A Cost-Benefit Analysis of Denver's Forests to Faucets Program, 2011-2019

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Executive Summary

The purpose of this report is to estimate the net economic benefits (total benefits minus total costs) from investing in proactive wildfire mitigation and source water protection by the Forests to Faucets (F2F) initiative in the watersheds serving Denver Water between the years 2011-2019. Previous assessments of wildfire mitigation impacts on source water protection have considered how future prioritization and the spatial extent of F2F treatments can influence economic return on investments. This study provides a retrospective analysis of the costs and benefits of F2F investments to date and incorporates a wider range of values at risk beyond source water protection in the calculation of net benefits from wildfire mitigation activities under the F2F program.

To address F2F program accomplishments, we implemented a wildfire risk assessment that included fire behavior modeling and effects assessments for pre-mitigation conditions (baseline conditions) and compared these to two post-mitigation scenarios: (1) only considering mitigation activities on federal lands within Denver Water's Zones of Concern (**ZOC**), which approximates the work targeted by funding from Denver Water, and (2) considering all (**ALL**) mitigation activities on federal lands reported within a five-mile radius of Denver Water's collection system, which approximates the combined impacts of the Denver Water and US Forest Service partnership. The values at risk quantified in this study were classified as: (1) Source Water Protection, which captures the values of protecting drinking water, including infrastructure protection, and reservoir-based recreation, and (2) Community and Environmental Stewardship, which captures several co-benefits from wildfire mitigation activities conducted under the F2F program, including private home loss, suppression costs, and lost access to terrestrial recreation sites.

We present eight sets of results based on a combination of assumptions about burn probability (**conditional vs expected fire occurrence**) and wildfire behavior following fuel treatments (**assumed vs modeled treatment effectiveness**), which provides bookends to the expected range of benefits, for the two post-mitigation scenarios. At the top end of these bookends we estimate expected benefits to values at risk from wildfire mitigation at USD 85 million within the ZOC and USD 149 million for the full study extent (ALL). At the bottom end of these bookends we estimate the expected benefits to values at risk at USD 12 million within the ZOC extent and USD 26 million for the full study extent (ALL). The estimated fuel treatment costs for these two extents are USD 22 million (ZOC) and USD 63 million (ALL).

The net economic benefits (total benefits minus total costs) of the F2F program ranges from a high of USD 63 million (ZOC) and USD 85 million (ALL) conditional on wildfire occurring and assumed treatment effectiveness, to a low of negative USD 11 million (ZOC) and negative USD 38 million (ALL) under expected wildfire occurrence and modeled treatment

effectiveness, when wildfire is followed by extreme rainfall events and using no discount rate. While we tried to capture the full range of additional values at risk beyond source water protection in our analysis, we acknowledge additional benefits likely remain unaccounted for. A sensitivity analysis that doubles the economic value of avoided costs shows that under these more optimistic scenarios the F2F program would result in a as much as USD 147 million (ZOC) and USD 234 million (ALL) in net benefits under conditional fire occurrence and assumed treatment effectiveness, to a low of USD 1 million (ZOC) and negative USD 12 million (ALL) under expected fire occurrence and modeled treatment effectiveness (with no discount rate), when wildfire is followed by extreme rainfall events and using no discount rate.

Overall, these findings suggest that the F2F program is providing important benefits to Denver Water, the US Forest Service, and surrounding communities. However, our findings also highlight that the net benefits from the F2F program have been constrained by a combination of limits on the potential for wildfire and severe erosion in the watersheds serving Denver Water, the high costs of fuel treatment, and the placement of past wildfire mitigation activities. Specific to the latter, past F2F treatments were not always located in the highest risk areas due to a number of factors including accessibility, operability, and land ownership. The economic impacts of future wildfire mitigation activities in the F2F program could be improved with better spatial prioritization of treatments where the highest amount of risk can be reduced.

The report below is structured as follows. In section 1 we provide an overview of the F2F program and the goals of this analysis. Section 2 provides a general literature review on what is known regarding the effects of wildfire on values at risk. The details of our methodological approach, including how we define the study area extent, databases used for spatial information on fuel treatments, and our modeling approach, are found in Section 3. The results of our analysis are detailed in Section 4 and Section 5 provides a discussion about these results and suggestions for the F2F program.

1. Introduction

Previous wildfires in the watersheds surrounding the Denver metropolitan area in Colorado signaled the vulnerability of the region's water supplies to extreme fires. In 1996, the Buffalo Creek fire burned 11,600 acres of the Upper South Platte Watershed at mostly high severity. The fire combined with an estimated 100-year return interval rainstorm to cause extreme erosion, flooding, and transport of sediment and debris into Strontia Springs Reservoir (Moody & Martin, 2001). Only six years later, the 2002 Hayman fire burned another 138,000 acres of the Upper South Platte Watershed. The large areas of high severity impacts and tree mortality from the fire led to widespread erosion, flooding, sedimentation, and water quality impacts during subsequent rainstorms. As a result, Denver Water spent more than USD 33 million on erosion control, rehabilitation, and dredging to lessen the impacts to Strontia Springs and Cheesman Reservoirs (Lynch, 2004; Jones et al., 2017).

In order to proactively mitigate the impacts of extreme wildfire on the watersheds surrounding the Denver metropolitan area, Denver Water and the US Forest Service (USFS) started collaborative efforts in 2010 to strategically invest in forest management through the Forests to Faucets (F2F) partnership (Denver Water/USFS Partnership, 2017). The partnership focus is financing wildfire risk mitigation through fuel treatments on federal and non-federal lands that are important source areas for drinking water supplies. The F2F partnership began with a 5-year agreement that treated an estimated 48,000 acres between 2011-2016. Denver Water contributed USD 14.5 million and USFS contributed USD 21.5 million to phase one of this partnership. A second 5-year agreement for the years 2017-2021 supported projects reducing wildfire risk on an estimated 39,000 acres, with the two partners contributing USD 11.5 million and USD 14.6 million respectively. The second phase included the Colorado State Forest Service and Natural Resources Conservation Service as additional partners to mitigate risk of wildfires on high priority non-federal lands to complement the federal lands focus. While the majority of these funds are spent on proactive wildfire mitigation efforts (e.g., mechanical thinning), money is also allocated to reforestation and noxious weed control. Wildfire risk reduction efforts on federal lands are focused on the Arapaho-Roosevelt, Pike-San Isabel, and White River National Forests. Funds contributed by Denver Water are focused primarily on previously identified zones of concern (ZOC) within watersheds that supply their drinking water (J.W. Associates, N.D.). While the main goal of these investments is source water protection, Denver Water recognizes the benefits to community and environmental stewardship values (c0-benefits) in their watersheds and works with stakeholders to partner on mutually beneficial projects.

While the costs incurred due to a wildfire event can be devastating, less is known about the efficacy of avoiding or reducing these costs through proactively investing in wildfire risk mitigation activities such as thinning and prescribed fire (Agee & Skinner, 2005, Reinhardt et al., 2008, ERI, 2013, Milne et al., 2014). A handful of studies have estimated the return on investment (ROI) or net economic benefits (total benefits minus total costs) of wildfire mitigation activities for source water protection through cost-benefit analysis (Flagstaff Watershed Protection Project Monitoring Committee, 2014; Buckley et al., 2014; Kruse et al., 2016; Jones et al., 2017). The majority of these studies are prospective assessments (ex-ante analysis) that rely on predictions of what might happen in the future, versus retrospective assessments (ex-post analysis) that look at past activities. Prospective assessments are able to spatially target wildfire mitigation activities to the areas that will have the highest impact on values at risk (e.g., Jones et al., 2017), thus optimizing the potential benefits from wildfire mitigation activities. Prospective assessments suggest that treatment prioritization is important for program efficiency due to widely varying protection benefits across spatial locations and treatment types (Kalies & Kent, 2016, Sidman et al., 2016, Jones et al., 2017). Some of these prospective assessments find that the avoided costs to source water protection are small relative to other avoided impacts to values at risk, such as home and structure loss, wildfire suppression costs, and impacts to rural recreation economies (e.g., Buckley et al., 2014). There are fewer retrospective assessments of the efficiency of actual investments in wildfire mitigation activities for source water protection, where on-the-ground realities can influence where and how wildfire risk mitigation work is done despite efforts to focus work in the highest priority areas (USDA, N.D.).

