Natural disturbances, such as wildfire, can have significant impacts on geomorphic processes and watershed functions (Moore et al. 2008; Neary et al. 2008; Silins et al. 2009). Incremental effects on many watershed values can also occur, along with delayed recovery, resulting from post-fire land management activities (e.g., salvage harvesting) (Peterson et al. 2009). However, information is very limited regarding the potential impacts of wildfire and salvage harvesting on critical watershed values such as water quantity, water quality, and aquatic ecology. To sustain Canada’s forest resources, natural resource managers and policy-makers will need to understand the role of water in forest ecosystems and the likely hydrologic and geomorphic effects of wildfire. Further, it will be necessary to utilize this knowledge to adapt post-disturbance land management activities to ensure that any negative impacts will be less severe than would be experienced had no adaptation occurred.

Of growing concern over the past two decades is the increased occurrence of large and severe wildfires and longer fire seasons, which have been driven primarily by warmer temperatures, earlier spring snowmelt, and drier vegetation (Stocks et al. 2003; Westerling et al. 2006). In the most recent report from the Intergovernmental Panel on Climate Change Working Group II, which highlights the impacts, adaptations, and vulnerabilities related to climate change, it was concluded with very high confidence (at least a 9 in 10 chance) that the frequency and severity of wildfire, as well as other natural disturbances (insect outbreaks, drought, and extreme weather events) will increase in North America in coming decades as a result of climate change (Intergovernmental Panel on Climate Change 2007). Projections for Canadian forests have indicated an increase of 74–118% in wildfire season length, fire severity, and area burned by the end of the century (Flannigan et al. 2005).
Continued from page 1

Results from two recent needs assessments were indicative of the growing concern over the potential hydrologic and geomorphic effects of wildfire. Respondents from the forest industry, provincial and federal governments, First Nations, academia, natural resource consulting, and community stewardship groups agreed that improved knowledge and quantification of the hydrologic and geomorphic impacts of natural disturbance was a top priority (Redding and Nickurak 2008; Redding et al. 2008). In response to the needs assessments, a recent workshop entitled “Wildfire and Watershed Hydrology” was hosted by FORREX in Kelowna, BC, on June 3–4, 2009. The intent of this workshop was to present preliminary and final results of ongoing and recently completed research projects on the hydrologic and geomorphic effects of wildfire. Its primary goal was to provide new information to assist decision making and to provide feedback to researchers that would help refine research plans and interpretation of results. A secondary goal was to provide participants with a forum for discussion and sharing of ideas to help deal with the challenges associated with shifting natural disturbance regimes.

Key Findings from Workshop Presentations

The technical presentations during the workshop provided results from wildfire research in British Columbia, Alberta, and the United States, highlighting the state of knowledge on many topics and identifying gaps in our understanding of the potential effects of wildfire and post-fire salvage harvesting on aquatic systems. Additionally, several presentations focused on post-fire treatment options, ecohydrologic effects of wildfire, and the potential downstream implications. The key findings from these presentations are summarized below.

• The occurrence and severity of wildfire is a function of many natural factors, including fuel availability, temperature, humidity, precipitation, wind, lightning strikes, and anthropogenic factors. Climate change can affect most of these natural factors and therefore influence the wildfire season across a range of temporal and spatial scales. Thus, in some regions (e.g., British Columbia’s Southern Interior), increased wildfire frequency, severity, and area burned are projected to increase over the coming decades.

• Natural disturbances that cause the loss of forest cover can result in reduced precipitation interception losses and increased snow accumulation amounts, but with high inter-annual variability. Snowmelt and ablation rates may also increase after disturbance due to increased net radiation.

• Reduced transpiration rates can result in increased soil moisture following wildfire and post-fire salvage harvesting.

• Peak flow and annual water yield responses to wildfire are likely to be watershed-specific. In the short to medium term, water yields typically increase following natural disturbances that cause mortality of the overstorey vegetation. Peak flow magnitudes generally increase following wildfire, but may also decrease due to desynchronization of snowmelt across the watershed. The onset of the melt period and the timing of peak flow may occur up to 2–3 weeks earlier in burned watersheds. The rate of recovery varies widely and is primarily influenced by the local climate regime and post-disturbance vegetation.
Where wildfire causes tree mortality in the riparian zone, the loss of root cohesion can reduce stream bank strength and have important implications for channel morphology (e.g., channel widening). Soil erosion and debris flow risk is often, but not always, increased after wildfire. Increased risk has been linked to the potential for high-intensity rainstorms or rapid snowmelt on water-repellent (hydrophobic) soils, as well as the legacy of forest operations (e.g., roads, landings, skid trails).

The volume of in-stream wood loading may increase after wildfire, with important long-term implications for channel morphology and the creation of aquatic habitat.

Given the variety of ways in which wildfire can influence watershed geomorphic processes (surface runoff and erosion, debris flows, loss of bank strength, increased wood loading), and the fact that these processes operate over a range of time scales and lags, geomorphic response to wildfires is complex and contingent on the sequence of post-fire weather events and hydrologic response.

A well co-ordinated, rapid assessment of the risk of post-fire erosion, as exemplified by the US Burned Area Emergency Response (BAER) teams in Australia, can provide land managers with the knowledge necessary to understand the risks to water resources and infrastructure and to evaluate treatment options.

The use of mulching treatments (e.g., wood chips and straw mulch) can be effective in reducing the risk of erosion and sediment production from burned hillslopes, but timing of application and consideration of mulch quality (e.g., minimize potential for weed seeds) are critical to the success of these treatments.

Water-repellent soils do not appear to have an effect on forest tree regeneration.

Following wildfire, numerous changes in water quality are possible, with variable rates of recovery. Potential effects include increased turbidity, nutrients (e.g., nitrogen and phosphorus), dissolved organic carbon, heavy metals (e.g., mercury), and temperature. All of these parameters can be negatively influenced by salvage-harvesting activities.

Even small changes in water quality can have significant impacts on aquatic ecology, resulting in greater algal production, increased aquatic invertebrate abundance, and shifts in invertebrate community structure.

Wildfire-related changes in water quality present several public health protection challenges for water purveyors and can potentially increase the risks for drinking water treatment. Thus, appropriate protection of source waters is often a more effective and less expensive option to ensure high-quality drinking water, as compared with increased treatment levels.

The culmination of the workshop was a panel discussion, during which five professionals engaged the audience in a discussion on where and when to salvage harvest or use other land management options (e.g., do nothing). The primary topics of this discussion included the following.

Despite much recent work, there is still uncertainty about the effects of various natural disturbances (e.g., wildfire and mountain pine beetle) and the potential incremental effects of salvage harvesting on a range of water values.

However, it was agreed that salvage logging can potentially increase watershed risks. These risks need to be considered and weighed against various watershed values when making any post-disturbance land management decisions.

The current economics and jurisdictional authority of the forest industry are challenging and, in most cases, prohibitive to the use of many other post-disturbance management options (e.g., mulching treatments).

From the perspective of the water purveyors, the potential incremental challenges for water treatment that may be created by post-disturbance land management require greater consideration.

Information Needs

A number of continuing information needs were identified. Despite the recent research efforts, many unknowns still exist regarding the effects of wildfire and post-fire salvage harvesting on water quantity and quality. Some of the more specific information needs identified included:

- A demand for more watershed- or basin-scale research on the hydrologic and geomorphic effects of wildfire and post-fire salvage harvesting.
- More research focused on addressing shifts in the hydrologic regime (both timing and quantity) due to wildfire and post-fire salvage harvesting.
- A high level of uncertainty persists regarding how long it will take for water quality and quantity in disturbed (wildfire and post-fire salvage-harvested) watersheds to return to pre-disturbance levels (hydrologic recovery).
- As a result of the high variability from previous studies, the actual effects that wildfire and salvage harvesting will have on water quality remain unclear.
Continued from page 3

- Further research focused on the ecological implications of disturbance at both the watershed and landscape scales.
- More information on the fate and transformation of chemicals from wildfire runoff and the implications for drinking water treatability.
- Testing and developing risk assessment and post-fire rehabilitation tools should continue to be a priority.
- Researchers, and water supply and treatment professionals, should communicate more regularly to enhance the value of study results. For example, water quality data are not always collected or reported in ways that are meaningful for water treatment professionals.

Workshop Evaluation

A post-workshop evaluation (completed by 61% of participants) indicated that 92% of respondents increased their knowledge of the key hydrologic processes affected by wildfire and related salvage harvesting by attending the event. Further, 98% of respondents said that their expectations for the workshop were met. Most respondents noted that the knowledge gained from the workshop could be directly used to assist land management decision making and/or to support policy development. Overall, the workshop was rated as ‘excellent’ by 66% of respondents, with the remaining 34% rating the workshop as “good.”

Additional Information

The workshop handbook with two-page summaries from each presenter is available at: www.forrex.org/program/water/PDFs/Workshops/Wildfire_Handout.pdf

The workshop evaluation summary is available at: www.forrex.org/program/water/PDFs/Workshops/Wildfire_Watershed_Hydrology.pdf

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References


A Portable Rainfall Simulator: Techniques for Understanding the Effects of Rainfall on Soil Erodibility

Ashley Covert and Peter Jordan

Introduction

Rainfall simulations are used to help us understand the effects of rainfall on soil properties under various conditions. To study the effects of wildfire on runoff generation and soil erosion during rainstorms, we constructed an effective yet simple rainfall simulator that was inexpensive, portable, and easily operated by two people on steep, forested slopes. The simulator generated results that were useful in understanding runoff and sediment production in burned and unburned forests. This article describes how to construct the simulator and install plots for field data collection.

Background

Studying soil erodibility properties in nature can be extremely difficult because of the natural variability of rainfall intensity, location, frequency, and duration, as well as variable slope and soil conditions. On a small spatial scale, rainfall simulators can be useful tools to help quantify the amount of infiltration excess runoff (Hortonian overland flow) and erosion generated by different rainfall intensities, considering factors such as slope, soil type, burn severity condition, and the type of forest floor. These data can help us understand basic water balance equations and the effects and importance of the forest floor on water storage. The data can be used to generate specific soil parameters such as infiltration, soil erodibility, hydraulic conductivity, and water repellency that can be used to drive erosion process models such as WEPP (Water Erosion Prediction Project) (Flanagan and Nearing 1995).

Various types of rainfall simulators have been built in the United States and Canada for use on agricultural soils (Meyer and Harmon 1979; Shelton et al. 1985; Humphry et al. 2002), on skid trails (Commandeur and Wass 1994; Foltz and Maillard 2003), and for rangeland, forested and burned slopes (Commandeur 1992; Robichaud 2000; Brady et al. 2001; Pierson et al. 2003; Kinner and Moody 2008).

There are two basic designs of rainfall simulators: drip tube and nozzle. The drip tube design consists of a constant-head water reservoir placed at the top of the simulator, which feeds a grid of several hundred capillary tubes (Munn and Huntington 1976; Commandeur and Wass 1994). The nozzle design uses a water source that feeds one or more nozzles at a constant specified pressure. Of the two water application methods, the nozzle design has several advantages in that it is more portable, can produce greater and different intensities, and can create a more random drop pattern similar to natural rain (Kinner and Moody 2008).

Rainfall Simulator Design

The simulator consists of an extendible tripod base that supports a single, fixed spray nozzle above the plot (Figure 1). A small fire pump was used to draw water from a collapsible, 273-L still-well water bladder to supply constant pressure to the nozzle.

The tripod base is constructed of three dry-wall support rods (Task Quick Support Rod) extendable to 3.3 m with flat articulated feet that can be spiked into the ground for stability. The upper portion is a

Figure 1. Rainfall simulator on a 50% slope.
A small pump (Shindawa GP25) delivered water from the water bladder to the simulator through a 12.7-mm garden hose (Figure 2). An adjustable valve at the base of the simulator, along with a pressure gauge at the outlet of the pump and one at the nozzle, were used to achieve the desired nozzle pressure.

Four collapsible water bladders were used for water supply. Three of these were filled in the truck from a nearby creek using a large pump (Mark 26) and 3.8-cm fire hose. The water from one of the bladders in the truck was then transferred to the fourth bladder located approximately 5 m vertically upslope from the simulator for each 20-minute simulation. These water bladders were compact and portable making them ideal for transport.

Rainfall Characteristics

Intensity
The rainfall simulator described in this article was designed to simulate high-intensity, short-duration rainfall similar to that generated by convective rainstorms. This type of rainfall (as opposed to rain-on-snow or snowmelt) causes the dislocation and transport of surface soil particles and is the leading cause of post-fire erosion events in the United States (Gartner et al. 2005). The simulator generated an average rainfall intensity of 74 ±3 mm per hour for 20 minutes, which is similar to the maximum 100-year storm intensity (73 ±24 mm per hour) for a 15-minute period near Castlegar, BC (Environment Canada 2008). An intensity of this magnitude was necessary to generate runoff on unburned forest floors and thereby show a comparison with runoff from burned sites (P. Robichaud, pers. comm., July 2007). Depending on the objectives of the study, simulated rainfall intensity and duration can be varied by altering the nozzle type and water pressure. The rainfall intensity we achieved was the maximum possible with our simulator setup; however, a larger water source and different nozzle types could be used to generate greater intensities. Other, more complex rainfall simulators are also available that can produce higher intensities (Robichaud 2000; Pierson et al. 2003).

Drop Size and Velocity

We assessed the drop characteristics to ensure comparability with other rain simulation studies. A tripod-mounted digital camera was used to photograph the raindrops at 1/500 second shutter speed against a 10 x 10-cm grid backdrop. To calculate fall velocity and diameter of drops, the length and width of 200 drops falling closest to the grid were measured directly from 10 consecutive photographs. Figure 3 illustrates the distribution of drop sizes.

Because of our simulator’s smaller nozzle size, the median drop size of 1.4 mm was approximately three-quarters of that measured by Humphry et al. (2002). Drop-size distribution fell between 0 mm and 6 mm, with the majority falling between 0 mm and 3 mm. In comparison, Cerda (1997) observed raindrop sizes in natural, high-intensity rainstorms (maximum 120 mm per hour) to range from...
0 mm to 3.87 mm from measurements taken over a 7-month period in the Mediterranean, which is also comparable to measurements in the United States.

The velocity for the median drop size of 1.4 mm was estimated at approximately 6.9 mm per hour, which is 7% higher than terminal velocity of drops measured by Epema and Riezebos (1983). The less frequent, larger drops in the 1.5–3 mm range fell 5% slower than similar-sized drops at terminal velocity. Drops greater than 3 mm fell at approximately 75% of terminal velocity. Epema and Riezebos (1983) found that drops greater than 3 mm require a fall distance of approximately 13 m to reach terminal velocity, which is difficult to achieve with this apparatus; however, only 6% of drops generated by this simulator were greater than 3 mm.

Plot Setup

For our study, a sample of five 1-m² plots was grouped in each study site (e.g., high burn severity, moderate burn severity, and unburned). Because of the time needed to set up the plots and equipment, the plots were grouped together so that minimal movement of the equipment was necessary.

A 1-m² steel plot border, constructed of 3-mm steel plate with 10-cm sides was installed for each plot. These borders were pounded into the soil approximately 5 cm deep leaving 5 cm above ground to prevent inflow and outflow of water from the plot. The downslope edge of the border was level with the ground surface so the surface runoff and sediment flow directly into a trough (Figure 4). The trough is a PVC gutter pipe with a cap at one end and an open valve at the other. The trough was set into the ground below the lower lip of the plot border, and placed on a slight slope so that the runoff and sediment from the plot drained from it into sample bottles. A plexiglas shield was placed over the trough to ensure that only runoff, and no rainfall, entered the trough.

This style of trough did not provide enough of a gradient, resulting in a significant amount of sediment settling in the bottom and leading to an underestimation of sediment in each minute (~25% per bottle); however, the settled sediment was collected at the end of the 20-minute simulation and added to the total sediment value. A more precise method uses a funnel-shaped collector (Commandeur and Wass 1994).

Wind blowing during simulations can change the amount of rainfall reaching the plot. As a preventative measure, a tarpaulin could be draped over some bamboo poles around the simulator.

Operation

After the plot border was installed, the simulator was centred over the plot using the level and plumb bob to achieve the correct height and position. A calibration was then done to ensure the correct rainfall intensity.

For the calibration, a 1-m² waterproof tray was placed over the plot border to catch the rainfall and to keep the plot dry during calibration. The pump at the water bladder and pressure at the nozzle were set to the desired level for one minute. The water captured in the tray was measured in a 1000-ml graduated cylinder to determine the resulting rainfall intensity. If the intensity was incorrect, the pressure was adjusted

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and the calibration re-run until the volume reached the desired amount for the simulation.

After calibration, the plot cover was removed, the timer started, and the valve was opened to start the simulation. The time for runoff to start was recorded when the first drip entered the first 1-L sample bottle. Individual sample bottles were used to collect a 30-second sample of runoff and sediment for every minute of the 20-minute experiment. After the rain was turned off, another bottle was immediately placed under the nozzle until runoff ended. A final bottle was used to collect the remaining sediment from the trough, resulting in a total of 22 bottles per simulation.

