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Hydrologic effects of a changing forested landscape—challenges for the hydrological sciences

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Introduction

Of all the ecological services of forests, a sustainable water supply may be the most important. Streamflow from forests provides two-thirds of fresh water supply in the United States. Removing forest cover temporarily increases the proportion of precipitation that becomes streamflow, and this effect has spurred political pressure to cut trees for the purpose of augmenting water supply, especially in western states where population and water demand are rising. However, this strategy is not sustainable: increases in flow are typically short-lived, and the combination of roads and repeated timber harvests can 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 current complex issues, including climate change, wildfires, changing patterns of development and ownership, and changing societal values. These are the main conclusions of a recent report released by the National Research Council, 'Hydrologic effects of a changing forest landscape' (NRC, 2008). This commentary summarizes and interprets findings from the report focusing on important implications for hydrologists.

Motivation for the NRC Committee on Hydrologic Impacts of Forest Management

Drought, outbreaks of insects and pathogens, wildfire, and ecological succession are altering forests' ability to provide abundant clean water in the headwaters of our water supply systems. In the western United States, many of these headwater watersheds are on federal lands and generate most of the water needed for agricultural, municipal, recreational, and ecological uses. Simultaneously, private forests throughout the United States have undergone major changes in ownership and management, and large areas have been converted to exurban land use. These developments have exacerbated long-standing conflicts related to federal laws and other policies that govern forest and water management. As a result, many forested regions are finding it hard to balance flood protection, water supply for urban areas and agriculture, and water releases for endangered species protections. These stresses have led to renewed calls for 'forest protection' to sustain water resources—but what does this really entail? The following sections summarize the key findings in NRC (2008).

Findings of the Report

Forests are essential for water supplies

Forests account for 33% of land area, process nearly two-thirds of the fresh water supply, and provide water to about 180 million people in the United States. However, few forests are managed primarily for water; instead water quantity and quality are byproducts of other forest management objectives, such as timber production, recreation,

or species protection. Water supply management is challenging because the laws governing forest management and watershed management are fragmented among agencies and among components of the hydrologic cycle. Fragmentation of ownerships and interests, combined with fragmented responsibility for managing and regulating forest management, has made integrated management of forests and water at the watershed scale virtually impossible. Management of water quantity and quality from forested areas is also becoming more challenging due to growing water demand, changing climate, increasing human population and development, and changes in land use and forest ownership.

The principles of forest hydrologic responses to management are well established, but prediction is still a challenge

Forest hydrology examines the flowpaths and storage of water in forests, and how forest disturbance and management modify hydrologic responses. For decades, forest hydrology research has focused on how forests can be managed without adversely affecting flooding, erosion, and water quality (Bosch and Hewlett, 1982; Brooks *et al.*, 2003; Chang, 2003; Ice and Stednick, 2004). The past century of forest hydrology has led to a clear understanding of the processes regulating water movement through forests and has produced general principles of hydrologic responses to harvest, roads, and application of chemicals that are familiar to most hydrologists. Although these principles can help manage forests for water, it is difficult to predict the specific effects of forest management on water quantity and quality in unmonitored basins, over long time periods, or in large watersheds.

Active forest management has limited potential to increase water supplies over the long term

With dwindling water supplies, governments are turning to forest management as a possible means of augmenting water yield. Numerous paired watershed experiments have shown that forest harvest can increase water yields, particularly in areas where precipitation exceeds potential evapotranspiration. However, the increases in water yield from vegetation removal are often small and short-lived, and are less when the water is most needed, such as in dry years and in dry areas. Operationally, it is difficult to harvest enough area frequently enough to cause a detectable change in water yields. The combination of road infrastructure and widespread, repeated timber harvests needed to augment water yields often impairs water quality.

Contemporary forest hydrology requires a landscape perspective

Our understanding of the processes regulating hydrologic responses to changes in forests is based on small areas (e.g. first- or second-order catchments) over short time scales (e.g. several years) under relatively stable system conditions. However, changes in climate, forest species composition and forest structure, and land development and ownership are now affecting forests and the water they provide in a complex, dynamic fashion.

Today's forest and water managers need scientific advances in forest hydrology that can help them understand and predict how forest dynamics will affect water quantity and quality across large areas and over long time scales. Hydrologists have intensively studied the short-term increases in streamflow due to forest management, but some long-term studies have shown that post-harvest changes in forest composition and growth can reduce streamflow to below pre-harvest levels (Jones and Post, 2004), while climate change may be reducing streamflow from reference forested watersheds (Mote *et al.*, 2003). However, long-term paired watershed studies are rare: only a few sites in the United States maintain and provide access to multiple decades of post-harvest paired streamflow records (see http://www.fsl.orst.edu/climhy/). Resurrection of old paired watershed studies and maintenance of current long-term reference watershed records are essential to predict long-term changes due to forest succession and climate change, as well as test the effects of forestry practices being implemented in the twenty-first century.

