Forest Management to Protect Colorado's Water Resources

A Synthesis Report to Support House Bill 16-1255

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COLORADO
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COLORADO STATE FOREST SERVICE
COLORADO STATE UNIVERSITY

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Executive Summary

The Colorado Water Plan is a collaborative framework that sets forth objectives, goals and actions by which Coloradans can collectively address current and future water challenges through feasible and innovative solutions. As a majority of the state's water supply flows from forested watersheds, the Colorado State Forest Service (CSFS), a service and outreach agency of the Warner College of Natural Resources at Colorado State University, is an active partner in working to achieve these goals.

Per the mandate of House Bill 16-1255: Concerning Additional Methods to Manage Forests to Secure Favorable Conditions for Water Supply, this synthesis report includes the results of recent research documenting the effects of wildland fire, insect and disease outbreaks, a changing climate, and roads and human disturbance on Colorado's forests and water supply. It describes the challenges and potential benefits of forest management treatments for water quantity and quality needs. It also includes a brief summary of the potential costs to – and effects on – watersheds, communities, water users and infrastructure if forest management does not occur.

Forest disturbances, such as wildfire and insect and disease outbreaks, are a natural part of the cycle of change in forested landscapes. Over the last two decades, however, Colorado has witnessed both growing numbers of large, high-severity wildfires and unprecedented levels of tree mortality caused by bark beetle outbreaks. Recent research has advanced scientific understanding regarding the watershed implications of these disturbances, yet much remains to be learned. Projections of increased disturbance frequency and severity have therefore created concerns regarding the sustained delivery of clean water from headwater forests.

Science-based forest management can reduce hazardous fuels levels linked to wildfire risk and severe fire behavior, and can create forest stand conditions that are less susceptible to bark beetle infestations. Active treatments aimed at protecting human safety, homes and other infrastructure play an important role in reducing costs to communities and water users in the expanding wildland-urban interface. Additionally, the application and evaluation of Forestry Best Management Practices are known to limit erosion and water quality impairment from forest harvesting and road building, and road use by industry, recreationists and rural landowners. Partnerships are essential for completing management activities, with the CSFS working with public and private partners to achieve watershed health and water supply protection goals.

Figure 1. Sediment flowing into the Milton Seaman Reservoir as a result of erosion and runoff after the 2012 Hewlett Gulch Fire in Larimer County. Photo: Brad Piehl, JW Associates Inc.

Front Cover: Dillon Reservoir in autumn.
Photo: Shutterstock

Back Cover: Poudre River, Larimer County.
Photo: Nancy Dadisman, CSFS

Background

The Colorado Water Plan (CWCB, 2015) is a collaborative framework that sets forth objectives, goals and actions by which Coloradans can collectively address current and future water challenges through feasible and innovative solutions. The Colorado State Forest Service (CSFS) is an important partner in working to achieve these goals, as the forested watersheds of Colorado are headwaters for rivers that flow through 19 states to provide water for downstream users. These watersheds also provide abundant recreation and tourism activities and revenues; habitat for diverse wildlife species; and jobs and materials for a sustainable wood products industry.

This synthesis report focuses on providing scientific information about the benefits and challenges of managing Colorado's forests to secure favorable conditions for water supply, as directed by House Bill 16-1255 and as a supplement to the Colorado Water Plan.

Colorado's River Systems

Figure 2. Colorado's river systems provide water to 19 states and Mexico.

Below is the key tenet of HB 16-1255 addressed in this report:

> "IN CONJUNCTION WITH THE COLORADO WATER CONSERVATION BOARD," the CSFS shall "COMPILE AND SUMMARIZE FINDINGS FROM EXISTING STUDIES TO QUANTIFY AND DOCUMENT THE RELATIONSHIP BETWEEN THE STATE WATER PLAN ADOPTED PURSUANT TO SECTION 37-60-106 (1) (u), C.R.S., AND THE IMPORTANCE OF FOREST MANAGEMENT IN PROTECTING AND MANAGING COLORADO'S WATER RESOURCES."
>
> Also per the legislation, the report includes a brief summary of:
>
> "(A) THE POTENTIAL COSTS TO AND EFFECTS ON WATERSHEDS, COMMUNITIES, WATER USERS, AND INFRASTRUCTURE IF APPROPRIATE FOREST MANAGEMENT DOES NOT OCCUR AND A FORESTED AREA BURNS; AND
>
> (B) THE POTENTIAL BENEFITS OF COMPLETING FOREST MANAGEMENT TREATMENTS."

The Colorado Water Conservation Board (CWCB) was created more than 75 years ago to provide policy direction on water issues. The CWCB is Colorado's most comprehensive water information resource, with a mission "To conserve, develop, protect and manage Colorado's water for present and future generations." The agency maintains expertise in a broad range of programs and provides technical assistance to further the utilization of Colorado's waters.

Established in 1955, the CSFS is a service and outreach agency of the Warner College of Natural Resources at Colorado State University and also provides staffing to the Division of Forestry in the Colorado Department of Natural Resources. The mission of the CSFS is "To achieve stewardship of Colorado's diverse forest environments for the benefit of present and future generations." The CSFS has a lasting commitment to provide timely, relevant forestry information and education to the citizens of Colorado to achieve resilient forests and communities, utilizing a non-regulatory approach and strategic partnerships with other agencies and institutions (CSFS, 2016b).

The Importance of Healthy Forests for Water Supplies

Water is a fundamental but limited resource in semi-arid Colorado and throughout the West. A majority of Colorado's public water supply originates in the forests of the Rocky Mountains (Hutson et al., 2004). More than 24.4 million acres of native Colorado forestland, ranging from high-elevation alpine forests to lower-elevation piñon pine and riparian forests on the plains, impact the state's water supply by protecting soil and preventing erosion, filtering contaminants, enhancing soil moisture storage and groundwater recharge, and reducing the likelihood of flooding by protecting and maintaining plant communities (CSFS, 2009; CSFS, 2016b). As a result of internal ecosystem processes, the water flowing from undisturbed forested watersheds typically has lower nutrient and sediment concentrations compared to flows from watersheds dominated by urban or agricultural land uses (USGS, 1999; Ryan, 2000; Ice and Binkley, 2003; MacDonald and Stednick, 2003).

While a majority of the state's water originates on the western side of the Continental Divide, only 11 percent of the state's population resides there. Networks of pumps, ditches, tunnels and reservoirs move the water to – or store it on – the eastern side of the Divide, where 70 percent of the state's water is consumed (Harding, 2014). Surface water supplied from Colorado's forests supports a variety of needs, including use as public drinking water, agriculture/irrigation supply, industrial uses (i.e., for mining or manufacturing), recreation opportunities, and habitat for aquatic life (USFS, 2008).

As a headwaters state, Colorado also carries the responsibility of providing water not only for its own population, but to multiple downstream users. Four major U.S. rivers begin as snowmelt in the mountains of Colorado – the Arkansas, Colorado, Platte and Rio Grande (USGS, 1990). These rivers drain one-third of the lands within the lower 48 states and provide essential water supplies to 19 states and Mexico. Projected growth in Colorado's population and in areas beyond the state's borders, combined with projected shifting and potentially increasing water consumption patterns in some sectors, means there is an increasing need for ensuring the delivery of reliable and high-quality water supplies from Colorado's forested watersheds (CWCB, 2010; USCB, 2017).

Forest Condition, Disturbances and Water Supplies

There is an important connection between the quality of water and the health of the forested watershed from which it flows, and active management may help maintain forest health and avoid watershed disturbance and impaired water supply (Ryan and Glasser, 2000). The Colorado Water Plan discusses regulations, guidance and policies aimed at protecting the quality of our water resources and mandates that management for water quality and quantity must be integrated (CWCB, 2015).

The Colorado Statewide Forest Resource Assessment (CSFS, 2009) identified 642 watersheds susceptible to damaging wildfire, and 371 forested watersheds with high to very high risk from post-fire erosion. Many of these watersheds, encompassing about 9.4 million acres of spruce-fir, aspen and pine forests, contain critical infrastructure for municipal drinking water supplies, such as intakes, reservoirs and trans-basin diversion structures (Figure 3). A majority of the land within these identified watersheds is federally managed, but privately held forestlands account for 2.72 million of these acres (Figure 4). In Colorado, almost 1.4 million acres of public and tribal lands, and another 636,000 acres of private and family-owned forestlands, are classified as having high fire risk and a high importance to water supply (American Forest Foundation, 2015).

