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WATER, CLIMATE CHANGE, AND FORESTS

Watershed Stewardship for a Changing Climate

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WATER, CLIMATE CHANGE, AND FORESTS
Watershed Stewardship for a Changing Climate

Abstract

Water from forested watersheds provides irreplaceable habitat for aquatic and riparian species and supports our homes, farms, industries, and energy production. Secure, high-quality water from forests is fundamental to our prosperity and our stewardship responsibility.

Yet population pressures, land uses, and rapid climate change combine to seriously threaten these waters and the resilience of watersheds in most places. Forest land managers are expected to anticipate and respond to these threats and steward forested watersheds to ensure the sustained protection and provision of water and the services it provides.

Effective, constructive watershed stewardship requires that we think, collaborate, and act. We think to understand the values at risk and how watersheds can remain resilient, and we support our thinking with knowledge sharing and planning. We collaborate to develop common understandings and goals for watersheds and a robust, durable capacity for response that includes all stakeholders and is guided by science. We act to secure and steward resilient watersheds that will continue to provide crucial habitats and water supplies in the coming century by implementing practices that protect, maintain, and restore watershed processes and services.

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WATER, CLIMATE CHANGE, AND FORESTS

Watershed Stewardship for a Changing Climate

CONTENTS

INTRODUCTION | WATER, CLIMATE CHANGE, AND FORESTS

> **Forests are key determinants** of water supply, quality, and quantity, in both developing and developed countries. The importance of forests as watersheds may increase substantially in the next few decades, as freshwater resources become increasingly scarce...
>
> – Bates et al. (2008)

Clean, fresh water is our most important natural resource. It is essential to sustaining people, agriculture, industry, and ecosystems. It is also a resource in crisis worldwide. Existing freshwater supplies are highly stressed in many parts of the world, including the United States, owing to mismatches between supply and demand (fig. 1).

Water pollution, invasive species, and increased urban and rural development further threaten our capacity to supply adequate clean water and support the ecosystems upon which society depends. In some areas, these conditions are causing significant social conflict and competition between water users.

Climate change will likely intensify these problems by altering the quantity, quality, timing, and distribution of water. For example, in some areas, less winter snow and earlier spring runoff will reduce water availability during the summer and fall. Altered streamflow and erosion regimes and higher air temperatures will affect water quality and aquatic ecosystems. Fire and flood frequency and severity will likely increase, and stream networks may contract.

Addressing these fundamental hydrologic changes and their interactions is a formidable and urgent challenge, but there is much we can do to respond. Actions taken now can enable society and ecosystems to adapt to the changes that have already occurred or been initiated, thereby reducing future impacts and conflicts. Forest management provides important opportunities for adaptation because forests are the most plentiful source of the cleanest water; are the last refuges of valued species that have been extirpated from other areas; are often located in the mountains and thus provide the first opportunity to store, filter, and release water for downstream uses; and provide the earliest opportunity to measure precipitation and streamflows, thereby allowing water managers to forecast supplies and adjust downstream water storage systems.

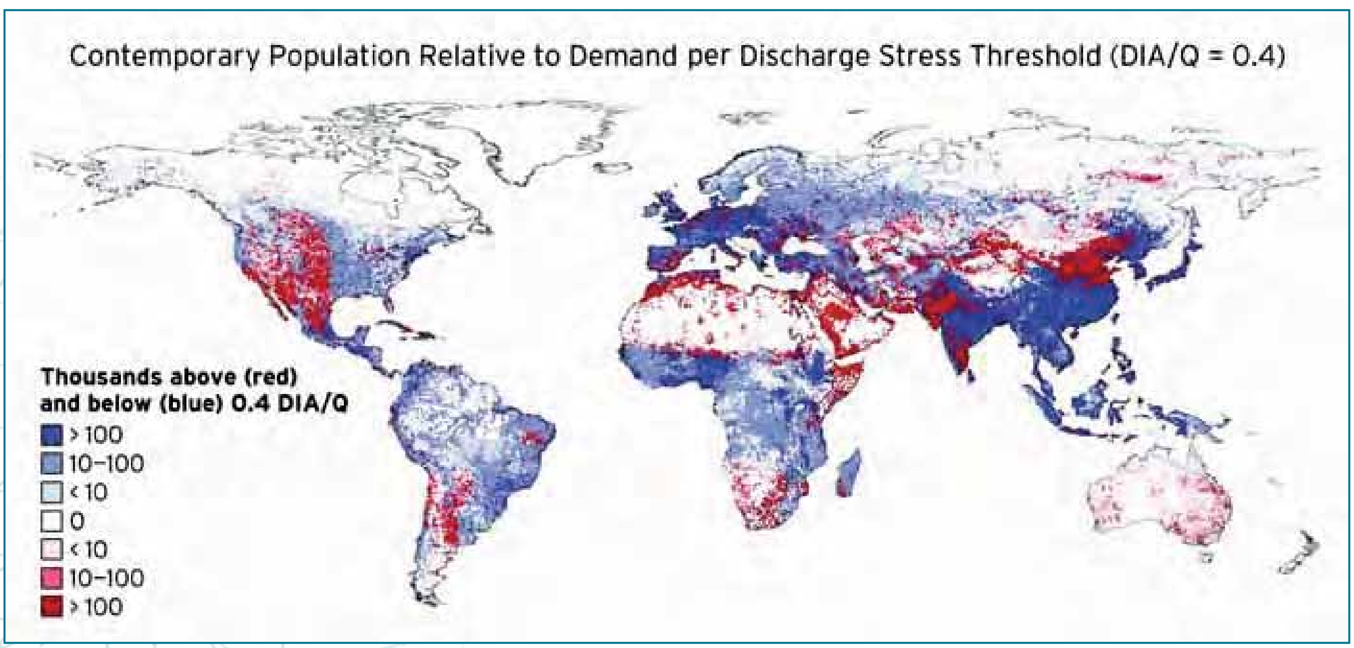


Figure 1—Global population with relatively low (blue) and high (red) water stress. Water stress is measured with an index of water use and streamflow, DIA/Q, where DIA is the use of water by homes, businesses, industry, and agriculture and Q is streamflow, both on a mean annual basis (Vörösmarty et al. 2000).

This report describes some adaptation opportunities associated with forest management, specifically in the context of water and aquatic ecosystems. The first two sections describe the importance of forests to the Nation's water resources and summarize observed and projected effects of climate change on the hydrologic cycle and forested watersheds. Following sections outline a feasible framework for response, focused on **thinking**, **collaborating**, and **acting**.

A central theme of this report is that adaptation actions should generally focus on maintaining or improving watersheds because healthy, resilient watersheds are more likely to supply desired ecological services in the face of climate change (US GAO 2007). This will necessitate actions that address not only the effects of climate change itself, but all of the dominant stressors negatively affecting watersheds. Specific actions include advancing and sharing knowledge about water and climate change, incorporating climate change into planning, implementing practices to protect and restore key watershed processes and services, encouraging innovation, connecting water users to their watersheds through markets and outreach programs, and leveraging efforts to reduce water demand. Some of these are novel practices and will thus require more exploration and definition as they are applied. Others are not entirely new, but will need to be applied in new ways and at unprecedented scales in the future. Extensive collaboration and cooperation will be essential.

The actions described in this report represent some initial steps that can be taken until more comprehensive adaptation strategies are developed and limitations in knowledge and capacity are addressed. The Forest Service is uniquely positioned to participate in these efforts and to help define future ones (see box on next page). The agency manages 193 million acres of national forests and grasslands, connects with thousands of domestic and international communities through many different programs, conducts basic and applied research on water and forests, and has a large professional work force. The national forests, for example, can be managed to supply clean water for downstream users and support species that depend on aquatic and riparian habitats. Forest Service research can continue to illuminate connections between climate, forests, and water, enabling forest management to be tuned to meet tomorrow's needs. Perhaps most importantly, partnerships between federal land managers, states, private landowners, researchers, and the international community can be strengthened to sustain freshwater systems in an era of unprecedented challenges.

Mitigate we might, adapt we must.

— William Nordhaus, 1994

Two types of actions can be taken in response to climate change:

Adaptation refers to changes in natural or human systems that enable society to moderate the impacts or exploit benefits of climate change. Restoring degraded habitats, conserving water, or gathering more information on snowpacks are examples that help people and ecosystems adapt to changing climate.

Mitigation can reduce future warming by decreasing emissions and enhancing sinks of greenhouse gases (Julius and West 2008, IPCC 2001). For example, water in forests can be used in high-head, low-flow hydroelectric facilities to produce power with minimal greenhouse gas emissions.

This document is about **adaptation,** specifically in the context of forests, water, and aquatic ecosystems.

Adaptation is a learning process. Mistakes will be made. Some actions will be incorrect; others will occur too late. Learning from these mistakes will be essential. Planning, collaboration, and integrated research will enhance the speed and ease with which we learn. Our hope is that the collected observations, summaries, ideas, and examples herein contribute to the understanding of many and inspire steps forward to secure a future with clean and adequate water supplies.

Tapping our roots: water and the Forest Service

In the 1880s and 1890s, the United States experienced widespread flooding and erosion. The resulting damage led to a compelling question: Could floods be controlled by land treatments in the headwaters of large rivers? In response, Congress in 1897 reserved headwater forests for the purpose of "securing favorable conditions of water flows." In 1905, Congress established a new agency, the Forest Service, to manage the forest reserves for high-quality water and timber in the public's interest. Gifford Pinchot was asked to lead the organization as the first Chief. Those forest reserves and other lands acquired since then now make up the National Forest System.

Pinchot and federal policymakers of the time were most concerned about preserving forests to sustain critical watershed functions. In his 1905 "Primer on Forestry" Pinchot wrote: "A forest, large or small, may render its service in many ways. It may reach its highest usefulness by standing as a safeguard against floods, winds, snow slides." Five years later, Henry S. Graves, the agency's second Chief, established Wagon Wheel Gap Experimental Watershed on the Rio Grande National Forest in Colorado to study the effects of forest management on water. Today, the agency's mission is to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations. This mission rests on a tradition of managing forests to protect the Nation's water supplies, the importance of which increases dramatically in the face of the challenges posed by climate change. The Forest Service can help society meet those challenges by maintaining, adapting, and expanding its current activities and programs associated with water resources.

Forest Service role in water and watershed stewardship

National Forests and Grasslands

- Manages 193 million acres (78 million hectares) of national forests and grasslands that contain 400,000 miles (644,000 kilometers) of streams, 3 million acres (1.2 million hectares) of lakes, and many aquifer systems that serve as the largest source of drinking water in the contiguous United States.
- Administers over 90,000 water rights in cooperation with states.
- Protects and improves habitat for more than 550 rare, threatened, and endangered aquatic species.
- Provides outdoor recreation to more than 130 million visitors per year near streams, lakes, and other water resources.
- Supports access and operations for more than 200 hydroelectric facilities.
- Improves, protects, and enhances watershed health during forest management activities on public lands.
- Restores degraded watersheds, streams, and wetlands.

State and Private Forests

- Helps landowners and communities manage forest lands that provide drinking water to more than 180 million people.
- Partners with states, local governments, and private partners to protect, enhance, and restore forested watersheds and to promote the understanding and use of agroforestry in agricultural watersheds.
- Assists urban communities to conserve, expand, and manage green infrastructure and open space to reduce development impacts.
- Works to permanently conserve open space critical to watershed health.
- Detects, suppresses, eradicates, or prevents destructive forest pests and invasive species that threaten watershed health.
- Works with communities to reduce wildfire risks to priority watersheds.

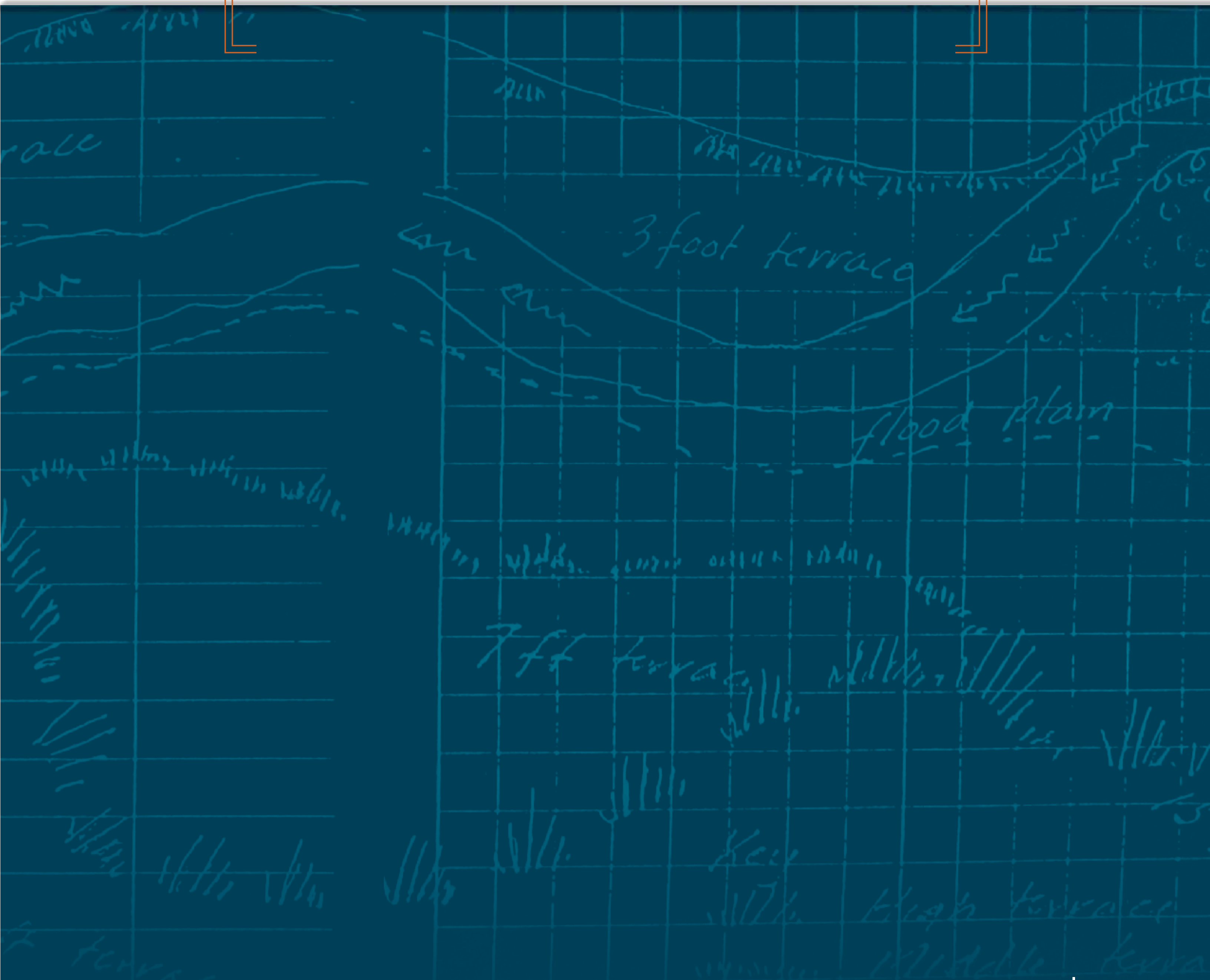
Research and Development

- Measures streamflow, snowpacks, weather, and water quality in long-term experimental watersheds to understand how forests affect water availability, timing, and quality.
- Studies effects of climate change, major disturbances, water management, land use, and energy development on streams and aquatic resources.
- Provides information needed by land and water managers to determine how their actions affect water and aquatic habitat and how to more effectively protect and restore watersheds.
- Provides strategies for solving complex environmental problems that involve multiple conflicting values and cumulative effects.
- Develops strategies, methods, and equipment for restoring ecosystems and measuring the improvements.
- Tracks trends in atmospheric, hydrologic, vegetation, and socioeconomic conditions.

International Forestry

- Works with U.S. international agencies, other countries, and nonprofit partners to assist countries around the world in protecting and managing important forests, watersheds, and ecosystem services.
- Develops and implements management strategies that protect the values of transboundary watersheds for all stakeholders.
- Shares information and technology to help address public health, emergency response, and other issues involving forests.

BACKGROUND | # FORESTS AND WATER



FORESTS AND WATER | Forests Provide Many Ecosystem Services. Watershed Services Are the Most Important.

Forests supply many ecosystem services, which are the benefits people derive from nature. This chapter describes those services associated with the provision of water and other critical watershed functions, known as watershed services. Many of these services are vital for life and human well-being and cannot be replaced (see box on next page).

Forested watersheds, for example, are essential to sustaining the Nation's freshwater supply. More than 50 percent of this supply originates on forest lands. In the Western United States, 65 percent of the water supply comes from forests. National forests alone provide 18 percent of the Nation's water, and over half the water in the West (Brown et al. 2008) (see fig. 2). High-elevation forests are particularly important because these headwater catchments store vast quantities of water as snow during the winter, then release it gradually through spring and summer, sustaining downstream water supplies during dry seasons.

Forested watersheds reduce storm runoff, stabilize streambanks, shade surface water, cycle nutrients, and filter pollutants. Consequently, the quality of this water is typically the best in the Nation (Brown and Binkley 1994). Water from these areas is often cooler and generally contains less sediment, nutrients, and chemicals than water from other lands (Binkley et al. 2004, Chang 2003, Dissmeyer 2000, Wear and Greis 2002). Streams in forested watersheds also often provide high-quality habitat for sensitive aquatic species.

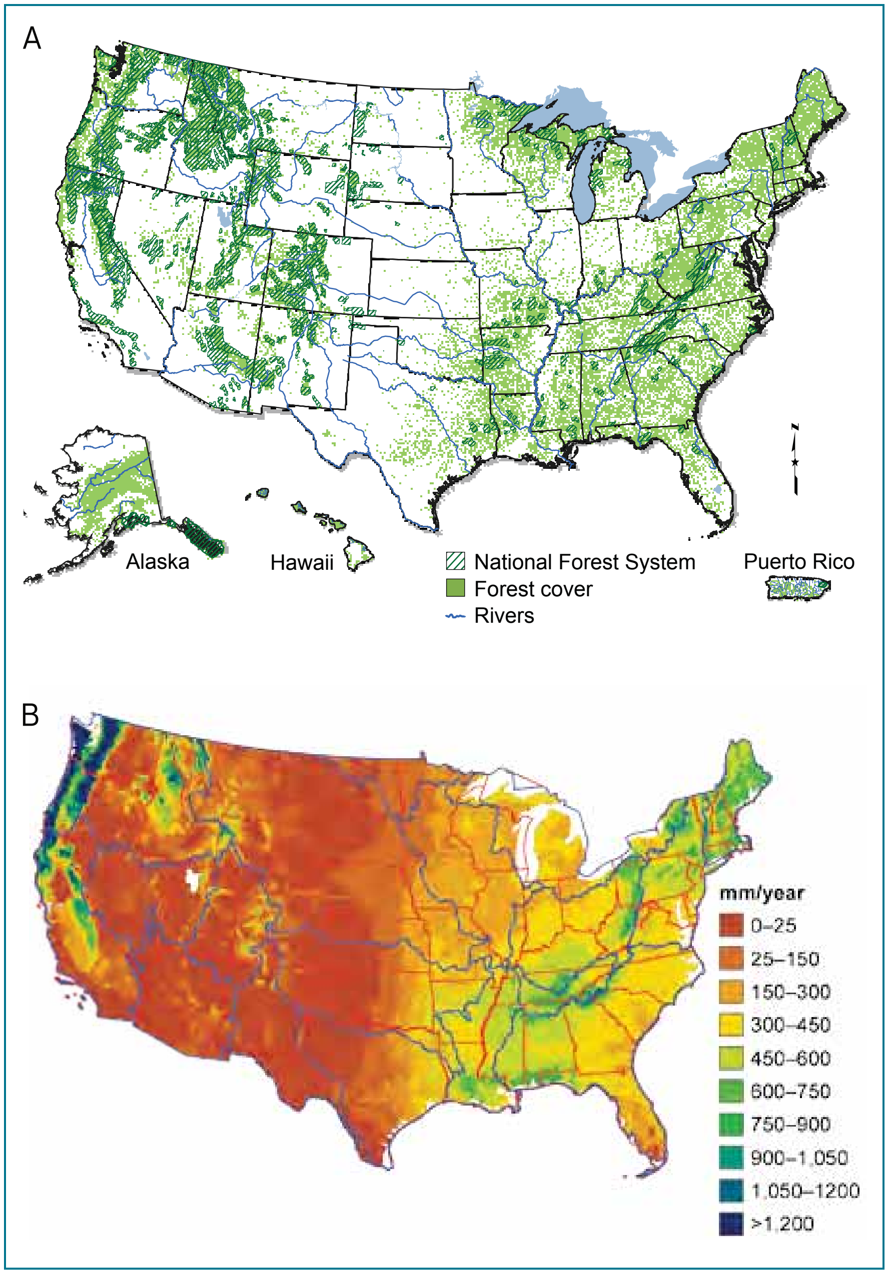


Figure 2—The areas that produce the largest volumes of water in the United States are forested. The quality of this water is typically the best in the Nation. (A) Forests in the National Forest System. (B) Mean annual water supply per unit area of land (mm/year), 1953–1994 (from Brown et al. 2008).

This large volume of high-quality water from forests is immensely valuable because it supports many uses, ranging from meeting basic human needs to providing habitat for rare and endangered species. It fills our rivers, streams, lakes, and aquifers; sustains fish, plants, and wildlife; supports food, energy, and industrial production; enables navigation; and pours from the faucets of our homes and businesses. Some of these uses are described in further detail in the following sections.

What are ecosystem services?

Ecosystem services are benefits obtained from nature that are critical to human health and well-being. These services are typically grouped into four categories: regulating, supporting, provisioning, and cultural (Millennium Ecosystem Assessment 2005). Watershed services are a subset of ecosystem services that are associated with water and watersheds (fig. 3). Definitions of these different types of services and examples pertaining to watersheds are provided below.

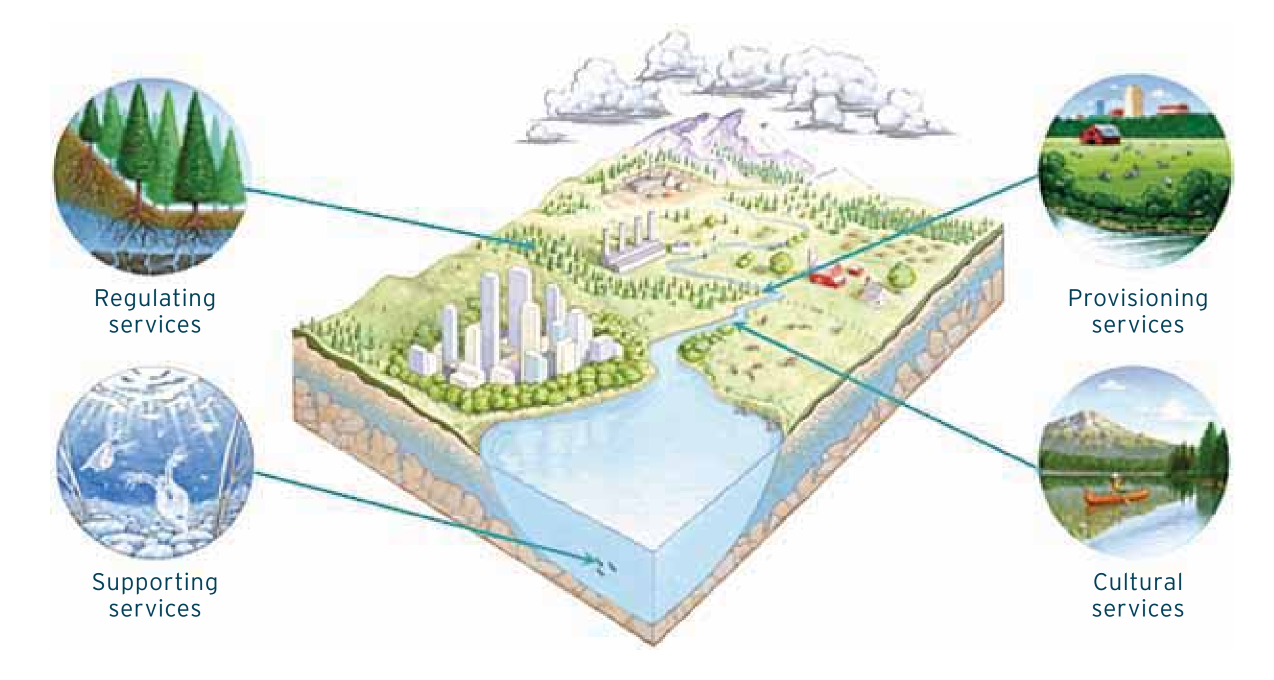


Figure 3—Watershed services.

- **Regulating services** are benefits obtained from the regulation of ecosystem processes. Examples include flow regulation (surface and groundwater flow), erosion control, water purification, and water temperature control.
- **Provisioning services** include products obtained from ecosystems. Principal watershed services from forests include freshwater supply for domestic, agricultural, commercial, industrial, and other uses.
- **Supporting services** include the basic ecological elements and processes necessary to sustain ecosystems. These include processes like soil development, and nutrient and water cycling.
- **Cultural services** are nonmaterial benefits people obtain from forests through recreation, spiritual enrichment, reflection, and aesthetic experiences. Forests provide significant water-based recreational opportunities in the form of boating, fishing, skiing, camping, hiking, sightseeing, and other activities. They also offer education and interpretation opportunities and afford protection for culturally and historically important water resources.

These services are provided naturally by well-functioning ecosystems. They are immensely valuable, because if they are compromised, replacing them is often not possible or is very costly. Ecological economists have begun efforts to value some ecosystem services, with the ultimate goal of enhancing efforts to more efficiently use, maintain, and protect them. Provision of water is a vital ecosystem service provided by forests, so one might ask: **What is the value of water?**

Water is essential for life—The Nation's total supply of water and ecosystem services provided by healthy watersheds are priceless. Because forests provide so much of the country's water, they are of tremendous importance. A lower bound on the total value of water from national forests alone is estimated to be several billions of dollars per year (Brown 2004). An accurate estimate of the total value is impossible to achieve, however, because only some products and services are assigned an economic market value. Moreover, these values apply at the margin, whereas forests tend to provide a large (nonmarginal) portion of the total water supply (Brown 2004).

Domestic Use

One of the most important uses of water from forests is domestic consumption. As presented in *Water and the Forest Service* (Sedell et al. 2000), at least 3,400 cities and towns in 43 states, with a total population of more than 60 million people, obtain at least a portion of their drinking water from watersheds located on National Forest System lands. In the Rocky Mountain Region alone, more than 33 million people in 13 states are dependent on water from national forests (fig. 4). State and private forests are critical as well, particularly in the Eastern United States. For example, New York City satisfies the needs of more than 10 million people by tapping water from the Catskill and Delaware watersheds, which are 90 percent forested. To date, this has enabled the city to avoid substantial water treatment costs (Germain et al. 2007).

