SUSTAINABLE FOREST MANAGEMENT NETWORK
RÉSEAU DE GESTION DURABLE DES FORÊTS
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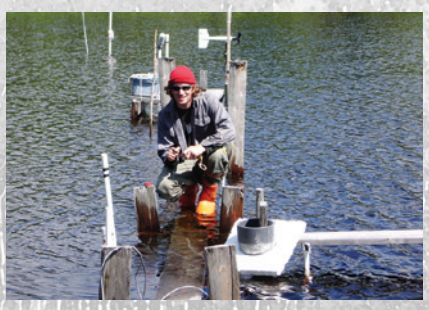
Scientific theory, data and techniques for conservation of water resources within a changing forested landscape

Irena Creed | Gabor Sass | Fred Beall | Jim Buttle | Dan Moore | Margaret Donnelly

A STATE OF KNOWLEDGE REPORT



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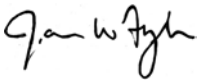
Foreword

The State of Knowledge program was launched by the Sustainable Forest Management Network (SFMN) to capture the knowledge and wisdom that had accumulated in publications and people over a decade of research. The goal was to create a foundation of current knowledge on which to build policy, practice and future research. The program supported groups of researchers, working with experts from SFMN partner organizations, to review literature and collect expert opinion about issues of importance to Canadian forest management. The priority topics for the program were suggested by the Network's partners in consultation with the research theme leaders. Each State of Knowledge team chose an approach appropriate to the topic. The projects involved a diversity of workshops, consultations, reviews of published and unpublished materials, synthesis and writing activities. The result is a suite of reports that we hope will inform new policy and practice and help direct future research.

The State of Knowledge program has been a clear demonstration of the challenges involved in producing a review that does justice to the published literature and captures the wisdom of experts to point to the future. We take this opportunity to acknowledge with gratitude the investment of time and talent by many researchers, authors, editors, reviewers and the publication production team in bringing the program to a successful conclusion.



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We would like to acknowledge Springer-Verlag for providing permission for the inclusion of Chapter 2 ("The Effects of Forest Harvesting on Forest Hydrology and Biogeochemistry"), Chapter 4 ("Bird's Eye View of Forest Hydrology: Novel Approaches using Remote Sensing Techniques"), and "Chapter 5 ("Digital Terrain Analysis Approaches for Tracking Hydrological and Biogeochemical Pathways and Processes in Forested Landscapes") that were published in *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*.

We would like to thank Mr. Johnston Miller (The University of Western Ontario) for editorial comments that improved the quality of this report.

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Executive Summary

This State of Knowledge (SOK) report builds on a companion SOK report entitled "*Hydrological principles for conservation of water resources within a changing forested landscape*", which presents a suite of hydrological principles that provide a foundation for the development of sustainable forest management strategies to conserve water resources.

With this report, our objective is to review the state of science resources (including data and tools) behind the sustainable management of forests from the perspective of conserving water resources and minimizing adverse effects resulting from forest management activities. We also provide a current synthesis of field studies and available datasets, as well as the scientific achievements and challenges facing the application of digital tools including digital terrain analysis, remote sensing and hydrological modelling. Finally, we provide recommendations for scientists, policy makers and resources managers with respect to future research and monitoring endeavours, analysis of integrated datasets and training of the next generation of forest hydrologists and forest managers to promote the practice of sustainable forest management.

Where does sustainable forest management come from?

Sustainable forest management strategies for the conservation of water resources are based on the results of hundreds of scientific studies from Canada and abroad. These studies have sought to understand the consequences of management activities on hydrological processes in forested landscapes. In order to do so, research has been conducted at a series of experimental study sites, most being headwater catchments, spanning a diverse range of forested regions. In Canada, there are approximately 50 sites which have produced most of the forest hydrology research.

Do forest management activities change hydrological processes?

They potentially do, but the effects are variable across spatial and temporal scales. Different forest types will respond differently to forest harvesting, and the responses in a given forest will differ over the course of a year. Additionally, global change is altering how we look at the effects of forest harvesting, because it is modifying the fundamental hydrological processes occurring within our forests.

Future research should focus on maintaining and expanding the monitoring network of sites that are examining the long-term hydrological and biogeochemical characteristics of a wide variety of natural and harvested forests. These sites could be used to investigate how we can translate results from experimental catchments to larger regional drainage basins. Specifically, it is important to learn more about how the effects of forest harvesting change with scale and how they compare with other land use/land cover changes. It is also important to look beyond issues of annual water yield and consider other aspects of streamflow regimes including streamflow magnitudes (high and low flows), timing of streamflows, frequencies, and the durations of streamflow events.

The effects of forest harvesting on forest hydrology and biogeochemistry

Water quantity and quality issues, especially as they relate to the provision of safe and sufficient drinking water supply will be increasingly important under a changing climate, particularly since many predict an increased frequency and severity of extreme weather events. For these reasons, it is crucial to have a clear understanding of the impacts of forest harvesting on water. The key questions asked by hydrologists working in managed forests are:

1. How do forest management activities alter hydrological processes?; and
2. How do we mitigate the impacts?

We now have a fairly good grasp on many of these changes, although knowledge gaps remain, specifically for subsurface (ground water) hydrological processes.

Changes in hydrological processes

In general, basins that have been harvested produce greater water yields. This response, however, is highly variable and is affected by such factors as climate, geology, soils, topography and vegetation. Additionally the effects of forest harvest are not static, and diminish over time as the forest re-grows. Some potential reasons why greater water yields can be expected in harvested areas are:

- Higher snow accumulation, accompanied by more rapid snow melt in the spring due to higher radiation exposure.
- Higher melt rates in regions subject to mid-winter rain-on-snow events, due to an increase in wind-driven inputs of sensible and latent heat to the snow surface.
- Higher soil water content during the snow-free season as a result of fewer trees intercepting rain and snow, and an overall reduction in evapotranspiration due to reductions in leaf area.

Increased amounts of water in the soil in harvested watersheds translate into higher water tables, increased groundwater recharge, and greater groundwater discharge to streams and rivers; although the magnitude of these effects are highly variable. Higher soil water could also lead to increased subsurface flow and change the rate at which water is able to infiltrate into the soil. If infiltration rates have been altered through forestry operations, there can be resulting increases in overland flow. The magnitude of all these effects, however, depends on the techniques used to remove the trees (e.g., soil compaction from equipment, roads).

The issue of increased peak flows due to forest harvesting, and the associated risk of flooding, is a contentious issue in hydrology. However, there is general consensus that forest harvesting has a proportionally larger effect on smaller rather than larger basins, and that effects are generally observed when more than 20% of a basin area is harvested. There is also general consensus that low flows during dry periods increase following harvesting due to increased soil and groundwater recharge, at least for the first five to ten years following harvest. Again, these effects are highly variable and longer-term effects (10 years +) are virtually unknown.

Water quality

Water quality issues are complex and interconnected. In fact, the effects of forest harvesting can be difficult to tease apart from issues such as climate, vegetation and land use history. Also, there are many indicators that represent quality based on different variables and that affect the ecosystem in diverse ways.

Stream temperature is an important water quality indicator that influences such properties as dissolved oxygen levels, and can be modified by several factors related to forest harvesting, including increased solar radiation at the water surface. Sediment concentrations can impact the quality of drinking water and habitat quality for fish spawning. Sediments can also act as a vector for some nutrients and contaminants. Sedimentation is mostly a result of the construction of roads and stream crossings for logging operations. In general, sediment yields peak shortly after harvesting and decline with forest regrowth. The maximum sediment supply to streams, however, may not occur immediately after harvesting, particularly in the case of landslides.

Nutrient and contaminant levels in forested streams do not all react in the same way to forest harvesting, although there are general trends for most water chemistry indicators; and, in many cases, a lag is observed between forest harvesting and biogeochemical response. For example, loss of vegetation causes nutrient and contaminant concentrations to increase followed by a decline as result of uptake by forest regrowth.

Canada's national hydrological datascape

Knowledge generated by research regarding hydrological processes of forests and the effects of forest management activities on these processes are fundamentally based on hydrological datasets. These datasets provide forest hydrologists and managers with spatially distributed information about water quantity and quality, which can be used as a baseline to measure the response of hydrological systems to forestry operations within a watershed. The majority of Canada's forested watersheds are not gauged; thus managers must make informed decisions with the data that are available. Currently, there are two main sources of hydrological information in Canada:

1. Experimental study sites targeting locally-focused hydrological issues and/or research; and
2. Water Survey of Canada (WSC) river and lake hydrometric gauging sites (for discharge and lake level monitoring).

Experimental study sites

Many of the Canadian experimental watersheds were established by Federal and Provincial agencies along with university scientists in the 1970s. Several hundred scientific papers have resulted from these research watersheds at the local scale, but there have been few attempts to place these results in a national context and extrapolate results from these studies to other sites that are not gauged. One of the most valuable research efforts is the HydroEcological Landscapes and Processes (HELP) project. It identified 46 research sites across Canada and compiled, organized, and synthesized the knowledge into a framework to quantify hydrological, geomorphic, and ecologic processes in forests. Most of these 46 sites measure streamflow at the watershed outlet water temperature, lake out-flows, as well as air temperature and precipitation on a daily basis. Approximately half of the HELP's research sites are still active, many with invaluable long-term data records; however, maintaining funding for these sites has been difficult.

Water Survey of Canada (WSC)

The national Water Survey of Canada hydrometric archive operated by Environment Canada contains more than 2000 stations in forested regions across the country. Approximately 700 stations are still active, although there are gaps and areas of uncertainty in data records. Small basins in the boreal forest have only minimal coverage with few sites having records greater than 35 years.

To move forward, it is important to consolidate existing data and to increase data availability. The number of active gauging stations and experimental watersheds are decreasing, but developing relationships among government, university, and local stakeholder groups can help maintain or even improve upon the resources currently available.

Methods used for hydrological research

The earliest forest hydrology studies used field based methods to study hydrological processes and how they are affected by management activities; however, the recent proliferation of powerful desktop computing coupled with new remote sensing instruments has opened up a completely different vantage point for understanding and managing forests.

The fields of digital terrain analysis, remote sensing and hydrological modelling have great relevance for understanding the hydrological patterns and processes of forested ecosystems. These tools can be readily integrated into forest planning strategies since they are applicable to the study and management of forests at broad spatial and

long temporal scales. This does not mean, however, that the classic monitoring framework is obsolete, since digital tools will always rely on field corroboration. The future of both forest hydrology and forest management, from a hydrological perspective, will require an integrated planning and monitoring framework using all these tools, at a range of spatial scales from hillslopes to continental drainage basins.

Bird's-eye-view of forest hydrology: Novel approaches using remote sensing techniques

Remote sensing uses devices that detect electromagnetic radiation to observe phenomena from a distance. A variety of remote sensing techniques can be used to estimate components of the water budget at different spatial and temporal scales, giving forest managers additional information regarding the distribution of water in forest catchments to facilitate planning decisions.

Most early remote sensing sensors were optical; however, radiation in those wavelengths cannot penetrate clouds and vegetation. Consequently, these sensors are primarily used to monitor open areas of water such as lakes and wetlands. Alternatively, microwave radiation can penetrate vegetation and clouds, allowing a more un-restricted observation of forested landscapes. Both of these sensors measure the reflectance or backscatter of electro-magnetic radiation from the objects that they observe. Selecting the appropriate sensor is an important first step in any remote sensing study. Some of the factors that managers should consider are the record-length, spatial resolution of imagery, and how radiation will interact with the object of interest and the atmosphere. Unfortunately, most airborne and satellite sensors were not specifically designed for hydrological applications, so data must be analyzed with care. Often, multiple sources of imagery can be combined to answer specific questions.

Visible and infrared imagery, and more recently microwave sensors can provide some information about how water enters a forested catchment through rainfall; the spatial resolution, however, is usually quite coarse. Visible and infrared imagery is also useful to determine the leaf area index which provides a good estimate of the amount of rainfall interception by the canopy. This is one of the most useful applications of remote sensing in hydrology and is used extensively in hydro-ecological models. Light Detection And Ranging LiDAR data can also provide information about the canopy structure, including gaps, height, soil bulk density, and surface area.

Remote sensing is able to provide new information about water stored in a landscape. While optical sensors can be used to estimate the area of surface water in a landscape, active microwave sensors and imaging radars can penetrate canopies and clouds and operate during day or night, giving more and higher resolution information about wet areas beneath the canopy. It is difficult, however, to monitor groundwater using remote sensing because the electromagnetic radiation used by current sensors cannot penetrate the ground. Alternative methods can be used to estimate groundwater recharge and discharge.

There are also a variety of methods to measure the different ways that water leaves forested catchments. Satellite-derived vegetation indices, surface temperature and surface albedo have been used to map daily evapotranspiration at approximately 1-km spatial resolution, and much work is being done to improve these estimates. A disadvantage, however, is that discharge can only be estimated in rivers that are wide enough to be detected by sensors.

One particularly useful application of remote sensing for forest management is in the designation of hydrologically relevant buffer zones, which mitigate the effects of land use activities on nearby surface waters. Remote sensing-derived maps can be used to assess the organization of surface flowpaths prior to the design and placement of such buffer strips.

To move forward, it is essential that new sensors, especially microwave, microgravity, and airborne geophysical sensors, are designed with the specific purpose of sensing hydrological phenomena. There is also a wealth of existing remote sensing data that in many cases is either inaccessible, discarded due to storage issues, or goes unused due to complexity of interpretation. A coordinated public and private effort is needed to archive these data and increase public access. There also needs to be increased interdisciplinary training for non-experts so that remote sensing analysis can be adopted by a broader audience.

Digital terrain analysis approaches for tracking hydrological and biogeochemical pathways and processes in forested landscapes

Digital terrain analysis (DTA) is an increasingly valuable tool used to map the movement of water and nutrients across forested landscapes. DTA holds great promise for forest managers since it can be used to identify critical features that should not be disturbed by management activities. Currently, DTA is being used to map hydrologically sensitive areas (e.g., wetlands and small streams) and minimize the impact of placing roads, culverts and cut blocks.

DTA is effective because in many landscapes, topography controls water flow by directing water from high elevations to low elevations due to gravity. Topography also forces water to converge and diverge due to the shape of the land surface. However, the dominance of topography as a primary control on water flow needs to be carefully considered for each landscape as there could be other biophysical factors that influence water flow, such as geology, soils, and vegetation.

In order to understand how DTA can help in the management of forests, it is important to have a basic understanding of the principles of this technique. In most cases, a square grid with a defined resolution is laid over top of an area, and for each cell the elevation is measured using photogrammetry, laser altimetry (LiDAR) or interferometric techniques. The resultant surface is called a Digital Elevation Model (DEM). DEMs are used to model how a drop of water would move across these digital surfaces. The preferred source of DEMs is LiDAR, as the laser beams can penetrate the forest canopy and record very accurate surface elevations. It is important to consider the spatial resolution of DEMs since most DTA techniques are very sensitive to the spatial resolution at which they were derived. The hydrological features being modeled should be properly matched against the spatial resolution of the DEM, since overly-coarse resolutions will misrepresent patterns, while overly-fine resolutions will contain too much detail to be useful.

DTA techniques have been developed to map hydrological pathways and areas of hydrological storage. For example, LiDAR-derived DEMs have significantly improved our ability to map canopy-shaded rivulets and wetlands within headwater forests. Not only do we have a better idea where streams begin, but we also have better assessments of where water is stored on the surface and how these different features are connected via surface saturated areas. This improved mapping of hydrological features has allowed for improved predictions of streamflow, including the different components of the hydrograph and water transit times through catchments.

