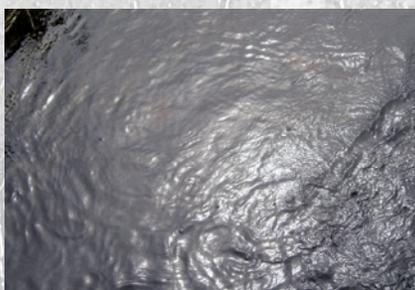




Hydrological principles for conservation of water resources within a changing forested landscape

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

A STATE OF KNOWLEDGE REPORT







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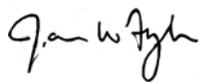
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Foreword

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 The projects involved a diversity of workshops, consultations, reviews of published and unpublished materials, synthesis and writing activities.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.



Jim Fyles
Scientific Director



Fraser Dunn
Chair of the Board

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Sustainable Solutions Consulting (Fisher, C., Hayward, J. and Lichty, H.). 2008. Umbrella policies and the forest umbrella. Report to the Sustainable Forest Management Network State of Knowledge Project on Implications of Forest Management Activities on Water Resources Under a Changing Global Climate. University of Western Ontario. 121 pp.

JSD Environmental Consulting (Frisic, J., Linley, D. and Sotomayor-Taca, S.). 2008. Conserving water resources: a framework for evaluating forest planning and operational practices. Report to the Sustainable Forest Management Network State of Knowledge Project on Implications of Forest Management Activities on Water Resources Under a Changing Global Climate. University of Western Ontario. 71 pp.

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Table of Contents

3	Foreword
4	Acknowledgements
7	Executive Summary
<hr/>	
9	1.0 Introduction
9	1.1 Background
11	1.2 Purpose
<hr/>	
13	2.0 Current approaches to planning for the future of water
13	2.1 Federal legislation and regulations pertaining to water management
16	2.2 Provincial and territorial legislation and regulations and private certification related to water
16	2.3 Rules- versus results-based approaches to regulating forest management
<hr/>	
19	3.0 A new approach to planning for the future: backcasting
<hr/>	
23	4.0 Hydrological principles for sustainable management of forested ecosystems
23	4.1 Introduction
24	4.2 A principled approach
32	4.3 Outcome of a principled approach: a resilient forest
32	4.4 Conclusions
<hr/>	
33	5.0 Barriers to integrating hydrological principles into practice
33	5.1 Survey of current policies and practices
36	5.2 Perceived barriers to integrating hydrological principles into policies and practices
37	5.3 Priority needs for promoting better or best management practices
38	5.4 Summary
<hr/>	
41	6.0 Management actions to facilitate integrating hydrological principles into practice
<hr/>	
55	7.0 Conclusions and recommendations
<hr/>	
57	8.0 References
<hr/>	
65	Appendices
67	1 Forest planning and operational practices to promote the conservation of water resources: a survey of current practices and operations guidelines
77	2 Provincial and Federal guidelines used to assess degree of policy adherence to hydrological principles

List of Figures

- 20 Figure 1. Management using backcasting is an alternative to the ‘business as usual’ forecasting approach
- 26 Figure 2. Principle 1, delineate hydrological systems by considering the dominant processes and pathways of water
- 27 Figure 3. Principle 2, conserve hydrological features that serve critical functions such as recharge, storage, and discharge of water along surface and subsurface pathways
- 28 Figure 4. Principle 3, maintain hydrological connectivity among the critical hydrological features
- 30 Figure 5. Principles 4 and 5, respect temporal variability and spatial heterogeneity of hydrological systems
- 31 Figure 6. Principle 6, maintain redundancy and diversity of hydrological form and function
- 33 Figure 7. Provincial distribution of survey respondents across Canada
-

List of Tables

- 14 Table 1. Most important pieces of Federal legislation pertaining to water management
- 21 Table 2. Five-level framework for planning for sustainability of complex systems
- 25 Table 3. Hydrological principles of sustainable forest management
- 39 Table 4. Degree of representation of hydrological principle concepts in current forest policy in Canada
- 44 Table 5. Site susceptibility to soil erosion
- 48 Table 6. Stream crossing construction standards related to temporal variation in flow conditions
-

List of Boxes

- 15 Box 1. Department of Fisheries and Ocean’s Environmental Process Modernization Plan includes Operational Statements designed to streamline the review and approval process of management activities
- 15 Box 2. Operational Statements to be met for ice bridges and snow fills in order to avoid a full DFO review
- 18 Box 3. British Columbia leads in the adoption of a results-based approach to forest management
- 43 Box 4. The importance of maintaining soil properties during forest operations
-

Executive Summary

This report presents a set of hydrological principles that can be used to inform forest policies and practices and be translated into actions for sustainable forest management in Canada. These principles were developed as part of a backcasting-from-principles approach to planning that envisions a desired future constrained a set of principles, and then considers the policy and practical steps necessary to arrive there. Many of the concepts underlying the hydrological principles are currently represented in some provinces and territories. However, these principles should serve as the first step in opening a dialogue between forest hydrologists, managers and policy makers. This will help to establish a unified framework for sustainable forest management across the country.

Principle 1. Determine hydrological system boundaries and consider the entire hydrological system within which management actions take place.

Management Action 1A: 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.

Principle 2. Conserve critical hydrological features by minimizing disturbance to areas involved in the source, movement and storage of water.

Management Action 2A: Minimize disturbance to soils, especially within or near areas that focus the recharge of water into subsurface pathways.

Management Action 2B: 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).

Management Action 2C: Minimize disturbance to storage areas (such as wetlands and ephemeral saturated areas).

Principle 3. Maintain connections between hydrological features by minimizing disruptions to water, sediment and nutrient flows.

Management Action 3A: 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).

Management Action 3B: Locate roads, bridges, culverts and harvest areas to ensure surface and subsurface hydrological connectivity is maintained and flow is neither impeded nor enhanced.

Principle 4. Respect the temporal variability in hydrological processes, over short-term (i.e., daily operations) and long-term time scales (i.e., 100 year planning horizons).

Management Action 4A: Recognize there is natural variability in hydrological processes at multiple scales from daily to multi-decadal.

Management Action 4B: Recognize there is human induced variability in hydrological processes of different severity (ranging from past management practices to climate change).

Management Action 4C: Recognize that the timing, frequency and magnitude of extreme events may be changing because of the interplay between natural and anthropogenic factors that are hard to separate.

Principle 5. Respect the spatial heterogeneity in hydrological processes, among different scales of a watershed (e.g., stand, hillslope, catchment, basin) and among different hydrological regions (e.g., discharge dominated versus evapotranspiration dominated).

Management Action 5A: Consider how scale influences dominance of hydrological processes (moving from headwaters to regional basins).

Management Action 5B: Consider how geographic context including climate, bedrock geology, surficial geology, soil type and depth, and topography influences dominance of hydrological processes and patterns.

Principle 6. Maintain redundancy and diversity of hydrological form and function within forested watersheds.

Management Action 6A: Consider watershed functions that might be most impacted by future extreme events and plan to protect features that perform those functions.

Management Action 6B: Consider multiple ecosystem services when assessing “tradeoffs” in making development choices.

Management Action 6C: Consider the interactive nature of the hydrological system with climatic, geomorphic, ecologic and socio-economic systems.

The way forward for scientists, managers, and policy makers to implement our suggested backcasting-from-principles approach is to:

- 1) Reach consensus on hydrological principles through open dialogue;
- 2) Embed the hydrological principles into a framework of principles, policies and practices;
- 3) Integrate the hydrological principles with social, economical and ecological principles; and finally
- 4) Develop a process for effective monitoring and adaptation of the backcasting-by-principles process.

This report is the first of two State of Knowledge reports. The companion document entitled “*Scientific theory, data and techniques for conservation of water resources within a changing forested landscape*” outlines the current scientific concepts and contemporary data, tools and techniques that can be used to integrate these principles into forest management.

1.0 Introduction

1.1 Background

Canada's forests cover over 40% of our land area and are an integral part of our Canadian heritage (Canada Forest Service 2010). They provide resources and services required for the survival of many communities, including timber, clean air and water resources (Dudley and Stolton 2003, Canadian Boreal Initiative 2005). Unfortunately, the continued sustainability of our forests may be at risk due to ever increasing demands for resources in forest landscapes (e.g., timber, oil and gas extraction, mining, and recreation) at a time when climate change is creating greater uncertainties in their future (Schindler 1998, Millar et al. 2007). These risks pose a great challenge for decision makers (i.e., from operational managers to government policy makers) who need relevant science to inform themselves. Therefore, we need science that will lead to a predictive understanding of how forests function and how they adapt and/or respond to current and anticipated changes in environmental conditions.

The interplay between forests and water

The trees, soils and wetlands of Canada's forests represent one of the world's largest terrestrial carbon storehouses, and play a critical role in regulating global climate (Anielski and Wilson 2005). However, one of the most important services that forests provide is a safe and sustainable supply of water (National Research Council (NRC) 2000, Gabor et al. 2001, Dudley and Stolton 2003). Forests store and filter the majority of our surface fresh water supply, in turn

providing significant benefits to Canadians by contributing to healthy watersheds and healthy communities (NRC 2000, United Nations Development Program 2006). These ecological services provided by the boreal forest are estimated to be worth 2.5 times the market value of the natural resources extracted from it each year (Anielski and Wilson 2005).

With increasing resource demands imposed on forested landscapes, there is an increasing risk of a crisis to communities dependent on water resources within and/or downstream of these landscapes – particularly those communities without alternative water resources. Early warnings of this pending crisis are marked by the increased profile found in popular media of issues related to water supplies in remote communities. A particularly vulnerable group is aboriginal communities. For example, of the 738 First Nation communities in Canada (most of which are in forests), about two thirds have drinking water systems that are at medium-to-high risk. This is despite the 2 billion dollars spent by the federal government between 1995 and 2003 to upgrade their water treatment systems (Canadian Broadcasting Corporation 2006).

The risk to drinking water is also related to alterations in our forests that are compromising the “natural” treatment of water resources.

The risk to drinking water systems is related to the management of water resources (e.g., the technology used for water supply and the ability of aboriginal communities to manage this technology). However, the risk is also related to alterations in our forests that are compromising the “natural” treatment of water resources (NRC 2000, Gabor et al. 2001, Dudley and Stolton 2003).

Climate change: the wildcard

Under current projections for climate change in Canada, water resources on our forested landscapes are expected to become front and centre to social, economic and environmental decisions. In fact, Dr. David Schindler, one of the world’s leading authorities in environmental sciences, predicts water will be Canada’s foremost ecological crisis early in this century (Schindler 2001). There is an urgency to understand the scientific, management and policy links between forests, climate change and water resources.

Under current projections for climate change in Canada, water resources on our forested landscapes are expected to become front and centre to social, economic and environmental decisions.

Climate warming, and catastrophic events associated with climate change including fires, insect infestations, droughts, and floods are expected to influence the hydrological cycle in ways that may adversely affect water quality and water quantity. Scientists who focus on forest disturbance have documented effects on water resources (e.g., Carignan and Steedman 2000, Buttle et al. 2000, 2005, 2009). However, the effects of climate change on these dynamics are largely unknown, and are expected to vary among regions.

In wetter forest regions, climate change could exacerbate forest management effects on water resources. For example, the frequency of flooding is likely to increase because of more frequent extreme rainfall events

(Intergovernmental Panel on Climate Change 2001) in combination with increasing peak flow discharges after timber harvest (Jones and Grant 1996, 2011, Thomas and Megahan 2001). In contrast, drier forest regions are likely to see increased droughts as a result of climate change (Schindler and Donahue 2006).

Current management efforts

Forests are managed primarily for timber; thus changes to water quantity and quality are byproducts of other forest management objectives. As water supplies become at risk due to increasing demand and variable supply, it is critical to manage water supplies from forests more effectively. Managers also face increasing challenges to manage forest landscapes for multiple objectives and to demonstrate sustainability and responsible stewardship through voluntary, regulatory and certification standards.

As water supplies become at risk due to increasing demand and variable supply, it is critical to manage water supplies from forests more effectively.

While forest management planning in Canada does address water resources in many jurisdictions, the focus has traditionally been on single objectives (e.g., no net loss of fish habitat). There has been some recent movement toward more integrated consideration of water and water-related resources (e.g., *British Columbia Forest and Range Practices Act* (2004) includes consideration of water quantity, water quality and aquatic habitat), but this broad focus has not been uniform across Canada.

An important limitation to incorporating water-related resources in traditional approaches to forest management and planning strategies has been the tendency to focus on minimizing potential adverse effects through avoidance or mitigative measures at a local or stand level scale (e.g., guidelines for the avoidance of sensitive sites, stream crossing and road construction

procedures, and retention of riparian buffers) (British Columbia Ministry of Forests 1995, Donnelly 2003, Jeglum et al. 2003, Manitoba Conservation 2005, Ontario Ministry of Natural Resources 1995).

These guidelines were also developed under a pre-cautionary approach or based on political acceptability rather than scientific merit. An excellent example is the case of buffer strip placement (Castelle et al. 1994). Where forest management has occurred at the scale of a watershed, indicators such as equivalent clearcut area or change in annual water yield have been used. These are often weak measures of forestry effects on channel stability, water quantity and water quality (e.g., Whitaker et al. 2002). Management tools need to be developed for monitoring, including a suite of indicators for use in Criteria and Indicator frameworks (Canadian Council of Forest Ministers 1995).

Management tools need to be developed for monitoring, including a suite of indicators for use in Criteria and Indicator frameworks.

1.2 Purpose

This report focuses on the scientific foundations of sustainable forest management from the perspective of conserving water resources and minimizing adverse effects due to forest management activities. The goal of the report is to provide a science-based conceptual framework that can be used for both short-term (i.e., daily operational decisions) and long-term (i.e., 100 year planning horizons) planning for sustainability in Canada's forests, with a specific focus on water resources.

We first provide an overview of Canada's federal and provincial legal context for the management of water resources. We then introduce an alternative way to plan for the future using the concept of backcasting-from-principles. The essence of this approach involves planning for a preferred as opposed to a probable future, and is therefore very amenable to its use in sustainability planning. A key component of backcasting is the identification of principles that govern the future state of the system we envision. As such, we

introduce a set of hydrological principles that provide a framework for policy and operational practices designed to ensure the conservation of water resources within a sustainable forest management (SFM) approach.

If forest managers develop SFM strategies and practices based on these hydrological principles, they can expect their operations to be less risky in terms of environmental effects, resulting in aquatic systems that are resilient to natural and anthropogenic disturbances. Finally, the report provides an assessment of how current forest practices in Canada align with these hydrological principles and suggests potential implementation options.

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The report is structured as follows:

- **Chapter 2** reviews the current forest management policy framework that addresses forest water resources at both the federal and provincial levels.
- **Chapter 3** presents an alternative approach to forest planning. In many organizations around the world, 'backcasting-from-principles' is replacing the traditionally used 'forecasting' methodology of sustainability planning.
- **Chapter 4** introduces six hydrological principles that provide the foundation for incorporating water resource conservation into a sustainable forest management framework. The principles are embedded in a hydrological systems approach that fully integrates hydrology into ecosystem-based management.
- **Chapter 5** discusses current forest management policy and practice with respect to the hydrological principles.

- **Chapter 6** suggests ways to incorporate the hydrological principles into forest policy and operational practices.
- **Chapter 7** contains conclusions and recommendations to assist decision makers in fully integrating hydrological concepts into their decision-making processes.

This document is a companion to the State of Knowledge report entitled “*Scientific theory, data and techniques for conservation of water resources within a changing forested landscape*” which presents the scientific theory underlying our current knowledge of forest hydrological processes and patterns. It also provides a suite of tools which offer great potential for application in the management of forests.

2.0

Current approaches to planning for the future of water

Canada is a forest nation. The 2010 *State of Canada's Forests* Annual Report identifies approximately 400 million hectares of forest in Canada. This represents 10% of the world's forest, including 30% of the circum-polar boreal forest.

The vast majority (93%) of Canada's forest is publicly owned, with the provinces and territories responsible for 77% and the federal government for 16%. Much of the 7% that is privately owned belongs to large operators, but there are also over 425,000 family owned woodlots. Out of all of Canada's forests, 8% is completely protected while approximately 40% receives some degree of protection. Commercial forests comprise 56% of Canadian forests, mostly in British Columbia, Ontario and Quebec, while 28% of the total has been designated for timber purposes.

Governance of water resources on forested lands are shared between the federal, provincial and municipal governments. This results in a complex environment for the development and revision of policies and guidelines, approval for development activities and compliance monitoring. This section discusses the current legal framework that pertains to the conservation and management of water in the context of forestry.

2.1 Federal legislation and regulations pertaining to water management

In Canada, Natural Resources Canada is the federal agency responsible for (1) forest science and technology, focusing on strategic issues that require long term studies (such as climate change – mitigation and adaptation); (2) national forest policies and development of

knowledge, tools and technologies to manage Canada's forest sustainability; (3) providing strategic advice to Canada's forest sector; and (4) external affairs (e.g., trade, commerce, treaties and conventions related to forests and forest products), including promoting trade of Canadian forest products and monitoring implementation of international trade regulations (Canadian Council of Forest Ministers 2007).