Following the field experiments, each 30-second sample was dried and weighed in the laboratory to determine the runoff rate (millimetres per hour) and sediment yield (grams per hour) for each minute of the simulation. Figures 5 and 6 provide examples of the results for runoff and sediment yield.

Time and Costs
The time required to install plot borders, set up the simulator, run a calibration and a simulation can range from 45 minutes to 1.5 hours depending on the conditions of the site and proximity of plots. Additional time is needed to establish sites and bring water and equipment to the site. In an average 9-hour day, our two-person crew could complete three simulations if the plots were adjacent (within several metres) to each other.

The final cost of the simulator, and associated equipment, was approximately $1300; $500 of this amount was for two steel plot borders. This simulator was designed to be inexpensive and simple to use and operate. Our costs were greatly reduced by our ability to borrow pumps, bladders, and hoses from the Wildfire Management Branch of the BC Forest Service. If purchased, the cost of the pumps, hoses, and bladders used would be approximately $7000; however, a similar system could be set up for lower cost if different pumps were used or if equipment could be rented.

Other Potential Research Applications
Rainfall simulators have been used for many different types of applied research. The simulator designed for this project can be altered for different rainfall intensities and rainfall characteristics. Our research compared runoff and erosion rates between unburned forests and burns of varying severity. However, adjustments to the nozzle and pressure could be used to:

- examine the threshold for rainfall intensity that generates erosion on different slopes;
- examine the different water-holding capacities of different forest floor types and depths;
- test the infiltration rates for different soil types;
- test the effectiveness of different hillslope stabilization techniques; or
- observe the difference in erodibility between wet and dry soils.
Conclusion
This article is intended to help in the construction and application of a rainfall simulator for use in forested environments. The overall design of the simulator presented here is simple, lightweight, inexpensive, and versatile enough to be modified to achieve various objectives. The simulator generated sufficient rainfall characteristics and intensity to assess the relative difference in runoff and sediment yield in different burned and unburned conditions. The resulting data can be used to help understand soil erosivity and to aid forest management applications such as risk assessment and prescription of mitigation treatments.

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References


Understanding the Types of Aquifers in the Canadian Cordillera Hydrogeologic Region to Better Manage and Protect Groundwater

Mike Wei, Diana Allen, Alan Kohut, Steve Grasby, Kevin Ronneseth, and Bob Turner

Introduction

Groundwater is often viewed as a mysterious and challenging resource to manage as it is hidden underground. Generally, the only obvious sign of groundwater to the public is water flowing from a spring or from a well. Where and how the groundwater got to the spring or well and how much is available are questions of interest when trying to protect the resource. Extending knowledge of groundwater and aquifers—permeable, water-bearing geological formations or deposits that transmit and store groundwater—to communities and land and water resource decision makers has been a challenge in British Columbia because of the general lack of comprehensive studies in many areas. If similar types of aquifers have similar characteristics, it may be reasonable to extrapolate knowledge from well-studied areas to predict properties of a specific aquifer where little is known. Although this inferred knowledge does not replace actual testing and assessment of the local aquifer, it can be useful, as a first step, to develop a working hypothesis about the local aquifer, especially in sparsely studied areas. This article describes a system of categorizing aquifers in the Canadian Cordillera Hydrogeologic Region (first described by Halstead [1967] and here referred to as the “Region” or “Cordillera”) based on general hydrogeological characteristics (Figure 1). Categorizing aquifers promotes increased general knowledge and understanding of the characteristics of local aquifers in this Region, and thus supports the management and protection of local groundwater resources.

The Canadian Cordillera Hydrogeologic Region occupies the mountainous region that covers much of British Columbia (except the Peace River country), as well as the Rocky Mountain foothills of southwestern Alberta, the southern part of the Yukon Territory, and part of the Northwest Territories; it is the westernmost of Canada’s hydrogeologic regions (Figure 1; Sharpe et al., in press). Aquifers in the Region supply water to an estimated 1 million persons for drinking water, as well as for irrigation, aquaculture, and industrial processing needs. The Region’s climate varies widely from Mediterranean conditions along the southwest coast to polar conditions.
at high mountain elevations and in the north. Mean annual precipitation generally decreases from west to east across the Region (following the general movement of the weather fronts), ranging, for example, from 3306 mm at Tofino on the west coast of Vancouver Island to 293 mm at Kamloops and 472 mm at Banff, Alberta. Annual precipitation also generally increases with elevation due to orographic effects.

Seasonal climatic variations control the annual quantity and form of precipitation, thereby affecting the timing and amount of runoff to streams and recharge to aquifers in the Cordillera. Coastal areas experience highest precipitation during the winter months, with much of it falling as rain, except at higher elevations where it may fall as snow. In these coastal areas, groundwater recharge mostly occurs during the winter months when the rate of evaporation and transpiration are at their seasonal lowest. Consequently, the natural groundwater levels in coastal areas show a seasonal high during winter or early spring, and decline from spring to late fall (see Figure 2a). In contrast, interior areas have their highest precipitation during the summer months, but much of this is evaporated or transpired and does not normally contribute to groundwater recharge. In the interior, snow accumulations during the winter months, and at higher elevations, are important for recharge during the spring and early summer when snowmelt occurs. Thus, groundwater levels in the interior generally are at a seasonal high in late spring or early summer and then decline over the summer and early fall. The groundwater level generally reaches a seasonal low during the winter months, when precipitation at the land surface is frozen (see Figure 2b).

Glacial history, surficial and bedrock geology, and tectonic history greatly influence the occurrence, distribution, and characteristics of aquifers in the Region. Most surficial or unconsolidated aquifers are formed by deposition of sand and gravel in moving water under a fluvial or, if by moving water during glacial times, a glaciofluvial environment related to the last period of glaciation. Glaciofluvial sand and gravel aquifers formed during ice advance tend to be overlain by till or glaciolacustrine clay and silt, and are lithologically confined. Glaciofluvial sand and gravel aquifers formed during the melting of the
ice are commonly unconfined. The bedrock geology of the Cordillera is extremely varied and complex due to the Region’s geologic, tectonic, and volcanic history. Holland (1976) generalized the bedrock geology of the Region into six main bedrock types:

1. intrusive igneous rocks;
2. flat-lying lava, and some sedimentary rocks;
3. flat or gently dipping sedimentary rocks;
4. folded sedimentary rocks;
5. folded and faulted volcanic and sedimentary rocks; and
6. foliated metamorphic rocks of various ages.

Despite the presence of different types of bedrock in the Cordillera, bedrock permeability exists mostly as a result of development of fractures or faults from tectonic forces or, in limestone, from development of dissolution cavities (karst). In the Cordillera, fractures and faults developed in igneous intrusive, foliated metamorphic, and folded and faulted volcanic and sedimentary rocks, give these types of rocks sufficient secondary permeability to form aquifers. The permeability, however, is often anisotropic because the fractures or faults are discrete and have specific orientations in the bedrock. The porosity and storativity of fractured or faulted bedrock are also very low (e.g., porosity of less than a few percent). Extensive areas of central British Columbia are underlain by relatively unaltered, flat-lying lava of Tertiary age (e.g., the Cariboo-Chilcotin area). These are mostly basalts and individual flows that can be hundreds of metres thick. This lava forms an important aquifer because groundwater typically occurs in joints, and in fractured and weathered contact zones between the lava flows.

The Province of British Columbia and the Canadian Government (through the Geological Survey of Canada and Environment Canada) have conducted groundwater studies in the Region since the 1950s. The Province of British Columbia has also been mapping and classifying developed aquifers in the Region since 1994 (for background on the BC Aquifer Classification System, see adjacent sidebar and Berardinucci and Ronneseth 2002). This work, and the resulting inventory, has enabled the identification of aquifer types within the Region and improved our understanding of their general hydrogeologic characteristics.

**Major Aquifer Types in the Canadian Cordillera Hydrogeologic Region**

In the Cordillera Hydrogeologic Region, aquifers generally fall into the following six categories (refer also to Figures 3a and 3b).

**Unconsolidated Sand and Gravel Aquifers**

1. Unconfined\(^3\) fluvial or glaciofluvial aquifers along river or stream valleys
   a. Aquifers along major higher-order rivers, where the potential of hydraulic connection with the river exists,
   b. Aquifers along moderate-order rivers, where the potential of hydraulic connection with the river exists, or
   c. Aquifers along lower-order (< 3–4) streams in confined valleys, where aquifer thickness and lateral extent are more limited

2. Unconfined deltaic aquifers

3. Unconfined alluvial fan or colluvial aquifers

4. Aquifers of glacial or pre-glacial origin
   a. Unconfined glaciofluvial outwash or ice contact aquifers,
   b. Confined\(^4\) aquifers of glacial or pre-glacial origin, or
   c. Confined aquifers associated with glaciomarine environments

**Bedrock Aquifers**

5. Sedimentary rock aquifers
   a. Fractured sedimentary bedrock aquifers, or
   b. Karstic limestone aquifers

6. Crystalline rock aquifers
   a. Flat-lying or gently-dipping volcanic flow rock aquifers, or
   b. Crystalline granitic, metamorphic, meta-sedimentary, meta-volcanic, and volcanic rock aquifers

The categories of aquifer types are based on geologic and hydrologic properties, as well as on practical considerations, such as data availability. The main geologic factors are the origin and type of the geologic deposit that comprise an aquifer (e.g., sand and gravel aquifer forming a delta at the mouth of a river or a plutonic granitic fractured bedrock aquifer). The origin and type of geologic deposit often governs an aquifer’s hydraulic properties, such as the nature of the porous medium (porous sand and gravel, or fractured bedrock) and ability to transmit and store water. Another consideration is the hydraulic connection between an aquifer and a river, stream, or lake. A direct hydraulic connection can be advantageous for potential well yields because pumping could induce infiltration of surface water into those aquifers. A practical consideration, particularly for unconsolidated aquifers buried at depth, is that it is often difficult to identify the origin of these buried unconsolidated sand and gravel aquifers based on very limited well record data. Buried unconsolidated sand and gravel aquifers are grouped into confined, unconsolidated sand and gravel aquifers of glacial or pre-glacial origin (Type 4b). Descriptions of the aquifer types are presented directly below; many of the aquifer types are illustrated in Figures 3a and 3b, which represent aquifers in a coastal and interior setting, respectively.
The BC Aquifer Classification System

The British Columbia Aquifer Classification System was developed in 1994 (Kreye and Wei 1994). Its objective was to interpret raw data (primarily well records and geologic mapping) to identify and classify aquifers, and thus:

- provide a framework to direct detailed aquifer mapping and characterization;
- provide a method of screening and prioritizing management, protection, and remedial efforts on a provincial, regional, and local level;
- identify the level of management and protection an aquifer requires;
- build an inventory of the aquifers in the province; and
- increase public knowledge and understanding of their local aquifer.

The aquifer classification system has two main components (Figure A-1):

- classification component
- ranking value component

The classification component classifies an aquifer on the basis of its level of development and its vulnerability to contamination. The classification component categorizes an aquifer based on its current level of groundwater development and vulnerability to contamination (categories A, B, and C for high, moderate, and low vulnerability, respectively). The level of development (categories I, II, and III for high, moderate, and light development, respectively) compares the amount of groundwater withdrawn from an aquifer (demand) to the aquifer’s inferred ability to supply groundwater for use (productivity). The level of vulnerability (categories I, II, and III for high, moderate, and low vulnerability, respectively) of an aquifer is based on whether or not an aquifer is confined.

The combination of the three development and three vulnerability categories results in nine aquifer classes. The nine aquifer classes have an implied priority from a general management and protection standpoint, from IIIIC, which is the lowest priority, to IA, which is the highest (Figure A-2).

The ranking value component assigns a number value to indicate the relative importance of an aquifer. Assigned values are derived from the following criteria:

1. aquifer productivity;
2. aquifer vulnerability to surface contamination;
3. aquifer area or size;
4. demand on the resource;
5. type of groundwater use; and known documented groundwater concerns related to:
   6. quality; and
   7. quantity.

The ranking value is determined by summing the points for each criterion (Figure A-3): the lowest ranking value possible is 5, and the highest ranking value possible is 21. Generally, the aquifer with the greater ranking value has the greater priority. Figure A-3 shows the ranking values applied for each criterion.

The classification and ranking value components are determined for the aquifer as a whole, and not for parts of aquifers.

To promote the appropriate use of the aquifer classification system, a guidance document was produced to assist users in interpreting and using the aquifer maps. This document can be found at: [www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/reports/aquifer_maps.pdf](http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/reports/aquifer_maps.pdf)

The aquifer maps and other hydrological information are also available online at: [www.env.gov.bc.ca/wsd/data_searches/wrbc/index.html](http://www.env.gov.bc.ca/wsd/data_searches/wrbc/index.html)
Type 1 – This category covers sand and gravel aquifers that are generally shallow, unconfined, and occur along river or stream valleys. Often both fluvial and glaciofluvial sand and gravel deposits form an aquifer along the river or stream valley bottom. Therefore, shallow sand and gravel aquifers underlying river or stream valleys—whether of fluvial or glaciofluvial origin—are categorized as the same general aquifer type. This category is further subdivided into the following three sub-categories.

- Type 1a – Aquifers found along major higher-order rivers with potential hydraulic connection to the river. These rivers are generally of low gradient and the depositional energy is relatively low to cause deposition of mostly sand, silt, some clay, and some gravel (e.g., the Chilliwack-Rosedale aquifer along the Fraser River near the City of Chilliwack).

- Type 1b – Unconfined sand and gravel aquifers found along moderate-order rivers with potential hydraulic connection to the river. These rivers have higher gradients compared to rivers of higher stream orders and the depositional energy is relatively high to cause deposition of mostly sand and gravel (e.g., the fluvial sand and gravel deposit along the Cowichan River on the east coast of Vancouver Island near the community of Duncan; the fluvial and terraced glaciofluvial sand and gravel deposits along the Kettle River at the Southern Interior community of Grand Forks).

- Type 1c – Sand and gravel aquifers found along lower-order (< 3–4) streams in confined valleys with floodplains of limited lateral extent, where aquifer thickness and size are more limited (e.g., fluvial or glaciofluvial deposits along a mountain stream).

Type 2 – This category covers sand and gravel aquifers that are shallow, unconfined, and which form deltas at the mouth of rivers and streams (e.g., the Scotch Creek aquifer at Shuswap Lake). Older deltas buried at depth below till, glaciolacustrine, or glaciomarine deposits have not been included here because it is generally difficult to identify buried sand and gravel as deltas based on limited data. These buried aquifers would be categorized under sand and gravel aquifers of glacial or pre-glacial origin (i.e., aquifer Type 4b).

Type 3 – This category covers sand and gravel aquifers that form alluvial fans or are of colluvial origin near the land surface. As with Type 2 aquifers, this category excludes older alluvial or colluvial aquifers buried at depth.
Vedder River Fan aquifer at the City of Chilliwack is an example of this type of aquifer.

**Type 4** – This category covers known glaciofluvial sand and gravel aquifers, as well as other sand and gravel aquifers identified in well records as occurring at depth, underneath till or glaciolacustrine deposits, and glaciomarine sand, sand and gravel aquifers. This category is further subdivided into the following three sub-categories.

- **Type 4a** – Unconfined glaciofluvial outwash or ice contact sand and gravel aquifers, generally formed near or at the end of the last period of glaciation. The Abbotsford-Sumas Aquifer is perhaps the most well-known and studied aquifer of this type in the Cordillera Region.

- **Type 4b** – Confined sand and gravel aquifers underneath till, in between till layers, or underlying glaciolacustrine deposits. The Quadra Sand, which occurs in the Georgia Depression on the east coast of Vancouver Island and along the southern mainland coast, is an excellent example of a confined glaciofluvial sand and gravel aquifer consisting of sand and gravel deposited as the glacier advanced south along the Georgia Depression. Other confined glaciofluvial sand and gravel aquifers occur between till layers, which is indicative of deposition during glaciation. Still other confined sand and gravel aquifers may be fluvial, alluvial, or colluvial deposits from a time prior to glaciation (and therefore lie underneath till or glaciolacustrine deposits). Unless a confined sand and gravel aquifer has been well studied, it is often difficult to determine its geologic origin and geomorphology based on limited data. Therefore, any water-bearing sand and gravel occurring underneath till, in between till layers, or under glaciolacustrine deposits is included in this sub-category.

- **Type 4c** – Sand and gravel aquifers that occur underneath known sand, silt, and clay deposited under a marine environment near the coast. Most of the few known aquifers in this category occur in the deep marine sediments at depth in low-lying areas in the Fraser Lowland, in Surrey and Langley, east of Vancouver.