A second unresolved issue in forest hydrology is how to 'scale up' findings from the general principles of forest hydrology developed in small, homogeneous watersheds to improve predictions of hydrologic responses across large, heterogeneous watersheds and landscapes. Hydrologists have invested much effort in identifying cumulative watershed effects resulting from multiple land use activities over time within a watershed (Reid, 1993; MacDonald, 2000). The runoff, erosion, and sedimentation resulting from extreme storm events forcefully illustrate a cumulative watershed effect. Both extreme storms and extreme droughts trigger public interest in better understanding how land use affects the amount, timing, and quality of streamflow from forested watersheds. Assessing cumulative watershed effects requires an understanding of how the principles of forest hydrologic response vary over time and among land uses within a watershed.

Many factors can alter forest water yield and water quality

Conditions have changed in forested watersheds. Watershed conditions used to estimate sustained water yield when water supply systems were built in the United States, and those in reference forested watersheds used for forest hydrology studies, are different now due to such factors as changes in fire regimes and insect and disease outbreaks. These changes undermine the benchmarks managers rely upon for sustainable water yield from forests, making attainable goals for future managed water yield from forests highly uncertain.

Many changes in forests may be rapidly altering water supplies in ways that are relatively poorly understood at the time and space scales needed by water managers. These factors include the following: (1) climate change, forest disturbance, and changing forest management; (2) legacies of past forest management practices; and (3) exurban sprawl and changes in private forestland management.

Climate change, forest disturbance, and changing forest management. The first-order effects of climate change on forests and water are becoming increasingly evident, and research is needed to predict both the indirect and direct effects of future climate change on forests and water. A warming climate is already reducing snowpack amounts and duration, and peak snowmelt runoff has already been advanced by up to 3 weeks in some regions (Hodgkins *et al*., 2003; Dettinger *et al*., 2004; Payne *et al*., 2004). Projected water resources may not meet future demands, even with conservative estimates of climate change (Barnett *et al*., 2004). Climate change is also likely to increase the size and severity of wildfires, and forests in the western United States are already experiencing larger, more severe fires and longer fire seasons (Kasischke *et al*., 2006; Westerling *et al*., 2006). On public lands, there is an increasing emphasis on pre-emptive thinning to reduce fire risk (Graham *et al*., 2004). In the 2000s, much of the western United States has been experiencing bark beetle outbreaks at unprecedented levels, apparently as the result of warming climate (Logan *et al*., 2003). Key research questions include the following:

- How large are the direct water yield and water quality responses to climate change (e.g. due to changes in temperature and timing, amount, and type of precipitation) compared to the indirect hydrologic responses to climate change (e.g. due to changes in wildfire and insect/disease outbreaks, or evapotranspiration)?
- How do the hydrologic effects of wildfire or insect/disease outbreaks compare to those of thinning to reduce the risk of wildfire?
- How do the hydrologic effects of salvage logging after fires or insect and disease outbreaks compare with those of the original disturbance?

Legacies of past forest management practices. Forest management has changed in many respects, but research is needed on how the legacies of past management, or lack of management, continue to affect forest hydrology. For example, clearcutting has left a legacy of even-aged forest plantations, while nearly a century of fire suppression has altered forest structure, species composition, and insect outbreak dynamics in some forests of the United States and Canada but not others (Fleming *et al*., 2002; Bebi *et al*., 2003). Extensive road networks remain in place on public and private forest lands, even though timber harvest levels have often dropped dramatically. Forest roads are major sources surface erosion, landslides, and sediment loads in streams (Swanson and Dyrness, 1975; Reid and Dunne, 1984; Wemple *et al*., 2001; Sidle and Ochiai, 2006). In the past, widespread grazing of domestic cattle led to erosion (Anderson *et al*., 1976), and predator eradication enhanced populations of native grazers on public forestlands, but recently predator reintroductions may have reduced grazing near streams and enhanced riparian vegetation, especially in national parks (Halofsky *et al*., 2008). Key research questions include the following:

- What are the effects of past forest management and fire suppression on current and future water yields and water quality?
- How have changes in domestic and native grazer populations and grazing behaviour in forests affected water quantity and quality from forests?
- What are the long-term, large-scale effects of road networks on water quantity and quality?

Exurban sprawl and changes in private forestland management. Forest area in the United States increased from the late 1800s through the middle 1900s, but net forest area declined from the early 1950s to 1997 (Powell *et al*., 1993; Smith *et al*., 2004). Much of this loss was due to urbanization: forest land was the largest source of land conversion to developed uses in the 1990s, and forest area is expected to decrease by an additional 3% by 2050 relative to 1997 because of forest conversion to urban and developed uses (Alig *et al*., 2003). Continuing urbanization and increasing construction of second homes in forested settings has expanded the area of 'urban–forest interfaces' or 'wildland–urban interfaces' throughout the country, increasing concerns about protection from forest disturbances such as wildfire and landslides.