Irrigated Agricultural Use

Irrigation for agriculture is a major use of freshwater, accounting for 40 percent of all withdrawals in the United States (Hutson et al. 2004). It is even more important in the arid West, where these withdrawals compose 81 percent of the total extraction in 11 states (Brown et al. 2008). This use is highly concentrated, with California (32 percent), Idaho (18 percent), and Colorado (12 percent) collectively using 62 percent of western irrigation water to irrigate 17.25 million acres (7 million hectares) (fig. 5). These irrigated lands typically support high-value crops, making irrigated agriculture a major economic sector in Western States. Streamflow is an important source of this irrigation water, large portions of which originate on national forests (Brown et al. 2008)

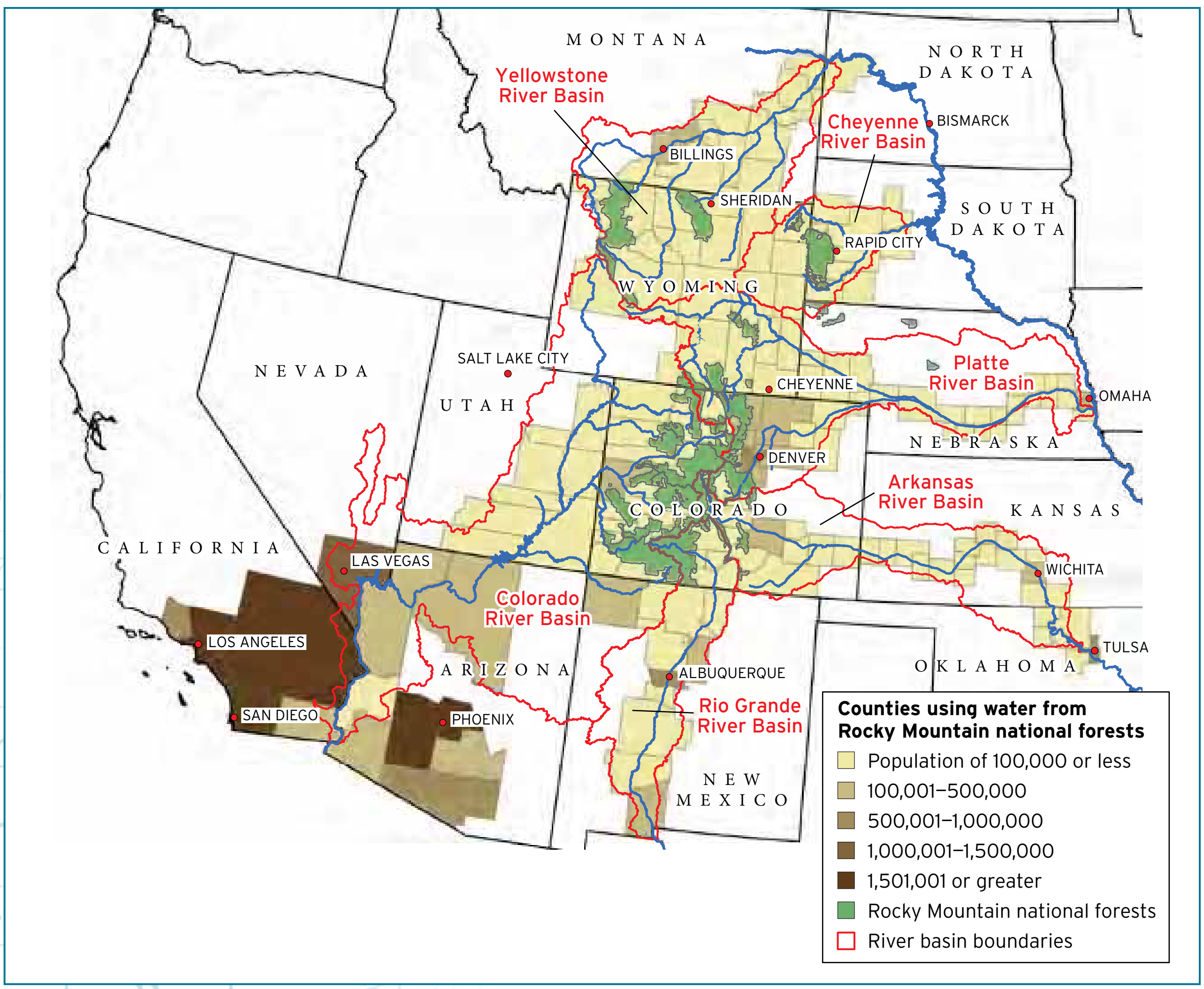


Figure 4—Counties depending on water from the national forests of the Rocky Mountain Region.

Hydropower Production

Production of electricity is essential to modern societies. About 6 percent of the nation's electricity is supplied by hydroelectric facilities (U.S. Department of Energy 2003). This is enough to power 28 million households and is the energy equivalent of about 500 million barrels of oil each year. In the West, hydropower supplies an even greater percentage of energy, amounting to about 15 percent in California, for example. Although these facilities can have substantial impacts on aquatic ecosystems, they provide a renewable source of power with minimal greenhouse gas emissions. Most of the water that drives these facilities flows from forests. With more than 325 hydroelectric dams, representing 15 percent of all facilities nationwide, national forests play an essential role in hydropower generation (fig. 5).

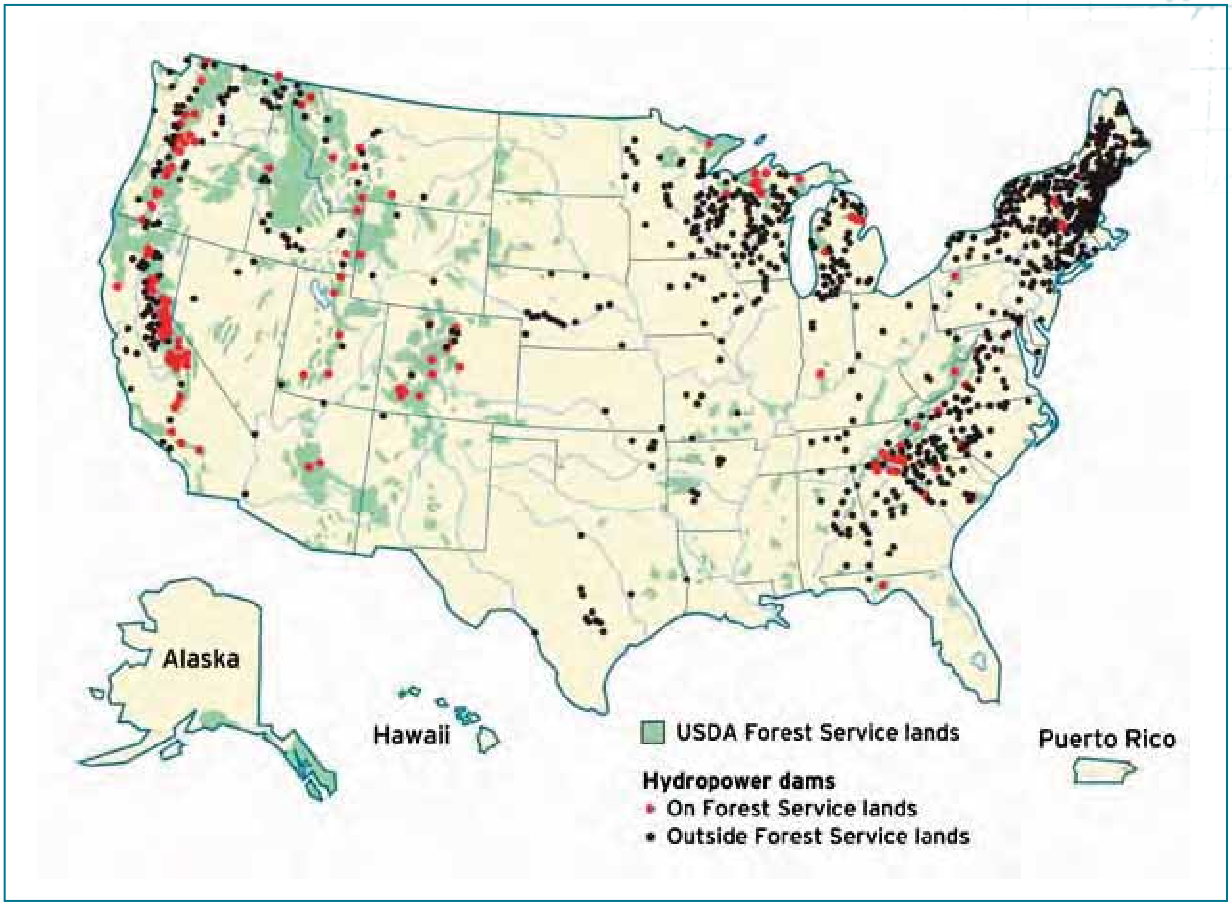


Figure 5—Hydroelectric dams in the United States, both on and off national forests.

Aquatic Species and Habitats

Aquatic species are some of the most imperiled in the United States and the world (Richter et al. 1997). Many of these species inhabit forest lands because the quality of water and other habitat features are often much better than in other areas. National forests, in particular, are critically important for the conservation of these species, as they provide habitat for more than 550 rare, threatened, and endangered aquatic species (fig. 6). More than two-thirds of watersheds containing at-risk freshwater mussels include lands managed by the Forest Service. In the interior Columbia River basin, more than 66 percent of the remaining spawning and rearing habitats for species like bull trout (*Salvelinus confluentus*), stream-type Chinook salmon (*Oncorhynchus tshawytscha*), and westslope cutthroat trout (*Oncorhynchus clarki lewisi*) are found on federal lands, principally national forests (Lee et al. 1997, Rieman et al. 2007). In the Southwest, virtually all known remaining populations of Colorado River cutthroat trout (*Oncorhynchus clarki pleuritieus*), gila trout (*Oncorhynchus gilae gilae*), and Apache trout (*Oncorhynchus apache*) occur on federal lands (Rinne 1990, Young et al. 1996).

These lands are equally important in the Southeast, where about two-thirds of the crayfish species in North America reside, many of them on national forests (Taylor et al. 2007). The value of these forest lands for the conservation and recovery of aquatic species will increase dramatically in the future as private lands are further developed and societal demands for water increase.

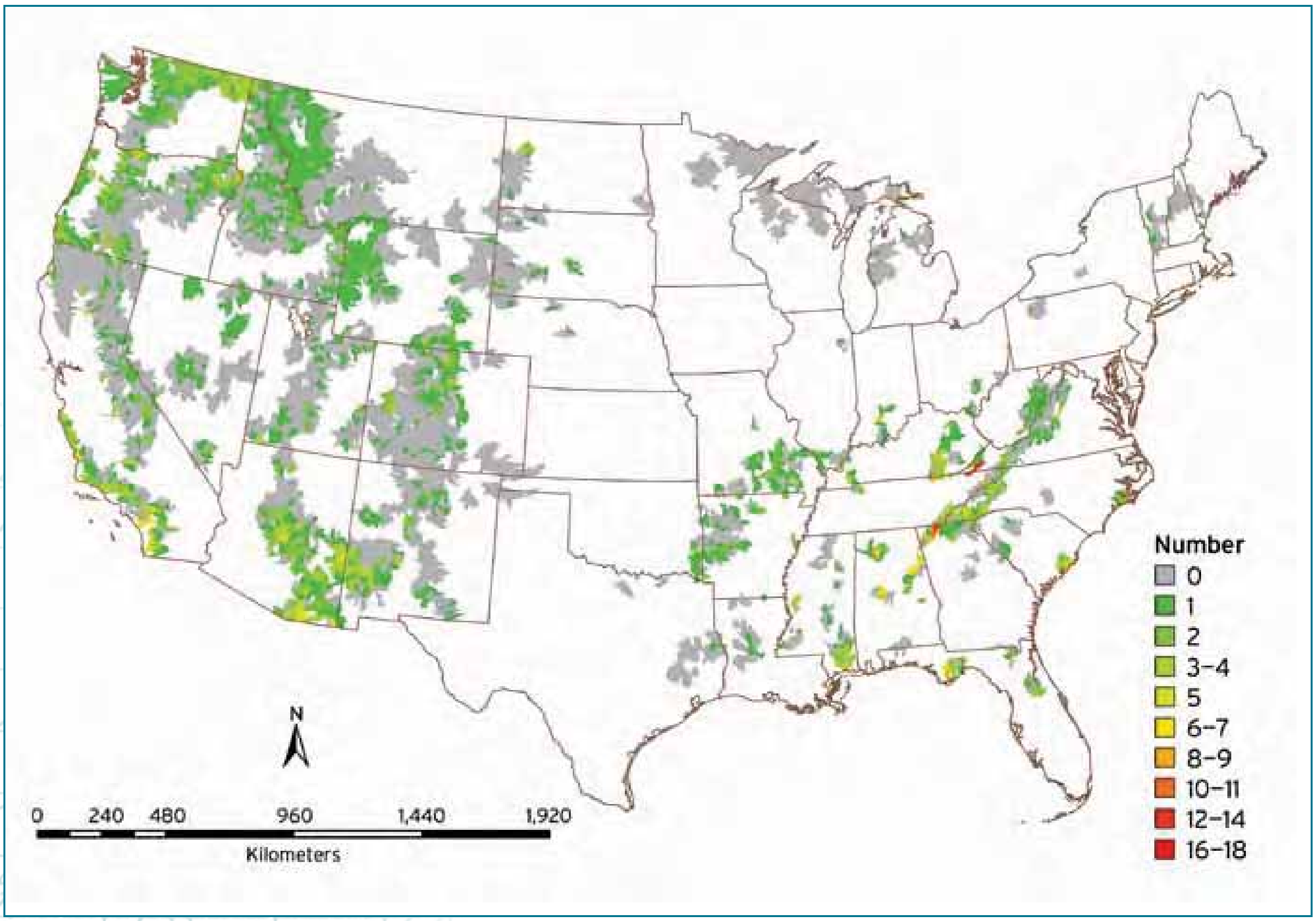


Figure 6—Number of aquatic species listed as threatened or endangered under the Endangered Species Act in watersheds that contain National Forest System lands (Brown and Froemke, in press).

Critical Watershed Services Are Threatened by Existing Impacts

Although forests naturally supply a steady flow of watershed services, long-term provision of these services is not guaranteed. The amount and quality of these services depend on the condition of the forest—when watershed conditions are stressed or degraded, critical services can be threatened or compromised. Today, essential watershed services are threatened by a variety of human impacts on watersheds and aquatic ecosystems.

In many areas, these systems have suffered from significant alterations of natural flow patterns, water pollution, and habitat degradation and fragmentation (Postel and Richter 2003). Similar impacts exist in many places, but they differ dramatically in magnitude and extent.

In the Eastern United States, for example, some critical watershed services are threatened by development of private forests (fig. 7). In the arid and semiarid Western United States, over-allocation and use of water is a principal threat to watershed services and a source of significant social conflict (fig. 8). Development threats are not isolated to the Eastern United States, however, nor are water supply shortages confined to the West. For example, parts of the Southeast have large and growing water availability and supply problems.

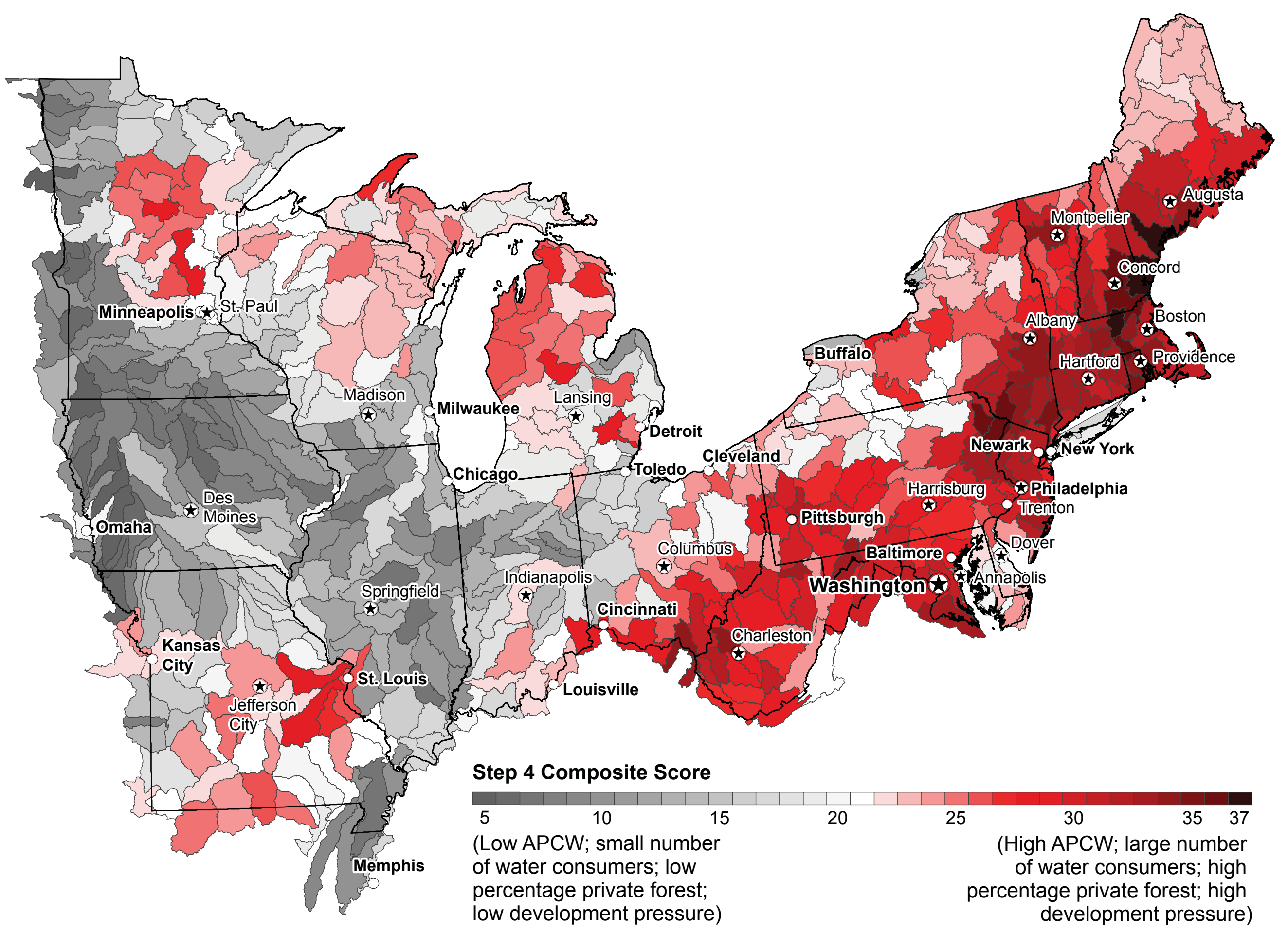


Figure 7—Level of development pressure on primary drinking water supplies in the Northeast United States. Red areas indicate a combination of highly important watersheds with severe pressure, as measured by an index, ability to produce clean water (APCW) (Barnes et al. 2009).

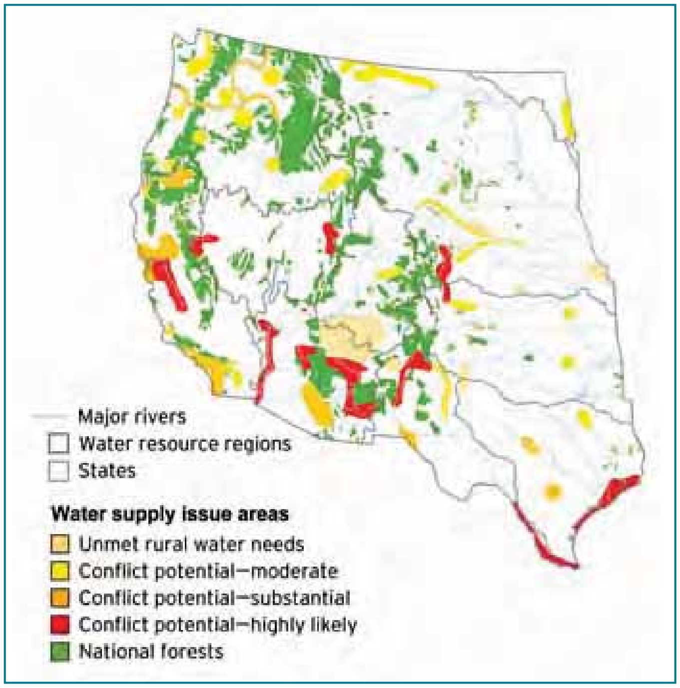


Figure 8—Water supply conflicts in the Western United States, 2005. Half the water supply in the West comes from National Forest System lands, shown in green. Thus, attempts to resolve supply conflicts through additional water diversion and storage often have significant implications for national forest resources. In particular, water quality and aquatic ecosystems can be significantly affected by these activities, whether they are located on or downstream of the forests. Adapted from USDI Bureau of Reclamation 2005.

Climate Change Further Threatens Essential Watershed Services

Climate change has directly affected and will continue to affect the global hydrologic cycle and thus the quality, quantity, and timing of streamflows from forests. It has also initiated indirect effects on water resources, such as increased extent and severity of wildfire and forest mortality. Together, these effects will interact with existing threats and impacts (fig. 9). As a result, the consequences of this episode of climate change may be larger than those that occurred during previous shifts in climate of similar magnitude (Reid and Lisle 2008).

The next section summarizes the observed and projected changes in climate for the 20th and 21st centuries, describes some of the direct and indirect effects of these changes on watershed hydrology, and explains how some of these changes will interact with existing impacts. It then describes how those changes will affect the flow of watershed services from forests: the water we drink, food we grow and eat, the energy we generate, the recreation we enjoy, and the quality and livability of our communities.

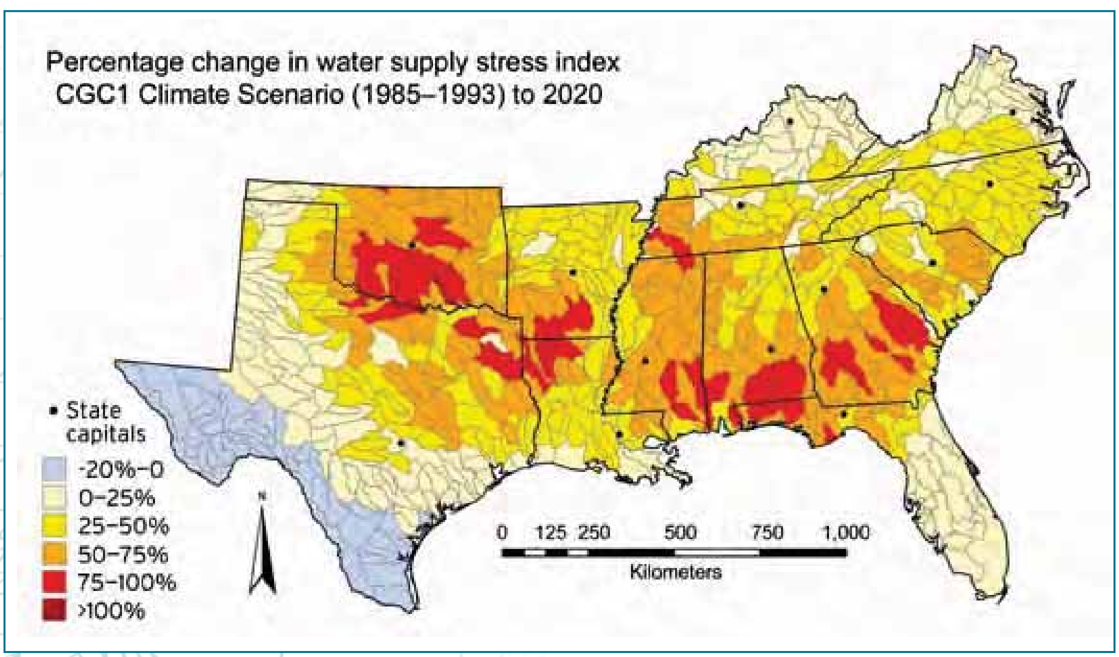


Figure 9—In some areas, climate change will interact with population growth to further increase water supply stress. This figure displays the combined impact of future changes in climate and population growth on a computed water supply stress index in the Southeast for 2020 compared to the 1985–1993 conditions (Sun et al. 2008).

BACKGROUND

CLIMATE CHANGE: Hydrologic Responses and Ecosystem Services

CLIMATE CHANGE: Hydrologic Responses and Ecosystem Services

Knowledge of climate change is based on decades of research involving observations of the past and projections of the future. This growing body of science has demonstrated that the Earth's climate warmed rapidly during the 20th century, leading to significant changes in the hydrologic cycle. These changes are expected to intensify in the future and have large impacts on forests and the watershed services they provide. This chapter summarizes these changes and expected impacts, based on the work of leading authorities such as the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Climate Change Science Program (CCSP), as well as many other individual scientists and institutions around the world.

Observations Show Patterns of Global and National Climate Change in Recent Decades

Numerous and diverse observations during the last decades of the 20th century show that the Earth's climate is currently warming and precipitation is increasing. Mean global annual surface air temperature has increased 0.74 ± 0.18 °C (1.33 ± 0.32 °F) since 1906 (Solomon et al. 2007), a change indicated by higher daily minimum temperatures (Easterling et al. 1997). Temperature increases are widespread over the globe, with the greatest increases occurring at the higher northern latitudes. Land has warmed faster than the oceans (Solomon et al. 2007). Total global precipitation has increased over the same period (Nicholls et al. 1996), but not all areas are experiencing increases. For example, substantial decreases have been observed in many midlatitude areas (Bates et al. 2008). Lower elevations are receiving more precipitation as rain and less as snow, and late spring snow cover has decreased (Barnett et al. 2008). Areas affected by drought appear to have increased since the 1970s (Solomon et al. 2007). Observed global warming is linked to these changing precipitation patterns as well as to sea level rise, decreases in snow and ice extent, and changes in the frequency and intensity of extreme events such as heat waves, drought, and heavy rainfall.

Comparable levels of warming have been recorded for the United States, and both local and regional precipitation patterns are changing. For example, since 1950, the frequency of heat waves in the Pacific Northwest has increased, as has the frequency of warm nights (Alexander et al. 2006). A northward shift of Pacific storm tracks has been observed, and storm intensity has increased over the North Pacific and North Atlantic (McCabe et al. 2001). Interannual variability in precipitation has changed in many parts of the West as well, meaning wetter wet years and drier dry years (Hamlet and Lettenmaier 2007, Luce and Holden 2009, Pagano and Garen 2005). The frequency and intensity of extreme cyclones has increased markedly in the North Pacific, with an associated upward trend in extreme surface winds between 25° and 40° N latitude and major changes in cyclone-related circulation patterns in the Gulf of Alaska (Graham and Diaz 2001). In a broad review of the literature on extreme events, Huntington (2006) concluded that observed trends are consistent with an intensification of the hydrologic cycle during part or all of the 20th century at regional to continental scales (table 1).

Additional Changes Are Projected for the 21st Century

Complex mathematical models of the climate system, known as Global Circulation Models (GCMs), are used to project future climates. These models consistently project increases in average temperatures across the globe. Increases are expected to be strongest inland and at higher latitudes, with lesser warming along the coasts (fig. 10). Warming is likely to be especially pronounced in high latitudes in winter. Warmer air can hold more water vapor, which is itself an important greenhouse gas. This may further accelerate warming, with perhaps twice the effects of increased CO_2 alone (Dessler et al. 2008).

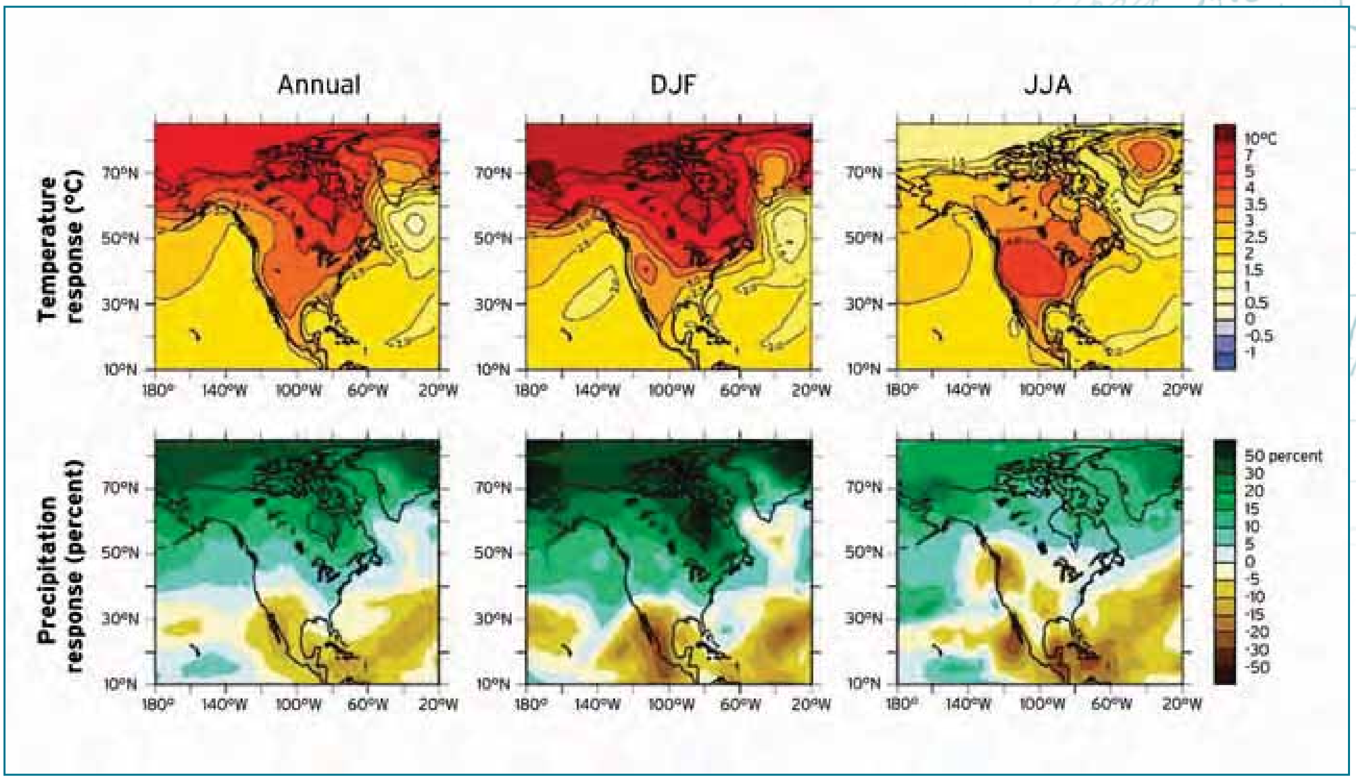


Figure 10—IPCC Combined Global Climate Model projections of temperature and precipitation over North America at the end of the 21st Century (2007). DJF refers to winter months; JJA refers to summer months. Projected boundaries should be regarded as highly uncertain, and projected changes are large scale. Large divergence from these broad-scale patterns are expected at smaller spatial scales. Temperature projections are more reliable than precipitation projections.