DTA can also be used to identify hydrological controls on the formation of biogeochemical pools. Many of the DTA techniques that track the movement of water from land to surface waters are applicable for monitoring nutrients due to the close interrelationship between water and nutrient movement. For example, there is a rich literature on applying DTA techniques to predict the export of nutrients from catchments. DTA has also found use in the prediction of land-atmosphere transfer of nutrients with considerable focus on the production of greenhouse gases including carbon dioxide, methane, and nitrous oxide.

Looking into the future, the advances in the vertical and horizontal accuracy of DEMs must continue and be made broadly available across different forest types. Additionally, an improved integration and validation with field-based measurements, remote sensing, and distributed hydrological modelling, complemented by the establishment of global benchmark datasets, will further improve the applicability of DTA data. Improved imaging of subsurface features, such as bedrock topography, would substantially improve our ability to model hydrological processes in terrain where surface topography is not the dominant control on water flow (e.g., boreal plains).

Virtual ecosystems: Using hydrological models to understand the past and predict the future of water in forests

Quantitative ecological models are mathematical descriptions of ecosystems processes. These models serve as virtual laboratories, providing opportunities to manipulate components and functions more easily than in natural systems. In forest hydrology, quantitative ecological models can be used to understand the water and associated nutrient and sediment cycles.

In order to select the appropriate model when using quantitative methods, it is important to have clear what the overall goal of modelling is. It is also important to consider the context, function, performance, and evaluation of available models. Defining the model context places the proposed modelling exercise into a larger scientific, management, policy, and geographic context; the latter characterized by scale and an expectation of uncertainty. The function of the model determines which part of the hydrological cycle needs to be considered, what level of detail is needed to describe the hydrological processes, and what modelling resources are required. Once a potential model has been selected, its performance is optimized by adjusting key parameters to improve model fit. Finally, it is important to evaluate the model by inspecting and analyzing the output and determining the error of the computed data.

Hydrological models can be used in different ways to aid in the decision making process of managers:

1. Models can be used to define the reference condition of forests that have not been monitored for long enough for determining the range of natural variation in hydrological properties (usually streamflow). Hydrological models can also be used for virtual experiments such as simulating the possible impacts of harvesting activities. Experiments can be designed to separate the effects of multiple disturbances, such as climate, fire, harvesting, or acid rain.
2. In terms of forecasting, models can be used to simulate possible futures under changing environmental, management, and climatic scenarios. For example, global circulation models are used to predict future climate scenarios that will potentially impact the hydrological cycling of water within forests.

It can be difficult, however, to apply these models for planning and management at the regional and local scales. There are several modelling methods that allow continental climatic information to be downscaled to local levels, but it can be difficult to incorporate all of the effects of climate change accurately, including all the ecosystem processes that will be altered, into a locally applicable model.

Recommendations

Based on the current state of science and analytical tools reviewed in this document, we make the following recommendations in order to improve our future understanding of forest hydrology in Canada:

- **Create a national data archive for forest hydrology**: A centralized database would encourage cross-site comparisons and synthesis of meta-experiments. This will greatly expand knowledge generation and increase the incorporation of these resources into forest management planning and operations. Due to most hydrological data being funded by federal and provincial governments, we advocate for the public distribution and access of these dataset at no cost.
- **Continue existing and establish new monitoring networks**: Many crucial questions in forest hydrology, especially those related to climate change, can only be addressed by analyzing long-term datasets. Canada needs to take a lesson from the USA where there is a network of long-term observation sites.
- **Encourage and adopt emerging technologies for quantitative analysis**: The integration of remote sensing imagery in hydrological models will continue to be a critical research area. Further integration of digital terrain analysis, remote sensing, and distributed simulation modelling data sets using GIS-based spatial decision support systems will be especially important for managers and other decision makers. We need improved sensors for in-situ sampling as well as for airborne and satellite remote sensing of various hydrological phenomena.
- **Promote integration of datasets at relevant scales**: We need to integrate spatially explicit forest modelling processes with hydrological tools to enhance our ability to upscale results from headwater catchments to regional drainage basins, consider in-stream as well as lake and wetland processes, and forecast the cumulative effects of forest management activities on water resources through time.

- **Develop a national watershed classification system**: An ecohydrology-based watershed classification system would enable planners to recognize the spatial variability in and between different catchments to refine forest management prescriptions based on site conditions and associated hydrological processes, as well as to minimize the potential for adverse effects from harvest or renewal activities on water resources and lotic ecosystems.
- **Promote hydrological training and knowledge transfer**: The goal of this report was in part to promote the application and adoption of the hydrological knowledge and techniques presented herein within forest management. We need enhanced knowledge transfer from product developers and users in digital terrain analysis, remote sensing, and distributed simulation modelling to forest hydrologists and managers.

1.0 Introduction

The importance of conserving and protecting Canada's water resources cannot be overstated. Canada is well endowed with both forests and water, which provides the country with a social and economic advantage that will only grow during the 21st century. It is essential that all parties to water resource management, from local communities through industry and all levels of government, improve our collective stewardship of Canada's most valuable natural resource: water. Since forested areas provide Canadian communities, industries and ecosystems with the large majority of their water, sustainable forest management has a crucial role to play in conserving and protecting water resources.

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The foundation of sustainable forest management (SFM) is the application of sound scientific principles applied through cutting-edge tools and techniques, all underwritten by high quality data. This applies to all aspects of forest management, from stand-level prescriptions to government policy. SFM endeavors to manage the forest resource to ensure that current forest values, goods and services are provided now and in the future. This requires both terrestrial and aquatic ecosystems to be considered in terms of ecosystem structure, function, and resiliency at multiple scales, both over time and across space.

The foundation of sustainable forest management (SFM) is the application of sound scientific principles applied through cutting-edge tools and techniques, all underwritten by high quality data.

This report focuses on the science behind sustainable management of forests from the perspective of conserving water resources and minimizing adverse effects due to forest management activities. After reviewing the state of knowledge of the effects of harvesting on forest hydrology and biogeochemistry, we provide an overview of current and emerging tools and technologies for managing water resources, along with a discussion of Canadian water research sites and data repositories.

The tools and technologies presented include remote sensing, digital terrain analysis, and watershed modelling techniques to address many of the hydrological issues faced by forest managers and policy makers today. They provide guidance for future investments in research and monitoring. This report will be useful to forest managers engaged in such activities as the development of strategic forest management plans, research and monitoring programs, and the development and reporting of indicators of SFM related to

aquatic systems. Policy makers will also find it useful in terms of program development for provincial databases and inventory programs, as well as for the development of policy and guidelines pertaining to forest management planning and state of the forest reporting.

Hydrological principles: a framework for policy and practice

This document builds on a companion State of Knowledge (SOK) report on hydrological principles for conservation of water resources within a sustainable forest management framework entitled *"Hydrological principles for conservation of water resources within a changing forested landscape"*. A suite of hydrological principles is shown in Table 1; these principles provide a foundation for the development of sustainable forest management strategies to conserve water resources. The hydrological principles are intended to provide a framework for policy and operational practices designed to ensure that water resources are conserved within a sustainable forest management approach.

If forest managers develop SFM strategies and practices based on hydrological principles, they can expect their operations to be less risky in terms of environmental effects. This results in aquatic systems that are resilient to disturbance and environmental perturbations. Additional advantages include a communication framework to inform the public about water conservation strategies during consultation processes associated with forest management plan development, preservation of social license to operate, and continued market access. Similarly, the hydrological principles can provide a policy framework to ensure that aquatic elements of the landscape are sustainably managed, and promote resilient aquatic ecosystems.

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Computer-based data and tools

Computer-based digital data and tools are a prime focus of this report because they lend themselves very well to planning and management applications at the scales at which forest management decisions are made. Although these digital data and tools do not replace the need to make ground-based measurements, they can be used for the characterization and prediction of hydrological patterns and processes at landscape scales. For example, the mapping of surface hydrological flowpaths using ground-based methods is prohibitively expensive and therefore unfeasible at the landscape scale; while the same task using digital terrain analysis and/or airborne or satellite remote sensing is becoming a routine process.

Of course, all of these digital data and tools require ground-based measurements either for their parameterization, calibration or corroboration; thus these varied data sources are completely complementary. It is the combined use of ground, airborne and satellite remote sensing and simulation datasets that results in tremendous insights in the hydrological sciences, as well as successful forest management strategies.

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Geographical context

The data and tools presented in this report must be placed in a geographic context due to the highly variable nature of Canada's forests and associated hydrology, climate and landforms. In fact, acknowledgement of spatial and temporal factors that influence hydrological processes is one of several key hydrological principles for managing water resources (Table 1).

The influence of these geographic factors means there is no single data source or standard tool that can be used without modification for hydrological assessments. One must always be wary of temptations to apply

Table 1. **Hydrological principles of forest management** (Creed et al. 2011)

Hydrological Principles	Management Actions
1. Delineate hydrological system boundaries: Consider the entirety of the hydrological system within which management actions take place.	A) Delineate hydrological system boundaries based on knowledge of dominant hydrological flowpaths (many hydrological systems will coincide with topographic boundaries but in some places other factors control hydrological response units).
2. Conserve critical hydrological features: Minimize disturbance to hydrological features with critical source, transfer and storage functions.	A) Minimize disturbance to soils, especially within or near source areas that focus the recharge of water into subsurface pathways. B) Minimize disturbance in filter areas around streams, wetlands and lakes, and other sensitive sites (required buffer width will depend on dominant hydrological processes in given locale to maintain water quality of receiving water bodies). C) Minimize disturbance to storage areas (such as wetlands and ephemeral saturated areas).
3. Maintain hydrological connectivity: Minimize disruptions to water, sediment, nutrient flows within terrestrial system.	A) Consider the interconnectedness and interdependence of water pathways through watersheds when developing management plans (i.e., look beyond the forest stand and consider where the stand occurs with respect to the watershed and water flows). B) Locate roads, bridges, culverts and harvest areas to ensure surface and subsurface hydrological connectivity is maintained and flow is neither impeded nor enhanced.
4. Respect temporal variability: Acknowledge temporal (historic) factors that influence hydrological processes.	A) Recognize there is natural variability in hydrological processes at multiple scales from daily to multi-decadal. B) Recognize there is human induced variability in hydrological processes of different severity (from past management practices to climate change). C) Recognize the timing, frequency and magnitude of extreme events may be changing because of the interplay between natural and anthropogenic factors that are difficult to separate.
5. Respect spatial heterogeneity: Acknowledge spatial (geographic) factors that influence hydrological processes.	A) Consider how scale influences dominance of hydrological processes (moving from headwaters to regional basins). B) Consider how geographic context including climate, bedrock geology, surficial geology, soil type and depth, and topography influences dominance of hydrological processes and patterns as well as forest type and age.
6. Maintain redundancy and diversity of hydrological form and function: Manage with the ethos that redundancy and diversity of hydrological form and function contribute to a forest that can absorb outside disturbances.	A) Consider watershed functions that might be most impacted by future extreme events and plan to protect features that perform those functions. B) Consider multiple ecosystem services when assessing tradeoffs in making development choices. C) Consider the interactive nature of the hydrological system with climatic, geomorphic, ecologic and socio-economic systems.

methods and tools developed or tested in one region to another region without local calibration. Similarly data extrapolation from areas with different climate, bedrock and/or surficial geology is likely not appropriate.

The influence of geographic factors on hydrological processes means there is no single data source or standard tool that can be used without modification for hydrological assessments.

Structure of the report

In this report, the reader is first introduced to the state of scientific knowledge regarding the effects of forest harvesting on hydrology and biogeochemistry. Subsequently, we provide a brief description of existing ground based hydrological datasets available in a national context. These datasets served in part to generate the current state of knowledge and which hopefully will serve us for many more years to improve our understanding of forest hydrological processes. The subsequent three chapters follow a sequence from digital data and tools that are amenable for the static characterization of landscapes to more dynamic characterization. Here are brief synopses of the chapters:

- **Chapter 2** synthesizes research examining the **hydrological effects of forest harvesting** by assessing areas of agreement and disagreement, as well as limitations.
- **Chapter 3** provides an overview of potential sources for **hydrological data** in Canada, and the locations and basic attributes of long-term research or monitoring sites where hydrological data have been collected. Gaps in the current hydrological data sources are highlighted along with possible ways to fill those gaps.
- **Chapter 4** examines novel approaches for collecting hydrological data and their analysis using **remote sensing** techniques.
- **Chapter 5** details recent developments in **digital terrain analysis** techniques for tracking hydrological and biogeochemical pathways and processes in forested landscapes. This section includes ways to link science to practice and methodologies for operationalizing digital terrain analysis for application to forest management planning.
- **Chapter 6** combines remote sensing techniques and digital terrain analysis with **watershed modelling** to look at watershed-level assessments. The data requirements and output of these models are examined in terms of forest management planning requirements.
- **Chapter 7** contains **conclusions and recommendations** to assist resource managers to integrate hydrological assessments into their forest planning and practices. It also identifies research and monitoring priorities to guide future research endeavors.

BOX 1

Terminology: Catchment, watershed, and drainage basin

Hydrologists use the terms catchment, watershed, and drainage basin interchangeably. All three terms signify an area of land where water from rain and melting snow or ice drains down the contributing hillslopes into a body of water, such as a stream, river, lake, or ocean separated from adjacent systems by a drainage divide. The terms refer to both the land surfaces from which water drains and the streams, rivers and lakes that convey the water.

In this report we follow this custom, although we try to reserve the use of the word catchment for small, headwater watersheds and basin for large, regional watersheds.

2.0 The effects of forest harvesting on forest hydrology and biogeochemistry[1]

Copyright permission to re-publish Chapter 2 was only provided for the printed version of this document. To access the full text, tables, and figures included in this chapter please refer to the original Springer publication:

http://www.springerlink.com/content/978-94-007-1362-8/contents/#section=906241

[1] Buttle, J.M. 2011. Chapter 33: The Effects of Forest Harvesting on Forest Hydrology and Biogeochemistry. In: Levia, D.F., Carlyle-Moses, D.E. and Tanaka, T. (Eds.), *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions* (pp.659-674). Ecological Studies Series, No. 216, Springer-Verlag, Heidelberg, Germany. **Re-published with permission of Springer-Verlag.**

3.0 Canada's national hydrological datascape

"Hydrology is a difficult science because it deals with open systems that are very difficult to observe. When we do not yet have an adequate measurement technique for the rainfall falling on a catchment, or for continuously determining the increments of discharge along a stream channel, or measuring the changes in bulk storage in the sub-surface; then doing hydrological science rigorously is going to be difficult."

BEVEN (2008)

3.1 Introduction

Forest managers require high quality datasets to aid and improve their decision making and minimize the effects of forest management activities on hydrological systems. In an ideal world, every manager would have access to spatially distributed water quantity and water quality datasets that would provide not only a baseline to measure the response of the hydrological system to forestry operations in a watershed, but also typical hydrological responses under best management practices.

Access to high quality datasets greatly facilitates adaptive management and improves response time needed to ameliorate negative impacts.

Such information would greatly facilitate adaptive management (e.g., continuous improvement or 'learning while doing' through the monitoring and testing of predicted forest management activity responses or forecasts). It would also improve response time needed to ameliorate negative impacts.

Changes to the hydrological system can be measured at different points along a flowpath. In uplands, soil moisture is a good integrative variable; in lowlands, where water is channelized, water can be measured as streamflow or lake level. Ideally, streamflow is measured at multiple points along a stream network and not just at the watershed outlet.

Unfortunately, most of Canada's forested watersheds are currently ungauged (i.e., streamflow measurements are not taken), which is not surprising given the vast area covered by forests.

Most of Canada's forested watersheds are currently ungauged, therefore, the best strategy is to use data collected at select watersheds across the country and extrapolate knowledge from gauged to ungauged basins.

