July 2008

Hydrologic Effects of a Changing Forest Landscape

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 report identifies actions that scientists, forest and water managers, and citizens can take to help sustain water resources from forests.

The connections among forests, water, and people are strong: forests cycle water from precipitation through soil and ultimately deliver it as streamflow that is used to supply nearly two-thirds of the clean water supply in the United States. Changes in forested headwater areas (which include the tributary streams that feed into rivers) influence the quantity and quality of downstream water resources; in this way, forests and water are closely intertwined.

Demand for water in the United States is increasing, and forest managers today are asked to provide higher quantities and qualities of water. Meeting these increasing water supply needs in dynamic times of climate change, shifts in human population, and changes in land use and ownership has heightened tensions among competing uses for forests and water. Forest hydrology—the study of how water moves through forests—has a critical role to play in resolving such tensions by increasing the understanding of how forest properties influence downstream water resources. Forest hydrologists analyze how changes to forest cover including wildfires, insects and disease, road networks, and timber harvesting alter the flow of water through forests.

Reduction in forest cover, through timber harvesting, for example, can increase streamflow in the short term. These increases in water yield are generally not sustained over the long-term, however; any increases in water yield are most likely to occur during high precipitation events and not likely to occur during drier times when water demand is high. Removing trees for water yield can also cause degraded water quality (due to increased water temperatures and sedimentation), increased risk of flooding in downstream areas, and negative ecological impacts, such as loss of habitat and other ecosystem services otherwise provided by forests. The indirect and interacting effects of forest change on water resources underscore the need to better understand how forest management and modifications trigger hydrologic effects at the large watershed scale and over long periods of time.

At the request of the U.S. Bureau of Reclamation and the US Forest Service, the Water Science and Technology Board of the National Research Council convened 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 forests.

State of Forest Hydrology Science

Forest hydrology draws from several branches of hydrological sciences, water resources engineering, and forestry to address primary questions about forests and water: What are the flowpaths and storage reservoirs of water in forests and forest watersheds; how do modifications of forests influence water flowpaths and storage; and how do changes in forests affect water quantity and quality?

Researchers seeking to answer these kinds of questions have obtained most of their data from what are known as "paired watershed" studies. Using this approach, two watersheds that are similar in size, initial land use or land cover, and other attributes are selected for study. Both are monitored, and while one is left as a "control," the other is "treated" (subjected to manipulations such as forest cutting, road building, fires, and so on). The measured changes in the streamflow and water quality between the two watersheds quantify the effects of forest treatment and growth. Paired watershed studies, along with process measurements, plot-scale studies, and hydrologic modeling, are important elements of forest hydrology. However, study plots and paired watershed studies have generally been conducted in small, homogenous, areas and over short time spans, ranging in size from less than a square meter to 2 km^2 and typically spanning only a few growing seasons.

Future Research Needs: A Landscape Perspective

Forest hydrology science has led to a clear understanding of general principles of water movement through forests. These principles focus on general hydrologic responses to changes in forests in small areas over short time scales. Forests are now being affected by many interacting factors, including climate change, forest disturbances, forest species composition and structure, and land development and ownership, which can break up forests into smaller, noncontiguous parts. Today's forest and water managers need forest hydrology science that helps them understand and predict how such factors will affect water quantity and quality across large areas and over long time scales.

The most important unresolved issue in forest hydrology is how to "scale up" findings from the general principles of forest hydrology that were developed in small, homogeneous watersheds to improve predictions of hydrologic responses across large, heterogeneous watersheds and landscapes. A landscape perspective allows analysis of forest and water connections over larger areas so as to be able to use the general principles of forest hydrology to make predictions about forests and water that can address current and anticipated future issues, including cumulative watershed effects, climate change, and forest management practices in the 21st century.

Cumulative Watershed Effects

Cumulative watershed effects are the hydrologic effects resulting from multiple land use activities over time within a watershed. Extreme precipitation events often reveal cumulative watershed effects and spur public interest in better understanding how land uses in forested headwaters are related to downstream flooding and other effects. Assessing cumulative watershed effects requires an understanding of the physical, chemical, and biological process that route water, sediment, nutrients, pollutants, and other materials from slopes and headwater streams to downstream areas. Future research in this area should strive to elucidate the relationships among forests, water flowpaths and quality, and watershed land use over large spatial and long temporal scales.

