Forest legacies, climate change, altered disturbance regimes, invasive species and water

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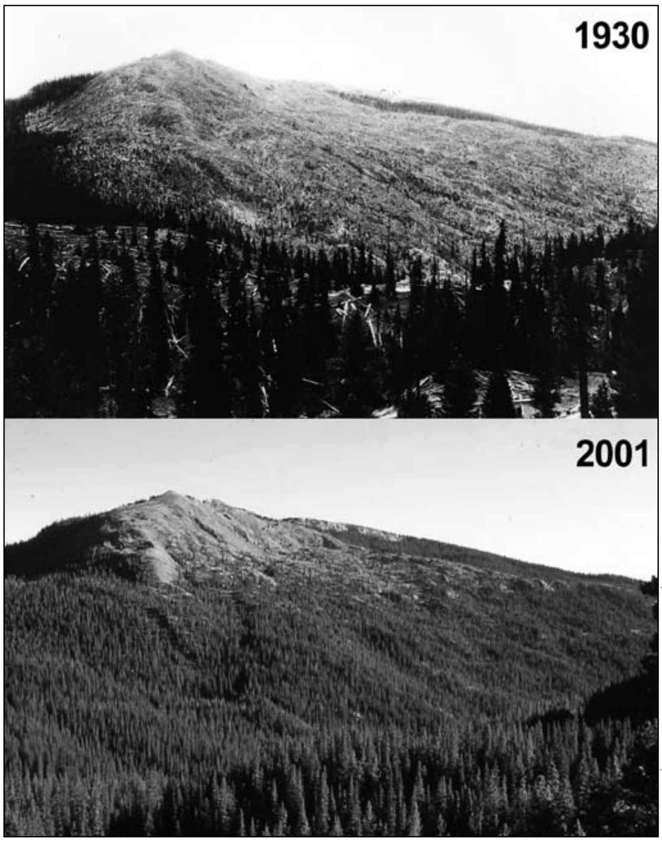
Climate change is one of many drivers affecting forest hydrology.

Climate is a major driver of forest species distributions and the growth rate and structure of forests. Thus, climate change can potentially have significant effects on mountain forest hydrology, particularly the amount of water available downstream. However, many other factors influence forest biomass and mountain hydrology, and climate change effects cannot be viewed in isolation from previous land use histories (i.e. forest legacies), altered disturbance regimes (e.g. fire frequency, insect outbreaks, floods) and invasive species. Based on research from Colorado, United States, this article examines the many factors that must be considered in seeking to predict changes in water availability.

FOREST LEGACIES

Few current landscapes in the United States have escaped human influence, for example through logging, mining, agriculture, grazing by domestic livestock, elimination of large carnivores, human-caused wildfire and/or pollution. Many landscapes continue to undergo changes caused by human use, while others are reverting to their natural state (Figure 1). The quality and amount of water available



1
Repeat photography of a subalpine watershed in Colorado, United States

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downstream is likely to be affected by changes in the composition, structure, canopy cover and biomass of the forest as it responds to past human land use and other disturbances, e.g. from forest fire. For example, many watersheds in the Rocky Mountains of Colorado were affected by logging, mining and increased human-caused fires between 1850 and 1900 (Veblen and Lorenz, 1991). Stream flow probably increased following those disturbances, remaining high while forests were recovering. Current stream flow might logically be expected to be less owing to increased interception of snow by maturing forest canopy and increased water use by the forest. Climate change in the late twentieth century must be measured against the backdrop of forest and landscape legacies.

