Peer-reviewed Synthesis Article

Hydrologic Models for Forest Management Applications: Part 1: Model Selection

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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.

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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).

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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. Lumped 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 km^2), others are limited to medium-sized watersheds (< 100 km^2), and a few are limited watersheds greater than 500 km^2. 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.

Table 1. Model complexity evaluation criteria.

	Low complexity	Medium complexity	High complexity
Data requirements	Monthly precipitation and temperature	Daily precipitation and temperature	Hourly to daily precipitation and temperature
	No additional meteorological forcings required	Additional meteorological forcings may be required	Additional meteorological forcings may be required
	No need for spatial data	Requires spatial data (DEM, soils, and forest cover)	Requires spatial data (DEM, soils, and forest cover)
	Less than 25 parameters	About 25–75 input parameters	Typically over 75 input parameters
	Parameters are experimentally based (no calibration required); models suitable for ungauged basins	Minimal number of calibration parameters; some models applicable to ungauged basins	Medium to high number of calibration parameters; models applicable to gauged basins only
Resource requirements	Low data preprocessing effort	Medium data preprocessing effort	High data preprocessing effort
	Does not require GIS analysis	GIS analysis required for some models	GIS analysis required for most models
	Can be completed by one person	Can mostly be completed by one person	May require project team
Time requirements (Cost[a])	Less than 2 weeks	About 2 weeks to 2 months	About 2–6 months
	Less than $10 000	About $10 000–$40 000	From about $40 000 to more than $100 000

[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

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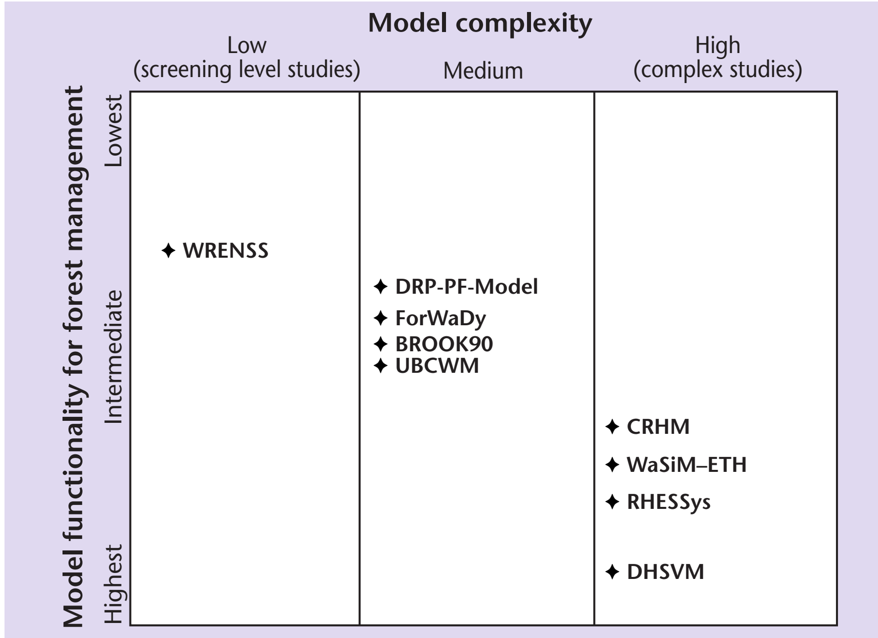

***Figure 1.** Forest management functionality and complexity ranking of short-listed models. Refer to Beckers et al. (2009) for ranking of all models considered in the study.*

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 km^2 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

Table 2. Advantages and disadvantages of short-listed models. See Beckers et al. (2009) for other models.

Purpose	Model name	Main advantages	Main disadvantages
Annual yield	WRENSS (WinWrnsHyd/ ECA-AB)	Easy to use procedures with low data requirements	Limited functionality (annual yield, hydrologic recovery)
Peak flow	DRP-PF-Model	Valuable province-wide (British Columbia) databases provided; simple treatment of road effects	Limited functionality (only peak flows); limited model testing to date
Water balance	BROOK90	Useful for site water balances; moderate complexity	Empirical degree-day method for snowmelt; no channel routing
	ForWaDy	Linkage with forest growth models; moderate complexity	No channel routing; limited model documentation and testing
Watershed hydrology	CRHM	Strong focus on cold regions hydrology (blowing snow/frozen soils)	Simplified channel routing; functionality limited to boreal forests
	DHSVM	Powerful for a wide range of watershed hydrology applications	Difficult to use; functionality may be limited to mountainous watersheds; high model parameterization requirements
	RHESSys	Potential for ecohydrology application (forest growth, mortality); simple groundwater components	Difficult to use; high model parameterization requirements
	UBCWM	Widely used; modest data requirements; glaciers and upland lakes	Elevation bands and simplified forest cover limit forest management functionality
	WaSiM-ETH	Can handle glacial melt, groundwater, lakes, and reservoirs	Complex model; no testing to date in forest management context

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.