**Type 5** – This category is further subdivided into two sub-categories: (a) fractured sedimentary rocks and (b) karstic limestone rocks. The Nanaimo Group of fractured and faulted sedimentary rocks in the Gulf Islands and east coast of Vancouver Island is a classic example of the former sub-category. The limestone formations in the Rocky Mountains are an example of the latter sub-category. For fractured sedimentary rocks, groundwater flow occurs mostly along joints and in fractures and faults. Although this classification may also apply to karstic limestone, the major difference is that groundwater may flow in open dissolution channels and large cavities in karstic limestone aquifers.

**Type 6** – This category is subdivided into two sub-categories: (a) flat-lying to gently dipping volcanic flow aquifers and (b) fractured crystalline rocks. Groundwater flow in flat-lying to gently dipping volcanic rocks can be through joints and fractures, but also in broken, weathered zones between flows. The large volcanic flow bedrock aquifer in the Central Interior of British Columbia near 70-Mile House is an example of this type of aquifer.

Groundwater flow in fractured crystalline rocks is mostly along joints, fractures, and faults. This sub-category includes igneous intrusive or metamorphic rocks (such as the fractured granodiorite aquifer underlying the Saanich Peninsula, north of Victoria). The meta-sedimentary, older volcanic, and meta-volcanic rocks are most similar in hydrogeological properties to granitic and metamorphic rocks and, therefore, have been included in this sub-category.

**General Aquifer Characteristics**

A summary of some of the characteristics for each category or sub-category of aquifer is presented in Table 1, including size, reported well depths and yields, representative transmissivity values, and potential hydraulic connection to surface water. The summary information in Table 1 was compiled from available well records, attribute data associated with the classified aquifers, and available groundwater reports.

Generally, sand and gravel aquifers (Types 1, 2, 3, 4a) are of limited size (< 1 km² to over 100 km², with average sizes of a few to 10s of square kilometres). Their limited size reflects the variable topography and relief of the Canadian Cordillera Hydrogeologic Region. Bedrock aquifers can be larger, but even so, aquifers in the Cordillera are not typically considered “regional” aquifers.

Table 1 also shows that unconfined sand and gravel aquifers (Types 1, 2, 3, and 4a) are generally shallower (inferred from the well depth) than confined sand and gravel aquifers (Types 4b and 4c) and bedrock aquifers (Types 5 and 6). The shallower, unconfined sand and gravel aquifers (Types 1, 2, 3, and 4a) are considered highly vulnerable to contamination whereas the generally deeper, confined sand and gravel aquifers (Type 4b and 4c) are considered to have a moderate to low vulnerability. In the Region, widespread nitrate contamination from human activities is found in unconsolidated, unconfined aquifers (Types 1b, 2, 4a) where intense agricultural activity occurs or a high density of on-site sewage disposal systems and shallow water tables are present; these are the most vulnerable aquifers.

Continued on page 17
Table 1. Summary of hydrogeologic characteristics of the major aquifer system types in the Cordillera Hydrogeologic Region (Source: Rivera in press; reproduced with permission of the Geological Survey of Canada).

<table>
<thead>
<tr>
<th>Aquifer type</th>
<th>Range; average size (km²)</th>
<th>Average range; average median well depths (m)</th>
<th>Average range; average median well yields (L/s)</th>
<th>Range; geometric mean transmissivity (m²/d)</th>
<th>Hydraulic connections with surface water?</th>
<th>Examples of aquifer types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unconfined aquifers of fluvial or glaciofluvial origin along river valley bottoms</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>a. Aquifers along higher-order rivers</td>
<td>&lt; 1–140; 27</td>
<td>12–83; 23</td>
<td>2–17; 3</td>
<td>350–22 000; 4500</td>
<td>Common</td>
<td>Agassiz, Chilliwack-Rosedale</td>
</tr>
<tr>
<td>b. Aquifers along moderate-order rivers</td>
<td>&lt; 1–120; 15</td>
<td>11–53; 22</td>
<td>2–41; 6</td>
<td>1–36 000; 1300</td>
<td>Common</td>
<td>Grand Forks, Duncan, Chemainus, Nechako, Merritt</td>
</tr>
<tr>
<td>c. Aquifers along lower-order streams</td>
<td>&lt; 1–23; 7</td>
<td>9–43; 19</td>
<td>1–22; 4</td>
<td>160–240; 200 (based on two values)</td>
<td>Common</td>
<td>Cache Creek, Little Fort</td>
</tr>
<tr>
<td>2. Unconfined deltaic aquifers</td>
<td>&lt; 1–19; 4</td>
<td>5–27; 12</td>
<td>2–15; 6</td>
<td>960–2390; 1500</td>
<td>Common</td>
<td>Scotch Creek near Chase</td>
</tr>
<tr>
<td>3. Unconfined alluvial, colluvial fan aquifers</td>
<td>&lt; 1–54; 5</td>
<td>13–47; 24</td>
<td>2–23; 4</td>
<td>25–5600; 710</td>
<td>Common in aquifers adjacent to surface water</td>
<td>Vedder River Fan at Chilliwack</td>
</tr>
<tr>
<td>4. Aquifers of glacial or pre-glacial origin</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>a. Unconfined glaciofluvial aquifers</td>
<td>&lt; 1–90; 8</td>
<td>12–59; 24</td>
<td>1–22; 3</td>
<td>2–89 000; 690</td>
<td>Common in aquifers adjacent to surface water</td>
<td>Abbotsford, Langley, Hopington</td>
</tr>
<tr>
<td>b. Confined glacial or pre-glacial aquifers</td>
<td>&lt; 1–330; 13</td>
<td>20–83; 39</td>
<td>0.8–12; 2</td>
<td>1–120 000; 250</td>
<td>Limited</td>
<td>Quadra Sand aquifers in the Georgia Basin, Okanagan and Coldstream valleys</td>
</tr>
<tr>
<td>c. Confined glacio-marine aquifers</td>
<td>2–190; 32</td>
<td>23–180; 61</td>
<td>0.1–14; 0.6</td>
<td>45–410; 150</td>
<td>Limited</td>
<td>Nicomekl-Serpentine in Surrey and Langley</td>
</tr>
<tr>
<td>5. Sedimentary rock aquifers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Fractured sedimentary rock aquifers</td>
<td>&lt; 1–700; 24</td>
<td>22–140; 56</td>
<td>0.1–3; 0.3</td>
<td>0.1–480; 4</td>
<td>Limited</td>
<td>Nanaimeo Group aquifers in the Gulf Islands and east coast of Vancouver Island</td>
</tr>
<tr>
<td>b. Karstic aquifers</td>
<td>2–36; 11</td>
<td>35–130; 75</td>
<td>0.1–1; 0.3</td>
<td>N/A</td>
<td>Unknown, but possible</td>
<td>Limestone aquifers in the Central Canadian Rockies, Sorrento, Fort St. James</td>
</tr>
<tr>
<td>6. Crystalline rock aquifers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Flat-lying volcanic flow aquifers</td>
<td>&lt; 1–6500; 420</td>
<td>21–130; 62</td>
<td>0.1–3; 0.3</td>
<td>11–47; 23 (based on three values)</td>
<td>Limited</td>
<td>Aquifer classification #124 around 70 Mile House</td>
</tr>
<tr>
<td>b. Fractured igneous intrusive, metamorphic, fractured volcanic, or metavolcanic aquifers</td>
<td>&lt; 1–540; 31</td>
<td>28–150; 71</td>
<td>0.1–5; 0.4</td>
<td>0.2–400; 9</td>
<td>Limited</td>
<td>Saanich granodiorite, granitic aquifers along Sunshine Coast, metabasalt aquifer at Metechosin near Victoria</td>
</tr>
</tbody>
</table>
To support local management and protection of groundwater, however, it may not be practical to conduct detailed aquifer characterization studies for each of the more than 900 developed aquifers known to exist in the Canadian Cordillera Hydrogeologic Region. Therefore, if an aquifer’s type can be categorized through simpler assessment techniques such as interpretation of local well records and surficial and bedrock geologic mapping, then it may be possible to ascertain some general characteristics of the local aquifer (e.g., local extent, shallow or deep, expected productivity, potential connection to surface water, confined/unconfined) based on similar types of aquifers studied elsewhere.

Understanding and categorizing a local aquifer’s general characteristics may allow decision makers to start developing broad management and protection strategies. For example, it may be important for a drinking water officer to recognize the need to assess the potential connection between surface water and groundwater and to establish disinfection requirements for the operation of a public water supply well that is drilled into a Type 1, 2, or 3 aquifer. Where Type 1, 2, 3, and 4a aquifers exist and are relied upon as a water supply source, a local government may want to consider the use of more detailed vulnerability mapping to identify areas of high vulnerability or high risk to aid in planning or zoning land use. Finally, local governments may want to consider establishing more stringent pumping test requirements under water servicing by-laws for new subdivision developments where the source of water supply is from a fractured rock aquifer (Type 5b or Type 6 aquifer).

Conclusions
Knowledge of local aquifer characteristics is key to managing the local groundwater resource.

Acknowledgements
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The authors would also like to acknowledge the constructive comments of T. Redding and two anonymous reviewers.

Endnotes

1 Anisotropic means physical properties of an aquifer or a geologic formation, such as permeability, is not the same in all directions.
2 Storativity means the amount of water an aquifer will release or yield from its pores when the groundwater level is lowered as, for example, during pumping.
3 Unconfined means the aquifer is not overlain by a low permeable geological formation or deposit, such as clay or till
4 Confined means the aquifer is overlain by a low permeable geological formation or deposit, such as clay or till.
5 Transmissivity is the ability of an aquifer to transmit groundwater and is a product of the aquifer’s hydraulic conductivity and thickness.

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Groundwater Vulnerability Assessments and Integrated Water Resource Management

Jessica E. Liggett and Sonia Talwar

Introduction

Canada has a disproportionate share of the world’s water and, as such, many Canadians hold the mistaken belief that our renewable freshwater resources are unlimited. Also, as groundwater is “hidden” below ground, it is hard to understand the processes affecting the resource. Groundwater is vulnerable to contamination from human activities, and is very difficult to remediate once contaminated. British Columbia has over 900 developed aquifers and almost 750 000 British Columbians (about 20% of the population) rely on groundwater as their drinking water source (BC Ministry of Environment 2009). To properly manage and protect the resource, it is therefore important to determine areas where groundwater may be more vulnerable to contamination.

“Vulnerability” is the degree to which human or environmental systems are likely to experience harm due to perturbation or stress, and can be identified for a specified system, hazard, or group of hazards (Popescu et al. 2008). In hydrogeology (the study of groundwater), vulnerability assessments typically describe the susceptibility of the water table, a particular aquifer, or a water well to contaminants that can reduce the groundwater quality (e.g., nitrates, industrial chemicals, gasoline). The contaminants may originate from a natural source (e.g., rock containing arsenic) or be introduced by human activity (e.g., agriculture: fertilizers; industry: chemical storage and spills).

Groundwater vulnerability assessments often result in a map of areas where the resource is vulnerable to contamination from surface activities. Vulnerability assessments prioritize areas for further investigation, protection, and monitoring. As part of integrated water resource management, vulnerability assessments are integrated into a program of groundwater characterization and risk analysis, with tiered approaches for assessing vulnerability, hazard potential, and risk.

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vulnerability and protection in the context of integrated water resources management. Numerous communities in British Columbia have undertaken vulnerability assessments for the purpose of water resource management. This article also provides an overview of some of these studies including the Fraser Valley (Wei 1998), Langley (Golder Associates 2005), Gulf Islands (Denny et al. 2007), Oliver (Liggett et al. 2006), and Vancouver Island (Liggett and Gilchrist 2009). The British Columbia Aquifer Classification System is also briefly described.

Groundwater Vulnerability: An Overview

What is Groundwater Vulnerability?

No single standardized definition for groundwater vulnerability exists; however, the concept describes the relative ease with which the groundwater resource could be contaminated. This is based on the idea that the physical environment can provide the resource with some degree of protection from contamination. Groundwater vulnerability has been defined as “an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts” (Vrba and Zaporozec 1994:7). The National Research Council (1993:16) defines it as “the tendency or likelihood for contaminants to reach a specified position in the ground water system after introduction at some location above the uppermost aquifer.” Although it is technically feasible to assess the vulnerability of groundwater to other hazards, such as drought, overpumping, and subsurface disturbance in mines or injection wells, this article focuses on groundwater vulnerability to water quality degradation (e.g., contamination).

Groundwater can be contaminated from fertilizers, pesticides, road salt, chemical spills, septic systems, landfills, and many other human actions. It may occur in a small area (e.g., a leaking gas tank) or over a very large area (e.g., from fertilizers in an agricultural area). Contaminants may also be released in a single event, or continuously over time. Once groundwater becomes contaminated, it is very difficult to remediate: groundwater moves slowly, so flushing out an aquifer can take a very long time. By mapping areas of high and low vulnerability, it is possible to identify which areas are more susceptible to contamination, and thus work to prevent contamination in the first place.

Groundwater vulnerability is related to the source–pathway–receptor model of contamination (Figure 1). A contaminant “source” (e.g., gasoline from a leaky tank) infiltrates into the ground and migrates downwards through the unsaturated zone (area above the water table) and intersects a “receptor”: the groundwater system is a “resource receptor.” Once the gasoline is in the groundwater system, it follows another pathway, more horizontally through the saturated zone (area below the water table where the pores are completely filled with water), and can be intersected by a “source receptor,” such as a water well or spring. Groundwater vulnerability assesses the pathway portion of this model; that is, how easily contaminants can move from the source to the receptor.

Groundwater vulnerability can be determined for any point of interest in the subsurface (National Research Council 1993), but vulnerability assessments are typically performed for the water table (e.g., Stigter et al. 2006), uppermost aquifer (e.g., Liggett and Gilchrist 2009), or a particular well (e.g., Frind et al. 2006). Continued on page 20
as receptors. Vulnerability assessments are usually performed in relation to contaminants released at the surface, migrating downwards through the unsaturated zone towards the water table and/or laterally through the saturated zone. The vulnerability to sources such as injection wells or underground storage tanks can also be addressed, although this article will not discuss methods for these types of assessments.

Within the scientific community, there is on-going debate about whether groundwater vulnerability is solely an intrinsic property of the land and subsurface, or whether it also encompasses properties of the contaminant type, loading, fate, and transport. Vrba and Zaporozec (1994), the Natural Research Council (1993), and the European community have recognized “intrinsic vulnerability” as the natural susceptibility to contamination based on the physical characteristics of the environment, and “specific vulnerability” as accounting for the transport properties of a particular contaminant or group of contaminants through the subsurface (Figure 2). To understand how vulnerability is characterized in an area, it is therefore important to be aware of the parameters used to assess vulnerability in a particular study.

An assessment of groundwater risk can be made with the hazard(s)—the pollution potential from the surface (e.g., types, loading, distribution, toxicity, etc.)—and the consequence of losing the resource at the receptor, in addition to the vulnerability (Figures 1, 2) (e.g., Geological Survey of Ireland 1999; Birkmann 2006). In some cases, no differentiation exists between specific vulnerability and risk assessments, with hazard types, distribution, loading, and transport all included at the risk-assessment stage (Figure 2) (e.g., Focazio et al. 2002). Other forms of risk assessment do not include the consequence factor, as this is typically a difficult parameter to quantify (e.g., Uricchio et al. 2004; Birkmann 2006). To generalize, risk is a function of the vulnerability, hazard potential, and consequence; however, the exact indicators used, how they are combined, and what terminology is used is not consistent between scholars and practitioners. Additionally, the level of detail of vulnerability, hazard, or risk assessment may vary depending on the study.

How are Vulnerability Assessments Performed?

Groundwater vulnerability assessments are a means to synthesize complex hydrogeologic information into a form usable by planners, decision and policy makers, geoscientists, and the public. The development of vulnerability maps is useful for many aspects of water management, including: prioritizing areas for monitoring, protection, and further investigation; and the development of risk assessments, resource characterization, and education.

Since vulnerability itself cannot be directly measured, other information such as geology, depth to water, soil types, hydraulic properties (parameters describing water flow and storage in the subsurface), and precipitation are used to assess the relative ease with which contaminants can reach and move through the groundwater system. In addition, parameters such as depth to water and hydraulic conductivity may be extrapolated, based on known points, to areas with limited or no data.

Many methods integrate such information to determine the vulnerability. The methods vary from simple, qualitative, inexpensive, indexing assessments to complex,
qualitative, costly, numerical modelling assessments (Focazio et al. 2002). The approach used to determine vulnerability for a particular project will depend on numerous factors, including the purpose and scope of the study, scale, data availability, time, cost, and end-user requirements.

In general, vulnerability assessments are categorized as:

- index (and overlay) methods,
- statistical methods, or
- process methods (Gogu and Dassargues 2000; Focazio et al. 2002).

Table 1 provides examples of each of these three methods and they are discussed in turn below.