Several key federal agencies, such as Fisheries and Oceans Canada (DFO), Environment Canada and Transport Canada, are responsible for water management legislation and regulations (Table 1). These agencies are responsible for fishery, navigation and shipping matters, and have jurisdiction over international boundary waters and those found on federal lands, including First Nations and the territories. Perhaps the single most important piece of legislation regarding the interface of forest and water management activities is the *Fisheries Act* administered by the DFO.

Perhaps the single most important piece of legislation regarding the interface of forest and water management activities is the *Fisheries Act* administered by the DFO.

As part of the *Fisheries Act*, the DFO operates under a 'no net loss' policy. Under this policy, any project that has the potential to affect fish habitat directly or indirectly must follow a review and approval process.

As a result, forest companies must submit forest development or management plans, individual project details or proposals for specific activities (e.g., stream crossing installations) that may harmfully alter, disrupt or destroy fish habitat or create a barrier to fish migration. These plans must then be authorized by DFO prior to resource development activities.

Additional federal approvals may be required by DFO's Navigation Protection Program for activities, such as the installation of in-water structures. There are also additional federal acts and regulations that may apply

depending on the type of project under consideration (*Environmental Assessment Act, Planning and Development Acts, Species at Risk Act*, etc., see Table 1). The DFO Conservation and Protection staff monitor compliance with the *Fisheries Act* and enforce the fish habitat protection provisions of the Act.

As part of the DFO's *Environmental Process Modernization Plan*, the review and approval process has recently been streamlined to enable routine reviews of lower risk projects to be replaced by clear guidelines (Fisheries and Oceans Canada 2010a) (Box 1, 2).

Table 1. Most important pieces of Federal legislation pertaining to water management

Department	Legislation	Description
Fisheries and Oceans	<i>The Fisheries Act</i>	Regulates activities, potential environmental effects and grants authorization for activities with the potential to cause impacts on fish and fish habitat including the harmful alteration, disruption or destruction of fish habitat.
Environment Canada	<i>Canada Water Act</i>	Authorizes various federal-provincial arrangements and establishes federal water quality management programs for inter-jurisdictional waters.
Environment Canada	<i>The Species at Risk Act</i>	Protects wildlife species at risk and their habitat. Species at risk are identified by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), an independent body of experts responsible for identifying and assessing species considered to be at risk. Species that have been designated by COSEWIC may then qualify for legal protection and recovery under SARA.
Environment Canada	<i>Canadian Environmental Protection Act</i>	Provides the framework for protecting Canadians from all forms of pollution caused by toxic substances. It encompasses the entire life cycle of toxic substances including their transport, use and storage.
Environment Canada	<i>International River Improvements Act</i>	Regulates activities affecting water quality and environment of international rivers flowing from Canada.
Transport Canada	<i>The Navigable Waters Protection Act</i>	Regulates activities that have the potential to affect navigation of waterways including stream crossings. Authorization is required from the Coast Guard under <i>The Navigable Waters Protection Act</i> for crossings deemed navigable.

BOX 1

Department of Fisheries and Ocean's *Environmental Process Modernization Plan* includes Operational Statements designed to streamline the review and approval process of management activities

(Fisheries and Oceans Canada 2010a)

Operational Statements describe the conditions and measures to be included in a project to ensure that negative impacts to fish and fish habitat are avoided.

A DFO review is not required if the project design meets the conditions listed in the applicable Operational Statement.

The Operational Statements are designed for specific provinces and territories to reflect environmental differences and provincial and territorial laws and regulations. Operational Statements have been developed for a suite of activities, including:

- temporary stream crossings,
- clear span bridges, and
- ice bridges and snow fills,
- culvert maintenance.

In addition to the Operational Statements, DFO has developed an information series on best practice guidelines, which are standardized or approved practices for common projects in and around water designed to meet federal, provincial and territorial regulatory requirements and minimize associated fish and fish habitat impacts (Fisheries and Oceans Canada 2010b).

For projects that do not meet the conditions of the Operational Statements or pose higher potential risk of negative effects, a review process is required.

BOX 2

Operational Statements to be met for ice bridges and snow fills in order to avoid a full DFO review

(Fisheries and Oceans Canada 2010b)

- Ice bridges are constructed of clean (ambient) water, ice and snow.
- Snow fills are constructed of clean snow, which will not restrict water flow at any time.
- The work does not include realigning the watercourse, dredging, placing fill or grading or excavating the bed or bank of the watercourse.
- Materials such as gravel, rock and loose woody material are not used.
- Where logs are required for use in stabilizing shoreline approaches, they are clean and securely bound together, and they are removed either before or immediately following the spring freshet.
- The withdrawal of any water will not exceed 10% of the instantaneous flow, in order to maintain existing fish habitat.
- Water flow is maintained under the ice, where this naturally occurs.
- When the measures to protect fish and fish habitat when constructing an ice bridge or snow fill listed in the Operational Statement are incorporated.

2.2 Provincial and territorial legislation and regulations and private certification related to water

The provinces and territories have been given constitutional authority over natural resources, including the authority to make laws relating to the conservation, development and management of forestry resources. Each province has developed its own legislation, policy, regulations, standards and programs to allocate harvesting rights and management responsibilities in public forests. Provinces and territories must also consult with aboriginal people where its actions may adversely affect an established or asserted aboriginal or treaty right (Canadian Council of Forest Ministers 2007).

Each provincial and territorial government has designated one or more agencies to manage its water (usually the provincial environment agency). These agencies oversee water allocation and utilization, as well as commercial and urban development activities that may have an effect on water resources (including both water quality and water quantity aspects). As a result, water resources within managed forests are subject to provincially developed forest management guidelines, in addition to the legislation under provincial environment agencies.

Each provincial and territorial government has designated one or more agencies to manage its water.

Along with the mandatory governmental regulations, the forestry industry is regulated by voluntary associations with private certification systems operating in Canada: the Forest Stewardship Council (FSC), Canadian Standards Association (CSA), Sustainable Forest Initiative (SFI) and International Standards Organization (ISO). Certification can offer timber companies certain market advantages by allowing a company to publicize their sustainable forest practices. The FSC is the only framework that emphasizes the protection of ecological function, including water resources. It has strong, specific regulations for the use and disposal of chemicals, the prevention of erosion, the protection of riparian areas, and the construction

of stream crossings and forest roads. The other three standards emphasize environmental performance, rather than ecosystem health or well-being.

Along with the mandatory governmental regulations, the forestry industry is regulated by voluntary associations with private certification systems.

2.3 Rules- versus results-based approaches to regulating forest management

Provincially- and territorially-based forest management guidelines in Canada often have the same underlying principles in terms of management strategies and objectives, namely the sustainable management of forest resources. However, the approach used to achieve these strategies or objectives often varies.

A principal difference exists in terms of the way forest management guidelines are designed and enforced, namely whether they are based on rules- or results-based approaches.

DEFINITION 1

Rules-based approach – onus on government

Prohibitions, guidelines and controls are the primary management tools. If industry meets these rules, they are not accountable for the performance of their management strategies.

A rules-based (or prescriptive) approach to forest management involves the development of a policy and regulatory framework, which includes management objectives and strategies and provides a series of management guidelines. These management guidelines describe in detail specific activities that are prohibited or controlled, as well as desired management outcomes. The province, rather than a forest company, is responsible for setting management objectives and

conducting compliance monitoring to ensure the desired outcomes are achieved. This results in less accountability for licensees. As long as the regulatory requirements are met, the licensee has done its job, even if the management objectives are not met.

DEFINITION 2**Results-based approach – onus on industry**

Management strategies are the primary management tools. Industry must continually improve or adapt their strategies until the desired performance is achieved, as specified by the province.

A results-based approach to forest management uses a different approach to ensure sustainability objectives are achieved. Under this approach, the industry is responsible for developing management strategies and approaches based on a suite of specified objectives or requirements, to achieve a series of results or outcomes as specified by the province. The results-based approach requires: 1) the design of management strategies to achieve the standards and practices governed by regulation, and 2) the design of monitoring programs to ensure effectiveness of the management strategies.

The underlying philosophy for the results-based approach is that the management strategies continuously improve and adapt until the desired outcomes are achieved.

The underlying philosophy for the results-based approach is that the management strategies continuously improve and adapt until the desired outcomes are achieved. The core principles that govern a results-based approach include (1) legally enforceable, demanding standards that ensure industry will strive for continuous improvement; (2) active enforcement to ensure industry is accountable for meeting the standards; and (3) transparency, particularly publishing of information to promote environmental progress.

Several provinces, including Ontario, Saskatchewan and British Columbia (Box 3), are beginning to incorporate the results-based approach into policy.

It is clear that the forest management policy framework in Canada is complex and variable. Although government agencies are responsible for developing legislation, guidelines, and regulations to protect water and forest resources, the companies that manage forests are responsible for much of their implementation. If we are to address the complex management issues that face us today, we must work together to find potential solutions that are sustainable and yet economically and environmentally feasible.

If we are to address the complex management issues that face us today, we must work together to find potential solutions that are sustainable and yet economically and environmentally feasible.

British Columbia leads in the adoption of a results-based approach to forest management

A results-based approach is the underlying principle of the *British Columbia Forest and Range Practices Act* (FRPA), introduced in 2004, to make forest companies more accountable for management outcomes.

Management strategies

The forest industry is responsible for developing results and strategies to sustainably manage the 11 resource values (subject areas) identified under the FRPA (e.g., biodiversity, soils, water). The role of government is to ensure compliance and evaluate the effectiveness of forest and range practices in achieving government's objectives for FRPA's resource values.

Monitoring the strategies' successes

In British Columbia, the FRPA has designated that Resource Stewardship Monitoring (RSM) be used to monitor the effectiveness of the strategies and practices utilized by the forest industry. RSM was designed to help identify implementation issues regarding forest policies, practices, legislation, and Forest Stewardship Plan results and strategies. For instance, an RSM program designed to determine if fish values are protected in riparian systems asks the question, "Are riparian forestry and range practices effective in maintaining the structural integrity and functions of stream ecosystems and other aquatic resource features over both short and long terms?" To answer this question and assess the effectiveness of the management strategies employed, the RSM program has developed a list of 15 questions to be answered by a forest manager (Tripp et al. 2009). As a result, RSM is a fundamental component of implementing continuous improvement of forest management in British Columbia.

3.0

A new approach to planning for the future: backcasting

Planning for the future can be classified into three main typologies (Carlsson-Kanyama et al. 2008):

- 1) probable – what will happen?
- 2) possible – what could happen?
- 3) preferable – what should happen?

The first two typologies ask the question, “What is the future?” They employ a forecasting approach to planning for the future that is based on current trends and their likely trajectories, while using different assumptions about the factors affecting these trends.

The third typology is distinct from the other two because it reverses the question about the future to ask, “what future would we like to see and how do we get there?” This approach has been termed backcasting (Robinson 1982) and has become influential in the field of sustainability. Its appeal stems from the fact that current policies, practices, and individual behaviour, are considered unsustainable and new visions of the future are needed (Robinson 1990, Robèrt et al. 2002).

The essence of backcasting is the articulation of desirable futures and the identification of how these futures can be attained.

The essence of backcasting is the articulation of desirable futures and the identification of how these futures can be attained. The process involves working backwards from a desired future to the present, and

evaluating the necessary steps (in terms of policy, management, technology and behaviour) an individual or organization must take to reach that goal (Figure 1). While the overall purpose involves imagining and evaluating the steps that lead to a preferable future, there are also predictive elements to the approach because scientific, technological, and social realities must be honoured within realistic constraints. The typical time horizon for backcasting approaches is 25-50 years. This gives enough temporal distance between the present and the future for significant change to occur (Robinson 2003).

The typical time horizon for backcasting approaches is 25-50 years.

Backcasting has undergone significant evolution from its initial formulation (Robinson 2003). One of the ways it has changed is by shifting the focus from scenario analysis (*backcasting from scenarios*) to the selection of principles (*backcasting from principles*). Backcasting from scenarios can be challenging, particularly when considering issues of sustainability where multiple environmental, social, and economic aspects of the systems need to be considered in detail. Instead of imagining multiple scenarios, the focus can be shifted to finding key principles that must be part of any future scenario. In this way principles act as constraints on the type of scenarios that might be imagined.

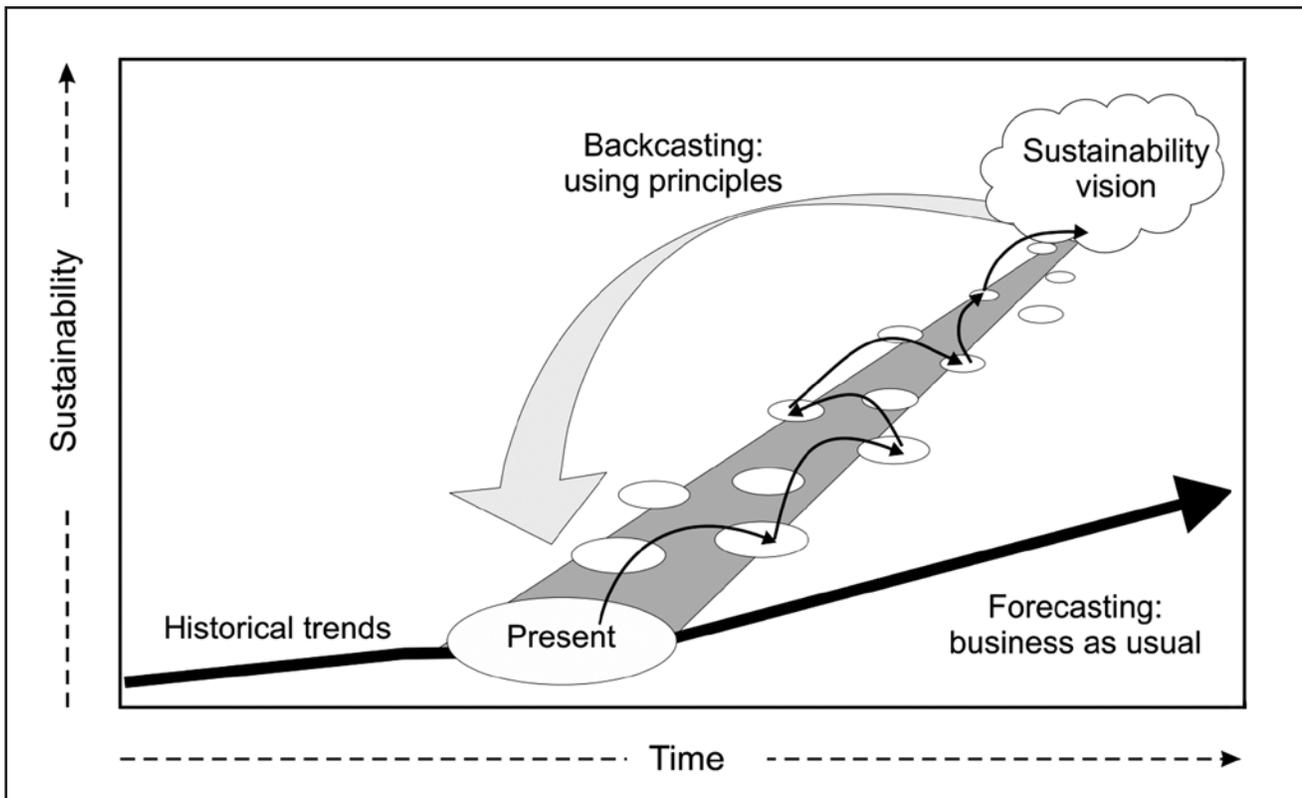


Figure 1. Management using backcasting is an alternative to the ‘business as usual’ forecasting approach. For example, many forest management plans forecast tree growth many decades into the future using the assumption that tomorrow’s climate will be similar to today’s. Backcasting starts by painting a desired vision and determines the most useful steps to get there. While steps may change and some may backfire, the principles that guide the way are based on sound science and continually help to redesign the way forward.

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Robèrt et al. (2002) introduced a five-level system of principles and associated actions (Table 2). Level 1 principles are foundational principles describing the “ecological” (including thermodynamic, geomorphological, hydrological, biogeochemical, ecological) as well as societal (including social norms, values, belief systems that define the way humans interact with the natural environment) constitution of the system. These principles are based on the best available scientific

knowledge and can be taken as ‘immovable’ for the backcasting exercise.

Level 2 principles, according to Robèrt et al. (2002), are principles for sustainability that define the system conditions for a favourable outcome of the backcasting exercise. Often, these are just the reframing of the Level 1 principles. For example, the Level 1 principle might be “Organisms have evolved to tolerate substances at a given concentration” and the Level 2 principle would follow as “In a sustainable society, nature is not subject to systematically increasing concentrations of substances extracted from the Earth”.

Level 3 principles are principles of sustainable development that address strategies leading to the desired state (e.g., the precautionary principle). Level 4 is action oriented and describes concrete measures that will lead to the fulfillment of the higher-level (i.e., levels 1, 2, 3) principles (e.g., nutrient concentrations in receiving water-bodies downstream from manage-

Table 2. Five-level framework for planning for sustainability of complex systems (modified from Robèrt et al. 2002)

Levels	Types of principles
1	Principles of ecosphere [Ecological and social constitution of system]
2	Principles for sustainability [System conditions that need to be met in order to achieve success]
3	Principles for sustainable development [Strategy or process for achieving success]
4	Actions [Concrete measures to meet desired outcomes]
5	Tools and metrics [Assessment, management and monitoring of actions]

ment activities must not exceed a given threshold). Level 5 is about the appropriate tools for monitoring and audit of the entire process (e.g., nutrient levels should be monitored at regular intervals during the year with additional sampling following spring melt and summer storms).