The limited information available makes it challenging for forest managers to make informed decisions regarding hydrological effects when designing management scenarios or predicting future water resources under a changing climate. In the absence of specific datasets, the best strategy is to use data collected at select watersheds across the country and extrapolate knowledge from gauged to ungauged basins.

In Canada, there are two main sources of hydrological information available for forested areas:

1. Experimental study sites targeting locally-focused hydrological issues; and
2. Water Survey of Canada (WSC) river and lake gauging sites (for discharge and lake level).

The aims of this chapter are to:

- review in detail these two main sources of hydrological data for forested areas,
- show the information gaps that still exist, and
- make recommendations regarding the future of hydrological data to improve the sustainable management of Canada's forests in terms of their water resources.

3.2 Experimental watersheds

Hydrological knowledge of Canada's forests has advanced tremendously thanks to research conducted at multiple experimental sites established across the country since the International Hydrological Decade of the 1970s. These sites were generally established by federal and provincial agencies, with frequent participation by university scientists, and most are relatively small (median size 3.5 km^2).

Efforts have been made during the last 30 years to compile the datasets and draw conclusions from the results of these studies (Bosch and Hewlett 1982, Hetherington 1987, Buttle et al. 2000, 2005, 2009), but there have been few attempts to place these findings into a national context to facilitate extrapolation of results to other sites of interest located in ungauged stations. One exception is the HydroEcological Landscapes and Processes project (HELP) project, funded by the Sustainable Forest Management Network (SFMN), one of Canada's Network for Centres of Excellence.

Hydrological knowledge of Canada's forests has advanced tremendously thanks to research conducted at multiple experimental sites; however, few attempts have been made to place these findings into a national context and to facilitate extrapolation of results to other ungauged sites.

The HELP project - synthesizing hydrological data from forest sites

The objective of the HELP project was to compile the disparate hydrological data from experimental studies across Canada, and organize and synthesize the knowledge into a framework for quantifying hydrological, geomorphic and ecologic processes of forest landscapes (Krezek et al. 2008).

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A central component of the HELP project is the development of a hydrological database that pulls together diverse isolated pieces of information to form a coherent picture of the water resources in Canada's forests. Criteria for inclusion of research sites include the following:

1. At least one hydrological indicator is measured;
2. There is published reference to the site;
3. Sites are primarily forested; and
4. Site location information, experimental documentation and study dates must be available.

Based on the above criteria, 46 research sites have been identified (Figure 4 and Table 3).

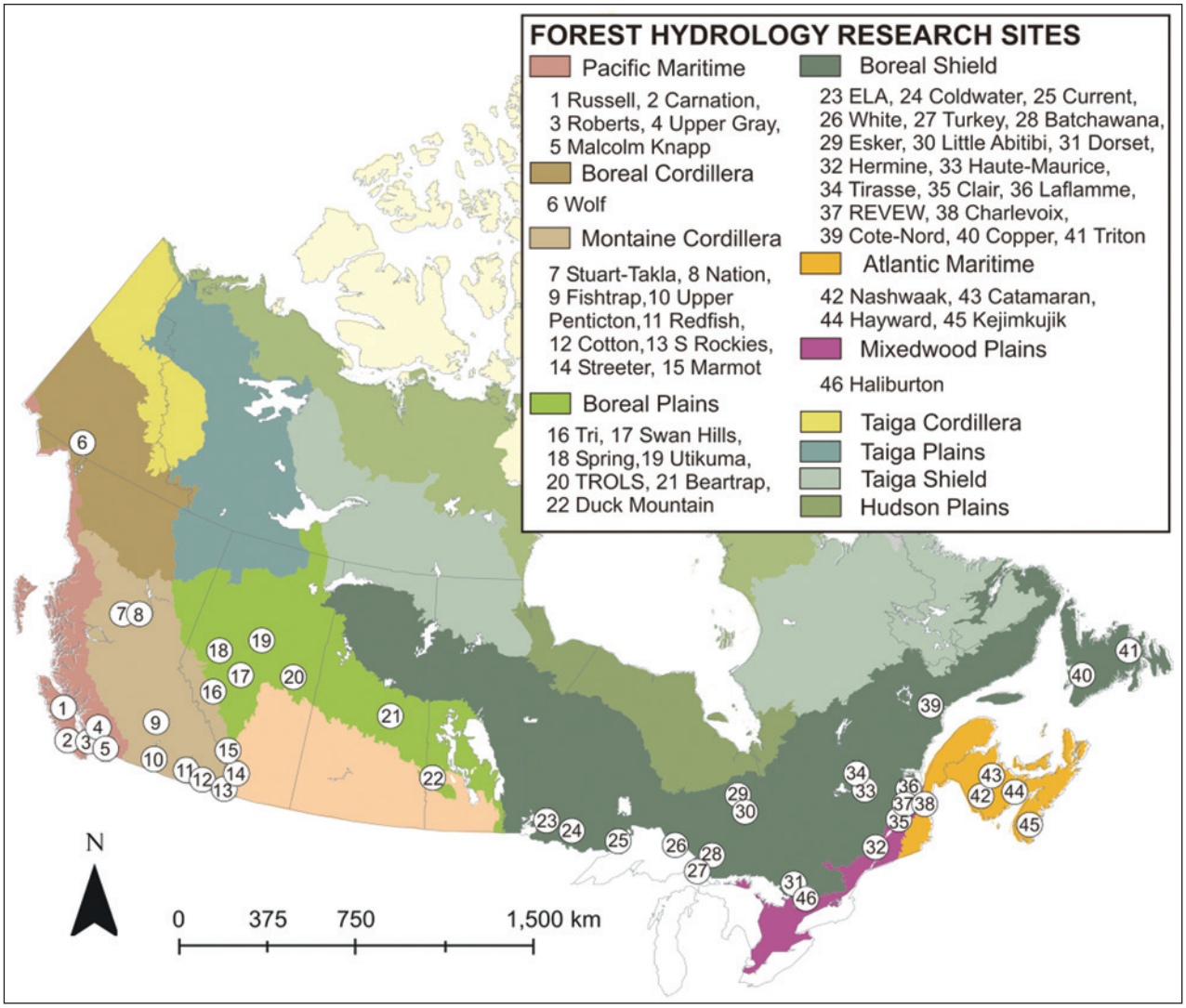

Figure 4. Location of forest hydrology experimental study sites in different ecozones of Canada (modified after Krezek et al. 2008).

These sites are distributed across the country and represent most of the major forested ecozones in Canada, except the more northerly forests and grass mixed forest types (Hudson Plains, Taiga Shield, Boreal Cordillera, and Taiga Plains) (Figure 4). Most sites have experienced some type of forest management activity, predominantly clearcut harvesting. Wildfires were the dominant disturbance in three sites (sites 9, 13, 17, all in western Canada). Twelve undisturbed sites (sites 6, 19, 21, 22, 31, 32, 34-36, 45) and two older second growth sites (sites 4, 11) are also included, serving the important role of reference sites.

Individual metadata pages have been developed for 24 of the 46 research sites. These include a description of the landscape of each site, the experimental design, and contact information (Figure 5). They allow comparison of hydro-meteorological characteristics of research sites in different landscapes across the country, and indicate the status of field-based studies of forest hydrology.

Given the importance of these databases, we believe that renewed institutional support is to finish the compilation and archiving of records of these critical Canadian databases is required. (See http://canforhydro.org for status of the HELP project).

Table 3. **Basic descriptive information on forest hydrology experimental study sites organized by ecozones**

ID	STUDY SITE	Latitude (dd)	Longitude (dd)	Min Area (ha)	Max Area (ha)	No. Basins	Forest Status	Ecozone
1	Russell Creek, BC	50.18	126.16	—	3100	1	Logged	Pacific Maritime
2	Carnation Creek, BC	48.92	125.00	19.4	988	5	Logged	Pacific Maritime
3	Roberts Creek/ Flume Creek, BC	49.42	123.64	16	61	3	Logged	Pacific Maritime
4	Upper Gray Creek, BC	49.60	123.60	—	14950	1	2nd growth	Pacific Maritime
5	Malcolm Knapp/ UBC Research Forest, BC	49.25	122.55	12	89	6	Logged	Pacific Maritime
6	Wolf Creek, YT	60.53	135.12	1450	19500	3	Natural	Boreal Cordillera
7	Stuart-Takla, BC	54.87	125.38	3700	5200	5	Logged	Montane Cordillera
8	Nation River, BC	55.20	124.23	230	410	3	Logged	Montane Cordillera
9	Fishtrap Creek, BC	51.12	120.20	—	13500	1	Fire	Montane Cordillera
10	Upper Penticton Creek, BC	49.62	119.42	370	500	3	Logged	Montane Cordillera
11	Redfish Creek, BC	49.62	117.05	1500	2600	4	2nd growth	Montane Cordillera
12	Cotton Creek, BC	51.35	118.85	105	1736	9	Logged	Montane Cordillera
13	Southern Rockies, AB	49.37	114.40	358	1315	7	Fire and Logged	Montane Cordillera
14	Streeter Creek, AB	50.11	114.07	51	589	4	Logged	Montane Cordillera
15	Marmot Creek, AB	50.95	115.00	212	940	4	Logged	Montane Cordillera
16	Tri Creeks, AB	53.16	117.24	1480	2820	3	Logged	Boreal Plains
17	Swan Hills/ Forest Watershed and Riparian Disturbance (FORWARD) Project, AB	54.20	115.78	13100	24800	3	Fire and Logged	Boreal Plains
18	Spring Creek, AB	54.94	117.73	1530	2100	2	Logged	Boreal Plains
19	Utikuma Lake/ Hydrology Ecology and Disturbance (HEAD) Project, AB	55.90	115.03	5	500	24	Natural	Boreal Plains
20	Terrestrial and Riparian Organisms, Lakes and Streams (TROLS) Project, AB	54.77	111.99	189	5669	3	Logged	Boreal Plains
21	Beartrap Creek/ Prince Albert Model Forest, SK	53.86	104.62	—	11600	1	Natural	Boreal Plains
22	Duck Mountain, MB	51.36	101.26	10300	423000	15	Natural	Boreal Plains
23	Experimental Lakes Area (ELA), ON	49.66	93.74	36	1393	6	Logged	Boreal Shield
24	Coldwater Lakes, ON	49.12	92.15	70	194	3	Logged	Boreal Shield

continued on the next page

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ID	STUDY SITE	Latitude (dd)	Longitude (dd)	Min Area (ha)	Max Area (ha)	No. Basins	Forest Status	Ecozone
25	Current/ Escape Lakes, ON	48.56	89.24	—	20	1	Logged	Boreal Shield
26	White River, ON	48.06	85.81	130	820	3	Logged	Boreal Shield
27	Turkey Lakes, ON	47.01	84.42	3	1150	13	Logged	Boreal Shield
28	Batchawana River, ON	47.00	84.52	15	23617	30	Logged	Boreal Shield
29	Esker Lakes, ON	49.38	81.01	n/a	20000	14	Logged	Boreal Shield
30	Little Abitibi, ON	49.07	81.03	29	9192	20	Logged	Boreal Shield
31	Dorset Experimental Lakes, ON	45.38	79.13	21	23	5	Natural	Boreal Shield
32	Hermine, QC	45.98	74.02	—	5	1	Natural	Boreal Shield
33	Haute-Maurice, QC	48.52	73.42	62	136	5	Logged	Boreal Shield
34	Lac de la Tirasse, QC	49.20	73.63	—	56	1	Natural	Boreal Shield
35	Lac Clair, QC	46.95	71.67	—	226	1	Natural	Boreal Shield
36	Lac Laflamme, QC	47.32	71.13	—	68	1	Natural	Boreal Shield
37	Ruisseau des Eaux-Volées Experimental Watershed (REVEW), QC	47.27	71.46	122	917	2	Logged	Boreal Shield
38	Charlevoix, QC	47.00	70.50	37	279	7	Logged	Boreal Shield
39	Cote-Nord, QC	50.72	67.50	83	409	7	Logged	Boreal Shield
40	Copper Lake, NL	48.83	57.83	114	124	4	Logged	Boreal Shield
41	Triton Brook, NL	48.60	54.59	—	23297	1	Logged	Boreal Shield
42	Nashwaak, NB	46.30	67.03	125	660	3	Logged	Atlantic Maritime
43	Catamaran Brook, NB	46.94	65.91	—	5200	1	Logged	Atlantic Maritime
44	Hayward Brook/ Holmes Brook, NB	45.87	65.19	136	1520	7	Logged	Atlantic Maritime
45	Kejimkujik National Park, NS	44.33	65.20	874	72300	4	Natural	Atlantic Maritime
46	Haliburton/ Gull River, ON	44.73	78.82	4.5	702	9	Logged	Mixedwood Plains

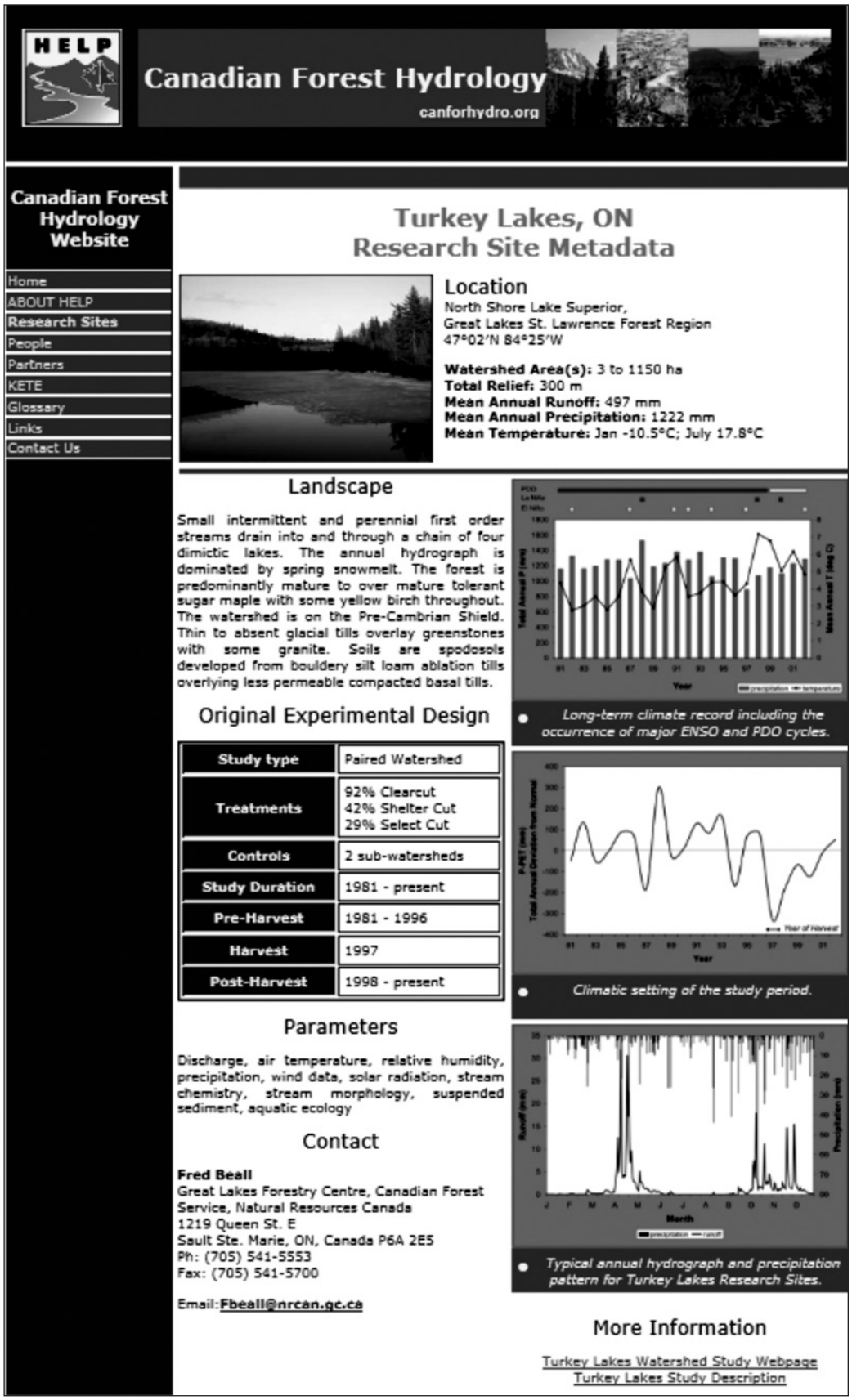

Figure 5. Example of metadata sheet compiled for Turkey Lakes Watershed experimental site by HydroEcological Landscapes and Processes (HELP) project (http://canforhydro.org).