The purpose of this study is to estimate the net economic benefits from investments in wildfire mitigation and source water protection through the F2F partnership in the watersheds serving Denver Water between the years 2011-2019. This covers F2F phase one and the first three years of F2F phase two. While previous prospective assessments of the impacts of wildfire mitigation on source water protection have considered how future prioritization and extent of treatments could influence ROI in one of Denver Water's source watersheds (e.g., Jones et al., 2017), in this study we provide a retrospective (ex-post) cost-benefit analysis of actual F2F investments to date and incorporate a wider range of values at risk in the calculation of net benefits from wildfire mitigation activities under the F2F partnership. Thus, this analysis contributes to a greater understanding of how past wildfire mitigation activities have affected future wildfire behavior and values at risks, and it provides insights into how to improve the effectiveness of future wildfire mitigation activities aimed at protecting source drinking water supplies.

2. Overview: Impacts of Wildfire on Values at Risk

Throughout this report, we classify values at risk from wildfire as: (1) Source Water Protection, which captures the value of protecting drinking water, through infrastructure protection, water treatability, and water-based recreation, and (2) Community and Environmental Stewardship, which captures the co-benefits of source water protection. This classification aligns closely with the three priority areas that guide Denver Water's investments—drinking water treatability, infrastructure protection, and community/environmental stewardship. One variation in our classification of values at risk from Denver Water's priority areas is that we consider reservoir-based recreation under Source Water Protection versus under Stewardship, as this aligns with our modeling approach; terrestrial recreation values are included under Stewardship values. A list of all potential values at risk due to wildfire and heavy rain events in recently burned areas were identified through meetings in 2019 with Denver Water and USFS staff involved in the F2F project (Table 1). Below we briefly summarize the peer-reviewed and grey literature about the impacts that wildfire has on these values at risk.

Table 1: Potential values at risk from wildfire events identified with Denver Water and USFS staff.

Value Category	Potential Values at Risk
Source Water Protection	- Reservoir & water delivery infrastructure - Hydropower generation - Water quality and treatability due to turbidity/TSS, manganese, and other chemicals (TOC, N, P) - Reservoir-based recreation
Community & Environmental Stewardship	- Non-water infrastructure (private homes, utility buildings) - Wildfire suppression costs - Post-fire recovery & rehabilitation costs - Public health impacts - Recreation - Wildlife - Timber - Carbon storage & sequestration

2.1 Source Water Protection

Sedimentation resulting from post-fire runoff and erosion has negative consequences for reservoirs, and their related infrastructure, which leads to a number of economic costs. Worldwide, between 0.5 and 1% of total water storage volume is lost annually due to sedimentation (Schellenberg et al., 2017), with potentially much greater local impacts (Jones et al., 2017). This reduces reliability of water supplies for drinking and other purposes, and often results in the need to dredge reservoirs to maintain their capacity over time. Sedimentation can also impact reservoir outlets, straining dam gates and other mechanical structures. If not removed over time, the buildup of sediment could require dam replacement, which would be cost-prohibitive in many cases. Sediment may be mobilized gradually by hillslope and channel erosion (Moody and Martin, 2001), or abruptly by debris flow (Cannon et al., 2010). Debris flows are concerning for their potential to disrupt water conveyance through open canals or shallow pipelines. High severity wildfires remove existing vegetation and change soil properties, exacerbating both erosion and debris flows processes.

Excessive sediment and debris also pose a risk for hydroelectric power production. Hydroelectric power is growing in importance for many water utilities, including Denver Water, as a way to meet sustainable energy targets. One of the key benefits of hydroelectric facilities is their ability, in conjunction with water storage, to provide flexible power generation. Hydropower production may be lost if severely degraded water quality prevents conveyance through the system.

Wildfire can directly impair water quality through increased contaminant mobilization and transport. A variety of water quality indicators may restrict use or increase treatment costs including sediment, nutrient, and heavy metal concentrations. Water erosion is the primary process by which contaminants are mobilized following fire (Smith et al., 2011, Abraham et al., 2017). This leads to often drastic increases in suspended sediment in surface water sources. Turbidity levels in three Rocky Mountain Front Range streams showed between 5 and 100-fold increases in the first year following fire (Rhoades et al., 2018). Other studies in the Rocky Mountain region of the US have shown post-fire increases in total suspended solids (TSS) of 2-fold, to over 30-fold (Malmon et al., 2007). Variability in sediment delivery to streams and reservoirs can be explained by the magnitude, intensity, and frequency of post-fire rainstorms (Smith et al., 2011, Robichaud, 2000). The largest increases in sediment concentrations occur after large intense summer rainstorms (Smith et al., 2011), and in the Colorado Front Range, these thunderstorms are the primary driver of post-fire erosion and runoff (Wilson et al., 2018).

Suspended sediment also mobilizes and transports other water-quality contaminants downstream (Murphy et al., 2015; Cawley et al., 2018). Contaminants of the greatest concern to drinking water supplies include nitrogen, phosphorus, organic carbon, and trace metals (Smith et al., 2011, Hohner et al., 2016, Abraham et al., 2017). Fire retardant chemicals like ammonia, phosphorus, and cyanide used in fire suppression have been detected up to 2700 m downstream of application sites (Sham et al., 2013). Harmful contaminants tend to increase immediately following a fire and peak in the first two years after (Smith et al., 2011; Sham et al., 2013). However, in a long-term study of the impacts of the Hayman fire in Colorado, post-fire nitrate levels were elevated for the first 5 years following the fire and remained significantly higher than pre-fire concentrations for another 8 years (Rhoades et al., 2018). Increases in water contaminants following fire can increase water treatment costs or require operational changes to utilize alternative sources (Writer et al., 2014; Warziniack et al., 2017). Elevated levels of suspended sediment can also make bacterial and virus detection more difficult, lead to greater bacterial growth, and make disinfection more difficult and costly (Smith et al., 2011).

Reservoir-based recreation values can be impacted post-fire due to discoloration of water resources from sedimentation or algae blooms following contamination. Post-fire sedimentation and reduced water quality can result in large fish kills and reduce the insect populations that fish depend on, reducing fishing and guiding opportunities for years following wildfire. It took more than 10 years after the Hayman fire before fisheries on the South Platte were recovered to 70% of their original level (Baca, 2012). Accumulation of debris in reservoirs following post-fire flooding, including forest vegetation and human infrastructure, often makes boating, fishing, and other activities less desirable and/or unsafe. Recreation can also be directly impacted due to closures of reservoirs during wildfires or post-fire flooding.

2.2 Community & Environmental Stewardship

Loss of homes and property (built infrastructure) from fire and post-fire flooding constitutes a large proportion of community costs incurred from wildfires in Colorado. The 1996 Buffalo Creek fire caused over USD 1 million in privately insured property losses (Lynch, 2004). The private and public property damage from post-fire flooding was even greater than the direct damage from the fire itself. The Hayman fire in 2002 caused close to USD 40 million in insured property losses (USD 280 per acre) (Lynch, 2004). However, because the Buffalo Creek and Hayman fires burned primarily on federal lands, the impact to private home loss was lower than when fires occur on non-federal lands. The 1989 Black Tiger fire outside of Boulder, Colorado caused building damages close to USD 1,900 per acre and the 2010 Fourmile Canyon fire, also outside of Boulder, saw insurance claims close to USD 217 million. The most costly wildfire to property in Colorado was the 2012 Waldo Canyon fire, resulting in over $453 million in insured claims after burning just over 18,000 acres. This was followed closely by the 2013

Black Forest fire with $420 million in estimated insurance claims. Nationally, several major fires in California have resulted in billions of dollars per fire in insured losses (RMIIA, n.d.).

