

Hydrologic Effects of a Changing Forest Landscape

Committee on Hydrologic Impacts of Forest Management

Water Science and Technology Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

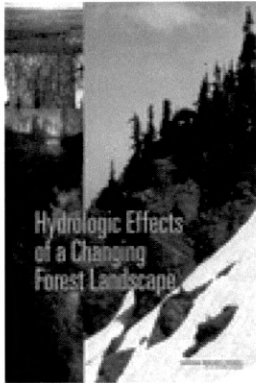
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Free Executive Summary



Hydrologic Effects of a Changing Forest Landscape

Committee on Hydrologic Impacts of Forest Management, National Research Council

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Of all the outputs of forests, water may be the most important. Streamflow from forests provides two-thirds of the nation's clean water supply. Removing forest cover accelerates the rate that precipitation becomes streamflow; therefore, in some areas, cutting trees causes a temporary increase in the volume of water flowing downstream. This effect has spurred political pressure to cut trees to increase water supply, especially in western states where population is rising. However, cutting trees for water gains is not sustainable: increases in flow rate and volume are typically short-lived, and the practice can ultimately degrade water quality and increase vulnerability to flooding. Forest hydrology, the study of how water flows through forests, can help illuminate the connections between forests and water, but it must advance if it is to deal with today's complexities, including climate change, wildfires, and changing patterns of development and ownership. This book identifies actions that scientists, forest and water managers, and citizens can take to help sustain water resources from forests.

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Summary

The forests of the United States cover about one-third of the country's land area and are managed for a number of purposes—timber harvesting, wilderness, habitat, and recreation—but arguably their most important output is water. Precipitation is cycled through forests and soil, and ultimately some is delivered as streamflow to receiving bodies of water. In this way, forests process nearly two-thirds of the freshwater supply in the United States.

Demand for water in the United States is increasing, and forest managers today are asked to provide higher quantities and qualities of water. Water supply managers question whether different land use management in forested headwaters can help meet downstream water quantity or quality demands. Meeting water supply needs is becoming more difficult because elevated water demand is occurring simultaneously with changes in climate, human population and development, land use, and ownership. How to manage forests and sustain water supplies will be a primary challenge in the twenty-first century.

The science of forest hydrology investigates the rates and pathways of water movement through forests. Forest hydrology researchers have amassed a comprehensive understanding of how water is connected to and moves through forests. A strong evidence base has emerged for understanding basic processes and principles of water movement through forests that can be used to predict the general directions and magnitudes of hydrologic effects of changes in forest cover, climate, and land use.

As the demand for water increases in the United States, water managers increasingly draw upon this strong scientific foundation and seek input from the forest hydrology community to identify ways to ensure reliable supplies of water. The U.S. Department of the Interior's Bureau of Reclamation is the largest wholesaler of water in the United States, providing water for more than 31 million people and 10 million acres of irrigated farmland. The U.S. Forest Service (USFS) manages 193 million acres of land for a continuing supply of timber, favorable conditions for streamflow, recreation, wilderness areas, and other objectives. These two agencies requested that the Water Science and Technology Board of the National Research Council (NRC) convene a committee to study and produce a report on the present understanding of forest hydrology, connections between forest management and attendant hydrologic effects, and directions for future research and management needs to sustain water resources from forested landscapes (see Statement of Task, Box S-1). In response, the NRC appointed the Committee on Hydrologic Effects of Forest Management, a group of 14 experts, to generate this report.

BOX S-1
Statement of Task

This study will examine the effects of forest management on water quantity, quality, and timing. The report will reflect on the state of knowledge, relevant policy implications, and research needs that would advance understanding of connections among hydrology, science, and land management and policy in forested landscapes.