Types of hydrological measurements made

There are some clear trends related to the hydrological measurements being made at these experimental research sites (Krezek et al. 2008). The primary hydrological variable collected at most of the study sites is streamflow; however, it is measured only at the outlet of watersheds. The most important hydrological variables for the remaining sites are water temperature and lake out-flows.

Most sites collect a minimum of air temperature and precipitation (rain and snow) data, unless a representative Meteorological Survey of Canada (MSC) site is located close by. Many research sites with primary meteorological stations also have additional meteorological measurements (e.g., wind, solar radiation, relative humidity) and hydrological data (e.g., snow studies, ground water, soil moisture). Twenty-two sites have aquatic ecology measurements (e.g., fisheries studies) and/or water quality measurements (e.g., water chemistry, dissolved oxygen).

Status of the sites and site records

In terms of activity, approximately half of the research sites are still active. Of the active sites, not all have ongoing scientific research, but they are being monitored for basic hydrological variables (Figure 6). Many of the sites have long-term data records, which are invaluable for studying ecohydrological change under variable climate conditions. Regrettably, maintaining funding for these sites is often difficult. In some cases, associations with other government agencies involved with data collection (i.e., MSC or WSC) have maintained the monitoring (e.g., Hayward Brook, Nashwaak, Kejimkujik) or preserved archived data records (e.g., ELA, Streeter Creek, and Marmot Creek), extending their longevity.

Some research studies, especially those that began in the late 1960s and early 1970s, have exceeded the length of most research professionals' careers, leading to many scattered or lost data sets. Therefore, a secondary benefit of the HELP project is the archiving of published data, making them readily available for future research applications.

Figure 6 indicates the duration of pre-disturbance, harvesting, and post-disturbance conditions monitored by these studies. For example, the Turkey Lakes Watershed site has the longest pre-disturbance hydrological record of any site (16 years). Such long records are critical when assessing the natural variability in a region's climatology and hydrology. Data collected after forest disturbance can then be compared to the range of natural variability. This can help determine whether the hydrological system has been moved beyond the pre-disturbance range of conditions, and can be useful when setting targets in forest management planning and in scenario evaluation.

Long records are critical when assessing the natural variability in a region's climatology and hydrology. Data collected after forest disturbance can then be compared to the range of natural variability under pre-disturbance conditions.

3.3 Hydrometric networks: the Water Survey of Canada

The second major source of hydrological data for forest managers is the Water Survey of Canada's (WSC) national hydrometric network operated by Environment Canada (www.ec.gc.ca/rhc-wsc/). The network currently monitors streamflow (and chemical parameters at some stations) at 2,500 stations located across Canada and maintains an archive of 5,500 stations, of which approximately 700 are in forested regions.

The Water Survey of Canada's (WSC) national hydrometric network monitors 2,500 stations located across Canada and maintains an archive of 5,500 stations, of which approximately 700 are in forested regions.

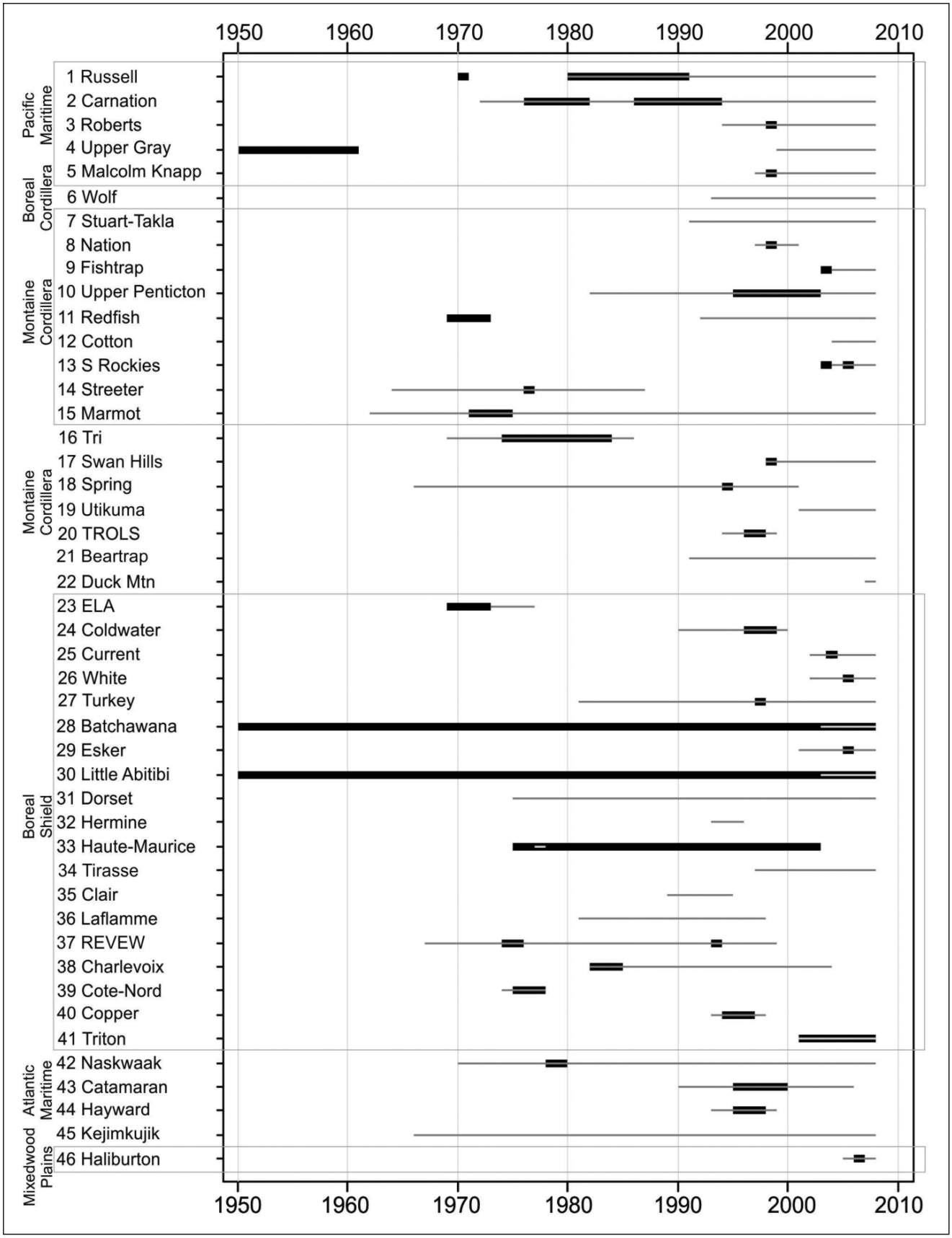

Figure 6. Activity of watershed studies including (a) pre-disturbance and post-disturbance phases, and/or natural forests (thin lines) and (b) disturbance phases (thick lines); current as of 2007.

The median size of the WSC catchments being monitored is about 650 km^2, compared to a median of 3.5 km^2 for the experimental catchments (described in section 3.2), a two orders-of-magnitude difference. However, WSC data are collected for purposes other than assessing the impacts of forest management. Data from some of the WSC streamflow gauging stations have been used to assess the hydrological properties of forest landscapes and streamflow response to forest disturbance in parts of Canada, but it is very difficult to use streamflow records from larger basins to detect any hydrological consequences of forest disturbance (Buttle and Metcalfe 2000). In larger basins, regional factors, such as surficial geology and the presence of lakes and large wetlands, reduce the variability in streamflow metrics (Sanford et al. 2007) and obscure the impacts at the size of current forest harvest blocks (10-200 ha) (e.g., McRae et al. 2001; The Ontario Forest Management Guide for Natural Disturbance Emulation www.mnr.gov.on.ca/en/Business/Forests/Publication/MNR_E000509P.html)[2,3].

It is very difficult to use streamflow records from larger basins to detect hydrological consequences of forest disturbance.

An analysis of the monitoring by WSC stream gauges in forested areas of Alberta, Quebec and New Brunswick (Buttle and Murray 2007) revealed that much of the boreal forest is not monitored at the small basin scale (<10 km^2); and if monitored, the length of monitoring is short with very few sites having more than 35 years of record. There is also a lack of monitoring in the northern part of the boreal forest, even for larger basin sizes. This information is required in order to determine the relative impacts of forest disturbance and other factors (e.g. climate change) on the natural range of variability and frequency of extreme events in streamflow. Thus the data provided by the WSC's national hydrometric network is essential for monitoring and assessing water resources at broad scales, it is, with a few exceptions, insufficient for evaluating local forest management impacts.

This lack of small basin scale stream gauges is significant because it is very difficult to use streamflow records from larger basins to detect any hydrological consequences of forest disturbance (Buttle and Metcalfe 2000).

Much of the boreal forest is not monitored at the small basin scale and the length of monitoring is short with very few sites having more than 35 years of record. There is also a lack of monitoring in the northern part of the boreal forest, even for larger basin sizes.

3.4 Gaps in Canada's current sources of hydrological data

We need to be able to predict downstream effects of disturbance in headwater systems. We also need to be able to assess and predict the cumulative effects of resource development (forestry, oil and gas, mining) and other land uses on aquatic systems.

Unfortunately, the present streamflow monitoring network (experimental and WSC) does not provide adequate coverage of streamflow conditions to address many water resource research and management issues at the appropriate scales across Canada's various forest ecozones.

[2] McRae, DJ, Duchesne, L.C., Freedman, B, Lynham, T.J. and Woodley, S. 2001. Comparisons between wildfire and forest harvesting and their implications in forest management. Environ. Rev. 9: 223-260. Tables 1 and 2 compile data of cut block sizes for Canada. While there is considerable variation, all provinces, other than Ontario, limit cut blocks to less than 150 ha, sometimes much smaller (3.5 ha in PEI). In Ontario, cut blocks can exceed 260 ha, where justified, but the majority of cuts are less than 100 ha. That said, multiple cut blocks occur within a given watershed and can add up to significant fractions of a watershed.

[3] The Ontario Forest Management Guide for Natural Disturbance Emulation (www.mnr.gov.on.ca/en/Business/Forests/Publication/MNR_E000509P.html) specifies that less than 80% in the Boreal and 90% in the GLSL must be less than 260 ha.

Even though experimental study sites collect a suite of hydrological measurements that are highly relevant to hydrological processes, most of the study sites are located in small (<10 km^2) headwater catchments making the extrapolation of hydrological understanding to larger, regional catchments (>10 km^2) problematic.

WSC gauging stations, in contrast, are located within much larger basins (>500 km^2) and cover much longer time periods (Figure 7). While there are hydrological data at small and large basins, there is a dearth of gauging stations within basins in the 10-500 km^2 range.

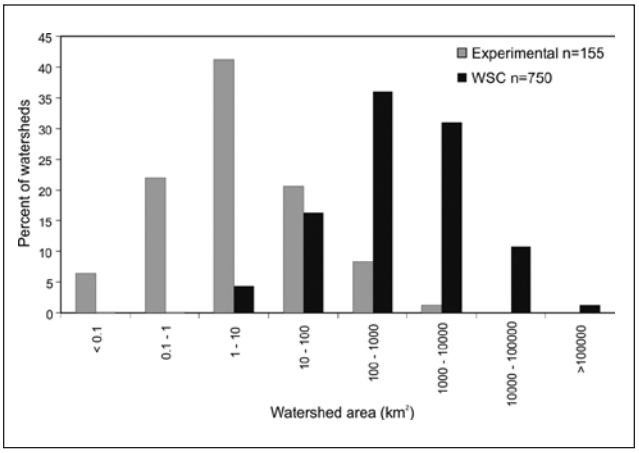

Figure 7. Frequency distribution of watershed areas for experimental research sites in Canada compared with the WSC hydrological data base. The WSC sites have natural, unregulated measurements located within forested regions. Most of the experimental research sites (n=46) have more than one study catchment, which resulted in an overall sample size of 155.

There is a dearth of gauged basins in the 10-500 km^2 range. Also, for the gauged basins where forest harvest has occurred, the links between forest management activities and streamflow have not yet been clearly established.

There is a century of students from North America documenting the effects of forest management activities at small basin scales (cf. NRC 2008 and references within). However, scientists have not clearly established the link between forest management activities and streamflow at intermediate and large basin scales. This knowledge is important because it could lead to alternate practices to minimize effects at scales that are relevant to downstream water supplies.

Scaling relationships: from headwaters to regional basins

To understand the link between forest management activities and hydrological effects at local and larger scales, we need to establish scaling relationships between small headwater catchments and larger regional basins.

Questions such as: how does hydrological behaviour under 'natural' conditions propagate across scales? and how do harvesting related disturbances propagate? need to be answered. Insights related to these questions were provided in part by the SFMN-funded Scalable Indicators of Disturbance project. The project showed that in some of Ontario's forested landscapes the range of variability in streamflow properties (low flows in central Ontario [Sanford et al. 2007]; mean annual peak runoff in southern Ontario [Buttle and Eimers 2009]) may be considerable for small drainage basins, but begins to stabilize above a particular basin size threshold. Such behaviour is consistent with the Representative Elementary Area (REA) concept, which hypothesizes similarity in basin response above a threshold area.

The Representative Elementary Area (REA) concept hypothesizes similarity in basin response above a certain area. It also hypothesizes a tendency for larger basins to average the variability in local runoff patterns observed across smaller areas. This should be considered when attempting to predict effects based on data obtained at a different scale.

The REA concept also hypothesizes a tendency for larger basins to average the variability in local runoff patterns observed across smaller areas (Wood et al. 1988). This averaging behaviour needs to be considered

when attempting to use the results from research basins to predict the cumulative effects of forest management activities for larger drainage basins.

The occurrence and magnitude of critical threshold areas should be examined for various forest landscapes. This could provide guidance to managers on the relationships between harvest disturbance levels and streamflow response.

3.5 Recommendations and conclusions

In order to effectively incorporate the hydrological principles into a forest management framework, forest planners and managers need access to relevant hydrological databases. Based on the current state of the hydrological datascape, we recommend the following steps be taken by the hydrological community as a whole.

3.5.1 Consolidate existing data and bring them under a common umbrella

A large volume of data relevant to sustainable forest management already exists, with the experimental studies conducted across the 46 headwater sites and the hundreds of WSC sites collecting streamflow data in Canada. However, many of the datasets collected at the experimental sites are being lost as people retire, studies are completed or discontinued, or as older storage devices become obsolete.

Many of the datasets collected at the experimental sites are being lost as people retire, studies are completed or discontinued, or as older storage devices become obsolete. These copilation efforts need to be continued.

The compilation effort that begun with the HELP project needs to be continued. All existing relevant datasets should be archived, along with the WSC and MSC datasets, which are already online. There are also other spatial datasets available (e.g., leaf area index, soil moisture, snow cover) which may inform managers about site conditions, hydrological flowpaths or soil moisture storage. Such datasets should be clearly identified and linked to the proposed hydrological portal as well.

