do not represent a real depiction of where forest licensees will build them, however, they do provide an indication of how much road, and corresponding disturbance may occur thus providing an idea of the impacts resulting from road building activities.

A second scale of interpreting the results occurs at the watershed assessment unit level where the total hazard values were summed over the entire area of an assessment unit. The GIS product for this value was represented using polygons rather than grids.

Interim outputs derived during modeling activities include GIS files showing the potential spatial distribution of deposits resulting from mass wasting events, the location of barriers to slope coupling, and coupled/uncoupled slopes.

6.3 Altered Peak and Low Flows

The proposed approaches to assessing peak-flow and low-flow hazards are less well developed than the proposals for increases in coarse and fine sediment. The overall approach is parallel, in that the initial step is to assess the inherent hazard by identifying key variables for the assessment watershed, and then adjusting relevant variables based on proposed or existing development, before assessing the impacts of those changes on predicted hazard in comparison to background hazard. The main difference is that the focus of the assessment is at the watershed level itself, rather than at the individual pixel summed up for the watershed (see Figure 6.9). A more complete review of issues related to peak flows and an alternative more complex approach to peak flow and low flow hazard modeling can be found in Carver *et al*. 2009a and Carver *et al* 2009b.

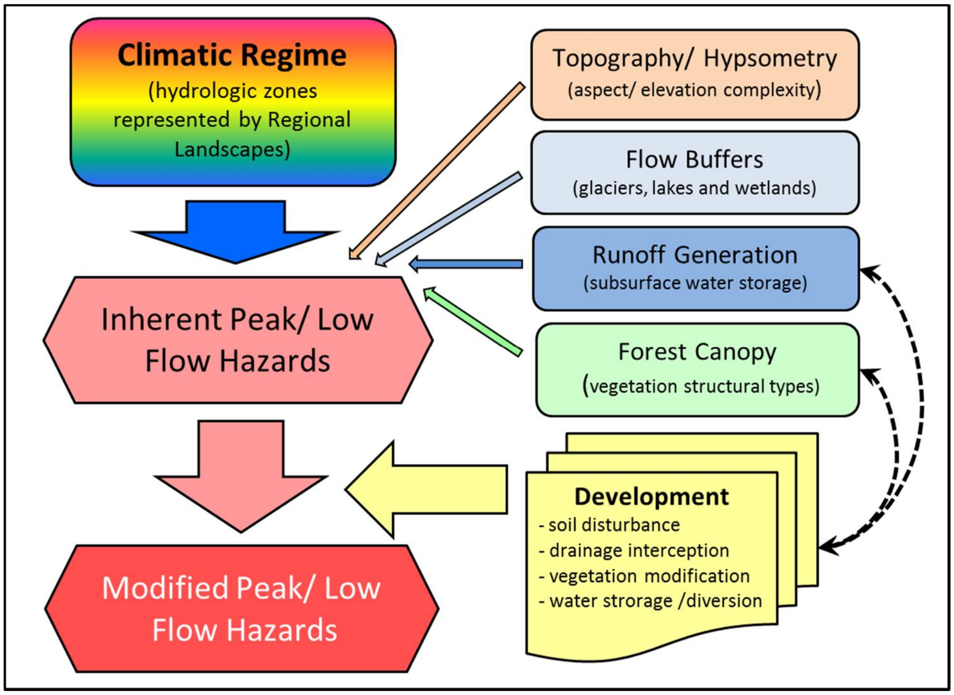

Figure 6.9. Schematic representation of the approach to assessing potential impacts on peak flows and low flows.

The proposed variables for characterizing background peak- and low-flow hazards can be grouped into five components:

- **Climatic Regime/ Hydrologic Zone.** Regional landscape (RL) mapping is used to represent climatic regimes, with each RL considered as an individual hydrologic zone. A collection of climatic and hydrologic variables is proposed for characterization of each RL to differentiate their relative hazards with respect to peak flows and low flows. These variables are intended to be indicators of properties such as: drought timing and frequency, the likelihood of rain-on-snow and other extreme precipitation events, the snowmelt regime and the seasons and magnitudes of peak flows and low flows.
- **Basin Topography.** Basin topography can affect the distribution of regional precipitation patterns, and in part determines how incoming precipitation inputs are transformed into runoff. Five variables have been proposed to characterize topographic features. Basin orientation has the potential to affect local storm event intensity, while the other variables are related to snowmelt, potential evapotranspiration and allocation of water between runoff and infiltration.
- **Runoff Generation.** Runoff generation variables are intended to characterize watershed level water storage capacity, infiltration rates, subsurface flow regimes, and their effects on discharge rates. This component is primarily based on characterizations of underlying bedrock and the types and depth of

unconsolidated surficial materials. Detailed terrain, soil and bedrock mapping are the best sources for this data, however various alternatives are suggested for use when these are unavailable.