Shifts are also expected in the spatial distribution, timing, interannual variability, and phase (solid vs. liquid) of precipitation. These changes are less consistent geographically than those associated with temperature. Some areas will likely receive more precipitation and some will receive less, with expected high variability in time and space (fig. 10). In general, wet areas and higher latitudes are likely to become wetter, while dry areas and the middle latitudes are likely to become drier (Hamlet and Lettenmaier 2007, Jain et al. 2005, Pagano and Garen 2005). Thus the Northern and Eastern United States are expected to receive more precipitation, while the Southwest will likely become drier. Changes from snow to rain are expected primarily at the lowest extent of current snow lines (Knowles et al. 2006). These projected changes in precipitation are much less certain than those for temperature.

More details regarding observed and projected regional-scale climate changes in the United States and its territories are provided in table 1.

Table 1—Regional trends and projections of changing climatic conditions

Region	Observed 20th century climate	Projections for 21st century
Northeast	**Warmer and wetter.** • ↑ T: up to 4 °F (2 °C) along coastal margins. • ↑ P: 20 percent on average; extremes appear to be increasing, while land area experiencing drought appears to be decreasing. • Period between first and last dates with snow on the ground has decreased by 7 days since about 1950. **Significant climate variability. Extreme events such as floods, droughts, heat waves, and severe storms are characteristic.**	**Warmer, but projected temperature increases are among the lowest compared to other regions. Greatest increases expected for winter minimum temperatures.** • ↑ winter minimum T: 4–5 °F (2–3 °C); up to 9 °F (5 °C) by 2100. **Uncertain changes in precipitation.** • P: little change, or up to 25 percent ↑ P by 2100. Increased variability in precipitation in coastal areas. Uncertain changes in the frequency and intensity of winter storms.
Southeast	**Temperature trends in the Southeast vary between decades.** • 1920s-1940s: warm period. • 1960s: cooling trend. • 1970s–present: ↑ T, 1990s as warm as 1920s–1930s. **Large increases in precipitation.** • 20–30 percent or more over last 100 years across much of the region.	**Wide range of plausible scenarios for temperature and precipitation over the next century.** • ↑ T: warming expected across Southeast by 2090s; rates projected by different climate models differ significantly. • ↑ P: one climate model projects up to 20 percent increase by 2100.
Midwest	**Variable temperature response. Wetter.** • ↑ T: up to 4 °F (2 °C) in the north, including upper Great Lakes. • ↓ T: 1 °F (0.5 °C) in the south, along the Ohio River valley. • ↑ P: 10–20 percent.	**Temperatures and precipitation are expected to increase at a greater rate than observed in the 20th century.** • ↑ T: 5–10 °F (3–6 °C) across the region. • ↑ P: 10–30 percent. **Increases in the proportion of precipitation coming from heavy and extreme precipitation are very likely.**
Great Plains	**Variable temperature and precipitation response.** • ↑ T: up to 2 °F (1 °C) across Northern and Great Plains. • ↑ T: up to 5.5 °F (3 °C) in parts of Montana, North Dakota, and South Dakota. • T: no trend in southern Great Plains. • ↑ P: 10 percent in eastern Great Plains. • ↓ P: 10 percent in Montana, North Dakota, eastern Wyoming, and Colorado. **Texas has experienced significantly more high-intensity rainfall. The snow season ends earlier in the spring, reflecting the greater seasonal warming in winter and spring.**	**Warmer throughout the region, with the largest increases in the western parts of the plains. Different climate models project different levels of warming. More warming is expected in winter and spring than in summer and fall.** **Variable precipitation response.** • ↑ P: across region according to one model; another projects increases only across the northern portions of region. • ↓ P: east side of Rocky Mountains.

Source: National Assessment Synthesis Team 2001.

Table 1—Regional trends and projections of changing climatic conditions (continued)

Region	Observed 20th century climate	Projections for 21st century
West	**Warmer and generally wetter.** • ↑ T: up to 2–5 °F (1–3 °C). • ↑ P: in much of region, up to 50 percent in some areas. • ↓ P: in Arizona. **Highly variable climate with exceptionally wet and dry periods. The length of the snow season decreased by 16 days from 1951 to 1996 in California and Nevada. Extreme precipitation events have increased.**	**Continued warming and increased precipitation.** • ↑ T: 3–4 °F (2 °C) by 2030s and 8–11 °F (4.5–6 °C) by 2090s. • ↑ P: in winter, especially in California. **More extreme wet and dry years.**
Pacific Northwest	**Warmer and wetter.** • ↑ T: 1–3 °F (0.5–1.5 °C) • ↑ P: 10 percent on average; 30–40 percent in eastern Washington, northern Idaho. **Significant recurring patterns of year-to-year variability.** • Warm, dry years with light snowpack, low streamflows. • Cool, wet years with heavy snowpack, high streamflows.	**Much greater average warming over the region.** • ↑ T: 3 °F (1.5 °C) by 2030s. • ↑ T: 5 °F (3 °C) by 2050s. **Wetter on average across the region.** • ↑ P in winter. • Same or ↓ P in summer.
Alaska	**Warmer and wetter.** • ↑ T: 4 °F (2 °C) since 1950s. • ↑ P: 30 percent from 1968 to 990. **Growing season has lengthened by more than 14 days since the 1950s.**	**Continued warming and generally increased precipitation.** • ↑ T: 1.5–5 °F (1–3 °C) by 2030 and 5–18 °F (3–10 °C) by 2100. • ↓ P: 20–25 percent in north and northwest. • P: up to 10 percent along the south coast.
Islands	**Warmer.** • ↑ T: 1 °F (0.5 °C) in Caribbean. • ↑ T: 0.5 °F (0.25 °C) in Pacific Islands.	**Pacific and Caribbean islands will possibly be affected by changes in patterns of natural climate variability (such as El Niño-Southern Oscillation); changes in the frequency, intensity, and tracks of tropical cyclones; and changes in ocean currents. These islands are very likely to experience increasing air and ocean temperatures and changes in sea level.**

(T = Temperature; P = Precipitation as rain, hail, or snow.) Data regarding projected impacts are being updated at a very rapid rate. Therefore, the most recent and local projections should be identified on a regular basis and used accordingly.

Source: National Assessment Synthesis Team 2001.

Changes in Climate Will Differ With Spatial Scale

Climatic changes at global, national, and regional scales will greatly influence conditions at smaller scales, down to individual watersheds. The changes will differ between watersheds and among locations within them. Factors such as topography, elevation, aspect, local airflow patterns, vertical mixing and transport, lapse rates, and the tendency for inversions to form will govern conditions at individual sites, with important implications for land and water management activities (fig. 11).

Most watershed management actions are planned, designed, and conducted at intermediate scales: between 1 and 500 square kilometers. This is the scale where watershed processes and their relation to services can be readily discerned and analyzed, and the scale at which decisions are most commonly made. Global climate models, however, provide only very large-scale projections, and regional downscaling of models considers only a subset of intermediate-scale influences, unlike the analysis shown in figure 11. Thus the reliability of projections is weak for the typical scale of watershed planning and decisionmaking, necessitating a scenario-based approach. That is, projections are useful for constructing a range of plausible scenarios, but not in reliably predicting future climates at management-relevant scales.

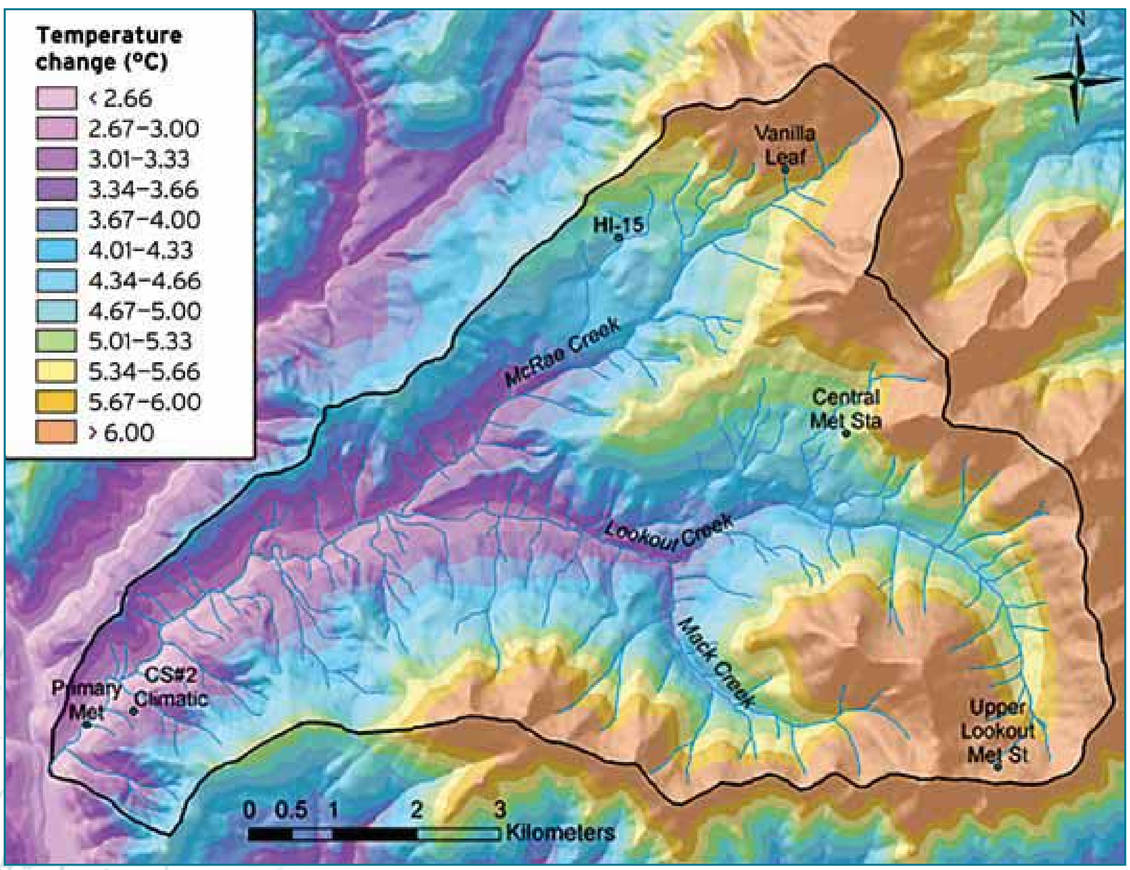


Figure 11—Complex topography can result in complex change. Model results for January maximum temperature change from current conditions on the H.J. Andrews Experimental Forest in western Oregon, assuming a 2.5 °C regional temperature change and accounting for topographic and airflow influences. Climate changes in individual watersheds, the scale at which management activities are generally planned, can differ greatly from average changes over larger regions (Daly et al. 2009).

Climate Change Is Hydrologic Change

The hydrologic cycle—the pathway of water movement on Earth and in the atmosphere—is strongly coupled to the climate system. The distribution of water on the Earth's surface plays a central role in governing temperature and precipitation patterns. It is also controlled by those patterns. As a result, hydrologic changes, particularly the changes in snowpacks and runoff patterns described below, are among the most prominent and important consequences of climate change.

Snowpacks

Over many areas of the Western United States, snow water equivalent (SWE) on April 1 declined during the second half of the 20th century (Lettenmaier et al. 2008, Mote et al. 2005, Regonda et. al. 2005). The largest relative declines in April 1 SWE (many in excess of 50 percent) have occurred in western Washington, western Oregon, and northern California, with more moderate declines in the northern Rockies. The southern Sierra Nevada and portions of the Southwestern United States experienced increases in April 1 SWE during this period. In areas where decreases were observed, the largest changes have been at low and mid elevations, with little to no change observed at the highest elevations (often above 8,000 feet [2440 meters]) or in regions that have experienced increases in winter precipitation (Moore et al. 2007, Regonda et al. 2005, Stewart 2009). Recent trends in the amount and timing of snowmelt are expected to continue into the future.

Runoff

Spring runoff is occurring earlier in snow-dominated watersheds throughout much of the West. Changes in the center-of-timing of spring flows (date at which half of the year's runoff has occurred) show shifts on the order of 1 to 4 weeks earlier between 1948 and 2002 (Stewart et al. 2005). The largest changes in snowmelt runoff timing are occurring at low and mid-elevation sites, whereas high-elevation sites (over 8,000 feet [2440 meters]) generally show little change (Regonda et al. 2005). Earlier spring flows may yield lower late-season flows (Cayan 1996).

Besides changes in streamflow timing, altered total annual flows have been observed. For example, a recent analysis by Luce and Holden (2009) revealed large regional-scale declines in annual streamflows in the Pacific Northwest for the driest 25 percent of years (fig. 12). The implications of these changes are large, as water supply conflicts are already greatest during those years. Changes in average annual streamflows are also projected for the future. For example, Lettenmaier et al. (2008) made projections for average annual runoff for 2041–2060 in each of 18 water resource regions in the United States and compared them to observed data from the 1901–1970 period. They predicted increased annual runoff in the Eastern United States, little change in the Missouri and Lower Mississippi basins, and decreased runoff in the Pacific Northwest and California. Annual runoff in the interior West and Southwest is expected to decrease by as much as 20 percent (fig. 13), with serious consequences for water supply in the Colorado River system (Barnett and Pierce 2008, Rajagopalan et al. 2009).

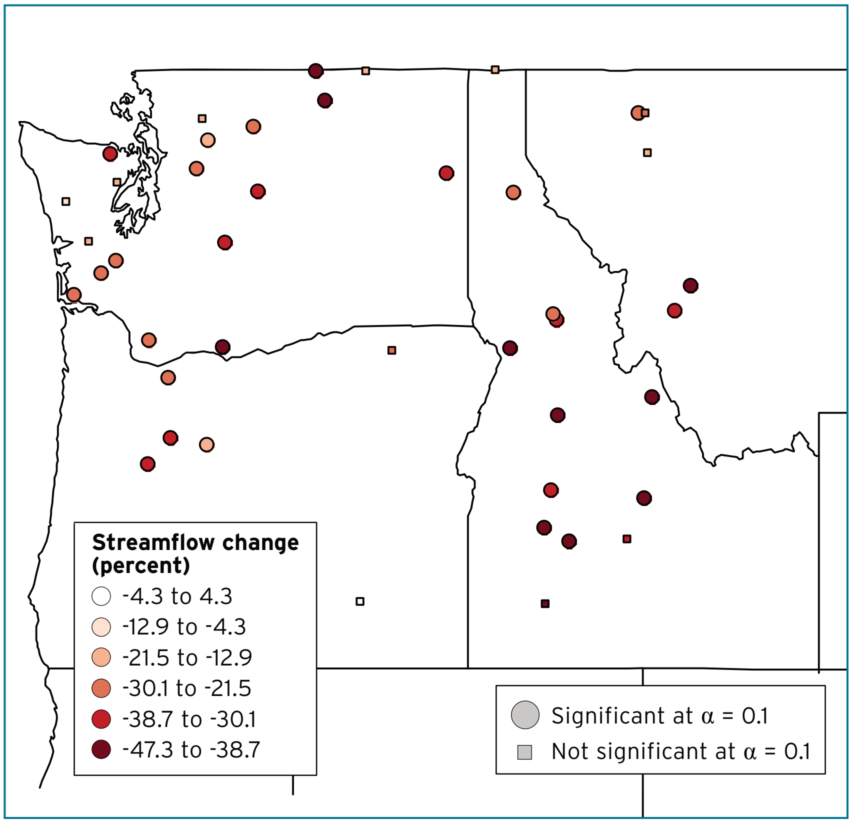


Figure 12—Percentage change in the annual streamflow of the driest 25 percent of years in the Pacific Northwest (Luce and Holden 2009).

Groundwater

Timing and rates of groundwater recharge will shift to reflect the changing patterns of precipitation and runoff. The resulting changes in groundwater levels will, in turn, influence stream baseflows. Groundwater withdrawals may increase in some areas in response to losses or increased variability in surface water supplies. Saltwater intrusion may increase in some coastal freshwater aquifers due to sea-level rise and, in some cases, reduced precipitation.

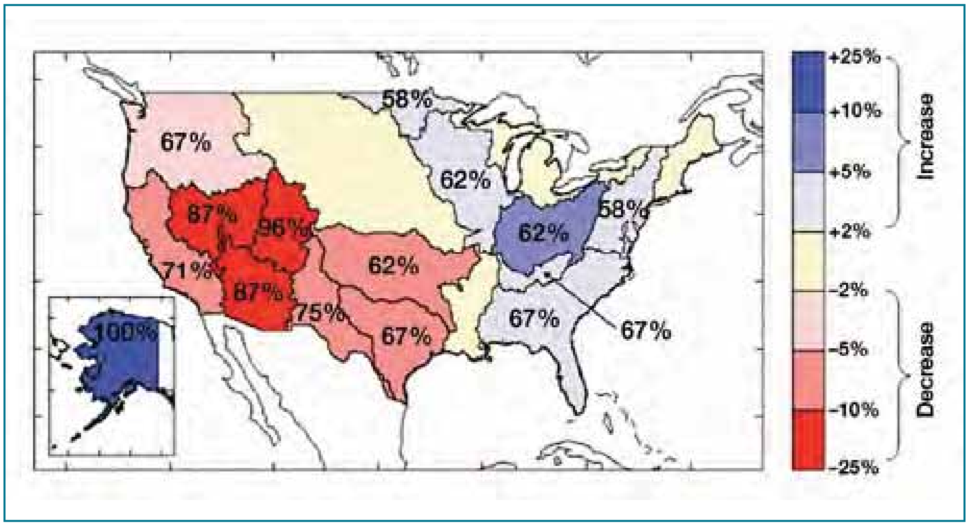


Figure 13—The color represents median changes in runoff interpolated to U.S. Geological Survey water resource regions from Milly et al. (2008) from 24 pairs of Global Circulation Model simulations for 2041–2060 relative to 1901–1970. Percentages are the fraction of 24 runs for which differences had the same sign (positive or negative) as the 24-run median. Results were replotted from Milly et al. (2008) by Dr. P.C.D. Milly, USGS. Source: Lettenmaier et al. (2008).

Climate Change Will Affect Forest Disturbance Regimes

Besides these direct effects on the hydrologic cycle, climate change will directly and indirectly alter ecological disturbances that are influenced by hydrologic processes. Specifically, alterations in the frequency, extent, and magnitude of floods, forest mortality, and fire are expected, each with serious implications for people and ecosystems.

Flood Severity

Flood severity is expected to increase in much of the West because increased interannual variability in precipitation will cause increased runoff in wet years and increased rain-on-snow probability in low-elevation snowpacks (Hamlet and Lettenmaier 2007). A recent study found a relation between sea surface temperatures and global peaks in the number and severity of Atlantic hurricanes over the past 1,500 years, suggesting that warming will contribute to intensification of hurricanes and other cyclonic storms (Mann et al. 2009).

Forest Mortality and Fire

Warmer temperatures, less water, or more water can cause changes in vegetation and increase forest mortality (Allen et al. 2010, van Mantgem et al. 2009). For example, temperature increases have contributed to widespread outbreaks of mountain pine beetles across vast areas of the Rocky Mountains (Logan and Powell 2001). Increased wildfire spread and severity, also related to changes in hydrology, have also been observed (Morgan et al. 2008, Westerling et al. 2006). Together, insects and fire have already affected large areas of the West (fig. 14). Forests in the south and Great Lakes regions are under similar stress (Julius and West 2008, Westerling et al. 2006).

Of these effects, those associated with fires present the most alarming risks for forested watersheds. Fires are burning hotter and covering larger areas. The resulting changes in vegetation cover and soil characteristics can dramatically increase flooding and mass wasting, with severe impacts to downstream infrastructure and aquatic ecosystems (Istanbulluoglu et al. 2004, Miller et al. 2003). Postfire landscapes experience changes in water quality, flow quantity

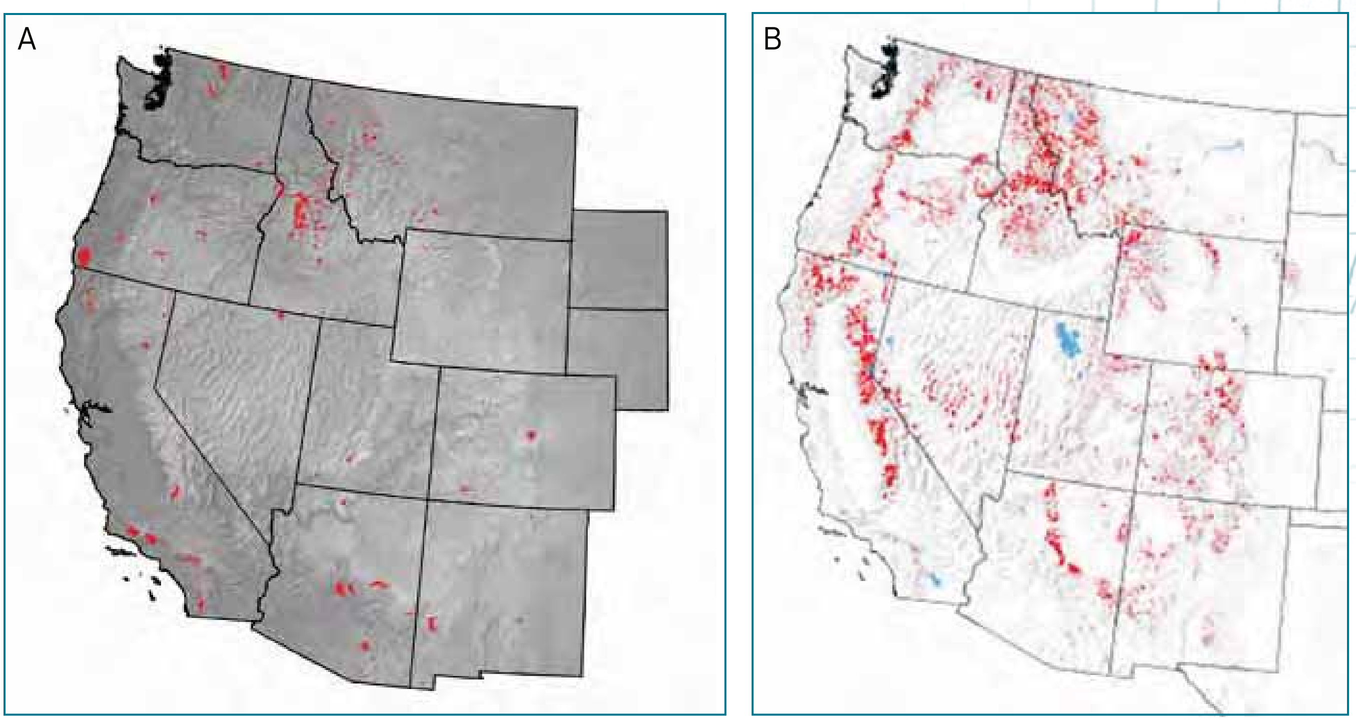


Figure 14—The area of forested lands in the Western United States affected by wildfire and forest insect infestations has increased markedly in recent decades. This is in part due to climate warming, which increases moisture demand, reduces fuel moisture, and leads to favorable conditions for insect infestation and wildfire spread (Westerling et al. 2006). (A) Boundaries of all fire perimeters on Forest Service lands in the Western United States, 2001–2007. (B) Extent of areas at high risk of forest mortality from insects and disease.

and timing, nutrient cycles, aquatic food webs, fish population structure and abundance, and stream and riparian habitat (Bisson et al. 2003). Fires can also increase stream temperatures by killing forests that shade streams (Dunham et al. 2007). These increases can further compound stream temperature increases caused by higher air temperatures (Isaak et al. 2009).

Increased fire extent may also ameliorate some effects of climate change. For example, fires lead to increased water yield by killing trees and reducing evapotranspiration (Luce 2005). This could mitigate some of the effects of reduced streamflows caused by reduced precipitation in certain areas. However, the magnitude of these changes is unclear and may be limited. First, the increased flows will decrease over time if forests regenerate in the burned areas. In addition, the “new” water made available from the loss of forest cover would come earlier in the year, when it is needed least.

Altered Hydrologic and Disturbance Regimes Will Affect Forests and the Watershed Services They Provide

Water is a central organizer of ecosystems (Sedell et. al 2000). Thus, changes in the hydrologic system and associated disturbance regimes will likely have significant impacts on forests and the watershed services they provide to people. In addition to changes previously described, water quality, aquatic habitats and species, and soil resources will be affected significantly.

Water Quality

Water temperatures are expected to increase because of the combined effects of increased air temperatures and wildfire. Erosion is expected to increase as a result of higher peak flows and reductions in ground cover from reduced snowpacks, as well as increased intensity and frequency of wildfire and hurricanes. Sediment loads are thus expected to increase, affecting municipal water supplies and aquatic habitats.

Aquatic Habitats and Species

The majority of streams in the Western United States are likely to show reduced annual runoff and shifts in runoff timing because of changes in precipitation timing and type; seasonally flowing streams are expected to show decreases in flow duration. Decreased flows will likely shrink habitats of all aquatic species at the upstream end. The same influences will result in the contraction and loss of wetlands. Altered flows and higher air temperatures will result in warmer water temperatures at sites where flow remains present, with resulting changes in the composition of aquatic communities and increases in primary productivity. Temperature changes will likely shrink habitats of cold water species near the downstream end, compounding losses from the upstream end (Dunham et al. 2007). Thus, these species are perhaps at greatest risk. Bull trout, for example, are already limited to high elevations and northern areas. Projected habitat distributions under climate change are greatly reduced by temperature effects alone (Rieman et al. 2007). Increased temperatures from wildfire could substantially restrict this range even further (Dunham et al. 2007) (fig. 15).