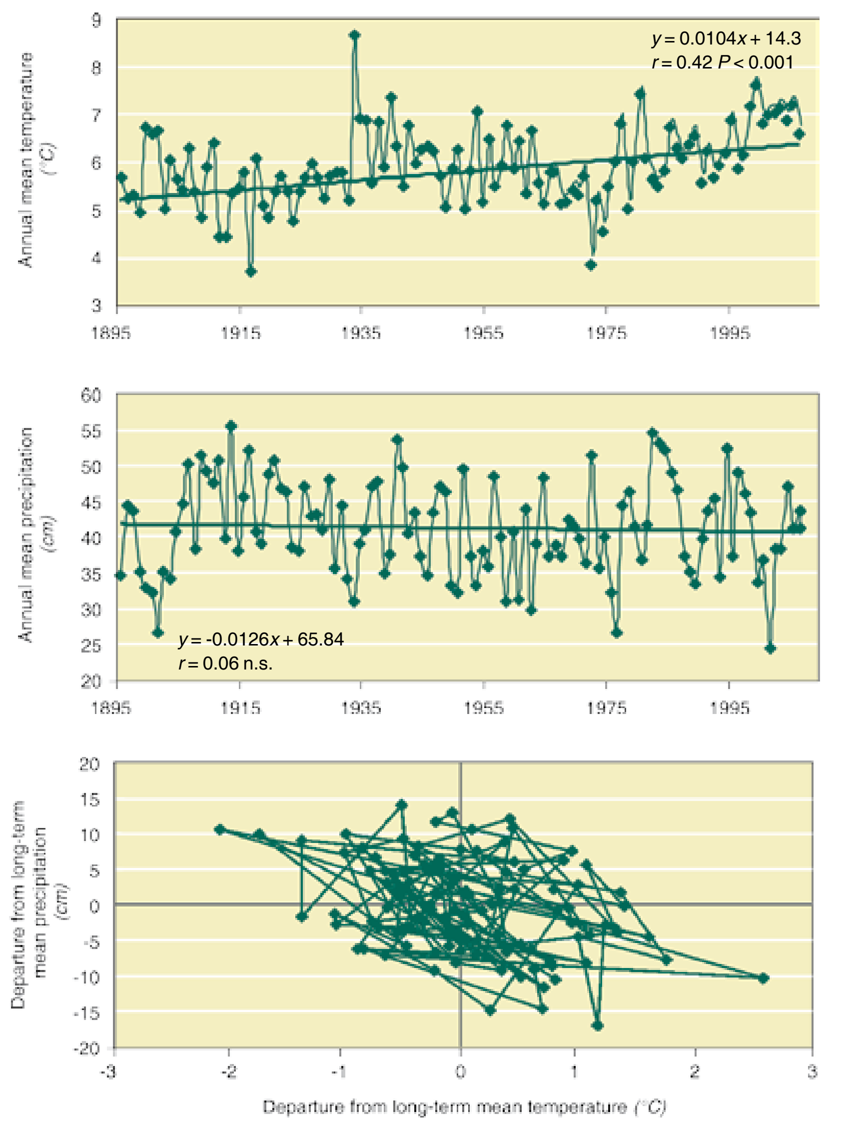
CLIMATE CHANGE AND STREAM FLOW

Climate change is not new to montane watersheds (Pielou, 1991). For example, in the upper Colorado River Basin in the United States, mean annual temperature has increased significantly since the end of the Little Ice Age (around 1850). As shown in Figure 2 (top) average temperature has increased by 1°C since systematic measurements began in 1895. In recent years the warming has been greater still; accelerated by human activities, change rates have become extremely rapid in some areas. At watershed weather stations in the western third of Colorado, precipitation has declined slightly but not significantly over the same period, decreasing on average by less than 3 percent (Figure 2, middle). Annual variation in temperature and precipitation has been significant (Figure 2, bottom), fluctuating sporadically from warm-dry years to cool-wet years, or from warm-wet years to cool-dry years, with many years in each quadrant. (The long-term average is at the centre of the diagram.) Forest plant and animal species in the watershed have been subjected to fluctuations in mean temperature of almost 5°C and a 30 percent range in annual precipitation since the beginning of the climate record.

Many long-lived forest plant and animal species have persisted despite these annual fluctuations in climate; indeed the fluctuations may have heightened their adaptability to long-term climate shifts. Still, annual fluctuations may have lesser effects on forest structure than extreme events such as droughts lasting several years or repeated years of warmer-than-average winters, which exacerbate major outbreaks of forest insects. Thus, rare climate scenarios may have long-lasting effects on forest structure and biomass and later downstream flows.