Fires affect local communities not only through direct damage and destruction of homes and other structures, but also through lost revenue to local businesses due to restricted access caused by both fire and post-fire flooding. Fox (2016) estimates that property values decreased 6.7% from flooding following the Shultz fire near Flagstaff, AZ in 2010. The same study estimated USD 15 million in lost retail sales over a five-year period (Fox, 2016). These losses have been seen in Colorado as well. A Durango restaurant worker reported a drop in between USD 100-300 a day in tip revenue following the 416 fire in 2018 (Colorado Public Radio, 2018). The 2018 Spring Creek fire caused business closures resulting in a 50% decrease in store revenue in the community during peak tourism season (Colorado Public Radio, 2018). The 2012 High Park fire cut the number of rafting days on the Cache La Poudre in half, resulting in an estimated USD 7 million in losses for the local economy (Ferrier, 2017).

Suppression costs represent a significant proportion of total fire costs (Lynch, 2004). Suppression costs are influenced by fire intensity, area burned, and housing values within 20 miles of ignition (Gebert et al., 2007). During the Bobcat Gulch fire in 2000, suppression expenditures totaled USD 3.8 million (USD 362 per acre). The Hayman fire in 2002 led to USD 43 million (USD 400 per acre) being spent on suppression (Lynch, 2004). The nearby High Park fire in 2012 had suppression costs close to USD 38 million (USD 440 per acre) and the 2013 Black Forest fire led to suppression costs around USD 9 million (USD 650 per acre). In Colorado, wildland fire suppression expenditures between 1995 and 2004 were on average USD 800 per acre in 2004 dollars (Gebert et al., 2007). The ability of proactive wildfire mitigation to reduce future suppression costs depends on a number of factors, including the specific fuel treatment activities (i.e., prescribed burning), the scale of treatments compared to the size of the wildfires that occur, and proximity of those wildfires to the WUI (Thompson et al. 2013; Loomis et al., 2016). The effectiveness of proactive mitigation to reduce fire suppression costs is often dependent on fire managers' knowledge of and decisions to leverage these features to their advantage. When utilized effectively, fuel treatments provide opportunities to halt fire spread and reduce overall suppression costs by keeping fire sizes small. Post-fire, recovery and rehabilitation costs are often incurred to address revegetation needs and erosion control (Lynch, 2004; Sham et al., 2013).

Wildfire events represent a threat to the physical and mental health of people directly adjacent to and downstream from burned areas. In one Southern California study, the cost of illness due to wildfires was estimated at USD 9.50 per person per day due solely to the opportunity cost of missing work. The same study found that community members were willing to pay much more (USD 84 per person) to avoid the health impacts of the fire (Richardson et al., 2012), indicating that the total health costs were much higher. Another public health concern created by wildfire is the mental health impact felt by affected communities. One study found that community members at lower income tiers and those with negative financial impacts were the most likely to have significant psychological distress following a fire (Eisenman et al., 2015).

Land-based recreation activities are important to many communities for both community well-being and attracting tourism. The long-term effects of fire on recreation are mixed. The economic impact is correlated to accessibility of the area and the severity of the fire (Molina & Silva, 2019). Economic losses occur primarily when a recreation area becomes completely closed, while lower intensity fires that don't result in closures can sometimes increase visitation and satisfaction (Sanchez et al., 2016). Seasonal losses due to closures of backcountry wilderness have been found to cost upwards of USD 200 per visiting person; this includes lost revenue for the communities surrounding wilderness areas (Sanchez et al., 2016). Prescribed fires—even those directly in or adjacent to recreation areas—have been shown to increase the visitation and value of those recreation areas in the years and decades following treatment (Hesseln et al., 2004). High-intensity crown fires, however, cause closures, decrease visitation, and diminish overall value (Molina & Silva, 2019).

The impact of wildfire on wildlife varies considerably by species and fire intensity (Horncastle et al., 2018; Geary et al., 2019). For example, low to moderate severity fires can increase forage for ungulates (Cherry et al., 2018) and enhance hunting opportunities for predators (Geary et al., 2019). However, severe fire events can destroy food sources, impacting small mammals (Horncastle et al., 2018), and kill large amounts of wildlife, as seen in the 2019 Australian bushfires. Wildfire can interfere with hunting access or quality resulting in short-term displacement of hunting, but wildfire may improve hunting in future years. Extreme fires in Colorado have harmed the habitat of endangered and threatened species, including the Pawnee Montane Skipper butterfly. The Hayman fire in 2002 destroyed 47% of the species' habitat (Lynch, 2004). Using an estimate of the willingness to pay to protect the Pawnee Montane Skipper butterfly's habitat, the authors found that the lost value in butterfly habitat from the Hayman fire was about USD 11 million (Lynch, 2004). Loss of timber is also common (Ager, 2019), but is less relevant economically in central Colorado where timber revenue is low.

Finally, forest ecosystems are important sinks for offsetting and sequestering anthropogenic carbon emissions. Fire exclusion policies over the last century have led to a buildup of carbon stocks in many western US forests. When forests are treated for wildfire mitigation—either through prescribed burns or mechanical thinning—some carbon is lost (Hurteau et al., 2011). Research suggests there is a tradeoff between maximizing both storage and stability of carbon stocks in these forests (Hurteau et al., 2019). Restoring forests with thinning and prescribed fire reduces carbon storage in the short term but increases stability and resilience of the remaining carbon stock as it becomes less susceptible to irreversible landscape conversion as a result of historically uncharacteristic large fire (Liang et al., 2018, Chambers et al., 2016). Reducing tree density to restore forest structure typically results in a 30-40% decline in carbon, however, several studies have shown that, in the long-term, carbon is more stable in these conditions compared to untreated areas (Krofcheck et al., 2017, Liang et al., 2008).

3. Methods

3.1 Geographic Extent

The full geographic extent for this assessment is the area within a five-mile buffer around Denver Water's collection system (Figure 1). This extent includes the north and south collection systems. The south system, which includes storage and conveyance infrastructure in the South Platte, Bear Creek, and Blue River Watersheds, provides 80% of Denver Water's supply. The north system is comprised of collection, conveyance, and storage infrastructure in Upper Williams Fork, Ralston, Fraser River, and South Boulder Creek Watersheds. Wolford Mountain Reservoir was excluded from this assessment because it does not directly influence drinking water supply and because no F2F partnership projects were located on the Medicine Bow-Routt National Forest. Similarly, the Plum Creek Watershed, which drains to Chatfield Reservoir, was excluded from the assessment for consistency with Denver Water's representation of their collection system and because no F2F partnership projects were placed in this watershed.

The full study area (Figure 1) covers 3,818,355 acres across Boulder, Clear Creek, Gilpin, Grand, Jefferson, Park, Summit, Teller, Douglas, and Arapahoe counties, spanning five HUC-8 (medium-sized river basin) watersheds: Upper South Platte River, South Platte Headwaters, St. Vrain, Colorado River Headwaters, and Blue River. Three national forests—Arapaho-Roosevelt, Pike-San Isabel, and White River—make up most of the land area (61%). While the wildland urban interface (WUI) has been expanding in recent years, population density remains low across much of the study area. Most of the population is concentrated in small communities along interstate 70, highways 40 and 285, and in dispersed developments in the foothills west of Denver and Boulder.

3.1.2 Wildfire Mitigation Treatment Extent

For the 2011-2019 period, the F2F program reports completing fuel treatments, reforestation, and noxious weed control work on about 95,000 federal and non-federal acres within our study area extent (Figure 1; Table 2). Around 45,500 of the 95,000 acres reported as F2F program accomplishments were focused on invasive species removal and planting trees on past burn scars. These projects were excluded from this analysis. The remaining 49,500 of the 95,000 acres reported as F2F program accomplishments were intended to reduce wildfire hazard with a mix of forest management actions such as tree cutting, biomass removal, and prescribed fire. These activities were the focus of this analysis. However, the F2F reported acreage is a running total of annual accomplishments, and does not account for overlapping activities completed in different years.