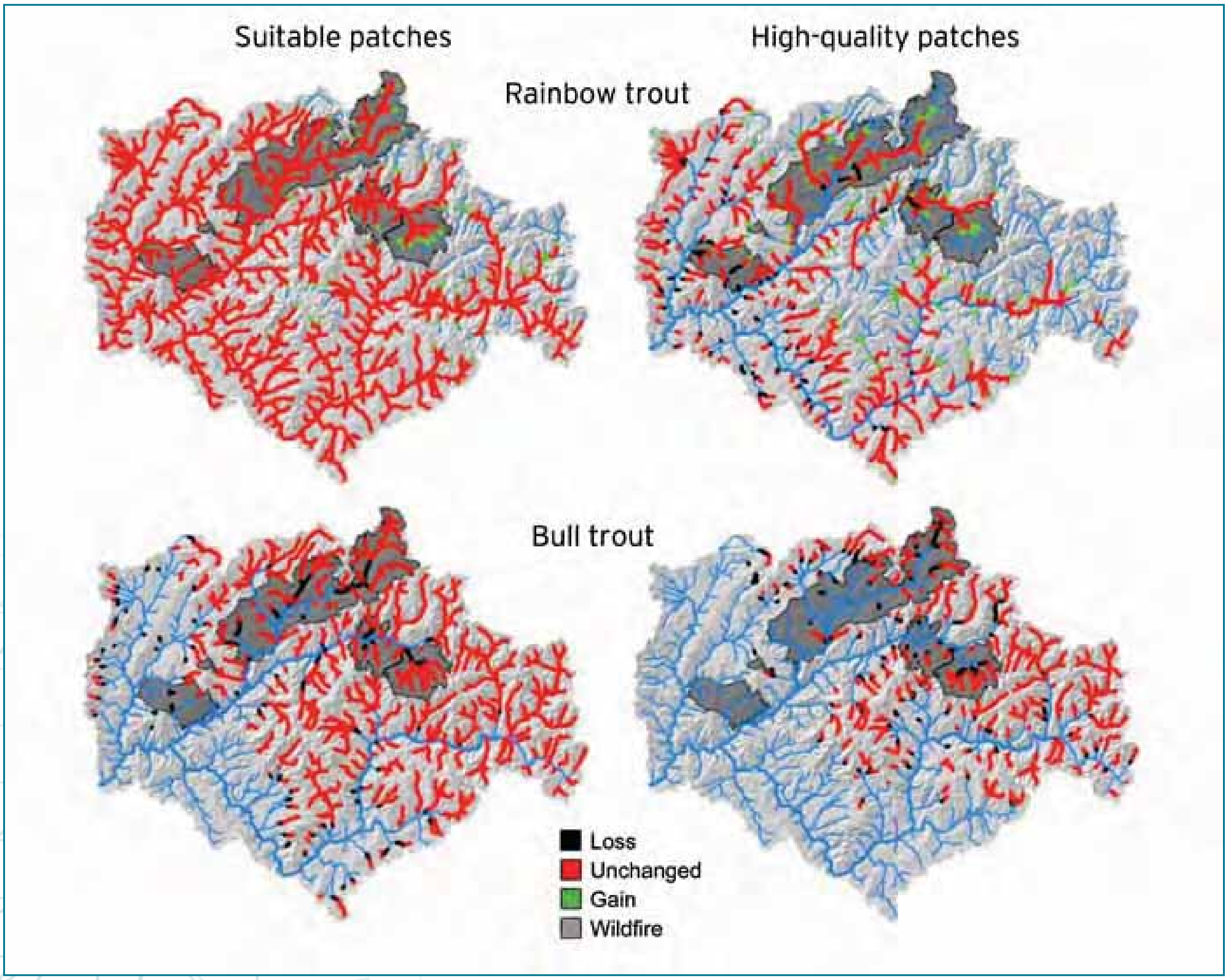


Figure 15—Effects of recent climate change and recent wildfires on stream temperature and thermal habitat for rainbow trout *(Oncorhynchus mykiss)* and bull trout (*Salvelinus confluentus*) in a mountain river network (Isaak et al. 2009). The two separate but related factors have generally decreased habitat for bull trout. Habitat for rainbow trout has decreased in some areas, but increased in others.

Soil Resources

Increased flooding and fire are expected to result in substantial increases in erosion and potential losses in soil productivity. Changes in temperature, evapotranspiration, precipitation, and runoff will affect soil moisture over most or all landscapes. The extent of water supply shortages and soil moisture decline will likely vary greatly, depending on watershed soil properties and the size and behavior of water storage in the landscape. In many areas, soils are likely to dry earlier in the year, stressing existing vegetation and leading to changes in vegetation communities, forest die-off, and insect outbreaks. Increased decomposition rates will deplete soil organic matter more rapidly. Furthermore, decreased carbon fixation because of lower water availability and increased moisture stress may reduce loading of organic matter from forest litter.

Some of these and other changes in ecosystems and ecosystem services are depicted in figure 16 and summarized in table 2.

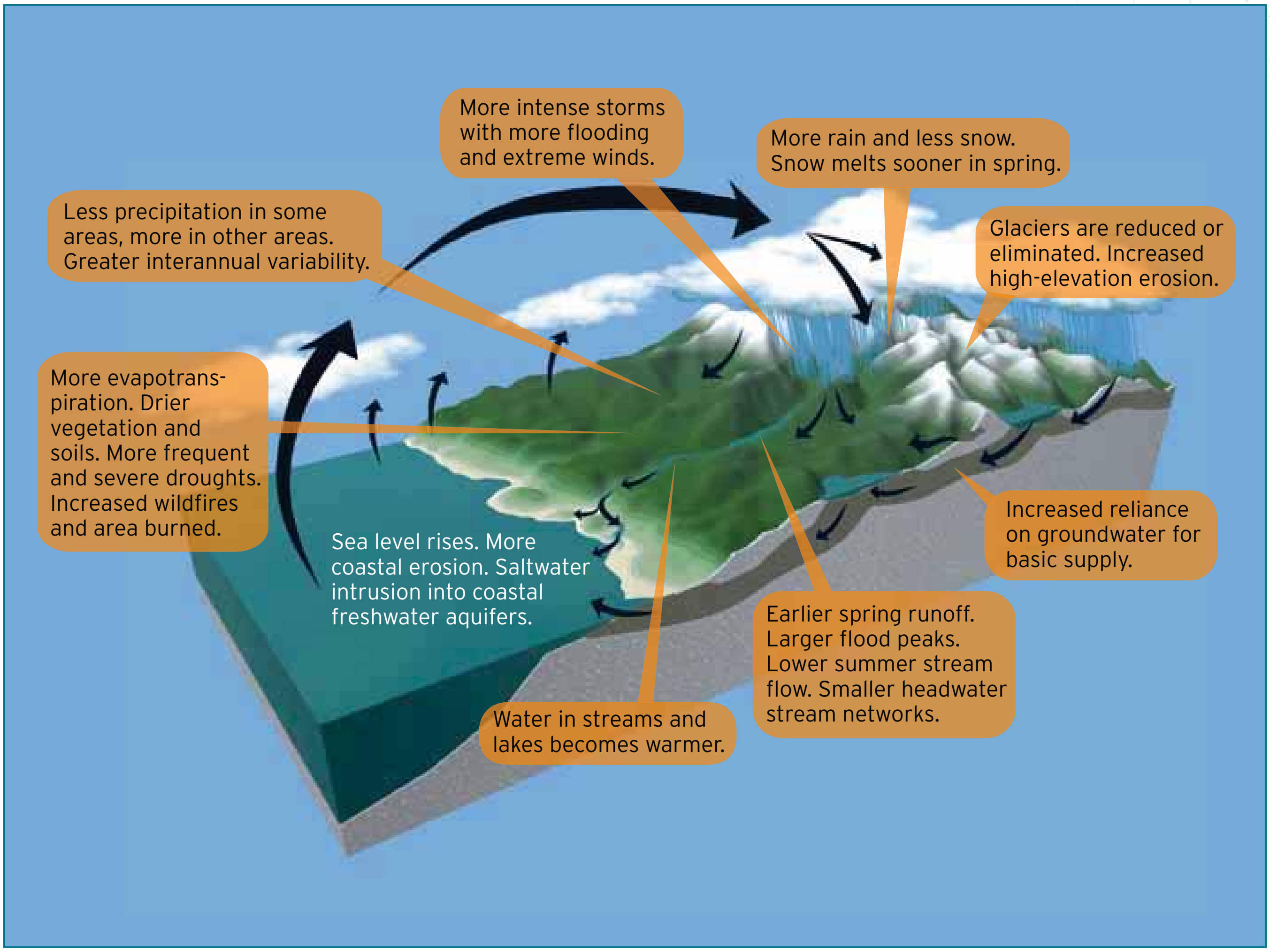


Figure 16—Examples of potential direct and indirect effects of climate change on the hydrologic cycle. Most components are intensified by climate warming. Base image from the COMET Program, used by permission.

Table 2—Some projected climate changes, hydrologic effects, and potential consequences to ecosystem services

Projected changes	Regional variation	Anticipated watershed response	Potential consequences to watershed services
Warmer air temperatures	More pronounced at higher latitudes and higher elevations, and in inland areas. Coastal areas are likely to warm the least.	• Less total streamflow, owing to more evapotranspiration. • Reduced flow duration and discharge in seasonally flowing streams. • More erosion and stream sediment pollution from fires, floods, landslides, and other large-scale disturbances. • Warmer water temperatures in streams and lakes. • Increased primary productivity in surface waters. • Increased soil organic matter decomposition rates. • Drier soils earlier in the year.	• Changes in the amounts, quality, and distribution of water-dependent habitats and associated biota; most changes will be adverse for coldwater fishes. • Changes in the availability of water supplies. • Decreased quality of water supplies, increased treatment costs. • Decreased reservoir storage. • Decrease in coldwater aquatic habitats. • Increase in warmwater aquatic habitats. • Increased irrigation needs.
More frequent, longer, and dryer droughts	Highly variable, mostly Western United States	• Larger and more frequent fires, caused by lower summer soil moisture, warmer temperature, more wind leading to: ▪ More frequent forest mortality. ▪ Reduced vegetative cover on watersheds. ▪ Short-term increases in water yield and flooding. • Greater near-term inputs of large wood to streams, followed by decreased inputs in the long term. • Reduced groundwater recharge.	• Decreased natural flood regulation, resulting in damage to infrastructure and developed areas. • Decreased soil productivity. • Altered recreational and cultural experiences. • Greater frequency of toxic blue-green algae in lakes and reservoirs. • Altered nutrient inputs and cycling in streams and lakes. • Increased depletion of groundwater.
Changes in precipitation amounts and timing	Wetter and higher latitude areas become wetter; drier and lower latitude areas become drier. Summer rainfall might increase in some areas and decrease in others. Dry-season rainfall might increase or decrease.	• Altered timing and volume of runoff. • Altered channel forms reflecting changes in runoff, peak flows, and sediment loads. • Changes in drought severity. • Changes in vegetation. • Altered erosion rates. • Changes in groundwater recharge and corresponding changes in stream baseflow.	• Increases or decreases in availability of water supplies. • Complex changes in water quality related to flow and sediment changes. • Increases or decreases in capacity for hydropower generation. • Ecological changes related to moisture availability in soils, streams, lakes, and wetlands.

Table 2—Some projected climate changes, hydrologic effects, and potential consequences to ecosystem services (continued)

Projected changes	Regional variation	Anticipated watershed response	Potential consequences to watershed services
Less snowfall, earlier snowmelt, increased snowpack density	Most vulnerable are "warm snowpacks" at lower elevations and lower latitudes. Western near-coastal mountains have the greatest areas of vulnerable snow.	• Higher winter flows. • Lower summer flows. • Earlier and smaller peak flows in spring. • More frequent rain-on-snow flooding in some areas. • More erosion of areas previously protected by snow. • Changes in stream channels because of altered flows and modified sediment and wood inputs. • Altered patterns of groundwater recharge.	• Changes in the amounts, quality, and distribution of aquatic and riparian habitats and biota. • Decreased capacity for hydropower generation in summer when demand is greatest. • Changes in the availability of water supplies. • Decreased quality of water supplies, increased treatment costs. • Decreased reservoir storage. • Decreased soil productivity. • Potential for increased frequency of toxic blue-green algae in lakes and reservoirs. • Altered recreational and cultural experiences.
Intensified storms, greater extremes of precipitation and wind	Highly variable, degree of change highly uncertain. Rainfall variability will likely increase.	• Greater likelihood of flooding. • Increased erosion rates and sediment yields. • Altered channel forms. • Changes in the delivery of blow-down wood to streams.	• Decreased quality of water supplies, increased treatment costs. • Reduced reservoir storage from increased sedimentation. • Changes in aquatic and riparian habitats. • Increased damage to roads, campgrounds, and other facilities. • Reduced availability of water-related recreation (e.g., fishing, skiing, and so on).
Loss of glaciers, smaller glaciers	Lower elevation glaciers affected most.	• Short-term increases in summer flow in glacier-fed streams, followed by long-term reduction of flows. • Modification of temperature regimes in glacier-fed streams. • More erosion from newly exposed surfaces.	• Modified alpine vegetation near glaciers. • High-elevation erosion hazards. • Changes in the availability of water supplies.
Rising sea level	Coastal areas, and islands affected.	• Loss of beaches and tidal wetlands; changes in area of estuaries. • Inundation of coastal lowlands. • Increasing salinity in remaining estuaries and tidal wetlands. • Greater saltwater intrusion into freshwater aquifers.	• Increased vulnerability of coastal areas to storm damage. • Habitat changes. • Loss of water supplies. • Reduced coastal fishery resources. • Displacement of human populations, increasing pressure at the wildland interface.

The Effects of Climate Change Are Cumulative

The effects of climate change will not play out on pristine landforms. They will interact with existing conditions and generally increase the severity and extent of existing problems such as species extirpation, water pollution, and water scarcity. As described in the first section, many watersheds have already been altered by large-scale water diversions, impaired water quality, and degraded habitat conditions. On national forests, past grazing, timber harvesting, mining, and road development have left a legacy of altered watershed conditions that persist over wide areas. For example, uncontrolled grazing on public lands prior to the 1930s contributed to soil compaction and gully erosion, reduced soil productivity, increased sediment yields, altered vegetation, and modified fire regimes. Historical clearing of riparian forests for agriculture in the Eastern United States is considered one of the most significant impacts on coldwater fisheries in that region. Early mining activities produced long-lasting impacts from toxic chemical waste, altered aquatic and riparian food webs, and physical damage to watersheds and streams (Julius and West 2008). Extensive road networks were built to support intensive timber management across much of the landscape. These aging road systems still exist, but the original management objectives no longer do, nor does the funding needed to maintain or decommission them. This is a critical issue because poorly built and maintained forest roads are major sources of landslides, sediment loads, flow alteration, and habitat fragmentation in streams (NRC 2008).

Thousands of nonnative invasive species have infested millions of acres of forests, rangelands, and aquatic ecosystems across the Nation. In many areas, aquatic invasive plants, mollusks, and fish are replacing native species and degrading water quality. Shifting climates change the distribution of sites hospitable to the invaders, and climatic changes that alter the frequency and intensity of environmental disturbances, such as wildfire, can degrade soil quality resulting in greater opportunity for invaders to spread beyond their present locations. Most changes will likely help the invaders; others may assist native species.

Loss of private forests to homes and other development is particularly problematic. As recently reported by the National Research Council (2008), "Forests that once provided high quality runoff are becoming developed parcels that can adversely affect runoff patterns and water quality." Urban land in the contiguous United States is expected to nearly triple over the next several decades (Nowak and Walton 2005), and loss of private forests to housing growth and other development uses is projected in rural and exurban areas (Radeloff et al. 2005, Stein et al. 2005). Much of this change is piecemeal, and small fragmented changes produce cumulative watershed impacts that are difficult to mitigate (NRC 2008).

Given these impacts, effective climate change adaptation strategies will focus not only on the direct impacts of climate change. Instead, they will need to focus on maintaining or restoring watershed resilience, which will require that all of the principal impacts and threats to key watershed processes and services be addressed.

Hydrologic Change Will Complicate National Forest Management in Many Ways

The direct, indirect, and cumulative effects of climate change will greatly complicate management of national forests and other forests in multiple ways. Many of the greatest challenges are associated with water and aquatic resources, as described below.

Water Use and Diversion

Climate change will strongly affect the amount, timing, and variability of water available for both onsite and offsite uses in the coming decades, because of changes in precipitation and snowmelt. This, combined with a larger population, will increase the demand for consumptive uses of water from national forests and other public lands. Requests to develop or expand facilities to store or divert water for municipal, industrial, and agricultural uses will also increase. In many cases, these increased demands will conflict with other resource objectives, such as protecting and restoring aquatic habitats and species.

Water Quality Management

Although the quality of water from national forests is generally high, past management activities have caused impairments in some areas. Most of these are associated with erosion, sedimentation, and increased temperatures. Excessive nutrient loading and metals pollution are also common water quality problems. In recent years, substantial efforts have been focused on addressing these impairments and preventing new ones through protection and restoration efforts. Unfortunately, water quality impacts associated with altered hydrologic and disturbance regimes will make it more difficult to meet water quality standards and support the full range of water uses. In some cases, existing standards may not be attainable. These conditions may create substantial legal and social conflicts and reduce the ability of land managers to meet multiple resource objectives.

Aquatic Habitat Management

Climate change, past impacts, and the ongoing development and fragmentation of streams across private lands will dramatically increase the role of national forests and other conserved wildlands as refugia for aquatic species. This may increase demands for greater habitat protections, which could conflict with meeting other management objectives such as increasing energy production, recreation access, and water diversions.

Climate change also raises questions regarding priorities for habitat protection and restoration. In recent years, scientists and managers have placed considerable emphasis on identifying those areas with the greatest conservation and restoration potential, so that limited resources could be focused where they will provide the most benefit. Unfortunately, the distribution and character of habitats and associated biota will change markedly in some areas in response to altered streamflows and disturbance regimes. Thus, areas that provide high conservation value today may not in the future. A critical challenge is to accurately predict how those habitats will change and species distribution will shift over time. These shifts in habitats and biota will also elevate the importance of removing the vast number of barriers to migration resulting from dams, water diversions, and road crossings. Increasing fire extent further elevates the importance of addressing these barriers, as well-connected habitats greatly increase the likelihood that populations can rebound quickly from disturbance. Increasing wildfire size and severity will make efforts to restore riparian shade more challenging. Existing challenges in controlling invasive species and their impacts on native species may be exacerbated by climate change, as altered hydrologic and disturbance regimes are likely to favor invasive species in some watersheds.

Soil Management

Forest management and watershed function depend on productive, porous soils. Ongoing and projected climate changes compound the effects of other factors on soil resources, and increase the need for watershed treatments to restore degraded soils and stabilize sites at increased risk of erosion, loss of porosity, and loss of soil organic matter.

Fire and Fuels Management

Increased fire frequency, severity, and extent will accelerate demands for aggressive fuels management. Although fuels treatments may reduce the watershed effects of fire in some circumstances (Ritchie et al. 2007), they can also cause adverse effects on aquatic ecosystems, particularly when new roads are built or old, unmaintained roads are kept open to support these activities. Thus forest managers will be increasingly faced with the challenging question of which is worse for aquatic habitats, wildfire or the active measures intended to suppress it (Bisson et al. 2003).

Forest managers will also be faced with increasingly complex challenges associated with managing postfire landscapes. Larger burned area, combined with increased human populations at risk of postfire flooding and mass erosion events, will increase the need to accurately assess postfire risks and target mitigation actions accordingly.

Vegetation Management

Vegetation management. Projected climate changes will affect forest vegetation by increasing the elevation of the maximum treeline expansion in northern zones, increasing the elevation of the minimum tree line in semiarid zones, and increasing drought stress, plant disease, and competition from invasive species. Widespread temperature-induced drought stress is expected to cause increases in the amount of biomass consumed by fire throughout much of the West. Current temperature-related insect infestations are expected to continue. Increased tree mortality from insects has already been observed throughout the West (van Mantgem et al. 2009), raising concerns about the future distribution of forest vegetation. Decreases in growth resulting from changes in water balance have also been observed (Littel et al. 2008).

Forest managers will need to determine the types and densities of vegetation that sites will support in the future. This issue will be particularly acute after large-scale disturbances such as wildfire and insect and disease outbreaks. In addition, managers may be increasingly pressured to manage vegetation for the primary purpose of producing more streamflow, despite the proven limitations of such efforts (see box on next page).

In rangeland ecosystems, temperature increases and longer growing seasons will lead to the expansion of winter range. Shifts in forage productivity and the presence of exotic plant species in grasslands will likely affect forage quality and fire frequency. Higher temperatures will reduce livestock

Do trees take our water?

As demand for water increases, especially in the arid West, people have asked: **Can we remove trees to produce more water?** Because science shows that water yields can be increased by cutting trees, there is a temptation to consider removing forest cover to enhance water supply. Increased water yield from removing forest cover, however, is not sustainable over the long term, nor is the increase significant at scales that make a meaningful difference in water supply (Ziemer 1987).

The issue was recently summarized by the National Research Council (2008: 1):

> 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.

So what is the answer? The primary driver of water yield in large basins is precipitation, which will likely become more variable with a changing climate. Optimizing long-term water yield, water quality, and healthy aquatic and terrestrial ecosystems will best be accomplished by keeping watersheds forested and in good condition and using available supplies as efficiently as possible. Efficient use can be facilitated through better information about the state of water storage in the snowpacks, water bodies,and soil in headwater watersheds.

production during the warm and dry season, although warmer temperatures may increase production during the winter season. The carrying capacity of rangelands is very likely to change and become more variable, but the degree and rate of change is unknown.

Infrastructure

Climate change is expected to result in more extreme weather events, leading to increased flood severity, more frequent landslides, and increased variability of streamflow. Each of these changes increases the probability of damage to roads, bridges, trails, and other infrastructure. Developments in high-risk settings—such as rain-on-snow zones, coastal areas, and landscapes with unstable geology are most vulnerable. Such damage can have consequences ranging from relatively minor inconvenience (loss of recreational access) to major impacts (resource damage, destruction of property, and loss of life). The distribution and likelihood of infrastructure damage owing to climate change is not known and will remain very difficult to predict.

Existing dams, roads, bridges, culverts, campgrounds, and other infrastructure were originally designed assuming a fixed envelope of climatic variability to determine acceptable risk. Because this assumption is no longer valid (Milly et al. 2008), likelihood of failure is no longer known for the aging facilities. In addition, uncertainty in designing new facilities for acceptable risks is now greater. Determinations of acceptable risk will be more difficult, requiring scenario-based approaches to infrastructure planning, design, maintenance, and restoration.

The increased variability increases the premium on current, complete, and accurate snowpack and soil moisture information to improve streamflow forecasts at daily to seasonal time scales. Such data are used for early warning of floods and drought and are important for optimizing the management of storage and releases from reservoirs used for both water supply and flood control. Given that the past is increasingly less useful as a guide, it is becoming necessary to hedge against potential flooding, reducing the amount of water that can be kept in storage for later irrigation. Improved information reduces the amount of hedging necessary.

> The United States should develop and expand a variety of forecasting and predictive models and systems.
>
> – National Science and Technology Council, Subcommittee on Water Availability and Quality 2007.

Power Production

A growing U.S. population will continue to increase demand for electricity. This will add to existing water supply and quality challenges, since virtually every means of power production requires substantial volumes of water (fig. 17). Demand for hydroelectric generation, in particular, is expected to increase in the future because of its lower carbon emissions (Bates et al. 2008). As a result, additional generating facilities will likely be proposed on national forests, as these areas have the substantial volumes of water and vertical relief needed for hydroelectric facilities. This will include both large generating facilities on mainstem rivers as well as smaller high-head, low-flow facilities on small streams. Proposals to change the operation of existing facilities to benefit aquatic ecosystems may receive increased resistance if they substantially reduce power production.

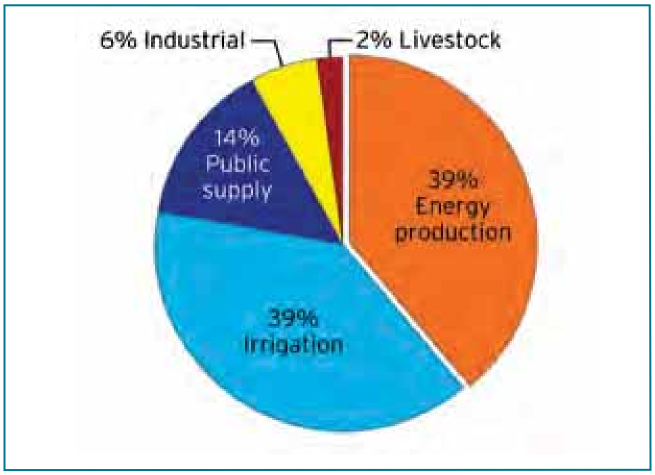


Figure 17—Percentage of U.S. water supply used for various purposes. The links between water and energy are fundamental. Energy production requires very large amounts of water, and the continued delivery of fresh water requires dependable, low-cost energy for pumping, distribution, and treatment. Water is used to produce all forms of energy, with consumption ranging from <0.001 gallons per kilowatt-hour (gal/kWh) (0.004 liters per kilowatt-hour [L/kWh]) for solar and wind, to 0.047 gal/kWh (0.178 L/kWh) for thermoelectric, to 18 gal/kWh (68 L/kWh) for hydroelectric. Conserving water translates to energy savings, but the reverse is also true, making water and energy conservation an inextricably interlinked challenge (Torcellini et al. 2003).

Recreation

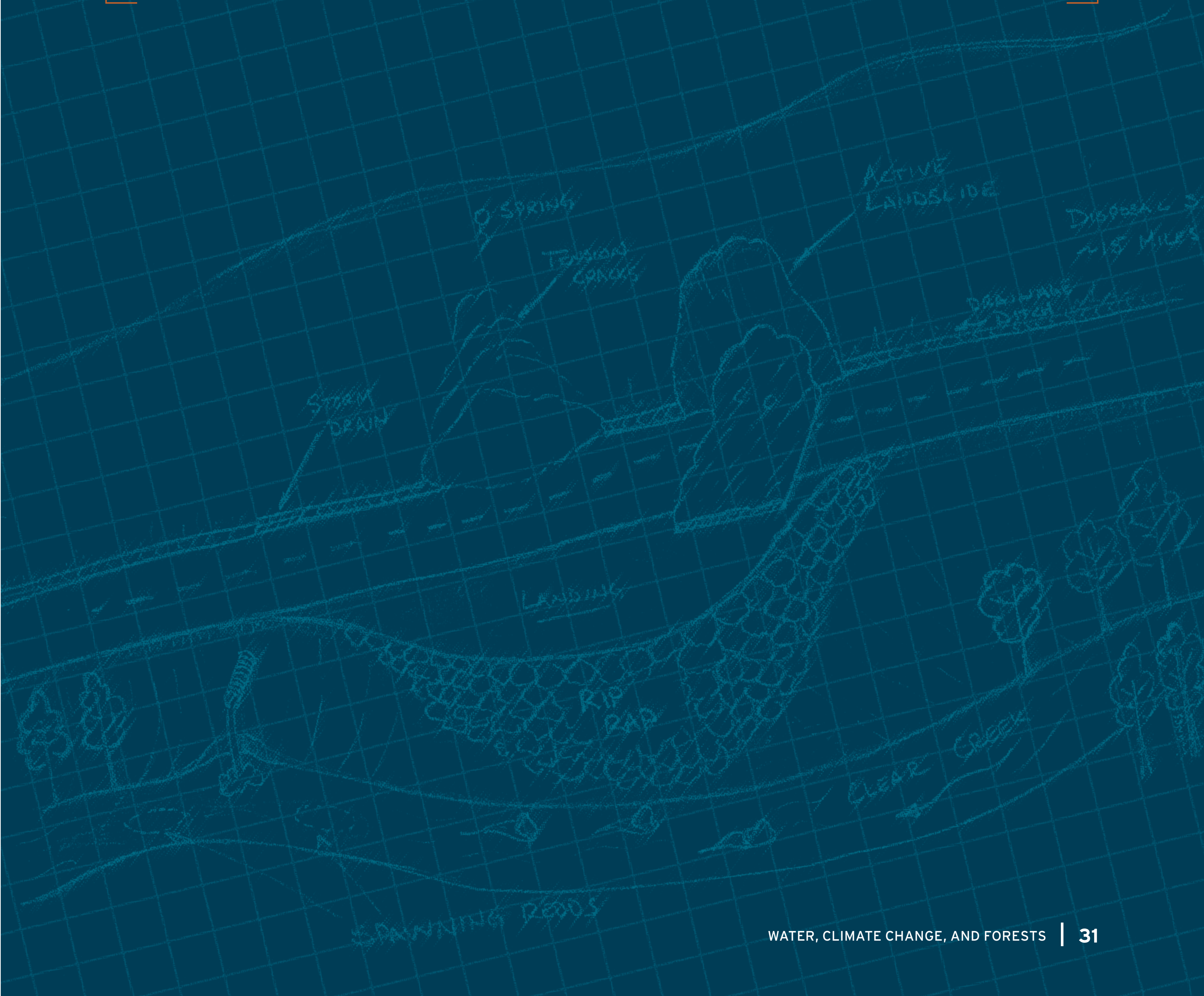
The majority of recreation activities on public lands, from camping and fishing to skiing and kayaking, are water related and vulnerable to climate change. Changes in water availability will affect recreation opportunities and shift patterns of use. Alpine skiing, for example, will decline in areas of receding snowpacks, and the demand for snow making, which requires local water and power supplies, will likely increase (Nolin and Daly 2006). Wildfire activity will increasingly constrain summer recreation activities. Fishing and hunting opportunities will shift with changes in the distribution of fish and game species. Recreation developments, such as campgrounds and ski areas, that are located in areas of high risk to flooding or landsliding will be damaged more frequently.