Indexing methods are very popular because they are easy to implement, inexpensive to produce, use readily available data, and often produce categorical results (Focazio et al. 2002). Index methods also assess vulnerability spatially over large regions and can therefore show the vulnerability of the water table or uppermost aquifers in a region (i.e., resource receptor). In index-based methods (Figure 3), parameters depicting the physical properties of the system, such as depth to water and lithology, are mapped based on either existing data sets (e.g., well data, geological maps) or field data. Subjective numerical values or ratings are then assigned to each parameter map. The rated maps are combined to produce a relative indication of the vulnerability spatially over an area. In most cases, the vulnerability value is categorized into a set number of categories (e.g., three categories: high, medium, low; Figure 3). With the use of a geographical information system (GIS), digital maps of each parameter are easily rated and combined to produce the final vulnerability map. Index-based methods are best suited to produce regional-scale screening tools for use in decision making, and for prioritizing focus areas and level of site assessments. These methods are limited because of the subjective nature of the rating schemes, and because the hydrogeologic system is not explicitly represented. Note that the availability of data and interpolation methods used affect the reliability and scale of the final map. Table 1 provides examples of indexing methods and indicates the sub-parameters used in each method.

Statistical methods of assessing vulnerability involve the calculation of the probability of a particular contaminant exceeding a certain concentration. These methods are typically used in places with diffuse sources of contamination, such as to detect nitrates over agricultural areas. Statistical methods usually start with an analysis and mapping of water quality from known sites (e.g., samples from wells or soil). These maps can then be integrated into

<table>
<thead>
<tr>
<th>Name and reference</th>
<th>Type(^a)</th>
<th>Examples</th>
<th>Parameters(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Index Methods</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GOD (Foster 1987)</td>
<td>INV</td>
<td>Gogu et al. (2003), Neukum and Hötzl (2007)</td>
<td></td>
</tr>
<tr>
<td>EPIK (Doerfliger et al. 1999)</td>
<td>INV</td>
<td>Viaas et al. (2005), Neukum and Hötzl (2007)</td>
<td></td>
</tr>
</tbody>
</table>

**Logistic Regression (Helsel and Hirsch 1992)**

**Process Methods**

| Surface to Aquifer/Well Advection Time (SAAT/SWAT) (Ontario Ministry of the Environment 2006) | INV | N/A | | |
| Numerical Models (e.g., MODFLOW [US Geological Survey], FEFLOW [DHI Software]) | INV or SPV | Frind et al. (2006), Butscher and Huggenberger (2008) | | |

\(^a\) INV = intrinsic vulnerability; SPV = specific vulnerability.

\(^b\) D = depth to water; R = recharge/infiltration; A = aquifer characteristics (material, conductivity, etc.); S = saturated zone characteristics (e.g., flow patterns, layering, hydraulic gradient); U = unsaturated zone characteristics (material, hydraulic conductivity, soil moisture); O = other characteristics (e.g., explicit level of confinement, karst features, permeable pathways).
linear regression models in which the contaminant concentration is related to a series of factors such as geology, well depth, and/or land use (Focazio et al. 2002) (Table 1). Statistical methods produce spatially distributed probabilities of exceedance, rather than a categorized high, medium, and low ranking. These methods can show vulnerability to either a resource receptor (e.g., the water table) or a source receptor (e.g., a water well), and may be used instead of indexing methods when there is a specific interest for a particular contaminant over a large area and sufficient data exists on water quality in relation to the contaminant in question.

Process-based methods are powerful for assessing groundwater vulnerability. These physically based methods do not provide an output of simple relative values (Focazio et al. 2002). Instead, process-based methods use deterministic approaches to estimate time of travel, contaminant concentrations, and duration of contamination to quantify areas of high and low vulnerability (Figure 4). These approaches may include analytical solutions (e.g., Dupuit approximations) or numerical computer models (e.g., SAAT, SWAT, MODFLOW, MIKE-SHE). Some of these process-based methods include only the unsaturated zone (e.g., SAAT), and others include both (e.g., SWAT, MIKE-SHE) or only the saturated zone (e.g., MODFLOW). Additionally, process-based methods can assess groundwater flow or contaminant transport within the subsurface. The method and model of choice depends on the scope of a particular study.

Interpretation is needed to classify the results from process-based methods into specific categories of vulnerability (e.g., high, medium, low). Process-based models can show a representation of the flow system, and are ideal for determining vulnerability of a source receptor (e.g., a water well) (Figure 4); however, these methods are data-intensive and require extensive resources to develop. These methods are also typically applied at local scales, to determine well vulnerability, rather than at regional scales to a resource receptor (e.g., the water table or an aquifer; Frind et al. 2006). To illustrate how far from and in what geometry water will be drawn into the
well, numerical models are typically used to develop capture zones around municipal supply wells (Figure 4). From these capture zones, well-head protection areas can be established. Regardless of the method used, care must be taken when interpreting vulnerability assessments and maps. The parameters used to assess the vulnerability for a particular study, as well as the assumptions and limitations of the method, should be clearly documented and understood. In the case of index methods, the resultant vulnerability maps are not meant as a replacement for site-specific investigation. Most methods do not account for contaminants introduced below ground. Intrinsic vulnerability mapping methods do not account for specific properties of a contaminant, and do not provide an assessment of the hazard potential. For an area where intrinsic vulnerability has been mapped, a classification of low vulnerability does not mean the groundwater will not become contaminated. If a high hazard exists (e.g., intensive agriculture), then the risk and actual presence of contamination may be quite high (e.g., Stigter et al. 2006).

**Vulnerability Assessments within Integrated Water Resources Management**

The management and protection of groundwater resources is only part of an overall water management strategy. Although surface water resources are often more evident to people than “hidden” groundwater resources, managing the water resource presents a challenge of navigating the interface between natural ecosystems and human influence. To effectively capitalize on the valuable information resulting from groundwater vulnerability assessments, it is helpful to consider some broad tenets for water management.

Integrated water resources management (IWRM) has been identified as a useful paradigm for the development of policies to ensure widespread access to freshwater internationally (Policy Research Initiative 2005). Here, we focus on the vulnerability of groundwater resources to contamination and identify the ways in which groundwater vulnerability assessments can form a fundamental part of IWRM.

Continued on page 24

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**Figure 4. Schematic diagram of process-based methods of assessing vulnerability to a well.**

Top: Numerical modelling can show the direction, magnitude, and timing of groundwater (or contaminant) flow into a well. Bottom: Plan view of the same system showing the well capture zone outlined on the surface for purposes of well-head protection planning. Contours may represent time of travel, time to reach maximum contaminant concentration, etc.
Integrated water resources management is a process that promotes the co-ordinated development and management of water, land, and related resources to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Global Water Partnership 2000). Even though the world’s supply of freshwater is estimated at 35 million km$^3$ (Environment Canada 2004), many global citizens lack access to safe drinking water and appropriate sanitation. With such global disparities in water access and to ensure environmental sustainability, the need is reinforced to develop ways of working toward international goals for freshwater, such as those established for Agenda 21 (United Nations Conference on Environment and Development 1992) and the United Nations Millennium Development Goals.

Integrated water resources management is based on four principles that were established following an international consultative process that concluded with the International Conference on Water and the Environment in Dublin in 1992. These principles provided the foundation for the recommendations made at the United Nations Conference on Environment and Development in Rio de Janeiro later the same year. The four IWRM principles are:

1. Freshwater is a finite and vulnerable resource essential to sustain life, development, and the environment.
2. Water development and management should be based on a participatory approach, involving users, planners, and policy-makers at all levels.
3. Women play a central part in the provision, management, and safeguarding of water.
4. Water has an economic value in all its competing uses and should be recognized as an economic good.

The third principle points to the need to ensure that the water sector is gender-aware (Global Water Partnership 2000), perhaps of acute importance in less-developed countries. The fourth principle highlights the challenge of water management when water is widely viewed as a free good that arrives, for the most part, as precipitation from the skies. The first two principles are most directly relevant to this article since the first principle underscores the issue of water vulnerability and the second principle emphasizes the need for inclusive, participatory approaches to water management. At its core, IWRM is a philosophy rather than a blueprint. It acknowledges that local variability and local context will necessitate various water management strategies to sustainably manage the resource.

While watershed management approaches have become increasingly commonplace for surface water management in recent years, there has been perhaps less consideration of how groundwater is included in the overall policy development for freshwater. Indeed, the importance of groundwater protection is not often taken into account in water management (Nowlan 2005). From a potential contamination perspective, the groundwater resource may be exposed to contamination as a result of activities that take place on the land surface. At once, this implicates a tight coupling between land use decisions and groundwater resource management decisions. This coupling highlights the need for methods and evaluation strategies to determine water management options that are balanced with the commercial, industrial, agricultural, and community design directions occurring in our urban and rural landscapes throughout British Columbia. By selecting some means of evaluating groundwater vulnerability (see Table 1), we begin to bring in the groundwater piece of the larger IWRM puzzle.

The issue remains, however, of how to implement the principles of IWRM, particularly with respect to groundwater. A promising approach is to develop guidelines that advise different courses of action under differing vulnerability circumstances. The actual implementation of the course of action may be triggered, for example, by a development permit application. Piscopo (2001) identified five vulnerability classes as well as groundwater assessment requirements for each class (Table 2). Areas classified as low vulnerability required a groundwater assessment report that was to include a desk study to identify concerns and potential risk to groundwater. In areas of moderately high vulnerability, the requirement was a demonstrated groundwater protection system, including a desk study, site investigation, and monitoring program (Piscopo 2001).

Integrated watershed management is inherently complex since it requires the synthesis of multiple spatial and temporal data sets together with the identified priorities and values of water users and water managers. The process balances many constraints and opportunities ranging from the environmental, engineering, technical, and institutional, to the jurisdictional, economical, cultural, social, and political. In practice, an intrinsic groundwater vulnerability assessment is usually performed first, and the mapping results can be used independently or integrated into further risk assessment and watershed management. Much of water management becomes a question of managing risks since variations in water flows and groundwater recharge, for example, may lead to flood events and drought. Such variations might be due to climatic conditions or land mismanagement.
Table 2. Example of groundwater assessment requirements for various vulnerability classifications summarized from Piscopo (2001).

<table>
<thead>
<tr>
<th>Vulnerability classification</th>
<th>Groundwater assessment requirements</th>
</tr>
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<tbody>
<tr>
<td>Low</td>
<td>Groundwater contamination assessment report: Requires a desk study to identify hazards and risk to groundwater or the environment, and the need for any further action. A standard format hydrogeological report would most likely result.</td>
</tr>
<tr>
<td>Low-moderate</td>
<td>Site investigation with monitoring: Requires limited site investigation, groundwater monitoring, testing, and delineation of flow system in addition to desk study.</td>
</tr>
<tr>
<td>Moderate</td>
<td>Detailed site investigation and monitoring: Requires more detailed site investigation including ongoing monitoring and protection design factors (e.g., natural attenuation, physical barriers) in addition to requirements above.</td>
</tr>
<tr>
<td>Moderately high</td>
<td>Demonstrated groundwater protection system: The vulnerability is high enough such that a contaminant spill cannot be tolerated. Requires, in addition to the above, that protection design factors must be effectively demonstrated. A feasibility plan for remediation must be included with on-going monitoring.</td>
</tr>
<tr>
<td>High</td>
<td>Demonstrated remedial action plan/prohibition: Requires a remedial action plan including above and a demonstrated remedial action plan that analyzes the effectiveness of remediation in achieving designated water quality criteria, and the financial capacity of the responsible party to enact the plan. If the risk to groundwater is still unacceptable, the activity may be banned by the responsible authority.</td>
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</table>

and can have a dramatic effect on economic, environmental, and social systems (Global Water Partnership 2000). Contamination of the water resource leads to human health risks and affects ecosystem functioning, which adversely affects economic development.

Integrated water resources management is undertaken through collaborative and stakeholder-driven processes (Natural Resources Canada 2005). Land use planning processes are public processes that require input from subject area experts and concerned citizens. By linking water management, and groundwater vulnerability in particular, with land use management, an approach is created that can examine the spatial and temporal variations in land use scenarios as communities and ecosystems grow and change over time. This represents a shift from the current status quo where “water planning currently follows from decisions about land use and economic development” (Brandes and Brooks 2007:22). In linking water planning and land use planning together, decision makers can consider a set of scenarios and select a path that is most in line with the desired future of their community. In British Columbia, official community plans can incorporate policies specifically for water management and require that well-head protection plans, best management practices, and development permit areas are included as part of the permit approvals process. Groundwater vulnerability is by no means the only criteria of importance; to make balanced decisions for long-term water security, tradeoffs and consequences should be realistically considered and assessed to work within the complexity of human-natural systems. Vulnerability assessments are a key component of the integrated management of water resources. These assessments can help guide decision making about future development and the options available to protect and monitor the groundwater resource in the context of IWRM.

Vulnerability Assessments in British Columbia

Several large- and small-scale assessments of groundwater vulnerability have taken place in British Columbia. Table 3 presents examples of some of the vulnerability mapping projects undertaken and their use in water resource management. These examples show various motivations behind the initiation of the vulnerability assessment project and illustrate how vulnerability maps can be used in water management.

BC Aquifer Classification System

The British Columbia Aquifer Classification System (ACS; see detailed description on page 13 of this issue) was developed in 1994 as a means of providing:

1. a framework for directing detailed aquifer mapping and assessment;
2. a method of screening and prioritizing management, protection, and remediation over provincial to local levels;
3. identification of level of management and protection for aquifers;
4. an inventory of aquifers; and
5. increased public knowledge and understanding of groundwater resources (Kreye et al. 1994).

This system has been implemented across the province and has delineated over 900 aquifers since 1994. Once delineated, aquifers are assigned a classification and ranking value. The classification component includes an assessment of the level of intrinsic

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</tr>
</tbody>
</table>
Table 3. Selected vulnerability assessments in British Columbia.\textsuperscript{a}

<table>
<thead>
<tr>
<th>Location</th>
<th>Rationale</th>
<th>Approach (method)</th>
<th>Outcome (result)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraser Valley (Wei 1998)</td>
<td>Initiated from need to determine vulnerability of aquifers in province and to compare methods of assessing vulnerability in this area.</td>
<td>DRASTIC and AVI Indexing method of intrinsic vulnerability mapping</td>
<td>Use of vulnerability maps to compare nitrate concentrations in groundwater and evaluate differences between two methods. Both methods were found suitable for assessing vulnerability in the Fraser Valley.</td>
</tr>
<tr>
<td>Langley (Fraser Valley; Golder Associates 2005)</td>
<td>Initiated as part of regional Water Resource Management Strategy (WRMS). The WRMS was initiated to provide an established framework for managing water quality and quantity throughout the Township.</td>
<td>Aquifer Vulnerability Index (AVI) Indexing method of intrinsic aquifer vulnerability</td>
<td>Use of vulnerability map to inform future planning and development. Opportunity to couple with groundwater flow model</td>
</tr>
<tr>
<td>Gulf Islands (Denny et al. 2007)</td>
<td>Initiated because of history of groundwater studies on the Islands, of water scarcity in summer months, and of saltwater intrusion. Vulnerability mapping could help focus groundwater management on the Islands.</td>
<td>DRASTIC-Fm Indexing method of intrinsic aquifer vulnerability Fractured media parameter added to DRASTIC to account for local hydrogeological conditions (fault and fracture flow; Surrette and Allen 2008)</td>
<td>Use of vulnerability map in Official Community Plan on North Pender Island, and collaboration with Natural Resources Canada and Islands Trust to provide tools for understanding groundwater on Gulf Islands. Map released as a GSC Open File for public access (#5333), and included in a community atlas through the Canadian Parks and Wilderness Society (<a href="http://cpaws.org/files/atlas-gulf.pdf">http://cpaws.org/files/atlas-gulf.pdf</a>)</td>
</tr>
<tr>
<td>Oliver (Okanagan Valley; Liggett et al. 2006)</td>
<td>Initiated through collaborative sustainable development planning with Smart Growth on the Ground (Smart Growth on the Ground 2006). Process involved multiple stakeholders designing community priorities for future development. Water quality was identified as a key priority.</td>
<td>DRASTIC Indexing method of intrinsic aquifer vulnerability</td>
<td>Use of vulnerability map as layer in land use allocation model to provide scenarios of future development based on the priorities outlined by the community.</td>
</tr>
<tr>
<td>Vancouver Island (Liggett and Gilchrist 2009)</td>
<td>Initiated by regional health authority because of need for source water protection tools.</td>
<td>DRASTIC Indexing method of intrinsic aquifer vulnerability Large-scale application of methodology over all of Vancouver Island.</td>
<td>Potential use of vulnerability map in future land-use/water planning, source water protection, and development of guidelines and responses for vulnerability categories (e.g., high, medium, low).</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Aquifer vulnerability maps for the Gulf Islands, Okanagan, and southeast Vancouver Island will soon be available on the National Groundwater Database (http://ngwd-bdnes.ctis.nrcan.gc.ca/).
An example of the tag assigned to a particular aquifer is IIIA(15), where “III” indicates the level of development (low in this case), “A” indicates the level of vulnerability (high in this case), and “(15)” indicates the ranking value.