1. What is the state of knowledge of forest hydrology?
2. What are information and research needs regarding forest hydrology in forested lands?
 - Topics could include sediment-related watershed processes; surface and groundwater hydrology; biological and ecological aspects; and extrapolation of small-scale study results to large-scale management practices.
3. What are the new issues that need to be addressed to ensure clean and plentiful water?
 - Topics could include extreme weather events, climate change, fire, and invasive species.
4. How well are forest hydrologic impacts understood over short and long temporal scales and small and large spatial scales?

STATE OF FOREST HYDROLOGY SCIENCE

Forest hydrology is the study of water in forests: its distribution, storage, movement, and quality; hydrologic processes within forested areas; and the delivery of water from forested areas. Forest hydrology research uses field measurements, experiments, and modeling to characterize and predict hydrologic processes and their responses to natural disturbance and management of forests. It draws upon disciplinary knowledge from several branches of hydrological sciences, water resources engineering, and forestry to address primary questions of forests and water:

- What are the flowpaths and storage reservoirs of water in forests and forest watersheds?
- How do modifications of forest vegetation influence water flowpaths and storage?
- How do changes in forests affect water quantity and quality?

“Paired watershed” studies have been a primary empirical approach in forest hydrology. In paired watershed studies, two watersheds that are similar in size, initial land use or land cover, and other attributes are selected for study; both are monitored—one is then left as “control,” and the other is “treated” (i.e., subject to manipulations such as forest cutting, road building, etc.). The measured changes in the relationship of streamflow and water quality between the treated and the control watersheds quantify the effects of forest treatment and

regrowth. Most paired watershed studies in forest hydrology were begun in the 1940s, 1950s, and 1960s, but many of these studies were discontinued in the 1980s.

Paired watershed studies, process measurements, plot-scale studies, and hydrologic modeling are important elements of forest hydrology science. Study plots and paired watershed experiments generally range in size from less than a square meter to 1-2 km², and time scales for plot and process studies most commonly span only a few growing seasons. However, some USFS Experimental Forests and Ranges have conducted watershed studies spanning several decades or longer, particularly those designated as Long-Term Ecological Research (LTER) sites, funded by the National Science Foundation.

Forest Hydrology Processes and General Principles

Forest hydrology studies show that changes in forest structure and composition, and associated changes in forest soils and hillslopes, can alter the storage and flowpaths of water through soil and subsoil, which modifies water yield, peak flows, low flows, water chemistry, and water quality (see Figure S-1). The general principles of water movement in and through forests are understood with a high level of certainty (Table S-1).

Using Forest Hydrology Science to Inform Management Decisions

The current body of forest hydrology science supports forest and water management decisions in many ways. Forest hydrology science has led to a clear understanding of general principles (Figure S-1, Table S-1) of water movement through forests. These principles indicate the general magnitudes and directions of direct hydrologic responses to changes in forests over short time scales and in small areas. However, today's forest and water managers need forest hydrology science to predict or indicate the indirect and interacting hydrologic responses in forest landscapes that are changing over large areas or long time scales.

A pressing question for forest hydrologists is whether cutting trees in forested headwaters will augment water yield downstream for agricultural, municipal, or other uses while maintaining desired ecological attributes associated with forested landscapes. Although it is possible to increase water yield by harvesting timber, the increases in water yield from vegetation removal are often small and unsustainable, and timber harvest of areas sufficiently large to augment water yield can reduce water quality. The potential for increasing water yield from forest management is low, which reflects that increases are less likely in seasons when water demand is high and increases tend to be much smaller in drier years.