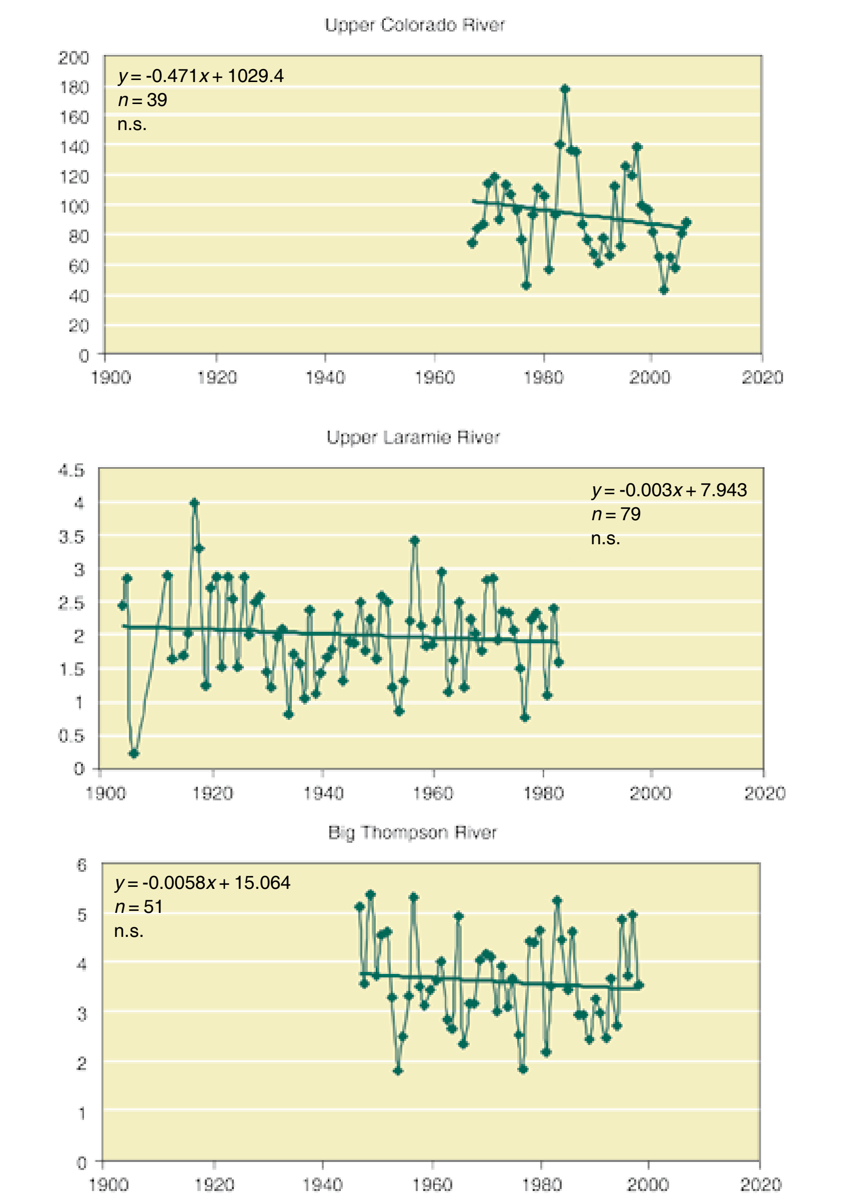
Stream flow affects the timing and delivery of water downstream for agricultural and domestic uses. An analysis

2
Long-term temperature (top), precipitation (middle) and annual fluctuation (bottom) for the Colorado River Basin



Source: Western Regional Climate Center, wrcc@dri.edu of three upper-elevation watersheds in Colorado showed no significant trends in stream flow but high annual variation (Figure 3). Other investigators have shown tendencies for earlier snowmelt and peak stream flows of several watersheds in the western United States under current and projected climatic conditions (Leung *et al.*, 2003; Stewart, Cayan and Dettinger, 2004, 2005). Storm runoff and rain added to snow events may be more common in a warming climate. However, multi-year droughts may be even more detrimental. It is likely that many water supply systems that developed under historically wetter conditions may be inadequate during exceptional droughts. Mega-droughts, such as a drought in the lower Colorado River in the mid-1100s believed to have lasted 60 years or more (Meko *et al.*, 2007), should capture the attention of today's water planners.

3
Annual stream flow data for three upper-elevation watersheds in Colorado (discharge, m³ per second)



Source: USGS, 2007

Stream flow depends heavily on the amount, timing and form of precipitation. Generally, snow remains in the watershed longer than rain. Groundwater storage, loss and recharge also have an influence on stream flow. Other important factors include the periodicity and sequencing of wet and dry years relative to groundwater recharge and water supply systems (e.g. irrigation systems, canals, dams) which buffer the effects of drought.

There is little doubt that future climate change will affect water supplies – fluctuations in climate have always done so. However, this influence is interlinked with forest and landscape legacies, altered disturbance regimes and invasive plants, insects and pathogens.

ALTERED DISTURBANCE REGIMES

Humans have caused changes in many natural systems by altering historic disturbance regimes such as the frequency, intensity and pattern of wildfires and insect outbreaks. Likewise, flood control with dams, reservoirs and canals has an obvious effect on flow patterns in many watersheds. Fire suppression has greatly reduced the number of wildfires each year in the United States (Figure 4, top), while the area of each fire appears to be on the increase (Figure 4, bottom). Extensive logging and very large fires in the first half of the twentieth century altered many forested watersheds in the Colorado Rocky Mountains, as evidenced by hundreds of repeat photographs (Veblen and Lorenz, 1991). Subsequent even-aged and dense forest regrowth undoubtedly added to forest homogeneity and the amount of fuels available for wildfires today in some areas.