The ACS is designed for use as a screening tool to set groundwater management priorities in a standardized fashion at local, regional, and provincial levels (Kreye et al. 1994). It does not provide site-specific information, and the classification is generalized over the entire mapped aquifer. The mapping of aquifers is based on the availability of data, particularly water well data, and therefore not all areas have been mapped. Alternate methods of mapping vulnerability can be applied to areas already mapped with the ACS. Providing that sufficient data is available at a smaller scale, these methods (such as DRASTIC) may be able to show variations in vulnerability across a single aquifer mapped by the ACS. This allows the assessment of smaller-scale variations in vulnerability. Areas assessed as high vulnerability with the ACS may possibly appear as lower vulnerability when mapped using a different method on a smaller-scale, or vice versa. This is to be expected, especially since the study of a given area moves from a general, screening tool method, to more local, site-specific methods.

Conclusions

Groundwater vulnerability assessments provide a tool for highlighting areas where groundwater is more susceptible to contaminants introduced at the land surface. These assessments can vary from qualitative indexing methods to quantitative process methods, depending on the purpose of a study. Intrinsic vulnerability assesses the susceptibility of the receptor (e.g., water table, aquifer, or well) based on the natural properties of the land and subsurface; specific vulnerability also includes properties of a certain contaminant’s transport through the subsurface to the receptor. Responses guiding the level of assessment required in areas of “high” or “low” vulnerability can be developed and implemented at the community or regional level (e.g., for Oliver, see Liggett et al. [2006]; for the Gulf Islands, see Denny et al. [2007]; assessments for Vancouver Island are ongoing).

Additionally, vulnerability assessments can be incorporated within IWRM to bring groundwater protection within the fold of community growth and land use planning. In this way, groundwater vulnerability assessments could be consulted during official community plan reviews and other land use planning processes. The ongoing production and use of vulnerability assessments can contribute significantly to both water management and to heighten awareness of the issue of groundwater protection in British Columbia.

Acknowledgements

We are grateful to Diana Allen (Simon Fraser University), and Mike Wei and Kevin Ronneseth (BC Ministry of Environment) for their fundamental contributions to vulnerability mapping in British Columbia.

References


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Smart growth on the ground (Oliver, BC): www.sgog.bc.ca/content.asp?contentID=156

Well protection toolkit: www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/wells/well_protection/wellprotect.html

BC Aquifer Classification System: www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/Aq_Classification/Aq_Class.html


Vancouver Island vulnerability mapping website: http://web.viu.ca/gwaternuar/


LaMotte, A.E. and E.A. Greene. 2007. Spatial analysis of land use and shallow groundwater vulnerability in the watershed adjacent to Assateague Island National Seashore, Maryland and Virginia, USA. Environmental Geology 52(7):1413–1421.


Natural Resources Canada. 2005. Freshwater: The role and contribution of Natural Resources Canada. Strategic Policy Branch, Ottawa, ON.


The mountain pine beetle (MPB) infestation continues to expand in British Columbia's Southern Interior, raising concerns about the potential impacts on the region's water resources. To address this issue, FORREX and the Southern Interior Beetle Action Coalition (SIBAC) delivered a 1-day workshop in Kelowna on June 2, 2009. The primary audience was water purveyors who may have to deal with the potential downstream effects on water supply and treatment systems. A large number of community water systems in the Interior could incur increased treatment costs if water quality is degraded due to an MPB infestation; therefore, a critical need exists for water purveyors, as well as land managers, to understand the range of potential impacts that can occur. Although a number of recent publications synthesize the research on the effects of MPB and salvage harvesting (Winkler et al. 2008; Redding et al. 2009), extension efforts have not been directed towards the supply of safe drinking water. This workshop provided a more operationally oriented follow-up to the MPB and Watershed Hydrology workshop held in Kelowna in 2007 (Redding and Pike 2007).

Below we list the workshop presentation titles with reference to their respective summaries, which are available on the FORREX website (www.forrex.org/program/water/PDFs/Workshops/MPB_Handout.pdf).

Then we highlight some of the key points raised during the presentations and panel discussion, and outline information needs and results of the post-workshop evaluation.

Workshop Summary

Mountain Pine Beetle and Water Management: Workshop Summary

Todd Redding and Kevin Bladon

Overview Presentations

• The Mountain Pine Beetle Story: The Path of the Outbreak and Future Opportunities
  – Lorraine Maclauchlan, BC Ministry of Forests and Range (pp. 19–20)
• Mountain Pine Beetle and Watershed Hydrology
  – Rita Winkler, BC Ministry of Forests and Range (p. 21)
• Climate Change and Water in Western North America: Knowns, Unknowns, and Adaptation Strategies
  – Kathleen Miller, National Centre for Atmospheric Research (pp. 37–38)

Emerging Research Results

• Quantifying the Peak Flow Impacts of Mountain Pine Beetle and Salvage Harvest in the Fraser River Drainage
  – Markus Schnorbus, Pacific Climate Impacts Consortium (pp. 22–23)
• Effects of Mountain Pine Beetles and Timber Harvesting on Stand Attributes and Snow Hydrology
  – Pat Teti, BC Ministry of Forests and Range (pp. 24–25)
• Water Quality Related to Mountain Pine Beetle Infestation: A BC Regional Comparison
  – Sandra Brown, University of British Columbia (pp. 26–27)
Perspectives from Water Resource Managers

- Okanagan Community Watershed MPB–Hydrological Risk Assessment
  - Bill Grainger, Grainger and Associates Consulting Ltd. (pp. 28–29)
- MPB Impacts on Water Utilities and Potential Mitigation Strategies
  - Bob Hrasko, Black Mountain Irrigation District (p. 30)
- Impacts of the Mountain Pine Beetle on Community Water Supplies
  - Don Dobson, Dobson Engineering Ltd. (pp. 31–32)
- Duteau Creek Watershed Assessment and Protection Planning
  - Renee Clark, Regional District of North Okanagan (pp. 33–34)
- District of Lake Country Watershed Management
  - Jack Allingham, District of Lake Country (pp. 35–36)

Panel Discussion

“What critical issue of the mountain pine beetle infestation related to water resources will shape the future of impacted communities?”

Panel members:
- Rob Birtles (Interior Health Authority)
- Renee Clark (Regional District of North Okanagan)
- Geoff Kendall (Indian and Northern Affairs Canada)
- Markus Schnorbus (Pacific Climate Impacts Consortium)
- Dave Wilford (BC Ministry of Forests and Range)

Key Findings from Workshop Presentations and Panel Discussion

A common theme heard throughout the workshop presentations was that the death of pine forests following the MPB infestation may have effects on the quantity, timing, and quality of water from affected watersheds. This concern can be summed up with the phrase “more water, more quickly, more often.” The actual magnitude and direction of hydrological effects will depend on watershed characteristics and weather, as well as post-MPB forest management actions (salvage harvesting). “More water” refers to the potential for increased streamflow and groundwater recharge due to increased winter snowpacks and a reduction in evaporative losses to the atmosphere in beetle-affected stands. “More quickly” refers to the potential for earlier snowmelt due to increased radiation and more rapid streamflow response to melt runoff and rainfall as a result of altered hillslope flowpaths. “More often” refers to an increased frequency of streamflow events of a given size, relative to an undisturbed or unharvested watershed. Subsequent presentations supported the “more water, more quickly, more often” mantra, with the following key points noted by researchers for consideration by water resource managers.

- Snowmelt rates in salvage-harvested stands are greater than those in stands where dead pine are retained; this effect can persist for about 30 years.
- Model simulations indicate that peak flow magnitudes increase with the area of salvage harvesting.
- A regional study found little short-term influence of the MPB infestation on chemical water quality across the province, and that water quality concerns arising from the infestation are primarily related to forest management responses (e.g., road building and salvage harvesting).
- As water quality is degraded, treatment costs increase. This can be relatively more problematic for water systems that do not have back-up sources (e.g., off-line storage or groundwater sources) and a relatively low ability to install the required treatment infrastructure. For this reason, a multi-barrier approach to drinking water protection (source water protection through to treatment) is desirable.
- Water managers have very limited to no control (and potentially little input) on the land management activities that occur in the source water areas. This makes it difficult to ensure water quality stays high from the source to the tap. Therefore, it is important that water purveyors work closely with land and water management agencies and license holders conducting activities within the watershed to ensure that source water concerns are included in the management of upland water source areas.
- The MPB and salvage harvesting are not the only (or even primary) threats to water quality in community watersheds. Forest fire risk and the possible damage to stream channels and riparian zones by off-road vehicle enthusiasts and livestock are also concerns in maintaining clean water supplies.
• Within the Southern Interior, climate change has the potential to affect water quality through warmer water temperatures and, when combined with forest disturbance, increased nutrient loading to lakes and reservoirs, which can lead to algae blooms. These effects are expected to be greater at mid- and low-elevation reservoirs.

• First Nations’ water systems in the province are at considerable risk as the watersheds are outside reserve boundaries and capacity issues affect the operation of the water distribution and treatment systems.

• Uncertainty surrounds the post-infestation effects of forest regrowth on water supplies in the mid- to long term.

• Given the changes in land cover and climate, the assumption of stationarity in flood frequency is likely violated. This creates increased uncertainty about the planning and design requirements for a flood of a given return period (e.g., 1 in 100 year flood).

• Strategies must be developed to account for uncertainties related to climate change and disturbance; all land management and policy decisions should be:
  – robust to predictable changes,
  – resilient to surprising changes, and
  – adaptable to changing conditions and new information.

Continuing Information Needs
A number of continuing information needs were identified during the presentations and panel discussion and in the post-workshop evaluation survey. Strong support was evident for continued research into the effects of the MPB and salvage harvesting on water quantity and quality. Some of the more specific information needs identified included:

• Reduced uncertainty about the role of understorey and regeneration on hydrologic recovery
• How well do hydrologic models predict the potential effects and how can these models be linked with field research
• Given the potential interacting effects of MPB and climate change, what are the potential implications for low flows as forests regrow

Workshop Evaluation
Of the 79 workshop attendees, 44 (56%) completed the post-workshop evaluation survey, providing valuable information for the development of future events and extension products. Over 70% of survey respondents indicated that they had greater knowledge of the potential hydrological and water treatment effects of the MPB infestation and salvage harvesting after attending the workshop. Overall, the workshop was rated as good or excellent by 96% of the respondents. Several respondents suggested that a follow-up workshop be held within 2 years as the infestation starts to decline and more research results and operational case studies become available.

Sources of Further Information
The workshop handout with two-page summaries of each presentation is available at: www.forrex.org/program/water/PDFs/Workshops/MPB_Handout.pdf

In addition, video of selected presentations will be available on the SIBAC website (http://sibacs.com/).

Acknowledgements
The workshop was funded by SIBAC and the BC Ministry of Forests and Range through the Forest Investment Account–Forest Science Program. The workshop organizing committee included Kevin Bladon and Todd Redding (FORREX), Micky Werstiuk and Reiner Augustin (SIBAC), Dan Moore (UBC), Axel Anderson (Alberta Sustainable Resource Development), and David Scott (UBC Okanagan). The organizing committee thanks Gord Austin for assistance with event co-ordination and Kathie Swift for assistance during the event.

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References


Information Note

An Informal Survey of Watershed Model Users: Preferences, Applications, and Rationales

Sean W. Fleming

Introduction

If you ask 20 hydrologists for their opinions on watershed models, you are likely to receive 20 different answers. This seems a well-known trait of the watershed modelling community, but it is perhaps not so widely understood that the situation is somewhat unique to the discipline. Though intellectual diversity is healthy and indeed needed for science to progress, most other fields of science and engineering seem a little more unified and coherent in their modelling philosophies and tools. Consider the closely allied field of groundwater modelling, for instance. There is a consensus on how groundwater models should be constructed, such as agreement that models should in general solve a governing differential equation, and agreement on what that equation is. Differences between groundwater modelling packages lie instead with important, but strictly secondary, issues such as the specific numerical solution methods adopted (e.g., analytical vs. finite-difference vs. finite-element), additional physical complications accommodated (e.g., wetlands), or pre- and post-processing utilities or graphical user interfaces (GUIs). In contrast, fundamental modelling concepts and methods may be quite different between watershed models (e.g., IHACRES vs. SHETRAN). Further, there has been a remarkable proliferation of process-oriented watershed modelling packages, each representing a different tack on the problem.

The reason for this lack of a consistent view on how to model the transformation of meteorological forcing to streamflow seems straightforward. Such a tool is not a mathematical-computational representation of a process, but a representation of very many processes, both physical and biological; most of those individual constituent processes are themselves inherently difficult to model and/or constrain by data; and the operative, important processes vary from one region, and even one catchment, to the next. On top of this, watershed hydrology spans a wide range of goals, from fundamental scientific enquiry into the nature of the world around us to very practical, focused, applied questions. Each goal has its own set of requirements: a forest hydrology research model can afford to favour high detail over fast run times, for instance, whereas in general an operational river forecast model cannot. The net effect of all these considerations is a plethora of available models to choose from (e.g., Table 1 of Singh and Woolhiser 2002; see also Beckers et al. 2009a–c).

Making a selection from that smorgasbord of models can be challenging, and it is interesting and potentially valuable to see how water resource science and engineering professionals make these choices. To this end, a survey of model users was conducted, with the respondents asked to answer the following questions.

1. What process-oriented watershed model(s) have you used, or supervised the use of, in the course of professional employment work in the last 10 years?
2. To what end is/was this model(s) used?
3. What was the motivation in selecting that particular watershed model or set of models?

Methods

A number of multiple-choice answers to each question was offered in the survey questionnaire, but respondents were also encouraged to provide additional answers, if appropriate. Respondents were also able to provide more than one response to each question, and generally did so. Attention was restricted here to process-oriented watershed models; that is, models which explicitly attempt to represent deterministic system physics in some way, ranging from very simple bulk or semi-empirical parameterizations through to detailed numerical solutions of governing differential equations. Purely empirical (statistical, machine-learning, hydroinformatics, and/or soft-computing) methods were not considered here.

The survey questionnaire was emailed to a distribution list of nearly 200 professionals engaged in some aspect of watershed hydrology, with instructions to email answers directly back to the author and also to forward the survey to whoever else they thought might be appropriate.
Results
A reasonably good cross-section of hydrological professionals was obtained in the end, with a total of 47 responses received from both North America and Europe across three broad sectors: academia (24%); government, including government-owned corporations (47%); and the private sector (primarily consulting, 29%). Of the responses received, two were disqualified because they did not clearly address the specific questions posed in the questionnaire. The responses to the survey questions are summarized in Figures 1–3.

The survey is informal and not statistically rigorous, but nevertheless seems to provide some useful insights into community views. Some of the results might be expected, such as the popularity of very well-established modelling codes like HSPF, HBV, TOPMODEL, and HEC-HMS, or the importance of the physical suitability or reputation and track record of a model as reasons for its adoption. The survey thus succeeds in providing some tangible reinforcement for what one might have intuitively surmised. However, there are also a few surprises. For instance, although the great apparent popularity of the UBC Watershed Model is undoubtedly in part a survey artefact, reflecting the author’s geographic location and the partial subjectivity of the email list used in distributing the questionnaire, it also seems to speak to some genuine issues in model application, including:

- familiarity with a model
- a model’s local track record and reputation among project participants or stakeholders
- relative model parsimony (relatively simple structure and small number of parameters), speed of implementation, and applicability in the presence of very limited data
- having all major hydrological processes represented in the model (e.g., glacier melt contributions to flow for applications of the UBC Watershed Model in British Columbia).

Evidently these advantages can, in practice, far outweigh modernity, detail, or sophistication. Another result that may be surprising regards one of the uses to which models are put: although prediction in ungauged basins is of course an important research topic, the survey results suggest that it may be one of the most common types of watershed model application overall. Another interesting result is that what might be called “institutional”...
considerations or constraints (answers f, l, m, o, s, and t to Question 3) collectively amount to a full 21% of the responses, suggesting that issues which are essentially non-technical in nature can play an important minority role in model selection. This proportion increases to 27% if cost (answer i) is also included.

The survey questionnaire wrapped up by providing respondents with an opportunity to share any additional thoughts regarding what makes for a good and useful watershed model, and in what directions they might feel future watershed model development, support, and distribution should go. Roughly half the survey respondents answered this open-ended question. The answers were diverse, but some common threads emerged. Tying back to the issues raised in the introduction to this article, the concept of a single, universally correct model was rejected by most. Rather, answers to this final survey question stressed the following model attributes:

- suitability for purpose
- user support in the form of easy-to-use GUIs and good documentation
- captures main hydrologic processes for system under study
- physical transparency, including a clear correspondence between model parameters, physical hydrological processes, and predicted hydrograph dynamics
- parsimony, ease of calibration, and speed of implementation

**Conclusion**

In combination, these results provide guidance to hydrological scientists and engineers browsing the wares at ModelMart, as well as to those model developers who hold a genuine interest in producing software that is relevant to the user community. This current survey effort is informal and preliminary, and the results may also be used to motivate and guide the development of a more...
comprehensive and statistically reliable survey of watershed model users.

