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

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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).

Several detailed studies of climate trends, future climate predictions, and potential effects on hydrology in Alberta and British Columbia indicate that a changing climate will alter watershed processes, which in turn may affect many aspects of short- and long-term watershed management.

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

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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).

Table 1. Climate change model evaluation criteria.

Hydrologic implication of climate change	Model evaluation criteria
Atmospheric evaporative demand	• Solar radiation, humidity, and wind speed
Altered vegetation composition affecting evaporation and interception	• Leaf area index • Stomatal resistance • Forest growth (productivity) • Forest survival (mortality) • Temporal input control
Snow accumulation and melt	• Physical/analytical snowmelt equations • Rain-on-snow simulation
Permafrost, river and lake ice	• Frozen soil influence on water movement • River and lake ice model component
Glacier mass balance adjustments	• Glacier melt model component
Altered streamflow	• Groundwater • Lakes • Wetlands • Water consumption (water supply systems)
Stream and lake temperatures	• Water temperature model component
Increased frequency/magnitude of disturbances	• Channel routing (floods) • Multiple vegetation layers (wildfires, pests) • Vegetation albedo (wildfires, pests) • Soil albedo (wildfires) • Hydrophobicity (wildfires) • Landslide simulation

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 2. Climate change model ranking.

Model evaluation criteria	Model complexity								
	Low	Medium				High			
	WRENSS	BROOK90	ForWaDy	DRP-PF-Model	UBCWM	CRHM	DHSVM	RHESSys	WaSiM-ETH
Radiation, humidity, wind speed		✓	✓			✓	✓	✓	✓
Leaf area index	✓	✓	✓			✓	✓	✓	✓
Stomatal resistance		✓	✓			✓	✓	✓	✓
Forest growth (productivity)								✓	
Forest survival (mortality)								✓	
Temporal input control	✓			✓				✓	
Physical/analytical snowmelt			✓		✓	✓	✓	✓	✓
Mixed rain/snow processes			✓		✓	✓	✓	✓	✓
Frozen soil/ permafrost						✓			
River and lake ice									
Glacier melt					✓				✓
Stream temperature									
Groundwater		✓			✓	✓		✓	✓
Lakes					✓				✓
Wetlands									
Water consumption					✓				✓
Channel routing (floods)				✓	✓		✓	✓	✓
Multiple vegetation layers			✓				✓	✓	✓
Vegetation albedo		✓				✓	✓	✓	✓
Soil albedo						✓	✓	✓	✓
Hydrophobicity (wildfires)									
Landslide simulation							✓		

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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 WRENSS (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., Wigmosta 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., Lanquaye 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 understorey 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 currently being investigated with the VIC model (Schnorbus et al. 2009). Improvements in the simulation of altered peak and low flows in a changing climate are often contingent on advances in the previously discussed topic areas (evapotranspiration, snow accumulation and melt, permafrost and river and lake ice processes, glacier mass balance adjustments, etc.). Furthermore, model accuracy for predicting future streamflow conditions may be reduced if a model was developed and calibrated for simulating snowmelt-dominated watershed conditions and is subsequently used to assess the consequences of a shift to mixed or rainfall-dominated regimes. Additional model improvements include processes related to groundwater, wetlands and lakes, and other factors such as human water consumption (water competition) that affect streamflow. Presently, this capability is limited among the models reviewed (Table 2).

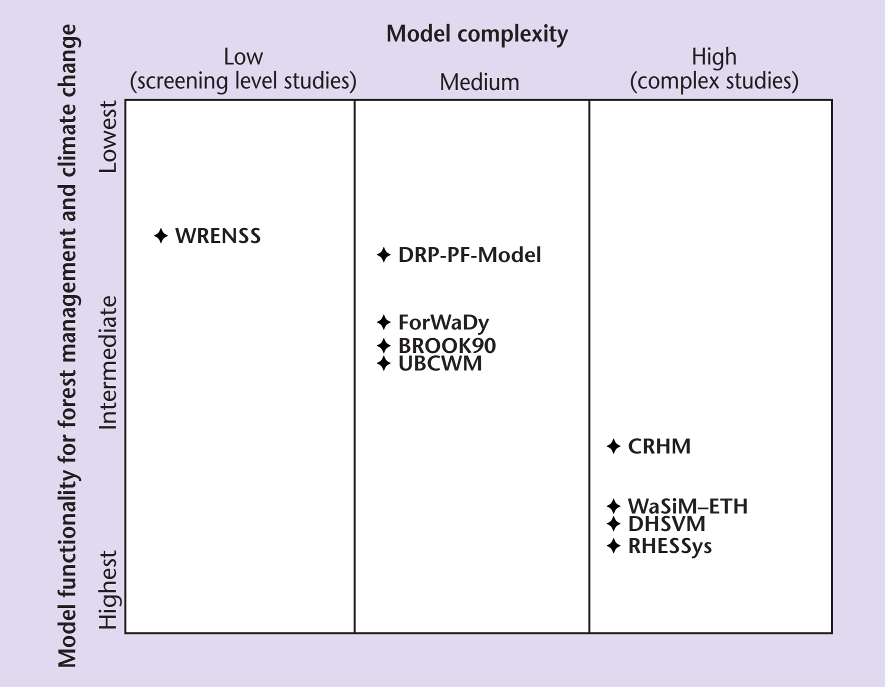

Figure 1. Combined forest management and climate change functionality of short-listed models. Refer to Beckers et al. (2009) for ranking of all models considered in the study.

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 km^2) 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.

> *Although the capabilities of the reviewed watershed models to examine climate change questions varies, the development of new models is not necessarily required.*

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. Instead, an incremental enhancement of existing models could likely provide the important information needed to guide forest management decisions. Further efforts are required to enhance and organize the data resources that will allow application of the complex, physically based models which are best suited for addressing climate change questions. 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.

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