Data on F2F partnership fuel treatments for this assessment were obtained from the USDA Forest Service Region 2, the three participating national forests, and the USDA Forest Service FACTS database. Non-spatial accounting of treatment accomplishments from Region 2 were used to evaluate the completeness of forest-level spatial data. The forests each provided spatial and attribute data describing the location and type of treatments implemented through the F2F partnership. The forest-level spatial data only accounted for fuel treatment on approximately 25,000 unique acres, and approximately 7,500 acres from the Arapaho-Roosevelt National Forest were outside the study area (Figure 1). The discrepancy in total area treated is likely due to a combination of the lag between planning, implementation, and reporting as well as spatial overlap between treatments in different years. The significant acreage treated outside the study area reflects that USFS match projects were not always constrained to within or nearby the Denver Water collection system.

To address the time lag in forest-level reporting, we supplemented the forest-level spatial data with the USFS FACTS enterprise data, which includes spatial and attribute data on planned and completed treatments. Our assumption was that FACTS activities within the analysis area (Figure 1) and during the partnership timeline primarily represent partnership accomplishments. A total of 63,345 acres of fuel treatments in the full study area were accounted for in the combined dataset over the years 2011-2019 (Figure 2 & Table 2). Fuel treatments were concentrated in the Pike and San Isabel (44,531 acres), with similar acreages treated in Arapaho-Roosevelt (9,680 acres) and White River (9,134 acres). This analysis does not account for an estimated 2,000 acres of forestry work Denver Water supported during this time period on non-federal lands. The >60,000 acres of fuel treatments across the full study extent are the best approximation of the work on federal lands that has been completed in and nearby Denver Water's source watersheds, but are not a perfect representation of the F2F accomplishments.

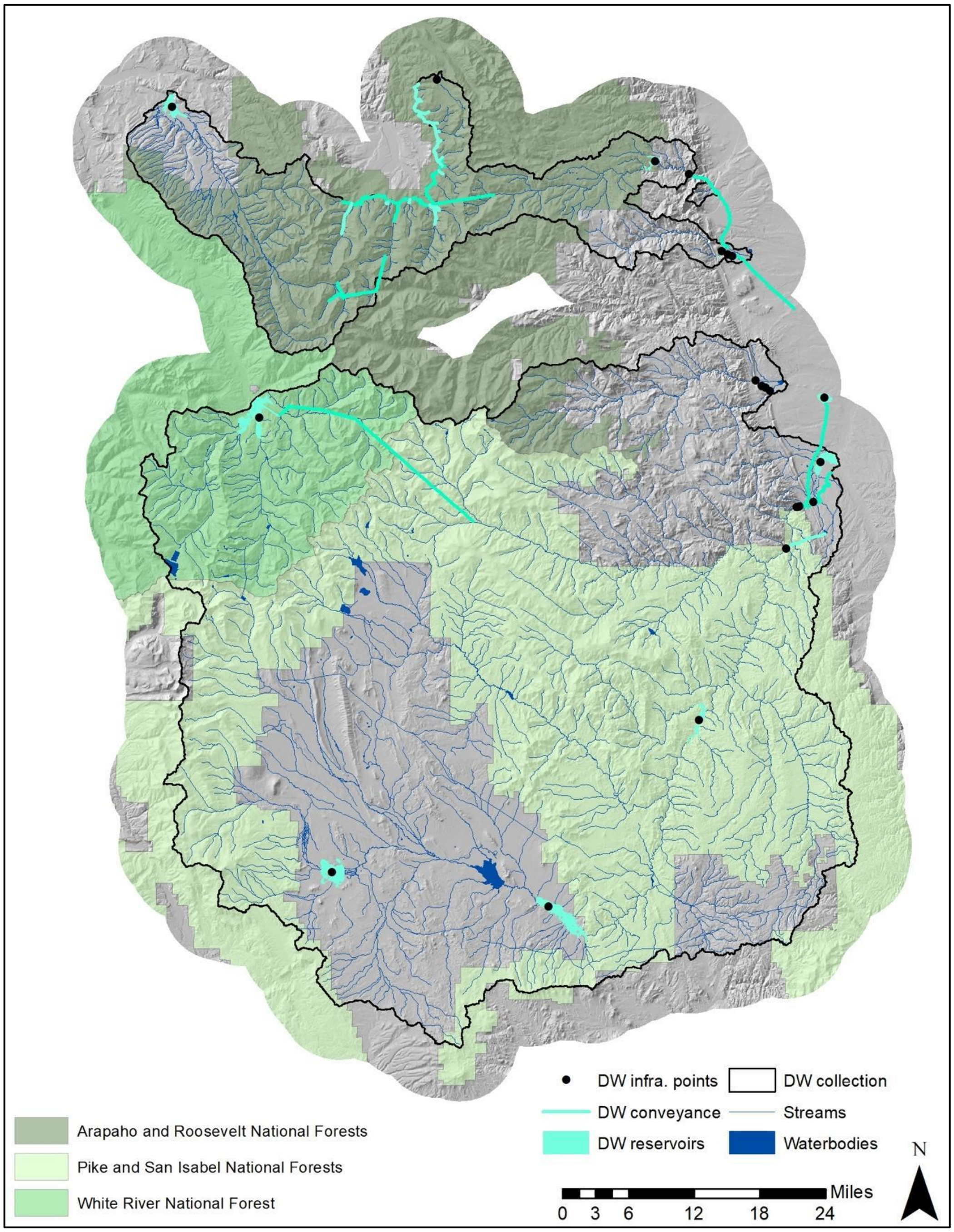

Figure 1: Study area consisting of a five-mile buffer around the extent of Denver Water's catchment system included in this assessment.

Denver Water prioritized fuel treatments within their ZOC (Figure 2), which represent the watershed areas thought to be most strongly connected to water supply reservoirs and other infrastructure. The study area includes all Denver Water ZOC except those around Wolford Mountain Reservoir as explained earlier. Just over 22,000 of the total treated acres that we mapped as part of the F2F program or the USDA FACTS database fell within these ZOC. Again, this acreage does not exactly match the F2F program internal accounting, which shows just over 27,000 acres of hazardous fuel treatment accomplishments within ZOC. For this assessment we provide cost-benefit calculations for wildfire mitigation activities completed across the entire study area (referred to as ALL throughout the report) and separately for the ZOC areas (Figure 2), since the latter are a priority for source water protection.

3.2 Wildfire Mitigation Treatment Activities and Costs

Fuel treatments identified in this assessment from the databases described above were classified into general canopy and surface fuel treatment categories for modeling (Table 2). Canopy treatments included mechanical thinning, clear cutting, prescribed fire, thinning plus prescribed fire, and no reported canopy manipulation. Most canopy treatments were mechanical thinning (35,296 acres). Surface fuel treatments included prescribed fire (including wildfire reported as fuel treatment), lop and scatter, mastication, no reported surface fuel modification, and manage, which represents efforts to reduce residual fuels from tree cutting including biomass removal and piling and burning. These classifications were used to estimate treatment effects on canopy and surface fuels and subsequent fire behavior as described in Section 3.4 and the companion technical report.

Table 2: Wildfire mitigation treatments by canopy (bold) and surface fuel (grey italics) type and National Forest (acres) for the years 2011-2019 included in this analysis.

Reported Canopy and Fuel Treatment Type	Arapaho-Roosevelt NF	Pike-San Isabel NF	White River NF	Total
Mechanical Thinning	3,793	28,952	2,551	35,296
No surface fuel modification	669	24,154	1,889	26,711
Lop and scatter	574	33	201	808
Manage fuel	2,467	4,089	462	7,018
Masticate	82	676	0	759
Prescribed Fire	0	11,085	105	11,190
Thinning + Prescribed Fire	45	2,828	0	2,873
Clear cut	3,500	0	6,139	9,639
No surface fuel modification	505	0	791	1,296
Lop and scatter	402	0	0	402
Manage fuel	2,578	0	5,150	7,728
Masticate	14	0	198	212
No Canopy Manipulation	2,343	1,666	339	4,348

Lop and scatter	350	6	0	356
Manage fuel	1,698	1,635	314	3,647
Masticate	295	24	25	344
Total	*9,680*	*44,531*	*9,134*	*63,345*

Since F2F and USFS internal project reports do not provide a per acre fuel treatment cost, the costs of fuel treatment were estimated based on a combination of recent fuel treatment projects in the study area, published literature sources, and professional opinion. In general, fuel treatment costs vary by slope and accessibility, and estimates in the literature range between USD 1000 and USD 2500 per acre (Skog & Barbour, 2006, Hartsough et al., 2008, Buckley et al., 2014). In a previous assessment of the impacts of mechanical thinning in Denver Water's ZOC an average cost of USD 1500 per acre was used for accessible areas (close to roads and low slopes) and USD 2500 per acre for less accessible areas (Jones et al., 2017).