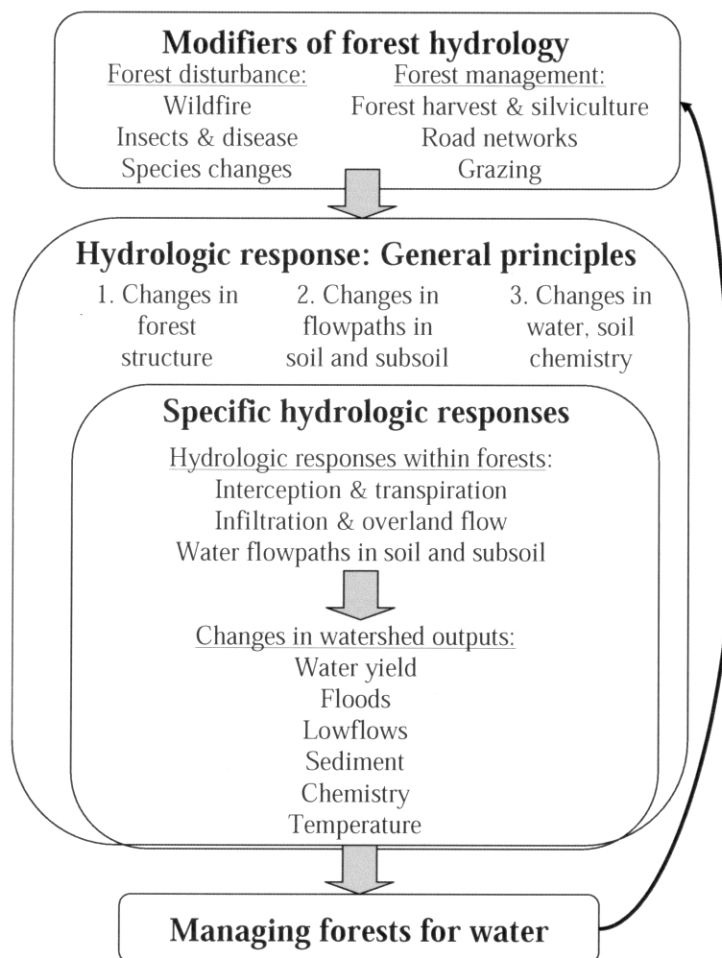


FIGURE S-1 Forest hydrology examines the flowpaths and storage of water in forests and how forest disturbance and management modify hydrologic responses. Hydrologic responses to changes in forests fall into three categories of general principles, as well as specific hydrologic responses, discussed in the text. The final section of this chapter evaluates the state of knowledge of forest hydrology and its implications for managing forests for water, including feedbacks to processes that modify forests.

TABLE S-1 General Principles of Forest Hydrology Describing the Direct Effects on Hydrologic Processes of Changes in Forest Structure, Changes in Water Flowpaths, and Application of Chemicals

Principles of Hydrologic Response to Changes in Forest Structure	
1	Partial or complete removal of the forest canopy decreases interception and increases net precipitation arriving at the soil surface
2	Partial or complete removal of the forest canopy reduces transpiration
3	Reductions in interception and transpiration increase soil moisture, water availability to plants, and water yield
4	Increased soil moisture and loss of root strength reduce slope stability
5	Increases in water yield after forest harvesting are transitory and decrease over time as forests regrow
6	When young forests with higher annual transpiration losses replace older forests with lower transpiration losses, this change results in reduced water yield as the new forest grows to maturity
Changes in Water Flowpaths in Soils and Subsoils	
7	Impervious surfaces (roads and trails) and altered hillslope contours (cutslopes and fillslopes) modify water flowpaths, increase overland flow, and deliver overland flow directly to stream channels
8	Impervious surfaces increase surface erosion.
9	Altered hillslope contours and modified water flowpaths along roads increase mass wasting
Hydrologic Response to Application of Chemicals	
10	Forest chemicals can adversely affect aquatic ecosystems especially if they are applied directly to water bodies or wet soils
11	Forest chemicals (fertilizers, herbicides, insecticides, fire retardants) affect water quality based on the type of chemical, its toxicity, rates of movement, and persistence in soil and water
12	Chronic applications of chemicals through atmospheric deposition of nitrogen and sulfur acidify forest soils, deplete soil nutrients, adversely affect forest health, and degrade water quality, with potentially toxic effects on aquatic organisms

NOTE: These general principles are not predictions, so qualifying adjectives such as "may," "usually," etc. are omitted. See Chapter 3 for factors that influence when, where, and to what extent these principles apply.