Colorado's Water Supply Infrastructure

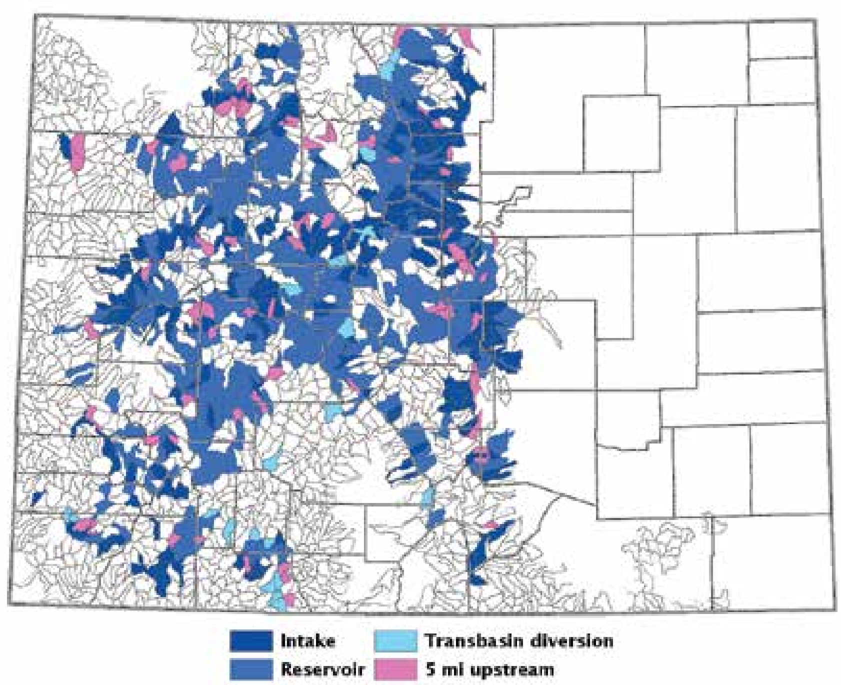

Figure 3. Many of Colorado's water supply sources have intakes, reservoirs or trans-basin diversion structures that face risks from wildfire and forest disturbance.

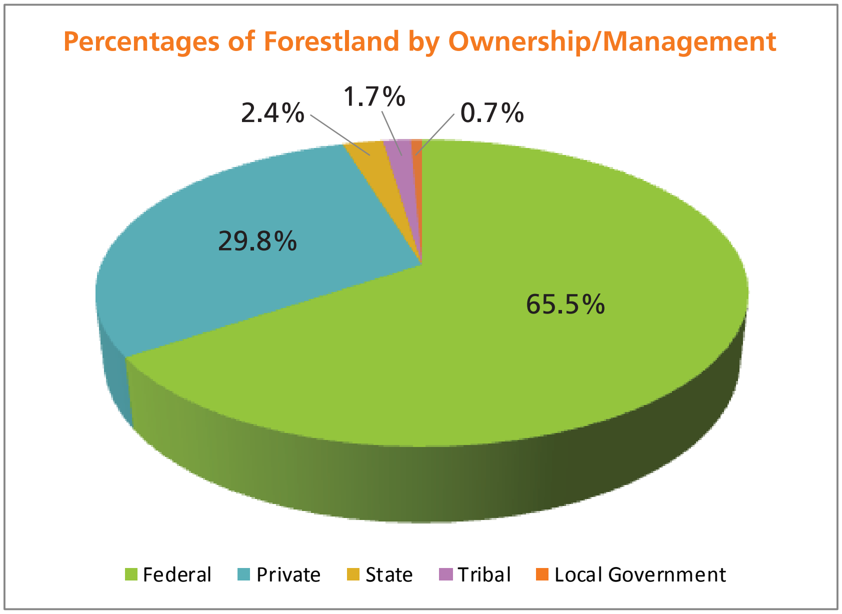

Figure 4. The majority of forestland in Colorado is either federally or privately owned.

Additional modeling efforts using geospatial tools to identify forest wildfire risk, potential impacts to watershed health and quality, and opportunities for mitigation have been carried out for the Rocky Mountain region (e.g. Thompson et al., 2013) and are ongoing for Colorado (e.g. Gannon et al., 2017). The identification of these risks is important in directing active management efforts and securing funding to protect these resources. For example, from 2002 to 2012, the federal government appropriated an average of $141 million annually for wildfire protection, with 86 percent of the total provided as grants to states to enhance state, local and rural firefighting capacity through a wide variety of activities, such as fuels reduction, capacity-building and fire prevention efforts (Gorte, 2013).

Impacts of Fire on Forests and Water Supplies

Wildland fire is part of the natural process of forest regeneration. Yet historic fire suppression policies, increased mortality from insect and disease outbreaks, and a changing climate have altered both the timing and severity of fire regimes in many areas, such as in the ponderosa pine forests of southwestern Colorado that historically experienced more frequent surface fires (Korb et al., 2012; Westerling et al., 2006). In other forest types, such as spruce-fir and lodgepole pine, infrequent yet high-severity fires are more common (Shoennagel et al., 2004). Management activities that are suitable for one location or forest type are likely unsuited for another, requiring science-based consideration of management objectives and site capabilities prior to application of best practices to protect resources (e.g. Romme et al., 2006; Reinhardt et al., 2008). The infrastructure required to deliver and treat water is typically built within or adjacent to the wildland-urban interface (WUI), due to the proximity of source water supplies. In the WUI, increasing exurban development and population growth, combined with an increase in the number and size of wildfires in many forest types, have substantially increased fire control and recovery costs (Theobald and Romme, 2007; Dale, 2010; Westerling, 2016).

Fire severity typically is measured in terms of loss of organic material due to combustion, and is an index that attempts to capture the effects of fire intensity, fire residence time and pre-fire conditions as related to fuel moisture, species and stand composition, and other physical site characteristics (Keeley, 2009).

Figure 5. The 2016 Beaver Creek Fire, north of Walden. Photo: Weston Burch

Figure 6. Much of the 2013 West Fork Complex Fire in southwest Colorado burned at high severity. Photo: Joe Duda, CSFS

Wildfire severity often affects watershed processes that regulate sediment, streamflow and nutrient responses (Keeley, 2009; Rhoades et al., 2011; Moody et al., 2013). Therefore, both land managers and water providers are concerned about the threat of high-severity wildfire since these events result in greater impacts to vegetation, soils and water supplies.

Post-Fire Sediment Production and Transport

Severe wildland fires that are followed by high-intensity summer rain events can result in high sediment yields. For example, burned areas in ponderosa pine forests were found to yield 25 times more sediment than unburned areas, and yields from hillslopes burned at moderate or high severity tend to be an order of magnitude higher than those burned at low severity (Johansen et al., 2001; Gannon et al., 2017). Post-fire erosion measured on the Colorado Front Range produced between 3.5 to 4.5 tons per acre of sediment annually after high-intensity fires that burned between 1994 and 2000 (Benavides-Solorio and MacDonald, 2005). Recovery of vegetation over a six-year period following the Front Range burns reduced the levels of erosion to those observed from low-intensity fires (Benavides-Solorio and MacDonald, 2005).

High-severity fires impact forest soils through exposing them to erosion by the removal of vegetation and duff, and facilitating the formation of a waxy, water-repellent hydrophobic layer at or below the soil surface. This layer is due to fire-induced volatilization of naturally occurring organic compounds, and can reduce infiltration rates of water into the soil (Moody and Martin, 2001; MacDonald and Stednick, 2003; CSFS, 2009). The strength and distribution of the hydrophobic layer depends on the pre-fire type and distribution of vegetation, the soil texture, soil moisture, fire severity and time since burning (Huffman et al., 2001). The effects of fire-induced hydrophobicity dissipate over time, with experiments in the Front Range of Colorado suggesting a weakening of effects in as little as three months after burning, though some sites may still be more hydrophobic than unburned areas 22 months or more after fire (Huffman et al., 2001).

The hyper-dry conditions often experienced during extreme fire weather events, combined with hydrophobicity effects and the effects of ash deposition and movement, can lead to almost all of the rainfall occurring immediately after a severe fire to become runoff. This runoff can transport soluble nutrients and organic pollutants into water supplies, and increase the likelihood of extreme flooding and debris flows (Rhoades et al., 2011; Moody and Ebel, 2012; Bodí et al., 2014). The amount of sediment delivered to the water supply and the amount of geomorphic change to stream channels occurring after severe fire varies, however, depending on a number of factors including precipitation regime and rainfall intensity, site characteristics and spatial scale (Benavides-Solorio and MacDonald, 2005; Moody et al., 2013; Wohl, 2013; Kampf et al., 2016). Detrimental effects on stream temperatures, water chemistry and aquatic ecosystems can occur on timescales from a few years to decades, or even centuries in stream channels with high amounts of aggradation (Kershner et al., 2003; Isaak et al., 2010; Mahlum et al., 2011). Increased sediment loadings delivered from streams also can shorten reservoir life and result in increased maintenance costs (Collins and Kimbrel, 2016).

Figure 7. Post-fire erosion near Cheesman Reservoir following the 2002 Hayman Fire. Photo: Kristin Garrison, CSFS

Wildfire and Water Quality

Delivery of post-fire nutrients, sediments and pollutants to surface waters has implications for aquatic biota, fisheries, recreation, water supply infrastructure and treatment. Drinking water treatment processes also operate most efficiently and economically when source water quality remains constant. The spatial and temporal heterogeneity of fire effects, combined with those of precipitation events, can result in unequal system loading and a need to develop site-specific treatment plans (Writer and Murphy, 2012). Increased nutrients can promote algal growth, impairing water taste and odor and releasing toxic compounds. Dissolved organic carbon can form potentially carcinogenic by-products during drinking water disinfection, and metals such as manganese can increase chemical treatment costs and increase disposal costs for larger volumes of sludge generated from treatment (Writer and Murphy, 2012). Little is known about what regulates the magnitude and duration of post-fire water quality effects, making it difficult for water providers and land managers to evaluate risks and develop management strategies (Writer and Murphy, 2012; Bladon et al., 2014; Martin, 2016).