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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 sub-basins. 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 understorey shrub). These numerous limitations may be important in certain operational settings and can only be overcome by applying suitable higher-complexity models.

Hydrologiska Byråns Vattenbalan-savdelning – Environment Canada (HBV-EC: Moore 1993) is not one of the short-listed models because its functionality in a forest management context is limited by an "overly simplistic representation of canopy influences on snow deposition" (Moore et al. 2007); however, a rewrite of HBV-EC is currently under way with an intended application to forest management (Dr. R.D. Moore, pers. comm., 2009). The new model will have a target conceptualization between the HBV-EC and DHSVM. This development is promising and should be closely monitored. A feature of the HBV-EC that sets it apart from most other models is the availability of the Green-Kenue Graphical User Interface (***www.nrc-cnrc.gc.ca/eng/ibp/chc/software/kenue/green-kenue.html***) to simplify data input and analysis of outputs.

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.

High-complexity models offer a wider range of capabilities for answering forest management questions in Alberta and British Columbia when the greater demands on data, time, and resources can be overcome.

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. The sections below discuss some of the barriers that will need to be addressed in order to create such an environment.

Data Availability

Hamilton (2007) discussed the lack of data to operate models and the problems this creates in making decisions from model outputs. Improvements are taking place, notably in the compilation of climate data for British Columbia (Spittlehouse 2006), water portals in Alberta (***www.albertawater.com***), and other efforts to assemble existing databases of forest cover and disturbances (e.g., DRP-PF-Model). Nonetheless, additional data is required to support the use of physically based models (e.g., leaf area index, soil cover, soil depth) and data at high resolution is needed for use in small watersheds. Historical databases of temperature and precipitation could be supplemented with algorithms that generate the additional meteorological variables, such as short- and long-wave radiation and relative humidity, required to run physically based models (e.g., MTN-Clim in RHESSys: Tague and Band 2004; Schnorbus and Alila 2004b). Compilation and maintenance of this data will likely require an effort at the federal and/or provincial government level.

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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 modellers 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 ungauged 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

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2009). 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.

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.

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.

Acknowledgements

Funding for this hydrologic model review was provided by the British Columbia Forest Investment Account–Forest Science Program, through the Provincial Forest Extension Provider (FORREX); Alberta Sustainable Resource Development, Forest Management Branch; and the BC Ministry of Forests and Range, Future Forest Ecosystems Initiative. In-kind support was provided by the Pacific Climate Impacts Consortium.

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References

Alila, Y. and J. Beckers. 2001. Using numerical modelling to address hydrologic forest management issues in British Columbia. Hydrological Processes 15:3371–3387.

Alila, Y. and C.Q. Luo. 2007. Delineating the limits on peak flow and water yield responses to clearcut salvage logging in large watersheds. In *Mountain pine beetle and watershed hydrology workshop: Preliminary results of research from BC, Alberta and Colorado. Ramada Inn, Kelowna, BC, July 10, 2007. pp. 43–44.* ***www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*** *(Accessed August 2009).*

Beckers, J. and Y. Alila. 2004. A model of rapid preferential hillslope runoff contributions to peak flow generation in a temperate rain forest watershed. Water Resources Research 40, W03501, doi:10.1029/2003WR002582.

Beckers, J., B. Smerdon, and M. Wilson. 2009. Review of hydrologic models for forest management and climate change applications in British Columbia and Alberta. FORREX, Kamloops, BC. FORREX Series Report No. 25. ***www.forrex.org/publications/forrexseries/fs25.pdf***

Eaton, B. and R.D. Moore. 2007. Chapter 4 – Regional hydrology [Draft]. In *Compendium of forest hydrology and geomorphology in British Columbia. R.G. Pike et al. (editors). BC Ministry of Forests and Range Research Branch, Victoria, BC and FORREX Forum for Research and Extension in Natural Resources, Kamloops, BC. Land Management Handbook. In preparation.* ***www.forrex.org/program/water/compendium.asp*** *(Accessed August 2009).*

Federer, C.A., C. Vörösmarty, and B. Fekete. 2003. Sensitivity of annual evaporation to soil and root properties in two models of contrasting complexity. Journal of Hydrometeorology 4:1276–1290.