- **Flow Buffers.** The area and distribution of lakes, wetlands and glaciers are examined for their potential to relieve peak flow increases due to their position and size in the watershed, and their ability to assist in sustaining seasonal low flows.
- **Forest Canopy.** The extent of forest cover is used to indicate the potential for declines in snow interception and transpiration, locally increased snow accumulation, and increased snowmelt rates, due to loss of existing forest cover. An index is developed based on the proportion of the basin in various vegetation structural classes (e.g., closed forest, open forest, shrubland, non-vegetated).

The primary factors for assessing the potential for development to increase peak flows are related to roads and other major soil disturbances, and in some cases to changes in vegetative cover. Roads and other soil disturbances primarily intercept subsurface flows, change timing of runoff, and modify background drainage patterns. Changes in vegetation are primarily related to changes in interception, snow distribution, snowmelt rates and evapotranspiration.

A summary of development factors with potential to affect peak and low flows include:

- **Surface Disturbance.** Roads and/or other disturbances that result in compaction, decreased infiltration and subsurface flow interception, and alterations of surface drainage patterns.
- **Vegetation Change.** Location, area and relevant characteristics of disturbance that removes or modifies forest cover, including location with respect to aspect and elevation.
- **Water Storage/ Diversion.** Location and characteristics of development that withdraws, stores, or releases surface waters. The location and operational management of such facilities are key factors in determining their impacts on peak and low flows.
- **Dewatering Potential.** Potential for increases in coarse sediment inputs that may infill the channel making low flow surface waters unavailable in some reaches (can be derived from the coarse sediment hazard).

Table 6.8 provides a summary of the specific variables proposed for the determination of the inherent hazards, and the rationale for their inclusion. Tables 6.9 and 6.10 summarize the specific development activities proposed for consideration in the determination of potential development impacts. Figure 6.10 provides a proposed structure for modelling peak flow. Low flow structure would be similar, but with modified data inputs.

The calibration of Low Flow hazard is somewhat dependent on determining what constitutes a significant change, e.g., is there a linear increase in hazard up to complete dewatering of the channel, or are there significant thresholds? Where chronic low flows are already critical, any change may be significant, whether decreased discharge, or increased duration of low-flow conditions. Significance will depend on what values are at stake, be they aquatic habitats or human uses, and whether there are already water withdrawals that are inducing low-flow conditions. There is also the potential for interactions between low flows and dilution ratios for chemical discharges into waterways.

Where aquatic habitats are critical, significance of low flows may depend on timing in relation to fisheries requirements, or the significance may depend on an interaction with water temperatures. Low flow assessments for aquatic habitat may require assessment by stream reach rather than by AW (see Section 6.5 for further discussion of reach assessments).