While Level 1 principles are defined by our state of knowledge in natural and social sciences, Level 2 principles are specific to the theme undertaken. In many settings, the principles for sustainability are chosen by experts (e.g., scientists, industry practitioners, government personnel). However, the latest research on backcasting methods has revealed the power of a participatory approach in the selection of the principles (Swart et al. 2004). Instead of professionals only, the principles are selected and described by the community of stakeholders. By involving all of the stakeholders, the group can teach each other about the diverse issues, and the resultant social learning becomes as important as the outcome of the backcasting exercise (Robinson 2003).

Sustainable forest management is an important vision for Canada. Backcasting (sensu Robèrt et al. 2002, Robinson 2003) has not been employed within a sustainable forest management context in Canada. Although elements of it, such as visioning the future, have definitely been espoused (e.g., Yafee 1999, Leech et al. 2009), backcasting-from-principles has not been presented explicitly as a unified forest management framework.

We have an opportunity to change the way we manage forests, particularly given the uncertainties associated with a changing global climate. We believe that backcasting can help us achieve our sustainability goals for forested landscapes. In the next chapter, we present a set of hydrological principles that we believe need to be the constraints of any future sustainable management framework.

The latest research on backcasting methods has revealed the power of a participatory approach in the selection of the principles.

4.0

Hydrological principles for sustainable management of forested ecosystems¹

4.1 Introduction

Forests provide some of the cleanest and most plentiful freshwater supplies, sustaining many downstream communities. However, forested landscapes around the world are changing as a result of human activities including forest management, fire suppression, mountaintop mining, conversion of natural forests to plantations, and climate change (Brockerhoff et al. 2008, Cyr et al. 2009, Miller et al. 2009, Johnston et al. 2010, Kelly et al. 2010, Palmer et al. 2010). Given these ongoing changes, forest management needs to be forward looking, flexible, responsive to ongoing changes, attune to local conditions, and open to the application of a more diverse range of management options and prescriptions (Williamson et al. 2009) in order to ensure sustained supplies of high-quality water.

Forest scientists and managers are aware of the importance of conserving water resources in a changing landscape. Specifically, they know that forest management strategies should lead to preservation of hydrological flows, mitigation of extreme hydrologic events, retention of soils and sediments, conservation of productivity and biodiversity, as well as maintenance and purification of water supply. As such, conservation of water resources is already a forest management objective in most institutional settings (e.g., a necessary criterion in forest certification systems). However, on a global basis, water is still not getting the recognition it deserves in forest management.

We believe two major barriers exist to effective conservation of water resources:

- 1) Lack of a well-articulated conceptual framework; and
- 2) Lack of practical strategies for implementing such a framework.

Two major barriers exist to effective conservation of water resources:

- 1) Lack of a well-articulated conceptual framework; and**
- 2) Lack of practical strategies for implementing such a framework.**

The framework should consist of a set of principles based on hydrological theory. These could then form the basis of an ecosystem management strategy that ensures the sustainability of water and related resources in forested landscapes. This is a natural link since hydrological processes drive so many of the geomorphic, biogeochemical, and ecological processes in forest ecosystems. Hydrological principles and associated policies and practices that are based on current data and models will better enable the broad forest hydrology community (including industry,

¹ Republished with permission: Creed, I. F., Sass, G. Z., Buttle, J. M. and Jones, J.J. 2011. Hydrological principles for sustainable management of forested ecosystems. *Hydrological Processes*, 25:2152-2160.

governments, academia, and citizens) to develop sustainable management policies and practices that lead to safe and secure water resources.

To support the development of these principles, this chapter synthesizes our state of knowledge on the implications of forest management on water resources under a changing global climate. The synthesis is based on: previous scientific reviews of long-term small watershed studies; policy; planning and operational practices; as well as interviews and workshops with scientists and managers. Our objective is to share experiences from across Canada, and to propose a set of principles embedded within a systems approach to guide forest management to a desired future with safe and secure water supplies (Table 3).

While some if not all of these principles enjoy widespread use and recognition, their adoption may be selective or incomplete. Our question is: How generalizable are these principles? Our hope is to initiate a larger discussion amongst forest scientists, managers and policy makers who either generate or use the science, and to seek consensus for a core set of scientifically based principles for sustainable management of forested ecosystems.

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4.2 A principled approach

Our principles are rooted in the classic systems approach including the description of a system's boundaries, components, spatial and temporal relationships, and its position within other systems. Hydrologists have long argued that as a society we need to adopt a hydrological systems perspective when addressing water

related issues. This provides the foundation for our principles. While some may argue “why watershed” when other perspectives may be valid (e.g., a landscape), we argue that hydrological systems must be considered in our management objectives even at the landscape perspective. Water is, if not a dominant control, then at least a first order one on ecosystem structure and function – if it is not conserved it becomes very difficult to satisfy many other ecosystem services.

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A hydrological systems approach encourages us to refocus management from purely ecological objectives, such as maintaining the habitat of a single species within a forest stand, to eco-hydrological objectives that try to preserve the hydrological, energetic, and biogeochemical basis of biodiversity, productivity, and integrity within the watershed. Such an approach facilitates consideration of:

- 1) Transfer of both energy (photosynthesis, evapotranspiration) and matter (sediment, nutrients and biota) along hydrological flowpaths at varying spatial scales;
- 2) Interdependence and connections between ecosystem subunits; and
- 3) Cumulative effects of management activities.

A hydrological systems perspective also integrates the often-divergent terrestrial and aquatic approaches to forest management.

PRINCIPLE 1 **Define system boundaries based on knowledge of hydrological response units**

Forest management should define hydrological response units based on the dominant hydrological flowpaths on the landscape.

Table 3. Hydrological principles of sustainable forest management

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 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, 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 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.

Determining a system's boundary is one of the most important and challenging aspects of working with ecosystems, given that many ecosystem processes are very diffuse and dynamic. A good working definition of a hydrological system is required to place management activities in a hydrological context to know from where water is coming (upstream) and where water is going (downstream). This principle builds on the concept of ecosystem management already in use by forest managers, but applies it at the scale of a watershed rather than a forest stand or a landscape (Figure 2).

Determining a system's boundary is one of the most important and challenging aspects of working with ecosystems, given that many ecosystem processes are very diffuse and dynamic.

When considering forests as hydrological systems, the level of difficulty in delineating system boundaries depends on the dominant water processes and pathways. In many forest regions hydrological systems can be delineated by topographic divides. However, in drier climates, and in regions with deep and heterogeneous geological deposits, water flow is best predicted by knowledge of local, intermediate and regional ground water flow systems and not just topographic gradient (Devito et al. 2005). Water flows along

preferred pathways resulting from macropore networks or substrates with much higher hydraulic conductivities than the surrounding matrix. The delineation of hydrological response units for these systems is much more difficult given subsurface controls on flows.

Digital elevation models have revolutionized the automatic delineation of topographically defined hydrological systems and implementing management boundaries based on topography is straightforward. The remaining challenge is to develop techniques for automatic delineation of non-topographically defined hydrological systems.

PRINCIPLE 2
Conserve critical hydrological features along the hydrological system

Forest management should conserve areas where precipitation infiltrates into the ground (e.g., recharge zones), where water exits the ground and discharges into receiving bodies of water (e.g., discharge zones), and where water is stored along the hydrological network.

Hydrological systems have critical features where certain hydrological processes dominate during specific time periods, and their consideration ensures the conservation of hydrological function. We need to extend the traditional concept of buffer zones widely used in forest management to a broader range of features. These include recharge, storage and discharge functions, given their importance based on regional biophysical and climatic conditions. This principle promotes a more sophisticated approach to protecting

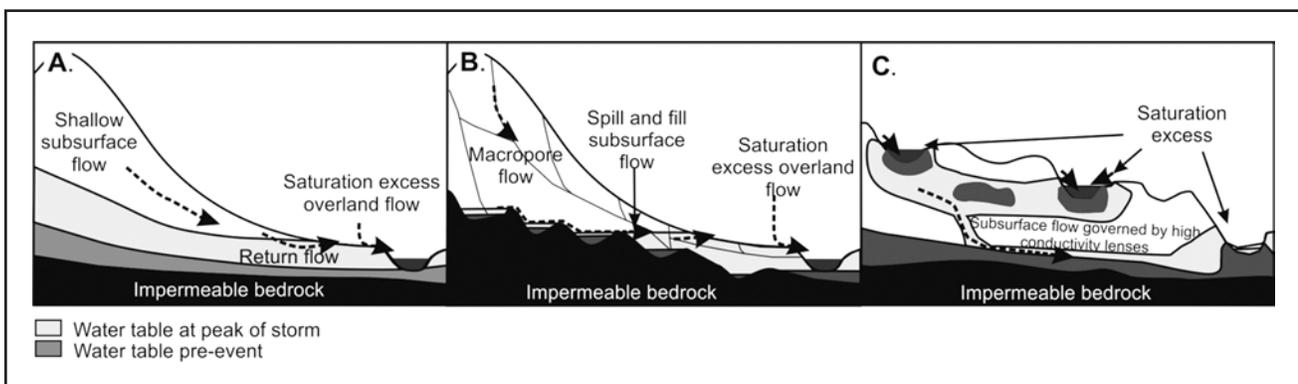


Figure 2. Principle 1, delineate hydrological systems by considering the dominant processes and pathways of water: (A) Variable source area hydrology where surface topography controls hydrological flows, (B) Variable source area hydrology where bedrock topography controls hydrological flows, and (C) Non-variable source area hydrology in sub-humid, flat landscapes where surficial geology controls hydrological flows (from Creed and Sass 2011).

water resources by identifying critical areas across the landscape rather than simple, fixed-width buffers around water bodies (Figure 3, Buttle 2002).

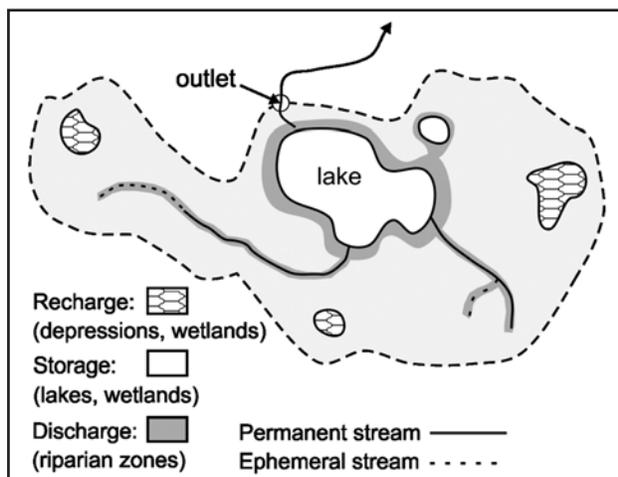


Figure 3. Principle 2, conserve hydrological features that serve critical functions such as recharge, storage, and discharge of water along surface and subsurface pathways.

The forest floor is an important recharge area characterized by low bulk density, high macroporosity, high saturated hydraulic conductivities, and consequently high infiltration rates that create conditions where most water reaching the forest floor enters shallow or deeper subsurface flowpaths (Neary et al. 2009). Forest management can disturb the forest floor and compact soil, forcing water to flow overland and increasing sediment and nutrient transfer to receiving water bodies (Croke and Hairsine 2006, Kreutzweiser et al. 2008). These impacts can be minimized by avoiding areas of focused recharge on hillslopes such as topographic depressions, and by conducting work during biologically and hydrologically inactive parts of the year.

Furthermore, water is stored in various surface (e.g., wetlands) and subsurface (e.g., soil matrix, aquifers) features along the hydrological system. Water storage is important for biological uptake and also attenuates water release from watersheds to reduce flood potential. Forest management planning should consider how activities may alter water movement into and out of storage and how they will impact sediment and nutrient load.

Finally, riparian and hyporheic (region beneath the stream bed where mixing of surface water and shallow groundwater occurs) zones along ephemeral and

permanent stream corridors and adjacent to wetlands, rivers, and lakes are important discharge areas. Water is transferred from subsurface flowpaths to surface flowpaths, making these areas important for biogeochemical activity. Nutrient laden water emerges into the rooting zone and is consumed by organisms, converted to gaseous forms, or exported to surface waters (Creed and Beall 2009). Forest management planning must recognize the hydrological and biogeochemical importance of discharge areas and conserve them using buffers. Plans should also recognize that not all landscapes may have this biogeochemical filtering functionality (Buttle 2002).

Many maps used for the identification of hydrological features are out of date and/or have inadequate spatial resolution.

Many maps used for the identification of hydrological features are out of date and/or have inadequate spatial resolution. For example, important hydrological features such as ephemeral and 1st order streams and wetlands underneath the forest canopy are often missing on government topographic maps, even though they influence recharge, storage and discharge functions (Creed et al. 2003, Bishop et al. 2009). This omission may partly reflect the expense of field inspections for mapping hydrological features at the appropriate spatial and temporal scales. However, recent developments using digital terrain analysis (Creed and Sass 2011) combined with a time series using remote sensing techniques and/or modelling techniques (Sass and Creed 2011) show promise for delineating surface hydrological features, including recharge, storage and discharge areas, under a forest canopy.

Recent developments using digital terrain analysis combined with a time series using remote sensing techniques and/or modelling techniques show promise for delineating surface hydrological features.

PRINCIPLE 3
Maintain hydrological connectivity between hydrological features

Forest management should maintain all existing hydrological connections and prevent the creation of new connections to ensure that the hydrological system can handle the rate of water, sediment and nutrient movement.

Management activities undoubtedly sever (e.g., by disruption of existing ephemeral or permanent streams) or enhance (e.g., by formation of extensive road networks) some connections between hydrological features. The disturbance can be minimized with knowledge of where and when hydrological connectivity is most vulnerable. This principle considers hydro-

logical connectivity as a system property that reflects the degree to which a system facilitates or impedes water flows between system elements (Figure 4).

Hydrological connections may occur along surface and subsurface flowpaths and can be transient or permanent. They are naturally dynamic due to such factors as changes in climatic conditions and ecological activity both at the surface (e.g., beavers creating dams) or subsurface (e.g., roots creating macropore networks). Most landscapes are hydrologically disconnected most of the time; however, they may quickly reach full connectivity in a non-linear, step-wise fashion (Lehmann et al. 2007, Sass and Creed 2008). Hillslope features that increase connectivity are surface saturated and inundated areas, macropore

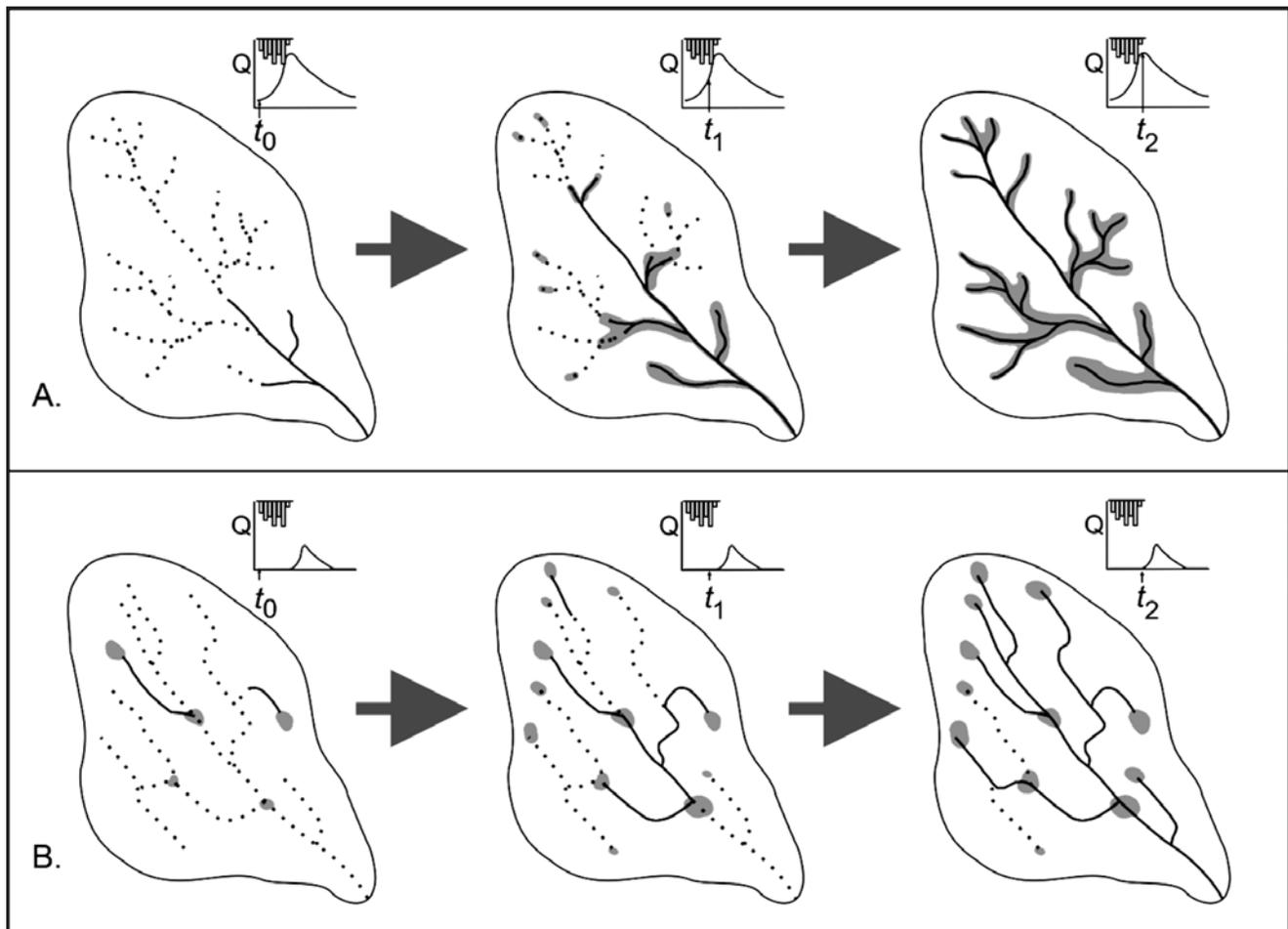


Figure 4. Principle 3, maintain hydrological connectivity among the critical hydrological features. Hydrological system (A) exhibits a rapid increase in surface connectivity in response to an event, whereas system (B) exhibits a much lesser degree of surface connectivity with much smaller expansion of its variable source areas. Solid and dotted lines represent saturated and dry stream channels, respectively. Shaded areas represent surface saturation. The inset hypothetical hydrographs are measured at the basin outlet (from Todd et al. 2006).

networks, and water tables bridging hillslopes to streams across riparian areas (Tromp-van Meerveld and McDonnell 2006, Sass and Creed 2008, Jencso et al. 2009). Hydrological connectivity is critical for determining the timing and magnitude of discharge (Western et al. 2001, Lindsay et al. 2004) as well as determining nutrient, sediment and organismal transfers within and between terrestrial and aquatic systems (Pringle 2003, Stieglitz et al. 2003, Croke and Hairsine 2006).