3.5.2 Reverse the trend of closing ground based monitoring stations

Since the golden age of hydrometric monitoring during the 1970s, hundreds of stations have been shut down as cost saving measures. This trend clearly needs to be reversed since remote sensing of discharge is generally not possible.

More affordable monitoring, such as the installation of automated sensors, can be implemented to continue the data collection effort.

More affordable monitoring, such as the installation of automated sensors, can be implemented to continue the data collection effort.

In our opinion, government and university scientists need to work together with local stakeholders, including the public, to monitor their environment. For example, high schools could sponsor and operate sensors that measure hydrological variables to provide experience to students while decreasing overall monitoring costs. Data would be checked by professionals and compiled in centralized databases.

3.5.3 Complement ground based data with remote sensing data

Remote measurement of discharge is only possible on the largest rivers such as the Mackenzie or Athabasca; however, open water extent, saturated zone extent, and lake chlorophyll *a* can be measured remotely.

Other variables that can be useful in hydrological modelling, such as leaf area index and digital elevation models should also be linked to the hydrology portal for easy identification and overlaid with other spatial datasets.

Remote sensing images provide an excellent source of data on characterizing present and past land cover in order to assist in teasing out the separate effects of climate variability and forest disturbance.

Remote sensing images provide an excellent source of data on characterizing present and past land cover in order to assist in teasing out the separate effects of climate variability and forest disturbance.

Landsat (a series of satellites operated by US government organizations used to gather optical information about the Earth's surface) databases go back to the early 1970s, providing the longest record of land cover at regional scales.

Information on land cover needs to be integrated with the hydrological datasets compiled for the experimental and WSC watersheds.

3.5.4 Integrate data with hydrological models to improve prediction in ungauged basins

In lieu of collecting new data, which is definitely needed in many parts of our forests, the existing databases can be used to build hydrological models of different complexity to improve prediction in ungauged basins. Model predictions can be constrained to give results with acceptable uncertainty bounds and can be combined with remote sensing data layers, such as soil moisture and snow cover, to provide forest managers with additional information to aid in decision making.

The existing databases can be used to build hydrological models of different complexity to improve prediction in ungauged basins.

In conclusion, we advocate a strategic data collection regime that relies on multiple stakeholders and is interfaced with existing datasets. This will help build a comprehensive picture of our hydrological systems in forested landscapes across the country.

4.0 Bird's-eye view of forest hydrology: Novel approaches using remote sensing techniques[4]

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http://www.springerlink.com/content/978-94-007-1362-8/contents/#section=906241

[4] Sass, G. Z. and Creed, I. F. 2011. Chapter 3: Bird's-eye view of forest hydrology: Novel approaches using remote sensing techniques. In: Levia, D.F., Carlyle-Moses, D.E. and Tanaka, T. (Eds.), *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions* (pp.45-64). Ecological Studies Series, No. 216, Springer-Verlag, Heidelberg, Germany. **Re-published with permission of Springer-Verlag.**

5.0 Digital terrain analysis approaches for tracking hydrological and biogeochemical pathways and processes in forested landscapes[5]

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http://www.springerlink.com/content/978-94-007-1362-8/contents/#section=906241

[5] Creed, I. F. and Sass, G. Z. 2011. Chapter 4: Digital terrain analysis approaches for tracking hydrological and biogeochemical pathways and processes in forested landscapes. In: Levia, D.F., Carlyle-Moses, D.E. and Tanaka, T. (Eds.), *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions* (pp.69-95). Ecological Studies Series, No. 216, Springer-Verlag, Heidelberg, Germany. **Re-published with permission of Springer-Verlag.**

6.0 Virtual ecosystems: Using hydrological models to understand the past and predict the future of water in forests

"At the present stage of hydrological science, hydrologic modelling is most credible when it does not pretend to be too sophisticated and all inclusive, and remains confined to those simple situations whose physics is relatively well understood and for which the modeller has developed a good 'common sense' within his primary discipline."

KLEMEŠ (1986A)

6.1 Introduction

Models are mental constructs of how the world functions. By definition they are approximations and simplifications of reality, capturing the essence of the way systems work. Models may range from qualitative/perceptual models (with only pictorial or verbal descriptions of system components and functions) to quantitative/numeric models (with physics-based mathematical descriptions of system components and functions). In this chapter we refer to models specifically as quantitative descriptions of how ecosystems cycle water, nutrients and sediments.

Models can be viewed as virtual ecosystem laboratories, in which replicating and manipulating system components is infinitely easier than doing the same with real ecosystems.

The revolution in desktop computing has led to the proliferation of quantitative models that are used to understand the internal workings of ecosystems, but may also be used as predictive tools to test future "what-if" scenarios. In a sense, models can be viewed as virtual ecosystem laboratories, in which replicating and manipulating system components is infinitely easier than doing the same with real ecosystems. Models provide better control in understanding individual processes, and provide the ability to hindcast and forecast the behaviour of systems. The possibilities are limitless, but modellers should remember that despite their best efforts, models are just educated guesses about how the world works.

In forest hydrology, models can be used to understand the water cycle and associated nutrient and sediment cycles. They also have a large potential for informing the placement of access roads, bridges and culverts, harvest blocks, landings and buffers in forest planning.

Models can be used to understand the water cycle and associated nutrient and sediment cycles. They also can inform placement of roads, bridges and culverts, harvest blocks, landings and buffers.

Early work in models evolved from engineering requirements to properly design structures to withstand large floods. By the 1960s, research scientists had also realized the power of models for understanding catchment behaviour (Hewlett and Hibbert 1967). The driving questions of the day, then as now, concerned runoff processes (i.e., how much of the rainfall is turned into runoff and what is carried with it). The earliest catchment model was the Stanford Watershed Model (now called HSPF) (Crawford and Linsley 1966), a lumped parameter hydrological model able to simulate the primary hydrological processes. Since then, modelling has come a long way due to faster computing, more realistic representation of patterns and processes, and improved characterization of the earth's surface and subsurface.

The evolution of hydrological models is succinctly captured by Singh and Woolhiser (2002), who reviewed a comprehensive list of 69 hydrological models developed since the 1960s. The most sophisticated models can now address soil-vegetation-atmosphere transfers of water and energy, soil moisture storage, different runoff generation processes, shallow groundwater movement, and in-stream or in-lake processes. Hydrological models are increasingly being used to predict hydrological and biogeochemical responses to anthropogenic changes of system components (e.g., removal of vegetation during forest harvesting) (Tague and Band 2001b).

Models can assess the cumulative effects of anthropogenic activities in forests on the hydrological system.

A key strength of models from a forest management perspective is the ability to assess the cumulative effects on the hydrological system of anthropogenic activities in forests such as harvesting, building of roads and other linear features, as well as simulating the changes in forest composition due to climate driven forest dieback.

Despite the proven usefulness of models in tackling hydro-ecological problems, their utility in capturing the complex nature of ecosystem processes has been questioned, especially when used to predict system behaviour outside of their calibration period and place (Beven 1993). There are four main criticisms with respect to ecosystem models in general:

1. Most of the processes represented in models are derived at a point scale but applied to much larger scales;
2. There is a lack of data to parameterize models (especially spatially distributed models);
3. Most spatially distributed models need experts to run them; and
4. Models can sometimes give the same answer using entirely different parameter sets, leading many to question the veracity of the entire model structure.

The key to successful modelling is the selection of a parsimonious model driven by the question at hand.

The response from modellers is that in spite of the general shortcomings of models, there are models for many hydro-ecological questions that are useful for understanding and predicting ecosystem behaviour across a wide range of scales and geographies. The key to successful modelling is the selection of a parsimonious model driven by the question at hand: where simpler models exist they should be used (Rosbjerg and Madsen 2005). For example, if only water yield is needed, then a one-dimensional bucket model that characterizes discharge at the catchment outlet might be sufficient. On the other hand, more complex, spatially explicit models would be needed if the objective of the modelling exercise was to predict runoff post-harvest since the impact of harvesting depends on the location of the harvest block with respect to hydrological flowpaths.

Model evolution is an ongoing process; models are continually being improved.

Model evolution is an ongoing process. While there might be inherent limits to models in general, the continual improvement of models based on the

comparison of model predictions and observations increases the reliability of this ecosystem tool.

The goal of this chapter is to provide a synthesis on modelling for forest managers and hydrologists who are interested in exploring different hypotheses about system behaviour in forested ecosystems, as well as testing the possible outcomes of different management scenarios on water resources. Some of the key questions being tackled by modellers are related to water quality, including nutrient and sediment export from catchments, and water quantity, including peak flows, base flows and annual water yield within natural and managed systems. An overriding issue for scientists and managers alike is predicting the likely effects of climate change on the different components of the water cycle, from local to global scales.

Modellers are tacking questions related to water quality and water quantity. An overriding issue is prediction of the likely effects of climate change on different components of the water cycle.

This synthesis will focus on forested ecosystems in Canada, with an emphasis on how hydrological modelling is being used by forest hydrologists in science, management and policy. It comes on the heels of an excellent review by Beckers et al. (2009) who focus on hydrological models relevant for forest management and climate change applications in British Columbia and Alberta. We offer a broader scope geographically and application-wise, and focus on the potential of models in general rather than specific models.

Models are a key component of the digital hydrological toolkit, along with GIS, digital terrain analysis and remote sensing techniques. These tools can help society to manage multiple ecosystem services and aid in the drive towards long-term sustainability. We explore the themes of how models advance our knowledge of the natural variation of hydrological patterns and processes in forests, the influence of anthropogenic effects on this natural variation and the cumulative effects of climate change. We first review steps involved in the selection and application of hydrological models, then address model applications.

Models are a key component of the digital hydrological toolkit, along with GIS, digital terrain analysis and remote sensing techniques.

6.2 How to pick your model: a primer

Finding the appropriate model for a given purpose can be a great challenge, especially in today's model-saturated world where model abbreviations such as HSPF and TOPMODEL do not reveal much about their purpose or ease of use. While a standard model for forest hydrology would be nice, currently no model can be certified or "validated" to be applicable in any given catchment. As a result it is imperative to work through the exercise of picking the optimal model for each new modelling application.

Jakeman et al. (2006) offer a useful step-by-step modelling framework for the development and evaluation of environmental models. We have modified this framework and tailored it for forest managers and hydrologists who do not have the resources to develop or modify an existing model (Figure 17). There are a variety of considerations that have to be made to make an informed decision on model selection: context, function, performance, and evaluation. We start with the assumption that the hydrologist entering the process of selecting a model has a well-defined modelling goal.

6.2.1 Model context

Model goal and model context go hand in hand, since the goal of a modelling exercise is defined by its context. For example, the goal could be modelling peak flows given a changing climate, but the geographic location (e.g., northern Ontario), scale (e.g., first-order basin) and acceptable level of uncertainty (e.g., ± 15% of water balance components) need to be specified in order for model selection to proceed. Defining the

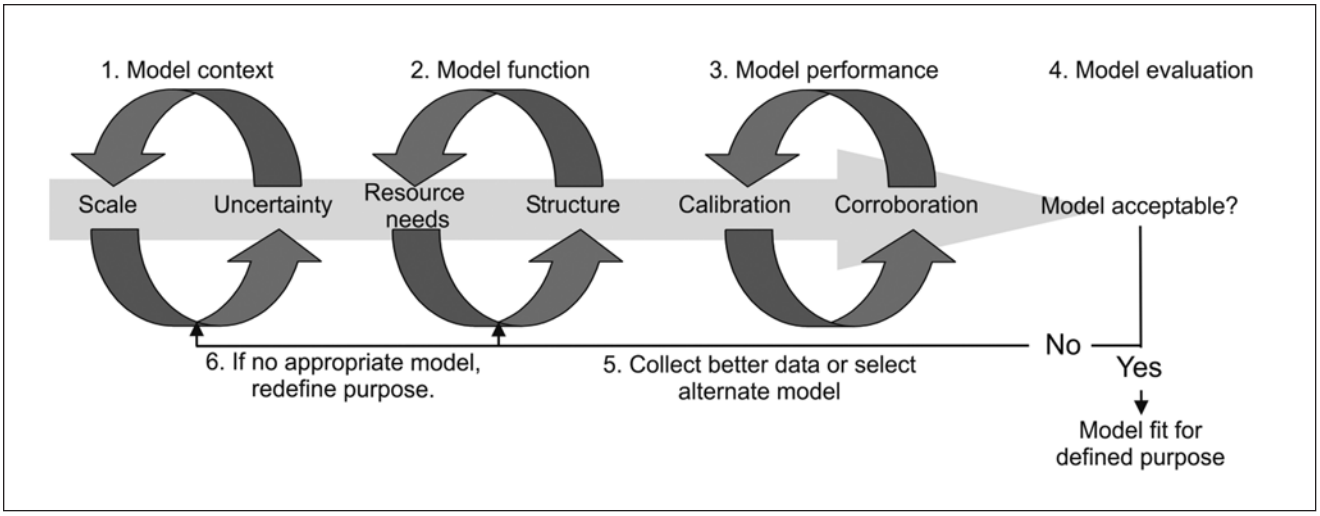

Figure 17. Model evaluation framework for forest hydrologists.

model context places the proposed modelling exercise into its larger scientific, management and policy environment as well as into its geographic context characterized by scale and an expectation of uncertainty.

Modelling studies are driven by different goals. These range from basic hypotheses testing about how ecosystems work to more applied goals such as evaluating the effects of different management scenarios. Especially in applied contexts, more than one stakeholder may be involved with the modelling, and their individual expectations will need to be balanced with those of others.

Model goal and model context go hand in hand, since the goal of a modelling exercise is defined by its context.

The initial scoping for the modelling exercise should keep the issues of scale and uncertainty at the forefront. The question of scale will determine the geographic extent of the system being studied as well as the larger context it fits within. Scale, through its strong association with surface heterogeneity, also has a strong influence on model structure as discussed in the next section. As scale increases, processes that are important at finer scales can be omitted and model structures can be simplified.

In applied contexts, such as evaluating the effects of different management scenarios, more than one stakeholder should be involved with the modelling, and their individual expectations will need to be balanced with those of others.

Acceptable levels of uncertainty have to be determined at the outset of the modelling study. For instance, models that serve to protect life and property (e.g., flood protection structures) require much lower uncertainty associated with the output than models that are used for understanding the natural behaviour of systems.

Scale and acceptable levels of uncertainty are important considerations to take into account while building a model.

6.2.2 Model function

Once the modelling context is defined, the stage is set for selecting a model that can answer the question under consideration at the appropriate scale with the appropriate level of uncertainty. Model selection enters the stage of considering model functionality, which asks the following critical questions:

1. Which part of the hydrological cycle needs to be incorporated in the model?
2. At what level of detail should the hydrological processes be described?; and
3. What will be the resource requirements for a model with the selected functional attributes?

Once the modelling context is defined, the stage is set for selecting a model that can answer the question under consideration at the appropriate scale with the appropriate level of uncertainty.

6.2.2.1 Model structure

Model structure is a determinant of model functionality. It is a multifaceted concept that considers process representation of the relevant parts of the hydrological cycle, the level of spatial and temporal detail (or discretization) needed to represent the processes, and the computational techniques needed to run the model (Table 9). Process representation and level of detail are in turn influenced by the climate, geology and topography of an area.

Process representation

Process representation describes the way sub-components of the system interact with other sub-components in terms of transferring energy and matter between them. For example, in forested ecosystems the canopy is an important sub-component as it intercepts precipitation (matter) and converts sunlight (energy) to be processed and used by other sub-systems. Models represent processes in three major ways:

1. Empirically, using experimentally derived relationships such as linear regressions (e.g., US Soil Conservation Service (SCS) curve number for calculating runoff);
2. Analytically, using simplifying assumptions to derive solutions of the governing equations describing conservation of mass, momentum and/or energy (e.g., Green-Ampt equation for describing infiltration); and
3. Physically, using equations describing conservation of mass, momentum, and/or energy (e.g., Penman-Monteith for ET).