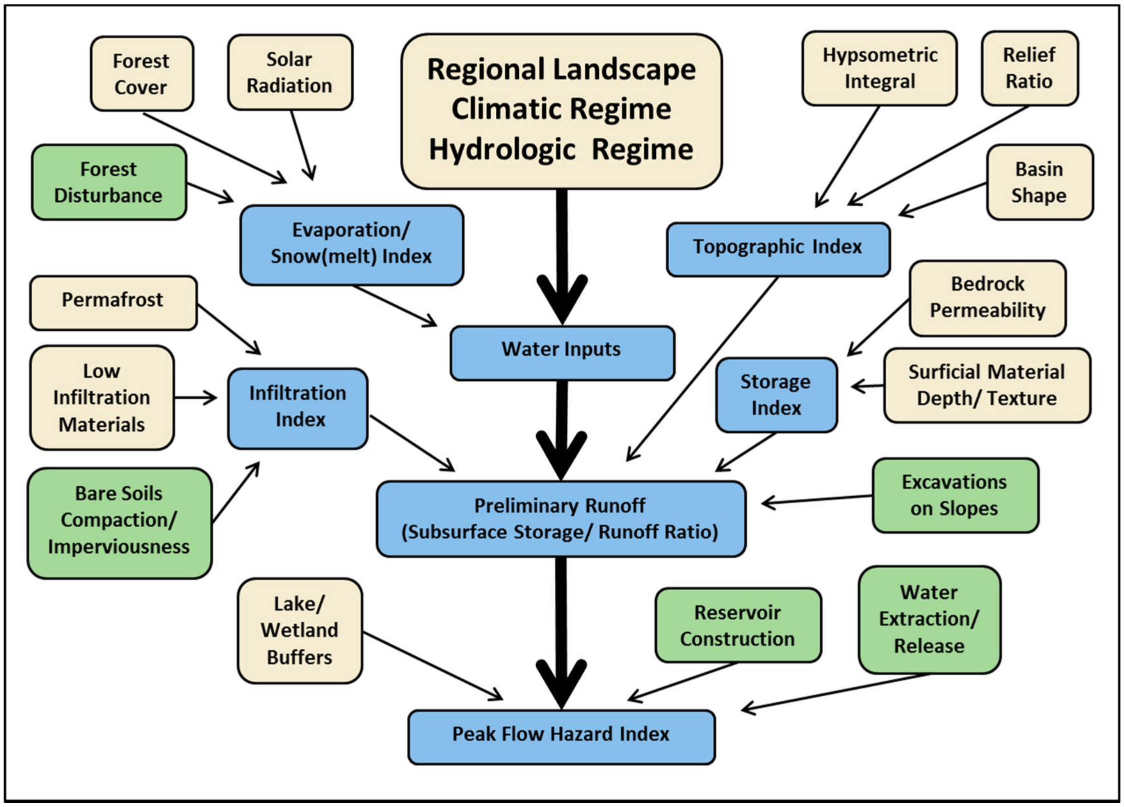

Figure 6.10. Proposed structure for modelling Peak Flow hazard. Tan coloured boxes indicate basic input nodes, green boxes are disturbance scenario input nodes, and blue nodes are computational nodes.

6.4 Altered Water Chemistry

Alteration of water chemistry most often results from the direct addition of some organic or inorganic substance to surface waters, usually as a result of industrial discharges (e.g., factories, mines, sewage treatment plants). However pollution can also result from non-point-source discharges, such as leaching from agricultural fields or roads that disturb sulphide-rich materials (gossan deposits). Water chemistry, specifically oxygen content, can also be altered by operational activities associated with dams. The significance of water chemistry alterations is somewhat dependent on downstream values such as fish habitat or domestic water use. Table 6.11 provides a summary of the specific variables proposed for the determination of the inherent hazards, and the rationale for their inclusion. Table 6.12 summarizes the specific development activities proposed for consideration in the determination of potential development impacts.

Table 6.8. Components and indices for assessing inherent Peak Flow and Low Flow hazards.

Component	Index	Specific Variables	Rationale	Data Source	Peak/ Low	Comments
Climatic Regime/ Hydrologic Zone Characterization	Hydrologic Flow Regime Type	# months w/ mean temp <0	To separate nival from pluvial zones; to recognize areas with potential for permafrost	Climate WNA	P (L)	Grouped by Regional Landscape/ Hydrologic Zone Mapping
	Rain-on-Snow	# months w/ mean temp >-1 and <1	To recognize zones with higher likelihood of rain on snow events	Climate WNA	P	Grouped by Regional Landscape/ Hydrologic Zone Mapping
	Drought-Induced Low Flows	min mo. precip (mo's w/ temp >0)	To define zones with a likelihood of drought-induced low flows	Climate WNA	L	Grouped by Regional Landscape/ Hydrologic Zone Mapping
	Peak Flow Intensity/ Timing	mean peak flow/ mean annual flow	To define zones where the average hydrograph already has an inherently high peak flow regime; to define the season of peak flows	Hydrologic Data	P	Grouped by Regional Landscape/ Hydrologic Zone Mapping
	Low Flow Intensity/ Timing	mean low flow/ mean annual flow	To define zones where the average hydrograph already has an inherently low low-flow regime; to define the season of low flows	Hydrologic Data	L	Grouped by Regional Landscape/ Hydrologic Zone Mapping
Basin Topography/ Hypsometry	Hypsometric Integral	HI= (Emean-Emin)/(Emax-Emin)	To rate AUs with regard to their topographic sensitivity for snowmelt synchronization, peakflow and low flow by identifying AUs with higher %'s of area at higher elevations	Modelling from DEM	P, L	Used in combination with Basin Relief Ratio and Basin Shape
	Basin Relief Ratio	Max relief/Max. Flow Length	To rate AUs with regard to their sensitivity for peakflow by identifying AUs with varying response times	Modelling from DEM	P (L)	Used in combination with Hypsometric Integral and Basin Shape
	Basin Shape	Width/ Length	To rate AUs with regard to their drainage patterns (e.g. dendritic vs.trellised) and potential relationship to peakflows	Modelling from DEM	P (L)	Used in combination with Hypsometric Integral and Basin Relief Ratio
	Solar Radiation Inputs	Latitude, aspect, slope, viewshed	To rate AUs with regard to their sensitivity for radiation-induced rapid snowmelt, by identifying AUs with higher %'s of area with southern	Modelling from DEM	P, L	Limit to months that correspond to peakflow(?); possible interaction with