Forest Practices Board. 2007. The effect of mountain pine beetle attack and salvage harvesting on streamflows. Victoria, BC. Special Investigation No. FPB/SIR/16, March 2007.

Gurtz, J., A. Baltensweiler, and H. Lang. 1999. Spatially distributed hydrotope-based modelling of evapotranspiration and runoff in mountainous basins. Hydrological Processes 13:2751–2768.

Hamilton, S. 2007. Completing the loop: From data to decisions and back to data. Hydrological Processes 21(22):3105–3106.

Hudson, R.O. and M.C. Quick. 1997. A component based water chemistry simulator for small subalpine watersheds. Canadian Water Resources Journal 22(3):299–325.

Hutchinson, D. 2007. Modelling hydrologic effects of landscape disturbance: An introduction. In *Mountain pine beetle and watershed hydrology workshop: Preliminary results of research from BC, Alberta and Colorado. Ramada Inn, Kelowna, BC, July 10, 2007. pp. 35–38.* ***www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*** *(Accessed August 2009).*

Ivanovic, R.F. and J.E. Freer. 2009. Science versus politics: Truth and uncertainty in predictive modelling. Hydrological Processes 23:2549–2554.

Kampf, S.K. and S.J. Burges. 2007. A framework for classifying and comparing distributed hillslope and catchment hydrologic models. Water Resources Research 43, W05423, doi:10.1029/2006WR005370.

Kimmins, J.P., D. Mailly, and B. Seely. 1999. Modelling forest ecosystem net primary production: The hybrid simulation approach used in FORECAST. Ecological Modelling 122:195–224.

Klemes, V. 1986. Operational testing of hydrological simulation models. Hydrological Sciences Journal 31:13–24.

Moore, R.D. 1993. Application of a conceptual streamflow model in a glacierized drainage basin. Journal of Hydrology 150:151–168.

Moore, R.D., D.G. Hutchinson, and M. Weiler. 2007. Predicting the effects of post-MPB salvage harvesting using a conceptual streamflow model (HBV-EC): Initial evaluation using a paired-catchment approach. In *Mountain pine beetle and watershed hydrology workshop: Preliminary results of research from BC, Alberta and Colorado. Ramada Inn, Kelowna, BC, July 10, 2007. pp. 41–42.* ***www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*** *(Accessed August 2009).*

Moore, R.D. and S.M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. Journal of the American Water Resources Association 41(4):763–784.

Pike, R. 1995. Current limitations of hydrologic modeling in B.C.: An examination of the HSPF, TOPMODEL, UBCWM and DHSVM hydrologic simulation models, B.C. data resources and hydrologic–wildfire impact modeling. MSc thesis. University of Victoria, Victoria, BC.

________. 2003. Approaching watershed modelling. Streamline Watershed Management Bulletin 7(3)22–23. ***www.forrex.org/publications/streamline/ISS26/streamline_vol7_no3_art8.pdf*** *(Accessed August 2009).*

Pike R.G., T. Redding, D. Wilford, R.D. Moore, G. Ice, M. Reiter, and D.A.A. Toews. 2007. Chapter 16 – Detecting and predicting changes in watersheds. In *Compendium of forest hydrology and geomorphology in British Columbia. R.G. Pike et al. (editors). BC Ministry of Forests and Range Research Branch, Victoria, BC and FORREX Forum for Research and Extension in Natural Resources, Kamloops, BC. Land Management Handbook. In preparation.* ***www.forrex.org/program/water/compendium.asp*** *(Accessed August 2009).*

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Pomeroy, J.W., D.M. Gray, T. Brown, N.R. Hedstrom, W.L. Quinton, R.J. Granger, and S.K. Carey. 2007. The cold regions hydrological model: A platform for basing process representation and model structure on physical evidence. Hydrological Processes 21:2650–2667.

Quick, M.C., A. Pipes, D. Nixon, E. Yu, A. Loukas, R. Millar, H. Assaf, and B. Start. 1995. UBC Watershed Model Manual, Version 4.0. Mountain Hydrology Group, Department of Civil Engineering, University of British Columbia. Vancouver, BC.