Summary of Hydrologic Effects

The effects of climate change on the Nation's water and aquatic resources will likely be profound and far reaching. Many forested headwaters—critical sources of abundant, cold, clean water—will be vulnerable to increased temperatures and to changing precipitation and disturbance patterns that will alter runoff timing and volume, sediment and nutrient loading, water quality, and aquatic habitats. Such effects will differ greatly in different areas and at different geographic scales and are challenging to predict with high degrees of certainty.

In some locations, hydrologic changes will lead to less water and increased need to protect habitats for imperiled aquatic species. Coupled with increased demand for water, these changes may result in a "perfect storm" of conflict. Fortunately, there is much we can do to respond. Adaptation actions taken now can minimize potential negative impacts and unlock new opportunities for the future. The primary objective of these adaptation efforts should be the maintenance and restoration of watersheds, with the goal of improving their resilience to climate change. Effective responses will require actions that address not only climate change, but all of the dominant stressors negatively affecting watersheds and their ability to provide desired watershed services. An outline of such an approach is provided in the next section.

MOVING FORWARD | **THINK** | COLLABORATE | ACT |



THINK | COLLABORATE | ACT

Adapting to Climate Change by Improving Watershed Resilience

Climate change is substantially altering many watershed functions and will threaten the stability of both social and natural systems. Scientists, land managers, and landowners alike must be prepared to understand, respond, and adapt to the anticipated effects of climate change. The most effective response to a warming world is a renewed commitment to the principles and practices of sound watershed management, with the objective of maintaining or improving watershed resilience. In the following sections, we lay a foundation for what can be done to improve watershed resilience in the face of climate change. Reponses have been grouped into three distinct categories: **think**, **collaborate**, and **act**. Because watersheds are affected by many different types of factors, the actions outlined here not only address the direct effects of climate change, but other key drivers as well.

Complex environmental and social problems like climate change must be adequately understood before they can be solved. Thus, thinking is a necessary first step toward effective adaptation. Although some effects of climate change are reasonably well characterized, many others are not. Consequently, we need to advance and share knowledge about water and climate change. Secondly, that knowledge will need to be incorporated into landscape and project-level planning. Both of these tasks will be extremely challenging and will require access to people with substantial expertise in Earth and aquatic sciences.

Advance and Share Knowledge About Water and Climate Change

With the substantial uncertainty surrounding the effects of climate change on water resources, improving watershed resilience will require managers to take action in an environment of great uncertainty. Thus, there is a strong need to advance the science and continually share new insights. Scientists and land managers will need to continue to cooperate so that the most relevant questions and data gaps are addressed, and scientific findings and perspectives are integrated into management. The following actions would help achieve those objectives.

Acquire Information About Watershed Resources at Multiple Scales

Land and water managers will need new information to respond effectively to shifting climatic regimes. They will need to track and evaluate changing watershed conditions, understand the effects of management practices, and forecast the quality, quantity, and timing of water supplies. In many areas, basic hydrologic data—precipitation, temperature, and streamflow—are lacking. Management decisions are particularly challenging because information on water quality, water temperatures, geomorphic processes, aquatic habitats, and biota is often not available. This need for reliable and relevant information will be amplified as more demands are placed on our water resources.

National efforts are underway to identify watershed data availability, needs, gaps, and protocols at various scales. A coordinated effort at multiple levels among federal, state, tribal, and local governments and with nongovernmental entities will help to achieve cost-effective solutions across boundaries. Scientists and managers will need to discuss the relative importance of different data, the extent and scale of need, options for acquiring the information, available resources, and willing partners. Means to store, analyze, and make available new information will also be necessary.

> Quantitative knowledge of U.S. water supply is **currently inadequate.**
>
> – U.S. General Accounting Office 2003

Expand Use and Application of New Technologies

Emerging technologies offer unprecedented opportunities to advance water resource knowledge and information. Some of the most promising ones include thermal infrared (TIR) imagery; digital temperature sensing (DTS); advanced automated samplers with telemetry; high-resolution digital topography; and spatially explicit, process-based hydro-ecological models.

The TIR imagery, for example, can generate thermal snapshots of entire river systems, allowing scientists and managers to understand and respond to the effects of a warming world (fig. 18). The DTS technology also monitors stream temperatures and can be used to characterize soil moisture over large areas (Selker et al. 2006). Such data could significantly improve the ability to forecast streamflows, predict changes in vegetation, assess threats to forest health, quantify wildfire risks, identify vulnerable and resistant landscapes, and provide early warning systems for threats to people, fish, and wildlife. It could also facilitate the implementation of more strategic and effective watershed management practices.

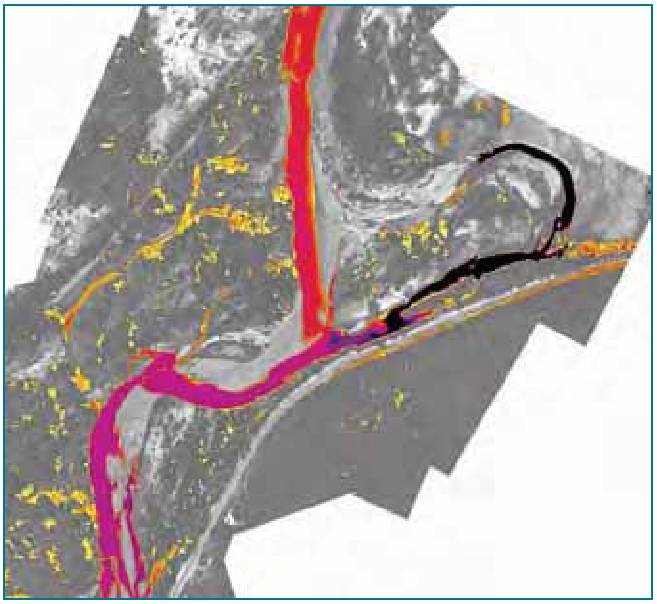


Figure 18—A thermal infrared image of Coeur d'Alene River, Idaho.

Advances in automated sampling and telemetry technologies are also providing important opportunities for wildland and urban water resource management. For example, stream and well monitoring stations linked via satellite telemetry can provide real-time information (Paulson and Shope 2007). Use of these systems could be expanded to collect and transfer hydrologic data to inform numerous activities that will be affected by climate change: water quality and supply management, flood warning, reservoir management, irrigation management, and hydropower generation.

New technologies are also enabling scientists and managers to quickly acquire some of the most important new data sets for watershed management, high-resolution digital models of topography, vegetation, and water bodies. Light Detection and Ranging (LIDAR), for example, can be used to create three-dimensional maps of channels and flood plains for entire stream networks (fig. 19) (McKean et al. 2008).

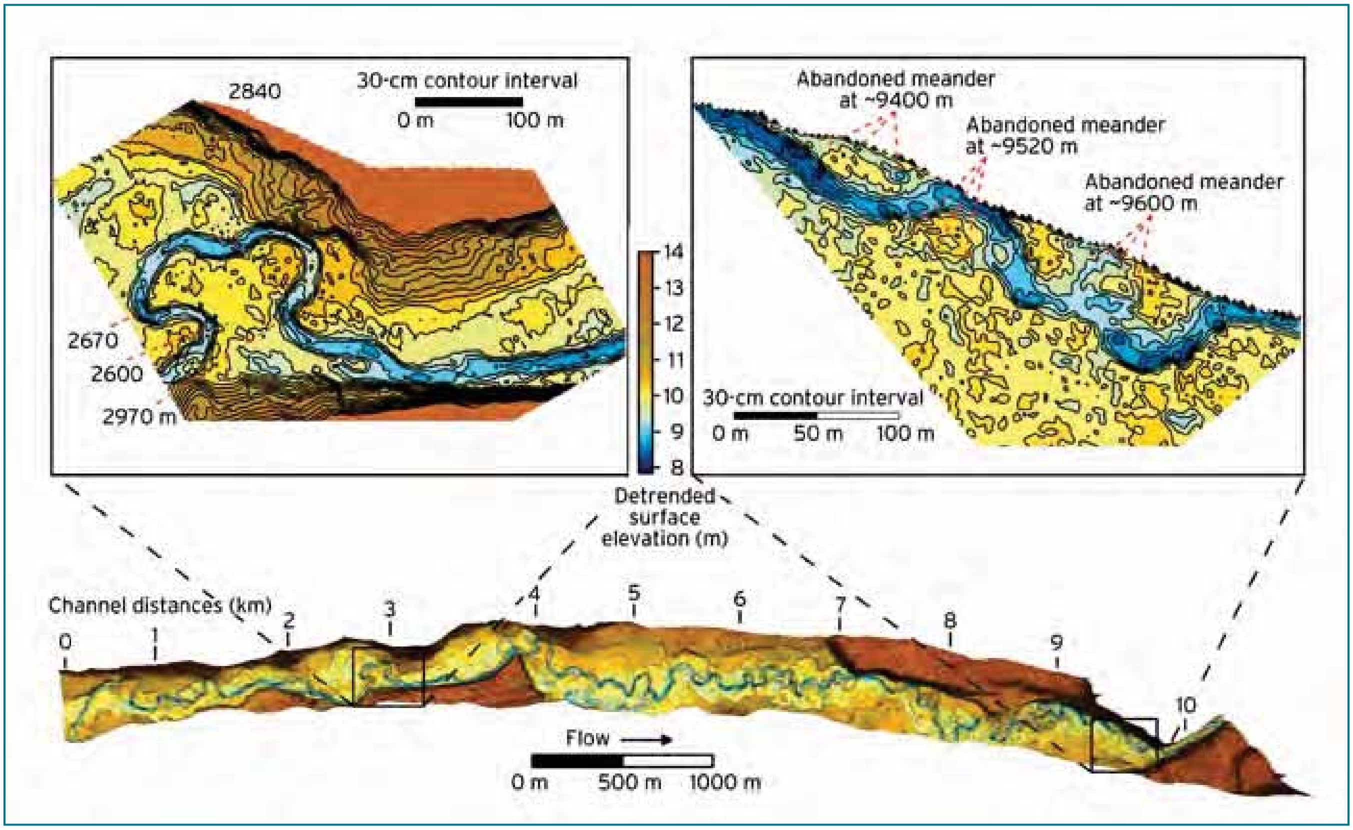


Figure 19—High-resolution stream channel and flood plain morphology of Bear Valley Creek, Idaho, obtained with the National Aeronautics and Space Administration's green LIDAR technology (McKean et al. 2008).

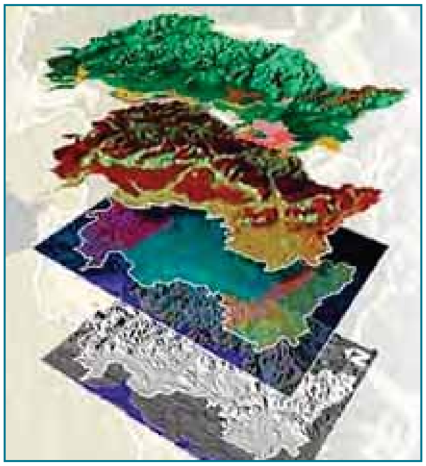


Figure 20—Conceptual image of process-based models that use multiple spatial data sets (e.g., climate, topography, soils, geology, land cover) to estimate the hydrologic behavior of landscapes under varying land-use scenarios, climatic conditions, and disturbance regimes.

Technological advances are also enabling scientists and managers to better and more quickly integrate and analyze these immense data sets to support land and water management decisions. For example, geographic information system (GIS)-based mathematical models can be used to predict important hydrologic changes under existing and potential conditions. The systems layer multiple data sets to build three-dimensional landscapes in which ecological, hydrologic, and climatic variables may be altered to test management alternatives and model outcomes (fig. 20) (Harvey 2007, Mitasova et al. 2006). These tools will be critical for scenario planning, water forecasting, restoration, and land use planning. An example is projecting changes in streamflow under different climate change scenarios, as shown in figure 21.

These new technologies could reduce present costs for soil and water resource inventories and monitoring, and provide broad geographic and temporal coverage. Expanded application of these technologies and collaboration with partners will enable scientists and natural resource specialists to improve the characterization and monitoring of water resources and better understand the processes controlling them.

Use the National Forest System and Other Public Lands as Learning Laboratories

Public forests and experimental research sites can make a significant contribution to understanding climate change and water. National forests typically encompass larger, relatively undisturbed areas, and often contain headwaters where water supplies and aquatic ecosystems are not yet influenced by upstream land and water uses. As such, they provide a favorable environment for assessing the ecological effects of climate change (US GAO 2007). Study sites and demonstration areas maintained on public lands allow scientists and managers to work together to increase our understanding of climate and ecosystems, evaluate management options, test solutions, and transfer knowledge to key stakeholders.

Experimental watersheds provide an especially important opportunity for advancing our understanding of the hydrology of forested watersheds, the effects of climate and vegetation change on water quality and quantity, and the impacts of natural and human disturbances. Many of these watersheds have long records of precipitation, streamflow, and other data and are thus uniquely positioned to address some of the most important questions facing us about climate change, water, and forests. (See box on page 36.)

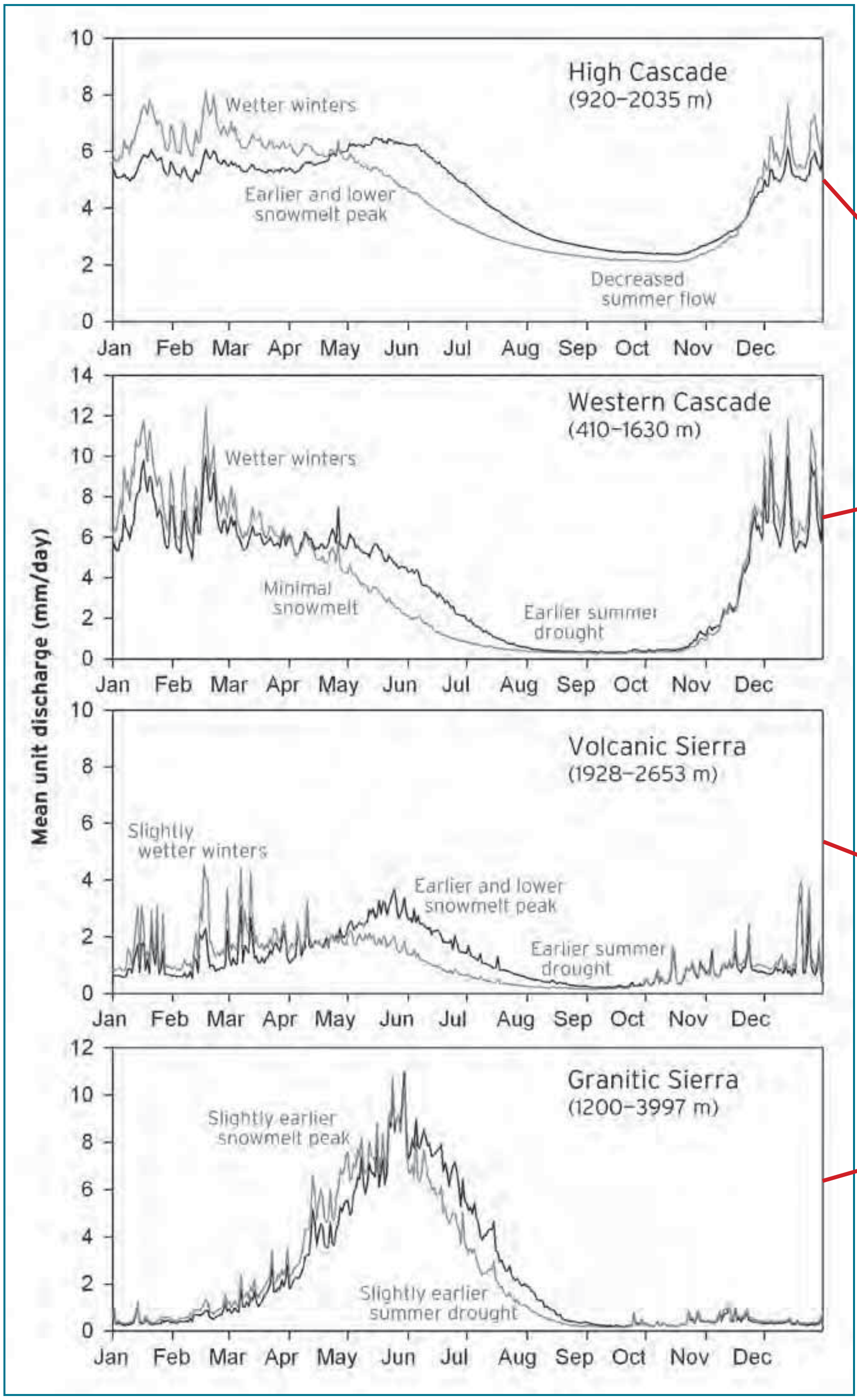


Figure 21—Process-based models can be used to assess streamflows under different scenarios. Here, model-based estimates of streamflow are provided for the current climate (black lines) and a projected future climate (grey lines) in diverse areas of the Pacific Coast USA (Tague et al. 2008). Streamflow response to climate change will differ among landscapes depending on dominant runoff mechanisms, which are often controlled by the geologic substrate.

Key questions that experimental watersheds can help answer in light of climate change

1. How are precipitation and air temperature changing in different locations, and how are these affecting water volume, timing, distribution, and quality?
2. How are changes in terrestrial hydrology affecting vegetation cover, types, and disturbance regimes, and how are these in turn affecting streamflows, surface and groundwater levels, and water quality?
3. How will changes in hydrologic regime and vegetation disturbance regimes alter sediment and nutrient inputs and stream channels?
4. At what rates are snowpacks, snowfields, and glaciers declining, and what will be the consequences for local flora and fauna and downstream ecology, hydrology, and geomorphology?
5. What are the most important gradients (such as elevation, distance into rain-shadow, aspect, latitude, longitude) driving patterns in climate change effects on water resources?
6. What are the most important pathways altering water quality, streamflows, soil erosion rates, surface and groundwater levels and aquatic habitats (pathways such as reduced precipitation, increased air temperature, increased disturbance severity and frequency, changes in infiltration, increased atmospheric deposition and evapotranspiration)?
7. How will changes driven by climate interact with the legacy of land management activities (such as harvest, road usage, fire suppression, grazing) to cause cumulative effects on water supply, quality, and timing and on aquatic habitats?
8. To what degree can forest management ameliorate climate change effects on streamflow, surface and groundwater levels, vegetation, wildlife, and aquatic and water-dependent ecosystems?
9. What are the most urgent adaptive changes needed in land, fire, and water management to ensure an adequate supply and quality of water both for people and for conservation of key aquatic species?
10. Where are the highest priorities for applying remediation to improve impaired waters and protect endangered aquatic species?

Integrate Climate Change in Planning

Analysis and planning have proven to be integral components of successful watershed management. These processes provide watershed and aquatic specialists the opportunity to evaluate impacts on water resources and to manage for their protection and restoration at project, watershed, national forest, and larger scales. Climate change greatly increases the importance of these efforts. It also adds some new dimensions to an already complex world. Existing analysis and planning frameworks now need to be expanded to include consideration of changes in watersheds and aquatic ecosystems owing to climate change and identification of measures to address them to the degree possible.

Specifically, effective planning efforts will require some of the following steps:

Set Priorities for Management by Watersheds

Watersheds are not equally valuable, nor are they equally vulnerable to adverse impacts from climate change. Setting management priorities can help to ensure that investments provide the greatest possible benefit. Priorities are best set at multiple geographic scales with multiple partners, and should address projected changes in climate. Otherwise, investments may not be effective in retaining or restoring critical, high-value watershed services.

Planning can also identify areas that warrant special protection or changes in management owing to their importance in capturing and storing water and supporting particularly valuable resources. Protection measures can be developed for individual projects, as discussed below, or in forest plans by applying protective prescriptions or land use designations.

Identify Water Uses and Needs

Future needs and demands for water can be identified through forest and community planning efforts. Specifically, the following questions will need to be addressed:

- What are the local and regional needs for water?
- How is climate change most likely to increase these needs or decrease the available supply or its reliability?
- Can water withdrawals from ground or surface water be developed or expanded in a manner protective of aquatic and water-dependent ecosystems under changing climatic and land use conditions? If so, where and how?

Sentinels of change: U.S. Forest Service experimental watersheds

For almost a century, the Forest Service has expanded and shared knowledge of wildlands and water. It conducted the first paired-watershed experiment on the Nation's forests beginning in 1909. Today, the Forest Service manages 15 experimental watersheds distributed across multiple biomes and climatic regimes. This network provides an unprecedented glimpse of the past—and unparalleled opportunities to grasp the consequences of climate change.

Hubbard Brook Experimental Forest

The Hubbard Brook Experimental Forest (fig. 22) in central New Hampshire has been a source of pioneering ecological research since 1955. It has the longest running precipitation and streamwater chemistry record in the United States, which has been critical to assessing ecosystem response to air pollution. These records are now being used by scientists to understand the implications and effects of climate change on Northeastern forests. Meteorological records dating back to 1955 show a consistent warming trend in mean annual air temperature. Winter air temperatures are warming more rapidly than summer temperatures and have greater variability (Campbell et al. 2007). In addition, snow water and snowpack depth have decreased (64 mm and 229 mm, respectively) in the last 50 years, and seasonal snowmelt appears to be occurring 10 to 17 days earlier.

Figure 22—Hubbard Brook Experimental Forest, New Hampshire.

Similar trends can be found in almost all of the biophysical records at Hubbard Brook. For example, phenology records suggest earlier onset of spring and a longer green-canopy period (Richardson et al. 2006), which together with changes in snowmelt timing could increase summer drought stress. Decreases in snowpack have also spawned interest in understanding the implications of increasing soil frost depth and duration on ecosystem processes such as nitrogen cycling. Scientists at Hubbard Brook are documenting and studying the impact of these climate change and variability indicators on ecosystem patterns and processes so that we can manage for resilient forest ecosystem services for the future.

Fraser Experimental Forest

In 2007, Fraser, Colorado, lost its recognition as the "Icebox of the Nation." Another location in the Midwest has shown colder temperatures in the recent record, and Fraser, in fact, shows a warming trend over the last few decades. This indicator of a changing climate in the Rockies is overshadowed by much more dramatic environmental changes. The forests around Fraser and across an increasing portion of the West are being affected by an unprecedented mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestation (fig. 23).

Figure 23—Trees killed by mountain pine beetles in Fraser Experimental Forest, Colorado.

The warmer winter minimum temperatures recorded during the past few decades, coupled with drought and aging forest stands have synchronized bark beetle outbreaks that extend from Colorado to British Columbia. Current beetle activity is predicted to kill nearly all the mature lodgepole pine in Colorado.

Forest Service researchers at the Fraser Experimental Forest (FEF) have been monitoring climate, snowpack, streamflow and vegetation since the 1940s. Research watersheds at Fraser are uniquely positioned to quantify the magnitude of this large-scale disturbance on water supplies from the high-elevation forests that supply water to much of the interior West. As the climate changes, forests altered by disturbances from insects, diseases, wind, and fire may dramatically affect the timing, amount, and quality of water flowing from forests. Long-term data from sites like FEF provide opportunities to detect, predict, and respond to these critical changes (fig. 24).

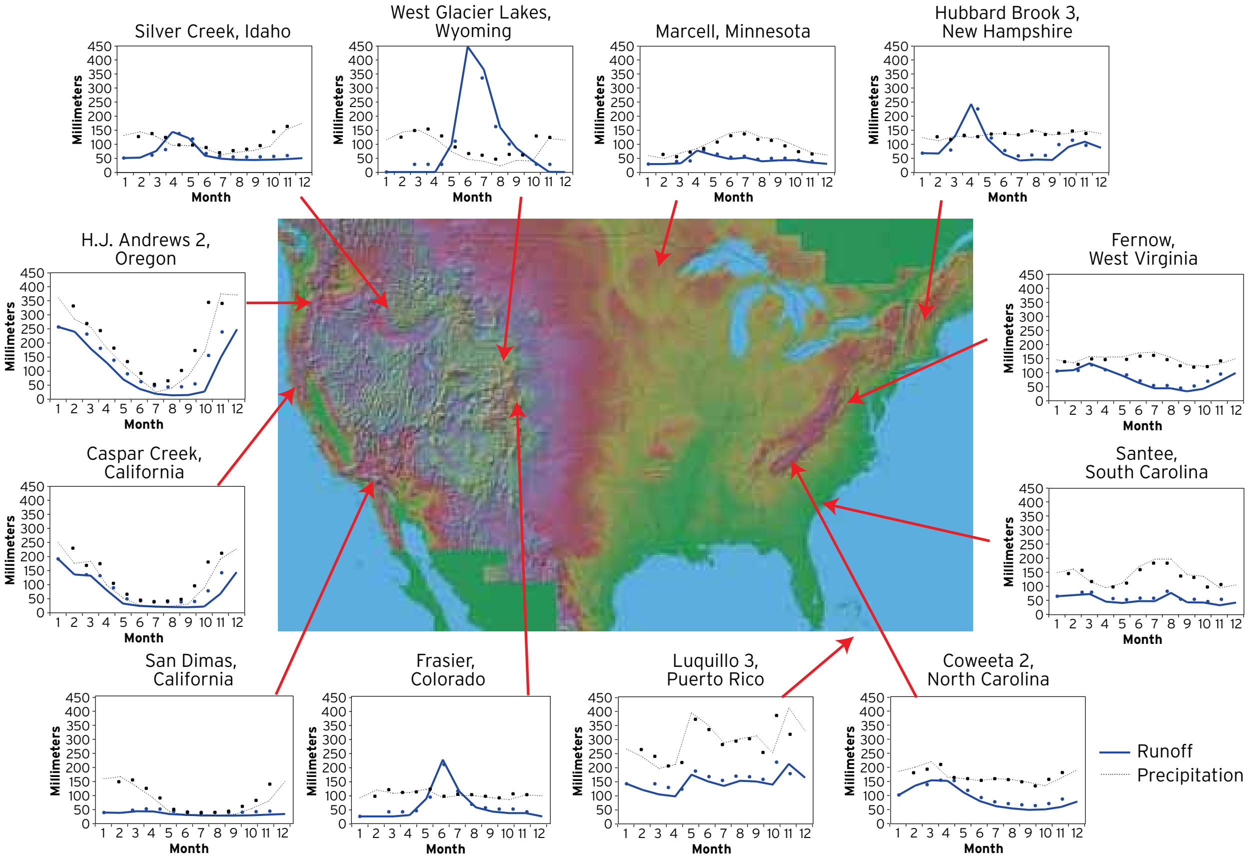


Figure 24—Average monthly precipitation and runoff are shown for each of the long-term stream gages at U.S. Forest Service experimental watersheds. These sites provide unparalleled opportunities for research and monitoring of forest management effects and climate change across a broad range of hydrologic regimes (Ziemer and Ryan 2000).

Specify Effective Protection Measures

Project-level planning is often the key to developing site-specific measures for protecting or improving aquatic and riparian resources. Measures are based on field investigation, modeling, and evaluation by interdisciplinary teams. These teams are responsible for planning, design, and implementation of land management activities such as timber and vegetation management, prescribed fire and fuel treatments, mineral and energy development, recreation management, range management, watershed restoration, and fish habitat improvement. The “Act” section of this report includes examples of protection measures for different management categories.

National forest management planning efforts have led to the development and application of analytical tools to assist watershed and aquatic specialists, such as:

- Watershed analysis (USDA and USDI 1995)
- Hydrologic condition assessment (McCammon et al. 1998)
- Watershed condition assessment (USDA FS 2009)
- Groundwater handbook (USDA FS 2007b)
- Roads analysis: Informing decisions about managing the National Forest transportation system (USDA FS 1999)

Climate change calls for two important additions to the planning toolbox: (1) assessment and integration of the uncertainty of hydrologic change into analysis and planning, and (2) assessment of watershed vulnerability to climate change.