Component	Index	Specific Variables	Rationale	Data Source	Peak/ Low	Comments
			slopes			forested area (?)
	Storm Track Exposure	Basin orientation	To rate AUs with regard to their sensitivity for smowmelt synchronization, by identifying AUs with higher %'s of area at higher elevations	Modelling from DEM/ Freshwater Atlas; storm data	P	Need more information regarding dominant stormtrack directions
Runoff Generation **(1's are primary option; 2's are an alternative option)**	Water Storage and Subsurface Infiltration	(1) Surficial material depth and texture	To define areas with various water storage and infiltration capacities – most desirable source of information	Terrain/ soil mapping	P, L	If no mapping – use alternative 2s
	Water Storage and Subsurface Infiltration	(2) Surficial material depth and texture	To define areas with varying water storage and infiltration capacities (morainal slopes, glaciofluvial/ morainal valley bottoms, colluvial fans/ cones, fluvial fans – moderate to deep soils)	DEM Modelling	P, L	Use in absence of terrain/ soil mapping; modelling of land surface shape and slope position to predict landforms
	Water Storage and Subsurface Infiltration	(2) Surficial material texture	To define areas with varying water storage and infiltration capacities (predicting morainal/ colluvial textures)	Bedrock Mapping	P, L	Use in absence of terrain/ soil mapping; group lithologies based resulting surficial material textures
	Water Storage and Subsurface Infiltration	(2) Rock and shallow surficial material	To define areas with minimal infiltration and water storage capacity (exposed bedrock and very shallow soils)	VRI/ FC; BTM	L (P)	Use in absence of terrain/ soil mapping
	Deep Water Storage	Bedrock lithology and jointing (permeability)	To define areas with various water storage and infiltration capacities; bedrock types can also be used as a secondary source of information on predicting terrain/ soil textures	Bedrock mapping	L (P)	Group lithologies based on permeability and resulting morainal textures
	Surface Infiltration	Bare soils, compacted soils, impermeable surfaces	To define areas where infiltration capacity is likely limited, or potentially modified by freezing and/or high intensity rainfall	BTM; VRI/ FC	P (L)	
	Permafrost	Extent of permafrost	To define areas where infiltration and subsurface flow may be affected by the presence of frozen soils	Permafrost mapping/ modelling	L	May need to develop a predictive model

Component	Index	Specific Variables	Rationale	Data Source	Peak/ Low	Comments
Flow Buffers	Assessment Unit Lake/ Wetland Flow Moderation	% area of lakes and wetlands	To rate AUs with respect to the potential for lakes and wetlands to moderate peakflows and augment low flows within the assessment unit	Freshwater Atlas	P, L	Set minimum area
	Downstream Lake/ Wetland Flow Moderation	% of area flowing through lakes and wetlands	To rate AUs with respect to their effects on buffering of downstream peakflows	Modellling from Freshwater Atlas and DEM	P	Set minimum area; for use in Channel Stability Hazard
	Glacial Flow Moderation	% area in glaciers	To rate AUs with respect to the potential for glacial melt to buffer summer low flows	Freshwater Atlas	L	
Forest Canopy	Area of Forest Cover	% area in forest cover	To define areas where forest cover can provide interception, moderation of snowmelt rates and increased infiltration capacity	VRI/ FC	P	Include crown closure and height classes?
	Forest Cover Distribution	% forested above and below H60	To define areas where removal of forest cover can potentially lead to runoff synchronization and increased water yield	DEM; VRI/ FC	P	As above; could be based on deciles or break by H40, H60, H80, if desirable

Notes: Without notation ï assume to be a primary choice of indices; (1) primary choice in indices; (2) secondary choice of indices if data for primary choices are unavailable

Table 6.9. Potential disturbance activities proposed for the assessment of development interactions with Peak Flow hazard.

Disturbance Activity	Mechanism	Disturbance Types	Rationale	Comments
Forest cover removal	Increased rate of snowmelt	Forest harvesting, linear corridors (transmission lines, seismic lines, etc.), fire and other disturbances (e.g., mining, urbanization, agriculture)	Increased rate of snowmelt in upper portions of watersheds may increase peakflows through synchronization of runoff	Additional potential effects in areas of permafrost
Creation of impervious surfaces (including compacted soil)	Soil exposure; soil compaction; Runoff generation	Roads (could include skid trails, seismic lines, etc.), severe fire and other soil disturbances (e.g., mining, urbanization, agriculture, site preparation)	Bare soils and especially compacted soils reduce infiltration and therefore have the potential to increase runoff and magnify peak flows	
Excavations on Slopes	Subsurface flow interception; Runoff generation	Roads and other terrain alteration (e.g., mining, pipelines)	Conversion of subsurface flow to surface runoff can reduce transit time and potentially increase peakflows	
Alteration of Surface Drainage Pattern	Surface flow diversion; reduced surface water storage	Roads, mines and other disturbances with stream crossings; draining of lakes and wetlands	Changing surface water drainage patterns, especially lakes, wetlands and flood channels can affect timing of runoff and potentially increase peak flows	
Reservoir Impoundment	Water storage/ release	Dams with regulated water storage and release alter timing of runoff	Timely storage and release of water in reservoirs can change the magnitude and timing of peak flows	
Water Extraction/ Diversion	Water withdrawal	Penstocks, industrial/ agricultural/ domestic water use, mining drainage diversions	Timely withdrawal of water from a watercourse can change the magnitude of peak flow	

Table 6.10. Potential disturbance activities proposed for the assessment of development interactions with Low Flow hazard.