Process representation describes the way sub-components of the system interact with other sub-components in terms of transferring energy and matter between them.

Some models use a combination of approaches to represent different processes. There are special, geographically unique watershed processes that need to be considered as well. These include fog drip, rain-on-snow events, lake and wetland storage and release. Some of these processes involve phase changes of water, and require careful consideration because of the associated transfers of matter and energy.

Level of detail for process descriptions

The level of detail for process descriptions depends on the type of geography as well as the required precision for model output (both in terms of space and in time). For example, drier climates will need to consider multiple storage compartments and their interactions.

The level of detail for process descriptions depends on the type of geography as well as the required precision for model output.

Table 9. **Structural properties of models characterized by spatial and temporal discretization, process representation (defined by relationships between system components and the outside world), and computational approach**

Structural property of model		Different approaches to representing structural property
Spatial discretization (horizontal)		Lumped
		Semi-distributed (hydrological response unit, elevation bands, hillslopes, sub-basins, topographic index, etc.)
		Distributed (grid cells, patches based on intersection of different GIS layers)
Spatial discretization (vertical)	Soil layers	Not represented
		Conceptual representation (unsaturated/saturated zones)
		Explicit soil depths
		Finite difference or finite element discretization (subsurface grid cells)
	Vegetation layers	Not represented
		Single layer (canopy)
		Two layers (canopy, shrub layer)
		Two or more layers
Temporal discretization		Annual
		Monthly
		Daily
		Hourly
Watershed processes		Empirical approaches
		Analytical approaches
		Physical approaches
Computational approach		Deterministic
		Stochastic

It is not necessary to enumerate all hydrological processes thought to occur in an area; instead the challenge is to find the dominant ones given the physical environment. More elaborate physical descriptions lead to higher degrees of complexity and usually greater demand for resources (both in terms of data and computational power), expert knowledge and finances. A wisdom passed down through the ages is encapsulated in Occam's razor, which says that if something can be described in simpler terms it is probably the more realistic explanation. The idea of parsimony is critical, but managers need to balance carefully the necessary process descriptions in order to get the right answers for the right reasons.

Discretization

Process representation is closely linked to model discretization, which describes how the model treats the spatial and temporal dimensions of the system being modelled (Table 9). The spatial dimension has both horizontal and vertical components. Horizontally, space may be:

1. Lumped (i.e., one or just a few units);
2. Semi-distributed (i.e., parts of the landscape with similar physical characteristics behaving identically); or
3. Gully distributed (multiple units each behaving under their own regime).

Process representation is closely linked to model discretization, which describes how the model treats the spatial and temporal dimensions of the system being modeled.

Distributed models are divided into parts based on a grid pattern or based on patches defined by uniqueness in geology, soils, climate and land use/land cover. In the vertical dimension, models may represent vegetation (e.g., canopy, trunk, shrub, and ground cover), soil and multiple surficial geology layers. In the temporal dimension, the most common timescales are daily, monthly and annual; however, some models focus only on individual precipitation events or on steady-state conditions.

The level of spatial and temporal discretization depends in part on the modelling question being asked. Unfortunately, the level of discretization is often driven by availability of data and not by science-based considerations.

Computational approaches

Different discretization and process descriptions might entail different computational implementations. Computationally, models can be categorized as deterministic or stochastic. With deterministic models, all model runs will give the identical answer given the same input data. In contrast, stochastic models will have different output for every model iteration due to the element of chance associated with the random selection of parameters from predefined distributions. Stochastic models are by nature preferable when testing the sensitivity of a model's performance to parameter distributions but do require long computation times.

Different discretization and process descriptions might entail different computational implementations. Computationally, models can be categorized as deterministic or stochastic.

Models and forest management

While most hydrological models can be used to answer fundamental hydrological questions regarding the water balance, only a small number of models are directly relevant to forest management. The most important issues for managers are planning and operations. Management has historically focused on maximizing biomass production with operational efficiency and minimal environmental effects (e.g., minimizing machinery downtime due to muddy conditions). However, managing for ecosystem services like water quantity and water quality is increasing, due to updated provincial regulations, forest certification requirements and the use of a criteria and indicators approach to SFM (Canadian Council of Forest Ministers 1995, Blumenfeld et al. 2009).

Addressing these management issues usually requires an explicit treatment of space since the position of harvest blocks, roads, and other disturbances determine their impact on the hydrological system. Embedded in the consideration of space is a requirement for high spatial resolution of input data when looking at the impact of linear features such as roads on hydrological flowpaths.

Different discretization and process descriptions might entail different computational implementations.

6.2.2.2 Model resource requirements

Models require data, computers and finances. The resources required are a direct function of model structure and complexity (Table 10). Data requirements usually create the most severe bottlenecks because data are scarce. On a practical level, data availability consequently often drives model selection given that most users will not have the ability or resources to collect more data in order to satisfy the requirements of perhaps more appropriate models (Beven 2004).

Data requirements can be broken into three categories:

- input data to force the model forward in time,
- spatial characterization data to describe the spatial differences between the different modelling units, and
- parameters with which to calibrate model equations.

Table 10. **Model complexity and its relation to data, resource and time requirements for any modeling exercise**

	Low complexity	Medium complexity	High complexity
Data requirements			
Climate forcing variables	Monthly precipitation and temperature	Daily precipitation and temperature	Hourly to daily precipitation and temperature
Additional forcing variables	No additional meteorological forcings required	Additional meteorological forcings may be required	Additional meteorological forcings may be required
Spatial data	No need for spatial data	Requires spatial data (DEM, soils, and forest cover)	Requires spatial data (DEM, soils, and forest cover)
# of parameters	Less than 25 parameters	About 25 to 75 input parameters	Typically over 75 input parameters
Calibration	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			
Preprocessing	Low data preprocessing effort	Medium data preprocessing effort	High data preprocessing effort
GIS analysis	Does not require GIS analysis	GIS analysis required for some models	GIS analysis required for most models
# of people required	Can be completed by one person	Can mostly be completed by one person	May require project team
Time requirements	Less than 2 weeks	About 2 weeks to 2 months	About 2 to 6 months

Models require data, computers and finances. Data availability often drives model selection.

Climate data drive most hydrological models, and often consist of only precipitation and temperature time-series. In river models, runoff time series may suffice as input and many steady-state groundwater models are driven by constant head or flux boundaries.

Spatially distributed data describe the land surface, including topography, geology, and vegetation. There are multiple sources, but there is much weaker coverage in remote areas and of the subsurface.

The real distinction between spatially distributed data and data that are used as parameters is that parameter values may end up being modified during the calibration process whereas the other descriptive datasets will not. Parameter values such as hydraulic conductivity come either from field measurements (i.e. from previous studies), or become adjustable model values (i.e. modified during the model calibration process).

Climate data drive most hydrological models. Spatially distributed data describe the land surface, including topography, geology and vegetation.

Data uncertainty is an important consideration in selecting input data; the old axiom "garbage in, garbage out" is very true. Model outputs will be as good as model input (Whitaker et al. 2003). At this point in the modelling process, there may be tradeoffs between a feasible model and the ideal model. The availability of the data will dictate some choices and may even change the overall purpose of the modelling exercise.

Data uncertainty is an important consideration; the old axiom "garbage in, garbage out" is very true.

Despite many technological advances, computational resource requirements are still an important consideration. Spatially explicit models covering large areas require extensive processing time (Table 10). Also, learning to assemble datasets and parameterize models can take some time. All of these factors play into modelling costs, which also can influence the type of model used.

Hydrological models for use in forest management

So what are the best models from a forest management point of view? In a recent review, Beckers et al. (2009) concluded there is no single "best" model for use in an operational forest management context. They identified nine models that could potentially be used for addressing forest management and climate change questions in British Columbia and Alberta (Table 11). These include one low-complexity model (WRENSS), four medium-complexity models (UBCWM, BROOK90, ForWaDy, UBC-UF), and four medium-complexity models (DHSVM, RHESSys, WaSiM-ETH, CRHM).

There is no single "best" model for use in an operational forest management context. Many cannot yet address questions of interest to forest managers, or are difficult and costly to apply.

What is striking from Table 11 is that the components that most interest forest managers are the least developed and represent an important knowledge gap. For example, only the most complex models, DHSVM and RHESSys, have the capability to address the effect of roads on hydrological systems. On the other hand, distributed models such as DHSVM and RHESSys are difficult to apply and populate with realistic data, requiring significant time, expertise and cost. As a result they are only applied to a few sites by a few experts.

6.2.3 Model performance

Calibration

Once a model has been chosen and the necessary data compiled, the model is ready for calibration. Calibration involves adjusting (tweaking in modellers' terms) a few key parameters that have a strong control on model output. In most modeling exercises this results in only two or three sensitive parameters (Jakeman and Hornberger 1993). For example, in RHESSys, hydraulic conductivity and the decay of hydraulic conductivity with depth are the two parameters that are "tweaked" during calibration.

Once a model has been chosen and the necessary data compiled, model is ready for calibration. Calibration involves adjusting a few key parameters that have a strong control on model output.

While many of these parameters start out as measurable values in the field, their final values used in the model can be totally dissociated from reality, and are often called effective parameters. Some people have argued that these parameters capture an emergent property of catchments such as a catchment integrated hydraulic conductivity value (C. Tague, personal communication).

Assessing performance

After each calibration run, model performance is assessed based on visual inspection of the hydrograph and statistical assessment of goodness of fit comparing

Table 11. Models that have been useful in the study of forest hydrology (modified from Beckers et al. 2009)

Category	Purpose	Abbreviated model name	Model complexity	Watershed discretization	Simulation of forest harvesting	Forest growth	Road construction and management
Forest hydrology models	Annual water yield	WRENSS (WinWrnsHyd/ECA-AB)	Low	Lumped	Mixed	No	No
	Peak flow	UBC-UF Peak Flow Model	Medium	Distributed	Empirical	No	As Hortonian overland areas
	Water balance	BROOK90	Medium	Lumped	Mixed	No	No
		ForHyM	Medium	Lumped	Empirical	No	No
		ForWaDy	Medium	Lumped	Mixed	No	No
	Watershed hydrology	DHSVM	Medium	Distributed	Physical	No	Road drainage network and structures
		RHESSys	High	Distributed	Analytical	Yes	Road drainage network and structures
Other models	Water balance	HELP	High	Lumped	Mixed	Yes	No
	Watershed hydrology	ACRU	Medium	Semi-distributed	Mixed	No	No
		CRHM	High	Semi-distributed	Physical	No	No
		HBV-EC	High	Semi-distributed	Empirical	No	No
		HEC-HMS	Medium	Semi-distributed	Empirical	No	No
		HSPF	High	Lumped	Mixed	No	No
		PREVAH	High	Semi-distributed	Analytical	No	No
		PRMS/MMS	High	Semi-distributed	Mixed	Yes	No
		SWAT	High	Distributed	Mixed	Yes	No
		UBCWM	Medium	Semi-distributed	Mixed	No	No
		WaSiM-ETH	High	Distributed	Analytical	No	No
		Watflood	High	Semi-distributed	Mixed	No	No
	Groundwater -surface water models	InHM (HydroGeoSphere)	High	Distributed	N/A	No	1-D overland flow segments
		Mike-SHE	High	Distributed	Mixed	No	No
		MODHMS	High	Distributed	Empirical	No	No
	Soil erosion	WEPP	High	Semi-distributed	Mixed	Yes	No
	River basin models	SSARR	High	Semi-distributed	Empirical	No	No
		VIC	High	Lumped	Physical	No	No

model output (daily discharge in most instances) with observations. The most common goodness of fit metric is the Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970), despite some investigators questioning its universal application (McCuen et al. 2006, Jain and Sudheer 2008).

After each calibration run, model performance is assessed based on visual inspection of the hydrograph and statistical assessment of goodness of fit comparing model output with observations.

While Nash-Sutcliffe and other goodness of fit metrics, such as the coefficient of determination and mean square error, may be low hurdles to test agreement between measured and simulated values (Sivapalan 2009), goodness of fit metrics and metrics of bias, together with good judgment, can help find the optimal parameters. Selecting the optimal parameter values is often done on a trial and error basis. Recent advancements in automatic calibration methodology have allowed parameters to be selected by optimizing single or even multiple objective functions (Madsen 2000).

Testing

Once the model is adequately calibrated, it is tested with a dataset not used during calibration, in a process called model testing. The same assessment methods are used as during model calibration. Once a certain level of fitness is reached, the model can be used for its intended purpose.

Once the model is adequately calibrated, it is tested with a dataset not used during calibration, in a process called model testing.

Model testing needs to be placed in context, because tested models cannot necessarily be transposed to a different climate or land use regime or a completely new geography. Even the most physically rigorous model can provide misleading results if used well outside its intended modelling space (Kuczera et al. 1993). Transposability, either in time or space, needs to be verified during the testing process (Klemeš 1986b, Refsgaard and Knudsen 1996). For example, if a model is to be used to assess the effects of drought, it should be calibrated against a wet period and tested during a dry period.

A tested model cannot necessarily be transposed to a different climate or land use regime or a completely new geography.

Almost all hydrological model calibration and testing is done at the catchment outlet using discharge as the assessment variable. This is completely acceptable if the purpose of the modelling exercise is to investigate water flows from a catchment. However, it leaves much to be desired if the goal of the modelling is to understand what is happening within the catchment.

Most hydrological model calibration and testing is done at the catchment outlet using discharge as the assessment variable. Ideally the catchment's internal workings would also be verified, but this is rarely done.

In an ideal world, the internal workings of a catchment are also verified. This could be accomplished using discharge measurements along the stream network (e.g., Sanford et al. 2007) or using spatial measurements of soil moisture or ET rates for example (e.g., Oudin et al. 2003), but the general lack of such data means that internal testing is rarely done. The use of remote sensing and distributed wireless measurement networks will go a long way in remedying this data gap.

6.2.4 Model evaluation

Error and uncertainty

No model output will perfectly match the observed measurements. The error contained in the output can be due to four different reasons (Butts et al. 2004):

1. random and systematic error in model inputs or boundary conditions;
2. random or systematic errors in outputs;
3. suboptimal parameterization; or
4. model bias.

It is imperative that some estimate of these errors be presented so that reasonable inferences can be made from the model output. At a minimum, measures of uncertainty can be computed by propagating values of the lower and upper bounds of parameter distributions through the model. There are also novel methodologies based on Monte-Carlo style likelihood estimation of parameter uncertainty (Beven and Binley 1992).

Most model users lack the expertise to alter a model's structure; the best chance at reducing error is to spend more time with parameterization and to ensure that the input data have the highest quality checks. For example, if the output is consistently biased, there could be some unrealistic parameter values.

The best chance at reducing error is to spending more time with parameterization and to ensure assuring that the input data have the highest quality checks.

Only model developers have the expert knowledge to tinker with the internal coding of the model to solve any random or systematic error in model output. They would also be able to add in processes/components that seem to be causing the high levels of error. Communication with model developers could be the most fruitful way forward if the modelling process stalls because of some systematic error, although this may not be possible for most managers.

Also, communication between model users and model developers could be a good strategy to minimize error.

Equifinality

Even if error is low, models can still suffer from the bane of all modellers: equifinality. Equifinality occurs when multiple parameter sets give similar model output; this can undermine confidence in the entire model edifice. Does equifinality imply that parameter values are all fictional? What about the serious thought that goes into designing the models? It is a serious criticism that may not have a satisfactory solution. Nevertheless, modellers need to strive to get the right answers for the right reasons (Sayama and McDonnell 2009). Some modellers say that reducing equifinality is the best hope (Beven 2004).