Research from across Colorado and western North America indicates that runoff following high-severity wildfires contributes elevated nutrient and sediment loads to drinking water treatment plants and reservoirs for longer than previously expected, although the duration and magnitude of post-fire water quality effects varies (Moody and Martin, 2001; Writer and Murphy, 2012; Rhoades et al., 2017). For example, the October 2012 Fern Lake Fire resulted in elevated levels of turbidity, nitrate and total dissolved nitrogen in the Big Thompson River (Mast et al., 2015). Intense rainstorms tended to increase turbidity, and nitrate pulses were recorded in snowmelt the second spring after the fire. Though these nitrate levels were 10 times higher than those observed in unburned conditions, and in excess of EPA and state nutrient criteria for healthy stream biota, they remained below human drinking water thresholds (Mast et al., 2015).

In contrast, increased stream nitrogen, temperature and turbidity levels were elevated for more than five years after the severe 2002 Hayman Fire, with nitrogen and temperature remaining elevated for more than 14 years after the fire (Rhoades et al., 2011; Rhoades et al., 2017b). One water quality adaptation strategy used by the City of Fort Collins, after the 2012 High Park and Hewlett Gulch fires impacted water supplies from the Cache la Poudre watershed, was to switch entirely to water from another source unaffected by the fires during times of extremely high turbidity. The city also shut down water intake to reduce sediment accumulation in delivery pipelines (Writer et al., 2014). This strategy, though effective in ensuring water delivery to the hundreds of thousands of customers in the area, would not be an option for utilities relying on a single-source water supply.

Figure 8. Debris flowing into Goose Creek in 2014, following the 2013 Papoose Fire/West Fork Complex on the Rio Grande National Forest. Photo: Mike Blakeman, USFS

Insect and Disease Effects on Water Supplies

Widespread tree mortality from insect outbreaks in Colorado and across western North America has prompted concerns about potential impacts on water quality and quantity. Research on recent bark beetle activity in Colorado and elsewhere has shown that watershed-scale effects on water supply are less dramatic than those occurring after wildfire or forest harvest. Tree losses can potentially affect the accumulation of seasonal snowpack and timing of runoff, particularly after dust-on-snow events, but evidence shows that stimulated growth of remaining live vegetation and forest regeneration may offset any gains in water

yield and mitigate nutrient losses after overstory mortality (Pugh and Gordon, 2013; Rhoades et al., 2013; Livneh et al., 2015; Rhoades et al., 2017).

Large-scale bark beetle outbreaks result in altered water and nutrient demands from living trees, and these changes have implications for nutrient export and impacts on stream water quality. A study of lodgepole pine forests in Grand County, Colo., for example, found elevated soil moisture and nitrogen levels beneath trees killed by bark beetles (Clow et al., 2011). However, comparisons of data from Colorado watersheds with varying forest management histories found that those with a mixture of tree sizes and ages have proportionally lower mortality and reduced effects on water quality for 10 years after a bark beetle outbreak occurs. This is because pine bark beetles preferentially attack larger-diameter, typically older trees, and growth of the smaller, younger trees spared from beetle attack responds vigorously (Rhoades et al., 2013; Rhoades et al., 2017).

Research remains ongoing regarding the susceptibility of insect-damaged forests to fire, and the resulting severity of fires in these stands, with associated impacts to water quality and quantity (e.g. Jolly et al., 2012). The effects of tree mortality on fuels and stand structure are complex, with differing effects depending on the stage and severity of an outbreak, stand composition, and topography and size of affected areas (Harvey et al., 2014; Pelz et al., 2015). Empirical and modeling studies in lodgepole pine and spruce stands suggest that the influence of beetle outbreaks on fire risk and/or severity is negligible, especially for short time intervals between outbreaks and fire, when compared to the influences of weather and climate on fire risk (Black et al., 2013; Harvey et al., 2014; Andrus et al., 2016).

Figure 9. The 2016 Beaver Creek Fire burned through dead and downed beetle-kill trees. Photo: Chris Green, USFS

Figure 10. The Beaver Creek Fire burned in "jackstraw" lodgepole pine stands, composed of downed trees and those at risk of falling. Photo: Beaver Creek Incident Management Teams

Increasing fire activity in Colorado is more closely tied to weather and climate variability than bark-beetle outbreaks, though heavy standing and downed fuels create hazardous conditions for firefighting personnel in insect-damaged areas (Abatzoglou and Williams, 2016; Andrus et al., 2016; Westerling, 2016; USFS, 2017). For example, the Beaver Creek Fire of 2016 occurred in gray stage, beetle-killed forest with much dead and downed timber and new tree growth of varying stages. The extreme fire behavior from low fuel moisture contents and the arrangement of large-diameter fuels on the forest floor, combined with grasses, forbs and young trees acting as ladder fuels, resulted in a dangerous situation for fire crews to operate in (USFS, 2017). The fire ultimately burned for five months, with a cost of over $30 million for suppression, which only represents a small fraction of the total costs of the fire to the communities and ecosystems affected (Dale, 2010; Paul, 2016). More research is needed to assess how large accumulations of fallen trees and increasing amounts of fine fuels from understory vegetation and tree regeneration may influence long-duration, severe fires.

Climate Change Effects on Forest Health, Fire and Water

The need to understand and adapt to the impacts of climate change is a challenge facing all of Colorado's forest users, owners and managers. Though the Earth's climate has changed through time, it is the scale and rapid rate of change in modern times that is taxing the resilience of ecosystems and that will continue to impact the services they provide into the future (IPCC, 2013; Childress et al., 2015). While forest insect outbreaks, fires and other disturbances like windstorms and floods are a natural and important part of change in forested ecosystems – and which influence forest structure, function and composition – climate change is altering the occurrence, timing, frequency, duration, extent and intensity of these forest disturbances (Dale et al., 2001; Westerling et al., 2006; Millar and Stephenson, 2015; Abatzoglou and Williams, 2016; Westerling, 2016).

Warming trends in Colorado parallel those observed regionally and globally, and increases in temperature are expected to continue (IPCC, 2013; Lukas et al., 2014). Warmer temperatures favor the rapid development of insect populations in the summer and facilitate survival of larvae over the winter (Romme et al., 2006). While some historic insect outbreaks may have been as severe and/or as widespread as in current times, several interacting modern factors such as human-induced warming and recent drought conditions have exacerbated natural disturbance processes (Dale et al., 2001; Jarvis and Kulakowski, 2015). Moisture stress also has been cited as the cause of increasing tree mortality in subalpine forests of spruce-fir, lodgepole pine, aspen and limber pine, aside from mortality observed from insect attacks (Smith et al., 2015). Similar drivers have been identified for the severe mountain pine beetle outbreaks in both lodgepole and ponderosa pine forests that occurred over 3.4 million acres across Colorado since 1996 (Chapman et al., 2012; CSFS, 2017).

Figure 11. Spruce beetle-killed trees on Wolf Creek Pass. Warmer, drier climatic conditions were a contributing factor to the outbreak. Photo: Dan West, CSFS

An advance in warming spring temperatures also can have a significant effect on summer soil moisture conditions, making lodgepole pine and spruce-fir forests – which have less frequent, yet often more severe, natural fire occurrences than other forest types – particularly susceptible to climate-driven changes in fire frequency and severity (Westerling et al., 2006; Shoennagel et al., 2011; Westerling, 2016). In many cases, modern forests can be described as "climate-limited" in terms of fire ignition rather than "fuels-limited," as there typically exists sufficient fuel to carry a fire. The occurrence of fire depends more on weather and climate events, such as drought, for suitable ignition conditions (Shoennagel et al., 2004; Safford et al., 2012). On a global scale, fire season length and affected area has increased significantly (from 1979 to 2013) across most continents, particularly during the last decade (Jolly et al., 2015).

Annual occurrences of and total area burned by wildfire are projected to increase substantially in this century in Colorado and the West as the climate warms further (Spracklen et al., 2009; Liu et al., 2010; Pechony and Shindell, 2010; Moritz et al., 2012; Yue et al., 2013; Westerling, 2016). A 50 to 200 percent increase in annual area burned is projected in Colorado by approximately 2050, compared to conditions of the late 20th Century, based on projected warming of 2.5 to 5 degrees F (Spracklen et al., 2009; Yue et al., 2013). Also, the length of the state's fire season is expected to expand by several weeks (Yue et al., 2013).

There are uncertainties associated with projections of change, particularly for changes in precipitation and streamflow (Bates et al., 2008; Barsugli et al., 2012; IPCC, 2013; Vano et al., 2014). It is therefore important to identify vulnerabilities and consider ways in which impacts to forest systems, and resultant impacts on water supply, can be adapted to or managed (Dale et al., 2001; Childress et al., 2015). For example, while sediment delivery to water sources is likely to increase with increased amounts of forest disturbance and increased flooding risks associated with earlier spring snowmelt, forest management activities that encourage the use of Best Management Practices will ameliorate these effects and protect water supplies (CSFS, 2010; Goode et al., 2012). Activities such as planting trees, thinning forests and conducting prescribed burning and/or fuels reduction treatments may help reduce the severe effects of fire. Flexibility in management approaches and adaptation to meet local needs will be critical, particularly when considering forest management effects on water quality and quantity.

Figure 12. Forest roads provide important recreational access, but can potentially contribute significant amounts of sediment to water supplies. Photo: Grace Mirzeler, Council of Western State Foresters

Figure 13. Rich Edwards, CSFS assistant staff forester, trains field staff on Forestry BMPs to protect water resources. Photo: Lisa Mason, CSFS

Roads, Harvesting Operations and Human Disturbance: Impacts to Water Quality

The Colorado Water Plan discusses regulations, guidance and policies aimed at protecting the quality of water resources and mandates that management for water quality and quantity must be integrated (CWCB, 2015). Like severe fires, roads, trails and forest management efforts can collectively contribute high amounts of sediment to water supplies unless best management practices are properly applied.