Disturbance Activity	Mechanism	Disturbance Types	Rationale	Comments
Forest cover removal	Increased rate of snowmelt	Forest harvesting, linear corridors (transmission lines, seismic lines, etc.), fire and other disturbances (e.g., mining, urbanization, agriculture)	Increased rate of snowmelt and more rapid spring runoff may result in less water to maintain low flows later in the summer	Also effects in areas of permafrost?
Forest cover removal	Decreased evapotranspiration	As above	Decreased evapotranspiration may increase the availability of water for low flows during the growing season	Also effects in areas of permafrost?
Creation of impervious surfaces (including compacted soil)	Soil exposure; soil compaction; Runoff generation	Roads (could include skid trails, seismic lines, etc.), severe fire and other soil disturbances (e.g., mining, urbanization, agriculture, site preparation)	Bare soils and especially compacted soils reduce infiltration, and therefore may result in decreased groundwater availability for maintaining low flows later in the summer and fall	
Excavations on slopes	Subsurface flow interception; Runoff generation	Roads and other terrain alteration (e.g., mining, pipelines)	Subsurface flow interception may result in decreased groundwater availability for maintaining low flows later in the summer and fall	
Alteration of surface drainage pattern	Surface flow diversion; reduced surface water storage	Roads, mines and other disturbances with stream crossings; draining of lakes and wetlands	Changing surface water drainage patterns, especially lakes and wetlands may reduce the volume of water available for maintaining low flows later in the season	
Reservoir Impoundment	Water storage/ release	Dams with regulated water storage and release alter timing of runoff	Timely storage and release of water in reservoirs can change the magnitude and timing of low flows	
Water Extraction/ Diversion	Water withdrawal	Penstocks, industrial/ agricultural/ domestic water use, mining drainage diversions	Timely withdrawal of water from a watercourse can change the magnitude of low flows	

Table 6.11. Specific variables for assessing inherent Chemical Alteration hazard.

Index	Specific Variables	Rationale	Data Source	Comments
Sulphide-rich bedrock	Bedrock lithology	To recognize zones with the presence of bedrock and terrain materials that may release deleterious chemicals when disturbed	Bedrock/ mineralization mapping	Group lithologies based on likely presence of sulphide-rich types

Table 6.12. Potential disturbance activities proposed for the assessment of development interactions with the Water Chemistry hazard.

Disturbance Activity	Mechanism	Disturbance Types	Rationale	Comments
Chemical discharge	Direct impact	Pollution discharges that significantly modify water chemistry (includes organic and inorganic)	Chemicals added directly to surface waters change water chemistry	
Disturbance of sulfide-rich materials	Chemical alteration/ release	Roads, mining exploration, mining, pipeline construction	Disturbance of bedrock and/or surficial materials that release chemicals through weathering and/or leaching, and these chemicals alter water chemistry (e.g., sulfide-rich gossan deposits, mine tailings)	
Reservoir/ spillway operation	Chemical alteration	Dams, reservoirs, penstocks	Water storage in reservoirs and release through penstocks and/or spillways changes the oxygen content of water, hence altering its quality for habitat	

6.5 Altered Channel Stability

The hazards for Altered Channel Stability and Altered Stream Temperature are not fully developed, but included mainly for completeness. These hazards are difficult to assess at the scale of this pilot project, and are more suited to detailed assessments tied to specific values and individual stream reaches.

The potential for changes in channel stability are primarily the result of changes in peak flow, coarse sediment inputs and changes in riparian function. Any development activities that affect those factors, or directly alter the channel itself have the potential to decrease channel stability. Table 6.13 provides a summary of the specific variables proposed for the determination of the inherent hazards, and the rationale for their inclusion. Table 6.14 summarizes the specific development activities proposed for consideration in the determination of potential development impacts. The activities described in Table 6.14 generally have a higher significance if they occur in the assessment unit that includes the reach in question; however, if they occur in an upstream assessment unit, especially if the lowest stream reach in that unit is coupled to the reach in question, they may also impact the reach question.

As discussed in the section on assessment units, the assessment of the potential for decreased channel stability requires a different type of assessment unit than the other hazards. In this case it is proposed that the assessment focus on a specific stream reach, but draw on appropriate hazard information from all the watershed assessment (WA) units that drain to that reach. This will require identification of key reaches with specific values for the assessment, and subsequent evaluation of contributing WA units that drain into those reaches, including the face unit or units that contain the reaches in question. The summation of hazards within those contributing watershed assessment units, while taking into account their relative degrees of influence, can then be used to determine the potential for channel destabilization within the reach in question.