Equifinality occurs when multiple parameter sets give similar model output; this can undermine confidence in the entire model edifice.

One way to reduce equifinality is to use other measures for model testing such as spatially distributed datasets, which can be used to narrow the possible set of parameter values (Franks et al. 1998). Another method is to use a handful of models and narrow parameter sets to look for convergence of model output (Georgakakos et al. 2004), but this is probably not a viable option for most forest managers due to its resource intensity.

A feaseble way to reduce equifinality is to use other measures for model testing such as spatially distributed datasets, which can be used to narrow the possible set of parameter values.

Further steps and options

If after going through the steps of evaluating a model as identified in Figure 17, an acceptable model accuracy is not reached, the modeller has a few options. First, more or better data can be acquired or errors can be corrected. Second, a different model can be chosen and the model selection steps repeated. For example, in larger drainage systems, models that include in-stream processing may be needed to better capture hydrological and biogeochemical processes.

If neither data nor models exist that can be used to answer the modelling question, the question itself needs to be changed or abandoned. While difficult to admit, modelling may be unfeasible in some instances. The uniqueness of place, non-linear dynamics, and threshold behaviour can throw curveballs to any well-intentioned modeller. Failure should be used as a learning exercise and may greatly inform hydrological modelling in general.

If neither data nor models exist that can be used to answer the modelling question, the question itself needs to be changed or abandoned. Modelling may be unfeasible in some instances and failure should be used as a learning exercise.

6.3 Models and forest management

Ecosystem management and the natural disturbance approach

Ecosystem management (EM) is a central tenet of a sustainable forest management approach in Canada. The primary goal of EM is to maintain the ecological integrity and health of the forest by managing the forest as an integrated system, within a conceptual framework designed to maintain ecosystem structure and function (Kimmins 2004, Gauthier et al. 2009).

The development of forest management practices that result in forest patterns and structure that more closely resemble those resulting from natural disturbance has been suggested by Hunter (1993) and others (Perera and Buse 2004, Bergeron and Harvey 1997, Attiwell 1994) as a means to achieve EM. This is best accomplished by designing management practices that result in forest conditions within the historic range of variability associated with natural disturbance regimes (Landres et al. 1999, Ontario Ministry of Natural Resources 2001; Andison 2003).

The development of forest management practices that result in forest patterns and structure that more closely resemble those resulting from natural disturbance has been suggested by experts as a means to achieve EM.

Managing hydrological systems; natural variability

Managing for a reference or natural condition has also been suggested for riverine systems (Poff et al. 1997), benthic macroinvertebrates (Reynoldson et al. 1997), in the biocriteria approach of the US Environmental Protection Agency (Davis and Simon 1995), and for biodiversity and ecosystem integrity of aquatic, wetland and riparian ecosystems (NRC 1992, Naiman et al. 2005). Similar to the natural-disturbance-based approach for managing forests described above, this paradigm stipulates that management should aim to maintain or restore the state (ecological and/or hydrological properties) of the hydrological system under management to a more natural condition that is chosen as a reference.

In the reference condition approach, a key concept is the importance of maintaining biological diversity and the variability inherent in natural systems.

A key concept of the reference condition approach is the importance of maintaining biological diversity and the variability inherent in natural systems. This is especially important when managing dynamic systems such as forests or hydrological networks. For

example, using a one-time measurement of a hydrological property like river discharge is not appropriate; instead, a discharge time-series that defines the range of natural variation is needed (Poff et al. 1997).

However, when determining the range of natural variation the big question becomes: what is a realistic time period for calculating it? Some might say 10 to 20 years (Richter et al. 1997), but given some of the longer natural cycles such as the Pacific Decadal Oscillation, 100 years might be more appropriate.

Another factor to consider when using the range of natural variation as a management goal is the social implications of a given range of variability. Perhaps society is not willing to accept the range of conditions (e.g., low flows and floods) and we may wish to modify the range of natural variation used for the modelling exercise to more closely align with societal values (Klenk et al. 2009).

The need to establish the range of natural variation for hydrological and forest systems is one of the reasons long-term observation networks such as the LTER (Long Term Ecological Monitoring program) in the USA are crucial. While long-term measurements of watershed hydrological variables are extremely valuable for providing ranges of natural variability, most catchments are ungauged. Hydrological models are essential for defining the discharge reference conditions of ungauged systems over long periods of time. Once the reference conditions are defined, potential effects of various forest management scenarios may be simulated under current and projected climatic regimes.

What is a realistic time period for calculating the range of natural variation? What are the social implications of managing for a given range of variability? How are reference conditions defined? What are potential effects of different scenarios?

6.3.1 Using hydrological models to define the reference condition: needs and approaches

If the key to successful management is defining the natural or reference condition, then getting high quality model output that is right for the right physical reasons is a top research need. There has been a lot of effort by modellers to improve the characterization of hydrological processes. These include interception (Ellis et al. 2010), evapotranspiration (Running et al. 1989, Lu et al. 2003), snowmelt (Coughlan and Running 1997, Jost et al. 2009), and runoff processes (Beckers and Alila 2004).

There is still a big research gap in interfacing surface water and groundwater models, as both types of models treat each other as a boundary condition. A notable exception is InHM, which has fully integrated surface and subsurface processes (VanderKwaak 2000).

There is still a big research gap in interfacing surface water and groundwater models.

For subsurface pathways, the barrier to advancement is in large part due to inadequate characterization of the subsurface (Beven 2004). For surface pathways, the greatest shortcomings are related to the modelling of dynamic watershed objects such as lakes and wetlands, which expand and contract on a regular basis (Creed et al. 2002).

Incorporating our latest understanding of hydrology processes into hydro-ecological models is well ahead of the inclusion of biogeochemical processes. There is a growing recognition that the next generation of models will need to be integrated ecosystem models that consider the linkages between climate, hydrology and elemental cycling of nutrients. Appropriate modelling of vegetation dynamics is key to accurate forest hydrological simulation as forest composition changes and individual species adapt physiology to match the changing climatic conditions.

The next generation of models will need to be integrated ecosystem models. They will need to consider the linkages between climate, hydrology and elemental cycling of nutrients.

One of the most advanced integrated modelling systems is a hierarchical regional ecosystem simulator: the Regional Hydro-Ecological Simulation SYStem (RHESSys). It consists of multiple submodels that simulate climate, water and biogeochemical cycling, with explicit consideration of scale in terms of process representation (Band et al. 1996, Tague and Band 2001a). RHESSys is one of the few models that can 'grow' forests and also allows for the simulation of forest management activities (Tague and Band 2001a) and fire spread (Krougly et al. 2009). Hwang et al. (2009) used RHESSys to demonstrate how forest ecosystems optimize carbon uptake by adapting physiological processes to make use of differential distribution of resources (water, light, and nutrients).

A few models can "grow" forests and allow for the simulation of forest management activities.

Hydrological connectivity: a dynamic property

As alluded to earlier, hydrological connectivity is the fundamental ecosystem property which is key to understanding hydrological and biogeochemical transfers between land and water and land and air. Hydrological connectivity is a dynamic property of ecosystems which controls the ease of movement of water, sediment and nutrients between different subcomponents of the system (Creed et al. 1996, Stieglitz et al. 2003, Istanbulluoglu et al. 2003). The successful simulation of hydrological connections is made difficult by the fact that many of these connections are controlled by non-linear and often threshold-dependent processes.

Hydrological connectivity is a dynamic property of ecosystems which controls the ease of movement of water, sediment and nutrients between different subcomponents of the system.

Hydrological connectivity can be affected by many forest management activities (road construction, harvest and riparian management areas). It is the focus of many regulatory requirements and best management practices. A hydrological model that could assist with refining management prescriptions for these areas would be beneficial to forest managers and the ecosystems they manage.

Hydrological connectivity is key to understanding hydrological and biogeochemical transfers between land and water and land and air.

Challenges and future options

Modelling the hydrological reference condition for forested ecosystems is not easy, because watersheds are complex systems characterized by non-linear dynamics. Despite our best intentions, there is a tradeoff between more realistic representations of processes and parameter identifiability.

Perhaps the best way forward will involve the integration and improvement of measurement techniques (ground-based and remote), for spatial and non-spatial ecosystem characteristics that can be used to reduce parameter uncertainty. For example, soil moisture data from remote sensing have been used in hydrological models for improved flood prediction (Oudin 2003).

6.3.2 Modelling the impacts of forest management activities

6.3.2.1 Areal versus linear features (harvest blocks versus roads)

Forest harvesting can be a major agent of change in forests and has important effects on downstream water quantity and water quality. Harvesting changes forests by removing vegetation, altering the age class distribution and composition, and disturbing the soil. These changes can alter ecological processes and functions and lead to loss of biological integrity. Extensive research and monitoring has been conducted on the hydrological effect of forest harvest, which in most places is accomplished using clear cut silvicultural systems (Hornbeck et al. 1993, Stednick 1996, Bonell 1998).

However, research has found that the effect of roads on modifying the hydrology of forests can be just as important as harvest-related effects (Tague and Band 2001b). Roads change the surface hydrological connectivity by channelling water and the associated sediments and nutrients along hard packed surfaces or associated ditches. Road networks may have a stronger influence on peak flows than harvest areas (Eisenbies et al. 2007). In fact, the environmental effects of roads in some forest areas have prompted the Environmental Protection Agency in the USA to consider reclassifying forest roads as point sources of pollution (Eisenbies et al. 2007).

Hydrological models can be used to simulate the possible impacts of harvesting activities, although their full potential has not been realized since many of the simulations have been done on a lumped basis. Only a few hydrological models have addressed road impacts (Table 11).

Forest harvest and roads both have important effects on hydrology and water quality. Models can be used to simulate such impacts, but their full potential has yet to be realized.

6.3.2.2 Scaling: from headwater catchments to larger basins

Much of our understanding of hydrological processes comes from studies conducted in small headwater catchments (first- to second-order basins). This is also true of paired-basin field studies investigating the effects of forest management. Such paired-basin studies can only be conducted in low order catchments where precipitation inputs, soil and geologic conditions, topography, and other variables are the same in the treatment and control catchments (Bonell and Bruijnzeel 2004). In higher catchment orders, the sources of variation in physical catchment characteristics increase substantially and control catchments are hard to find. At higher scales, virtual catchments created using modelling can fill the role of control watersheds (Eisenbies et al. 2007).

Virtual catchments created using modelling can fill the role of control watersheds.

It is important to consider what happens to water flow when catchment scale is increased. With respect to the integrated response at the outlet, there will be a lot of mixing of the different source waters. This is the reason some of the effects of forest management activities in low order catchments end up being averaged away (although there is probably a threshold in disturbance severity beyond which impacts are transferred downstream). Also, at higher orders, in-stream processes increase in importance and need to be represented in hydrological models.

Despite these concerns, Merz et al. (2009) found that many model parameters did not change with spatial scale. They found that some of the differences in model parameters had less to do with scale than with differences in geology and other physical characteristics. This is a challenge because as scale increases, the spatial heterogeneity also increases and the resultant dynamics may have as much to do with scale as with biophysical differences. Merz et al. (2009) also found that water balances can be modelled more reliably at larger scales than at finer scales.

At larger scales, response at the outlet reflects mixing of different source waters. This tends to "average away" some of the effects of forest management.

An innovative use of models at higher scales is change detection modelling where different model runs are made using the split sample technique and model parameters and output are analyzed to detect any changes (Seibert and McDonnell 2010). The aim is to define a representative modelling unit for which statistical description will suffice. The search for this representative unit is ongoing with some fruitful advances (e.g., Sanford et al. 2007).

6.3.2.3 Single versus cumulative impacts

In today's rapidly changing world, forests are subjected to multiple and repeated impacts. The effects of these impacts are cumulative and need to be assessed using a combination of field monitoring and numerical modelling. It is important to understand the effects of past land management on current hydrology and to separate them from the effects of the current environmental (and management) conditions they interact with.

It is important to understand the effects of past land management on current hydrology and to separate them from the effects of the current environmental (and management) conditions they interact with.

The key to understanding cumulative effects is the analysis of long-term datasets, since cumulative effects only manifest themselves after many years. Models can be used to extend past measurement records, and to forecast possible futures under changing environmental and climatic regimes as well as different management scenarios. Linking hydrological models to spatial forest planning tools can facilitate the selection of management options that will minimize effects on water resources.

The key to understanding cumulative effects is the analysis of long-term datasets. Models can be used to extend past records and to model future scenarios.

There are now a multitude of studies modelling the interactive effects of land-use and climate change (Istanbulluoglu et al. 2004, Ma et al. 2010). Given the complexity of ecosystem behaviour, the need for large datasets and expert knowledge requirements, cumulative effects are best analyzed by a team of scientists (e.g., FORWARD project, Putz 2003).

6.3.2.4 Current versus past impacts

Hydrologists have recognized that a landscape's current hydrological state is in part a function of past land uses; this is called the legacy effect (Foster et al. 2003, Jones et al. 2009). For example, the practice of clear-cutting and fire-suppression has changed the forest structure, species composition, and related vulnerability to insect infestation. Moreover, many agricultural landscapes on the eastern seaboard have reverted to forests, but their current state is now also influenced by past land use which, for example, had changed the soils and the seedbank.

A landscape's current hydrological state is in part a function of past land uses.

6.3.2.5 Modelling water yield and water quality in ungauged catchments

It is challenging to construct physically realistic models that account for land-use change, and that can be applied to ungauged catchments both in temperate and tropical regions. There are a number of promising, mostly lumped models that have been used in ungauged basins to simulate water yield.

Water yield

One model (SWAT, Arnold et al. 1998) has been effectively used to model the effect of land-use change (Govender and Everson 2005, He et al. 2008, Alansi et al. 2009). One of the key strengths of SWAT lies in its ability to model the relative impacts of changes in management practices, climate and vegetation on water quantity and quality. Other lumped models include HYLUC (Calder 2003), IHACRES (Croke and Jakeman 2003), and WRENSS (US EPA 1980). Some of these were specifically designed to estimate the change in annual water yield following a variety of silvicultural prescriptions (Swanson 1998).

SWAT is a model that effectively represents the effect of land-use change.

Water quality

Modelling downstream water quality has also been mostly done with lumped hydrological models connected to a GIS-based nutrient export model. For example, El-Kaddah and Carey (2004) used HSPF and a non-point source model (NPSM) integrated within a GIS-based software package. While they were successful at modelling water flows there was poor agreement with total nitrogen concentrations, which they attributed to the lack of good input data and the lack of nitrogen transformation processes built into NPSM. Francos et al. (2001) linked SWAT with a GIS-based water quality model to characterize a partly agricultural and partly forested landscape in Finland.

Modelling downstream water quality has also been mostly done with lumped hydrological models connected to a GIS-based nutrient export model.

Changing land uses, changing models

Mixed land use forests will be more widespread in the future, as agriculture and urbanization move into forested areas. Hence, models need to be able to handle multiple land uses to be effective tools. The bottom line will be getting the hydrology right, since the timing and magnitude of the flow determines the export. Lindgren et al. (2007) reported large differences between two models simulating total nitrogen export, mostly due to spatial variation of specific runoff. Some people have abandoned process-based modelling altogether due to the difficulty of capturing the necessary biogeochemical processes. Purely statistical techniques such as artificial neural networks and similar approaches (Nour et al. 2006) are gaining in popularity.

Models need to be able to handle multiple land uses to be effective tools.