Native insect and pathogen outbreaks are periodic and can be locally devastating to forest structure and biomass, which in turn affect water supplies. Large bark beetle outbreaks have affected several million hectares of United States forests in recent years. Defoliated forests may behave similarly to forests that have been burned, but the effect of defoliation may not be as extensive or continuous in many areas. While the co-evolution of native forest species with native insects and pathogens provides some ecosystem resilience, native forests are now additionally bombarded with non-native invasive pests for which natural defences are limited.

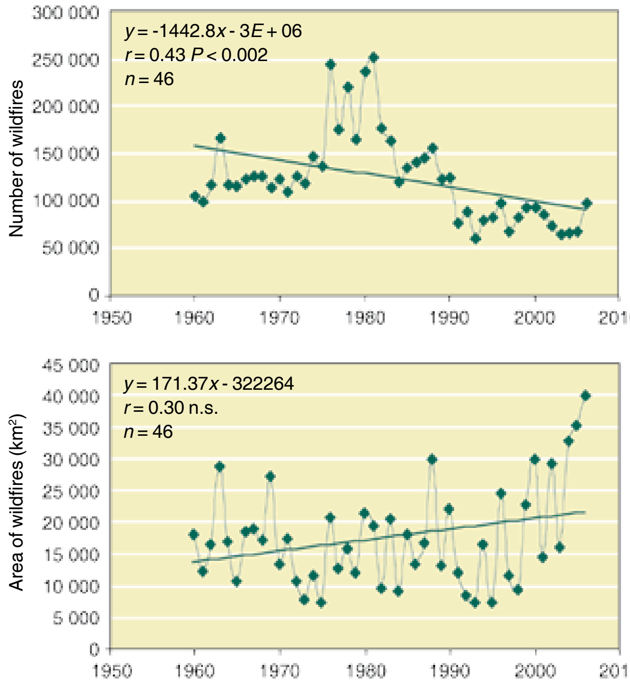
INVASIVE SPECIES

Non-native invasive forest pests and pathogens add significant stress to watersheds, with the ability to decimate large expanses of intact forest. Notorious examples in the United States, some introduced recently, include fungal and fungal-like diseases such as sudden oak death (caused by *Phytophthora ramorum*) (Figure 5), chestnut blight (caused by *Cryphonectria parasitica*), Dutch elm disease (caused by *Ophiostoma* spp. and spread by the elm bark beetle, *Scolytus multistriatus*) and white pine blister rust (caused by *Cronartium ribicola*); and insect pests such as gypsy moth (*Lymantria dispar*) and emerald ash borer (*Agrilus planipennis*). White pine blister rust, for example, has caused over 90 percent mortality to some subalpine forest stands in Glacier National Park, Montana. Because native forest species have not co-evolved with the pests, their natural defences may be limited.

Other harmful invasive non-native species may indirectly affect forest structure. Invasive earthworms in the United States are changing soil structure and nutrient cycling. Non-native grasses and shrubs, often dispersed by birds spreading the seeds, can alter the fuel loads in forests and thus the natural fire regimes.

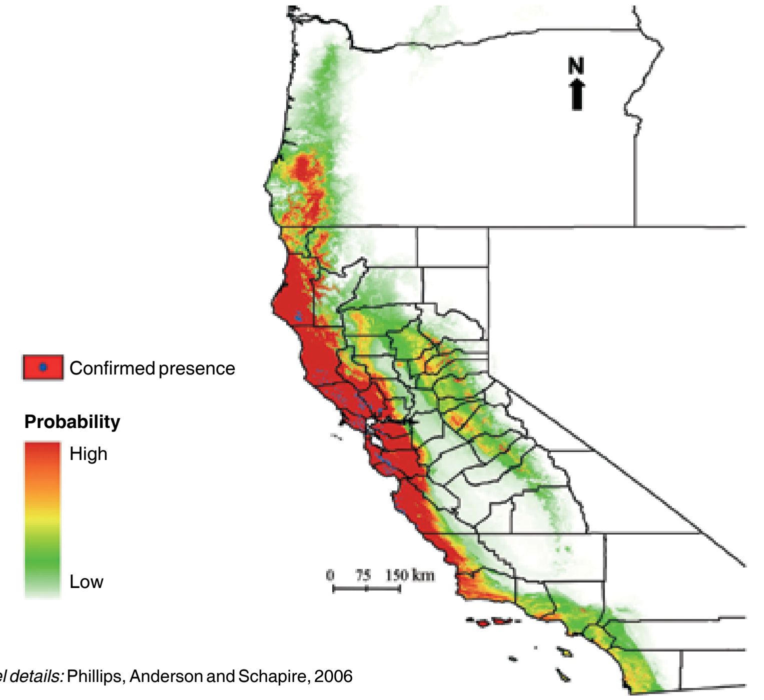
Some invasive species directly or indirectly affect stream water quality and quantity. For example, Japanese knotweed (*Fallopia japonica*), which has more shallow roots than native riparian species, can affect water quality