Most landscapes are hydrologically disconnected most of the time; however, they may quickly reach full connectivity in a non-linear, step-wise fashion.

Forest managers must recognize where these transient and permanent hydrological connections are located since placement of road networks and other management activities (e.g., skid trails, landings) can have severe downstream consequences. In steep landscapes, roads may route water to road fills and culverts and contribute to mass movements (Wemple et al. 2001, Eisenbies et al. 2007). On the other hand, in flat landscapes roads may enhance blockage of drainage pathways, especially where culvert design is inappropriate for site conditions (Alpac 2008). Given their dynamic nature, information on hydrological connections is needed not only at spatial scales relevant to forest operations, but also across temporal scales representative of the broad range of climatic conditions in a given forest region.

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The potential for mapping of hydrological features and the return periods of their hydrological connectivity using field measurements coupled with digital terrain modelling and/or airborne or satellite remote sensing in forest management plans has recently been illustrated (e.g., Creed et al. 2008).

PRINCIPLE 4 **Respect temporal variability of hydrological systems**

Forest management should respect the shifting dominance of hydrological processes due to climatic oscillations, climatic change, and forest management strategies such as fire suppression.

Hydrological systems are dynamic due to constantly changing meteorological and/or climatic conditions. Hydrological processes therefore shift in dominance with time. From a management point of view, it is important to understand these shifts over both short (e.g., intra-annual timing of peak runoff) and longer time periods (e.g., inter-annual timing of peak runoff). This principle recognizes that interactions of climatic factors (water and energy) create diversity in hydrological form and function that can defy simple generalizations. Forest management strategies should respect this temporal variability when defining management targets (Figure 5).

Forest management strategies should respect a hydrological systems' temporal variability when defining management targets.

Temporal variability in hydrological patterns and processes occurs at multiple scales and is influenced by human activity. Natural cycles, from day-to-day stochastic weather variability to longer-term climate cycles (e.g., El Niño-Southern Oscillation, Stenseth et al. 2002), are superimposed on directional changes driven by anthropogenic forcing (through forest conversion and afforestation as well as greenhouse gas emissions) (Brooks 2009). It has been suggested that forest watersheds be managed to sustain the natural

flow regime (Poff et al. 1997) or the natural range of variability (Landres et al. 1999). Such management is predicated on historical conditions. While these concepts are appealing as a forest management tool, their practical utility is limited by such factors as: the difficulty of obtaining relevant records; uncertainty about defining the reference period for assessing “natural”; and controversy about how to use the information (Bishop et al. 2009). Their practical utility is also limited by uncertain future conditions (Millar et al. 2007).

The best way to respect temporal variation is maintaining, reinforcing, and innovating long-term monitoring networks. These networks are required to understand the dynamic interplay amongst anthropogenic forcings (climate change, forest management) and the preservation of forest values, such as productivity and biodiversity, to assess the efficacy of mitigation strategies and plan adaptation strategies. Also, long-term monitoring is essential to quantify the “non-stationarity” in dynamic hydrological systems in order to pro-actively plan adaptation.

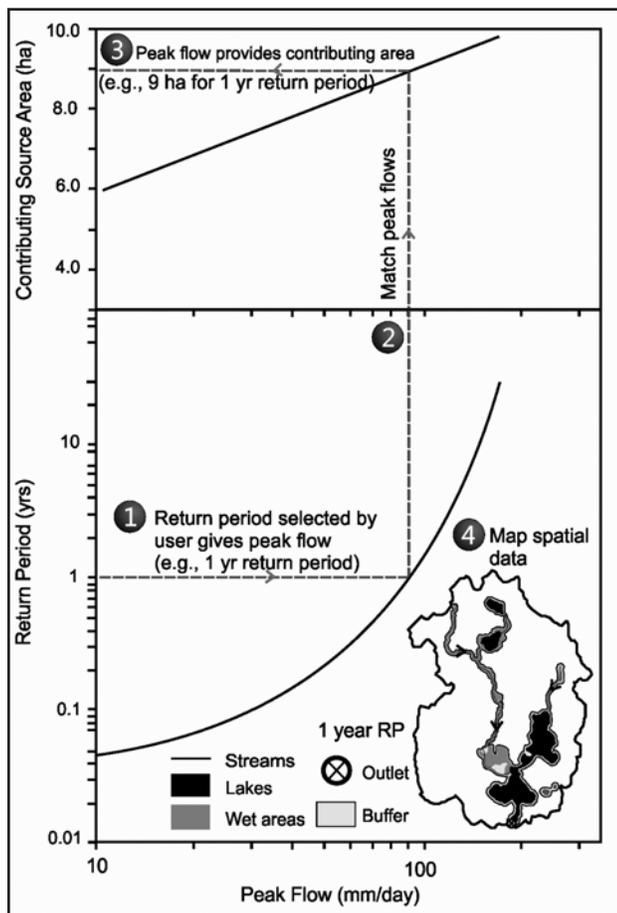


Figure 5. Principles 4 and 5, respect temporal variability and spatial heterogeneity of hydrological systems. This hypothetical nomogram illustrates how management plans can be based on the return period of peak flows (temporal variation) and their associated contributing source areas (spatial variation). Cut block, road or buffers could then be designed based on the degree of risk (i.e., return period of soil saturation or inundation) that the manager is prepared to accept (modified from Krezek 2001 and Creed et al. 2008).

The best way to respect temporal variation is maintaining, reinforcing, and innovating long-term monitoring networks.

PRINCIPLE 5 Respect spatial heterogeneity of hydrological systems

Forest management should consider the spatial variation of hydrological systems that is a consequence of the interplay of the spatial hierarchy of factors influencing hydrological processes both within a single watershed and among watersheds in different geographic settings.

Watersheds of different scales and different geographies have substantial differences in hydrological behaviour.

Watersheds of different scales (catchments to continental drainage basins) and different geographies will have substantial differences in hydrological behaviour. Forest management strategies should respect this hydrological variation when transferring data, tools and knowledge to different geographic areas. This principle recognizes that while the uniqueness of place is a general characteristic of nature, there are useful conceptual and practical approaches to address spatial variation when defining management targets (Figure 5).

The factors that control variation in space have been known for many years (Lotspeich 1980), but have only

recently begun to be organized into a predictive tool (Blenckner 2005, Devito et al. 2005, Winter 2001). While standard operating practices are often customized to a specific site, more information is needed to make them a “custom fit.” A scientific understanding of the changing dominance in hydrological processes is needed, so that “rules” developed from one region are not arbitrarily applied to another. A formal watershed classification system that reflects the changing dominance of hydrological processes would provide a solid foundation for the development and application of site-specific best management practices including buffer widths, road placement strategies and harvest block design.

A watershed classification requires national datasets on climate, bedrock and surficial geology, soils, topography, and vegetation at appropriate spatial resolutions (i.e., at least 10 to 25m). While access to data, and computer resource requirements, may present challenges in some jurisdictions, the lack of generally accepted methods for watershed classification presents the greatest impediment. Until a clear methodology emerges, managers will have to rely on our current understanding of hydrological processes.

PRINCIPLE 6
Maintain redundancy and diversity of hydrological form and function

Forest management should respect the redundancy and diversity of hydrological features to ensure maintenance of hydrological function over the range of natural variability of the system.

This principle recognizes that forest ecosystems have evolved to contain redundant processes that lead to resiliency (Figure 6, Holling 1973, Chapin 2009). When considering the hydrological basis for resiliency, we argue that a critical number of hydrological features performing diverse functions (recharge, storage, discharge) are needed to buffer the system against disturbances (natural or not). For example, clear cutting a watershed will result in a shift of hydrological

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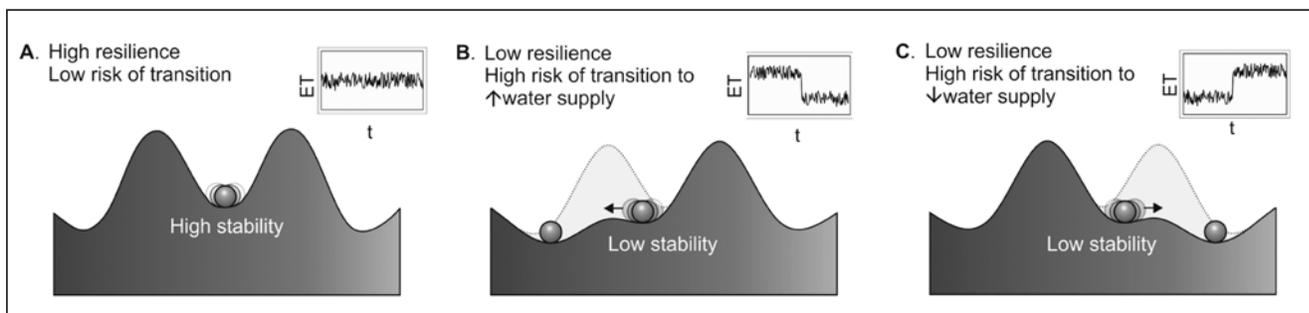


Figure 6. Principle 6, maintain redundancy and diversity of hydrological form and function. Forest ecosystem stability is defined by the depth of the basin of attraction. A deep basin of attraction (A) indicates a stable ecosystem and one that is resilient to small perturbations. A shallow basin of attraction (B and C) indicates an unstable ecosystem susceptible to a change of state from small perturbations. Forest management practices that may reduce the ecosystem’s stability (reflected in the shallow basin of attraction) during which small perturbations (arrows) may then force the ecosystem into a change of state. In this example, the ecosystem state is characterized by evapotranspiration (ET) thus a change of ecosystem state can result in either an increase (B) or decrease (C) in water production (Q). In B, changes that reduce ecosystem stability and result in a shift to a decrease in ET (and increase in Q) may include conversion from forest to residential lands. In C, changes in forest structure that reduce ecosystem stability and result in a shift to an increase in ET (and decrease in Q) may include forest fire suppression or forest biofuel plantations (modified from Scheffer 2010).

flows from subsurface to surface pathways, potentially leading to substantial increases in water, sediment and nutrient yields. However, cut blocks interspersed with forest to encourage infiltration will retain enough recharge and storage functions to prevent significant sediment and nutrient yields. Put another way, forest management that focuses on maximizing production of a single objective (e.g., timber production) may create systems with reduced redundancy that may be subject to ecosystem collapse.

Coupled hydrological monitoring and modelling provides a valuable tool for managers facing the challenge of quantifying an adequate level of hydrological redundancy, since this presents the best way to ask “what if” questions regarding the hydrological consequences of forest management activities (e.g., Peterson et al. 2009).

4.3 Outcome of a principled approach: a resilient forest

Resilience is an emergent system property that determines how systems deal with disturbance. Systems with resilience are able to respond to disturbance by reorganizing into a system with similar form and function. In contrast, systems with no resilience reorganize as completely different systems with different forms and functions. The concept of resilience is beginning to filter into the hydrological sciences (Peterson et al. 2009). We argue that forest management that adopts a principled approach along the lines suggested here will maintain hydrological resilience. Implicit in this principled approach is that the principles are “non-negotiable”: they cannot be traded off if ecosystem services from the forest are to be sustained.

We argue that forest management that adopts a principled approach along the lines suggested here will maintain hydrological resilience.

4.4 Conclusions

The many forces that modify forests create challenges for managers to provide safe and secure water supplies. One unifying approach to forest management could be based on considering our future dependency on water from forests and adopting hydrological principles to help guide us to this future. We suggest six hydrological principles based on our state of knowledge of the science, which could provide the basis for forest management practices to secure our forest water supplies for future generations. Most of these principles are obvious to forest hydrologists and managers, but they will require work to be translated into effective policies and practices.

One unifying approach to forest management could be based on considering our future dependency on water from forests and adopting hydrological principles to help guide us to this future.

5.0

Barriers to integrating hydrological principles into practice

In Canada, Standard Operating Procedures (SOPs), are usually unique to a specific company (or operating area) and reflect:

- 1) Provincial regulations and guidelines;
- 2) Forest management agreement and license conditions;
- 3) Company policies, objectives and management strategies;
- 4) Science and traditional knowledge; and
- 5) Local stakeholder input in terms of forest values and concerns.

We conducted a cross-country “check-up” of SOPs for protection and conservation of water resources. Specifically, a survey was sent to 98 Canadian forest managers from government (67 managers) and industry (31 managers) to document current policies and operational practices within their respective organizations (Appendix 1). For the 18 respondents (Figure 7), we evaluated if and how the hydrological principles presented in Chapter 4 are reflected in these policies, plans and operational practices (see below).

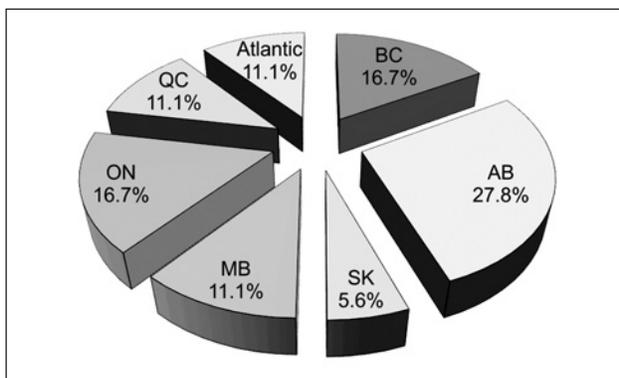


Figure 7. Provincial distribution of survey respondents across Canada.

We conducted a cross-country “check-up” of SOPs for protection and conservation of water resources.

5.1 Survey of current policies and practices

Survey results showed that water is a priority concern for forest managers. Water related issues or concerns were ranked as high relative to other forest management issues by 67% of forest managers. Forty-four percent of forest managers noted that stakeholders and Public Advisory Committees also rank water related issues high relative to other forest management issues.

The effects of forest operations on water quantity and water quality were identified as major concerns. Despite this, only about half of the organizations surveyed indicated they must complete an environmental assessment process associated with the development of forest management plans, or have specific or unique management considerations with respect to water systems in accordance with provincial legislation, policy and regulations.

The effects of forest operations on water quantity and water quality were identified as major concerns.

Sixty-percent of organizations surveyed indicated that certification had not improved water conservation practices.

The majority (83%) of organizations indicated they have certified forest operations under Canadian Standards Association, Forest Stewardship Council, International Standards Organization and/or the Sustainable Forest Initiative (all but two with annual audits). Of those that were certified, all respondents said that business interests (e.g., maintaining trade relations and market access, remaining competitive with other organizations) were considered in their decision to seek certification. This suggests that market pressure is the driving factor when deciding to seek certification of forest operations. Sixty-percent indicated that certification had not improved water conservation practices, citing the fact that legislation drives operations related to water conservation and/or their site already focused on water conservation prior to certification.

Below we further explore the survey results in the context of our hydrological principles presented in Chapter 4.

PRINCIPLE 1
Define system boundaries based on knowledge of hydrological response units

Forest management should define hydrological response units based on the dominant hydrological flowpaths on the landscape.