Fuel treatments considered in this assessment (Figure 2) were located in areas with favorable access and operable terrain, which suggest the lower end of the cost range is representative of the average treatment costs. Additionally, some of the completed treatments did not involve canopy manipulation (Table 2), which reduces costs, and some areas classified as prescribed fire were actually wildfires, which were not paid for out of the fuel treatment budget. To account for these variable treatment types and thus costs, we used an average fuel treatment cost estimate of USD 1000 per acre for all canopy and fuel treatment types in Table 2 in this assessment. We assumed no additional maintenance costs over the duration of the assessment period (see Section 3.3). Additionally, we assumed no project revenue from biomass or merchantable timber since projected revenue from these sources is minimal in the study region.

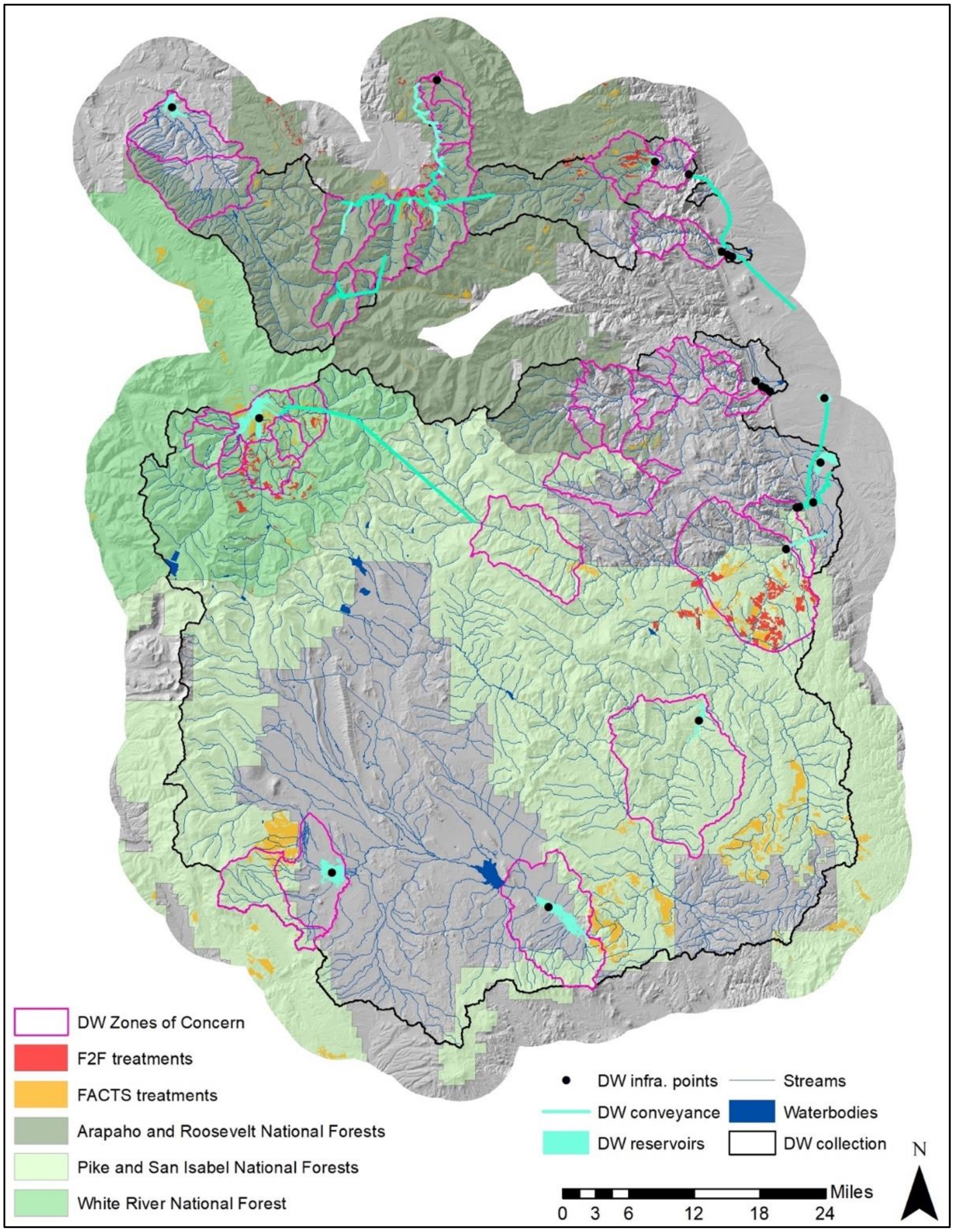

Figure 2: Summary of previous wildfire mitigation treatments on federal lands within Denver Water's zones of concern (ZOC) and outside the ZOC used in this assessment.

3.3 Risk Assessment Framework

Risk is an expected measure of value change from an uncertain process, such as wildfire, that is quantified as the product of event likelihood and event consequences. For wildfire, the chief uncertainties are where fires will ignite and under what weather conditions, which influence the rate and intensity of burning, and thus the fire extent and burn severity. Wildfire risk assessment relies on various forms of simulation modeling to make spatially explicit estimates of fire likelihood and fire intensity based on fuels, topography, and weather (Scott et al., 2013, Thompson et al., 2016). Given that both the primary objective of most wildfire risk mitigation treatment is to moderate fire severity and that there is considerable uncertainty in the ability of wildfire treatments to reduce fire spread in the absence of fire suppression (Agee et al., 2000, Reinhardt et al., 2008), we focus this assessment on wildfire mitigation treatment effects at changing fire behavior, holding fire likelihood constant. The assumption that fire likelihood is unchanged could underestimate the benefit of wildfire mitigation treatment, but previous studies have shown this effect to be small at the landscape scale (Thompson et al., 2013).

To address F2F program accomplishments, the risk assessment includes fire behavior modeling and effects assessments for pre-mitigation treatment conditions (**baseline conditions**) and comparing these to post-mitigation treatments for: (1) only those mitigation activities within the ZOC (**ZOC treatments**), and (2) all mitigation activities within the full analysis extent (**ALL treatments**) (Figure 2 & Table 2). The ZOC treatments scenario is meant to approximate the areas that were targeted for treatment by Denver Water funding in the partnership, whereas the ALL treatments scenario represents the combination of the Denver Water prioritized work and USFS funded match activities within and nearby the larger extent of the full source water collection system.

We use a 25-year treatment effectiveness time frame to measure benefits from wildfire mitigation treatments (Fialko, 2018). Fuel treatment longevity in Colorado is an active area of inquiry, but initial research suggests forest thinning should reduce torching (passive crown fire) for approximately 20 years and crowning (active crown fire) for approximately 40 years (Tinkham et al., 2016) at the typical regeneration density after forest thinning in Colorado montane zone forests (Francis et al., 2018). Less information is known about fuel treatment longevity in Colorado subalpine lodgepole pine and spruce-fir forests. The large diversity of forest types within the geography of the study area necessitate broad generalizations, and we acknowledge there is a range of fuel treatment longevity based on local species composition and growing conditions. Over the 25-year effectiveness period, we do not explicitly account for any additional maintenance costs. We instead assume a one-time USD 1000 per acre cost includes both initial treatment costs and any maintenance costs over time for the acres included in this assessment.