Generally, undisturbed forest vegetation and litter protect soil from erosion processes including rainsplash and overland flows and generally promote high rates of infiltration of water into the soil, resulting in low sediment yields (Baker, 1990; Binkley and Brown, 1993; Robichaud, 2000; Stednick, 2000; Macdonald and Stednick, 2003; Robichaud et al., 2010). Sediment yields from undisturbed forests in the western U.S. have been reported at values from near 0 up to 0.25 tons per acre annually, though values up to 11 tons per acre annually have been measured (Binkley and Brown, 1993; Stednick, 2000). Management activities such as timber harvesting and road construction do not typically increase erosion rates as significantly as severe fire; however, these activities may increase erosion rates to 0.05 to 0.25 tons per acre in a year, depending on logging and yarding technique, site preparation practice, operator technique, soil vegetative cover, slope, soil moisture, soil depth, and soil texture, among other environmental factors. The impacts of management activities are considered acceptably low when there is less than about 30 percent of bare soil exposed after a given management method is applied (Gary, 1975; Stednick, 2000; MacDonald and Stednick, 2003; Stednick, 2010).

Forest roads often are the dominant source of long-term sediment supply in forested watersheds, with estimates of sediment contribution from roads in various ecosystems having typical values ranging from 1 to 10 tons per acre annually (Elliott, 2000; MacDonald and Stednick, 2003). Estimates for Colorado are slightly higher and range from about 2 to 31 tons per acre in a given year (MacDonald and Stednick, 2003; L. MacDonald, pers. comm., Sept. 26, 2016). The impacts of erosion from unpaved roads are generally proportional to the amount of watershed affected, but increasing trends in road building and recreational trail usage, particularly in the wildland-urban interface (WUI), suggest potentially increasing risks to water quality and supply infrastructure in these areas. Low-density residential development in the WUI is estimated to increase 300 percent by the year 2030 over year 2000 values (Theobald and Romme, 2007). Treatments such as re-vegetation when roads are no longer needed, or maintenance efforts that include adding gravel, can substantially reduce erosion.

While some forest management activities potentially contribute to increased sediment loads in streams and lakes, the proper application of Forestry Best Management Practices (BMPs) can ameliorate or reduce these effects (CSFS, 2010). Forest activities also can increase nutrient concentrations in streams, but rapid re-establishment of vegetation and the use of BMPs (e.g., streamside buffers) can trap and remove sediments and nutrients, reducing potentially negative effects (Stednick, 2000; CSFS, 2010). Biennially since 2008, the CSFS, in cooperation with other state and federal agencies, has monitored the application and effectiveness of forestry BMPs in the state through an audit steering committee and sample site visits from a field monitoring team (CSFS, 2016a).

Potential Benefits of Forest Management

The Colorado Water Plan sets forth measurable actions that are being taken statewide to address water challenges, through the protection of watershed health and the environment. Actions such as addressing at least 80 percent of locally prioritized rivers with stream management plans and 80 percent of critical watersheds with watershed protection plans by 2030 are important statewide water supply management goals, which have parallels to the forest planning and management activities undertaken by the CSFS (CWCB, 2015).

The planning and application of forest management practices by public and private agencies, institutions and landowners to protect watersheds, reduce impacts from insect and disease outbreaks, and reduce the severity of wildfire – particularly in the wildland-urban interface – are needed to help provide high-quality water supplies for Colorado's growing population. In the following sections, brief examples are provided of the benefits of forest management and the potential costs if management cannot or does not occur and a forested area subsequently burns. The section addresses costs and benefits by three categories: at the watershed level, at the community/user level, and when considering infrastructure.

Watersheds

At the watershed level, costs and impacts in the absence of forest management are potentially the greatest, and yet direct, watershed-scale management actions to reduce these costs are difficult to implement. Wildland fire can consume tens to hundreds of thousands of acres per year in Colorado's forests, and insect and disease outbreaks can affect even greater acreages through time (e.g. CSFS, 2017). The objective of forest management is not to eliminate these natural disturbances on the landscape, but to reduce unwanted high-severity wildfire and highly destructive insect and disease outbreaks, and their damaging effects on water resources (CSFS, 2012).

From a forest management perspective, watershed-level effects of wildland fire, insect outbreaks and other large-scale disturbance include:

- Increased erosion of the land surface from vegetation removal, soil hydrophobicity, ash deposition, and the resulting deposition of sediments and nutrients into water supplies.
- Undesirable changes in forest composition and structure that may alter the reliability and timing of snowmelt and seasonal runoff.
- Reduced water quality through the loss of soil organic layers and understory trees and vegetation responsible for nutrient retention.

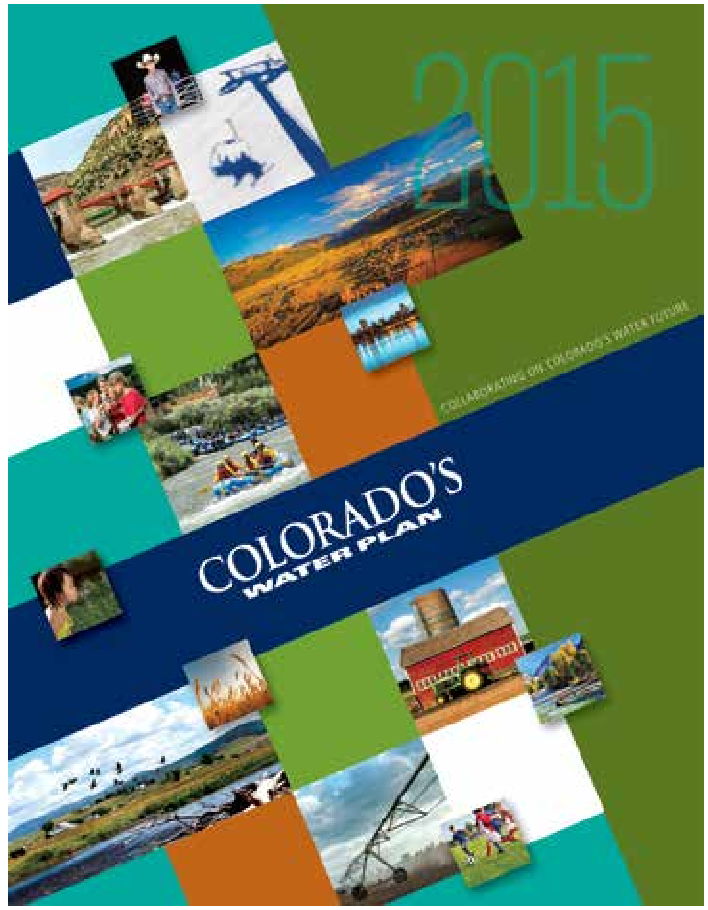

Figure 14. The Colorado Water Plan.

Potential costs, if forest management does not occur and a watershed burns, include:

- Increasing costs for treatment of impaired water supplies, reduced reservoir capacity and altered seasonal flows.
- Loss of previous use of the land (e.g., for recreation, fisheries and timber resources).
- Additional fire suppression and control efforts when resources of concern need protection, such as in the wildland-urban interface.
- The need to re-focus management efforts to rehabilitate the landscape.

Some direct examples of these costs include the more than $26 million Denver Water spent in initial response to the combined impacts of the Buffalo Creek and Hayman fires and subsequent heavy summer rainfalls; the $30 million-plus in losses associated with the Beaver Creek Fire; and impacts to the $13.2 billion outdoor recreation industry in Colorado (dollar amounts from

2011 and 2012 data) when recreationists can no longer access the resource (Outdoor Industry Association, 2012; Denver Water, 2017; Gannon et al., 2017; USFS, 2017). While many of these could be considered costs associated with a specific community or water user, wildland fire generally affects multiple communities and water users.

At the larger watershed level, few direct actions can be taken to reduce the severity or distribution of insect and disease outbreaks or the severity of wildfire under extreme weather or climate (drought) conditions. Even fuel treatments to reduce fire severity have costs associated with them, though the return on investment may be economically worthwhile. For example, a recently completed, detailed collaborative study for the upper Mokelumne watershed in the Sierra Nevada Mountains of California found that the economic benefits of landscape-scale fuel-reduction treatments outweighed the costs to implement the treatments (Buckley et al., 2014).

Reducing the Risk of Intense Wildfires

In most of the western U.S., forest productivity (or new growth) generally exceeds decomposition of dead wood, resulting in the accumulation of surface fuels in the absence of wildfire (Reinhardt et al., 2008). Pre-fire fuel treatments are designed to reduce fire intensity, preventing or reducing catastrophic impacts from severe fire on vegetation, soils, communities and water supplies (Martinson et al., 2003; Keeley, 2009). However, common misconceptions related to fuel treatments include: they completely fire-proof important areas to prevent homes in the wildland-urban interface from burning; they ultimately reduce fire size; they only need to be completed once to be effective; and that they have been proven to significantly reduce suppression and recovery costs (Reinhardt et al., 2008).