Forest management planning in most regions of Canada remains focused on the stand. Sixty-one percent of the organizations surveyed indicated that forest management decisions are predominantly made using stand-level criteria. These respondents follow specific guidelines for riparian buffers, site-specific harvest recommendations and road construction and stream crossing guidelines to maintain water quality and address fish habitat concerns. The remainder of the organizations surveyed (39%) considered watershed-level criteria within their planning approach, including watershed harvest levels (percent of a watershed disturbed) and watershed-based modelling

forecasts of annual water flows following harvest (limit changes to less than 15% of annual flow).

Through these responses, we identified several reasons why forest management is not based on hydrological response units, including:

- a traditional focus in forestry on stand level attributes, especially timber values;
- knowledge gaps among resource managers about the potential effects of forest management on hydrological processes at watershed scales (self-ranked knowledge of forest hydrology and related potential forest management effects ranged from 2 to 10 (on a scale of 1 low to 10 high), with an average of 7.3);
- the lack of availability and utilization of data and tools for watershed- or landscape-based planning; and
- the difficulty of adopting new knowledge in forest policy in a timely fashion because, in general, regulations and guidelines are not in place to support a watershed or landscape systems approach.

PRINCIPLES 2 AND 3
Conserve critical hydrological features and maintain connectivity among these features within the hydrological system

Forest management should conserve areas where precipitation infiltrates into the ground (e.g., recharge zones), where water exits the ground and discharges into receiving bodies of water (e.g., discharge zones), and where water is stored along the hydrological network. Management should also maintain all existing hydrological connections and prevent the creation of new hydrological connections to ensure that the rate of water, sediment and nutrient movement can be handled within the hydrological system.

Given that 61% of our respondents said they focus on the stand level during planning, it is clear there is an overall lack of adoption of a hydrological systems perspective when it comes to planning. This means that critical hydrological features and connectivity along the hydrological system may not be conserved. With the focus on the stand, upstream influences and downstream consequences of forest management activities may not be considered.

There is an overall lack of adoption of a hydrological systems perspective when it comes to planning.

However, even if a hydrological system perspective is present, companies may not have the data they need to plan using a systems approach. For example, half of the organizations surveyed indicated that their forest resource inventory is solely timber based, with 11% indicating timber-based inventory with some ecosystem-based values, and only 28% indicating that their resource inventory is ecosystem-based.

Even if a hydrological system perspective is present, companies may not have the data they need to plan using a systems approach.

The majority (89%) indicated that water and wetlands had been inventoried, but most indicated that these water and wetland inventories were based on provincial topographic maps (possibly supplemented by aerial photographs). Such datasets are often dated (most from 1970s and early 1980s) and of inadequate spatial and temporal resolution. For example, most (blue line) streamlines on these topographic maps are at least 2nd or 3rd order streams, with intermittent, ephemeral and 1st order streams missing. This is because most topographic maps are based on aerial photography where hydrological features may be hidden under the forest canopy.

Furthermore, the photographs represent only a “snapshot” in time and may not be representative of the average (or extreme) hydrological states. Only 13% of respondents indicated use of field surveys to map these features and their distribution and connectivity on the landscape.

PRINCIPLES 4 AND 5 Respect temporal variability and spatial heterogeneity of the hydrological system

Forest management should respond to the shifting dominance of hydrological processes due to climatic

oscillations, climate change and forest management strategies such as fire suppression. Forest management should also consider the spatial heterogeneity of hydrological systems that is a consequence of the interplay of the spatial hierarchy of factors influencing hydrological processes both within a single watershed (hillslope) and among watersheds in different geographic settings.

Of the organizations that responded to the survey, the age of the forest resource inventory was highly variable: greater than 10 years (28%); 5-10 years old (17%); 2-5 years old (17%); less than 2 years old (39%). The majority (94%) of the organizations surveyed said that SOPs were customized for each region, but also remarked that more information is needed to make a custom fit. For example, 94% of respondents have access to GIS data layers (although there were some complaints of inaccurate GIS data layers) and 100% have access to airborne and/or satellite imagery for inventory updates. Few forest managers had access to high resolution airborne or satellite imagery to map hydrological features and to update these maps with reasonable frequency and accuracy. While 61% of organizations surveyed said field inspections for hydrological features were conducted, it is logistically expensive to do comprehensive coverage over the time and space scales needed.

As hydrological systems are naturally dynamic, both in time and space, forest managers need maps that reflect current and past conditions, covering a range of hydrological responses (e.g., hydrological extremes showing critical hydrologic features and connections among features). Current forest resource inventories are not targeted to reflect these ranges of hydrological responses because most governments and industries do not have access to the required high resolution airborne and satellite imagery that could facilitate water/wetland inventory updates on a regular basis.

As hydrological systems are naturally dynamic, both in time and space, forest managers need maps that reflect current and past conditions, covering a range of hydrological responses.

PRINCIPLE 6

Maintain redundancy and diversity of hydrological form and function

Forest management should respect the redundancy and diversity of hydrological features to ensure maintenance of hydrological function over the range of natural variability of the system.

Maintaining the number and diversity of hydrological forms and functions leads to hydrological resilience. To maintain these features, forest managers should (1) be adaptive in their management approach, and (2) consider ecosystem services (shift from single values such as timber, to multiple values including ecosystem services provided by water resources).

All organizations surveyed indicated that there is an adaptive management framework (reflecting a continuous improvement philosophy) in place as part of their research and monitoring program. Within these adaptive management frameworks, the main drivers of an organization's choice of SOPs are a combination of provincial guidelines and standards, organization derived standards (enhancements designed to address organization policy, site specific situations, or achieve a higher code of practices); and/or specified practices adopted to meet certification standards.

All organizations surveyed indicated that there is an adaptive management framework (reflecting a continuous improvement philosophy) in place as part of their research and monitoring program.

Some (28%) of the organizations surveyed proactively seek information external to the organization, including government, industry groups, NGOs, academia, and consultants. Many (89%) are actively conducting (or supporting) water related research or monitoring activities. Compliance and effectiveness monitoring of SOPs are done by inspections and/or audits; however, only 61% indicated that water resources are monitored after harvest, and of these they were typically for one year, although some were up to 5 years. SOPs are

reviewed and/or updated on a frequent basis, with 61% indicating every 1-3 years; 28% every 3-5 years; and only 11% indicating "never." While SOPs are reviewed, some (33%) found that there are barriers to the implementation of alternative better or best management practices (BMPs), due to provincial requirements and regulations, lack of expertise and training and operational feasibility.

While SOPs are reviewed, some organizations found that there are barriers to the implementation of alternative better or best management practices (BMPs), due to provincial requirements and regulations, lack of expertise and training and operational feasibility.

We found that all organizations surveyed need to broaden the suite of ecosystem services they consider, as the majority of organizations remain focused on timber. The state of practice has not evolved to the point where those that do consider other ecosystem services can effectively and efficiently place monetary value, and have this monetary value considered when trade-offs are debated. Additionally, there is a need to incorporate values other than simply economics into decision-making.

5.2 Perceived barriers to integrating hydrological principles into policies and practices

The underlying concepts of SOPs are often similar, even though variability in approaches exists between various companies and different regions. From the surveys, we have identified the following barriers to the effective integration of hydrological principles into current policies and practices across Canada:

- 1) Management paradigms are focused on the stand, and need to shift to the system.
- 2) Management practices are based on incomplete and inaccurate data. While there has been a recent trend to new data acquisition (e.g., LiDAR), there

is a need to target the entire hydrological system and establish a standard temporal and spatial resolution across Canada. The bottom line is there is a need for cheap, rapid, and frequent monitoring of hydrological systems in order to accurately predict the probability of critical hydrological features and their connectivity. Furthermore, we need tools to translate this knowledge of hydrologic behaviour across hydrologic regions.

- 3) Companies require greater incentives to use BMPs and to monitor and update BMPs by trained water specialists on a regular basis. Provincial and certification standards are two main drivers of an organization's adoption of better management practices, and so there needs to be a higher code of standards to achieve a higher code of practice.
- 4) Management practices are based on fragmented, partial knowledge of BMPs that are currently available for different hydrological regions of Canada.
- 5) Management practices require greater compliance and effectiveness monitoring.
- 6) Forest managers need opportunities to improve their knowledge of forest hydrology, and the data and tools available to inform forest management strategies. Professional development with respect to conserving water resources is needed, especially as it relates to novel datasets and the tools required for using them.

5.3 Priority needs for promoting better or best management practices

BMPs are a widely used management tool in both Canada and the US to minimize adverse effects of forest harvest and other management activities on water resources. Several reports have recently been completed that summarize BMPs for Canadian and US forestry operations taking place near water (National Council for Air and Stream Improvement Inc. 2009a), as well as other BMPs for silvicultural and management activities (National Council for Air and Stream Improvement Inc. 2009b).

There is no central repository for BMPs in Canada, even though some have been compiled to provide information to the forest industry and contractors

(FPInnovations 2006). In contrast, the United States has a central repository that provides access to national, regional, state and local forestry BMPs for water quality (www.forestrybmp.net). This website includes information on education and training opportunities, relevant legislation and regulations, BMP materials, as well as contacts for more help. It is designed to portray the breadth of the water quality issue in the US as it evolves and to demonstrate the effectiveness of programs designed to maintain and even improve water quality. Canada needs a similar BMP repository, eventually linked with a unified watershed classification system.

There is no central repository for BMPs in Canada, even though some have been compiled to provide information to the forest industry and contractors.

There is also no national monitoring of BMP implementation, despite the fact that BMP programs rely on a high implementation rate. In Canada, there are only a few exceptions that actually track rates of implementation (Bulmer et al. 2008, Ontario Ministry of Natural Resources 2010). In contrast, in the United States, many states have assessed rates of implementation via surveys and are beginning to track trends. Trend data at the regional and national levels show generally high and increasing levels of implementation. The overall national (US) forestry BMP implementation rate is estimated to be 89%. Increased implementation of BMPs is likely a combination of federal and state legislation, regulation and extension in addition to certification programs and public pressure (Ice et al. 2010). We need to see similar tracking (and encouragement) of implementation of BMPs in Canada.

There is also no national monitoring of BMP implementation, despite the fact that BMP programs rely on a high implementation rate.

We need to coordinate research and monitoring activities at a national scale so that “standardized” research approaches can be used to compare the effectiveness of BMPs across the different hydrological regions of Canada.

Finally, there is no enforceable mechanism to assess the effectiveness of BMPs in different hydrological regions of Canada. While forestry companies and governments support a diversity of research and monitoring activities related to water (e.g., aquatic biodiversity, fish and riparian habitat, water quantity and quality, indicators of forest management effects), we need to coordinate these research activities at a national scale so that “standardized” research approaches can be used to compare the effectiveness of BMPs across the different hydrological regions of Canada.

5.4 Summary

It is clear that some hydrological principles are well integrated in current forest management policies and practices. For example, policies and guidelines are in place to minimize and prevent effects of harvest activities on hydrological features with respect to water quantity and quality (Table 4). However, others are not. For example, the use of a hydrological system approach and the associated multi-scale planning strategies is one area where policies and guidelines could be updated or developed to reflect recent research findings. The adoption of better management practices, the valuation of ecosystem services of water and wetlands, and the prediction and assessment of cumulative effects are other areas for improvement, particularly when considering the potential effects of climate change and the need to continually adapt our policies and practices.

The adoption of better management practices, the valuation of ecosystem services of water and wetlands, and the prediction and assessment of cumulative effects are other areas for improvement.

Table 4. Degree of representation of hydrological principle concepts in current forest policy in Canada

(based on review of guidelines, see Appendix 2)

Hydrological Principle	Current Forest Policy Status * no provinces/territories ** some provinces/territories
1. Delineate hydrological system boundaries:	
Forest management based on ecosystem-based management (EBM) or sustainable forest management (SFM) philosophy including hydrological objectives.	**
Acknowledge interdependence of hydrological components with landscape geomorphology, biogeochemistry and ecology.	**
Watersheds adopted as basic planning unit.	**
Cumulative effects recognized.	**
2. Conserve critical hydrological features:	
Soil and site disturbance minimized especially near recharge areas.	**
Riparian and filter area disturbance minimized.	**
Water storage areas conserved.	**
3. Maintain hydrological connectivity:	
Water pathways, sediment and nutrient flows are maintained.	**
Connectivity is maintained through careful placement and design of roads, crossings and harvest areas.	**
Water flow is neither impeded nor enhanced through access or management activities.	**
4. Respect temporal variability:	
Short- and long-term influences of anthropogenic activities and natural cycles on hydrological processes are considered.	**
Role of Natural Range of Variability (NRV) is recognized.	**
5. Respect spatial heterogeneity:	
Within system influences on hydrological processes are recognized (e.g., ridge, slope or riparian stands, north vs. south facing hillslopes, 1 st , 2 nd or higher order catchments).	**
Between system influences on hydrological processes are recognized (e.g., discharge dominated vs. evaporation dominated regions).	**
6. Maintain redundancy and diversity of hydrological form and function:	
Management philosophy embraces the maintenance of redundancy and diversity in form and function.	*
Adaptive management encouraged.	**

6.0

Management actions to facilitate integrating hydrological principles into practice

The 21st century will be the period when humanity gives water the priority it deserves in managed ecosystems. In Canada, water and water related issues and concerns are already a high priority for both forest managers and other stakeholders (see Chapter 5). In addition, changes in hydrological dynamics as a result of climate change are bound to enhance this focus on water resources. Despite this high priority given to water by managers and society, there are opportunities to improve how it is managed.

We believe the best way to improve the management of water resources, particularly under a changing climate, is to adopt a set of hydrological principles, based on the latest science, that are designed to conserve water resources on a long-term sustainable basis. These principles can be used by governments as a framework for developing forest management policy and guidelines that maintain the ecological health and integrity of terrestrial and aquatic systems. Similarly, industry can design or select a suite of best management practices that integrate these hydrological principles for implementation at a local level.

This chapter is focused on practical strategies for implementing these hydrological principles. We will elaborate on the possible management actions outlined in Chapter 4 by discussing some of the cutting-edge data and tools that are applicable to forest management at broad spatial scales. A much more detailed treatment of these methodologies can be found in the companion volume to this report that ties together the science with the data, tools and theory (*Scientific theory, data and techniques for conservation of water resources within a changing forested landscape*, Creed et al. 2011).

We believe the best way to improve the management of water resources, particularly under a changing climate, is to adopt a set of hydrological principles, based on the latest science, that are designed to conserve water resources on a long-term sustainable basis.

Our intent here is not to give full prescriptions, but to give a taste of the management actions that have been made possible through theoretical and technical advances in the fields of remote sensing, terrain analysis, and hydrological modelling.

PRINCIPLE 1

Delineate hydrological system boundaries.

Consider the entirety of the hydrological system within which management actions take place.

MANAGEMENT ACTION 1A

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).

The use of watersheds as a planning unit and analysis of watershed attributes is a widely accepted approach to planning. A fundamental element of a systems

approach involves the recognition that terrestrial and aquatic components in forested ecosystems are intricately linked, and activities in one component of the system will usually affect both systems. Management objectives and strategies should therefore seek to preserve the hydrological basis of productivity, biodiversity and integrity of all species in aquatic and terrestrial ecosystems (i.e., consider energy and matter transfers along hydrological flow paths at various scales).

The challenge for managers is mapping all the dominant flowpaths in the hydrological systems they are operating in. Two things make this mapping difficult:

- 1) flowpaths may be subsurface, which means undetectable in many cases; and
- 2) flowpaths are dynamic, which means that source areas of water shrink during dry periods and expand during wet periods.

While field sampling can easily provide answers at the point scale, they are not applicable at management scales. Fortunately, advances in remote sensing are addressing these limitations, especially for mapping surface water dynamics. For example, microwave sensors penetrate both clouds and vegetation and are amenable to mapping hydrodynamics at large geographic scales (Sass and Creed 2008). In addition, for large sections of Canada's forests there are multi-decadal microwave image series that can potentially provide an accurate picture of surface hydrodynamics.

Detecting subsurface water dynamics is more problematic, but airborne geophysical imaging techniques have shown promise in detecting things like bedrock topographies.

Detecting subsurface water dynamics is more problematic, but airborne geophysical imaging techniques have shown promise in detecting things like bedrock topographies (Vereecken et al. 2008). Furthermore, airborne and satellite remote sensing techniques that detect the discharge or upwelling of groundwater have been developed (Batelaan et al. 1993, Sass and Creed In Prep.). However, these discharge zones require further mapping so they can be tied to their contrib-

uting source areas.

The complementary step to delineating the hydrological system is the establishment of the water budget, which gives an indication of:

- 1) the total amount of water moving through the system; and
- 2) the amount of water separated into different flux and storage components, such as evapotranspiration, discharge and storage in surface and subsurface hydrological features.

The water budget is important for forest managers to determine because it gives an idea of the potential impact of harvesting activities, the optimal timing of these activities to reduce impacts, and it provides a way to assess overall effects to the hydrological system.

The water budget is important for forest managers to determine because it gives an idea of the potential impact of harvesting activities, the optimal timing of these activities to reduce impacts, and it provides a way to assess overall effects to the hydrological system.