The factors to consider in such an assessment include:

1. Localized channel factors
    - channel type and susceptibility to disturbance
    - riparian disturbance along the reach in question
2. Coarse sediment hazards
    - coarse sediment hazard of the local face unit(s) draining directly into the reach in question
    - coarse sediment hazards of upstream watershed assessment units
    - debris torrent delivery potential of stream reaches directly draining into the reach in question (an evaluation specific to this hazard rating)
    - riparian disturbance within upstream watershed assessment units
3. Peak flow hazards of upstream watershed assessment units
4. Relative influence and coupling of individual upstream assessment units (i.e. the relationships between contributing watershed assessment units and the stream reach in question)
    - distance and intervening channel gradient between upstream watersheds and the reach in question
    - buffering presence of lakes and/or reservoirs between upstream watersheds and the reach in question

The following diagrams illustrate the application of the macro-reach assessment procedure. Figure 6.11 illustrates the spatial components of the assessment: the reach in question, the assessment unit(s) that contain the reach in question, and the upstream reaches that potentially contribute to the Channel Stability hazard of the reach in question. The red AW unit in the diagram exerts the most influence on channel stability, as it contains the reach itself. The gold coloured AW units are connected directly to the reach, and therefore with sufficient gradient have the potential to deposit bedload directly into the reach. The upstream light tan AW units have minor influence on the reach due to the buffering effects of the lake. Figure 6.12 provides a schematic framework for the analysis procedure. Further work on application of the procedure is under development.

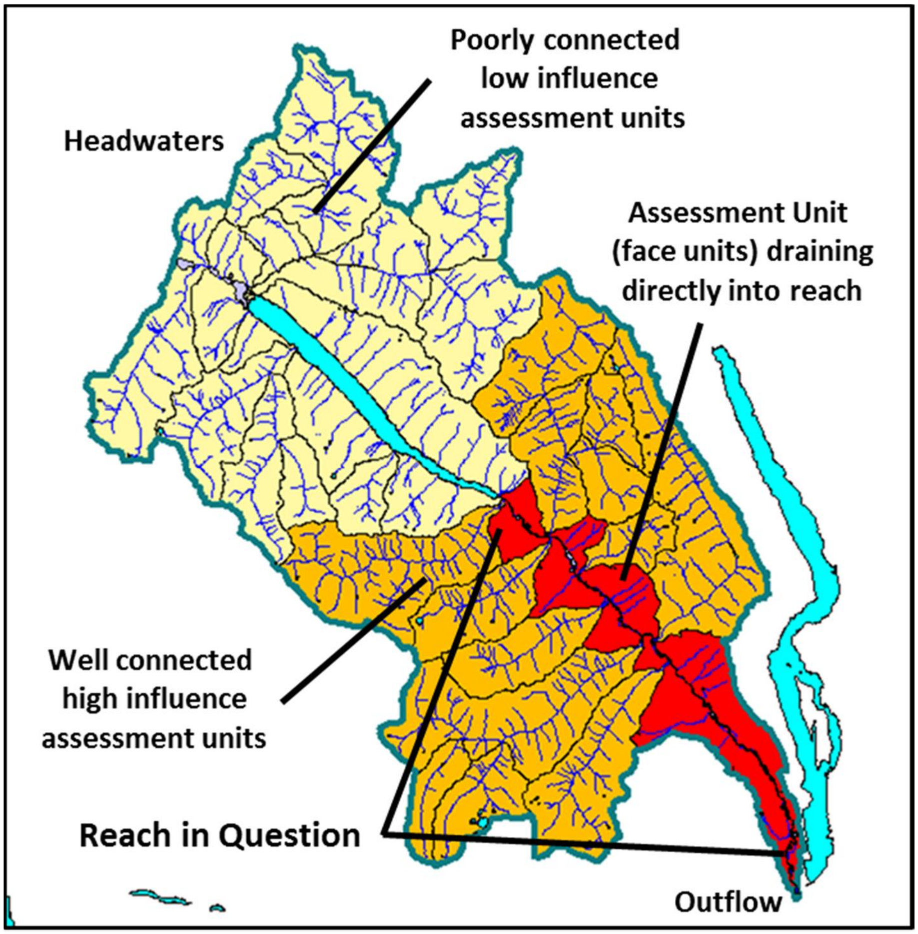

Figure 6.11. An example of assessment units and their contribution to assessment of Channel Stability hazard.