The proper application of fuels reduction treatments requires a scientific understanding of fire behavior responses to fuel structure changes (Martinson et al., 2003). Typical treatments include the use of prescribed fire and forest thinning with slash removal. The effects of past wildfires also are effective at reducing current fire severity (Martinson et al., 2003). During the 2002 Hayman Fire, extreme environmental conditions across much of the landscape overwhelmed the ability of fuel modifications to moderate wildfire severity. However, pre-fire fuel treatments may have altered fire spread patterns in many areas, and it was found that larger treatments were much more effective at potentially modifying fire behavior (Martinson et al., 2003). Coupled geospatial modeling approaches that combine information about fuel treatments with wildfire scenarios and resultant watershed responses allow managers and scientists to identify at-risk watersheds and target where the most cost-effective applications of fuel treatments would result in the maximum protection of important resources (Sidman et al., 2015; Gannon et al., 2017).

Figure 15. Pre-fire forest thinning efforts to reduce hazardous fuels in the Pine Glenn subdivision helped keep the 2013 Black Forest Fire on the ground, and likely spared some of the homes. Photo: Bill Cotton, Colorado State University

Influencing Water Quantity Through Forest Management

A concern addressed in detail in the Colorado Water Plan is how best to handle the "Supply-Demand Gap," or the projected shortfall between water supply and demand throughout the state (CWCB, 2015). A range of activities, such as conservation measures to reduce demand, increased supply via new reservoirs and water transfers between user groups, are underway to close the gap. Many years ago, increases in forest management activities also were proposed to increase water quantity. Intensive research efforts were directed at determining if management activities could positively affect the amount of water supplied as runoff from Colorado's forests, and the results have been variable.

Management practices such as partial cutting, or clearcutting, in colder, high-elevation spruce-fir dominated forests, can result in locally measurable increases in annual water yields and peak flows. This mainly occurs in the early spring due to less soil-water depletion by growing trees, and by reduced interception of snowfall by the canopy in winter (MacDonald and Stednick, 2003; Troendle et al., 2010). However, flow durations and low flows have not been observed to measurably increase, and in dry years a higher snow water equivalent (i.e., the amount of water held as snow) was needed to meet soil moisture demands – resulting in proportionally less runoff from harvested areas (Baker, 1986; Troendle and King, 1987; MacDonald and Stednick, 2003).

In lower-elevation regions, such as those occupied by ponderosa pine and Douglas-fir forests, increases in water yields are even more difficult to attain due to reduced amounts of precipitation and the dominance of evapotranspiration in these semi-arid

locations (MacDonald and Stednick, 2003). Increases in snow water equivalent from harvesting in these areas have primarily been limited to north-facing slopes (Haupt, 1979; Troendle et al., 2010).

Through time, any increases in runoff from tree harvesting efforts decrease with the re-establishment of forest vegetation, though the time scale varies depending on species and location. Decreases in water yields through time back to pre-harvest levels vary due to site-specific factors, but declines generally follow linear trends (i.e., 1958-1986 data, Troendle and Nankervis, 2000), with indications that annual water yields will return to pretreatment levels after about 60 years in spruce-fir forests, between 15 and 45 years in areas of faster-growing, high-elevation species such as aspen, and in as little as seven to 10 years in ponderosa pine forests (Troendle and King, 1985; Troendle and King, 1987; MacDonald and Stednick, 2003).

Figure 16. Forest harvesting can increase water yields in some forest types, and the response can persist for decades as the forest regrows. Photo: CSFS

Watershed Management Partnerships

Based on decades of CSFS experience, partnerships are critical for effecting change through forest management at the watershed scale. Examples of partnerships to manage impacts to forests and water supply at the watershed level in Colorado include activities on the Pikes Peak Watershed, the Colorado-Big Thompson Headwaters and the Upper South Platte Watershed.

More than 30 years ago, the CSFS contracted with Colorado Springs Utilities to implement management of 13,000 acres on the Pikes Peak Watershed. The goals of continued forest management include: protect water quality and improve water yields; identify and reduce wildfire risk; improve forest health and wildlife habitat; and maintain aesthetic qualities and recreational values (CSFS, 2017). Following the 2002 Hayman Fire, funding was increased to accelerate forest management to 200-300 acres of treatments annually, with another 200 acres of work scheduled for completion in 2017.

The Colorado-Big Thompson Headwaters Partnership between the Northern Water Conservancy District, U.S. Bureau of Reclamation, CSFS and USDA Forest Service involves the management of multiple areas of at-risk watersheds and those previously burned by wildfire, and that are susceptible to increased rates of post-fire runoff and erosion. A variety of factors, such as tree mortality from the mountain pine beetle epidemic, years of drought and warmer conditions, and the build-up of fuels in the forested landscape, have contributed to and complicated management of the high-intensity wildfires of the area that affect water quality conditions (CSFS, 2017). Partnership projects focus on fuels reduction and forest restoration through the removal of dead, dying and disease-infected trees; forest thinning; creating patch cuts in unnaturally dense stands; and creating fuelbreaks.

A watershed health-oriented partnership between the CSFS and Denver Water began more than three decades ago when a mountain pine beetle outbreak threatened forests in watersheds managed by the utility. Today, a Forest and Land Management Service Agreement (FLMSA) between the CSFS and Denver Water focuses on forest management across more than 50,000 acres, eight counties and five CSFS districts. Management of these lands has continued to evolve, expanding from the multi-year FLMSA to include several other agencies and projects, such as the

Figure 17. Forest and fuels management efforts in El Paso County are ongoing on the Pikes Peak Watershed, near Lake Moraine. Photo: Andy Schlosberg, CSFS

Upper South Platte Watershed Restoration Project, which has now treated more than 40,000 acres on Denver Water, USFS and private land (CSFS, 2017). More recent efforts in the Upper South Platte Watershed include the USFS From Forests to Faucets Project and the Upper South Platte Partnership (CSFS, 2017; Lockwood, 2017).

Figure 18. The 2012 fire season in Colorado resulted in the loss of six lives and hundreds of homes, and impacted thousands of residents and visitors. Photo: National Interagency Fire Center

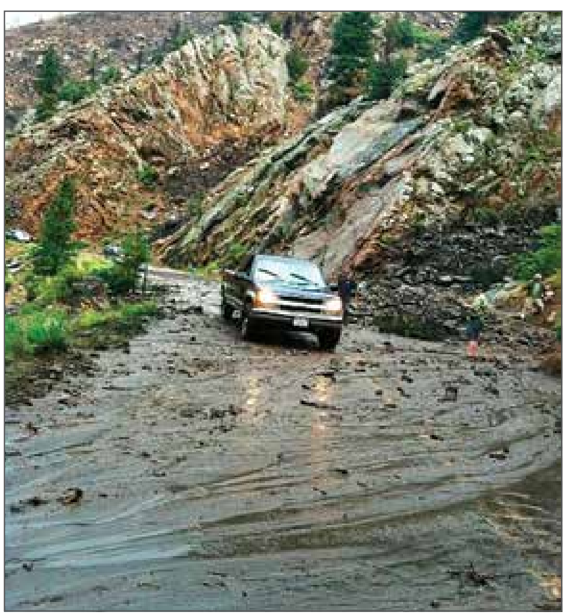

Figure 19. Mudslides in the lower Poudre Canyon after the 2012 High Park Fire impacted the highway and increased debris and sediment flows into the Cache la Poudre River. Photo: CSFS

Communities and Water Users

Wildland fire affects communities through the loss of homes and structures, and disruption of services and livelihoods. All water users (e.g., residential customers, municipal users, agricultural users) also are potentially affected by fire, through loss of use of the resource or increasing costs to cover treatment expenses or damage to utilities.

Effects of fire include:

- Loss of resources and disruption of services.
- Initial and potentially ongoing impairment of water supplies.
- Temporary closure of businesses and reduced recreational activity and tourism.

Potential costs, if forest management does not occur and an area burns, include:

- Higher costs of wildfire response and landscape rehabilitation to communities and users.
- Increasing costs for treatment of impaired water, borne by utilities within communities and individuals of all user groups.

Costs of wildfire response and rehabilitation for communities and users varies greatly depending on the size and severity of the incident. The most destructive wildfire in Colorado history, in terms of property losses, was the June 2013 Black Forest Fire. Estimated losses totaled $429.3 million (in 2015 dollars), resulting in over 4,000 homeowner and auto insurance claims (RMIIA, 2015). Also, the 2012 wildfire season in Colorado cost at least $584 million (in 2015 dollars) in fire damages to homes, damage from smoke, and damage to personal belongings and vehicles (RMIIA, 2015). These numbers do not include costs to utilities, or costs passed on to water users for damaged infrastructure and increased water treatment, but reflect the degree of damage possible from intense wildfire.

Infrastructure

The effects of fire on water supply infrastructure are generally related to costs of access, maintenance and usable life.

Effects of wildland fire include:

- Sedimentation of intakes, supply pipes and reservoirs.
- Damage to supply areas and equipment.
- Decreasing water quality to a point that the water supply becomes unusable with existing infrastructure.

Potential costs, if forest management does not occur and an area burns, include:

- A greater need to dredge sediment from reservoirs to extend useful life.

- Rehabilitation/replacement of equipment.
- Utilizing an alternate water supply, when possible.

One documented cost to fire-affected infrastructure is a portion of the nearly $150 million (cumulative) that has been spent on remediation efforts from when 15 percent of the total area of the catchment above the Strontia Springs Reservoir was disturbed by significant fire events, resulting in initial deposition of nearly 543 acre-feet of sediment into the reservoir, with ongoing accumulation rates of about 40 acre-feet per year (CSFS, 2013; Buckley, 2014; Denver Water, 2017; Gannon et al., 2017). Recently, fire behavior and erosion modeling and return on investment analyses have been completed for the reservoir to quantify how the extent and placement of fuel treatments may reduce sediment loading, and in return reduce dredging costs (K. Jones, pers. comm., April 15, 2017).