Conversion of forestlands to other land uses has been stimulated by substantial recent changes in private forest ownership. About half of the private forestland in the United States has changed hands in the past decade (Alig and Plantinga, 2004). Very few large, publicly traded, vertically integrated wood products manufacturing businesses remain that manage significant amounts of forestland. Instead, industrial private forested land and mills are more often owned by private timber investment management organizations and real estate investment trusts. These investment companies tend to have different expectations for return on investment and different management goals compared to the private forest industry (Kendra and Hull, 2005). At the same time, many family-held forestlands have been fragmented into smaller parcels during intergenerational transfers or when the

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new owners cannot agree on goals and purpose. Key research questions for hydrologists and social scientists include the following:

- How do changes in ownership affect forest management, and how do these changes affect water resources?
- What are the effects of the expansion of human settlements into forested areas, and the consequent changes in forest management, such as thinning for fuel reduction, on water quantity and quality?

Actions for scientists, managers, and citizens to take to sustain water resources from forests

The NRC committee recommends a number of actions for scientists, managers, and citizens and communities to improve understanding of the connection between forests and water, and to use that understanding to promote the production of water and aquatic resources from forestlands.

The science of forest hydrology—plot, process, paired-watershed, and modelling studies—provides the foundation for management of water and forest resources. Scientists should

- catalogue historical and modern hydrologic records to increase their availability to the scientific community for analysis and modelling;
- continue and reestablish small watershed experiments to detect long-term trends;
- use the whole body of paired watershed data as a 'meta experiment' to assess effects of geographic location on forest hydrologic responses;
- develop tools to better predict and analyse cumulative watershed effects;
- adopt new technologies for measurement, visualization, and prediction of hydrologic response;
- integrate hydrologic modelling with technological innovations in spatial and temporal analysis and long-term datasets; and
- work with economists and social scientists to examine changes in ownership and values of forests, and implications of biophysical changes in the forested landscape on society and livelihood.

Managers use forestry best management practices (BMPs) to mitigate the negative consequences of timber harvest, road construction and maintenance, reforestation, or other forest management practices. While forestry BMPs are widely used and locally effective (Binkley and Brown, 1993; Aust and Blinn, 2004), little research has investigated whether the current suite of BMPs will be effective in reducing cumulative watershed effects, maintaining viable fish populations, or preserving the integrity of forest and stream ecosystems over large areas and long time scales (Bisson *et al*., 1992; Swanson and Franklin, 1992). Adaptive management is an approach to natural resources management that promotes carefully designed management actions, assessment of the impact of these actions, and subsequent policy adjustments. Although there are many challenges to implementing adaptive management in forested watersheds (MacDonald and Coe, 2007), this approach can lead to forest management actions based on consensus among stakeholders, monitoring of experiment outcomes, and redesign of forest management practices based on this learning (NRC, 2004). Managers should

- catalogue individual or agency BMP designs, goals, and uses;
- make this information available to the public;
- monitor effectiveness of BMPs;
- analyse monitoring data for use in an adaptive management framework; and
- implement adaptive management approaches.

Citizens and communities depend on forests for water and many other ecosystem services. Watersheds that were mostly forested and owned by one entity a few decades ago now show greatly varied patterns of fragmented land uses and ownership. Cumulative watershed effects are most clearly visible through the lens of extreme events, which remind citizens and communities that water does not respect property boundaries. Since the time of John Wesley Powell, water researchers and policymakers have recognized the benefit of organizing land and water management around hydrologic systems and have promoted an integrated approach to watershed management (WWPRAC, 1998; Gregersen *et al*., 2008). Citizens and communities should

- use watershed councils for integrated watershed management
- participate in watershed councils
- help watershed councils grow in number and influence.

Conclusion

Reacting to the NRC report, Anne Bartuska, Deputy Chief of Research and Development for the US Forest Service, wrote, 'The vision into the next century and recommendations for action by the individual citizen, the public and the scientific community illustrates that everyone has a stake in the future of forests and water.' Hydrologic scientists studying physical, biological, and social processes involving forests and water all have key roles to play in building a strong science foundation to ensure future water supplies from forests.

Hydrological sciences are the foundation for understanding the connection between forests and water. However, as forested landscapes change, we need to move away from thinking of forest hydrology as a 'separate' science, and towards thinking of landscape hydrology that embraces the interactive effects

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of different land-based activities on water supplies. We need to invest in hydrologic sciences to prepare to deal with the complexities and uncertainties that we face today and into the future. These investments include monitoring and modelling of hydrologic processes over multiple spatial and temporal scales and training of hydrologists with transdisciplinary thinking. Finally, we must encourage formation of 'communities of practice' where citizens, managers, and scientists come together to develop common understandings of hydrologic sciences and create policy and practices that will be appropriate and adaptive to ensure sustainability of water supplies from forests in an uncertain future.

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