Providing an accurate water budget for forested systems may be as easy as measuring discharge and installing a rain gauge, but accessibility, cost and lack of surface flow in some geographic regions may introduce difficulty in water budget estimations. Remote sensing techniques offer some ability to sense components of the water budget, especially hydrological storages that cover large areas and change slowly (Sass and Creed 2011). There are currently operational systems at the global scale that provide daily or weekly updates on the distribution of snow cover, soil moisture and evapotranspiration. The best hope for operationalizing water budgets across a range of geographies and scales is the integration of field techniques, ground-based radar (for precipitation), airborne and satellite remote sensing, and hydrological modelling techniques (Sass and Creed 2011). A concerted collaborative effort by public and private interests could make this a reality.

PRINCIPLE 2

Conserve critical hydrological features.

Minimize disturbance to hydrological features with critical source, transfer and storage functions.

Functionally, it is important to distinguish between recharge, discharge and storage areas. While structurally, hydrological features may serve multiple functions and as a consequence management actions conserving one type of function might also conserve others.

MANAGEMENT ACTION 2A

Minimize disturbance to soils, especially within or near source areas that focus the recharge of water into subsurface pathways.

Forest soils typically have high infiltration capacities due to the high organic content and porosity, and the sheltering effect of overlying vegetation which limits direct, high-intensity rainfall at the soil surface. This means that most of the water reaching the forest floor recharges either into shallow or deep subsurface flow-paths. Overland flow is rarely observed in unmanaged forests.

Conversely, forest harvesting activities may compact soils and lead to deleterious effects downstream (Box 4). Compaction results either from direct compaction of the soil surface by machinery or indirect compaction of the soil surface by rain droplets as a result of vegetation and duff removal. Compaction changes the flow of water from vertical flow into the soil to horizontal

BOX 4

The importance of maintaining soil properties during forest operations (from Arnup 2000)

Concern	Best Management Practices
Structural changes to the soil including compaction and rutting	<ul style="list-style-type: none">• Avoid working in moist and wet soils, especially silt, clay and organic soils.• Schedule harvest and site preparation operations for the appropriate season for site conditions. Sensitive sites are best scheduled for frozen operating conditions or drier periods of the year.• Use low ground pressure harvesting equipment in summer operations on susceptible sites. Brush mats can be used on roads to minimize soil disturbance due to heavy machinery.• Minimize the number of passes within harvest areas during felling and skidding; design harvest blocks to ensure roads, high traffic locations and landings are kept to a minimum and located away from sensitive sites or moist areas.• Maintain surface debris, including logging slash and living vegetation. Spread slash and logging debris on susceptible sites, wet or heavy traffic areas to minimize soil impacts.• Choose harvest methods that are designed to protect advance growth since these will be useful on any upland or lowland site where soil disturbance is a concern.
Reduced infiltration capacity and increased overland flow rates post- harvest	<ul style="list-style-type: none">• Avoid removal (or re-distribution) of surface organic mat and surface vegetation during harvest operations or site preparation, especially on very shallow soils over bedrock and nutrient poor sites with coarse gravels and stones. Frozen conditions during harvest results in less site disturbance to both vegetation and soils.• Where possible, distribute slash and large woody debris to reduce overland flow and break-up slopes or potential drainage channels.• Re-vegetate sites quickly following harvest and use low-impact site preparation methods if feasible.

surface flow. This has two important consequences: the volume of water recharging into the soil is decreased and the volume of water flowing across the surface, with the potential to transfer nutrients and sediments, increases. Of these the enhanced potential for overland flow and increased erosivity is of greatest concern. Therefore, managers need an accurate spatial picture of site susceptibility to soil erosion.

The physical factors that affect soil erosion are related to soil texture, depth to impermeable layers, slope and drainage (Table 5). If spatial information on soil properties is readily available, simple GIS techniques can be used to map an overall soil erosion hazard, indicating zones that should be avoided at all cost (Table 5).

Remote sensing and terrain analysis can be used to routinely derive slope and drainage layers in most forest regions; however, care must be taken in regions where topography does not explain water flowpaths.

Unfortunately, the input layers are in many cases not available. Remote sensing and terrain analysis can be used to routinely derive slope and drainage layers in most forest regions; however, care must be taken in regions where topography does not explain water flowpaths (Creed and Sass 2011). In such instances, microwave sensors can be used to derive saturation and inundation maps which give estimates of general drainage conditions (Sass and Creed 2011).

Soil disturbance and associated erosion can be minimized by avoiding high-risk areas derived from risk maps, or by operating during periods when the ground and/or water is frozen. The utilization of low-impact equipment will also aid in minimizing disturbance. Forest management activities that are farther away from receiving water bodies have reduced potential for impact as overland flow has greater chance to re-infiltrate along the hillslope.

MANAGEMENT ACTION 2B

Minimize disturbance in filter areas around streams, wetlands, 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).

Table 5. Site susceptibility to soil erosion. A soil erosion rating is assigned to a site based on values assigned to each soil attribute (texture, depth to impermeable layer, slope, drainage). For example, a site with soil attributes (shaded cell values) that produce a site susceptibility ranking of 15 has a high erosion hazard (Newfoundland and Labrador Riparian Working Group 2007).

Item affecting soil erosion hazard	Soil erosion hazard				
	Very low hazard (0-2); low hazard (3-5); moderate hazard (6-11); high hazard (12-19); very high hazard (20-32)				
Texture	Gravel 0	Sand/loam 1	Loam/sand/clay 3	Silt and Clay 5	Silt and Fines 6
Depth to impermeable layer	> 100 cm 0	70-100 cm 1	50-70 cm 2	30-50 cm 4	< 30 cm 7
Slope	0-15% 0	16-30% 3	31-45% 6	46-70% 10	> 70% 15
Drainage	Rapidly Drained 0	Well Drained 1	Moderate Drainage 2	Imperfectly Drained 3	Poorly Drained 4

Forested areas bordering water bodies are considered filter areas, and are generally referred to as riparian zones or riparian management areas. Riparian zones are hydrological features where subsurface flow re-emerges or discharges to the surface and flows overland or just under the surface. Given that riparian areas are generally flat, characterized by species specializing at the terrestrial-aquatic interface, and have high microbial activity due to ideal wetness and chemical conditions, they can filter sediment as well as nutrients and thereby minimize adverse effects on water quality. The key in determining the efficacy of riparian zones as filters of sediment and nutrients is mapping water flowpaths across riparian zones: in some regions water flowpaths may bypass the riparian zone filters by moving deeper in the ground or by flowing along channels through the riparian zone.

The key in determining the efficacy of riparian zones as filters of sediment and nutrients is mapping water flowpaths across riparian zones.

The requirement for a buffer, and its width and management options should be based on the dominant hydrological processes for the site under consideration and the need to maintain water quality of receiving bodies. As a result, in some regions hydrological features may not need buffers from a hydrology point of view (e.g., Boreal Plain) and in others a wider buffer may be needed. Adaptive buffer-widths need to be considered, as constant buffer widths are not scientifically supported in some forested regions (Buttle 2002).

The requirement for a buffer, and its width and management options should be based on the dominant hydrological processes for the site under consideration and the need to maintain water quality of receiving bodies.

Remote sensing has the power to establish surface hydrodynamics of saturated and inundated areas and

be combined into a probability map of wetness (Sass and Creed 2008). Such probability maps can be used to delineate adaptive buffers by protecting all areas with high probability of saturation (Creed et al. 2008). They can also assist in identifying portions of the riparian zone where partial harvesting could be conducted without damage to the adjacent aquatic system.

Filter areas associated with non-perennial, 1st, 2nd, or 3rd order streams (low order) are more critical to healthy functioning watersheds than higher order stream channels (Tomer et al. 2009). Thus, greater care should be taken when developing and implementing standard operating procedures around low order streams. As detailed in Management Action 2C below, high resolution Digital Elevation Models (DEMs) are needed in order to even identify low order streams and wetlands.

Once a hydrologically relevant buffer width is found, standard operating procedures designed to minimize disruption to the forest vegetation or soils in filter areas are the best way to minimize harvest related impacts on water quality. Hydrological issues also need to be considered along with ecological considerations, including shade influences of riparian vegetation, structural support of stream banks, leaf litter inputs to microbes and invertebrates, large woody debris inputs into the water body itself (which stabilizes channels, diversifies stream habitat and provides essential cover) (Naiman et al. 2005, Lee et al. 2004). While riparian zones have previously been classified as ‘no-go’ zones for forest management, new strategies for managing riparian areas are being developed to test whether some level of disturbance in riparian areas may be acceptable, and even beneficial, depending on the site and management objectives (Newfoundland and Labrador Riparian Working Group 2007).

Once a hydrologically relevant buffer width is found, standard operating procedures designed to minimize disruption to the forest vegetation or soils in filter areas are the best way to minimize harvest related impacts on water quality.

MANAGEMENT ACTION 2C

Minimize disturbance to storage areas (such as wetlands and ephemeral saturated areas).

Water is stored in different parts of a hydrological system and for different periods of time. The largest volumes of water are stored in lakes and wetlands, as well as aquifers and the soil column itself. Hydrological features that act as storage areas need to be conserved in order to support plant growth and to reduce and delay the runoff of water from a hydrological system.

In general, these hydrologically sensitive features are not detectable on current government maps, as the maps lack the appropriate resolution and were derived using technology that does not penetrate forest canopies. A new type of imaging using laser altimetry (also named Light detection and ranging [LiDAR]) has revolutionized the detection of surface topographies under vegetated terrain, even in dense forests. Previously concealed wetlands can now be accurately detected (Creed et al. 2008, Creed and Sass 2011).

Hydrological features that act as storage areas need to be conserved in order to support plant growth and to reduce and delay the runoff of water from a hydrological system.

Forest managers need to take advantage of LiDAR-derived wetland maps. Some of the provinces have initiated province-wide mapping of wet areas using LiDAR-derived DEMs. Such mapping efforts should be emulated across Canada. The private sector will need help from governments as the acquisition costs of these mapping campaigns is substantial and the rewards can benefit multiple agencies.

Forest managers, with accurate maps of wetlands in hand, can plan to minimize the impact on storage features by avoiding them, or compensating for the impact.

PRINCIPLE 3

Maintain hydrological connectivity.

Minimize disruptions to water, sediment, and nutrient flows within terrestrial system.

MANAGEMENT ACTION 3A

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).

Forest management activities should not be considered in isolation within a forest, but examined based on their location with respect to hydrological features and the flowpaths that connect them. When developing forest management plans, managers should consider how forest management activities may influence hydrological flows, storage and discharge. Harvest areas and road networks can then be designed to maintain water pathway connectivity. Failure to do so can negatively affect water fluxes and create downstream water quality issues.

Hydrological connectivity can be assessed using static and dynamic methods. Static methods employ terrain analysis to derive flowpaths from DEMs (cf. Creed and Sass 2011 for a review of different terrain metrics for hydrological connectivity). These methods assume that topography can be used as a surrogate for hydraulic gradients that drive water flow. The commonly used topographic wetness index (Beven and Kirkby 1979) can be a quick way to assess where water is coming from and where it is likely to end up.

Forest management activities should not be considered in isolation within a forest, but examined based on their location with respect to hydrological features and the flowpaths that connect them.

Dynamic methods incorporate variation in hydrological flowpaths due to climatic fluctuations, and give a more realistic representation of the strongest connections. Microwave sensors provide the ability to detect saturation or inundation patterns under a canopy at frequent intervals (less than 35 days) (Townsend 1998, Sass and Creed 2008, Lang and Kasischke 2009). Alternatively, hydrological models have the ability to simulate surface hydrological conditions (Creed et al. 2001; Beckers et al. 2009). The added benefit of models is the fact that they can be used to forecast future conditions based on different climatic scenarios. While more effort is needed in generating dynamic maps, the value-added is substantial and can be constantly updated as climatic conditions change.

Forest managers can take either static or dynamic maps and use them as a base map, onto which they can superimpose their planned activities. A simple overlay will go a long way in helping to avoid disrupting or impeding hydrological flows. However, they are inadequate to predict the relative magnitude of change resulting from placement of roads, cutblocks, landings, and other management features. This is where the power of hydrological models can be brought to bear as they can be used to predict the magnitude of hydrological changes if certain management actions are carried out. The caveat is that the distributed models needed for this purpose have to be tested in a distributed way (i.e., not just lumped at the outlet), which requires a large, concerted effort.

Dynamic methods incorporate variation in hydrological flowpaths due to climatic fluctuations, and give a more realistic representation of the strongest connections.

Using either static or dynamic methods, the map of spatial relationships between hydrological features has to be at the foundations of all forest management plans. They will help in the protection of:

- 1) entire watersheds that are sensitive to hydrological disruptions and should be avoided by management activities; and
- 2) individual features within a watershed.

MANAGEMENT ACTION 3B

Locate roads, bridges, culverts and harvest areas to ensure surface and subsurface hydrological connectivity is maintained and flow is neither impeded nor enhanced.

For both the placement of linear and areal features, knowing the locations of hydrological connections becomes indispensable.

Hydrological connections are probably most sensitive to the placement of linear features, primarily roads and related features including culverts and stream crossings. If hydrological flowpaths are at the surface or just below the surface, roads placed in these areas can capture the water flowing through and move it along the impermeable road surface. This leads to enhanced erosion, especially in hilly terrain. In flat areas, inappropriate road placement may lead to flooding upstream of the road (which is always raised in comparison to the surrounding flat landscape). The alleviation of hydrological flow disruption is achieved by culverts that, if placed properly, minimize the negative impact of road construction. Stream crossings become critical design features where roads cross major surface flowpaths such as streams.

Hydrological connections are probably most sensitive to the placement of linear features, primarily roads and related features including culverts and stream crossings.

Hydrological connections can also be affected by areal features such as harvest blocks and landings, especially if they are in close proximity to receiving waters. Compaction due to machinery and rain, along with generally higher soil moisture due to loss of evaporation after harvest can make these areal features into sources of overland flow.

BMPs, regulations and policies addressing the location, construction and maintenance of roads, stream crossings and culverts are well developed across Canada and the United States (e.g., Table 6). They were developed in direct response to research results from

the 1970s and 1980s that determined that forest access roads and stream crossings were the primary forestry activities that negatively affected water quality.

Two critical things must be considered by forest managers when implementing these BMPs:

- 1) The mapping or modelling needs to be of high enough spatial resolution in order to identify non-perennial hydrological features under the canopy; and
- 2) Temporal and spatial dynamics need to be incorporated to capture the full range of hydrological conditions.

For example, the construction of roads must ensure that the bridge or culvert is designed to pass the peak flow of the stream within the length of time it is anticipated the bridge or culvert will remain on the site (Table 6).

When considering hydrological features and their connectivity, BMPs focus either on avoidance or mitigation. In terms of avoidance, large wetlands, lakes, streams, but also significant recharge and discharge areas need to be considered. In terms of mitigation, there are well-developed BMPs that forest managers have been using to minimize impact related to water quantity and water quality.

With respect to water quality, drainage control is critical to the successful retention of sediments both during and after construction. This needs to be considered in relationship to the existing drainage pattern on the site. Drainage structures include cross-drainages, ditches, turn outs and other structures that

divert water away from the road and disperse it into areas of undisturbed forest (Alberta Sustainable Resource Development 2009). Drainage structures (temporary or permanent) must be capable of controlling potential storm flows likely to be encountered during construction (New Brunswick Department of Natural Resources 2004).

BMPs targeting water quality include stabilization of exposed soils and creating features that slow the flow of water and sediments. Exposed soils should be covered with either temporary (e.g., straw mulch, brush, slash and tops, seeding and erosion control blankets or mats) or permanent (gravel, rip rap, vegetation), and used alone or in combination with other materials. In terms of slowing sediment transfer, sediment barriers (hay bales) or filter fences can also be used to trap sediment temporarily during road construction and along ditches until vegetation can be established permanently.

Attention to maintaining hydrological connections needs to continue after construction since culverts can become plugged, crossings can fail, and roads washed out. Structures which are no longer in use should be decommissioned and the natural flow regime reestablished.

Attention to maintaining hydrological connections needs to continue after construction since culverts can become plugged, crossings can fail, and roads washed out.

Table 6. Stream crossing construction standards related to temporal variation in flow conditions (British Columbia Ministry of Forests 2002).

Anticipated period the bridge or culvert will remain on the site	Peak flow return period
For a bridge or culvert that will remain on site for up to 3 years	10 years
For a bridge that will remain on site from 3 to 15 years	50 years
For a bridge that will remain on site for over 15 years	100 years
For a culvert that will remain on site for over 3 years	100 years
For a bridge or culvert within a community watershed that will remain on site for over 3 years	100 years

PRINCIPLE 4

Respect temporal variability.

Acknowledge temporal (historic) factors that influence hydrological processes.

Forest management strategies and operating practices require the recognition that hydrological processes are dynamic and are shifting due to climatic oscillations, climate change and other anthropogenic forces. The natural range of variability for the hydrological system under consideration can be used to inform management decisions and ensure that water, sediment and nutrient movements are at rates the system has evolved to handle.

Forest management strategies and operating practices require the recognition that hydrological processes are dynamic and are shifting due to climatic oscillations, climate change and other anthropogenic forces.