Figure 20. A Colorado mountain stream. Photo: Kathryn Seville

Conclusion

Sustained delivery of clean water is closely linked with the health of headwater forests, and projections of increased disturbance in these forests creates concerns regarding the future of Colorado's water resources. In recent decades, the state has witnessed both growing numbers of large, high-severity wildfires and unprecedented levels of tree mortality from bark beetle outbreaks. Research has advanced scientific understanding regarding the watershed implications of these disturbances and provided information to support proven forest management activities. Science-based forest management can create forest stand conditions that are less susceptible to bark beetle infestations, and also has been shown to reduce hazardous fuels levels linked to wildfire risk and severe fire behavior that can be harmful to watersheds.

More research needs to be done regarding the combined impacts of forest insect mortality, changing climatic conditions and accumulations of downed trees on fire severity, and regarding the effectiveness of pre-fire management activities on forest conditions. Additional research also is needed to better document the economic costs of pre-fire, landscape-scale management and catastrophic forest disturbances to communities and water users, from the perspective of management return on investment. Partnerships will continue to be key to implement effective management of forested watersheds for sustainable water supply and quality.

Figure 21. Mike Hughes, assistant district forester with the CSFS Fort Collins District, and his son plant seedling trees after the 2012 High Park Fire. Photo: Ryan Lockwood, CSFS

References

Abatzoglou, J.T. and Williams, A.P., 2016. Impact of anthropogenic climate change on wildfire across western U.S. forests. *Proceedings of the National Academy of Sciences,* 113(42): 11770-11775.

American Forest Foundation, 2015. Private forestland restoration is key to protecting Colorado's water supply. American Forest Foundation State Factsheet, 2 pp.

Andrus, R.A., Veblen, T.T., Harvey, B.J., and Hart, S.J., 2016. Fire severity unaffected by spruce beetle outbreak in spruce-fir forests in southwestern Colorado. *Ecological Applications,* 26(3): 700-711.

Bailey, R.G., 2010. *Cumulative watershed effects of fuel management in the western United States,* Chapter 2: Fire regimes and ecoregions. Elliot, W.J., Miller, I.S., and Audin, L. [Eds.]. General Technical Report RMRS-GTR-231. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 7-18.

Baker, M.B., Jr., 1986. Effects of ponderosa pine treatments on water yield in Arizona. *Water Resources Research,* 22(1): 67-73.

Baker, M.B., Jr., 1990. Proceedings of effects of fire management of Southwestern natural resources: Hydrologic and water quality effects of fire. General Technical Report GTR-RM-191. U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 31-42.

Barsugli, J.J., Vogel, J.M., Kaatz, L, Smith J.B., Waage, M., and Anderson, C.J., 2012. Two faces of uncertainty: Climate science and water utility planning methods. *Journal of Water Resources Planning and Management,* 138(5): 389-395.

Bates, B.C., Kundzewicz, Z.W., Wu, S., and Palutikof, J.P. [Eds.], 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Benavides-Solorio, J. and MacDonald, L.H., 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire,* 14: 457-474.

Binkley, D. and Brown, T.C., 1993. Forest practices as nonpoint sources of pollution in North America. *Water Resources Bulletin,* 29(5): 729-740.

Black, S.H., Kulakowski, D., Noon, B.R., and DellaSalla, D.A., 2013. Do bark beetle outbreaks increase wildfire risks in the central U.S. Rocky Mountains? Implications from recent research. *Natural Areas Journal,* 33(1): 59-65.

Bladon, K.D., Emelko, M.B., Silins, U., and Stone, M., 2014. Wildfire and the future of water supply. *Environmental Science and Technology,* 48: 8936-8943.

Bodí, M.B., Martin, D.A., Balfour, V.N., Santín, C., Doerr, S.H., Pereira, P., Cerdá, A., and Mataix-Solera, J., 2014. Wildland fire ash: Production, composition and eco-hydro-geomorphic effects. *Earth-Science Reviews,* 130: 103-127.

Buckley, M., Beck, N., Bowden, P., Miller, M.E., Hill, B., Luce, C., Elliot, W.J., Enstice, N., Podolak, K., Winford, E., Smith, S.L., Bokach, M., Reichert, M., Edelson, D., and Gaither, J., 2014. Mokelumne watershed avoided cost analysis: Why Sierra fuel treatments make economic sense. A report prepared for the Sierra Nevada Conservancy, The Nature Conservancy, and U.S. Department of Agriculture, Forest Service. Sierra Nevada Conservancy, Auburn, CA, 294 pp.

Chapman, T.B., Veblen, T.T., and Shoennagel, T., 2012. Spatiotemporal patterns of mountain pine beetle activity in the southern Rocky Mountains. *Ecology,* 93(10): 2175-2185.

Childress, A., Gordon, E., Jedd, T., Klein, R., Lukas, J., and McKeown, R., 2015. Colorado climate change vulnerability study: A report submitted to the Colorado Energy Office. Gordon, E. and Ojima, D. [Eds.], University of Colorado Boulder and Colorado State University, 190 pp.

Clow, D.W., Rhoades, C., Briggs, J., Caldwell, M., and Lewis, W.M., 2011. Responses of soil and water chemistry to mountain pine beetle induced tree mortality in Grand County, Colorado, USA. *Applied Geochemistry,* 26: S174-S178.

Collins, B.J., Rhoades, C.C., Battaglia, M.A., and Hubbard, R.M., 2012. The effects of bark beetle outbreaks on forest development, fuel loads and potential fire behavior in salvage logged and untreated lodgepole pine forests. *Forest Ecology and Management,* 284: 260-268.

Collins, K. and Kimbrel, S., 2016. Case study: How sedimentation affects Reclamation's operations. *The Knowledge Stream: Research and Development Office Newsletter,* Bureau of Reclamation, 2016-02: 14-15.

Colorado State Forest Service, 2009. Colorado Statewide Forest Resource Assessment: A Foundation for Strategic Discussion and Implementation of Forest Management in Colorado. Colorado State University, Fort Collins, CO, 96 pp.

Colorado State Forest Service, 2010. Forestry Best Management Practices to Protect Water Quality in Colorado, 2010. Colorado State University, Fort Collins, CO, 32 pp.

Colorado State Forest Service, 2012. *2011 Report on the Health of Colorado's Forests.* Colorado State University, Fort Collins, CO, 44 pp.

Colorado State Forest Service, 2013. *2012 Report on the Health of Colorado's Forests: Forest Stewardship Through Active Management.* Colorado State University, Fort Collins, CO, 40 pp.

Colorado State Forest Service, 2016a. *2015 Report on the Health of Colorado's Forests: 15 Years of Change.* Colorado State University, Fort Collins, CO, 32 pp.

Colorado State Forest Service, 2016b. *Five-Year Strategic Plan: 2016-2020.* Colorado State University, Fort Collins, CO, 12 pp.

Colorado State Forest Service, 2017. *2016 Report on the Health of Colorado's Forests: Fire and Water.* Colorado State University, Fort Collins, CO, 36 pp.

Colorado Water Conservation Board, 2010. State of Colorado, 2050 municipal and industrial water use projections, July 2010. Camp Dresser and McKee Inc. and Harvey Economics, 243 pp.

Colorado Water Conservation Board, 2015. *Colorado's Water Plan: Collaborating on Colorado's Future,* 567 pp.

Dale, L., 2010. The true cost of wildfire in the Western U.S. Western Forestry Leadership Coalition, Lakewood, CO, 16 pp.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., and Wotton, B.M., 2001. Climate change and forest disturbances. *Bioscience,* 51(9): 723- 734.

Denver Water, 2017. Professional services request for proposals: Strontia Springs – sediment management concept development. http://www.denverwater.org (Accessed March 7, 2017)

Elliott, W.J., 2000. *Drinking Water from Forests and Grasslands: A synthesis of the scientific literature,* Chapter 9: Roads and other corridors. Dissmeyer, G.E. [Ed.]. General Technical Report SRS-39. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC: 85-100.

Gannon, B., Wolk, B., Wei, Y., Kampf, S., Jones, K., MacDonald, L., Addington, R., Cheng, T., and Cannon, J., 2017. Connecting forests and water: Fuel treatment assessment and planning tools. *Colorado Water,* 34: 9-11.

Gary, L.H., 1975. Watershed management problems and opportunities for the Colorado Front Range ponderosa pine zone: The status of our knowledge. Research Paper, RM-139, U.S. Department of Agriculture, Forest Service, Fort Collins, CO, 32 pp.

Goode, J.R., Luce, C.H., and Buffington, J.M., 2012. Enhanced sediment delivery in a changing climate in semi-arid mountain basins: Implications for water resources management and aquatic habitat in the northern Rocky Mountains. *Geomorphology,* 139-140: 1-15.

Gorte, R., 2013. The rising cost of wildfire protection. Headwaters Economics, Research Paper, Bozeman, MT, 19 pp.

Harding, B., 2014. "DRAFT technical memo: SWSI climate impact support: Development of projected gauged flows." http://cwcbweblink.state.co.us (Accessed Oct. 8, 2014)

Harvey, B.J., Donato, D.C., and Turner, M.G., 2014. Recent mountain pine beetle outbreaks, wildfire severity, and postfire tree regeneration in the U.S. Northern Rockies. *Proceedings of the National Academy of Sciences,* 111(42): 15120-15125.