RESEARCH NEEDS IN FOREST HYDROLOGY

To meet the needs of the managers and users of forests and water, forest hydrology research has to move from principles to prediction. Predictions are needed to understand the indirect and interacting hydrologic responses to changes in forested landscapes associated with climate change, forest disturbances, forest species composition and structure, and land development and ownership, and how these changes will affect water quantity and quality downstream and over long time scales.

A Landscape Approach to Forest Hydrology

A landscape perspective on forest hydrology links scientific principles from plot, process, and small watershed scales with indirect and interacting hydro-

logic responses at larger spatial scales (i.e., within drainage basins and across large climatic and physiographic regions) in forest landscapes that are changing over long time scales. Within watersheds, forests are located in headwaters and downstream areas, on hillslopes and in riparian zones, and forests fulfill different water-related functions depending on their location. A key unresolved issue in forest hydrology is how to “scale up” findings from one part of a watershed to larger areas or to the entire watershed.

The temporal context for a landscape approach to forest hydrology involves expanding the temporal scale into the past to quantify the effects of antecedent forest management and disturbances and into the future to project and anticipate changes in land use and climate. For example, past forest harvest practices, road networks, fire suppression policies, grazing practices, and natural disturbances such as fire and wind have left legacies in forest structure and composition. These legacies affect hydrologic processes.

The research needs for a landscape approach to forest hydrology science involve studies that determine the following:

- How general principles developed in small, homogeneous watersheds can be used to improve predictions of hydrologic responses across large, heterogeneous watersheds and landscapes;
- How forests and forest management activities affect hydrologic processes, runoff, and water quality as a result of their position within a watershed;
- How local effects of roads can be scaled up to quantify the effects of road networks on water quantity and quality in larger watersheds and regions, particularly during large storms; and
- How long-term legacies of forest disturbance and forest management practices affect forests, water quantity, and water quality.

Forest Disturbance

Forests are dynamic ecosystems subject to both incremental and episodic disturbances that vary in frequency, severity, and extent. Probable hydrologic responses to fire, insects and disease can be inferred from the general principles of forest hydrology (Table S-1). However, compared to the extensive literature on hydrologic responses to forest management, relatively few studies have examined hydrologic responses to fire, insects, and disease in forests, especially at long time scales or in large watersheds.

The research needs for understanding hydrologic effects of forest disturbances involve studies that determine

- Effects of high- versus low-severity forest fires on water quantity, quality, and flooding, and how these effects vary over time and spatial scales; and

- Hydrologic responses to interacting and cumulative effects of forest disturbance (such as fire and insect outbreaks) and forest management (including thinning, salvage logging, roads, timber harvesting, and fire suppression).

Forest Management

Much of the forest hydrology literature focuses on the hydrologic effects of timber management practices and roads. Forest management practices evolve over time, resulting in new practices, such as thinning for fuel reduction, and best management practices (BMPs), such as managing wider riparian buffers for species protection. Moreover, recent increases in fire, insects, and disease in forests have spurred the adoption of forest management practices, such as thinning and salvage logging, whose effects on hydrology have received little study. The hydrologic effects of many of the new management practices and BMPs have not been studied, and dynamic forest conditions make it important to understand how contemporary practices influence water resources.

Research needs for understanding hydrologic responses to forest management involve:

- Studies that determine how contemporary forest management on public and private lands affects water quantity and quality and
- Improved forest hydrology models that reliably simulate the hydrologic and water quality responses of watersheds in varied forest conditions.