Redding, T., R. Winkler, P. Teti, D. Spittlehouse, S. Boon, J. Rex, S. Dubé, R.D. Moore, A. Wei, M. Carver, M. Schnorbus, L. Reese-Hansen, and S. Chatwin. 2008. Mountain pine beetle and watershed hydrology. In *Mountain pine beetle: From lessons learned to community-based solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):33–50.* ***www.forrex.org/publications/jem/ISS49/vol9_no3_MPBconference.pdf*** *(Accessed August 2009).*

Savenije, H.H.G. 2009. HESS Opinions "The art of hydrology". Hydrology and Earth System Sciences 13:157–161.

Schnorbus, M.A. and Y. Alila. 2004a. Forest harvesting impacts on the peak flow regime in the Columbia Mountains of southeastern British Columbia: An investigation using long-term numerical modeling. Water Resources Research 40, W05205, doi:10.1029/2003WR002918.

________. 2004b. Generation of an hourly meteorological time series for an alpine basin in British Columbia for use in numerical hydrologic modeling. Journal of Hydrometeorology 5:862–888.

Schnorbus, M.A., K.E. Bennett, and A.T. Werner. 2009. Quantifying the hydrologic impacts of mountain pine beetle and salvage harvest in the Fraser River Basin, British Columbia, Canada. EOS Transactions, American Geophysical Union 90(22), Joint Assembly Supplement, Abstract CG21A-23.

Silins, U. 2002. Streamflow models in integrated forest-watershed planning: How much complexity is warranted? 2002 Interior Watershed Conference, March 13–14, 2002. Kamloops, BC.

Spittlehouse, D.L. 2006. ClimateBC: Your access to interpolated climate data for BC. Streamline Watershed Management Bulletin 9(2):16–21. ***www.forrex.org/publications/streamline/ISS31/streamline_vol9_no2_art4.pdf*** *(Accessed August 2009).*

Swanson, R.H. 2005. Using the WinWrnsHyd program as a didactic tool. In *Proceedings, 73rd Annual Western Snow Conference, Great Falls, MO, April 11–14, 2005.* ***www.westernsnowconference.org/proceedings/pdf_Proceedings/2005 WEB/Swanson, R._Using The WINWRNSHYD Program as a Didactic Tool.pdf*** *(Accessed August 2009).*

Tague, C. and L.E. Band. 2004. RHESSys – Regional hydro-ecologic simulation system: An object-oriented approach to spatially distributed modeling of carbon, water and nutrient cycling. Earth Interactions 8(19):1–42.

Thyer, M., J. Beckers, D. Spittlehouse, Y. Alila, and R. Winkler. 2004. Diagnosing a distributed hydrologic model for two high-elevation forested catchments based on detailed stand- and basin-scale data. Water Resources Research 40, W01103, doi:10.1029/2003WR002414.

US Environmental Protection Agency. 1980. An approach to water resources evaluation on non-point silvicultural sources (a procedural handbook). United States Environmental Protection Agency, Environmental Research Laboratory, Athens, GA. EPA-600/8-80-012.

Weiler, M., M. Carver, C. Scheffler, and K. Rosin. 2009. Development of a peak flow hazard model for the Fraser Basin (British Columbia). Project Report: MPBI Project No. 7.29 submitted to Natural Resources Canada.

Werner, A.T. and K.E. Bennett. 2009. A review of hydrologic models for application in climate change studies for watersheds in the cold mountainous terrain. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC. Unpublished internal report.

Whitaker, A., Y. Alila, J. Beckers, and D. Toews. 2002. Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment. Water Resources Research 38(9):1172. doi:10.1029/2001WR000514.

________. 2003. Application of the distributed hydrology soil vegetation model to Redfish Creek, British Columbia: Model evaluation using internal catchment data. Hydrological Processes 17:199–224.

Whitaker, A., Y. Alila, P. Calvert, and D. Toews. 1998. Evaluation of existing hydrologic models for use in assessing the impact of forest management on peak flows. In *Proceedings of the Canadian Water Resources Association, 51st Annual Conference: Mountains to sea: Human interaction with the hydrologic cycle, June 10–12, 1998, Victoria, BC.*

Wigmosta, M.S., B. Nijssen, and P. Storck. 2002. The distributed hydrology soil vegetation model. In *Mathematical models of small watershed hydrology and applications. V.P. Singh and D.K. Frevert (editors). Water Resources Publications, Highlands Ranch, CO. pp. 7–42.*