We propose that hydrological systems be fully integrated into the concept of the NRV, as part of an ecosystem-based approach to managing both terrestrial and aquatic systems of a forest. Poff et al. (1997) observed that current management approaches for riverine systems fail to recognize the fundamental scientific principle that the integrity of flowing water systems depends largely on their natural dynamic character. Although this dynamic or random change is difficult to characterize or predict (Bishop et al. 2009), particularly in the face of many changing environmental variables and anthropogenic factors, the central concept of variability is important to consider if we are to maintain the integrity of both terrestrial and aquatic components of forest ecosystems (Landres et al. 1999).

We propose that hydrological systems be fully integrated into the concept of the NRV, as part of an ecosystem-based approach to managing both terrestrial and aquatic systems of a forest.

MANAGEMENT ACTION 4A

Recognize there is natural variability in hydrological processes at multiple scales from daily to multi-decadal.

The adoption of forest management practices that result in forests more closely resembling those derived from natural disturbance has been suggested by Hunter (1993) and others as a means to achieve ecosystem-based management (Attiwill 1994, Bergeron and Harvey 1997). The objective of using natural disturbance as a model is to design forest management practices that result in forest structures that fit within the range of variability for a suite of forest attributes based on historic disturbance regimes (Landres et al. 1999, Ontario Ministry of Natural Resources 2001, Andison 2003). It recognizes the importance of, and embraces, variability as a key element in maintaining biological diversity. This is often referred to as the natural-range-of-variability (NRV) theory of sustainable forest management (Landres et al. 1999), and is currently being implemented in policy and practice in many areas of Canada.

Forest management strategies should be designed to recognize and maintain variability in different aspects of hydrological systems. This includes their boundaries, internal features, and their connections. While hydrological variation can be measured from hourly to millennial scales, managers need to focus on annual changes in yield and in the magnitude and timing of low and peak flows. In order to capture these changes, long-term records are needed (Creed et al. 2011).

Mostly, this data has been collected by governmental agencies. However, the closure of monitoring stations and missing data periods have made the long-term characterization of hydrological properties of watersheds difficult. Furthermore, most managed systems are not gauged and therefore managers are faced with making management decision in the absence of watershed specific data or information.

Novel techniques in digital terrain analysis, remote sensing and modelling offer some solutions; however, the remote measurement of stream flow is not yet operational. Collaborative private and public efforts

are needed to ensure that key hydrological variables are measured on a long-term basis. This will enable the evaluation of the effects of forest management activities, and also to set management targets to keep key hydrological processes within the NRV.

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MANAGEMENT ACTION 4B

Recognize there is human induced variability in hydrological processes of different severity (from past management practices to climate change).

In many forested regions across Canada, natural variation is intertwined with past forest management practices, land use conversions, and regional and global changes in climate. For these reasons, in many regions it might be unreasonable to manage to some mythic NRV, which has been constantly shifting for the past few centuries. It has been suggested that NRV should be rechristened to HRV (historical range of variation) (Morgan et al. 1994). Under this conceptual model, the reference condition becomes a moving target defined both by the changing physical conditions as well as choices made by society as to what is important to keep in terms of form and function. Monitoring remains a key aspect and it feeds in directly to the planning processes. For example, large changes in precipitation patterns need to be reflected in species selection for reforestation.

MANAGEMENT ACTION 4C

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.

A key element of climate change is not so much that average temperatures or annual precipitation totals are changing, but rather that the climatic system is becoming more erratic; especially as it relates to the

timing, frequency, and magnitude of extreme events (Min et al. 2011, Pall et al. 2011).

These extremes manifest in temperature (e.g., 2010 Russian heat-wave) or precipitation amounts (e.g., increased incidence of snowstorms in US 2010/2011, extreme cyclone in Australia 2011). The effects of these climatic events (e.g. flooding) can be exacerbated by forest management activities that were designed for lower extremes.

Going forward into a future where climate change is proceeding much faster than the best climate scientists thought even 10 years ago, forest managers need to focus on the incidence of extreme events in the watersheds they are operating in.

Going forward into a future where climate change is proceeding much faster than the best climate scientists thought even 10 years ago, forest managers need to focus on the incidence of extreme events in the watersheds they are operating in. Which of them are increasing and which part of the hydrological system are they impacting the most? Good monitoring datasets will help managers design plans that are prepared for a more chaotic climate future.

PRINCIPLE 5 Respect spatial heterogeneity.

Acknowledge spatial (geographic and scale) factors that influence hydrological processes.

MANAGEMENT ACTION 5A

Consider how scale influences dominance of hydrological processes (moving from headwaters to regional basins).

In general, when moving from headwater to regional basins there is a shift in importance from hillslope control to in-stream control. This means that management actions in the headwaters are a lot more important with respect to water quantity and water quality impacts than in lower reaches of a regional drainage basin.

Unfortunately, our mapping of hydrological features and their connectivity is also of poorest quality in the headwaters. As stated above, non-perennial streams and wetlands do not appear on government maps currently used by many organizations and as a result no avoidance or mitigation is performed for unmapped hydrological features.

MANAGEMENT ACTION 5B

Consider how geographic context including climate, bedrock geology, surficial geology, soil type and depth, topography influences dominance of hydrological processes and patterns as well as forest type and age.

Dominant hydrological processes change with scale but they also change with geography. The spatial factors that control hydrological flow are: climate, bedrock and surficial geology, soil type and depth, topography, as well as vegetation type and age (Devito et al. 2005).

As with time, geographic variation occurs at scales ranging from hectares to many thousands of square kilometres. From a forest management point of view, the relevant variation should be based on broad scale maps of the dominant factors. So for example, going from the Boreal Shield to the Boreal Plain will necessitate a reevaluation of dominant flowpaths, as would going from the drier western portion of the Boreal Shield to the much wetter eastern portion.

Forest management would be very well served by a watershed classification system for Canada, because it would provide a hydrological context for planning activities. At a generic level, managers could use the watershed classification when developing watershed-based forest management strategies. The classification could be used to determine the factors that influence water inputs, the atmospheric pull on that water and the physical characteristics of the watershed that determine the apportioning of water into storage or release (Black 1997, Wagener et al. 2007). While it may be an onerous task to customize BMPs for each watershed, modification of such practices, at least at a regional scale, is needed to improve the relevance of guidelines related to buffer widths, road placement and harvest block design.

BMPs need to be adapted to not only the geographic context but also the scale of the hydrological system (whether headwater or higher order system). Forest managers also need to carefully evaluate the scientific basis of BMPs developed in other regions. For example, there are popular rules-of-thumb with respect to equivalent clearcut area (e.g., 20% harvest rule, beyond which elicits a hydrological response) as well as buffer-widths that have been widely used across North America. These rules need to be customized for each forest region, either based on local research, first-principles, or hydrology and the on-the-ground knowledge of the hydrological system.

Forest management would be very well served by a watershed classification system for Canada, because it would provide a hydrological context for planning activities.

PRINCIPLE 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.

The best strategy to address risk is the implementation of a suite of management strategies and BMPs designed to maintain redundancy and diversity. This is particularly important for the hydrological features most likely to be affected by future extreme events.

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The outcome of management strategies must also be monitored, in an adaptive management framework. This enables the detection of both expected and unexpected effects of management practices, and the effectiveness of our management strategies to meet the desired future state. Consider that forest hydrology is dominated by non-linear dynamics (including threshold and tipping points in forest ecosystem function), at multiple spatial and temporal scales (e.g., changes in hydrological regime after regional disturbances such as fire, pest damage and extreme weather events), which will influence the results of management strategies. If monitoring programs demonstrate that management strategies are not achieving the desired objectives, or if environmental variables change to a degree that management strategies are no longer achieving desired outcomes, forest planning and practices must be adapted to address this.

MANAGEMENT ACTION 6A

Consider watershed functions that might be most impacted by future extreme events and plan to protect features that perform those functions.

From an ecological perspective, maintaining adequate water on the landscape will probably be the most important objective in the face of a changing climate.

From an ecological perspective, maintaining adequate water on the landscape will probably be the most important objective in the face of a changing climate.

In drought prone areas, forest management needs to target conserving and perhaps enhancing water storage. This can best be done by minimizing the increase of hydrological connections.

In flood prone areas, the focus of management will again be storage and the connections between storage units and receiving waters. Forest managers working in different regions of Canada will need to keep informed about climatic trends, especially extreme events and correspondingly adapt their management

programs. The State of Knowledge report on climate change as it relates to forest management in Canada is the ideal place to start (Johnston et al. 2010).

MANAGEMENT ACTION 6B

Consider multiple ecosystem services when assessing tradeoffs in making development choices.

Forests provide multiple ecosystem services of which flood protection and clean water provision are just one. Given multiple challenges from climate change mitigation to maintaining timber production, trade-off mechanisms and conservation incentives will become increasingly important.

Water needs to be raised in priority and we argue that it cannot be traded off.

However, water needs to be raised in priority and we argue that it cannot be traded off. The ecosystem services provided by a healthy hydrological system are not just the ones directly linked to water quantity and quality. Rather water, next to energy from the sun, is the main driver, or at least the enabler, of other ecosystem services. As such, consideration of water or hydrological impacts of forest management activities needs to come in at a very early stage of the management process.

MANAGEMENT ACTION 6C

Consider the interactive nature of the hydrological system with climatic, geomorphic, ecologic and socio-economic systems.

An adaptive management framework that considers both the biophysical and socio-economic systems is needed. Policy makers and forest managers need to be adaptive in the face of increasing demands for resources, and the multiple stressors and cumulative effects of their utilization.

In the face of a changing global climate, with significant uncertainties, policy makers and forest managers need to consider alternate scenarios, such as those related to a future where demand shifts from timber to

biofuel. Alternatively, increasing demands for water may change demand from timber to safe and sustainable water supplies.

Given that the Earth is a complex, adaptive system with a propensity for change, flexible and adaptive policy and practices are paramount to the sustainable management of water resources in forested landscapes. The principle management objective going into an uncertain future must be to maintain ecosystem integrity and promote resilient systems. Effectiveness monitoring must become the cornerstone of all forest management activities, so we can assess the ability of our strategies and practices to achieve desired outcomes, and remain flexible within an adaptive management framework. Continued support of research and monitoring is critical, preferably through partnerships with government, industry, and universities, for revisiting objectives, developing new and innovative strategies and assessing societal wants.

In the face of a changing global climate, with significant uncertainties, policy makers and forest managers need to consider alternate scenarios, such as those related to a future where demand shifts from timber to biofuel.

7.0

Conclusions and recommendations

We have presented a new approach for incorporating respect for water resources into sustainable forest management planning. This backcasting-from-principles approach is being applied by an increasing number of organizations around the world as they move towards sustainability. The process is based upon imagining a sustainable vision of the future, constrained by biophysical and social principles, and determining the necessary policy and practical steps needed to reach that future.

Our goal in this state of knowledge report was to outline hydrological principles that should be part of a future sustainable forest management framework for Canada. Although these principles may be common sense to many forest scientists and managers, our aspiration was to start a structured dialogue that would lead to a comprehensive science-based framework. A framework of foundational principles that can be translated into effective policy, guidelines, management strategies and targets, and finally best management practices.

As part of this goal, we evaluated the degree to which forest management in Canada aligns with these hydrological principles. The results of a survey sent out to forest managers across Canada highlighted current policies and practices, providing a benchmark to assess if and how they support the hydrological principles. We then suggested options for the implementation of the hydrological principles using examples of best management practices from across the country that have espoused the principles presented here.

The way forward for scientists, managers and policy makers to implement our suggested backcasting-from-principles approach is encapsulated in the following main recommendations:

Reach consensus on hydrological principles

We have suggested six hydrological principles based on a hydrological systems approach. There might be more or they could be streamlined into fewer. A dialogue needs to take place between forest hydrologists, managers, and policy makers whose goal is to arrive at a consensus on these fundamental principles.

Embed the hydrological principles into a fully-fledged framework of principles, policy and practice

Following the hierarchy of principles presented in Chapter 3 and Table 2, the policy and implementation strategy needs to be fully formulated along with a suite of potential indicators and support for appropriate tools. An important component of this overall framework will be the development of scientific tools and datasets. Thus, there is a great need to continue and build on our ground-based, airborne and satellite monitoring systems of forests. The integration and analysis of these diverse and expansive datasets is now made ever more feasible with novel techniques in geomatics and modelling, and managers should make use of these tools (Creed et al. 2011). Science-based management that is frequently evaluated using new evidence will give us the best chance to grow resilient forests in perpetuity and reach our desired future forest state.

Integrate the hydrological principles into the full set of social, economic, and ecological principles

Once the hydrological framework is developed, hydrologists need to integrate their principles with other social, economic and ecological principles. This will help to build a comprehensive framework of principles for the sustainability of forest ecosystems. The process should be modelled after successful examples using a participatory approach to include all stakeholders. A secondary goal should be the social learning of all participants.

Develop a process for effective monitoring and adaptation of the backcasting process

The backcasting-from-principles approach is a type of adaptive management strategy. We believe strongly in the adaptive nature of science which constantly reinvigorates its thinking with new evidence, and draws new conclusions on how the world functions. As a result, even the fundamental principles can be modified as new evidence emerges. Forest managers also need to view their policies and plans as works in progress that are not moving along a linear path, but are embedded in a world that is undergoing rapid rates of non-linear change in many of its key systems and drivers. Adaptive management and thinking is only possible within policy environments that are flexible, adaptive and responsive to change.

8.0

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Appendices

- 1 Forest planning and operational practices to promote the conservation of water resources:
A survey of current practices and operations guidelines**
- 2 Provincial and federal guidelines used to assess degree of policy adherence
to hydrological principles (Table 4)**

Appendix 1 Forest planning and operational practices to promote the conservation of water resources: A survey of current practices and operations guidelines

SECTION ONE: Description of your Organization

S1Q1) Which Province(s) and /or Territory (s) do you manage forests within?

- AB BC MB NB NL/Labrador NS
 NU NWT ON PE QC SK YK

S1Q2) What is the total area of the forest you manage or conduct operations in?

- a. < 1,000 ha
 b. 1,000-10, 000 ha
 c. 10, 000 – 100, 000 ha
 d. 100, 000 – 1 million
 e. 1 million ha

S1Q3) What is the composition of your forest management area (s)?

____ % Crown lands ____ % Private lands ____ % Other (please specify) _____

S1Q4) What % of your volume comes from crown lands?

S1Q5) If wood comes from areas outside your management area (wood sourcing), what percent is:

____ % Crown lands ____ % Private lands ____ % Other (please specify) _____

S1Q6) What types of products does your facility/management area produce?

- a. Engineered wood products
 b. Lumber
 c. Oriented Strand Board
 d. Pulp
 e. My facility/management area does not produce products
 f. Other (please specify) _____

S1Q7) *What kind of tenure arrangements exist for the Crown lands managed or used by your organization as wood supply areas and what is your annual allowable cut under the various tenure types?*

Tenure Types	Annual Allowable Cut (m3)
<input type="checkbox"/> Co-management	
<input type="checkbox"/> License agreement	
<input type="checkbox"/> Volume licence	
<input type="checkbox"/> Joint venture	
<input type="checkbox"/> Wood supply area	
<input type="checkbox"/> Other (please specify)	

S1Q8) *What forest management responsibilities are associated with your specific tenure arrangement? Check all that apply.*

- a. Fire suppression
- b. Harvest planning /scheduling
- c. Insect and disease surveys
- d. Inventory
- e. Pre-harvest surveys/pre-planning
- f. Post-harvest assessment
- g. Regeneration and tending
- h. Wood supply and other modelling
- i. Other (please specify) _____
- j. None

S1Q9) *Do you have single or multiple management authorities operating on the same landbase?*

- Single Multiple

If Yes, is there a centralized or cooperative approach to developing Forest Management Plans?

- Centralized Cooperative Both
 Other (please specify) _____

S1Q10) *Is there an environmental assessment (EA) process associated with the development of your forest management plans?*

- Yes No

S1Q11) *Does your organization have any specific or unique licence conditions or management agreements relating to water or aquatic systems?*

- Yes No

If Yes, please describe: _____

S1Q12) *How would you rank your knowledge of forest hydrology and related potential forest management effects?*

- Low 1 2 3 4 5 6 7 8 9 10 High

S1Q13) *What best describes your organization's current forest management approach?*

Check all that apply.

- a. Ecosystem management
- b. Integrated resource management
- c. Maximize timber harvest
- d. Natural disturbance management
- e. Sustainable forest management
- f. Sustained yield
- g. Other (please specify) _____

S1Q14) *Are your forest operations certified?*

- Yes No Some

If Yes or Some, under what certification standards have you been registered?

- a. CSA (Canadian Standards Association)
- b. FSC (Forest Stewardship Council)
- c. ISO (International Standards Organization)
- d. SFI (Sustainable Forest Initiative)
- e. Other (please specify) _____

S1Q15) *How often are certification audits conducted?*

- Annually Every 2 years Every 3 years > 3 years

S1Q16) *Are there any requirements provincially/territorially to seek forest certification?*

- Yes No

If Yes, is a specific standard recommended?

- Yes No

If Yes, which standard?