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References


Introduction
Predicting the effects of forest management on watershed processes and streamflow is a complex activity. Intricate linkages often exist between disturbances and consequences for an affected resource (e.g., Alila and Beckers 2001; Moore and Wondzell 2005; Pike et al. 2007). Models are increasingly used to investigate the potential effects of forest management on hydrologic processes and the resulting consequences to watershed values (e.g., Hudson and Quick 1997; Whitaker et al. 2002; Schnorbus and Alila 2004a; Alila and Luo 2007; Forest Practices Board 2007; Moore et al. 2007). To date, modelling efforts have been primarily limited to the research community, and the routine use of watershed models by resource managers and their consultants is not widespread. Because of the large scale and intensity of recent forest disturbances (e.g., mountain pine beetle) and the ramifications of climate change, a need exists to develop and apply models that will examine the potential effects on watershed function and that will support management decisions (Redding et al. 2009).

Several reviews of hydrologic models with an emphasis on the suitability for forest management or climate change have been conducted (e.g., Pike 1995, 2003; Whitaker et al. 1998; Alila and Beckers 2001; Hutchinson 2007; Pike et al. 2007; Werner and Bennett 2009). Nonetheless, resource managers currently lack clear methods to identify the hydrologic model most appropriate to answer their specific forest management questions. Such methods need to account for the physiographic and biogeoclimatic setting, the size of the modelled watershed, the forest management questions to be addressed, the time step (e.g., daily, monthly) at which model outputs are needed to answer these questions, and the required accuracy of the outputs to be balanced with potential constraints such as time (budget), expertise, and data availability.

This article (Part I) provides a review of hydrologic models that could be applied to assess the watershed-scale effects of forest management in British Columbia and Alberta. The accompanying article (Part II) focuses on the suitability of these models to assess changes in watershed processes under a changing climate. Both articles are based on a detailed report by Beckers et al. (2009) that reviews 30 hydrologic models. Only those models identified as promising for operational forest management applications are discussed here. In addition, the detailed report considers five model review criteria, but only three are covered in this summary. The two main review criteria (model functionality and complexity) are discussed below.
Continued from page 35

**Model Functionality**

When selecting a hydrologic model, it is important to consider its ability to simulate the desired land use, disturbance, or climate change scenario (Whitaker et al. 1998; Alila and Beckers 2001). A model should also quantify the complex linkages between water-related concerns and forest harvesting and roads. This functionality aspect of model selection is affected by the hydrologic processes represented in the model, the equations adopted to simulate these processes, and by model discretization (Kampf and Burges 2007).

Empirical models that use simplified relationships to describe watershed hydrologic processes typically have low data requirements. Although this characteristic may be useful in data-limited settings, it may also result in less accurate predictions when applied outside the conditions for which the empirical relationships were determined (i.e., under land use change or a changing climate). Depending on the study objectives and constraints, this limited accuracy may be adequate for numerous model applications. For example, in many situations, absolute changes in streamflow do not need to be quantified, or cannot be simulated because of a lack of data. In such instances, it may only be necessary (or practical) to conduct a sensitivity analysis into the likely (relative) response of watershed outputs to forest cover removal. However, in other situations (e.g., high-value or high-risk watersheds), it may be more important that the chosen model provides accurate results. Generally, physical models that utilize the governing mass and energy conservation equations to describe hydrologic processes in more detail are characterized by a higher intrinsic accuracy for predicting the effects of forest disturbance or climate change; however, these models also suffer from high data requirements, which potentially may lead to decreased accuracy in data-limited settings. Thus, tradeoffs between model accuracy and data requirements are often required when selecting a model for a particular application.

A user’s ability to analyze specific land use or climate change scenarios may be affected by the choice of a lumped, a semi-distributed, or a fully distributed model. For instance, lumped models, which do not account for variability in forest cover characteristics within a watershed, will have difficulty simulating the spatial patterns of forest management because locations of individual cutblocks cannot be represented. This is particularly important in mountainous terrain (Whitaker et al. 2003). For example, if only a fraction of the land area within an elevation band of a mountainous watershed was harvested, average parameter values would have to be set over this area to account for a mix of forest and clearcut conditions, which is not realistic (Whitaker et al. 1998). In some instances, however, lumped models are still useful when investigating the implications of various percent cut levels on watershed hydrology without considering the location of the actual cutblocks. Lumpened models are also useful in gently sloping terrain where variations in terrain elevation, slope, and aspect are less important for watershed hydrologic response to forest harvesting.

Fully distributed models are most flexible in accounting for the spatial patterns of forest management, because the location of cutblocks and roads in a watershed can be explicitly represented. Semi-distributed models offer intermediate qualities between the capabilities of lumped and fully distributed models. The grouped response unit (GRU) and hydrologic response unit (HRU) approaches offer greater ability for representing harvesting plans compared to the relatively rigid watershed division approaches, such as the use of elevation bands or sub-basins. Incorporating digital elevation models (DEMs) into semi-distributed and distributed models can help to calculate topographic factors, such as slope, contributing area, aspect, and shading in steep and complex terrain. These factors may be critical in determining the spatial distribution of snowmelt and evapotranspiration processes within a watershed. In addition, DEMs can be used with precipitation models and temperature lapse rates to determine the climatic conditions across a watershed.

Spatial scale is also an important factor to consider when looking at model functionality. Models differ in the scale of application depending on the way in which model architecture represents the physical watershed and its hydrologic processes. Some models are better suited to stand or small headwater watersheds (e.g., < 10 km²), others are limited to medium-sized watersheds (< 100 km²), and a few are limited watersheds greater than 500 km². Apart from spatial discretization, the time step at which model simulations are performed (i.e., temporal discretization) is also important. Some models can only run on a specific time interval (e.g., sub-daily, daily, or monthly). Temporal discretization may have important implications for the ability of models to provide outputs relevant to forest management (e.g., instantaneous peak flows), and for data availability and preparation (model complexity). For example, most climate stations report daily meteorological variables, such as temperature and precipitation, while physical models are often best run at sub-daily time steps.
Continued on page 38

Table 1. Model complexity evaluation criteria.

<table>
<thead>
<tr>
<th></th>
<th>Low complexity</th>
<th>Medium complexity</th>
<th>High complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data requirements</td>
<td>Monthly precipitation and temperature</td>
<td>Daily precipitation and temperature</td>
<td>Hourly to daily precipitation and temperature</td>
</tr>
<tr>
<td></td>
<td>No additional meteorological forcings required</td>
<td>Additional meteorological forcings may be required</td>
<td>Additional meteorological forcings may be required</td>
</tr>
<tr>
<td></td>
<td>No need for spatial data</td>
<td>Requires spatial data (DEM, soils, and forest cover)</td>
<td>Requires spatial data (DEM, soils, and forest cover)</td>
</tr>
<tr>
<td></td>
<td>Less than 25 parameters</td>
<td>About 25–75 input parameters</td>
<td>Typically over 75 input parameters</td>
</tr>
<tr>
<td></td>
<td>Parameters are experimentally based (no calibration required); models suitable for ungauged basins</td>
<td>Minimal number of calibration parameters; some models applicable to ungauged basins</td>
<td>Medium to high number of calibration parameters; models applicable to gauged basins only</td>
</tr>
<tr>
<td>Resource requirements</td>
<td>Low data preprocessing effort</td>
<td>Medium data preprocessing effort</td>
<td>High data preprocessing effort</td>
</tr>
<tr>
<td></td>
<td>Does not require GIS analysis</td>
<td>GIS analysis required for some models</td>
<td>GIS analysis required for most models</td>
</tr>
<tr>
<td></td>
<td>Can be completed by one person</td>
<td>Can mostly be completed by one person</td>
<td>May require project team</td>
</tr>
<tr>
<td>Time requirements (Costa)</td>
<td>Less than 2 weeks</td>
<td>About 2 weeks to 2 months</td>
<td>About 2–6 months</td>
</tr>
<tr>
<td></td>
<td>Less than $10 000</td>
<td>About $10 000–$40 000</td>
<td>From about $40 000 to more than $100 000</td>
</tr>
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a Cost estimates based on estimated time requirements: 40 person hours per week and a $100 hourly rate (hourly rate typical of intermediate-level consultant).

Model Complexity

Choosing a model of appropriate complexity is as important as the ability of the model to perform the desired land use or climate change scenarios. Beckers et al. (2009) define model complexity based on the estimated data, resources, and time (which is a proxy for cost) required to parameterize and calibrate a model (Table 1). The reviewed models were organized into three categories (Figure 1). Low-complexity models are typically useful for screening-level studies that seek to assess the sensitivity of watersheds to the effects of forest management without quantifying these effects in absolute terms. Medium-complexity models are typically useful for studies that seek to assess potential effects of forest management in somewhat greater detail and typically require a greater amount of data and some calibration (streamflow data only) to achieve this additional confidence.

The practical use of high-complexity models may be limited to complex, high-value or high-risk planning studies and for research purposes. Most of the 30 models reviewed by Beckers et al. (2009) fall into the high-complexity category; model selection options in the low- and medium-complexity categories are relatively limited.

Figure 1 highlights the tradeoff between model functionality and complexity. Easy-to-use models with low data requirements and high functionality for quantifying the effects of forest management under a range of circumstances currently do not exist. This has made it difficult to find suitable models that can be reliably applied in an operational setting. Many forested watersheds lack data, which may force the selection of a lumped and/or empirical model. When more detailed results are needed, a fully distributed and/or physically based approach may be required, and it may be necessary to collect the detailed data to apply the model with sufficient confidence. In practice, medium-complexity models often provide the best tradeoff between data availability and functionality to address forest management issues; however, the models reviewed generally employ a lumped or semi-distributed watershed discretization, and this will affect the ability of simulations to account for the location of cutblocks and roads in a watershed.

Model Selection

Selecting an appropriate model for a particular forest management application is a complicated process that will depend on the study objectives and constraints. Site-specific, tailor-made model approaches are therefore...
needed (Savenije 2009) and allowing for proper lead time in planning a model study is critical.

Beckers et al. (2009) outline a six-step model selection process, with each step supplemented by summary tables to provide decision support. These steps are:

1. Use data, time, and resource constraints to determine an appropriate model complexity.
2. Select the top-ranked model in the chosen model complexity category using Figure 1.
3. Assess whether the model can address the forest management question(s) of interest.
4. Confirm that the model can be applied to the climate, physiography, and scale of interest.
5. Determine whether the model will generate the required outputs to support assessment at the appropriate planning scale and time scale.
6. Consider the main advantages and disadvantages of the selected model(s) and conduct a detailed review of the model (Appendices 1 and 2 in Beckers et al. 2009) to ensure that the selected model is appropriate.

Selection steps 1 to 3 revolve around model complexity and functionality considerations. If an inherent conflict exists between modelling constraints and project expectations (e.g., a model study for a high-value watershed is initiated with little or no data available), then a suitable model will likely not be identified. As such, it is important to identify the project’s expected outcomes early in the process (e.g., through stakeholder consultation) and to align data, time, and available resources accordingly. Alternatively, if it is impossible to alleviate modelling constraints, project expectations may require revision. It is also incumbent on the study proponent to clearly communicate modelling limitations to resource managers and stakeholders to avoid unrealistic expectations on what the model can provide. For instance, managers or stakeholders may view the model outputs as absolute whereas potential watershed sensitivities to forest management can often only be assessed with relatively large confidence margins. This gap in expectations versus model performance is frequently responsible for inappropriate model selection and may lead to loss of faith in the value of hydrologic modelling.

Step 4 considers the ability of models to:

- simulate rain-dominated, snowmelt-dominated, mixed/hybrid, or glacier-augmented watersheds (Eaton and Moore 2007);
- simulate various terrain types (mountainous versus undulating or flat);
- simulate processes that may be watershed-specific (e.g., groundwater, frozen soils, lakes and wetlands); and
- simulate watersheds of various sizes (small, medium, or large).

Determining an appropriate watershed application scale depends on the model, data, and computing power, and most often requires professional judgement. For example, models without a channel routing component should normally be applied only to stand-level water balance questions or small watersheds with first-order streams for which streamflow can be calculated as the sum of all runoff components (“water balance models” in Table 2). In contrast, the Variable Infiltration Capacity (VIC) model can only be applied to relatively large watersheds (2500 km² or greater) to assess the cumulative effects of large-scale disturbances. The VIC model is therefore unsuitable for typical forest management applications, but is useful for answering research questions and developing broad land use policy. The BC Ministry of Environment River Forecast Centre and the Pacific Climate Impacts Consortium have applied the VIC model to assess the effects of mountain pine beetle for the Fraser River basin (Schnorbus et al. 2009).

The model output assessment criteria considered by Beckers et al. (2009) for ranking of all models considered in the study.
al. (2009) in Step 5 were based on the data required to inform forest management decisions including (but not limited to) flood hazards, aquatic habitat, water availability, and potential for wetting up of sites. The ability of models to inform such decisions was linked to the following output capabilities: full hydrograph, annual yield, peak flow, low flow, snow water equivalent (snow cover), evapotranspiration, water balance (for soil column and/or watershed), soil moisture, soil infiltration, water table position, overland flow, shallow subsurface flow, macropore (preferential) flow, groundwater flow (baseflow), basin total runoff, and road flow.

Table 2, which corresponds to Step 6, reviews the general advantages and disadvantages of each model in an operational forest management context. Although model selection is often a site-specific process, this review should help resource managers to narrow down the choice of an appropriate model. This table focuses on those models identified as most promising for operational forest management applications (Beckers et al. 2009) as determined by considering model functionality and complexity.

### Low-complexity Models
In the low-complexity category, only a single model is available (Figure 1): the WRENSS procedure (US Environmental Protection Agency 1980) and its companion models WinWrnsHyd (Swanson 2005) and ECA-AB (Equivalent Clearcut Area – Alberta; Silins 2002). In Alberta, WRENSS and ECA-AB have proven useful to evaluate existing and future forest harvesting effects on annual water yields. These models have low data requirements, are easy to use, and allow quick evaluation of deviations from the average annual water yield under different forest management scenarios (area harvested and forest regrowth); however, modelled output is restricted to annual yield, water balance, and evapotranspiration. The WinWrnsHyd model may have some untested use for assessing changes in peak flows. Potential limitations with the model outputs include an inability to simulate absolute streamflow values, instead providing relative changes in annual streamflow due to harvest regimes.

### Medium-complexity Models
The short-listed models in the medium-complexity category include UBCWM, BROOK90, ForWaDy, and the Dominant Runoff Process based Peak Flow Model (DRP-PF-Model) (Figure 1). A summary of the suitability of these models for answering forest management questions follows.

Continued on page 40
The UBCWM model (Quick et al. 1995) is likely the preferred model for use in mountainous terrain and in settings where glacial melt or upland lakes are present. However, its simplified representation of forest cover and its use of elevation bands limit its ability to simulate spatially explicit forest management scenarios (Alila and Luo 2007). Nevertheless, it can be used with a companion routing model (UBC Flow Model) to examine sub-watershed flows (M. Schnorbus, pers. comm., 2009), allowing the simple modelling of the response of large, heterogeneous watersheds as an amalgamation of sub-watersheds connected by a routing network.

The BROOK90 model (Federer et al. 2003) is likely the preferred one for use in gradually sloped terrain unless it is important to model rain-on-snow processes or forest growth. For the latter, the ForWaDy model (Kimmins et al. 1999) may provide a viable alternative. The main limitation of both models is the lack of a channel routing routine, which restricts model application to water balance simulations at the forest-stand level or for small watersheds with no subbasins. Peer-reviewed publications that test the ForWaDy model against field data are currently lacking.

The DRP-PF-Model is being developed under the lead of Dr. M. Weiler at the University of Freiburg, Germany. The model represents an innovative approach to assessing peak flow changes due to forest disturbances. The model uses readily available spatial and climate data to address issues resulting from the limited specific data available for most British Columbia forested watersheds where operational decisions are required. The DRP-PF-Model can be used to assess effects of roads in a simplified fashion, and it is fully distributed and can be applied to large watersheds—capabilities currently not contained in any of the other models in the medium complexity category. Its functionality, however, is limited mainly to peak flows, and as the model is currently under development, it has only been subjected to limited testing (Weiler et al. 2009).

With the exception of the DRP-PF-Model, all models in the medium-complexity category are lumped or semi-distributed, which potentially restricts their ability to account for the spatially explicit aspects of forest management plans or to handle the intricacies of snowmelt processes in complex terrain. None of the models can provide output at sub-daily time steps, which may be important for simulating peak flows. These models are also inadequate to address road construction and management. The DRP-PF-Model offers a simplified, but untested, approach to the incorporation of road effects. None of the models can be applied to medium-sized watersheds in gently sloping terrain, and none has the ability to represent multi-layered forest vegetation (e.g., overstorey canopy and understory shrub). These numerous limitations may be important in certain operational settings and can only be overcome by applying suitable higher-complexity models.