6.4 Modelling the future of water resources under a changing climate

Global circulation models (GCMs) are routinely used to predict the future climate with increasing accuracy regarding global average temperature and precipitation. However, the local manifestation of GCM results, especially in terms of water, is highly variable and debated. A large scientific effort is underway to try to bridge the gap between predictions at the scale of GCM cells and the scales necessary for planning and management at regional and local levels (Fowler et al. 2007). Various statistical or dynamic downscaling methods have been proposed. An example of a dynamic model is the Vegetation/Ecosystem Modelling and Analysis Project (VEMAP) (Kittel et al. 1995). It has produced a database of precipitation and daily temperature maxima and minima at a 0.5° grid resolution for the contiguous USA between 1895 and 2100.

The magnitude, timing, and variability of hydrological fluxes may all change, with various effects on the ecology of forests and their waters. Vegetation changes can in turn have large effects on evapotranspiration.

The challenge of developing process-based models for predicting effects of climate change is that ecosystem processes (physical, chemical and biological) will also be changing. As a consequence we need models that can respond to these changing conditions. Pike et al. (2008) listed eight key hydrological consequences 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.

The magnitude, timing, and variability of hydrological fluxes may all change. This will have various potential effects on the ecology of forests and their waters.

The models of the future need to be able to address these changes. Local and regional models need to consider changes in vegetation, which will have very large impacts on evapotranspiration. Currently only RHESSys is capable of representing changes in the physiology of plants (Tague and Band 2004).

For cold-water hydrology, modelling freeze/thaw dynamics of glaciars and permafrost will be critical.

Runoff modelling will need to represent properly preferential flow through macropores, along bedrock/soil interfaces and especially along roads, because these objects significantly influence quick flows leading to extreme downstream flooding (Beckers and Alila 2004). Part of this modelling process will require determining the thresholds at which preferential flowpaths become activated (Tromp-van Meerveld and McDonell 2006).

In terms of cold-water hydrology, modelling the freeze/thaw dynamics of glaciers and permafrost will be critical. These dynamics have huge consequences for downstream freshwater ecosystems, including the human components (Loukas et al. 2002, Ma et al. 2010). They also have a huge potential to release vast quantities of methane hydrates (Mascarelli 2009).

6.5 Barriers to the operational use of models

Models are useful because of their ability to simulate future watershed conditions under varying management practices and changing climate (Beckers et al. 2009). However, hydrological models are not widely used by forest managers. This is due to several barriers which need to be overcome, from a scientific rather than management perspective.

6.5.1 Bridging the gap between hillslope complexity and watershed simplicity

Sivapalan (2003) argued that while we have greatly advanced our understanding of process complexity at the hillslope scale, we have not been able to translate this understanding to explain why things are much simpler to model and predict at the watershed scale. In building parsimonious watershed models, the right balance must be struck with keeping the necessary detail learned at the hillslope scale.

Given the fact that location of forest management activities matters, and spatial modelling is now widely used in forest management planning, the use of spatially distributed hydrological models will be necessary. This implies a need for fairly detailed descriptions of processes at the hillslope scale.

Given the fact that location of forest management activities matters, and spatial modelling is now widely used in forest management planning, the use of spatially distributed hydrological models will be necessary.

6.5.2 Incorporating field and remote sensing measurements in hydrological models

Models need field measurement for parameterization, calibration and validation. Most commonly the only type of measurement used by modellers is discharge obtained at the outlet of a catchment. However, field experimentalists measure a lot more than discharge. While datasets on groundwater head values or soil moisture are currently difficult to acquire, new ground-based (via wireless sensors) and remote sensing (RADAR, LiDAR, and Hyperspectral) datasets will provide modellers with much more than just discharge data. Reconciling field measurement with model output will most likely require the incorporation of tricky non-linear and threshold-type dynamics.

Models need field measurement for parameterization, calibration and validation. Field and remote sensing datasets can also be incorporated into model functioning.

The incorporation of field and remote sensing datasets might take different forms. Such datasets can be used solely to calibrate models and test model output, but they can also be readily incorporated into the functioning of the model. For example, hourly or daily remote sensing data on soil moisture might be fed into the model to update its water accounting. Moreover, remote sensing can provide frequent updates to vegetation parameters which are unrealistically treated as static in most models.

6.5.3 Integrating models at different scales

Integration of models from different scales needs to be strengthened. For example, future global climate is best modelled using global circulation models. However, local and regional hydrological predictions need to be made with models at finer scales. The global climate information has to be downscaled for the regional model, which can be further downscaled to local (watershed) models.

We have pointed out the differences in processes that can exist between hillslope and catchment scales; similar differences exist between headwater catchment models and the more regional models preferred by forest managers. This is why studying scaling in the treatment of cumulative and interactive processes is so important.

Differences exist between headwater catchment models and the more regional models preferred by forest managers. Integration of models from different scales needs to be strengthened.

If forest managers are to design and implement an integrated systems approach for both aquatic and forested ecosystems, a method to model processes at multiple scales is needed. For instance, the design of riparian buffers is generally done at a local scale, based on field inspections and aerial photographs, with little regard for activities up or down stream, or at a catchment or watershed scale.

In order to manage hydrological systems effectively at multiple scales, within an ecosystem management framework, integrated models are needed (Donnelly 2003). To truly integrate riparian management strategies at the stand scale with strategies at the landscape level (for instance regarding cumulative harvest or disturbance levels), we need to be able to predict the effects of management scenarios at multiple scales over the length of a planning period (generally 100 years).

Strategic forest management models (e.g., PATCHWORKS, Spatial Planning Systems 2008) are now able to forecast future landscape conditions spatially, based on a wide variety of variables and indicators. The ability thus exists to forecast the cumulative effects on water resources by using hydrological models that can incorporate the model output (forest landscapes) projected through time from a forest management model.

Strategic forest management models are able to forecast the cumulative effects on water resources by using hydrological models that can incorporate the model output projected through time from a forest management model.

6.5.4 Classifying models based on purpose and hydrological processes

The need for catchment classification is great. It would greatly aid model and parameter selection for ungauged catchments. A catchment classification would help to determine which models should be used where and when, and would readily lend itself to the development of guidelines for planning and operational practices specified for different types of catchments.

A catchment classification would help to select the best model and parameters for ungauged catchments.

6.6 Conclusions

Models are human constructs based on limited knowledge of how the 'real' world works, yet they give valuable insight for science and decision making. Given the global scale changes in climate and associated ecosystem processes such as fires, insect infestations and species migration, water resources will be greatly diminished for both ecosystem and human use. Hydrological models give us a tool that can help us evaluate how current trends and actions will influence the future.

Modelling will help us manage sustainably for multiple ecosystem services.

Scenario modelling is very useful in determining the best way forward. There are multiple barriers related to model parameterization, data collection, and process representation, but pooling resources between communities, agencies, academics and corporations will unlock the power of the collective to solve problems together.

We need to manage for multiple ecosystem services in order to achieve sustainability. Models will help in our efforts to implement adaptive management. Complexity in systems is inherent - we need to deal with it and see the forest through the trees.

Pooling resources between communities, agencies, academics and corporations will unlock the power of the collective to solve problems together.

7.0 Recommendations and conclusions

Field, remote sensing, and simulation-based methods for understanding forest hydrology have produced a substantial amount of information on water resources of Canada's forests. Some of this information has already been mined by scientists, and the knowledge generated has been implemented by forest managers. There is still considerable knowledge to be gained in organizing, analyzing and synthesizing the existing databases, and translating the knowledge into effective decision making. However, to improve the production of knowledge it is important to extend our observations to areas of Canada's forests that have not been adequately sampled to ensure that we have the understanding required to conserve water resources in all of Canada's forested landscapes.

In this SOK report, we have pointed out important gaps in scientific knowledge as well as the limits of the tools detailed. None of these tools offer a panacea in terms of understanding watershed behaviour. They all have their strengths and weaknesses, and in the final analysis they all rely on each other. In conclusion, we advocate a strategy based on expanding data collection using appropriate measurement tools, followed by fusion and assimilation of these new data with existing databases. This will allow to produce data products that can be readily accessed and analyzed by managers. The future is all about integrating and sharing data and knowledge.

The following subsections highlight the main recommendations for scientists, managers and policy makers to improve access to hydrological data, tools and techniques for effective management of water resources in our changing forested landscapes.

7.1 Create a national data archive for forest hydrology

It is important to continue research projects that seek to compile hydrological information nation-wide, such as the SFMN funded HELP project. It is also important to build a national forest hydrology web portal to bring together all the relevant datasets (WSC and research gauging stations, MSC meteorological data, field-based monitoring of soil moisture and other parameters, remote sensing) into a single, publicly accessible venue.

Currently, the HELP database and webportal are housed by CFS (http://canforhydro.org); renewed support could potentially grow this webportal/database into the needed Canadian warehouse for hydrological information. Such a centralized database would encourage value-added cross site comparisons and meta-experiments, greatly expand knowledge generation, and increase the incorporation of these resources into forest management planning and operations. This centralized web portal should also be linked to global datasets for ease of upscaling or downscaling hydrological information. Access is key to quick dissemination of information, and therefore we advocate the American model of freely sharing tax-payer funded datasets.

7.2 Continue existing and establish new monitoring networks

In this digital age of satellite sensors and distributed sensor networks, field based measurements of hydrological parameters are still crucial. Adequate sampling of hydrological parameters across the variety of hydrogeological systems present in Canada is necessary for understanding Canadian hydrological regimes, and to the development of accurate hydrological models. In general, Canada has lost many meteorological and water survey stations since the golden age of hydrometric data collection in the 1970s. This trend of closures, however, needs to be stopped and reversed. Ground based sensors cannot be eliminated, because they are key to measuring variables like discharge, deeper soil storage, and vertical profiles of snowpack temperatures. The existing hydrometric stations need to be maintained because many of the critical questions, especially those related to climate change, can only be addressed by analyzing long-term datasets. Canada needs to take a lesson from the USA where there is a whole network of long-term observation sites such as Long-Term Ecological Research [LTER], National Ecological Observatory Network [NEON], and Consortium of Universities for the Advancement of Hydrologic Science [CUAHSI].

In addition to continuing data collection at existing stations, the monitoring network needs to be expanded to stations targeting meso-scale watersheds, which size is more compatible with management activities. Government agencies should take the lead in developing a nationally coordinated ecohydrology monitoring network, and build partnerships with universities and local stakeholders, including the public, to increase monitoring of the environment. A national ecohydrology network will be crucial if Canada is to sustainably manage it's most strategic and valuable resource (water), in the face of increasing demands and increasing threats, such as climate change and assorted human activities. Other countries have supported and expanded their monitoring networks to enhance the protection and management of their national natural resources. Canada risks becoming irrelevant in international arenas if we cannot bring adequate data and knowledge of the natural resources under our stewardship to global climate change and adaptation discussions.

7.3 Encourage and adopt emerging technologies for quantitative analysis

We need improved sensors for surface and subsurface *in-situ* sampling and for airborne and satellite remote sensing of various hydrological phenomena. Ideally most of the new ground based sensors should be cost effective and easier to use in order to cover multiple key points in different sized watersheds. In terms of remote sensing sensors, the hydrological community needs, most of all, microwave sensors with multiple polarizations and frequencies. These will allow enhanced vegetation canopy penetration and better detection of soil moisture and snow water equivalent. In regions where groundwater contributions are an important component of the water balance, the development of new geophysical imaging systems along the lines of the GRACE sensor (which measures total water content) is crucial. We need sensors that can map the soil-bedrock interface, the critical water holding (aquifers), and conducting layers (sand deposits), to increase our ability to characterize the subsurface. In order to effectively image the surface of Canada's forests under the thickest of canopies, a satellite based and high spatial resolution (≈5m) LiDAR sensor is desperately needed as well.

The integration of remote sensing imagery in hydrological models will continue to be a critical research area for years to come. Further integration of digital terrain analysis, remote sensing, and distributed simulation modelling data sets with GIS-based spatial decision support systems will be especially important for managers and other decision makers. The transfer of statistical techniques from other fields (e.g., spectral analysis) has introduced significant opportunities for research in applying these methods to hydrological applications. Given the broad geographic variation of Canada's hydrological landscapes, the classification of suitable measurement and analytical tools for different locations or geographic areas is required. The digital toolkit, mentioned in section 7.2, will not achieve its fullest capabilities unless it is supported by comprehensive ground-based networks.

7.4 Promote integration of datasets at relevant scales

Hydrological scientists are currently focusing their efforts on research at the scale of headwater catchments (≈1 km^2), which is disconnected from the scale of management which occurs over drainage basins (≈100s km^2). If forest managers are to design and implement an integrated systems approach for managing both aquatic and forested ecosystems, a method to model processes at multiple scales over the length of a planning period is needed. We need to spatially integrate explicit forest modelling processes and hydrological tools, to enhance our ability to upscale results from headwater catchments to regional drainage basins, consider in-stream, lake and wetland processes. This integration will allow the forecasting of cumulative effects of forest management activities on water resources through time. In terms of predicting the effects of forest management under a changing climate, the global climate circulation models need to be downscaled from the currently available regional levels to local (watershed) levels.

The integrated modelling systems approach to forest hydrology consists in integrating the different types of data reviewed in this report. This system would embrace the strengths of hydrometric observatories, distributed wireless sensors, ground based radars, remote sensing systems, geophysical sensors, and hydrological models (static and dynamic). The measurements and modelled output can be compiled in a GIS setting and broadcasted on the internet. An example of such integrated modelling system is the use of static maps of digital terrain analysis, which can form the basis for dynamic modelling of processes and patterns that are calibrated by local and ground-based monitoring networks. Together with remote sensing data layers, such as soil moisture and snow cover, model predictions can be constrained to give results with acceptable uncertainty bounds. These results could be useful to managers in making decisions such as road and cutblock location and design, watershed-level harvest targets, riparian management strategies, and forest renewal prescriptions. These catchment scale analysis systems should be freeware with transparent code, like the Terrain Analysis System and its successor Whitebox (Lindsay 2005).

7.5 Develop a national watershed classification system

An ecohydrology-based watershed classification system is a critical tool for researchers, forest managers and policy makers when developing management guidelines and operational practices. The availability of such a tool would enable planners to recognize the spatial variability within and between different catchments, allowing the refinement of forest management prescriptions based on site conditions and associated hydrological processes. It would also allow to minimize the potential for adverse effects from harvest or renewal activities. For researchers, a classification system would provide a framework for codifying results and developing new knowledge of hydrological processes across scales. A watershed classification would greatly aid model and parameter selection for ungauged catchments, and help determine which models should be used where and when. The classification would also show where the gaps in our scientific understanding and management consideration are.

7.6 Promote hydrological training and knowledge transfer

Even if the best of data, tools and models are available, they will languish if there are not qualified people to use them. In an era of increasing water insecurity, it is essential to promote and enhance interdisciplinary training in water resource sciences and applications. Forest hydrologists have been slow to adopt and apply the novel hydrological techniques to forest management planning presented in this report. We need enhanced knowledge transfer from product developers in digital terrain analysis, remote sensing, and distributed simulation modeling, to forest hydrologists and managers. It is important that forest managers and scientists work together to better understand the complexity of the management questions as well as the potential solutions. It is also important the use of hydrological models in forest management planning, because it helps to reduce uncertainty and risks in terms of forest sustainability, economic and social values. Uncertainty, error and caveats associated with the latest

products need to be well documented, otherwise their use will not be universal. The users of spatial datasets will need to learn how to manage and process raw data, turn it into information, and then transform it into knowledge. An encouraging way forward is by using Web 2.0 technologies, where information flows both ways and "end-users" become "engaged-users".

In summary, meeting the coming challenges to forest water resources (increased demands, climate change and sustainability) requires improved data, new tools and the qualified people to integrate them into forest management. A revitalized forest hydrology community (industry, governments, academia and citizens) equipped with better data, tools and knowledge will ensure the future health of forest ecosystems, communities and the forest industry, and will demonstrate that we are responsible stewards of a significant proportion of the world's forest and water resources.

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