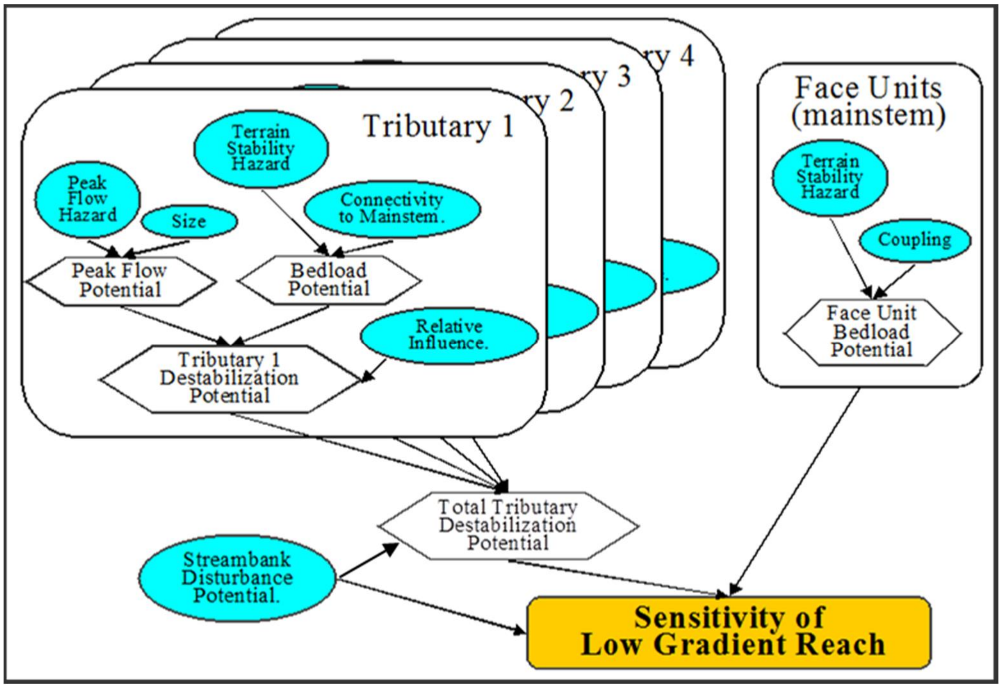

Figure 6.12. Schematic diagram of macro-reach assessment procedure.

6.6 Altered Water Temperature

As indicated above, the hazards for Altered Channel Stability and Altered Stream Temperature are not fully developed, but included mainly for completeness. These hazards are difficult to assess at the scale of this pilot project, and are more suited to detailed assessments tied to specific values and individual stream reaches.

Stream temperature in a given reach is determined by the temperature of surface water flowing into the reach, and the relative amount of subsurface flows that emerge in the reach. In general, reaches with significant groundwater inputs are less sensitive to temperature changes than those with minimal ground water inputs. The potential for changes in stream temperature are primarily the result of changes in riparian shading, summer low flow volumes and upstream storage that may affect inflow temperatures. Any development activities that affect those factors have the potential to affect water temperature in sensitive stream reaches.

Table 6.15 provides a summary of the specific variables proposed for the determination of the inherent hazards, and the rationale for their inclusion. Table 6.16 summarizes the specific development activities proposed for consideration in the determination of potential development impacts. The general lack of reach-specific information on stream temperatures and groundwater inputs makes it difficult to assess this hazard on a widespread basis.

Table 6.13. Specific variables for assessing larger stream reaches (4th order and more) for inherent Channel Stability hazard.

Component	Index	Specific Variables	Rationale	Data Source	Comments
Local Factors	Channel Sensitivity	Sensitivity Rating	Channel characteristics including type of substrate, gradient, stream bank composition, and past disturbance history all contribute to the stability and resilience of a stream reach	Channel Inventory and Assessment Data	Information often lacking – consider sensitivity breaks at 0%, 8%, and 16% channel gradient
	Local Forested streambank	% of stream bank with natural forest	Stream bank and riparian forests reduce bank erosion and increase channel stability	VRI/ FC; remote sensing	Local is the Watershed Assessment Face Unit(s) adjacent to the reach in question.
	Local Coarse Sediment Potential	Coarse Sediment Hazard Rating	Coarse sediment directly deposited into the reach from face units adjacent to the reach may impact stability (includes coupling)	See Bedload Hazard	
Upstream/ Tributary Factors	Upstream/ Tributary Coarse Sediment Potential	Coarse Sediment Hazard Rating(s)	Coarse sediment directly deposited into coupled upstream and tributary reaches may impact channel stability of the reach in question	See Bedload Hazard	
	Upstream Forested Streambank	% of stream bank with natural forest	Stream bank and riparian forests reduce bank erosion and increase channel stability	VRI/ FC; remote sensing	
	Upstream/ Tributary Coupling	Channnel gradients; Distance; Flow buffers	The likelihood for tributaries and upstream reaches to supply bedload to the reach in question will be a factor in relating upstream hazards to the reach in question	Freshwater Atlas; DEM	
	Peak Flow Hazard	Upstream/ Tributary Peak Flow Hazard(s)	Peak flow hazard of all upstream and tributary watershed areas will contribute to peak flow hazard for the reach in question	See Peak Flow Hazard	

Table 6.14. Potential disturbance activities proposed for the assessment of development interactions with the Channel Stability hazard.

Disturbance Activity	Mechanism	Disturbance Types	Rationale	Comments
Forest Canopy Removal in the Riparian Area	Riparian disturbance	Riparian forest harvesting or other disturbances that removes trees from the stream bank or increases windthrow hazard along the streambank	Removal of riparian forest can contribute to bank erosion and channel instability in tributaries and upstream reaches; if coupled this may contribute to channel instability in the reach in question	
Soil/ Terrain Disturbance	Soil exposure/ compaction/ displacement; flow interception & diversion	See Bedload Hazard	Increased bedload due to landslide and debris flow activity may result in channel instability or even channel infilling, eruption and relocation	
Forest Canopy Removal and others	Locally increased snowpack/ decreased evapotranspiration	See Peak Flow Hazard	Increased peak flows can result in increased bedload activity, bank erosion, debris floods and rapid channel movement	
Reservoir Construction/ Operation	Water Storage Release; sediment capture	Dams with regulated water storage and release	May affect channel stability due to magnitude and timing of water releases, and changes in coarse and fine sediment movement	

Table 6.15. Specific variables for assessing larger stream reaches (4th order and more) for inherent Water Temperature hazard.