High-complexity Models

Within the high-complexity category, the most promising models include DHSVM, RHESSys, WaSIM-ETH, and CRHM (Figure 1). A summary of the suitability of these models for answering forest management questions follows.

The DHSVM (Wigmosta et al. 2002) is likely the preferred one for use in mountainous terrain. In research applications, the DHSVM has been applied to forested watersheds and forest management questions in British Columbia (e.g., Whitaker et al. 2002, 2003; Schnorbus and Alila 2004a; Thyer et al. 2004; Beckers and Alila 2004; Forest Practices Board 2007). However, only limited efforts have been paid to make the model user-friendly. Furthermore, the model is most suitable for steep mountainous watersheds.

The RHESSys model (Tague and Band 2004) has capabilities not offered by the DHSVM through the incorporation of simple groundwater flow and eco-hydrological processes, such as forest growth and mortality; however, with a daily time step, the RHESSys is not suitable for simulating instantaneous peak flows or diurnal fluctuations in meteorological conditions.

The WaSIM-ETH model (Gurtz et al. 1999) offers a number of advantages over both the DHSVM and RHESSys models including the possibility of a rigorous treatment of groundwater processes, glacier and lake components, and channel routing that accounts for reservoirs and lakes. The main drawback is that the model components specific to...
forest hydrology (e.g., forest canopy interactions with precipitation) have not been tested.

The CRHM (Pomeroy et al. 2007) was specifically developed for prairie, tundra, and boreal forest settings, with corresponding consideration for cold region watershed processes (e.g., blowing snow, frozen soils). Within a forest management context, the CRHM may therefore be applicable to boreal forest settings in Alberta and British Columbia. The main limitation of this model appears to be the basic streamflow routing routine, which constrains applicability to small- or medium-sized watersheds.

Compared to the medium-complexity models, the above models offer a wider range of capabilities for answering forest management questions in Alberta and British Columbia when the greater demands on data, time (budget), and resources (GIS, model calibration, etc.) can be overcome.

Advancing the Operational Use of Models

Many questions related to the role of roads in watershed hydrology or the effect of changing the location of cutblocks in a watershed can only be realistically addressed with high-complexity models that require considerable data, time, and resources to set up and operate. Flexible models that can account for the spatial aspects of forest management and that better recognize and minimize tradeoffs between functionality and complexity need to be formulated. Until such models are developed and tested, it may be necessary to create an environment in which high-complexity models can be routinely, reliably, and consistently applied.

User Knowledge and Education

An intermediate-to senior-level professional with an advanced knowledge of disturbance effects on watershed processes is generally required to confidently apply most of the models reviewed here. Currently, only a few professionals and practitioners in western Canada are trained to properly apply hydrologic models or to adequately interpret the model output, including associated assumptions and limitations. Conversely, many hydrologic and groundwater modelers have backgrounds as engineers, geographers, or earth scientists, disciplines that often do not provide a strong understanding of forest hydrology and forest management. Interdisciplinary training in all of the above subjects is therefore needed.

Model Comparisons

Comparisons of model performance using experimental watershed data are needed. Additional tests should be designed to simulate the ways models would be run operationally, such as in settings in which only streamflow data is available (Klemes 1986). This would provide insights into the transferability of model parameters and into the potential accuracy issues that might arise when applying models in areas with limited data. This would help improve the consistency of model application at sites with insufficient data, including un-gauged basins. The resulting information about appropriate model parameterization and the transferability of these parameters might be incorporated into databases that could be readily accessed by model users. Compilation and maintenance of these databases may require an effort at the federal and/or provincial government level.

Model Uncertainty

When models are used to guide forest management decisions, managers or clients may view the model outputs as absolute. To avoid this potential misconception, study proponents should provide an estimate of the uncertainty in model outputs and communicate this uncertainty to end-users of the model results (Ivanovic and Freer...
Until better models are developed or existing models are improved, hydrologic modelling for operational forest management purposes needs to employ best practices that recognize tradeoffs between model functionality (accuracy) and complexity.

Better, more informed, decisions can be made when model uncertainties and limitations are known. Several methods that quantify model uncertainty (e.g., Monte Carlo simulations) take into account the confidence bounds of key model parameters; however, use of such techniques in an operational context is not widespread. To maximize the value of model results to the end-users, users should employ available methods to calculate uncertainty in the results and communicate it to managers.

Need for Better Models, Graphical User Interfaces, and Model Support
A few hydrologic models have been developed specifically with forestry applications, but most are not user-friendly and technical support is typically lacking unless special arrangements are made. Therefore, commercial software needs to be developed along with the associated increased availability of model support. Also required is the development of flexible modelling approaches that can be tailored by the user on a site-specific basis to better recognize and minimize tradeoffs between functionality and complexity (Savenije 2009). A few of the models reviewed here are linked to graphical user interfaces (GUIs) to facilitate model setup. This capability needs to be expanded to include more hydrologic models. Integration of GUIs with common databases (e.g., climate, forest cover, soils, and topography) could simplify model parameterization for watersheds with limited data. With such developments, GUIs could help ensure that models are consistently and appropriately applied and could enable comparisons of results from different watersheds.

Policy and Professional Precedents
Forest hydrology modelling is still generally confined to academic institutions with the resulting lack of policy and professional precedents (i.e., a case history of operational watershed hydrologic modelling studies). Therefore, forest managers and other end-users have little direction in deciding which models are appropriate for answering forest management questions, and under what conditions. The information provided here is a first step toward alleviating this knowledge gap, and model comparisons at experimental watersheds would provide further insight. This information could be used to provide either policy or soft guidance for model application to address forest management issues. It should clarify expectations about model selection, application, and calibration, and the associated reporting requirements. Providing this type of guidance will likely involve provincial and/or federal governments and multiple professional associations.

Conclusions
This review has summarized the capabilities and limitations of a broad range of hydrologic models for potential use in operational forest management in British Columbia and Alberta. It is important to realize that there is no “best” model—that is, one that is easy to use, has low data requirements, and can be applied with a high degree of confidence under all circumstances. Until better models are developed or existing models are improved, hydrologic modelling for operational forest management purposes needs to employ best practices that recognize tradeoffs between model functionality (accuracy) and complexity. To avoid unrealistic expectations of model capabilities and accuracy, study proponents should also clearly communicate modelling limitations (e.g., assumptions, uncertainty in results) to decision makers.

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Hydrologic Models for Forest Management Applications: Part 2: Incorporating the Effects of Climate Change

Jos Beckers, Robin Pike, Arelia T. Werner, Todd Redding, Brian Smerdon, and Axel Anderson

Introduction

In Alberta and British Columbia, several detailed studies of climate trends, future climate predictions, and potential effects on hydrology have been conducted (e.g., Rodenhuis et al. 2007; Pike et al. 2008a, 2008b; Sauchyn and Kulshreshtha 2008; Walker and Sydneysmith 2008). These studies indicate that a changing climate will alter watershed processes, which in turn may affect many aspects of short- and long-term watershed management. From an operational perspective, watershed-scale hydrologic models could be used to address a range of forest management uncertainties not limited to the assessment of future growing conditions, permanence of wetlands and small streams, and potential changes to flooding, low flow, and other disturbances (Pike et al. 2008b). However, using current hydrologic models to address such complex questions is expected to pose a number of challenges due to the inherent limitations of these models and data inadequacies that exist across British Columbia and Alberta.

The accompanying article (Part I) summarizes the results of a comprehensive review of hydrologic models applicable in a forest management context in British Columbia and Alberta (Beckers et al. 2009). This article (Part II) highlights the specific qualities required in a hydrologic model for climate change applications in a forest management context, reviews the suitability of several currently available models, and discusses suggested improvements for climate change and forest management applications.

Background

Our climate change review focuses on the nine short-listed models in Part I that were identified as suitable for addressing forest management questions. These included low complexity (WRENSS), medium complexity (UBCWM, BROOK90, ForWaDy, and DRP-PF-Model) and high complexity (DHSVM, RHESSys, WaSiM-ETH, and CRHM) models. Full model names and references are provided in Part I and in Beckers et al. (2009).

Pike et al. (2008b) discussed eight high-level hydrologic implications of climate change, including:

1. Increased atmospheric evaporative demand;
2. Altered vegetation composition affecting evaporation and precipitation interception;
3. Decreased snow accumulation and earlier melt;
4. Accelerated melting of permafrost, lake ice, and river ice;
5. Glacier mass balance adjustments;
6. Increased stream and lake temperatures;
7. Increased frequency or magnitude of disturbances; and
8. Altered streamflow.

Associated with each of these are specific processes (e.g., evapotranspiration), watershed outputs (e.g., timing and magnitude of peak/low flows, stream temperature), and other factors (e.g., growing conditions for trees, wildfire risk) that could be affected by anticipated shifts in meteorological and hydrological conditions. These processes, associated model inputs, watershed outputs, and other factors must therefore be present in hydrologic models to enable the investigation of climate change questions in a forest management context (Table 1).

The development of the model review criteria listed in Table 1 builds on the ranking of model functionality for addressing forest management questions (see Part I), and thus puts specific emphasis on those watershed processes, outputs, and factors whose interactions with forestry activities may be exacerbated by climate change. The sections below discuss...
suggested model improvements and other barriers that should be addressed to better quantify the possible effects of climate change. These discussions are organized by the eight broad hydrologic implications of climate change outlined above.

**Increased Atmospheric Evaporative Demand**

Evaporative demand is a function of air and surface temperature, solar radiation, humidity, and wind speed (Moore et al. 2008). Current climate scenarios indicate a potential increase in the atmosphere’s ability to evaporate water (Huntington 2008; Spittlehouse 2008). This will occur if the saturated vapour pressure of the air (a function of air temperature) increases more rapidly than the actual vapour pressure (i.e., the vapour pressure deficit increases). It will also increase if net radiation and wind speed increase (Pike et al. 2008b).

Increases in atmospheric evaporative demand may significantly affect water resources through greater evaporative losses from water bodies and changing water demands (Pike et al. 2008b). Incorporation of these weather variables in calculating reference evapotranspiration is therefore critical in assessing the potential consequences of increased evaporative demand due to climate change (Table 1).

Across the reviewed models, the greatest level of confidence in results should be provided by physically based approaches to calculating evapotranspiration, such as those employed in BROOK90, ForWaDy, CRHM, DHSVM, RHESSys, and WaSiM-ETH (Table 2). This is because physically based equations are not derived from historical data, as are empirical methods, and are thus better suited for predicting possible shifts in hydrologic responses outside historical ranges. Many of these models employ the Penman-Monteith equation, which is recommended by the Food and Agricultural Organization (FAO) of the United Nations and the American Society of Civil Engineers (ASCE) to determine reference evapotranspiration (Allen et al. 2005).

Although the theoretical understanding of suitable equations for calculating reference evapotranspiration is advanced, the main challenges in anticipating future increases in evaporative demand arise from a lack of understanding about possible changes in temperature, solar radiation, humidity, and wind speed. Projections of future climate change have focused primarily on analyzing and downscaling mean temperature and precipitation outputs from Global Climate Models (GCMs). Relatively little work has been done to extract and analyze the remaining variables, or to find adequate methods for downscaling data into formats suitable for use in hydrologic models, such as to point locations (representative of meteorological stations) or to high-resolution grids. Thus, improved methods need to be developed to downscale solar radiation, humidity, and wind speed from GCMs for use in hydrologic models.

### Table 1. Climate change model evaluation criteria.

<table>
<thead>
<tr>
<th>Hydrologic implication of climate change</th>
<th>Model evaluation criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric evaporative demand</td>
<td>• Solar radiation, humidity, and wind speed</td>
</tr>
<tr>
<td>Altered vegetation composition affecting evaporation and interception</td>
<td>• Leaf area index, stomatal resistance, forest growth (productivity), forest survival (mortality), temporal input control</td>
</tr>
<tr>
<td>Snow accumulation and melt</td>
<td>• Physical/analytical snowmelt equations, rain-on-snow simulation</td>
</tr>
<tr>
<td>Permafrost, river and lake ice</td>
<td>• Frozen soil influence on water movement, river and lake ice model component</td>
</tr>
<tr>
<td>Glacier mass balance adjustments</td>
<td>• Glacier melt model component</td>
</tr>
<tr>
<td>Altered streamflow</td>
<td>• Groundwater, lakes, wetlands, water consumption (water supply systems)</td>
</tr>
<tr>
<td>Stream and lake temperatures</td>
<td>• Water temperature model component</td>
</tr>
<tr>
<td>Increased frequency/magnitude of disturbances</td>
<td>• Channel routing (floods), multiple vegetation layers (wildfires, pests), vegetation albedo (wildfires, pests), soil albedo (wildfires), hydrophobicity (wildfires), landslide simulation</td>
</tr>
</tbody>
</table>
Table 2. Climate change model ranking.

<table>
<thead>
<tr>
<th>Model evaluation criteria</th>
<th>Model complexity</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WRENSS</td>
<td>BROOK90</td>
<td>ForWaDy</td>
</tr>
<tr>
<td>Radiation, humidity, wind speed</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Leaf area index</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Stomatal resistance</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Forest growth (productivity)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest survival (mortality)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temporal input control</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Physical/analytical snowmelt</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mixed rain/snow processes</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Frozen soil/permafrost</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>River and lake ice</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Glacier melt</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Stream temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Lakes</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wetlands</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water consumption</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Channel routing (floods)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Multiple vegetation layers</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Vegetation albedo</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Soil albedo</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hydrophobicity (wildfires)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landslide simulation</td>
<td></td>
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</tr>
</tbody>
</table>
**Altered Vegetation Composition Affecting Evaporation and Precipitation Interception**

A changing climate likely will reduce water availability (soil moisture) in some areas during parts of the year, which in turn may affect forest productivity (growth), species survival (mortality), and promote changes in age-class distribution and the composition of vegetation (Gayton 2008; Pike et al. 2008b). Issues surrounding forest growth and mortality must be carefully considered when applying hydrologic models for planning purposes (Table 1), as they can affect many aspects of forest management, and may influence hydrologic recovery and decisions regarding tree species selection following harvest. Furthermore, when conducting long-term model simulations and harvest planning in the context of climate change, it may be important to determine whether the model input can be easily adapted to represent gradual or abrupt changes in vegetation composition that might occur during the time period of interest. The ability of a model to allow for time-varying vegetation properties within a single model simulation (i.e., the ability to change properties without having to re-start the model) is referred to as “temporal input control” (Table 1).

The amount and type of vegetation and physiological characteristics likely will have an important effect on site water balance (Pike et al. 2008b). The interaction between vegetation and the atmosphere (i.e., evapotranspiration, precipitation interception) is determined by vegetation surface area (Monteith and Unsworth 1990; Shuttleworth 1993), typically represented as leaf area index (LAI). The LAI is also a primary reference parameter for plant growth. Thus, within a climate change context, explicit representation of vegetation (e.g., LAI) is a critical model parameter to describe forest characteristics, and potential effects of episodic or long-term changes.

Stomatal resistance (or the inverse, stomatal conductance) is another crucial parameter (Table 1) that is used to calculate vegetation transpiration rates from humidity (vapour pressure) gradients (Monteith and Unsworth 1990). Stomatal resistances vary between vegetation species and therefore are an important physiological parameter to assess the effect of vegetation on site water balance. Furthermore, the ability of models to simulate the closing of stomata (i.e., an increase in stomatal resistance) when atmospheric water demand exceeds water availability is the primary mechanism to assess plant response to drying conditions. Therefore, inclusion of multi-layered vegetation and associated vegetation parameters can be an important quality for a hydrologic model to possess.

Of the models reviewed, only RHESSys is able to account for forest mortality and forest growth (Table 2) through the inclusion of the BIOME-BGC sub-model (Running and Hunt 1993) to allocate carbon and nitrogen to leaves, roots, and stems that make up plant biomass (Tague and Band 2004). Temporal input control to allow for dynamic vegetation changes during the course of a single model run is also lacking in most of the models reviewed (Table 2). However, LAI and stomatal resistance are represented in some of the models. To improve the ability of hydrologic models to simulate the hydrologic effects of altered vegetation composition, suggested model improvements include:

- Adapting watershed models to include forest growth and mortality simulation capability or linking existing models to forest productivity and growth models.
- Adding temporal input control to some models.
- Overcoming the difficulty of applying models developed for humid or sub-humid conditions to produce acceptable results in more arid climates (e.g., Pike 1995; Tague et al. 2004). The current inability of these models to accurately account for semi-arid conditions may lead to a bias in evapotranspiration estimates.

Further to these model improvements, a need exists to:

- Survey current vegetation across British Columbia and Alberta to produce spatially explicit vegetation data sets that include up-to-date LAI and stomatal resistance information.
- Further research and refinement of predictions of future vegetation composition in both provinces. Physiological characteristics of future vegetation, such as LAI and stomatal resistance, require research and cataloguing in databases for use in physically based models.