Assess and Integrate the Uncertainty of Hydrologic Change

Existing predictions of the effects of climate change differ widely, and predictions made at a regional scale do not necessarily apply to all locations in the region. Climate change science is advancing rapidly, but uncertainty is expected to persist well into the future. To accommodate variation and uncertainty, scenario-based planning will be a key tool for assessing plausible outcomes and related options.

Scenario-based planning considers a range of potential ecological trajectories, and assesses the benefits and risks associated with an action or set of actions. It can be used in the design of contingency plans for unknown events or impacts. Such analyses may be used to provide decisionmakers with relevant information about specific impacts at a variety of spatial scales.

Conduct Watershed Vulnerability Assessments

Watersheds differ greatly in their vulnerability and resilience to climatic changes. Distinctions between the watersheds can be made by land management specialists based on a variety of important factors that differ at management-relevant scales: values at stake, exposure to climate changes, landscape sensitivity to the changes, adaptive capacity, and land-use allocations, among others. To design effective adaptation measures, important differences and distinctions are ideally best assessed by managers at management-relevant scales, especially at the subbasin, watershed, and subwatershed scales (USGS and NRCS 2009).

Despite the uncertainty regarding what hydrologic changes will occur, managers will be called upon to maintain the flow of ecosystem services from forested watersheds. Projected hydrologic changes in some watersheds may be minimal, but management to improve resilience may be high priority because of their increased importance as refugia for species or for their ability to sustain flows for downstream uses. Change in climate, added to past and existing stressors, will result in irrecoverable loss in some watersheds. Because time, funding, and personnel are limited, it is critical for managers to direct resources to watersheds where the investment has the greatest likelihood of maintaining desired outputs at the least cost. The essential question for managers is: In which watersheds will actions taken to maintain or improve watershed resilience be most useful? Watershed vulnerability assessments are the means to address this vital question.

More specifically, watershed vulnerability assessments are a tool that will provide managers with answers to the following questions:

- What key ecological services are provided by the watershed(s) in question and what is their local, regional, or national significance?
- What watershed processes, such as snow accumulation and streamflow generation, are most likely to be affected by climate change?
- What resources are most vulnerable to these changes and the land and water-use changes likely to accompany them? For example:
  - Which important aquatic species may be at risk of population decline or habitat loss because of these changes?
  - Which areas are most likely to be affected by changes in water supply or demand?
  - In which watersheds is the risk to these resources greatest?
  - Which watersheds are high priorities for management to sustain desired hydrologic functions under changing climate?
  - Which watersheds may serve as climate change refugia because they are expected to experience the least impact?
- What management actions may reduce the unwanted effects of climate change, protect high-value watershed resources, or increase watershed resilience?
- What measures can be used to detect and track evidence of climate-related change as early as possible?

National-forest-scale assessments could be conducted as part of the Land and Resource Management Planning process. In almost all cases, these assessments would need to be tied to broader bioregional analyses that capture the geographic range of the ecosystem services considered. They could also be used to update existing watershed analyses and develop geographically specific adaptation strategies. Existing and readily gathered data and information will support preliminary vulnerability assessments in some areas, but needed information is not available for many locations. This represents an important data gap.

MOVING FORWARD | THINK | **COLLABORATE** | ACT

THINK | COLLABORATE | ACT

Adapting to Climate Change by Improving Watershed Resilience

After thinking, direct action, of course, will be needed to ameliorate the hydrologic effects of climate change. Experience over the past few decades has demonstrated, however, the importance of another key step before action: collaboration. Watersheds often have multiple owners who frequently have varied interests and values. Consequently, multiparty collaborative efforts are generally necessary to effectively manage watersheds. Climate change intensifies the importance and complexity of these efforts. The Forest Service *Strategic Framework for Responding to Climate Change* recognizes this need, and prioritizes alliances and collaborative partnerships as a guiding principle for integrating climate change into the core mission of the agency (USDA FS 2008).

The following section describes a collaborative, participatory approach to adaptation based on connecting people, their lifestyles, and land-use decisions to their effects on critical watershed services.

Collaborate to Protect and Restore Watersheds

Watersheds have multiple owners with multiple interests. Only through collaborative efforts can watersheds be restored and managed to be resilient in the face of climate change. Watershed resiliency is not a goal unto itself. It is a means to an end, namely protecting the flow of water-related ecological services to and from our watersheds. Meeting this goal will require broadening of collaborative efforts internally, externally, and globally. Assessing, planning, funding, and implementing efficient and effective strategies to maintain and improve watershed resiliency will require a renewed commitment to collaboration. The Forest Service expects that its work will be conducted using an integrated, participatory approach. For example, interdisciplinary teams comprising people with skills in diverse disciplines (e.g., geology, soils, hydrology, fisheries, engineering, ecology, forestry) are used to design and implement projects. This form of internal collaboration has resulted in more integrated watershed projects. Increasingly, however, these efforts need to be expanded to engage a broad range of stakeholders throughout all phases of resource management. Developing, and more importantly maintaining, these types of partnerships requires substantial effort, and strong communication and commitment from natural resource managers.

Connect Water Users and Watersheds

Global water consumption by agricultural, domestic, and industrial sectors has increased dramatically throughout the 20th century. Postel et al. (1996), for example, estimated that humanity has appropriated over 50 percent of the renewable freshwater runoff that is geographically and temporally accessible. Projections indicate that water use will grow by 133 percent over the next 20 years (UNEP 2008). Personal demand for water is expected to increase with elevated global temperatures—a temperature increase of 1 °C may cause typical urban residents in the United States to increase their daily water use by as much as 11 liters (Protopapas et al. 2000). At the same time, soil degradation across the globe from forest clearing and agricultural pressures has resulted in increased runoff, increased erosion, and a reduced capacity to store water. Already nearly every region of the United States has experienced water shortages or stress owing to withdrawal rates and demands that exceed availability (Alcamo et al. 2003). Water resource challenges, exacerbated by a rapidly changing climate, call for innovative collaboration in determining where water is captured, stored, and released for each watershed and how that water is used.

The Forest Service has an opportunity to collaborate with the domestic and irrigation water providers; other federal, state, city, and county agencies; and a wide array of nontraditional stakeholders to increase public awareness of the ecosystem values of water, its source, and the impact of land use decisions on water quality and water supply. Increasing public awareness of their community's connection to water and watersheds, and the potential influence of climate change on the water-related ecosystem services they enjoy is challenging for several reasons. First, the scale of climate change disruption has the potential to be large, but the current and localized effects in many areas appear nonexistent to many. Watershed ecosystems are poorly understood by the public and seem geographically removed. The location of water use may also be far from where people live, especially for energy and agricultural production. Some geographic areas and populations may have experienced water scarcity in the past, which will aid in understanding the current problem and the link between healthy watersheds and the continued provision of this critical resource.

Identifying the most effective and appropriate behavioral changes is critical to public awareness. For suggested conservation measures to find traction with the public, individuals need to believe their choices are consequential, positive, and contribute to a larger goal or purpose. By tying water-related behavior changes to a specific watershed, and in turn linking that watershed to the theme of healthy, resilient forests, conservation programs will have a greater chance of success. One successful conservation campaign, launched in the summer of 2006, extended into people's lives with eye-catching signs, off-the-wall displays, and surprise "guerilla" tactics. The campaign successfully engaged the community in a shared awareness of water conservation and resulted in significant reductions in water use (fig. 25).

Courtesy of Denver Water

Figure 25—Denver's Use Only What You Need water conservation campaign.

Water conservation is one of the most cost effective and efficient ways to address water supply limitations. By using water more efficiently, supplies can be preserved, money and energy can be saved, and fish and aquatic ecosystems can be protected. Forest Service managers can lead by example, reducing the "water footprint" of Forest Service facilities and encouraging others to join them. Opportunities for water conservation exist wherever water is used, from domestic consumption (fig. 26) to agriculture to energy-related water use. The opportunity to improve water efficiencies and reduce demand through collaboration with nontraditional partners, such as hospitals, utilities, manufacturers, and other corporations, is beginning to emerge. Business entities are currently very interested in reducing their often significant water footprints, so as to simultaneously reduce cost, long-term strategic business risk, and carbon footprint. The mutual benefits are considerable and far reaching,

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Figure 26—The arid West has some of the Nation's highest per capita residential water use because of landscape irrigation. Xeriscaping and landscaping with native plants can attractively take the place of water-intensive lawns. Block pricing of domestic water can provide a powerful cost incentive for homeowners to reduce their water use and rethink the choices that require large water inputs.

yet localized and easily quantified, especially when a downstream corporation is drawing water from an upland watershed. Agriculture and energy interests should be the highest priority for partnership development, because their use of water is proportionately high (fig. 17), and significant opportunities for conservation exist.

Link to Research and Adaptive Management

New technologies provide enhanced access to an ever-expanding amount of information, and individuals' ability to synthesize, organize, and think critically about this information is more important than ever. Savvy and adroit leaders and staff understand the need to constantly gather information while maintaining their ability to make critical decisions and, in some cases, take the risks necessary to move projects forward in the midst of imperfect information or overwhelming choices.

Managing with uncertainty requires a commitment to adaptive management—a flexible, participatory management approach informed by scientific application, monitoring, and evaluation, resulting in careful adjustment. Collaboration applied to research can foster demonstration projects that bring beneficiaries and communities of practice together around management issues. Like adaptive management, participatory research is a process that involves testing new ideas, observing or monitoring results, evaluating success, and adjusting for improvement. Rather than involving only the land manager or resource professional, it engages a broader network in the iterative learning process—those who would be affected by advances in the research or management, those who use the watershed outputs being studied, or those who are designing similar methods of inquiry. In this way, science and land management are improved within a social context, and lessons are more widely shared.

Demonstration projects that integrate science, management, and learning in this way can help create a shared understanding of how land management activities can ameliorate the adverse impacts of climate change. Private landowners can engage in and learn from participatory research on public lands and become better informed about how their management actions—or inaction—will affect the delivery of ecosystem services as local climates change.

Improved communication is central to successful participatory research. In addition to publishing research results at the end of a demonstration project, scientists and managers must engage stakeholder participants in research design and decisionmaking and share observations and results through workshops, field visits, social networking, and ongoing dialogue.

Engage the Community

Over the past few decades, strong collaborative partnerships have developed around watershed issues in all parts of the country. Some of the most important collaboration occurs locally, because that is where watershed management practices are implemented. Several examples of these efforts are referenced in this report (for example, see the spotlights on the Verde River and the bottomlands of the Mississippi (app.). Partnerships at watershed and river-basin scales will assist effective planning and actions to improve watershed resilience on the ground. Improvement strategies that are cooperatively planned result in opportunities for each of the partners to leverage limited funding for improvement and assist in allocating those funds to the highest priority areas.

In the formulation of watershed management plans, both the attributes of the soil and water resources and the socioeconomic factors that affect land use decisions must be understood. The effects of various land-use practices on maintaining the long-term quality of soil and water resources in particular should be taken into account. Watersheds are connected from the ridges to the estuary or coral reef. Impacts incurred in one area can have cascading effects in other portions of the watershed. For example, loss of riparian forest in the lowlands can cause water temperature increases above that in which cold-water aquatic species will migrate to the uplands, thereby limiting nutrient enrichment in upland forests. Only through integrated, participatory approaches to watershed management, in which an understanding of the inherent capacity of various watersheds to produce resources and the factors limiting resource production are understood by all stakeholders, will successful and sustainable adaptation and mitigation strategies be developed and implemented. Our ability to understand and implement land-use decisions in line with that inherent capacity will determine how resilient a watershed will be in response to climate change.

The connected nature of watersheds necessitates the inclusion of wildland, agricultural, rural residential, commercial, and urban populations in watershed management decisions. Collaboration in rural and agricultural watersheds may involve different partners than wildland areas, but the concepts and utility of the process are the same. State and local governments, federal agencies, tribes, corporations, developers, health and environmental organizations, regional water managers, city planners, landowners, and others share common interests in watershed resources. Establishing partnerships with these groups is necessary to expand the reach of watershed stewardship to urban areas. Cities, which were once overlooked ecosystems within the traditional land management framework, are home to half of humanity and represent unique ecosystems critically relevant to climate change, watershed resiliency, and biodiversity protection. Creating and fostering durable relationships among diverse interests and organizations will increase the knowledge and capability of local groups to implement coordinated actions in response to climate change.[1]

[1] Examples of resources for locating watershed partnership organizations include the Environmental Protection Agency's Adopt Your Watershed (http://www.epa.gov/owow/adopt/), the National Watershed Network (http://ctic.purdue.edu/kyw/nwn/nwn.html), and the River Network (http://www.rivernetwork.org).

A study by the Trust for Public Lands and the American Water Works Association revealed that a 10-percent decrease in forest cover in a watershed can increase water treatment and chemical costs by as much as 20 percent (Ernst 2004). Many cities, including New York, Boston, Denver, and Portland, Oregon, recognize the value of their local forested watersheds and protect large tracts of land to sustain clean water supplies. Protecting these lands is a more cost-effective way to prevent pollution and maintain clean water sources than expanding water treatment plants and investing in new infrastructure. Land managers can help build a better case for watershed stewardship through land conservation and restoration efforts that clearly demonstrate the social link between healthy watersheds and human well-being.

Trees in cities are also important. With inner-city temperatures rising—a phenomenon known as the heat island effect—adding trees for shade serves the dual purposes of cooling ambient air temperatures and reducing the production of harmful ground-level ozone. Cooler temperatures reduce peak summer energy demand, thus reducing the demand for extraction of water to produce that energy.

Improving the extent and health of interconnected natural ecosystems and waterways through urban, suburban, and agricultural areas can serve multiple purposes in our climate change mitigation and adaptation toolbox. Increasing tree canopy and adding biofilters helps reduce total annual stormwater runoff. For every 10 percent of tree cover added to a community, annual stormwater runoff can be reduced by as much as 2 percent (Wang et al. 2008). Collaboration in rural and agricultural watersheds may involve different partners than wildland watersheds, but the concepts and utility of the process are the same. Lands converted from natural ecosystems to residential, commercial, and agricultural uses often have altered water bodies and aquatic habitats, produce greater surface runoff and more nutrient enrichment, and have less shade along streams. Urban and suburban communities alike are gaining interest in urban forestry as they recognize the role of tree canopies in reducing atmospheric carbon dioxide, improving watershed health, and enhancing quality of life and neighborhood economic value for local people.

Finally, not all watersheds or portions of watersheds are of equal value. As climate change alters temperatures and the amount and timing of precipitation and streamflow, protecting and restoring key portions of the landscape that capture, store, and slowly release water will be critical to maintaining species migration and survival. As climate change redefines traditional species' habitat, critical areas for conservation of watershed processes and biodiversity will be highly valued. Because public lands alone cannot be expected to meet all the needs of society, public-private partnerships are vitally important to ensure that key portions of watersheds are protected. In these cases, protection can be provided through a variety of options including deployment of conservation practices, establishing conservation easements, public purchase of the most critical lands, and developing ecosystem markets. Identifying and setting priorities for protection is best accomplished and supported through a collaborative process.

Link Water From Healthy Watersheds to Markets

As described earlier, ecosystem services are the benefits that people obtain from the natural environment. When an economic value is placed on a natural asset, it sets a framework for establishing an ecosystem marketplace. Among other things, these markets connect natural assets to beneficiaries who are willing to help pay for their stewardship (Collins and Larry 2007). Perhaps the most advanced market is for carbon sequestration. The U.S. voluntary carbon market grew by 240 percent from 2006 to 2008 (Hamilton et al. 2008). The growth of this market reveals that markets are influenced by environmental interest and economic goals. Experience also shows that investors are most attracted to ecosystem markets that have universally accepted standards. Attractive markets are also internationally fungible and feature tradable units, legal and financial accountability, an insurable product, and a scalable solution (http://www.fs.fed.us/ecosystemservices/).

Collaborative efforts are needed to increase our appreciation of the value of water from healthy watersheds. Highlighting the value of water will help land managers weigh land-use decisions such as the tradeoffs of maintaining intact forests to protect watershed values versus the commercial value of the timber resources if they were harvested and sold. A thorough valuation of the role of healthy watersheds in providing water-related ecosystem services may be used to make management and policy decisions in the near future.

Limited markets currently exist for water quality and quantity, although these markets and others for wetlands and biodiversity are expected to expand. By putting nature's assets on the balance sheet, new market opportunities can drive investments in land stewardship and restoration. Markets can also provide incentives for private landowners to protect or restore their land for the ecosystem services it provides. In many cases, investments in ecosystem protection and green infrastructure rehabilitation are more cost-effective alternatives to building new or improving the efficiency of existing infrastructure designed to meet the same goals.

The Forest Service can play a role in advancing ecosystem markets by implementing land management projects that demonstrate market-based concepts, supporting and promoting research that informs market development and improves market confidence, and developing partnerships and knowledge networks that lead to collaborative innovation and information sharing. It can also lead by making use of appropriate opportunities to demonstrate and share the values of forest watershed resources in producing clean water and in creating healthy aquatic habitats. The spotlight on building an ecosystem marketplace for Chesapeake Bay (app.) describes a collaborative effort to advance ecosystem markets for land stewardship activities that improve the health of the bay.

Employ New Methods that Facilitate Collaboration

Technological advances provide opportunities for natural resource professionals to improve collaboration and communication within the professional community and with the public. The progressive computer age is shaping how people share and consume information. Webinars have become a preferred education tool, social networking sites are a business mainstay, and podcasts are now a customary means of communication. Use of new technologies can help individuals and organizations share information and expand networks to learn from and reach a broader constituency.

However, new technologies provide enhanced access to an ever-expanding amount of information, making individuals' ability to synthesize, organize, and think critically about this information more important than ever.

Collaborate Globally to Support Sustainable Forests

Beyond U.S. borders, there is a need to advance and support land management planning and actions in developing nations that mitigate climate change, foster sustainable development, and promote watershed resiliency. In some parts of the world, climate-change-induced effects on water resources are already affecting lives and livelihoods, especially on islands and in coastal environments experiencing sea level rise and increasing storm surges (fig. 27). Worldwide, about half of all jobs are associated with water-dependent resources such as fisheries, forests, and agriculture (UNFAO 2004). Freshwater aquaculture is the fastest growing food production sector.[2]

Figure 27—In the winter of 2007 and again in 2008, coastal communities throughout the Federated States of Micronesia (FSM) experienced abnormally high tides that flooded homes, washed out beaches, and undercut and damaged roads and other infrastructure. Such events are expected to become more frequent and destructive, as sea level rises and storms intensify.

Forests represent tremendous opportunities to sequester carbon, whereas the loss of forests contributes additional CO_2 to the atmosphere. Reforestation of degraded areas and protection of existing forests worldwide offer the potential to reduce climate change effects (fig. 28).

[2] Globally, freshwater aquaculture has increased an average compounded rate of 9.2 percent per year since 1970, compared with only 1.4 percent for capture fisheries and 2.8 percent for terrestrial farmed meat production systems. Demand for freshwater fish will expand because of increasing human population and changing food preferences (Millennium Ecosystem Assessment 2005).

The U.S. Forest Service International Programs (IP) illustrate collaboration at the global scale. As illustrated in the box below, IP assists international partners in taking both adaptive and mitigation approaches that address climate change effects. International policy discussions on climate change have recently become more focused on the role of forests and grasslands in greenhouse gas production. Forest managers can support these efforts by collaborating with international partners in protecting forests from deforestation and degradation.

U.S. Forest Service International Programs: climate change efforts

With more than 100 years of experience managing national forests and grasslands, the U.S. Forest Service has valuable expertise to contribute to water and climate change in the global context. The Forest Service and developing countries share similar pressures to conserve natural resources without impeding economic growth and opportunities. Through its International Programs (IP), the agency is well positioned to assist other nations as they face forest-related climate change challenges.

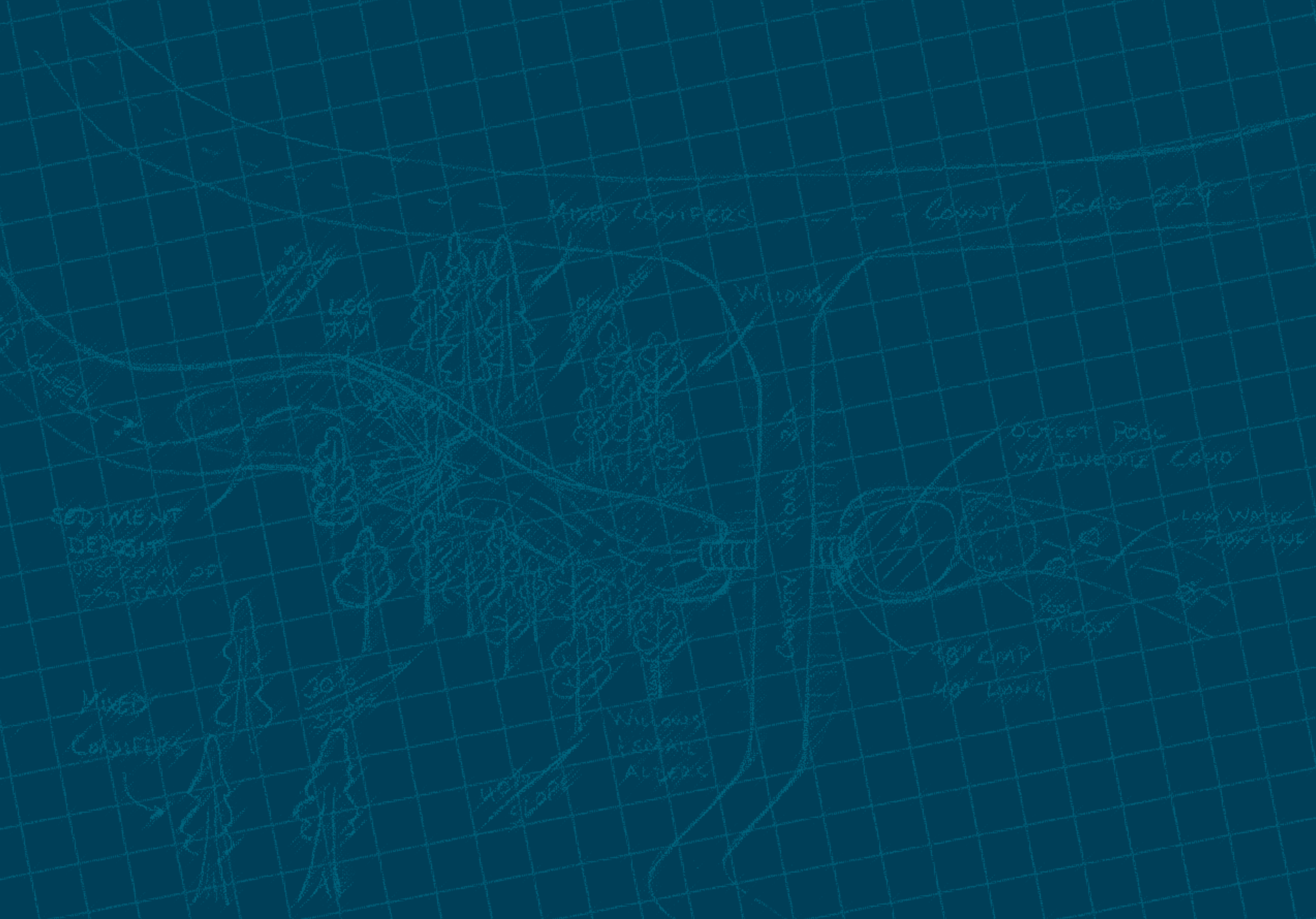
The IP has undertaken climate change initiatives with three primary components: reducing deforestation and land degradation, policy engagement, and technical cooperation. The scope of IP climate change efforts is worldwide, with cooperative programs on five continents. Forest Service IP employs a variety of tools and approaches to meet the goals of developing capacity, strengthening institutions, and developing economic alternatives to nonsustainable harvest and management practices. The program collaborates with other governments, nongovernmental organizations, communities, and private stakeholders to contribute technical expertise, develop and provide trainings, and participate in forest management and policy discussions to promote ecological, social, and economic sustainability benefits.

Figure 28—Deforested area on the island of Yap, Federated States of Micronesia, where soil productivity is completely degraded because of the removal of forests and the loss of critical organic layers. Runoff and soil erosion from these areas is greatly accelerated over natural conditions.

Examples From Eight Countries Where IP Is Engaged in Forest and Climate Change Activities:

- In Mexico, IP supports efforts to stop deforestation in areas that are critical to watershed-related ecosystem services.
- Liberia contains over 40 percent of the remaining closed-canopy rain forest in West Africa. IP works with the Government of Liberia to reorganize its forest service and forestry sector.
- In the Congo Basin, work is underway to increase local, national, and regional natural resource management capacity and improve knowledge of a poorly understood region.
- IP has collaborated with Russian partners to promote sustainable forestry practices and address forest health issues and invasive species. The partnership with the Russian Federal Forest Service focuses on combating illegal logging and forest fires.
- In Indonesia, IP provides assistance to manage and conserve forests at a landscape scale, and to improve fire response and control.
- In Jordan, technical assistance is provided to support Bedouin communities on community grassland improvement projects.
- IP works with forest technicians, managers, and supervisors in the Brazilian Amazon to apply forest management principles and reduced-impact logging methods.
- In the Central Highlands of Vietnam, IP is providing technical assistance to a "payments for ecosystem services" program to limit sedimentation to a hydroelectric facility by maintaining watershed forest cover and land uses.

MOVING FORWARD | THINK | COLLABORATE | **ACT** |



THINK | COLLABORATE | ACT

Adapting to Climate Change by Improving Watershed Resilience

Water resources will be affected significantly—and in some cases severely—by climate change, but temporal and spatial impacts will differ considerably across regions. There is substantial uncertainty regarding some of these impacts, but there is a very real need and opportunity for us to act. Informed and collaborative actions taken now can enable people to moderate future impacts or exploit benefits caused by climate change. Focusing management actions on improving and sustaining watershed resilience is a sound response to climatic change (US GAO 2007, Williams et al. 2007).

The details of managing for watershed resilience will differ depending on the landscape and the needs of surrounding communities. Objectives and activities will depend on dominant watershed processes, key ecosystem services, principal threats to those services, and social needs and values. Watershed stewardship practices—applied more extensively, strategically, and in some new ways—will improve watershed resilience and ecosystem services. This section presents two broad themes with many associated actions that can improve watershed resilience: (1) implement practices that protect and maintain watershed processes and services, and (2) restore degraded watershed processes.

Implement Practices That Protect and Maintain Watershed Processes and Services

More than a hundred years of land management and use has resulted in a wide range of watershed conditions on national forests and grasslands. Livestock grazing and timber management, road construction, mining and energy development, recreation facilities placement and operation, permitted water uses, and fire suppression activities all began before their influences and impacts on watersheds and aquatic systems were fully recognized. The Forest Service adapted by developing procedures, methods, and controls to protect water quality and other watershed resources. Water resources protection on lands managed by the Forest Service now is focused on best management practices (BMPs), which are considered the most effective means of preventing or reducing the amount of pollution by nonpoint sources to a level compatible with water quality goals.

Protection measures are applied to all Forest Service management activities, and most states have a codified set of BMPs that apply to forest management activities. Some of the following measures can be implemented at the project scale, and some are applicable to watershed, or forest, and other broad-scale planning efforts. The nine management areas and affiliated activities highlighted here include those measures most closely connected to watershed resilience as an adaptation to climate change.

Vital signs of a healthy, resilient watershed

A healthy, resilient watershed provides a sustained flow of desired ecosystem services over the long term. It resists and quickly recovers from disturbances such as floods, fire, and insect outbreaks.

Key watershed processes and functions, such as the following, occur at the desired rates and in the desired locations.

- Capture and storage of rainfall
- Recharge of groundwater reservoirs
- Minimization of erosion and protection of soil quality
- Regulation of streamflows
- Storage and recycling of nutrients
- Provision of habitat for native aquatic and riparian species

– Adapted from: Sprague et al. 2006.