Cumulative Watershed Effects

One of the biggest threats to forests, and the water that derives from them, is the permanent conversion of forested land to residential, industrial, commercial, and infrastructure uses. Cumulative watershed effects (CWEs) include the hydrologic effects resulting from multiple land use activities over time within a watershed. Assessing CWEs requires an understanding of the physical, chemical, and biological processes that route water, sediment, nutrients, pollutants, and other materials from hillslopes and headwater streams to downstream areas. CWE research strives to establish cause-effect relationships among forests, water, and watersheds over large spatial and temporal scales.

Research needs for CWEs involve the following:

- A landscape-scale approach to relate downstream conditions to changes in forest conditions and land use in the contributing watershed; and
- Spatially explicit models that identify, connect, and aggregate changes due to forest disturbance and management over time in large watersheds.

Climate Change

Some effects of climate change on forests and water are already evident, and future climate changes are likely to have major effects on forest hydrology. Observed direct effects of climate warming on forests and hydrology include such as changes in the timing of snowmelt runoff and increases in wildfires. More research is needed to better predict indirect effects of climate change, including evaluations of how changes in forests and forest management influence hydrologic response.

The research needs related to the hydrologic effects of climate change include:

- Direct effects of climate change on hydrologic processes in forests and on water yield and water quality from forests;
- Indirect effects of climate change on forest structure and species composition and the consequences of these changes for water yield and water quality; and
- Indirect effects of climate change on forest disturbance, including wildfires, insects and diseases, and the consequences of these changes for water yield and water quality.

RECOMMENDATIONS TO SUSTAIN WATER RESOURCES FROM FORESTS

Scientists who study forest hydrology, forest and water managers, and citizens who use water can take actions to sustain water resources from forests. Each of these groups has important roles to play in applying the current understanding, exploring research gaps and information needs, and pursuing recommended actions (Table S-2).

Recommendations for Scientists

Scientists are poised to advance forest hydrology science to address critical water issues. New research approaches should be pursued in addition to maintaining and expanding existing data. In doing so, **scientists should:**

- Continue current small watershed experiments;
- Reestablish small watershed experiments where research has been discontinued;
- Centralize historical records from watershed studies in digital, well-documented, publicly accessible databases;
- Use the whole body of paired watershed data as a “meta-experiment” to

better understand and improve utility for managers of hydrologic responses to forest disturbance and management over large spatial and temporal scales and a range of forest types;

- Expand the capability for visualization and increase the prediction accuracy of hydrologic response in large watersheds through geographic information systems (GIS), remote sensing, sensor networks, and advanced models; and
- Work with economists and social scientists to improve and communicate understanding of the value of sustaining water resources from forests.

Recommendations for Managers

Managers of forests and water play critical roles in providing water resources from forests. Because forests, forest management, and the climatic and social contexts of forests are dynamic, BMPs must be updated continually through an adaptive management approach. Forestry BMPs can mitigate the negative consequences of forest management activities (roads, timber harvest, etc.), but their effectiveness can be highly site- and storm-specific or difficult to quantify. Forest and water managers are well positioned to use rigorous monitoring to assess the effectiveness of BMPs. In response to their assessments, managers can adapt management approaches and modify the current suite of BMPs to increase their effectiveness and test the results.

To assist the evolution of BMPs, managers should:

- Catalogue individual or agency BMP use, design, and goals at the national level and make this information available to the public;
- Monitor BMP activities for effectiveness, and coordinate analyses of monitoring data for use in an adaptive management framework; and
- Design adaptive management approaches for forested watersheds that coordinate management, research, monitoring, and modeling efforts.

Recommendations for Citizens

Cumulative watershed effects, changes in land ownership and management, changing population and development patterns, and water supply concerns have spurred activity to protect watersheds and water quality from the grass-roots, community level. New community-level watershed councils and forest groups are proactive in watershed-based restoration and management. Water researchers and policy makers have long recognized the benefits of organizing land and water management around watersheds and taking an integrated approach to watershed management. An integrated watershed management approach can help track the effects of various land uses on water supply and quality. Citizens and communities can influence forest and water management at the local, regional, or watershed level.