**Decreased Snow Accumulation and Accelerated Melt**

Increased air temperatures as a result of climate change will likely lead to a decrease in snow accumulation, earlier melt, and less water storage for spring freshet and/or release to groundwater storage (Whitfield et al. 2002; Merritt et al. 2006; Rodenhuis et al. 2007; Sauchyn and Kulshreshtha 2008; Walker and Sydneysmith 2008). For long-term simulations, hydrologic models may have to initially represent predominantly nival conditions that become hybrid (mixed) conditions, or perhaps even pluvial over a single model run. Additionally, changes in the form of precipitation (rain or snow) in the late fall or early spring may become increasingly important factors to simulate. As such, the ability of hydrologic models to accurately model mixed regimes (e.g., rain-on-snow energy transfer) can be crucial. Snowpack accumulation and snowmelt are also important factors for other water balance components as these relate to albedo and snow-covered versus bare ground. Where models do not accurately capture the spatial extent of snow, errors can occur in estimating snowmelt contributions to streamflow or in predicting the onset of transpiration.
Models with physically based or analytical (temperature-radiation) snowmelt routines are better suited to predict the potential for accelerated melt under a changing climate than empirical models (Table 1). In our review, the CRHM, DHSVM, ForWaDy, RHESSys, UBCWM, and WaSiM-ETH models were found to be better suited in addressing climate change effects on snow accumulation and snowmelt compared to approaches employed by BROOK90, the DRP-PF-Model, and WRENESS (Table 2). While an understanding of the assumptions and limitations of various snowmelt calculation methods is relatively well advanced, continued research is needed on temperature and precipitation shifts and associated changes in snow accumulation and melt patterns across British Columbia and Alberta.

Accelerated Melting of Permafrost, Lake Ice, and River Ice
Rising air temperatures will affect ice-related watershed processes. Projections of milder winter temperatures mean that river and lake ice could develop later and disappear earlier than normal. Data suggests this has happened over the last century in British Columbia and other parts of Canada (Duguay et al. 2006; Rodenhuis et al. 2007). Permafrost can also be expected to respond to changes in temperature and precipitation (Pike et al. 2008b). These changes will have important implications on forest harvest scheduling (operable ground, seasonal water tables), terrain stability, and transportation (e.g., ice bridges). Permafrost thaw may also lead to altered soil nutrient cycling, carbon storage, and changes in vegetation distribution (Jorgenson et al. 2001). Depending on model application, the ability to simulate some or all of the above processes may be an important consideration when selecting a watershed model (Table 1).

River and lake ice formation and break-up processes are often the focus of specialized kinematic models (e.g., Beltaos 2007) that are not typically incorporated in watershed-scale hydrologic models (Table 2). Soil temperatures, however, are more widely accounted for in watershed models, typically to calculate the ground heat flux component of the snowpack energy balance (e.g., Wigham et al. 1994). Only the CRHM (Pomeroy et al. 2007) has the ability to assess frozen soil conditions (via soil temperatures) and associated effects on water movement (Table 2). The following general modelling improvements are therefore suggested.

- Improving the ability of hydrologic models to simulate the effects of permafrost thaw on hydrological processes applicable to the northern portions of British Columbia and Alberta and other areas where permafrost occurs. Frozen soil conditions may also be important to model in non-permafrost areas (i.e., effects on infiltration).
- Improving our understanding of how climate change will alter the three-way interaction between streamflow generation, water temperatures, and river and lake ice formation and break-up.
- Developing tools that allow resource managers to assess the importance of these interactions (and how they may change in the future) for forest management.

Glacier Mass Balance Adjustments
Recent studies have shown that glaciers throughout British Columbia and contiguous parts of Alaska are dominantly losing mass (Stahl et al. 2006; Rodenhuis et al. 2007; Stahl et al. 2008; Moore et al. 2009). For Alberta, a particular concern is more frequent reductions in water availability on the eastern slopes of the Rocky Mountains (Byrne et al. 1989; Demuth and Pietroniro 2002). In the long term, the reduction or elimination of the glacial melt water component in the summer/early fall will decrease streamflow volumes potentially affecting aquatic habitat and water availability. A number of geomorphological implications of glacier changes also exist, including: moraine-dam outburst floods, de-buttressing, and rock slope failures and jökulhlaups. Thus, for some watersheds, the ability to simulate changes in glacial melt contribution to streamflow may be critically important (Table 1).

Glacial processes are represented in WaSiM-ETH and UBCWM (Table 2) as these models can simulate increased melt rates due to climate change. However, to conduct long-term simulations it is also necessary that glacier mass balances are calculated and that glacier areas/volumes are adjusted (i.e., to simulate glacial retreat). This capability was specifically developed by Stahl et al. (2008) in HBV-EC and likely could be adapted or incorporated into other hydrologic models. Alternatively, stand-alone glacier mass balance models could estimate future glacier volume, which is a useful input to hydrologic models with glacier processes, such as WaSiM-ETH and UBCWM.

Increased Stream and Lake Temperatures
Stream and lake temperatures are projected to increase due to climate change, which could result in a number of specific concerns for water supplies and aquatic ecology. The effects of increased water temperatures will likely be compounded in areas where streamflow changes result in reduced seasonal flows (Pike et al. 2008b) (Table 1).

Models to predict stream temperatures fall into two general classes (Sridhar et al. 2004):
1. empirical relationships based on observations of stream temperature and stream properties (such as discharge, channel geometry, and streamside vegetation characteristics); and
2. models that represent the energy balance of the stream.

Recently, the use of physically based models to predict stream temperature has become feasible through interfacing with GIS methods.

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While numerous models have been developed to predict stream temperature (Webb et al. 2008), none of the hydrologic models reviewed here possesses this capability (Table 2). This limits the ability of resource managers to account for possible interactions between shifts in surface water flows or vegetation, and stream temperature due to a changing climate. To improve future stream temperature simulations, existing watershed models could be adapted to spatially simulate stream temperatures.

**Increased Frequency or Magnitude of Disturbances**

Storm frequency and intensity are projected to increase (Rodenhuis et al. 2007), likely increasing flooding hazards (Table 1). Watershed scenario modelling can be used to assess the suitability of current infrastructure (e.g., stream crossings) under potential future climate conditions and/or to determine the suitability of engineering design criteria. In some rain-dominated regimes, the ability of watershed models to examine such questions may depend on the accurate simulation of preferential runoff mechanisms (e.g., Carnation Creek on Vancouver Island; Beckers and Alila 2004). In snow or mixed regimes, accurate simulation of melt rates is important for predicting peak flows (e.g., Redfish Creek in southeast British Columbia; Schnorbus and Alila 2004).

Other forest disturbances that are projected to increase include wildfire, forest pests (insects), windthrow, breakage of trees, and landslides (Pike et al. 2008b). Of these disturbances, the modelling of landslides provides a clear synergy with watershed simulation (Table 1). Landslide modelling has been the focus of specialized physically based slope stability models such as dSLAM (Wu and Sidle 1995) and IDSSM (Dhakal and Sidle 2003), and more recently has been incorporated in the DHSVM (Doten et al. 2006; Table 2).

In contrast, specialized windthrow models (e.g., Languay and Mitchell 2005) currently offer minimal synergies with watershed modelling. This lack of synergy also holds true for predicting the occurrence of pests. However, it is critically important that hydrologic models incorporate (as inputs) the changes in physical watershed characteristics which may occur as a result of these forest disturbances. For example, an important aspect related to tree mortality is the change in canopy albedo (Table 1), which in turn affects the radiation energy balance of affected stands, especially as related to snow accumulation and snowmelt processes.

Forest fires also cause vegetation changes that, depending on fire behaviour, may include the removal of understory vegetation without canopy disruption or full combustion of the overstorey resulting in standing dead timber. These complex changes can only be represented in a straightforward fashion with models that allow for multiple (stratified) vegetation layers (Table 1). Fires can also cause changes in soil properties that affect the hydrologic response, including altered soil albedo and, under certain conditions, the formation of hydrophobic conditions (Agee 1993), which limit soil infiltration and percolation. Soil hydrophobicity declines over time; however, the process is poorly understood (DeBano 2000) and, as such, the ability to simulate this condition is challenging. Representing the potential effect of soil hydrophobicity on infiltration can be problematic because although it is possible to alter soil physical properties, none of the models reviewed allows soil properties to be changed temporally within a single model run to account for a decrease in hydrophobicity over time.

The current understanding of climate change influence on average meteorological conditions is much further developed than that of understanding potential changes in the frequency and magnitude of extreme events (Rodenhuis et al. 2007). An improved understanding of extreme events (temperature, precipitation, and wind) under a changing climate is needed to advance hydrologic modelling. Also needed is an increased ability to use models to investigate potential forest disturbances, such as landslides, fire hazards, pests (insects), and windthrow. The outputs from these models could then be used to parameterize hydrologic models for forest management purposes. In general, physically based models are better suited to parameterize the effects of these disturbances because of the inclusion of multi-layered vegetation and parameters such as soil and vegetation albedo (Table 2).

**Altered Streamflow**

The streamflow implications of a changing climate are expected to vary by region depending on the sensitivity of a watershed to temperature and precipitation changes and the watershed’s dominant water storage and release mechanisms. Most watershed models will calculate associated changes in streamflow, infiltration, soil moisture conditions, and shallow subsurface runoff, and the subsequent discharge of water to stream channels without the need to modify the model. Nonetheless, in certain settings, specific questions regarding the interaction of forest management and climate change may create difficulties for existing models. For example, changes in groundwater recharge rates associated with climate change (e.g., Scibek and Allen 2006 a,b) may have consequences for baseflow contributions for low flows, while the capability to account for the anticipated increased competition between human water use and for ecological values may be another important feature in selecting a model (Table 1). Regionally, a key driver is large-scale changes to vegetation due to the mountain pine beetle infestation that has affected large areas of British Columbia, the impacts of which are
When comparing model complexity and model functionality for addressing climate change in a forest management context, RHESSys has highest overall functionality, followed by DHSVM, WaSiM-ETH, and CRHM.

Model selection considerations within the context of forest management and climate change would normally be similar to those outlined in Part I with additional consideration for modelling watershed processes that will be affected by a changing climate (Table 2). A more detailed discussion of the individual models and their advantages and disadvantages is provided in Beckers et al. (2009).

Model Selection
Figure 1 compares model complexity (from Part I of this article in this issue) and model functionality for addressing climate change in a forest management context. Accordingly, this figure indicates that RHESSys has highest overall functionality, followed by DHSVM, WaSiM-ETH, and CRHM. The medium and low complexity models offer lower functionality.

When comparing model complexity and model functionality for addressing climate change in a forest management context, RHESSys has highest overall functionality, followed by DHSVM, WaSiM-ETH, and CRHM.

Model selection considerations within the context of forest management and climate change would normally be similar to those outlined in Part I with additional consideration for modelling watershed processes that will be affected by a changing climate (Table 2). A more detailed discussion of the individual models and their advantages and disadvantages is provided in Beckers et al. (2009).

Linking Hydrologic Models to Climate Change Projections
Climate change projections are generated from global-scale, global climate models (GCMs). The GCMs provide outputs at a resolution typically too coarse (e.g., grid cells > 100 km²) for use in forest management and most hydrologic modelling applications. Statistical downscaling techniques or regional climate models (RCMs) are therefore required to link GCM outputs to regional and local climate and hydrological models (Hutchinson and Roche 2008). Linking climate change projections to hydrological models is particularly onerous in complex mountainous terrain, a challenge that is well documented (e.g., Wood et al. 2004; Merritt et al. 2006; Stahl et al. 2008).

Statistical downscaling techniques are computationally efficient and are therefore used to explore a range of future climate scenarios. The following techniques are applied in western North America.

- The delta-method adjusts an historical measured weather time series from a meteorological station by the projected difference between current (often 1961–1990) and future (i.e., 2041–2070) conditions (e.g., Loukas et al. 2002; Toth et al. 2006).
- ClimateBC (Spittlehouse 2006; Wang et al. 2006) maps GCM data to the terrain of British Columbia by correcting for effects such as elevation and distance from the ocean.
- Bias-correction statistical downscaling (BCSD) produces a daily climate time series by correcting monthly GCM data to match the statistical properties of an observed gridded weather record (Wood et al. 2002; Widmann et al. 2003; Salathé 2005).
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- The Tree-GEN method developed by Environment Canada includes components from multiple statistical techniques to achieve optimal results (Stahl et al. 2008), but has been applied at only a few sites in British Columbia.

Climate change impacts in British Columbia and Alberta are currently under investigation by the Pacific Climate Impacts Consortium (PCIC). In particular, the PCIC is collaborating with the University of British Columbia to improve ClimateBC by creating additional components and extending the tool to western North America. The PCIC is also applying the BCSD technique for VIC modelling of several British Columbia watersheds.

In contrast to statistical techniques, RCMs are computationally expensive to run. However, these models are more representative of physical processes and therefore better conserve energy and water balances. The PCIC is working to conduct diagnostics of the Canadian Regional Climate Model. Initial results will be provided at a grid scale resolution of 45 × 45 km for Pacific North America. Future results for British Columbia may be available at a 10- or 15-km resolution. For the current lower-resolution RCMs, it is often advisable to downscale climate data before applying it in hydrologic models to better reflect local factors such as topography. Continued development of such tools and associated climate change data resources offers great synergies with watershed-scale applications of hydrologic models and is a focus of current research in British Columbia and Alberta.

**Conclusion**

Although the capabilities of the reviewed watershed models to examine climate change questions varies, the development of new models is not necessarily required. Examples include producing spatially explicit vegetation data sets with up-to-date LAI and stomatal resistance information, and incorporating weather variables such as solar radiation, humidity, and wind speed in climate change projections. A fundamental barrier to considering climate change in a forest management context remains the incomplete understanding of possible future climates, with current predictions offering a wide range of possible outcome scenarios. Research is therefore needed to better refine possible future shifts in temperature, precipitation, and other weather variables, and in particular the occurrence of extreme events. Continued development of tools to link hydrologic models to climate change predictions is also required.

**Acknowledgements**

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**References**


Beckers, J., B. Smerdon, and M. Wilson. 2009. Review of hydrologic models for forest management and climate change applications in British


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Information Note

Environmental Professional Certificate Program

The Environmental Professional Certificate Program (EPCP) is a professional-level program offered by the Natural Resources Extension Program (NREP) at Vancouver Island University. Highly applied in orientation, the program will provide environmental practitioners with leading-edge, practical field skills training and applications.

The EPCP target audience includes:

- Graduates of natural resource-related diploma and degree programs.
- Current environmental practitioners wishing to upgrade or expand skills and abilities.
- Individuals desiring a career in environmental assessment, monitoring, and rehabilitation, and fish, wildlife, aquatic, and terrestrial biology.

The program will focus on:

- Fisheries inventory, assessment, and rehabilitation – 25 days of classroom/field training
- Aquatic inventory and monitoring – 11 days of classroom/field training
- Environmental assessment, monitoring, and rehabilitation – 51 days of classroom/field training
- Wildlife – 10 days of identification (birds, amphibians, mammals), inventory/assessment
- Safety awareness, planning and certification – 15 days of classroom/fielding
- Communications skills – 15 days of classroom training
- GPS and GIS field operators level

An instructional staff of 14 industry experts will ensure that EPCP participants receive specialized, applied training. Participants will also receive certification in: Wilderness First Aid, Swift Water Rescue, GPS, Electrofishing, and ATV operation.

The EPCP offers 136 days of instruction delivered over a 6-month period and includes in-depth classroom lectures, demonstrations and case studies, and field training sessions. Approximately one-half of the program will be field-based, providing focused, realistic field scenarios and skills training.

To maximize student development, class size is limited to 16 full-time students, with one classroom instructor and two field instructors. Starting in September 2009, the EPCP will initially be delivered in Nanaimo, BC. Future plans include a September 2010 delivery in Nanaimo, BC.

Program graduates will be capable of designing, managing, and implementing diverse and multi-faceted environmental initiatives and projects, including:

- Fish, fish habitat, wildlife, vegetation inventory/assessment, and restoration projects
- Qualitative and quantitative fish and wildlife population estimation
- Water quality sampling programs
- Aquatic (invertebrates, water quality, aquatic plants) sampling and monitoring
- Mapping/GPS/GIS and orienteering
- Plant, fish, and wildlife identification

NREP is currently negotiating EPCP certification with several professional associations, and will announce those agreements as they are finalized.

The EPCP is also available for delivery in any community in North America. As set-up will require a 1-year lead time, prospective hosting organizations are advised to contact the NREP well in advance of any proposed delivery time frame. Community groups or organizations should contact the NREP Manager, for more information.

For information about costs, pre-requisites, registration, schedules, personal equipment requirements, etc., go to: www.mala.ca/nrep/EnvironmentalProfessionalCertificateProgram.asp

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Compendium of Forest Hydrology and Geomorphology – New Chapters Online

Six new chapters of the Compendium of Forest Hydrology and Geomorphology in British Columbia have been posted to the FORREX website. It is anticipated that the remaining chapters will be posted during Fall 2009. For more information on the Compendium, please see the table of contents below with links to available chapters, or visit: www.forrex.org/program/water/compendium.asp

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