Climate Change

The effect of climate change on forests and water is increasingly evident, and future aspects of climate change are likely to have major effects on forest hydrology. Direct effects of climate warming on forests and hydrology are being observed, such as changes in the timing of snowmelt runoff and increases in wildfires, but 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.

Forest Management

Forest management practices evolve over time. The forces that modify forests today are triggering forest managers to institute novel and contemporary forest management practices. These new practices—such as thinning for fuel reduction and best management practices that manage wider riparian buffers for species protection—have not yet been assessed for their attendant hydrologic effects. Hydrologic effects of these contemporary management practices need to be understood over long temporal and large spatial scales.

Actions for Scientists, Managers, and Citizens to Take

Scientists who study forest hydrology, forest and water managers, and citizens each have a role to play in sustaining water resources from forests. Through individual and collective actions, they can apply the current understanding, explore research gaps and information needs, and pursue the following recommended actions.

Scientists

Scientists are poised to advance forest hydrology science to address critical water issues. New research approaches should be pursued, and many of the current research agendas should be maintained or expanded. Scientists should:

- continue current small watershed experiments and re-establish small watershed experiments where research has been discontinued;
- catalogue historical and modern hydrologic records;
- use the whole body of paired watershed data as a "meta experiment" to better understand hydrologic responses to forest disturbance over large

Principles of hydrologic response to changes in forest structure	
1	Partial or complete removal of the forest canopy decreases interception (precipitation captured by leaves and branches) and increases net precipitation arriving at the soil surface.
2	Partial or complete removal of the forest canopy reduces transpiration (water lost from plants to the atmosphere).
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 reduces slope stability.
5	Increases in water yield after forest harvesting are transitory and decrease over time as forests regrow.
6	When forests of high interception (or higher annual transpiration losses) replace forests with lower interception (lower transpiration losses), this change reduces water yield as the new forest grows to maturity.
Principles for 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 landslides.
Principles of hydrologic response to applications 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.

spatial and temporal scales and across a range of forest types;
- expand capability for visualization and prediction of hydrologic response in large watersheds through geographic information systems (GIS), remote sensing, sensor networks, and advanced models;
- work with economists and social scientists to improve understanding of the value of sustaining water resources from forests.

Managers

Forests, forest management, and the climatic and social contexts of forests are dynamic; therefore, best management practices must be updated continually through an adaptive management approach. Forestry best management practices can mitigate the negative consequences of forest management activities, but their effectiveness can be highly site- and storm-specific and, thus, difficult to quantify. Managers should assess best management practices and modify the current suite of practices to increase their effectiveness. To do this, managers should:

- catalogue individual or agency best management practice design, goals, and use at the national level and make this information available to the public;
- monitor best management practices for effectiveness and analyze monitoring data for use in an adaptive management framework; and
- design adaptive management approaches that coordinate management, research, monitoring, and modeling efforts.

Citizens

Citizens and communities can influence forest and water management at the local, regional, or watershed level. 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. 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.

Committee on Hydrologic Impacts of Forest Management: Paul K. Barten, (*Chair,)* University of Massachusetts, Amherst; **Julia A. Jones, (***Vice-Chair,)* Oregon State University; **Gail L. Achterman,** Oregon State University; **Kenneth N. Brooks,** University of Minnesota, St. Paul; **Irena F. Creed,** The University of Western Ontario; **Peter F. Ffolliott,** University of Arizona; **Anne Hairston-Strang,** Maryland Department of Natural Resources; **Michael C. Kavanaugh,** Malcolm Pirnie, Inc.; **Lee Macdonald,** Colorado State University; **Ronald C. Smith,** Tuskegee University; **Daniel B. Tinker,** University of Wyoming; **Suzanne B. Walker,** Azimuth Forest Services; **Beverley C. Wemple,** University of Vermont; **George H. Weyerhaeuser, Jr.,** Weyerhaeuser Company; **Lauren Alexander** *(Study Director)* and **Ellen de Guzman** *(Research Associate),* National Research Council.

This report brief was prepared by the National Research Council based on the committee's report. For more information or copies, contact the Water Science and Technology Board at (202) 334-3422 or visit http://nationalacademies.org/wstb. Copies of *Hydrologic Effects of a Changing Forest Landscape* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu. Support for the study was provided by the U.S. Bureau of Reclamation and the U.S. Forest Service.