Haupt, H.F., 1979. Effects of timber cutting and revegetation on snow accumulation and melt in Northern Idaho. Research Paper INT-114, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 44 pp.

Huffman, E.L., MacDonald, L.H., and Stednick, J.D., 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes,* 15: 2877-2892.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004. Estimated use of water in the United States in 2000. U.S. Geological Survey Circular 1268, Reston, VA, 52 pp.

Ice, G. and Binkley, D., 2003. Forest streamwater concentrations of nitrogen and phosphorus: A comparison with EPA's proposed water quality criteria. *Journal of Forestry,* 101:21-28.

Intergovernmental Panel on Climate Change, 2013. *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. [Eds.]. International Organization for Standardization Standard Atmosphere, ISO 2533, Cambridge University Press, Cambridge, United Kingdom and New York, NY, 1535 pp.

Isaak, D., Luce, C., Rieman, B., Nagel, D., Peterson, E., Horan, D., Parkes, S., and Chandler, G.L., 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecological Applications,* 20(5): 1350-1371.

Jarvis, D.S. and Kulakowski, D., 2015. Long-term history and synchrony of mountain pine beetle outbreaks in lodgepole pine forests. *Journal of Biogeography,* 42: 1029-1039.

Johansen, M.P., Hakonson, T.E., and Breshears, D.D., 2001. Post-fire runoff and erosion from rainfall simulation: Contrasting forests with shrublands and grasslands. *Hydrological Processes,* 15: 2953-2965.

Jolly, W.M., Parsons, R.A., Hadlow, A.M., Cohn, G.M., McAllister, S.S., Popp, J.B., Hubbard, R.M., and Negron, J.F., 2012. Relationships between moisture, chemistry, and ignition of Pinus contorta needles during the early stages of mountain pine beetle attack. *Forest Ecology and Management,* 269: 52-59.

Jolly, W.M., Cochrane, M.A., Freeborn, P.H., Holden, Z.A., Brown, T.J., Williamson, G.J., and Bowman, D.M.J.S., 2015. Climate-induced variations in global wildfire danger from 1979-2013. *Nature Communications,* 6: 7531, 11 pp.

Kampf, S.K., Brogan, D.J., Schmeer, S., MacDonald, L.H., and Nelson, P.A., 2016. How do geomorphic effects of rainfall vary with storm type and spatial scale in a post-fire landscape? *Geomorphology,* 273: 39-51.

Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of Wildland Fire,* 18: 116–126.

Kershner, J.L., MacDonald, L.M., Decker, L.M., Winters, D., Libohova, Z., 2003. Ecological effects of the Hayman Fire: Part 6: Fire-induced changes in aquatic ecosystems. Hayman Fire Case Study. Graham, R.T. [Ed.]. General Technical Report RMRS- GTR-114. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT: 232-243.

Korb, J., Fulé, P.Z., and Stoddard, M.T., 2012. Forest restoration in a surface fire-dependent ecosystem: An example from a mixed conifer forest, southwestern Colorado, USA. *Forest Ecology and Management,* 269: 10-18.

Liu, Y.Q., Stanturf, J., and Goodrick, S., 2010. Trends in global wildfire potential in a changing climate. *Forest Ecology and Management,* 259: 685–697.

Livneh, B., Deems, J.S., Buma, B., Barsugli, J.J., Schneider, D., Moloch, N.P., Wolter, K., and Wessman, C.A., 2015. Catchment response to bark beetle outbreak and dust-on-snow in the Colorado Rocky Mountains. *Journal of Hydrology,* 523: 196-210.

Lockwood, R., 2017. From forests to faucets: Partnerships treat landscapes to protect Denver's Water Supply. *Colorado Water,* 34: 12-15.

Lukas, J., Barsugli, J., Doesken, N., Rangwala, I., and Wolter, K., 2014. Climate change in Colorado: A synthesis to support water resources management and adaptation, Second Edition, University of Colorado, Boulder, CO, 114 pp.

MacDonald, L.H. and Stednick, J.D., 2003. Forests and water: A state-of-the-art review for Colorado. Colorado Water Resources Research Institute Report No. 196, Colorado State University, Fort Collins, CO, 65 pp.

Mahlum, S., Eby, L., Young, M., Clancy, C., and Jakober, M., 2011. Effects of wildfire on stream temperatures in the Bitterroot River Basin, Montana. *International Journal of Wildland Fire,* 20(2): 240.

Figure 22. CSFS Steamboat Springs District Forester John Twitchell and State Forest Manager Russ Gross test water quality on the Colorado State Forest. Photo: Rich Edwards, CSFS

Martin, D.A., 2016. At the nexus of fire, water and society. *Philosophical Transactions of the Royal Society B: Biological Sciences:* 371.

Martinson, E., Omi, P.N., and Shepperd, W., 2003. Fire behavior, fuel treatments, fire suppression: Part 3. Effects of fuel treatments on fire severity. Graham, R.T. [Ed.]. Hayman Fire Case Study. General Technical Report RMRS-GTR-114, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT: 96–126.

Mast, M., Murphy, S., Clow, D., Penn, C., and Sexstone, G., 2015. Water-quality response to a high-elevation wildfire in the Colorado Front Range. *Hydrological Processes,* 30(12): 1811-1823.

Millar, C.I., and Stephenson, N.L., 2015. Temperate forest health in an era of emerging megadisturbance. *Science,* 349: 823-826.

Moody, J.A. and Martin, D.A., 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms,* 26: 1049-1070.

Moody, J.A. and Ebel, B.A., 2012. Hyper-dry conditions provide new insights into the cause of extreme floods after wildfire. *Catena,* 93: 58-63.

Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S., and Martin, D.A., 2013. Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews,* 122: 10-37.

Moritz, M.A., Parisien, M.A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J., and Hayhoe, K., 2012. Climate change and disruptions to global fire activity. *Ecosphere,* 3(6): 1-22.

Outdoor Industry Association, 2012. The Outdoor recreation economy: Take it outside for Colorado jobs and a strong economy. Boulder, CO, 2 pp. https://outdoorindustry.org (Accessed April 23, 2017)

Paul, J., 2016. Beaver Creek fire cost at roughly $300 million as massive blaze near Walden continues to smolder. *The Denver Post,* published online Nov. 21, 2016. http://www.denverpost.com (Accessed April 23, 2017)

Pechony, O. and Shindell, D.T., 2010. Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences,* 107(45): 19167-19170.

Pelz, K.A., Rhoades, C.C., Hubbard, R.M., Battaglia, M.A., and Smith, F.W., 2015. Species composition influences management outcomes following mountain pine beetle in lodgepole pine dominated forests. *Forest Ecology and Management,* 336: 11-20.

Pugh, E. and Gordon, E., 2013. A conceptual model of water yield effects from beetle-induced tree death in snow-dominated lodgepole pine forests. *Hydrological Processes,* 27: 2048-2060.

Reinhardt, E.D., Keane, R.E., Calkin D.E., and Cohen, J.D., 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *Forest Ecology and Management,* 256: 1997-2006.

Rhoades, C.C., Entwistle, D., and Butler, D., 2011. The influence of wildfire extent and severity on streamwater chemistry, sediment, and temperature following the Hayman Fire, Colorado. *International Journal of Wildland Fire,* 20: 430-442.

Rhoades, C., McCutchan, J., Cooper, L., Clow, D., Detmer, T., Briggs, J., Stednick, J. D., Veblen, T.T., Ertz, R.M., Likens, G.E., and Lewis, Jr., W.M., 2013. Biogeochemistry of beetle-killed forests: Explaining a weak nitrate response. *Proceedings of the National Academy of Sciences,* 110(5): 1756-1760.

Rhoades, C.C., Hubbard, R.M., and Elder, K., 2017a. A decade of streamwater nitrogen and forest dynamics after a mountain pine beetle outbreak at the Fraser Experimental Forest, Colorado. *Ecosystems,* 20: 380-392.

Rhoades, C., Miller, S., Covino, T., Chow, A., and McCormick, F., 2017b. Stream Water Quality Concerns Linger Long After the Smoke Clears: Learning from Front Range Wildfires. *Colorado Water,* March/April: 22-26.

Rocky Mountain Insurance Information Association, 2015. Your guide to understanding insurance: Catastrophe information quick links: Wildfire. http://www.rmiia.org (Accessed April 24, 2017)

Robichaud, P.R., 2000. Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA. *Journal of Hydrology,* 231-232(1-4): 220-229.

Robichaud, P.R., MacDonald, L.H., and Foltz, R.B., 2010. *Cumulative watershed effects of fuel management in the western United States,* Chapter 5: Fuel management and erosion. Elliot, W.J., Miller, I. S., and Audin, L. [Eds.]. General Technical Report RMRS-GTR-231. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 79-100.

Romme, W.H., Clement, J., Hicke, J., Kulakowski, D., MacDonald, L.H., Shoennagel, T.L., and Veblen, T.T., 2006. Recent forest insect outbreaks and fire risk in Colorado forests: A brief synthesis of relevant research. Colorado Forest Restoration Institute, Colorado State Forest Service, Colorado State University, Fort Collins, CO, 24 pp.

Ryan, D.F., 2000. *Drinking water from forests and grasslands: A synthesis of the scientific literature,* Chapter 22: Synthesis. Dissmeyer, G.E. [Ed.]. General Technical Report SRS-39, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC: 202-206.