Management Domain: Aquatic Habitat Biodiversity and Water-Dependent Ecosystems

Nearly all Forest Service management activities have the potential to affect habitats of aquatic and riparian species. These habitats range from large river systems and associated tributaries that support anadromous fish, to lakes and streams where warm water species flourish, to small or isolated springs and wetlands that support rare or endemic invertebrate species. Managers can consider how actions might impact these habitats, and implement practices to protect them.

Aquatic Ecosystems: Practices to maintain and improve watershed resilience

- √ Minimize temperature increases by maintaining well-shaded riparian areas and limiting groundwater withdrawals.
- √ Protect and restore longitudinal connectivity of stream systems to provide species with access to habitats that may be disconnected by changes in flow regime.
- √ Improve lateral channel-flood plain connectivity where human disturbance has isolated channels.
- √ Ensure that fish have access to seasonal habitats, such as off-channel or cool-water areas.
- √ Protect and restore riparian near-stream habitats and wetlands.
- √ Minimize ground disturbance and land-use changes that reduce groundwater recharge, and implement BMPs that encourage groundwater recharge from impervious and disturbed areas.
- √ Disconnect road drainage from stream networks to restore natural patterns of flow.
- √ Reintroduce beaver where appropriate.
- √ Strengthen community-based watershed management approaches with partners in multiownership watersheds.

Management Domain: Energy Development

Energy development on public lands managed by the Forest Service is governed by permits, regulations, and executive orders. Demands for energy development are likely to increase.

Energy Development: Practices to maintain and improve watershed resilience

- √ Increase understanding of water-energy interdependencies.
- √ Identify where, when, and under what conditions new hydroelectric facilities are suitable, at multiple scales.
- √ Locate new energy development sites and supporting road and infrastructure networks outside of wetlands, flood plains, riparian areas, fens, bogs, and meadows, and other water-dependent ecosystems.
- √ Protect surface and groundwater during energy development and production.
- √ Assess the impacts of producing and removing bioenergy materials on existing soil organic matter pools and carbon sequestration.
- √ Analyze the impacts of water consumption and return-water quality on ecosystem services.
- √ Wherever possible, include provisions for water recycling and reuse in gas, oil, geothermal, and other operations.
- √ Develop/enhance tools for better environmental protection while optimizing hydropower operations.
- √ Consider energy requirements for moving and treating water when developing measures for special-use applications, and when participating in water supply negotiations and land management planning.

A Closer Look: Fire and Fuel Management

High-severity wildfires can result in excessive erosion, elevated stream temperatures, and the loss of important resources and ecosystem services. Fire is a natural disturbance that maintains vegetation and contributes to watershed resilience, but decades of fire suppression and fuel accumulation have changed fire frequency and ecology. In addition, climate change has and will continue to exacerbate existing fuel and fire problems by changing precipitation patterns, snowmelt, and vegetation conditions.

Strategically reintroducing fire as a means to promote more resilient patterns of vegetation can help reduce the incidence of large-scale, uncharacteristic wildfires. But land managers face the challenge of optimizing an entire set of restoration activities, not just fuel reduction. Rehabilitating roads, enhancing riparian areas, removing fish barriers and balancing the needs of local residents with the agency's responsibility to protect water quality, forest health, and critical fish and wildlife habitat are also crucial watershed health priorities. Integrating biological data (such as critical habitat, forest stand condition, and riparian health) and physical data (such as postevent debris flow potential, water chemistry, and predicted postactivity stream temperature changes) into models that predict effects on critical watersheds following management activities or disturbance can help managers prioritize restoration activities.

This type of analysis helps managers identify areas where watershed conditions are resilient to or could benefit from wildland fire (maintenance conditions), areas where wildland fire is unacceptable and human intervention would be necessary to prevent losses of lives and property (engineered habitat), and areas with opportunities for using wildland fire to restore terrestrial or aquatic ecosystems (restoration areas). Managers in the South Fork Boise River (SFBR) basin are applying these models, as shown in the spotlight in the appendix.

Combining technical analyses with priority-setting systems based on critical watershed services will help ensure that management actions achieve results of value to watershed health and public needs. In many areas of the country, including the South, East, Rocky Mountains, and Sierras, fire and fuel management is complicated by private property, investments, and private forest land comingled with public ownership. In these situations, partnerships and cooperation are the keys to effective planning and management response. Among other measures, private landowners can address wildfire risks by collaborating on community wildfire protection plans and by ensuring defensible space around homes.

Management Domain: Fire and Fuels

In many regions, assessment, evaluation, and implementation of projects aimed at reducing fire severity and restoring fire-dependent ecosystems are at the top of managers' priorities. Considering watershed processes in these projects is necessary to protect soil and water resources. A successful large-scale approach to such planning is described in the spotlight on assessing wildfire risks and management opportunities for the South Fork Boise River (app.).

Fire and Fuels: Practices to maintain and improve watershed resilience

- √ Strategically target fuels and vegetation management activities to maintain resilient vegetative communities and reduce wildfire severity on a priority basis, informed by vulnerability assessments, watershed analyses, and strategies for carbon sequestration by forests.
- √ Include watershed management objectives in wildfire and fuels management plans.
- √ Where appropriate, reintroduce fire to approximate more resilient patterns of vegetation and disturbance.
- √ Develop partnerships with downstream water providers to encourage investment in the protection and restoration of forested watersheds.
- √ Maintain and protect soil and water resources, particularly soil infiltration capacity, during fire suppression activities, and rehabilitate suppression-related damage.
- √ Assess the impacts of removing fuels on existing soil pools, carbon pools, and nutrient cycling.

Management Domain: Infrastructure

Collectively, the American people have invested considerable resources in bridges, recreation areas, roads, and other facilities to serve the public. Some of these facilities, especially those near rivers and streams, or located on unstable landforms, are vulnerable to damage from higher peak flows associated with climate change (fig. 29). Managers depend on engineers and earth scientists to conduct risk assessments to support infrastructure development and maintenance decisions.

Figure 29—White River Bridge downstream of Mount Hood, Oregon, after the 2006 flood events.

Infrastructure: Practices to maintain and improve watershed resilience

- √ Identify high-risk watersheds and infrastructure sites and develop a range of design and treatment options based on climate-aware risk assessment and priority setting.
- √ Instead of "design storms" or "design runoff," use "design storm scenarios" with a range of explicit assumptions about changes in peak-flow probabilities to cope with uncertainties, and display risks in a more uncertain future. For example, consider infrastructure risks in which the 100-year storm becomes the 50-year storm, or the 10-year storm.
- √ Design culverts, bridges, and dams to limit the consequences of exceeding design capacity, consistent with the onsite and downstream values at risk. Build larger factors of safety into structures where failure would have substantial or unacceptable consequences. Reevaluate flood frequency distributions where possible. Where long records of streamflow are available, consider using only the most recent 30 years.
- √ Design in-channel structures to maintain hydrologic and biotic connectivity by allowing free passage of water, sediment, large wood, and aquatic organisms.
- √ Prioritize and treat road networks by storm-proofing and decommissioning to restore natural flow patterns, reduce erosion, and increase system durability.

Management Domain: Natural Disaster Response

Climate change is expected to increase the occurrence of weather-related emergencies like floods, landslides, drought, wind events, and wildfires. Natural hazards often result in loss or damage to capital investments such as roads and bridges, severe impacts on critical resources such as water supply and fish habitat, and loss of human life (fig. 30).

Natural Disaster Response: Practices to maintain and improve watershed resilience

- √ Make full use of existing emergency response programs and authorities.
- √ Review and update interagency coordination systems at national, state, and local levels.
- √ Advance technologies for early detection and warning systems.
- √ Increase emergency response training at all organizational levels.
- √ Build flexible, innovative, and responsive programs into existing management systems.
- √ Ensure that emergency response actions do not do more damage to resources than the emergency itself.

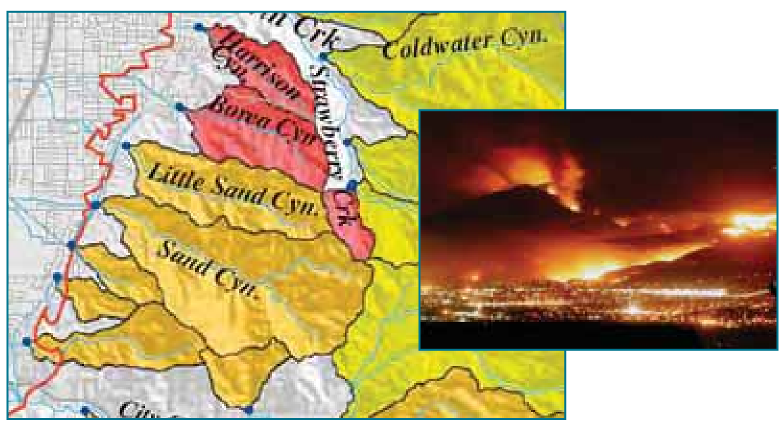


Figure 30—Probability of postfire debris flows associated with the Old Fire in Southern California. Red areas have highest potential, yellow areas the lowest. These risk models were developed by the U.S. Geological Survey and collaborators such as the U.S. Forest Service, Natural Resources Conservation Service, and various state agencies. Improved predictions of postfire effects are needed. Cooperative, interagency efforts offer the greatest potential for meeting critical information needs. Modified from Cannon et al. 2004.

Management Domain: Recreation

Demand for recreation on some Forest Service lands will likely increase significantly in the future. Most recreation activities on public lands and the facilities that serve them are located near water. Climate change brings increased risk of damage to these facilities, as well as those related to ski areas. Managers can also anticipate changes in the location and timing of recreation demand. Planning is needed to accommodate changes in uses and protection of water resources.

- √ Locate recreational facilities and design and manage uses to protect sensitive terrain and minimize risks to forest users.
- √ Plan and operate recreation programs to limit effects on vulnerable sites and to resources at risk.
- √ Build flexibility into permits so that periods of use or locations, or both, may be adjusted in response to changing climate and hydrologic conditions.
- √ Prepare for and adapt to changing recreation uses, needs, and opportunities.
- √ Use interpretive programs to inform the public about the changing climate and effects on recreation and resource values.
- √ Manage recreational access to avoid or minimize soil and water resource damage.

Management Domain: Soil and Water

Restoring watersheds, riparian areas, and streams is a major component of improving watershed resilience. Managers use a variety of means to plan and accomplish restoration activities including working with partners, and integrating soil and water objectives into fuels, vegetation, fisheries, recreation, mining, engineering, and wildlife projects.

Soil and Water: Practices to maintain and improve watershed resilience

- √ Design and implement measures to keep water on and in the land longer, including meadow groundwater restoration, road drainage control, and silvicultural treatments.
- √ Target treatments to restore impaired watershed condition and key functions on a priority basis, using watershed condition, climate change vulnerability assessments, and watershed analysis, as well as strategies for carbon sequestration by forests.
- √ Implement treatments to maintain and improve soil infiltration, nutrient cycling, and ground cover.
- √ Reduce hydrologic impacts of infrastructure, particularly road and road-stream crossings, to improve overall watershed condition and maintain local soil moisture regimes.
- √ Restore structure and function of degraded wetlands, meadows, riparian areas, and flood plains to enhance channel-flood plain connection, promote groundwater recharge and keep meadow ecosystems wetter longer.
- √ Set and meet soil quality objectives to sustain soil productivity and prevent soil erosion and sedimentation (Johnson et al. 2007).
- √ Reclaim abandoned mines and mine spoils to reduce pollution of surface and ground waters by toxic acidity and heavy metals, and restore water-based habitats.

Management Domain: Vegetation

Vegetation management is conducted on national forests by a variety of means. Merchantable timber is most commonly managed through timber sales, and timber stand improvement projects are used to manage submerchantable trees. Range and grasslands are typically managed using range management allotments. Watershed specialists provide managers with opportunities to protect and improve watershed condition during assessment, planning, and implementation of these projects.

Vegetation: Practices to maintain and improve watershed resilience

- √ Integrate watershed management and carbon sequestration into vegetation management plans and treatments.
- √ Identify, incorporate, and monitor "best management practices" as part of rapid response to disturbances from insects, drought, and fire.
- √ Schedule vegetation management, including timber harvest and fuel treatments, to limit adverse hydrologic effects, such as reduced infiltration and peak flow increases.
- √ Evaluate grazing management plans to address range and watershed conditions under changing climate scenarios.
- √ Revise grazing intensity where needed to improve riparian areas, streambanks, meadows, and wetlands.
- √ Protect soil quality to sustain soil productivity and prevent soil erosion and sedimentation.

Management Domain: Water Use and Diversions

Numerous water diversions and storage facilities exist on national forest lands (fig. 31). Impacts to groundwater, streams, aquifers, aquatic species, or water-dependent ecosystems may occur if individual or cumulative effects are not adequately addressed. Impacts from new or renewed land-use authorizations may be averted through planning, evaluation, authorization, and adaptive management. The number of requests and claims for water use on and from national forests will certainly grow in the future with increases in population and demand. At the same time, environmental needs to support aquatic species habitat and water-dependent systems also will increase.

Water Use and Diversions: Practices to maintain and improve watershed resilience

- √ Use existing authorities and cooperative agreements to set permit conditions for developments and diversions.
- √ Build flexibility into long-term special use authorizations and provide for permit term and condition modification as climate and hydrologic conditions change.
- √ Develop releases that mimic natural flows when possible.
- √ Work with permitting agencies to implement conservation plans that respond to increased demands for hydroelectric power generation.
- √ Use the latest scientific information to analyze and establish environmental flows (Richter et al. 2006), and flows for river restoration (Palmer et al. 2007).
- √ Monitor the effects of changes in flow regimes on affected systems.
- √ Ensure that adequate information about water distribution and ecological requirements is available to inform decisions intended to balance competing interests and demands.
- √ Share knowledge and expertise with water managers as new water uses, storage facilities, and diversions are proposed.
- √ Incorporate basinwide evaluations of current and future water needs so that access to scarce water on national forests and grasslands is provided equitably.
- √ Facilitate coordinated, cooperative approaches to water withdrawals among users.

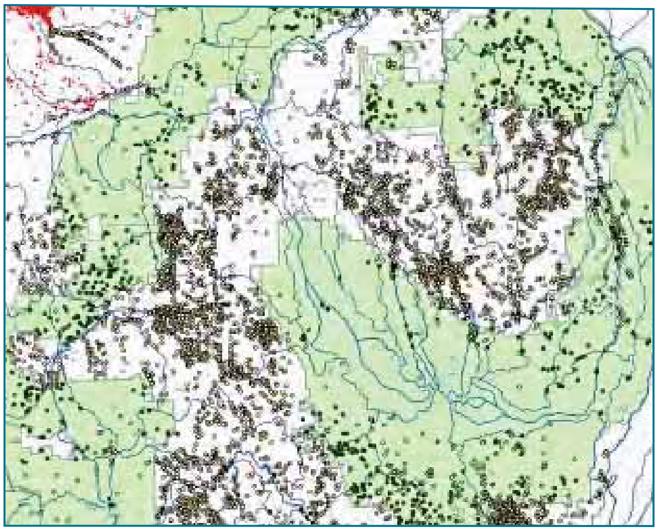


Figure 31—Points where water is diverted within and adjacent to the boundaries of the Umatilla and Wallowa-Whitman National Forests.

Restore Watershed Processes

Implementing restoration actions that maintain or improve conditions is key to providing resilient watersheds. Planning tools allow managers to determine which watersheds should have the highest priority for treatment. Priorities are often based on resource values at risk, maintaining or improving habitat for sensitive or listed aquatic species, and meeting requirments of the Clean Water Act. Treatments differ depending on the location and scope of need, but include measures to improve or maintain stream channels and valley bottoms, riparian areas, and upslope conditions.

"Without an active and ambitious restoration program in the United States, our swelling population and its increasing stresses on aquatic ecosystems will certainly reduce the quality of human life for present and future generations."

-National Research Council 1992

Restore Streams and Valley Bottoms

Activities that improve the condition of degraded channels and flood plains can extend natural storage, reconnect ground and surface waters, mediate local flood flows, and support aquatic habitats. Streams and valley bottoms, as well as adjacent flood plains, wetlands, meadows, and side channels, have attracted multiple users over time, leading to various degrees of change. Although some alterations are considered minor, others have brought dramatic change to the form and function of the aquatic system. Many riverine ecosystems no longer support key processes or deliver expected services. For example, overgrazing, road and railroad construction, channel draining and rerouting, and other land-use practices have caused extensive stream incision or downcutting (Loheide and Gorelick 2007). As a result, water tables are lower and wet meadows have been lost, leading to dramatic reductions in key ecosystem services such as streamflow regulation, water storage, water purification, fish and wildlife habitat, and recreational enjoyment.

Restoration efforts in some areas are promoting the recovery of some streams, valleys, and the ecosystem services they provide. Benefits are often direct and measurable onsite, and significant improvements in overall watershed condition are achieved as the cumulative effects of several projects occur. The spotlight highlighting Resurrection Creek restoration in Alaska (app.) illustrates a large stream and valley bottom project that had both local and watershed-wide improvements.

Elements of successful watershed protection and restoration programs

Watershed protection and restoration programs are more likely to succeed if:

- There is substantial federal leadership and funding.
- All levels of government, nongovernmental organizations, and other interested parties are involved.
- Comprehensive prioritization and planning techniques are applied.
- Actions address the most important conditions impairing or threatening critical watershed processes, regardless of political boundaries.
- Investments are long term.

—NRC 1992, Roni et al. 2002

New methods for restoring degraded stream and valley bottom systems are also in development. For example, the Feather River Coordinated Resource Management Group (FRCRM), a nonprofit partnership of 23 public and private stakeholders, is developing and implementing a novel technique called "plug and pond" on the Plumas National Forest in northern California. The method involves "plugging" incised channels to raise the bed level of the stream, and "ponding" water at a higher base level to create a more natural channel that reconnects flood plains and shallow groundwater, thus restoring hydrologic and ecological form and function (fig. 32). These restoration projects restore ecosystem services provided by healthy streams and may help to offset some of the local impacts of changing precipitation amounts and timing. Working with scientists to quantify and monitor the effectiveness of these projects is providing new information to expand their application and refine project designs.

Restore Riparian Areas and Bottomlands

Prior land uses and past management practices have removed forest vegetation from many riparian areas, adversely affecting water quality, stream and groundwater flows and levels, flooding, and aquatic species. Loss of these transition areas between terrestrial and aquatic ecosystems causes accelerated bank erosion, channel incision, alterations in stream channel form, loss of habitat, lower water tables, and elevated water temperatures, because of lack of shade and groundwater exchange. These impacts are considered primary factors in the decline of many fisheries, from trout streams in the east to salmon stocks in the Pacific Northwest. Restoring natural riparian vegetation is a prerequisite to stabilizing stream systems capable of supporting native aquatic life and to responding to extreme flow events associated with altered climate regimes. The National Research Council (2002) considers riparian restoration one of the most critical environmental challenges of our time and a national priority. Several ongoing projects in the Mississippi River Basin, as presented in Spotlight on Restoring Bottomlands (app.) provide examples of collaborative riparian restoration.

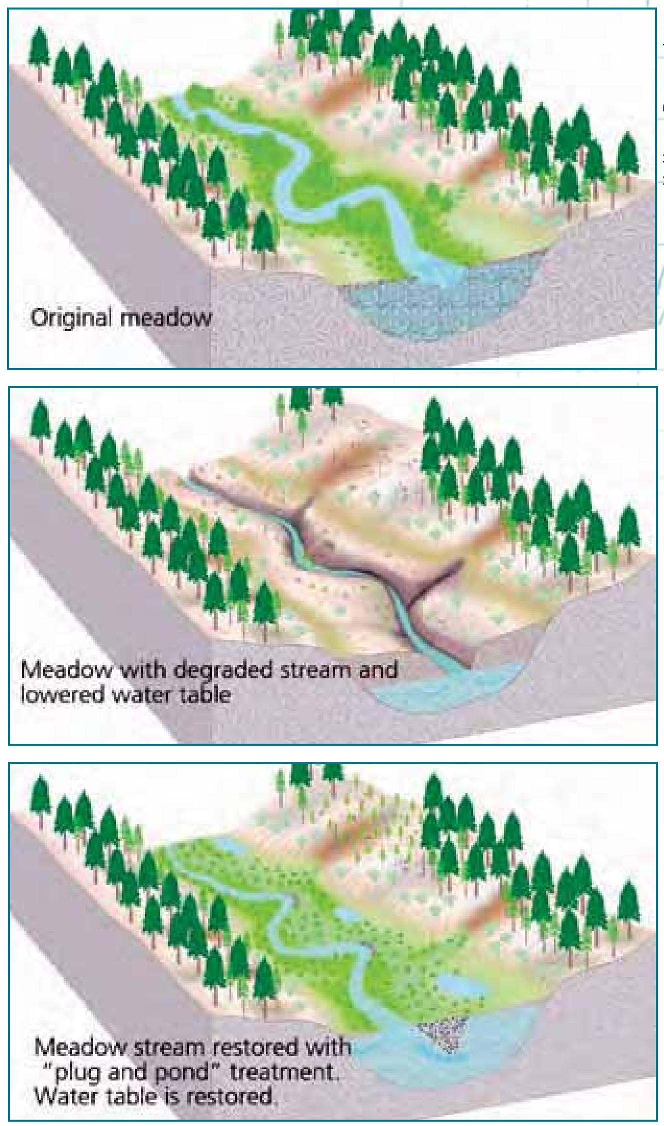


Figure 32—Restoring groundwater levels in eroded meadows and valley bottoms can increase watershed resilience in many forested watersheds. Warming and late-season drying trends greatly increase the ecological importance of wet mountain meadows and valley bottoms, which provide myriad ecological services. Restoring groundwater levels in these places adds resistance and resilience to watersheds, reducing the vulnerability of ecosystem services to climate change.

Restore Upslope Water Conditions

Prescriptions that improve "upslope" watershed processes can reduce soil loss and incidence of debris flows, increase groundwater recharge, and improve stream habitats. In some locations, past land management activities have stripped soils of protective cover, causing rill or gully networks to develop and deliver water, soil, and debris directly to drainages. Many treatments are used to stabilize or restore eroded hillslopes. Reshaping and revegetating them are among the most effective practices (fig. 33). Reclaimed soils and vegetation absorb and use water that would have quickly run off the landscape. In addition, downstream ecosystems recover as upstream hydrologic functions are restored and sediment inputs are reduced. Water that reenters soil recharges groundwater; reduces overland flow that contributes to flooding, channel aggradation, degradation, or widening; and reestabilishes seasonal flow timing.

Reconnect Flood Plains and Habitats

Improvements to flood plain structure and habitats maintain channel flow capabilities and help species adapt to changing conditions. Climate change will further fragment aquatic habitats by increasing temperatures, altering physical habitats, and contracting the perennial stream network. A substantial number of salmon and trout populations, many of which are already threatened, endangered, or considered for listing under the Endangered Species Act, may be lost owing to the effects of climate change over the next century unless fragmented aquatic ecosystems are reconnected, invasive species are controlled, and riparian vegetation is managed to provide a full range of ecological functions needed for healthy streams. One study (O'Neal 2002) predicted that 18 to 38 percent of suitable salmon and trout habitat would be lost by 2090 under current climate change scenarios, and these losses will be exacerbated by other management actions that impair watershed processes.

National forests alone contain 200,000 miles (322 000 kilometers) of fish-bearing streams—streams that are becoming increasingly important to conserving freshwater diversity. Some of these habitats, however, have been substantially fragmented by more than 440,000 miles (708 000 kilometers) of authorized and unauthorized roads. Surveys show that more than 20,000 road-stream crossings do not provide full passage for all species and life stages of fish (USDA FS 2001). Connecting, restoring and reopening existing, high-quality aquatic habitats is the first priority for enabling species to adapt to changing conditions (Roni et al. 2002) (fig. 34). Other options may include protecting and maintaining genetic diversity through conservation measures, restoring marginal habitats, identifying aquatic populations that are adapted to warmer waters to facilitate their transition, and relocating important populations to habitats that retain favorable conditions.

Gullied, degraded land.

Gully reshaping.

Ten years after restoration.

Figure 33—In South Carolina, early settlers cleared native forests and farmed them until erosion and nutrient losses made the land unproductive. Deep gullies formed on many eroding hillslopes to become a dominant landscape feature. When the Francis Marion-Sumter National Forest was created in 1936, it contained an estimated 200 square kilometers of actively eroding gullies and severely eroded soils. Some downstream valleys and stream channels were filled with up to 3 meters of soil from the eroding landscape (Trimble 1974). Decades later, many of the problem lands had still not recovered. Consequently, the forest initiated efforts that have helped to stabilize and recover 80 to 90 percent of gullies and eroded areas. Projects such as these are an effective adaptation response to climate change because restored hydrologic functions will help prevent flooding and erosion during large storm events and provide greatly improved soil moisture for forest growth. The national forest is also working to enhance its capacity to implement these projects through the use of advanced technologies such as LIDAR (James et al. 2007).

Figure 34—Restoring fragmented flow paths and habitats on the Chequamegon-Nicolet National Forest. At Armstrong Creek Crossing, five undersized culverts in various stages of disrepair (photo on left) were replaced with a 30-foot (9-meter) clear span wooden bridge (photo on right). The culverts, which had a total waterway opening of 24.5 square feet (2.3 square meters), would fill to capacity during a 2-year flood; the road would overtop during a 100-year flood. The realigned crossing restores flow to a meander that was abandoned when the culverts were installed, restores fish passage for brook trout, and improves habitat connectivity for other aquatic organisms. With a waterway opening of 200 square feet (19 square meters), the new structure can accommodate flood flows in excess of the 500-year flood and enable the stream to function more naturally during large runoff events. For additional examples, see http://www.stream.fs.fed.us/fishxing/case.html.

By 2100, more flood flows in fragmented hydrologic networks could double both the costs and the number of properties damaged (Kirshen et al. 2005). In watersheds dominated by a mosaic of forest, urban, and other land uses, flood plains and stream channels have often been altered so that floods can no longer follow traditional flow paths, be infiltrated and stored adequately in soils or aquifers, or be confined within undeveloped lands. Even in watersheds without significant infrastructure, past management activities may have affected the water's ability to flow in its natural path. The spotlight on Resurrection Creek (app.) illustrates flood plain and channel restoration efforts where past mining activities impaired both streamflows and fisheries habitat. This successful project and the partners involved were recognized for outstanding results in 2008 with a Rise to the Future Award from the U.S. Forest Service. These and other such flood plain restoration projects are the primary means to reconnect natural hydrologic systems to attenuate local flooding events. Other adaptation strategies may be considered in developed watersheds where restoring flood plains is not feasible because of cost or land limitations. Such solutions include engineered structural and nonstructural features to retain or divert flows. Engineers, scientists, and planners will need to consider the impacts of climate change and other influences by modeling hydrographs that incorporate potential changes in flow peaks, volume, and timing.

The principles and actions presented in these chapters suggest how land and water managers can incorporate climate change considerations into watershed management today and into the future. Many actions provide a means for managers to respond to the anticipated challenges of climate by focusing on maintaining and improving resiliency of watersheds managed by the Forest Service. This approach is necessitated by high uncertainty in the magnitude and extent of the effects on local watersheds, environmental services, and people. Because projected changes will occur across all watersheds, regardless of ownership, innovation and expanded partnerships will be key factors in creating successful ventures across ownerships and ecotypes. Ultimately, caring for the Nation's forests and grasslands at the watershed scale, in a way that enables species, ecosystems, or resources to adapt to change, will be the most rewarding climate change strategy. Healthy watersheds that are less vulnerable to changing conditions are more likely to supply a broad array of ecosystem services in the face of climate change and other disturbances.

> **"Good management** is the art of making problems so interesting and their solutions so constructive that everyone wants to get to work and deal with them."
>
> —Paul Hawken (1987)

CLOSING | WATER, CLIMATE CHANGE, AND FORESTS

History provides vivid examples of societies that were either destroyed or maintained when climates changed. Noted scientist and author Jared Diamond (2005) discussed the Greenland Norse (986 to c. 1420 A.D.) who thrived during a warm period, but were unable to survive like their native Inuit counterparts when the climate cooled. Accounts of the Norse settlements' demise suggest that they did not anticipate that changes would be long term and require adaptation. They were inflexible and did not adopt the approaches that allowed the Inuit to persist.