TABLE S-2 Current Understanding, Research Needs, and Recommendations for Sustaining Water Supplies from Forests

	Current Understanding	Information Gaps and Research Needs	Recommended Actions
Science	The body of forest hydrology science derives from almost 100 years of studies at small spatial and time scales Forest hydrology science has established general principles that are understood with a high degree of certainty describing direct hydrologic effects of forest management and disturbance Effects can be understood through changes in • Forest structure • Magnitudes, rates, and flowpaths • Erosion, nutrient cycling, and soil chemistry Reduced forest cover results in increased water yield that is • Generally short-lived • Greatest during times of water excess rather than water scarcity • Small or undetectable in water-scarce areas • May be associated with a decline in water quality	Hydrologic effects of past management, such as fire suppression, clear-cutting, roads Ways to quantify hydrologic responses at larger spatial and temporal scales Ways to scale up findings from small spatial and short time scales to larger spatial and longer time scales Use general principles to predict indirect hydrologic responses to changes in forest landscapes and interacting responses to forest management and disturbance	Enhance, maintain, and reestablish abandoned small watershed studies Combine existing data from the large body of small watershed studies and analyze them for large-scale trends as a meta-experiment Use new technologies, including sensor networks and remote sensing, to improve understanding of forest hydrology in changing landscapes Engage in adaptive management to help managers and community groups design monitoring strategies, develop and test models, and conduct studies relevant to management
Management	Forests in the United States are managed for a wide range of goals and objectives: timber harvesting,	Assessment of BMP effectiveness Principles and practices of adaptive management	Advance BMP evolution by rigorously assessing and developing new BMPs and

	road networks and road construction, high-severity wildfires, and exurban sprawl modify forest hydrology Forest management practices are evolving in response to environmental change, social and economic forces, and technological developments BMPs are used to mitigate impacts on water resources from forest management activities		measuring their effectiveness At the federal level, provide sustained support for adaptive management activities, enabling managers to partner with scientists to design and implement monitoring, develop and test models, and conduct studies relevant to management issues Increase role of agency technical expertise in watershed councils
Community	Integrated watershed management is a viable vehicle for both community groups and state and federal agencies to help manage water and forest resources at the community scale Citizens groups can influence local and integrated watershed management Community watershed groups benefit from state and federal agency technical expertise Existing laws can be used to strengthen the standing and influence of watershed councils New laws offer increased opportunities for community involvement	How watershed councils and their stakeholders view and utilize forest hydrology science and scientific expertise from federal agencies How industry-sponsored green certification and federal forest stewardship contracts affect water quantity and quality from forests	Use watershed councils to meet multiple goals of integrated watershed management at the community level Expand the number and influence of watershed councils Engage in adaptive management with scientists and managers

Watershed councils and citizen groups should work within communities and with state and federal agencies to:

- Use watershed councils as vehicles to meet multiple goals of integrated watershed management at the community level; and
- Participate in watershed councils and help them grow in number and influence over watershed uses at the community level.

CLOSING

Forest hydrology science has produced a solid foundation of general principles that describe how water is connected to and moves through forests and how hydrologic processes respond to forest disturbance and forest management. The forest landscape is dynamic: it is continually changing in response to climate, natural disturbance, and forest management, as well as demographics and development patterns. Forest hydrology science and management are adapting as land use and ownership within forested watersheds become more heterogeneous, changes in climate and its effects are becoming more evident, and new technologies provide improved capability to predict and visualize cumulative watershed effects over larger spatial scales and longer periods of time. Building on the strong foundation of general principles of forest hydrology, new forest hydrology research can fill information gaps in the coming decades (Table S-2). Forests are essential for the sustainable provision of water to the nation. It is incumbent upon scientists, policy makers, land and water managers, and citizens to use the lessons of the past and apply emerging research, technology, and partnerships to protect and sustain water resources from forested landscapes.