3.4 Wildfire Scenarios and Modeling

3.4.1 Burn probability

Fire likelihood is represented in this study using burn probability from the US national probabilistic wildfire risk components (Short et al., 2020) that were modeled with the Large Fire Simulator (FSim) (Finney et al., 2011). For this application, FSim was used to model large fire occurrence, growth, and containment over 10,000 future fire seasons based on 2014 fuel conditions from LANDFIRE (2016) with calibration to approximate the historical fire size distribution and rate of burning within biophysical regions with similar controls on wildfire activity. Annual burn probability (ABP) was calculated at 270 m resolution by tallying the number of times a pixel encountered wildfire divided by the total simulation years. For this assessment, ABP was resampled to 30 m resolution with bilinear interpolation to match other spatial products used in the analysis. ABP was also converted to an approximate fuel treatment planning period burn probability (PPBP) to estimate the likelihood of fuel treatments encountering wildfire over their effective lifespan using Eqn 1.

$$PPBP = 1 - (1 - ABP)^{25}$$ **Equation 1**

We report the effects of wildfire mitigation treatment in this report as both: (1) benefits conditional on fire occurrence (**CONDITIONAL on fire occurrence**) and (2) expected benefits accounting for the probability of fuel treatments encountering wildfire over a 25-year fuel treatment effectiveness period (**EXPECTED fire occurrence**). The first scenario calculates wildfire mitigation treatment benefits assuming treatments are burned once during the 25-year time frame. The second scenario calculates the expected treatment benefits accounting for the probability of the wildfire mitigation activities encountering wildfire as estimated in Eqn 1 (with this probability varying spatially across the landscape).

3.4.2 Fire behavior

Fire behavior was modeled for each fuel treatment scenario (Table 2) with FlamMap 5.0 (Finney et al., 2015). The basic fire behavior module in FlamMap predicts fire attributes for each pixel assuming heading fire (more extreme behavior compared to flanking or backing fire). We used Crown Fire Activity (CFA), a prediction of fire type in categories of surface fire, passive crown fire, and active crown fire (Scott and Reinhardt, 2001), as a proxy for low, moderate, and high severity burning, respectively. CFA is a reasonable proxy for burn severity in forested systems because crown fire initiation depends on surface fire intensity and total fire intensity is increased when more of the canopy is engaged in combustion. The required inputs for FlamMap include raster surfaces of fuels and topography and constant fuel moisture and weather conditions.

Surface and canopy fuels data from LANDFIRE (2014) representing 2010 conditions were used as the baseline for the assessment. Surface fuels are represented by categorical fire behavior fuel models (FBFMs), which represent common fuel loading and arrangements and their characteristic flame lengths and rates of spread (Scott and Burgan 2005). Canopy fuels are described in terms of canopy base height (CBH), canopy height (CH), canopy bulk density (CBD), and canopy cover (CC). The baseline fuels were modified in lodgepole pine forests to correct a crown fire underprediction bias by changing the FBFM to high load conifer litter (TL5) and lowering canopy base height by 30%. Fuel treatment activities (Table 2) were classified into general canopy and surface fuel types for modeling (Table 3; Table 4). Canopy fuels were then modified by treatment type with proportional adjustment factors (Table 3) and surface fuels were modified by treatment type with FBFM reclassifications (Table 4) informed from research in western US dry forests and professional opinion (Stephens & Moghaddas, 2005, Stephens et al., 2009, Fulé et al., 2012, Ziegler et al., 2017, Heinsch et al., 2018).

Table 3: Proportional adjustment factors used to simulate fuel treatment effects on baseline canopy attributes.

Treatment	Proportional adjustment factor			
	CBD	CBH	CC	CH
Thin	0.60	1.20	0.70	1.20
Rx fire	0.92	1.09	0.95	1.13
Thin and Rx fire	0.50	1.20	0.75	1.20
Clearcut	0.05	1.20	0.05	1.20

Table 4: Fuels management changes to the fire behavior fuel model (FBFM).

Category	Activities included	FBFM Change
Manage	Biomass removal, piling, pile burning	Assumed not to categorically change because fuels management reduces activity fuels generated by tree cutting
None	No fuels management reported	Assumed not to change because either no fuels management was needed, or it was not yet reported
Rx fire	Broadcast burning	Changed to the lowest intensity FBFM by category (e.g., timber understory, timber litter)
Re-arrange	Lop and scatter, mastication	Changed to slash-blowdown 1, which intensifies surface fire behavior

Most area burns in the Colorado Front Range under dry, windy conditions (Graham, 2003, Haas et al., 2015), so fire behavior was modeled for 3rd percentile fuel moistures and 97th percentile wind speeds (extreme fire weather) from the 16 Remote Automated Weather Stations (RAWS) located within five kilometers of the analysis area (Table 5). These settings were chosen to evaluate the performance of fuel treatments under the conditions they are most likely to encounter wildfire. This represents a conservative evaluation of fuel treatment benefits as they generally perform best under more moderate conditions (Kalies and Yocum Kent, 2016). Fuel moisture and 10-minute average wind speed percentiles were calculated from the RAWS data using FireFamilyPlus 4.1 (Bradshaw & McCormick, 2000). Fuels are classified in terms of the time required to equilibrate with atmospheric humidity in hours, which is a function of fuel diameter. Time classes of 1, 10, and 100 hours correspond to 0-0.25, 0.25-1, and 1-3 inches diameter, respectively. Wind speeds were converted from 10-minute average to 1-min average wind speeds for modeling per Crosby and Chandler (1966). The wind blowing uphill option was used in FlamMap to represent a consistent worst-case scenario across aspects.

Table 5: Fuel moisture and wind speed used in the fire behavior simulation.

Fuel moisture by class (%)					Wind speed
1-hr	10-hr	100-hr	Herbaceous	Woody	mph @ 20 ft
2	3	6	2	63	19

We account for the effects of wildfire mitigation on fire severity in this report as both: (1) modeled changes to fire severity (**MODELED treatment effectiveness**) and (2) assumed reduction in fire severity (**ASSUMED treatment effectiveness**). The first scenario models change to wildfire severity due to the primary effects of treatments on canopy and surface fuels as described in Tables 3 and 4 and the resulting fire behavior predictions from FlamMap. The second scenario assumes wildfire severity is lowered one level, unless already at low severity. For example, high severity wildfire changes to moderate severity and moderate severity to low severity. The second scenario gives the forest manager the benefit of the doubt that an appropriate treatment to mitigate crown fire hazard was prescribed. The assumed effectiveness scenario was added to this assessment because of uncertainty in both the baseline conditions and treatment intensity across the diverse projects in the analysis area.

3.5 Values at Risk

A collaborative and deliberative process was used with F2F program partners to determine which values at risk to include in this assessment. As mentioned, we first identified the full list of values at risk that were of concern to Denver Water and USFS partners (Table 1). Next, we evaluated the list of values based on the likely magnitude of impact and the ability to model them. We were able to model and monetarily value most values at risk that were of concern, including: (1) drinking water infrastructure, water treatability, and water-based recreation summarized under **source water protection**, and (2) property loss, recovery and rehabilitation costs, suppression costs, recreation, and endangered species values summarized under **community and environmental stewardship**. The data collected and methods used to analyze and monetarily value each of these values at risk are described below.

We were not able to quantitatively model or monetarily value a few values at risk identified as priorities (Table 1), these included human health impacts and carbon sequestration due to the lack of high quality impact models that are compatible with our risk assessment framework. The expectation is that wildfire treatment will positively affect these values and thus the calculated net benefits of the F2F program. We excluded timber revenue because there is limited high-value timber in the study area.

We also made some simplifications in our effects analysis for source water protection. Instead of directly predicting manganese and other contaminant concentrations of concern, we used total sediment amount as a proxy for the magnitude of change in water quality. Similarly, a unique analysis aimed at hydropower disruption based on triggering physical conditions was not completed. In both these cases, we accounted for post-fire impacts using Denver Water staff input to rate the importance of each source water infrastructure component for water treatment, operations, and stewardship as described in the next section and the technical report. Terminal reservoirs and diversions received high treatment ratings and critical conveyance, storage, or hydropower facilities received high operations ratings. These simplifications are warranted given the purpose of this assessment was to estimate program benefits over a broad spatial extent and multi-decade time span. Adding precision to the accounting of these variables would be best addressed with Monte Carlo simulation of discrete wildfire and rainfall events, which was beyond the scope of this assessment.