Today, overwhelming scientific evidence synthesized by the Intergovernmental Panel on Climate Change, the U.S. Climate Change Science Program, and others indicates trends of increasing temperatures and variable precipitation patterns that have begun to affect people and communities around the world. Scientists, governments, and industries are anticipating the consequences of warming and investing in research to reduce uncertainties and understand options. Resource managers, landowners, and citizens are working to understand these changes, the range of future conditions, and options for maintaining ecosystems, communities, and livelihoods.

The stakes for good watershed stewardship are raised dramatically by climate change and population growth. How best to respond is no mystery: watersheds must remain resilient to adapt to land use and climate change, rebound from disturbances, and adjust to new conditions. There is much we can do, and we have a long history and abundant knowledge and experience in doing this work: the science and practice of sound watershed stewardship.

We have good reason to hope and every reason to act. We know how to practice effective stewardship so that the watersheds we depend on and value will remain intact and continue to provide life-supporting services. Climate change offers us the opportunity to advance our skills, rethink our stewardship, innovate, and work with our partners for the benefit of healthy watersheds and communities.

America's forests and grasslands are immensely valuable, locally and globally. They will certainly remain as national jewels in a warming, crowded, and challenging future. These lands are and will continue to be crucial refugia for plants, animals, and fish displaced from other lands and waters. These lands will remain the "water towers" of the Nation, providing water security and prosperity to a growing population and future generations. As we work together, we can ensure that these valuable watersheds continue to meet the many needs of people and nature into the next millennium.

English Equivalents

When you know	Multiply by	To find
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	.394	Inches
Meters (m)	1.094	Yards
Meters	3.28	Feet
Kilometers (km)	.621	Miles
Square meters (m^2)	10.76	Square feet
Square kilometers (km^2)	.386	Square miles
Hectares	2.47	Acres
Cubic meters (m^3)	35.3	Cubic feet
Cubic meters	1.307	Cubic yards
Liters (L)	.0353	Cubic feet
Liters	.265	Gallons
Liters	33.78	Ounces (fluid)
Liters per kilowatt-hour (L/kWh)	.264	Gallons per kilowatt-hour
Degrees Celsius/Centigrade (°C)	1.8 °C + 32	Degrees Fahrenheit

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Examples of Watershed Stewardship

Spotlight on aquatic restoration in the Pacific Northwest: reevaluating priorities in the context of climate change

The U.S. Forest Service (USFS) recently began implementing an Aquatic Restoration Strategy to improve watersheds and aquatic habitats on national forests in the Pacific Northwest (PNW) Region. A central component of the strategy is the identification of priority areas for restoration, at river basin and watershed scales, with regional and local partners (fig. 35). Initial priorities were based on the existing condition of aquatic resources, the nature and scale of threats to those resources, the sensitivity of different watersheds to these threats, and opportunities for mitigating them. Areas with the healthiest native fish stocks and the greatest manageable risks are the initial focus for restoration.

Initial implementation of the strategy has been promising. For example, the USFS and numerous partners—federal, state, and local governments, nongovernmental organizations, private landowners—have developed watershed restoration plans for many of the priority watersheds and are concentrating their investments in these areas. Partners are substantially leveraging and amplifying each others' funding, skills, and capacity.

Figure 35—USFS priority river basins and watersheds for aquatic restoration in the Pacific Northwest. River basins (large polygons) with the highest priority for restoration are shown in blue, moderate priority are shown in light green, and lowest priority are shown in gray. Priority watersheds (small polygons) within the basins are shown in dark green.

For many reasons, however, success is far from guaranteed. Climate change is among the greatest uncertainties, as it is likely to magnify existing impacts and threats. To improve the likelihood of success, managers and researchers are collaborating to conduct a multiscale **climate change vulnerability assessment** for key aquatic species across the PNW Region. This assessment will use information regarding existing species population status, the location and distribution of key habitats, and projected changes in stream temperatures, low flows, peak flows, and disturbance regimes to determine species and locations that are most susceptible to climate change (see, for example, figures 36 and 37). Subsequent efforts will involve local managers and field specialists in identifying more localized constraints on these species and habitats and opportunities to address them through management activities.

Results of the vulnerability assessment may verify or alter existing restoration priorities, depending on how aquatic resources are likely to be affected and whether or not the effects can be mitigated.

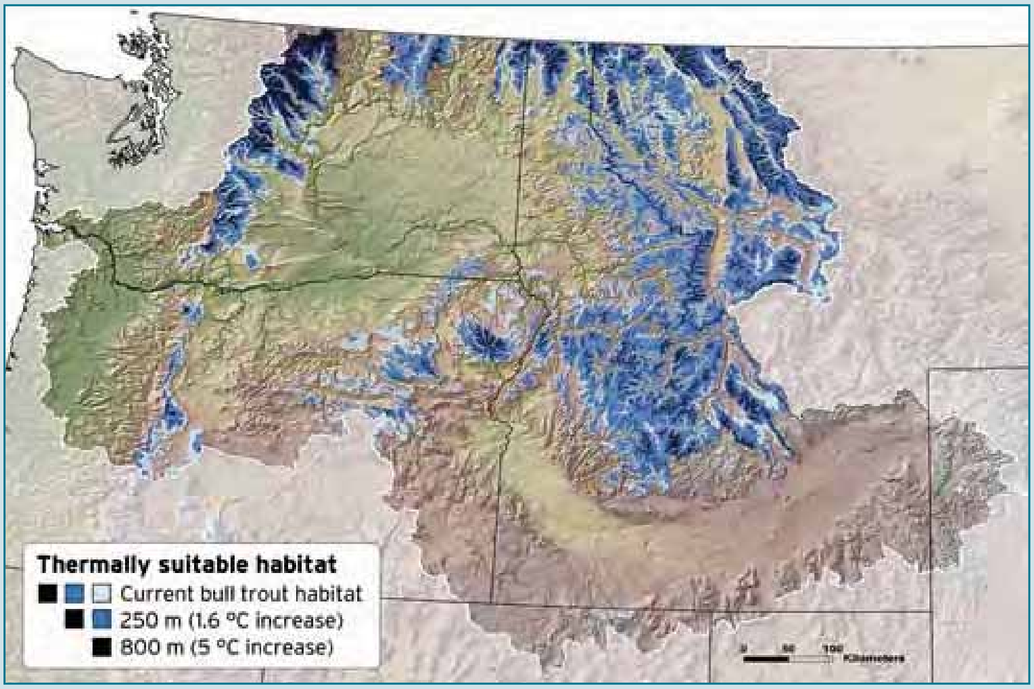


Figure 36—Areas with thermally suitable habitat for bull trout under current climate conditions and a projected 1.6 °C increase in air temperature (Rieman et al. 2007, Isaak et al. 2007). Model estimates exclude western Washington and Oregon.

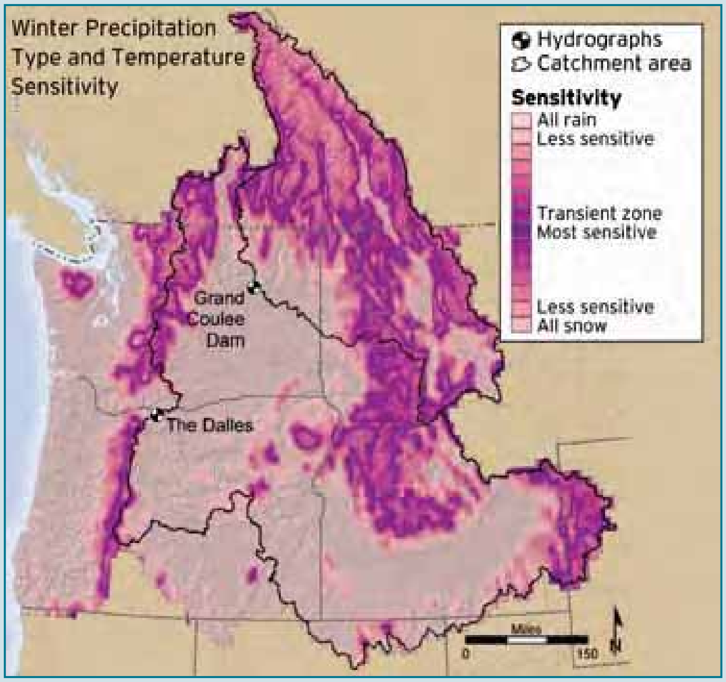


Figure 37—Likelihood of winter precipitation changing from snow to rain, potentially leading to increased winter peak flows and decreased summer low flows (Casola et al. 2005).

Spotlight on assessing wildfire risks and management opportunities for the South Fork Boise River

Location: South Fork Boise River (SFBR), Idaho

Background: The 2,500-km^2 SFBR watershed, which contains lands managed by the Boise and Sawtooth National Forests, has not experienced a significant fire in at least 100 years. The watershed supports people, communities, and infrastructure, a mix of low- and high-elevation forest types, and thousands of kilometers of streams inhabited by numerous species, including bull trout, that are protected by the Endangered Species Act.

Actions: Researchers at the U.S. Forest Service Rocky Mountain Research Station integrated spatial data on forest condition, bull trout (*Salvelinus confluentus*) habitat, wildland-urban interface, roads, and fish passage barriers into a map of maintenance, engineered, and restoration conditions. Researchers built a model to predict the persistence of bull trout habitat following wildland fire and postfire disturbances, such as debris flows. Results were used to prioritize subwatersheds for restoration work (fig. 38).

Based on this analysis, researchers determined that the density of restoration needs and presence of bull trout in the northwest portion of the SFBR made this area a high priority for restoration. The eastern portion of the SFBR has a small human footprint and large, well-connected patches of bull trout habitat. As a result, fire has been suggested as the primary tool for habitat maintenance and renewal in this portion of the watershed. The western portion of the watershed was identified as a high priority for fuel treatment because of the risk of high-severity wildfire in and around the wildland-urban interface.

Outcomes: With priority areas now identified, land managers are moving forward with implementing specific, high-priority restoration actions.

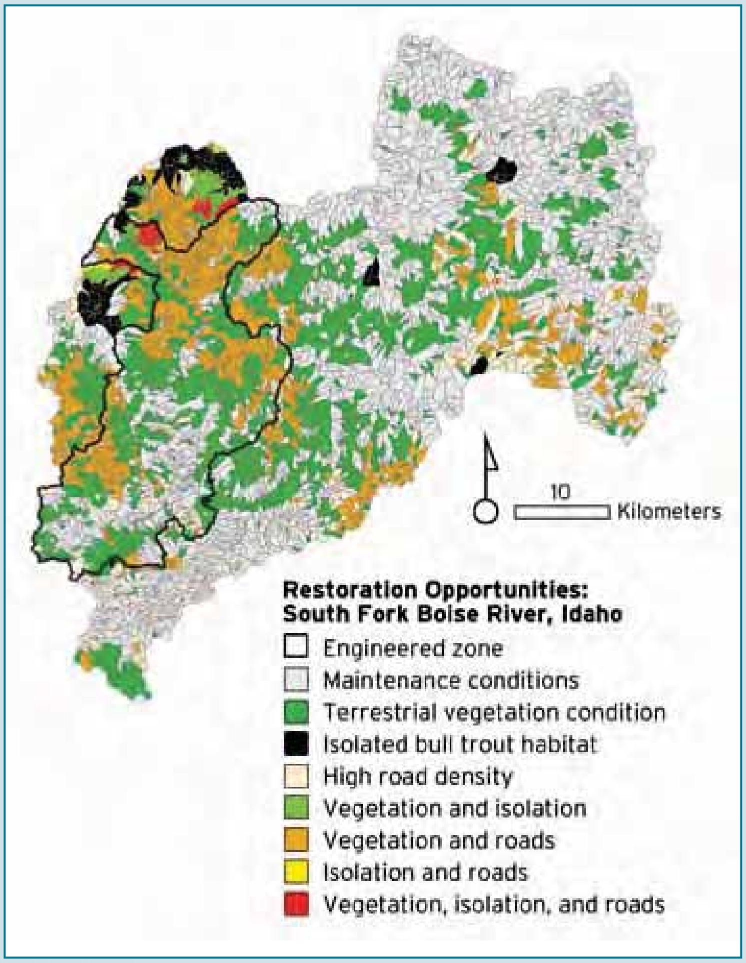


Figure 38—Subwatersheds identified for restoration work related to various conditions.

Spotlight on restoring the bottomlands of the Mississippi River

Location: Mississippi River basin


U.S. Geological Survey

Background: The Mississippi River drains nearly two-thirds of the contiguous 48 states. Key to the resilience of this river and the Gulf of Mexico downstream is the 1,500-mile (2400-kilometer)-long flood plain corridor. Prior to dense human settlement, streams and rivers bordered by forest and prairie delivered water, nutrients, and sediment to the Gulf. Sediment built and replenished soils, and floods were spread across extensive forested flood plains. Today, more than half of these bottomland hardwood forests have been cleared for farming or the cities that depend on the river for their commerce, recreation, and livelihood.

Climate change threatens to increase the loss of these bottomlands, as increased precipitation on bare soils will result in greater soil erosion and sedimentation. Partnership efforts that share common objectives—restoring flood plain forests and wetlands that are the heart of the river's ecological function—are underway along the entire river corridor.

Mississippi River Basin.

Actions: The Forest Service has played a key role in bringing together partners in the **Upper Mississippi Forest Partnership**. A recent assessment completed with the U.S. Geological Survey showed reforestation priorities along the river and is helping guide efforts on the ground. Working with the National Fish and Wildlife Foundation, the Mississippi Watershed Fund has been established and has provided over $500,000 in grants to complete innovative restoration projects.

In the **Middle Mississippi River Partnership**, the Shawnee National Forest with other federal and state agencies and nonprofit groups are restoring resilience to 195 free-flowing miles (314 kilometers) of the Mississippi River in Illinois and Missouri. The forest was able to expand its administrative boundary to allow purchase and donation of marginal cropland in the flood plain so it could be returned to highly productive bottomland hardwood forest. Over 3,000 acres (1200 hectares) have been acquired and restored to forest land. Partners work together to contribute resources or expertise on each property that is added.

Historically, the bottomland forest of the **Lower Mississippi Alluvial Valley** occupied 24 million acres (9.8 million hectares) in parts of seven states, and served as an immense filter for the river's floods and sediment and a buffer for the coastal plain of Louisiana. Now less than 5 million acres (2 million hectares) of this forest exists. Since the mid-1980s, active restoration programs by multiple agencies and nonprofit groups have reclaimed over 10,000 acres (4050 hectares)—an important step beginning the journey back to a healthy bottomland hardwood ecosystem.


Remaining forest in 1992 (shown in green).

Outcomes: Easement acquisitions, native forest reestablishment, wetland re-creation and water management improvements are returning natural hydrologic function to the river flood plain and improving watershed resilience. Concurrently, reconnection of forests is conserving them as rich habitats for wildlife and fish, improving water quality, enhancing recreation, and providing a scenic landscape even as climate change impacts are beginning to become more pronounced.

A closer look: improve or decommission roads

The national forest road system is vast. This network of about 380,000 miles (611 000 kilometers) of authorized roads and at least 60,000 miles (96 000 kilometers) of unauthorized roads is over twice as large as the entire federal highway system. These roads provide numerous benefits to society, including access for recreation and land management. Expansive road networks, however, can impair water quality, aquatic habitats, and aquatic species in a number of ways, often to a greater degree than any other activities conducted in forested environments (Gucinski et al. 2000, MacDonald and Stednick 2003, USDA FS 2001). Roads intercept surface and subsurface flows, adding to the magnitude and flashiness of flood peaks and accelerating recession of flows (Jones and Grant 1996). Road networks can also lead to greater channel incision, increased sedimentation, reduced water quality, and increased stream habitat fragmentation. Modern road location, design, construction, maintenance, and decommissioning practices can substantially mitigate these impacts, but most forest roads were built using older methods and are not adequately maintained owing to a lack of resources. In addition, many critical drainage components like culverts, are nearing or have exceeded their life expectancy.

These deteriorating road conditions threaten our ability to manage forests and pose significant risks to watersheds. Climate change elevates these risks by increasing the frequency and magnitude of large storm events and flooding.

There is a need to balance the benefits and costs of roads by decommissioning those we no longer need and improving those that are essential. A balanced portfolio of restoration actions will be needed to address this challenge. Intensive treatments, such as decommissioning and road realignments are essential, but can only be implemented on small portions of the landscape because of cost. These will need to be complemented with simpler, less expensive treatments, such as stormproofing roads by preventing streamflow diversions at road-stream crossings and outsloping roads, that can be applied across broad areas. Ongoing efforts to assess and reconnect streams that are currently fragmented by inadequate stream crossings will be equally important (Furniss et al. 2009).

Figure 39—In this project on the Lolo National Forest in Montana, the original road paralleled a stream channel that often eroded portions of the road, delivering large volumes of sediment to the stream. Through a stewardship timber sale contract, a new road was built away from the stream, and the old road was decommissioned.

Strategically applied road decommissioning or road improvements can help restore natural flow patterns, increase flood plain and habitat connectivity, decrease peak flows, and reduce erosion and temperature impacts. Such changes can help ameliorate climate change impacts and contribute to improved watershed resilience.

The Lolo National Forest in Montana has been a national leader in this type of work (fig. 39). From 1996 to 2007, the forest and its partners decommissioned 788 miles (1269 kilometers) of unneeded roads. Through stream crossing removals and replacements, the forest opened 333 miles (536 kilometers) of fish habitat by removing 329 stream crossings and replacing 55 others.

A closer look: sustain water flows and levels that support ecosystem and stream processes

A river's flow regime—the pattern of high and low flows between different seasons, years, and decades—is an indicator of overall health and resilience. It is generally recognized that some amount of water can be diverted from a river for human use without substantially compromising the river's ability to support a desired array of ecosystem services. As the amount of diverted water increases, so does the risk and likelihood that some desired services will be lost (Postel and Richter 2003). Balancing water use with the maintenance of key ecosystem features and processes has been a significant challenge for land and water managers. These challenges will increase in severity and extent as the combined effects of population growth, land use change, and climate change intensify water demand and create variability in supply. The spotlight on the Verde River, Arizona, below presents an example of threats to environmental flows and considerations for protection and management.

Spotlight on managing for environmental flows in the Verde River, Arizona

Location: Upper Verde River, Prescott National Forest, Arizona

"Water made the West, and its historic evaporation will unmake it—unless this generation is as creative as its forebears in finding sustainable ways to live with the 20 inch [annual precipitation band]."

— David M. Kennedy, 2008

Background: The Upper Verde River is a remarkable natural resource. Thirty-seven miles of this spring-fed, desert stream flow freely through the Prescott National Forest (PNF). It traverses deep limestone canyons, basalt mesas, and alluvial valleys lined with cottonwood (*Populus fremontii* Wats.), willow (*Salix* sp.), walnut (*Juglans major* (Torr.) Heller), sycamore (*Platanus occidentalis* L.), and ash (*Fraxinus velutina* Torr.) trees, and meadows of sedges and bulrushes. The riparian community and high-quality water provide for a remarkable diversity and abundance of fish and wildlife species, including one of the last assemblages of native fish species in Arizona. Because of these values, the Upper Verde was classified as eligible for designation as a Wild and Scenic River in 1993.

The river, however, is central to an increasingly common controversy in the arid West. Human populations in Arizona, especially in the Verde River Basin and Yavapai County, have skyrocketed in the last decade. This growth is taxing existing water supplies, and as a result, these communities are evaluating opportunities to import water from other sources. The primary source being considered is an aquifer connected to headwater springs that supply the river with cool, clean water.

Actions: If the aquifer's groundwater were pumped as proposed, 22 miles (35 kilometers) of river on the PNF might be dewatered. This would substantially adversely affect national forest resources and users and could result in severe reductions in water availability to downstream communities and holders of water rights. Despite these impacts, the Forest Service has limited recourse because it has no authority to manage the groundwater on adjacent lands.

Recognizing the importance of this issue, Congress enacted Title II of the Northern Arizona Land Exchange Act, which empowers the Forest Service to support communication and planning among stakeholders. Many diverse stakeholders are now involved in this effort, and unusual partnerships are converging to protect the treasures of the Upper Verde River. The municipalities proposing the project are interested in maintaining the river's integrity. To support these efforts, the PNF and the USFS Rocky Mountain Research Station are examining research priorities that would lead to a better understanding of how this unique desert stream functions.

Outcomes: The outcome of these efforts remains uncertain. Several key unanswered questions include:

- Will the need to protect environmental flows, surface water rights and high-value fish, wildlife, and recreation resources on the PNF influence the way people consider and use water resources that sustain the river?
- Will diverse stakeholders come together and develop a reasonable solution that meets people's needs for water, as well as the river's long-term capacity to provide other ecological services?

Spotlight on resurrecting Resurrection Creek, Alaska

Location: Resurrection Creek is a 161-square-mile (417-square-kilometer) watershed that flows northward into Turnagain Arm at Hope, Alaska.

Background: During the early 1900s, portions of the creek were heavily mined for placer gold with hydraulic mining equipment that used high-pressure water jets to strip away vegetation and soils so they could sort through underlying gravels for gold. The coarse tailings were placed into high piles along the valley bottom. The creek was diverted into a straight, steep, simplified channel along one side of the valley, separating it from the functional flood plain. Tailings piles had restricted overbank flood flows and left poor growing conditions for vegetation. Side channels that provide rearing habitat for salmon and streamside forests that provide habitat for eagles, bears, and numerous other riparian species were substantially degraded. Although the mining activity is over, the creek would have needed centuries to reestablish its original character without intervention.

The top photo shows Resurrection Creek in 2002; the bottom photo was taken in July 2006 following completion of construction illustrating the restored channel and flood plain through the valley.

Actions: In 2005, the Chugach National Forest and partners including the Youth Conservation Corps and local contractors began construction of a mile-long restoration project on Resurrection Creek. The project accomplished the following:

- Redistributed 140,000 cubic yards (107,000 cubic meters) of tailings to develop a new stream channel and flood plain.
- Excavated, shaped, and "stepped" 1.3 miles (2.1 kilometers) of new stream channel with natural pool/riffle/glide sequences, increasing the channel length by 30 percent.
- Shaped 50 acres (20 hectares) of flood plain to accommodate overbank flows while preventing flood cut-off of newly created meanders.
- Constructed more than 2 miles (3 kilometers) of new side sloughs and ponds adjacent to the new stream channel, providing flood relief for the main channel and high-quality rearing habitat for salmon and trout.

Young workers from the Youth Conservation Corps helped with vital restoration work at Resurrection Creek in Alaska.

- Placed more than 1,000 trees into 20 engineered log jams along the channel to allow for moderation of side slough flows, provide nutrients and cover for spawning and rearing fish, and capture additional natural logs and branches during flooding.
- Hauled and spread 8,000 cubic yards (6100 cubic meters) of soil and woody debris onto the new flood plains to enhance natural revegetation and future planting efforts.
- Moved an existing access road out of Resurrection Creek's flood plain.
- Removed 4,000 cubic yards (3000 cubic meters) of tailings to create additional parking for the Resurrection Pass Trailhead.

Outcomes: By 2006, the channel and flood plain were restored to conditions much closer to their pre-mining condition. All five Pacific salmon species are spawning in the creek once again. Fishermen and hikers of the popular Resurrection Trail that parallels the creek now see a natural, productive, meandering stream instead of an aging gravel quarry.

In the coming years, the channel is expected to continue changing, naturally shifting within the valley bottom as upstream and flood plain surface and groundwater flow pathways are reconnected. Riparian vegetation will recolonize streambanks and the flood plain. Large wood and sediment from upstream will become lodged into the new bed and banks, diversifying habitat features for aquatic species.

Spotlight on building an ecosystem marketplace for Chesapeake Bay

Location: Chesapeake Bay, Middle Atlantic Region

Background: The future health of Chesapeake Bay depends greatly on the actions of private landowners. Emerging ecosystem markets can provide landowner incentives to conserve or improve their land. Currently, access to markets is confusing and difficult without a centralized marketplace that connects landowners to potential buyers of ecosystem credits. The Alliance for the Chesapeake Bay, the Pinchot Institute for Conservation, the U.S. Forest Service, and other stakeholders are developing an ecosystem services marketplace for the Chesapeake Bay called the Bay Bank.™

The ultimate mission of the Bay Bank is to improve the health of Chesapeake Bay by fostering stewardship activities on private forest and farm lands that provide cleaner air, clean water, and quality wildlife habitat. The Bay Bank will also help to advance markets that protect valuable forests threatened by development. Keys to success include guaranteed high market standards, consistent and appropriate protocols for credit establishment and trading, and the ability to direct landowners to market opportunities.

Ecosystem Markets

Carbon sequestration–
Credits for increasing carbon storage and rates of removal from the atmosphere

Forest conservation–
Credits for maintaining and enhancing forest lands

Habitat conservation–
Credits for maintaining and/or enhancing endangered species and high-value habitats

Wetland conservation–
Credit for maintaining and enhancing wetland areas

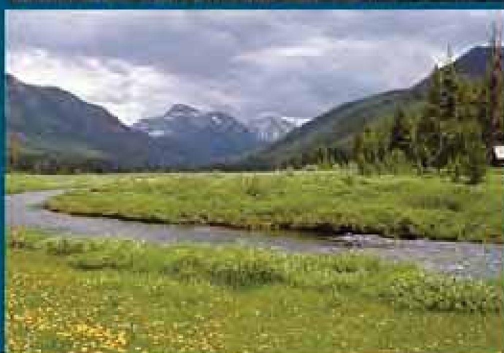
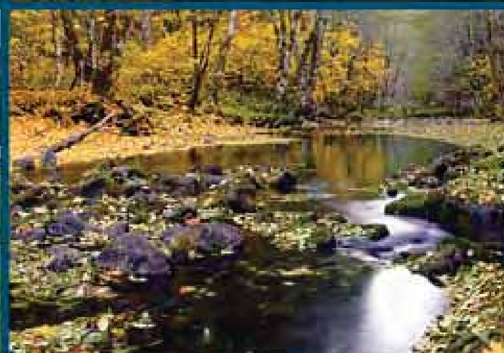
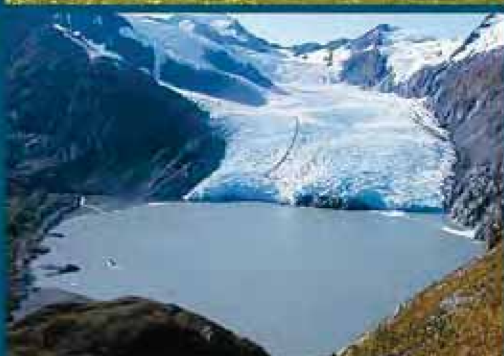
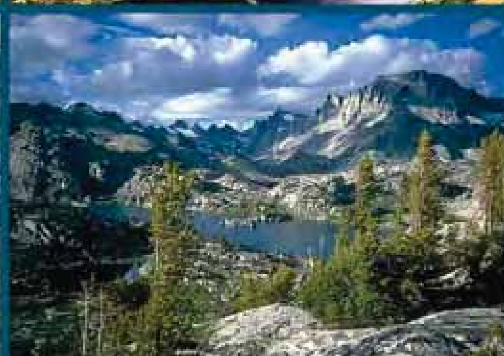
A marketplace of opportunity
for Chesapeake landowners

THE BAY BANK

Actions: Bay Bank development includes the following components:

1. **Baseline:** Analysis of current regulatory drivers for ecosystem markets in the Chesapeake, as well as state and federal regulations and guidelines for generating and trading credits.
2. **Forestry for the bay:** An effort to provide online, coached land stewardship; this program will provide the initial link between landowners and a spatial land registry.
3. **Spatial land registry:** A Web-based mapping tool that allows landowners to spatially select and register their parcels of land, identify land management practices that may generate credits, and determine eligibility for current and emerging ecosystem markets. The spatial land registry will link to the Bay Bank online marketplace.
4. **Verification and certification:** Requirements for on-the-ground verification of practices and third-party certification to ensure high-quality credits.
5. **Centralized marketplace:** An online portal for ecosystem market transactions in existing and emerging exchanges/registries.
6. **Regional trust mechanism:** A means to leverage funding streams to purchase credits generated by high-quality, third-party certified private stewardship activities and target investments for ecologically meaningful watershed restoration.



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