- a. CSA (Canadian Standards Association)
- b. FSC (Forest Stewardship Council)
- c. ISO (International Standards Organization)
- d. SFI (Sustainable Forest Initiative)
- e. Other (please specify) _____

A1Q17) Which factors were considered in your decision to seek certification of your forest operations? Select all that apply:

- a. Environmental Stewardship
- b. Maintain trade relations and market access
- c. Certification label or brand on material/products
- d. Remain competitive with other certified organizations
- e. Certification is best for the environment
- f. Public image
- g. Importance of water resources in system
- h. Provincially requirement or recommendation
- i. Pressure from NGO's or environmentalists to certify
- j. Mandatory to certify based on membership to Forest Products Association or
- k. Other agency
- l. Conservation of forest/timber resources
- m. Protection for natural habitat(s)
- n. Workers rights
- o. Ethical Reasons
- p. Other (please specify) _____
- q. Other (please specify) _____
- r. Not sure/no reason

S1Q18) Do you feel your certification system has improved your organization water conservation practices?

- Yes No

S1Q19) Does your organization have a public consultation process for forest management plans in terms of annual and or strategic planning?

- Yes No

If Yes, how is this accomplished? _____

S1Q20) Do you have Stakeholder or Public Advisory Committee involvement in the forest management plan?

- Yes No

If you answer YES to the above, how frequently does the committee meet on an annual basis?

- 1 2 3 4 5 6 >6 times a year

S1Q21) Where would your stakeholders or your Public Advisory Committees rank water related issues or concerns relative to other forest management issues?

- High Medium Low

S1Q22) What are the three most prevalent water related issues or concerns raised by your Stakeholders or Public Advisory Committees?

1. _____
2. _____
3. _____

S1Q23) Where would you rank water related issues or concerns relative to other forest management issues?

- High Medium Low

S1Q24) What are the three most prevalent water related issues or concerns you consider important with your organization?

1. _____
2. _____
3. _____

SECTION TWO: Water Resources - Inventory, Ecological Classification and Supporting Information

S2Q1) What type of Forest Resource Inventory do you have? For example, is it a Timber based or ecologically-based forest inventory (i.e. Values other than traditional tree inventory). Please explain.

S2Q3) How old is your forest resource inventory?

- < 2 years 2-5 years 5-10 years >10 years

S2Q4) Have wetlands and/or water resources been inventoried and/or classified?

- Yes No

If Yes, how was this completed?

S2Q5) Do you have access to soil and terrain classification and maps, landscape features, digital elevation models (DEM) etc?

- Yes No

S2Q6) Do you have access to satellite or LIDAR imagery, and/or supplementary photography for special features, inventory updates, depletions?

- Yes No

S2Q7) What type of site specific or local data is collected with respect to aquatic systems or wet areas prior to harvest planning?

- a. Site specific surveys conducted by staff
 b. Additional expert assistance sought for site specific data/management decisions
 c. No site inspections conducted
 d. Other (please specify) _____

SECTION THREE: Planning

S3Q1) *What positions in your organization are involved in planning or monitoring water crossings, riparian buffers and other activities associated with aquatic sites?*

S3Q2) *What type of harvest system is used for the majority of your operations? (check all those that apply)*

- a. Aggregate harvest
- b. Natural disturbance emulation
- c. Single pass
- d. Two pass
- e. Selective Harvest
- f. Softwood understory protection
- g. Variable retention
- h. Other (please specify) _____

S3Q3) *Are modified or different harvest systems used in association with wet areas and sensitive, or other aquatic resources?*

- Yes No

If Yes, please explain.

S3Q4) *How are water resources included in forest planning? (check all those that apply)*

- a. Harvest block layout and operational practices
- b. Inspections and monitoring
- c. Modelling including water flow and/or quality
- d. Riparian strategies
- e. Roads and stream crossings
- f. Special sites/critical habitat
- g. Watershed level considerations
- h. Other (please specify) _____

S3Q5) *Prior to harvest, are priority areas for water conservation identified by the Company or Province?*

- Yes No

If Yes, please describe how.

S3Q6) *If priority areas are identified, briefly highlight how mitigation measures are determined and implemented.*

SECTION FOUR: Operational Practices – Development, Implementation and Training

S4Q1) *What is/are the main driver(s) of your organization's Best Management Practices (BMPs)?*

- a. Provincial guidelines and standards
- b. Organization derived standards (enhancements designed to address organization policy, site specific situations or achieve a `higher` code of practice);
- c. Specific practices adopted to meet certification standards
- d. A combination of above
- e. None of the above
- f. Other (please specify) _____

S4Q2) *Are your BMPs regionally or nationally based?*

- a. Regional
- b. National

S4Q3) *External to your organization, where do you look for information on BMPs?*

- a. Academia/Research Publications
- b. Consultants
- c. Government
- d. Industry Groups
- e. Non-Governmental Organizations
- f. Other industry contacts
- g. Other: _____

S4Q4) *How often are your BMPs reviewed and or updated?*

- a. Annually
- b. 1-3 years
- c. 3-5 years
- d. 5 years
- e. Never

S4Q5) *What is the triggering process for a BMP review?*

S4Q6) *Who reviews the BMPs (internal, external)?*

- a. Internal field personnel
- b. Internal specialists
- c. Internal managers
- d. Internal executives
- e. Certification Auditors
- f. External consultants
- g. Government representative
- h. Stakeholders Committee
- i. No One
- j. Other (please specify) _____

S4Q7) *Are there barriers to the implementation of new or alternative BMPs?*

- Yes No

S4Q8) *If YES, the barriers are mainly due to:*

- a. Equipment
- b. Excessive cost
- c. Expertise/training
- d. Operational feasibility
- e. Public concerns
- f. Regulations and provincial requirements
- g. Safety
- h. Other (please specify) _____

S4Q9) *How does your organization ensure BMPs are properly implemented?*

S4Q10) *How does your organization assess the effectiveness of the BMPS?*

S4Q11) *How are your BMPs communicated internally?*

- a. Electronic bulletin
- b. Formal training
- c. Hard copies to individuals
- d. Postings in common areas
- e. Other (please specify) _____

S4Q12) *How are your BMPs communicated externally to those who are working on your lands?*

- a. Electronic bulletin
- b. Formal training
- c. Hard copies to individuals
- d. Postings in common areas
- e. Other (please specify) _____
- f. No external communication needed: _____

S4Q13) *Does your organization conduct research and monitoring activities related to water resources?*

- Yes No

If Yes, please indicate the area(s) your organization is conducting research and monitoring activities:

- a. Aquatic biodiversity
- b. Fish or fish habitat
- c. Forest management effects
- d. Indicators
- e. Water quality
- f. Water quantity/flows
- g. Riparian habitat and management
- h. Other (please specify) _____

S4Q14) *Is your organization a member of any organizations or partnerships relating to research or technology development and transfer?*

- Yes No

S4Q15) *Is there an adaptive management or continuous improvement framework in place as part of your research and monitoring program?*

- Yes No

S4Q16) *Is your organization currently funding or providing support (either financial or in-kind) for water related research or monitoring activities?*

- Yes No

If YES, please indicate the area(s) your organization is conducting research and monitoring activities:

- a. Aquatic biodiversity
- b. Fish or fish habitat
- c. Forest management effects
- d. Indicators
- e. Water quality
- f. Water quantity/flows
- g. Riparian habitat and management
- h. Other (please specify) _____

S4Q17) *After harvesting, do you implement specific forest renewal or rehabilitation measures to ensure ongoing water conservation?*

Yes No

If Yes, please describe:

S4Q18) *Are water resources monitored after harvest?*

Yes No

If Yes, for how long?

S4Q19) *Would you be willing to participate in a follow up interview discussing some of the above topics?*

Yes No

If Yes, please enter your contact information below:

Other comments?

Appendix 2 Provincial and Federal guidelines used to assess degree of policy adherence to hydrological principles (Table 4)

Alberta

Alberta Sustainable Resource Development (ASRD). 2006. Alberta Forest Management Planning Standard, Version 4.1. Edmonton, AB: Alberta Sustainable Resource Development, 114 pp.

Alberta Sustainable Resource Development (ASRD). 2009. Northeastern Alberta Operating Ground Rules. Edmonton: Alberta Sustainable Resource Development and Alberta Pacific Forest Industries, 98 pp.

British Columbia

British Columbia Ministry of Forests (BCMoF). 1995. Riparian Management Area Guidebook. Forest Practices Code of British Columbia Guidebook. Victoria: Province of British Columbia.

British Columbia Ministry of Forests (BCMoF). 1999. Interior Watershed Assessment Procedure Guidebook (IWAP). Version 2.1 Forest Practices Code Guide series.

British Columbia Ministry of Forests (BCMoF). 2002. Fish-stream Crossing Guidebook. Forest Practices Code of British Columbia Guidebook. Victoria: Province of British Columbia.

British Columbia Ministry of Forests (BCMoF). 2005. *The Forest and Range Practices Act*, Forest Planning and Practices Regulation.

British Columbia Ministry of Water, Land and Air Protection. 2004. Standards and Best Practices for Instream Works. Victoria, BC: Ecosystems Standards and Planning, Biodiversity Branch, BC Ministry of Water, Land and Air Protection, 168 pp.

Tripp, D. B., Tschaplinski, P.J., Bird, S.A. and Hogan, D.L. 2009. Protocol for Evaluating the Condition of Streams and Riparian Management Areas (Riparian Management Routine Effectiveness Evaluation). Forest and Range Evaluation Program, Victoria: BC Ministry of Forests and Range and BC Ministry of Environment, 111 pp.

Manitoba

Manitoba Conservation. 2005. Forestry Road Management Guidelines. Winnipeg, MB: Forest Practices Guidelines Committee, Manitoba Conservation, 28 pp.

- Manitoba Conservation. 2008.** Forest Management Guidelines for Riparian Management Areas. Winnipeg, MB: Forest Practices Guidelines Committee, Manitoba Conservation, 47 pp.
- Manitoba Natural Resources. 1989.** Forest Management Guidelines for Wildlife in Manitoba. Winnipeg, MB: Wildlife Branch, Manitoba Natural Resources, 14 pp.
- Manitoba Natural Resources. 1994.** Manitoba Stream Crossing guidelines for the protection of fish and fish habitat. Winnipeg, MB: Forestry Branch, Manitoba Natural Resources, 53 pp.
- Manitoba Natural Resources. 1996.** Manitoba Natural Resources Consolidated Buffer Management Guidelines. Winnipeg, MB: Forestry Branch, Manitoba Natural Resources, 4 pp.

New Brunswick

- New Brunswick Dept. of the Environment and Local Government. 2002.** Understanding the law: a Guide to New Brunswick's Water Classification Regulation. 16 pp.
- New Brunswick Dept. of Natural Resources. 2004.** Forest Management Manual for New Brunswick Crown Land. Fredericton, NB: Forestry Branch, New Brunswick Dept of Natural Resources, 137 pp.
- New Brunswick Dept. of Natural Resources. 2004.** Guidelines for roads and watercourse crossings. Fredericton, NB: Forestry Branch, New Brunswick Dept of Natural Resources, 81 pp.
- New Brunswick Dept. of Natural Resources. 2005.** Objectives and Standards for the New Brunswick Crown Forest for the 2007-2012 Period. Fredericton, NB: Forestry Branch, New Brunswick Dept of Natural Resources, 40 pp.

Newfoundland and Labrador

- Newfoundland Dept. of Environment and Conservation. 1998.** Environmental Protection Guidelines for Ecologically Based Forest Resources Management (Stand Level Operations). 19 pp.
- Newfoundland Dept. of Environment and Conservation. 2004.** Management of Protected Water Supply Areas. Water Resources Management Division, 20 pp.
- Newfoundland Dept. of Environment and Labour. 1992.** Environmental Guidelines for Bridges. Water Resources Management Division, Water Investigations Section, 30 pp.
- Newfoundland Dept. of Environment and Labour. 1992.** Environmental Guidelines for Culverts. Water Resources Management Division, Water Investigations Section, 18 pp.
- Newfoundland Dept. of Environment and Labour. 1992.** Environmental Guidelines for Diversions, New Channels and Major Alterations. Water Resources Management Division, Water Investigations Section, 17 pp.
- Newfoundland Dept. of Environment and Labour. 1992.** Environmental Guidelines for Fording. Water Resources Management Division, Water Investigations Section, 4 pp.
- Newfoundland Dept. of Environment and Labour. 1992.** Environmental Guidelines for General Construction Practices. Water Resources Management Division, Water Investigations Section, 18 pp.
- Newfoundland Dept. of Environment and Labour. 1992.** Environmental Guidelines for Pipelines. Water Resources Management Division, Water Investigations Section, 8 pp.
- Newfoundland Dept. of Environment and Labour. 1992.** Environmental Guidelines for Watercourse Crossings. Water Resources Management Division, Water Investigations Section, 8 pp.

Newfoundland Dept. of Environment and Labour. 1992. Environmental Guidelines for Pipelines. Water Resources Management Division, Water Investigations Section, 8 pp.

Northwest Territories

Forintek Canada Corp. 2007. Community Sawmills Opportunities Study. Report Prepared for Government of Northwest Territories, 105 pp.

Northwest Territories Environment and Natural Resources. 2005. Commercial Timber Harvest Planning and Operations Standard Operating Procedures, 26 pp.

Northwest Territories Environment and Natural Resources. 2010. Northern voices, northern waters: NWT Water Stewardship Strategy 2010, 84 pp.

Ontario

Ontario Ministry of Natural Resources. 1988. Timber Management Guidelines for the Protection of Fish Habitat. Toronto: Queen's Printer for Ontario, 23 pp.

Ontario Ministry of Natural Resources. 1990. Environmental Guidelines for Access Roads and Water Crossings. Toronto: Queen's Printer for Ontario, 62 pp.

Ontario Ministry of Natural Resources. 2010. Forest Management Guide for Conserving Biodiversity at the Stand and Site Scales. Toronto: Queen's Printer for Ontario, 211 pp.

Quebec

Government of Quebec. 2000. The Quebec Forest Act.

Quebec Ministry of Natural Resources. 1998. Updating the Forest System in Quebec: Reference Document on Issues and Orientations. 75 pp.

Quebec Ministry of Natural Resources and Wildlife. Forest Management Standards website.

Quebec Ministry of Natural Resources and Wildlife. Quebec Forests: Rigorous and Adaptive Forest Management website.

Quebec Ministry of Natural Resources, Wildlife and Parks. 2005. Forest Resource Protection and Development Objectives, General Forest Management Plans 2007-2012, Implementation document, 49 pp.

Saskatchewan

Saskatchewan Ministry of Environment. 2004. Legislated Manuals: Standards for Industry, Forest Operations Manual, 10 pp.

Saskatchewan Ministry of Environment. 2007. Legislated Manuals: Standards for Industry, Forest Compliance Manual, 24 pp.

Saskatchewan Ministry of Environment. 2007. Legislated Manuals: Standards for Industry, Forest Management Planning Manual, 262 pp.

Weyerhaeuser. 2009. Prince Albert Forest Management Agreement Area, Standards and Guidelines. 73 pp.

Yukon Territories

Dawson Forest Resources Management Planning Team. 2009. Dawson Forest Resources Management Plan Draft, 67 pp.

Government of Yukon. 2009. Landscape Planning Guidelines, Integrated Landscape Plan for the Champagne and Aishihik Traditional Territory, 45 pp.

Government of Yukon. 2011. *Forest Resources Act* and Regulations.

Yukon Energy, Mining and Resources. 2010. North Yukon Regional Land Use Plan, General Management Directions, Objectives and Best Management Practices, 33 pp.

Federal (Department of Fisheries and Oceans)

Best Practice Guidelines

www.dfo-mpo.gc.ca/habitat/what-quoi/bpg-gmp-eng.htm

Operational Statements (overview, by province/region)

www.dfo-mpo.gc.ca/habitat/what-quoi/os-eo/index-eng.htm

Standard Operating Policies.

www.dfo-mpo.gc.ca/habitat/role/141/1415/14155/fhm-policy/index-eng.asp

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- Government of Manitoba (Manitoba Conservation)
- Government of Newfoundland and Labrador (Department of Natural Resources)
- Government of Ontario (Ministry of Natural Resources)
- Government of Québec (Ministère des Ressources naturelles et de la Faune)
- Government of Yukon (Department of Energy, Mines and Resources)

Industries

- Abitibi Bowater Inc.
- Alberta-Pacific Forest Industries Inc.
- Canadian Forest Products Ltd.
- Daishowa-Marubeni International Ltd.
- J.D. Irving, Limited
- Louisiana-Pacific Canada Ltd.
- Manning Diversified Forest Products Ltd.
- Tolko Industries Ltd.
- Tembec Inc.
- Weyerhaeuser Company Ltd.

NGO

- Ducks Unlimited Canada

Aboriginal Groups

- Gwich'in Renewable Resource Board
- Heart Lake First Nation
- Kamloops Indian Band
- Kaska Tribal Council
- Little Red River Cree Nation
- Métis National Council
- Moose Cree First Nation
- Treaty 8 First Nations of Alberta

Institutions

- University of Alberta (host institution)
- British Columbia Institute of Technology
- Concordia University
- Dalhousie University
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- Memorial University of Newfoundland
- Mount Royal College
- Royal Roads University
- Ryerson University
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