4
United States wildfire statistics, 1960–2006



Source: National Interagency Fire Center, 2007

5
Potential habitat suitability map for distribution of **Phytophthora ramorum*****, the pathogen causing sudden oak death, in the western United States, prepared using maximum entropy distribution modelling technique***



Model details: Phillips, Anderson and Schapire, 2006

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Typical forest affected by sudden oak death, California, United States

by increasing the suspended sediment loads and turbidity (Talmage and Kiviat, 2002). A freshwater diatom, *Didymosphenia geminata*, is changing physical and biological conditions in streams and may indirectly affect stream water quality by forming masses or blooms that degrade fish habitat, smother submerged plants and invertebrates and restrict water flow while depleting dissolved oxygen (Spaulding and Elwell, 2007).

The cumulative effects of non-native invasive plants, insects and pathogens may affect forest structure and biomass and downstream water availability. Increased trade, transportation, and long-range transport may exacerbate the problem. Pest inspectors intercept additional forest pests every year.

AN INTEGRATED APPROACH

An integrated approach is needed to quantify and understand the effects of multiple factors on the quantity, timing and quality of downstream water from montane watersheds. Some investigators have tried to isolate the effects of recent climate change on disturbance regimes (e.g. Westerling *et al*., 2006), but a more comprehensive, integrated and long-term view may be warranted. The landscape legacy can directly affect wildfire frequency and size and the occurrence of invasive pathogens that add to the problem (Figure 6). Invasive forest plants, insects and pathogens can, in turn, directly affect the disturbance regime (e.g. invasive grasses altering the frequency of fire, white pine blister rust directly killing trees). Climate change and fluctuation can directly affect precipitation (timing, amount and form) and water storage, or it can indirectly affect water availability by influencing species composition and the occurrence of native and non-native pathogens and pests or the disturbance regime (the frequency or intensity of fires or native insect outbreaks). Continued land-use change and resource use add to the ever-changing landscape legacy (Stohlgren *et al*., 1998). An integrated approach and careful monitoring of many interacting factors may be the only way to quantify and predict the complex of changes facing many mountain watersheds.

To develop a predictive science, water managers have a long way to go. Despite the general trends discussed above, site-specific predictions and models of stream flow have eluded scientists. For example, in 2002 precipitation in Denver, Colorado was below average, and newspapers at the time predicted continued drought and low runoff for the city's water supply. However, subsequent years (through 2007) had much higher and even above-average runoff despite the regional trends of warmer temperatures (Denver Water, 2007). Unfortunately, scientists have yet to create accurate predictions of stream flow months to seasons in advance.

An integrated approach, which quantifies the current condition and past trends, can be combined with spatial and temporal modelling to develop likely scenarios of future change in forest structure and water supply. A strong "ecosystem forecasting" capability is the key: combining geographic information system (GIS) technologies with climate and land-use scenarios, while preventing and minimizing the effects of harmful invasive species. ◆

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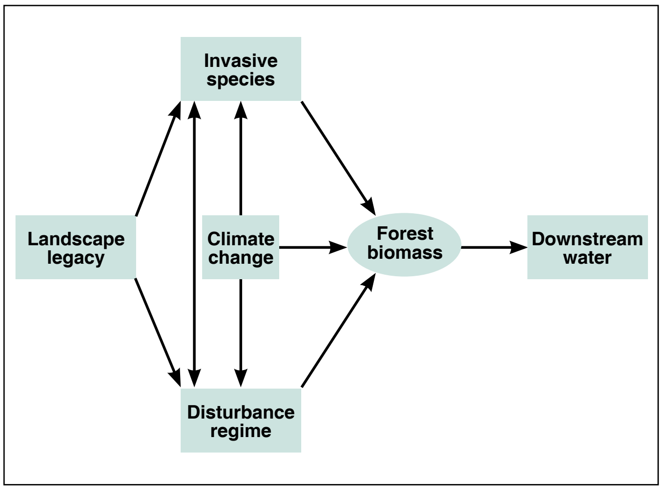
Multiple factors affecting the quantity, timing and quality of downstream water in mountain watersheds



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