Component	Index	Specific Variables	Rationale	Data Source	Comments
Climatic Regime/ Hydrologic Zone	Climatic Regime	Maximum temp. (# mos.>18C)	Temperature drivers of water temperature	Climate WMA	
	Low Flow	Low Flow Hazard	Reduced flows increase the impact of air temperature on water temperature	See Low Flow Hazard	
Temperature Buffers	Groundwater contribution	% groundwater contribution	Groundwater contributions to base flow moderate air temperatures	Field data/ modeling	Major factor, but virtually no data
	Glacier Cover	% glacier	Glacier meltwaters provide cold waters during high temperature periods	Freshwater Atlas	
	Permafrost	% permafrost	Permafrost meltwaters provide cold waters during high temperature periods	Permafrost mapping/ modeling	
	Riparian Cover	% upstream riparian forest	Riparian forest cover limits solar radiation from heating stream waters	VRI/ FC; remote sensing	

Table 6.16. Potential disturbance activities proposed for the assessment of development interactions with the Temperature hazard.

Disturbance Activity	Mechanism	Disturbance Types	Rationale	Comments
Forest Canopy Removal in the Riparian Area	Riparian disturbance	Removal of riparian canopy cover (e.g., forest harvesting)	Removal of riparian forest decreases shading and results in increased direct solar heating of the stream	
Soil/ Terrain Disturbance	Soil exposure/ compaction/ displacement; flow interception & diversion	See Bedload Hazard See Low Flow Hazard	Infilling of the channel may affect temperatures Reduced low flows may affect temperatures	
Forest Canopy Removal	Increased snow melt rates/ locally increased snow accumulation/ decreased evapotranspiration	See Bedload Hazard See Low Flow Hazard	Infilling of the channel may affect temperatures Reduced low flows may affect temperatures	
Reservoir Construction/ Operation	Water Storage Release	Dams with regulated water storage and regulated release	May affect water temperature though reservoir warming and selection of reservoir water layers for release	

7.0 IMPLEMENTATION

The first step in applying the assessment process is to determine which hazards are relevant to the values present in the study area. The second is to identify data sources for assembling GIS coverages for each of the relevant variables for each those hazards. Once the layers are assembled then the relevant models can be run to determine the inherent hazards ratings. The models for Bedload and Suspended Sediment are fully developed, however the others require further work.

To model the impacts of various types of disturbance, be they natural (e.g., fire, wind, forest pests) or developments, each associated disturbance/development has to be evaluated with regard to presence of each of the disturbance activities listed in the previous series of development tables. Where the disturbances or developments include activities listed in the table, a GIS layer must be created to indicate the locations of these processes, and the inherent hazard modeling adjusted to include these activities.

7.1 Calibration

All of the assessment modules will require calibration using baseline data, as well as impact data. Unfortunately, both of these types of data are often difficult to acquire, especially at the scale of the assessment watersheds. An ongoing process has begun to assemble hydrologic and climatic data relevant for the study area. Initially this data will be used to characterize the Regional Landscapes and hydrologic zones. However it will also be examined to determine whether there are examples of watersheds with various types and levels of disturbance, to begin to build a database for calibrating the response of watersheds to disturbance.

7.2 Interpretation

Interpretation of the results will require establishment of what are ñsignificant changes to the hydrologic regime.òFor example, what is a significant increase in peak flow, or a significant increase in fine sediment, or change in channel stability? This is further compounded by a consideration of the likelihood of such an occurrence. The following tables indicate some possible considerations.

Table 7.1 Possible definitions of risk ratings.

Risk Rating	Definition	Probability of Significant Hydrologic Impact (%)
Very Low	The assessed level of forest development is highly unlikely to have caused significant changes to the hydrologic regime	<5
Low	The assessed level of forest development is unlikely to have caused significant changes to the hydrologic regime	5-25
Moderate	The assessed level of forest development may have caused significant changes to the hydrologic regime	25-50
High	The assessed level of forest development is likely to have caused significant changes to the hydrologic regime	50-75
Very High	The assessed level of forest development is highly likely to have caused significant changes to the hydrologic regime	>75

Table 7.2 provides suggested general management responses in relation to risk level. This table can be used as a guide. After risk ratings have been determined, management implications may justify follow-up field work to investigate rating accuracy and better select the management response.

Table 7.2. Potential management response in relation to risk outcome.

Risk Rating	Possible Response
VL	few or no constraints
L	minor constraints
M	modify development; consider field work
H	modify and/or defer development; consider field work
VH	defer development and rehabilitate; consider field work

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