3.5.1 Source Water Protection

3.5.1.1 Modeling Hillslope Erosion

Reservoir and diversion exposure to post-fire sediment was modeled with linked hillslope erosion and sediment transport models as described in Gannon et al. (2019) with minor modifications. A summary of the methods is provided here with the details reserved for the companion technical report.

The National Hydrography Dataset Plus (NHDPlus) digital elevation model (DEM) and watershed network (USEPA and USGS 2012) provided the spatial topology for the analysis. Hillslope erosion was modeled at 30-m resolution using a Geographic Information System implementation (Theobald et al., 2010) of the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) by modifying the cover and soil erodibility factors to reflect post-fire conditions by burn severity (Larsen and MacDonald, 2007). To account for rainfall uncertainty, erosion was modeled at three levels of annual rainfall erosivity–531, 1280, and 5418 MJ mm ha^{-1} h^{-1}–corresponding to the 2, 10, and 100-year return intervals of historical rainfall erosivity from 14 stations located within or nearby the study area (Perica et al., 2013). We emphasize the 100-year return interval in our findings since Denver Water's motivation is to mitigate impacts from extreme fire and rainfall. RUSLE predicts gross hillslope erosion, so an empirical model of hillslope sediment delivery ratio (*hSDR*) from the western US (Wagenbrenner & Robichaud, 2014) was applied with a local calibration to estimate the proportion of sediment delivered to the stream network as a function of distance to stream. Channel transport was modeled with a channel sediment delivery ratio (*cSDR*) model (Frickel et al. 1975) adapted for channel types in the study watersheds to reflect that sediment transport should increase in efficiency with slope and discharge. We accounted for the total sediment load to water supply infrastructure over the first three post-fire years when accounting for physical impacts and costs. The technical report compares the model results to post-fire observations at multiple scales of measurement to validate that this approach makes reasonable predictions of post-fire sediment yields in the Upper South Platte.

3.5.1.2 Modeling Debris Flows

In several parts of the collection system, water is conveyed through open canals or shallow pipelines that are susceptible to blockage or damage from debris flows originating from upstream catchments (Figure 1). These conveyance structures are located primarily in the Upper Fraser Watershed and neighboring areas of the Blue River Watershed and a limited area of the South Boulder Creek Watershed. Conveyance infrastructure exposure to debris flow was modeled with an empirical model of debris flow probability and volume from the USGS (Cannon et al., 2010) and a channel sediment delivery ratio model for catchments that do not directly contribute to the conveyance structures. A summary of the methods is provided here with the details reserved for the companion technical report.

First, we delineated appropriate catchments within the contributing areas to vulnerable conveyance infrastructure to represent potential debris flow initiation zones. The USGS debris flow model consists of a multiple logistic regression model to predict debris flow probability and a regression model to predict debris flow volume (Cannon et al., 2010). Wildfire and fuel treatments influence the model via the percent area burned at moderate and high severity variable in the probability model and the area burned at moderate and high severity variable in the volume model. Variables related to topography and soils were held constant across scenarios. To communicate uncertainty in debris flow occurrence and volume due to rainfall variability, debris flow was modeled for 60-min duration storms with 2, 10, and 100-year return intervals from the NOAA frequency-duration atlas (Perica et al., 2013). The results of the debris flow model should be interpreted cautiously because we calculate the expected debris flow volume (m^3) as the product of debris flow probability and potential debris flow volume given the catchment burns. In reality, debris flows will either occur or not and their volumes would be best predicted by the volume model alone. For catchments that do not directly contribute to the conveyance infrastructure, debris was routed to the infrastructure using a sediment delivery ratio model as further described in the technical report.

3.5.1.3 Estimating an Economic Value for Source Water Protection

Given the diverse impacts to source water protection and sparse data for which to consistently quantify their precise economic costs across the system, we used a relative weighting approach to value sediment and debris flow impacts by infrastructure component. Denver Water staff from multiple departments collaboratively rated the relative importance of sediment impacts to their infrastructure on a scale from 0 to 100 representing none to highest impact in three categories: water treatment, operations (including storage, conveyance, hydropower), and stewardship (including community and environmental values). The three category relative importance values were then averaged into a composite importance value for each infrastructure component. Strontia Springs Reservoir was rated most important (96.7). Denver Water staff determined that the relative importance of debris flow impacts to conveyance infrastructure was similar enough to justify equal values.

To approximate the economic cost of sediment impacts throughout the system we indexed these relative importance values to the combined costs of: future projected dredging costs for Strontia Springs Reservoir (USD 130 per m^3) plus professional estimates of the costs of additional water treatment chemicals due to water quality impacts, lost hydropower generation, and impacts to recreation on or around water infrastructure (combined value of USD 20 per m^3). Thus, we indexed relative importance values to USD 150 per m^3 to capture the avoided cost to source water from reduced sediment due to wildfire mitigation activities. The relative indexing helps account for the fact that Strontia Springs Reservoir is particularly costly to dredge due to poor accessibility and steep slopes (Jones et al., 2017). While other water infrastructure in Denver Water's system and across the US have dredging costs closer to USD 25 per m^3 (Jones et al., 2017, Buckley et al., 2014), these differences are accounted for by the relative weighting approach. Specifically, the monetary values used for infrastructure components other than Strontia Springs ranged between USD 2-85 per m^3. We valued debris flow impacts to conveyance infrastructure at USD 20 per m^3, which was the professional estimate of removing debris volume. All infrastructure components received the same monetary value based on the relative importance ranking.

The method we adopted for monetary valuation of source water protection is most akin to the avoided costs method, which measures benefits in terms of the potential costs that would have been incurred without the project. Alternatively, a replacement cost approach could have been used. This replacement cost could be in terms of the replacement cost of water, if lost storage capacity could be substituted by purchasing water elsewhere, or the full replacement cost of water infrastructure. For example, the City of Loveland, CO commissioned a study that estimated a high-end cost of USD 36,860 per acre-foot for all aspects of new storage planning and construction in 2008 (City of Loveland, 2012), which converts to a value of USD 30 per m^3 of additional water storage (replacement cost). Denver Water recently assessed its ability to replace Strontia Springs Reservoir in the future if sediment concerns were not addressed and determined that the annualized costs to replace the reservoir (USD 7 million) were significantly more than removing sediment proactively. Since Denver Water deemed that preventing sediment and maintaining existing infrastructure (through strategies like the F2F program) is the priority versus replacing infrastructure retroactively, the avoided costs method is an appropriate approach to capture the economic benefits from the F2F program in terms of source water protection.

3.5.2 Community and Environmental Stewardship

3.5.2.1 Non-Water Infrastructure (Private Property and Denver Water Utility Buildings)

The potential for fuel treatments to reduce building loss was estimated using a model of home loss probability based on landscape characteristics. Price and Bradstock (2013) used multiple logistic regression to model home loss probability from structures exposed to the Black Saturday fires in Australia and found that landscape characteristics, in contrast to fine-grained information on the home ignition zone (Cohen, 2000), explained around 23% of variation in home loss. Their model predicts that the home loss increases with increasing proportion of crown fire activity and forest cover within a 1 km radius buffer around the home, the density of structures within a 50 m buffer radius around the home, and local slope. These findings are consistent with home loss studies in the US that suggest wildland urban interface disasters occur when extreme fire behavior close to a community overwhelms firefighting resources (Calkin et al., 2014) and that home loss is highest in areas of low housing density, which tend to have high proportions of natural vegetation nearby (Syphard et al., 2019). The low explanatory power of the Price and Bradstock (2013) model (R-squared = 0.23) suggests it is not appropriate for determining the fate of an individual structure. We instead use the model to estimate avoided structure loss and structure loss value across the entire analysis area assuming that the sum of marginal changes in home loss probability across many structures will result in an equivalent quantity of avoided home loss. Home loss value was calculated as the product of the median housing value and conditional probability of loss by structure. Data sources and details of the model implementation are provided in the technical report.