Ryan, D.F. and Glasser, S., 2000. *Drinking water from forests and grasslands: A synthesis of the scientific literature,* Chapter 1: Goals of this report. Dissmeyer, G.E. [Ed.]. General Technical Report SRS-39, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC: 3-6.

Safford, H.D., Stevens, J.T., Merriam, K., Meyer, M.D., and Latimer, A.M., 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *Forest Ecology and Management,* 274: 17-28.

Schoennagel, T., Veblen, T.T., and Romme, W.H., 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. *Bioscience,* 54(7): 661-676.

Schoennagel, T., Sheriff, R.L., and Veblen, T.T., 2011. Fire history and tree recruitment in the Colorado Front Range upper montane zone: Implications for forest restoration. *Ecological Applications,* 21(6): 2210–2222.

Sidman, G., Guertin, D.P., Goodrich, D.C., Thoma, D., Falk, D., and Burns, I.S., 2016. A coupled modeling approach to assess the effect of fuel treatments on post-wildfire runoff and erosion. *International Journal of Wildland Fire,* 25(3): 351-362.

Smith, J.M., Paritsis, J., Veblen, T.T., and Chapman, T.B., 2015. Permanent forest plots show accelerating tree mortality in subalpine forests of the Colorado Front Range from 1982-2013. *Forest Ecology and Management,* 341: 8-17.

Spracklen, D.V., Mickley, L.J., Logan, J.A., Hudman, R.C., Yevich, R., Flanning, M.D., and Westerling, A.L., 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research,* 114: D20301.

Stednick, J.D., 2000. *Drinking water from forest and grasslands: A synthesis of the scientific literature,* Chapter 10: Timber management. Dissmeyer, G.E. [Ed.]. General Technical Report SRS-39, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC: 103-119.

Stednick, J.D., 2010. *Cumulative watershed effects of fuel management in the western United States,* Chapter 8: Effects of fuel management practices on water quality. Elliot, W.J., Miller, I. S., and Audin, L. [Eds.]. General Technical Report RMRS-GTR-231, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 149-163.

Theobald, D.M. and Romme, W.H., 2007. Expansion of the U.S. wildland-urban interface. *Landscape and Urban Planning,* 83(4): 340-354.

Thompson, M.P., Scott, J., Langowski, P.G., Gilbertson-Day, J.W., Haas, J.R., and Bowne, E.M., 2013. Assessing watershed-wildfire risks on national forest system lands in the Rocky Mountain region of the United States. *Water,* 5: 945-971.

Troendle, C.A. and King, R.M., 1985. The effects of timber harvest on the Fool Creek watershed, 30 years later. *Water Resources Research,* 21(12): 1915-1922.

Troendle, C.A. and King, R.M., 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. *Journal of Hydrology,* 90: 145-157.

Troendle, C.A. and Nankervis, J.M., 2000. Estimating additional water yield from changes in management of national forests in the North Platte Basin. Report submitted to the U.S. Bureau of Reclamation, Lakewood, CO, 51 pp.

Troendle, C.A., MacDonald, L.H., Luce, C.H., and Larsen, I.J., 2010. *Cumulative watershed effects of fuel management in the western United States,* Chapter 7: Fuel management and water yield. Elliot, W.J., Miller, I. S., and Audin, L. [Eds.]. General Technical Report RMRS-GTR-231, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 126-148.

United States Census Bureau, 2017. Quickfacts: Colorado. https://www.census.gov/quickfacts/table/PST045216/08 (Accessed Jan. 25, 2017).

United States Forest Service, 2008. Forest Service strategic framework for responding to climate change, version 1.0. United States Department of Agriculture, Forest Service, Washington, D.C., 21 pp.

United States Forest Service, 2017. Fire behavior and safety in bug-killed timber, Beaver Creek Fire. United States Department of Agriculture, Forest Service, Medicine Bow-Routt National Forests, March 13, 2017, White Paper, 3 pp.

United States Geologic Survey, 1990. Water fact sheet: Largest rivers in the United States, Water Resources Division, Reston, VA, 2 pp.

United States Geological Survey, 1999. The quality of our Nation's water: Nutrients and pesticides: Circular 1225. U.S. Geological Survey, Denver, CO, 82 pp.

Vano, J.A., Udall, B., Cayan, D.R., Overpeck, J.T., Brekke, L.D., Das, T., Hartmann, H.C., Hidalgo, H.D., Hoerling, M., McCabe, G.J., Morino, K., Webb, R.S., Werner, K., and Lettenmaier, D.P., 2014. Understanding uncertainties in future Colorado River streamflow. *Bulletin of the American Meteorological Society,* 95: 59-78.

Westerling, A.L., 2016. Increasing western U.S. forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences:* 371(1696), 20150178.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science,* 313: 940-943.

Wohl, E., 2013. Migration of channel heads following wildfire in the Colorado Front Range, USA. *Earth Surface Processes and Landforms,* 38(9): 1049–1053.

Writer, J.H. and Murphy, S.F., 2012. Wildfire effects on source-water quality: Lessons from Fourmile Canyon fire, Colorado, and implications for drinking-water treatment. U.S. Geological Survey Fact Sheet 2012–3095, Boulder, CO, 4 pp.

Writer, J.H., Hohner, A., Oropeza, J., Schmidt, A., Cawley, K.M., and Rosario-Ortiz, F.L., 2014. Water treatment implications after the High Park Wildfire, Colorado. *Journal of the American Water Works Association,* 106(4): E189-E199.

Yue, X., Mickley, L.J., Logan, J.A., and Kaplan, J.O., 2013. Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century. *Atmospheric Environment,* 77: 767–780.

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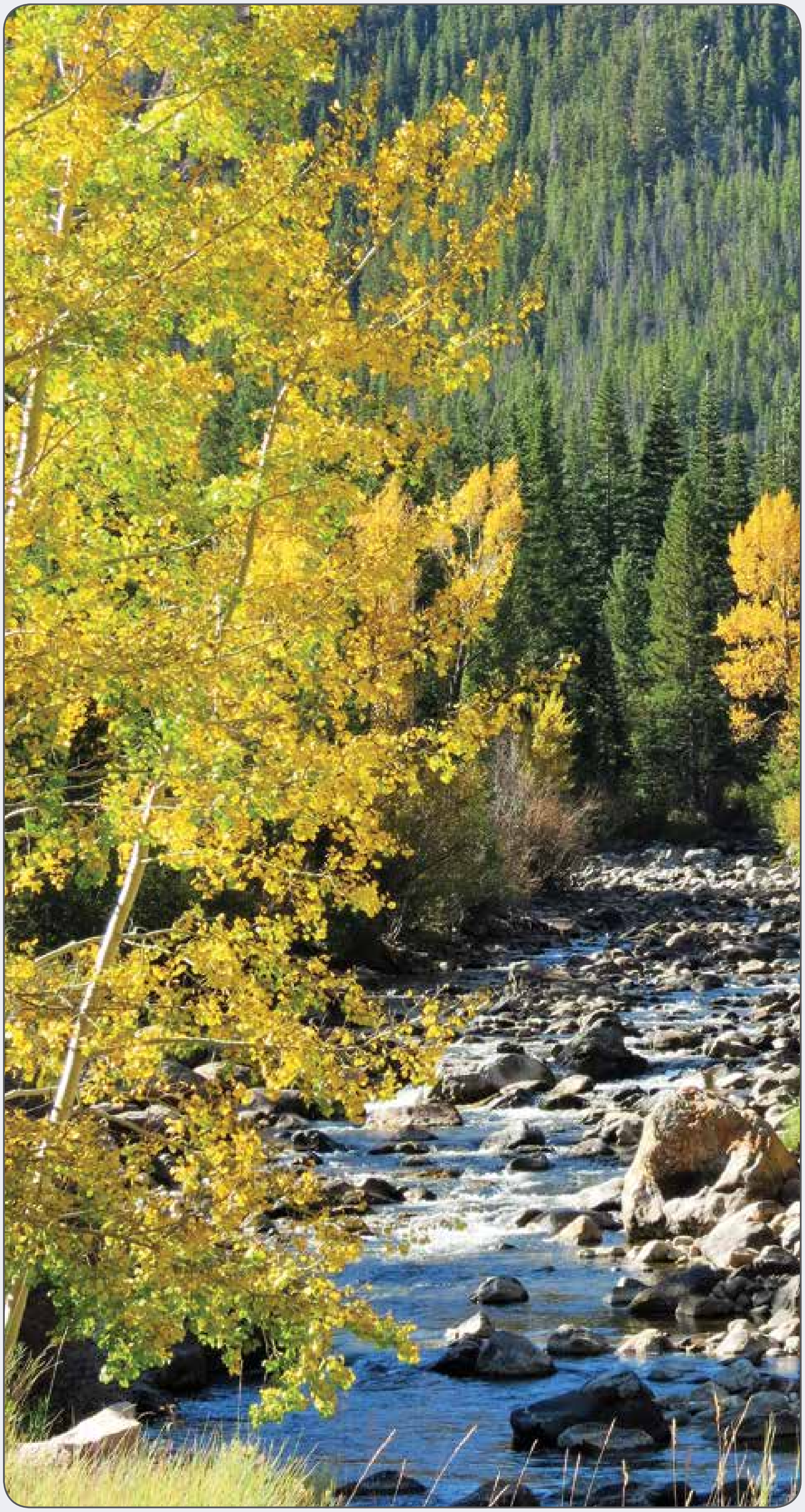

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