Non fire-resistant structures on Denver Water property, like caretaker facilities and equipment storage, were also included in this calculation. According to asset data sheets there are a total of 121 vulnerable structures within Denver Water's collection system. Market values of these structures were obtained from Denver Water. The combined total replacement value of Denver Water's vulnerable non-reservoir assets is around USD 25 million. The median value per vulnerable structure is approximately USD 240,000.

3.5.2.2 Suppression Costs

To estimate the potential influence of the F2F program on avoided suppression costs we used Thompson et al.'s (2013) finding that suppression costs would be reduced between 35% on treated acres, 23% on areas within a 2-mile buffer zone around treatments, and 13% for an entire landscape following wildfire mitigation. We used the 2-mile buffer avoided suppression costs estimate from the Thompson et al. (2013) study to approximate the potential avoided suppression costs in this assessment. First, we calculated the expected area burned within a 2-mile radius of treatments for the

ALL (88,922 acres) and ZOC (30,612 acres) study extents. The area expected to burn was multiplied by 0.23 (23%) to estimate the avoided area burned by investing in wildfire risk mitigation. Wildland fire suppression expenditures between 1995 and 2004 were on average USD 800 per acre in 2004 dollars (Gebert et al., 2007). The two estimates of avoided area burned were multiplied by USD 836 per acre (USD 800 in 2011 dollars) to get the avoided suppression costs attributable to wildfire mitigation. The estimated reduction in suppression costs is based on expected fire occurrence; this may underestimate the avoided suppression costs for the conditional fire model.

3.5.2.3 Recovery and Rehabilitation Costs

To estimate a monetary value for recovery and rehabilitation costs we used the estimated expenditures required to restore these ecosystems post-fire. This includes reforestation around reservoirs and on burn scars. USFS staff provided an estimate of USD 400-600 per acre tree planting costs in the study area. This is similar to the USD 450 per acre rehabilitation cost reported after the Hayman fire (Lynch, 2004).

The total area planted is typically less than the entire burn scar and is concentrated in high severity burn areas that are far from seed sources. Costs also vary by tree species. To simplify our estimate, we took the area burned in active crown fire as a proxy for high severity burning and multiplied it by an average cost of USD 500 per acre.

3.5.2.4 Recreation

To capture terrestrial recreation benefits from wildfire mitigation treatments, we focused on the potential impacts to hiking trails. Hiking is an important form of recreation in the study area, and there have been several long-term trail closures that have occurred from fire along the Front Range (e.g., Coloradan, 2019). The study area has an extensive combined network of hiking trails with a total of 248 trailheads and >6,000 km of trails in the three national forests and 476 trailheads and >8,720 km of trails in the overall study area. Data on trails were gathered from Colorado Parks and Wildlife's COTREX app that maintains a near-comprehensive state-wide map (Colorado Parks & Wildlife, 2019). Impacted trails were defined by the length of trail that overlapped with the extent of active crown fire (i.e., high severity fire). We assumed that high severity fire would result in closure of that section of trail only, rather than the entire trail network. We did not account for trail closures due to secondary effects of fire (e.g., erosion, road closures, complete closure of parks or forests). For the benefit estimations we assumed that any trail closure due to wildfire would last for one complete season. One year may be a conservative estimate for trail closures as some trails remain closed for several years following fire (Coloradan, 2019). We defined "season" as the months from May to October. This has been shown to account for 85% of national park visitation (Fisichelli et al., 2015), which may not accurately represent visitation to national forests, but does correspond roughly to hiking seasons and peak months for wildfire.

We assigned economic value to the benefits these trails provide based on visitor demand and the avoided costs of repairing damaged trails. For visitor demand, we used information on visitation rates (USDA Forest Service Natural Resource Manager, 2016) and the USGS benefit transfer toolkit (US Geologic Survey, 2019). The total annual visitation for each national forest in the study area was multiplied by the percentage of people who reported hiking as their primary activity in that forest. Then, using aggregated regional survey data from the USGS benefit transfer toolkit (US Geologic

Survey, 2019), we assigned a monetary hiking value per person per day (USD 68 for national forests; USD 51 for other public lands). For trail repair, we estimated the trail maintenance and construction costs that might be incurred in the event of severe crown fire (USDA Forest Service, 2014). The final sum of visitation value and repair/maintenance costs was around USD 40,000 per km of trail. This was used to estimate the total benefit to hiking trails in each scenario based on the length of trail that avoided fire damage.

3.5.2.5 Wildlife Habitat

Given the ecological uncertainty in how wildlife, and thus people that value wildlife, may be affected by wildfire, we focused on the economic impacts of wildfire mitigation activities on habitat for one endangered species that has been documented as being negatively affected by wildfire in this study area (Lynch, 2004). Specifically, we estimated the potential impact to the habitat of the Pawnee Montane Skipper, an endangered butterfly species in Colorado that has been negatively affected by past wildfires. Based on estimations used from previous willingness to pay surveys for endangered wildlife habitat in CO of USD 79 per acre in 1996 dollars, we used USD 113 per acre (2011 dollars) to estimate the economic value of protecting Pawnee Montane Skipper habitat (Lynch, 2004).

3.6 Impact Valuation Framework and Cost-Benefit Calculation

Using the data and methods described above the general steps to conduct the overall net benefit assessment (total benefits minus total costs) of wildfire risk mitigation activities under the F2F partnership were as follows:

(1) Estimated the biophysical impact to each value at risk under the four scenarios for no fuel treatments (baseline), ALL treatments, and ZOC treatments. Scenarios were as follows: (1) Conditional fire occurrence + Assumed treatment effectiveness; (2) Conditional fire occurrence + Modeled treatment effectiveness; (3) Expected fire occurrence + Assumed treatment effectiveness; (4) Expected fire occurrence + Modeled treatment effectiveness.

(2) Calculated the monetary value for each biophysical impact above based on methods described in Section 3.5. Calculated the change in avoided costs (benefits) to each value at risk as the difference between the baseline (no fuel treatments) and each post-treatment scenario.

(3) Calculated the treatment costs for both the ALL and ZOC spatial extents.

(4) Estimated the net benefits (total benefits minus total costs) without discounting and calculated the net present value (discounted net benefits) in 2011 dollars using a 3% discount rate following US federal guidelines (USEPA, 2014). For the latter, we distributed treatment costs over the eight years of the F2F project (2011-2019) and potential benefits over the full 25-year assumed treatment effectiveness period.

(5) Conducted two sensitivity analyses around net benefit calculations by (1) decreasing treatment costs to half (USD 500 per acre) and (2) doubling economic benefits (avoided costs). The first sensitivity analysis takes into account uncertainty in treatment costs for the different fuel treatment types (Table 2) and the second takes into account uncertainty in the monetary values for identified values at risk (Section 3.5) and the missing values at risk (e.g., health, carbon) in our benefit calculations.

4. Results

4.1 Burn Probability and Baseline Fire Behavior

Burn probability varies widely across the source water collection system owing to differences in fuels and climate (Figure 3). There is a stark contrast between the eastern slope of the Front Range and the high mountains. These areas fall in different fire modeling zones used in the FSim burn probability analysis (Short et al., 2020) and hence are calibrated to different levels of historical fire activity. The eastern slope of the Front Range has experienced substantial wildfire activity (e.g., Buffalo Creek, Snaking, Hi Meadow, and Hayman fires), so the predicted burn probability is generally high except where these fires have reduced fuels. In contrast, area burned by fire was historically low in the high mountains due to climate (cooler, wetter, and shorter fire season) and fuel differences (forests are primarily lodgepole pine, aspen, and spruce-fir). The short historical record of fire activity used to calibrate FSim and possibility of increasing fire activity with a changing climate (Spracklen et al., 2009; Litschert et al., 2012; Sankey et al., 2017) suggest our expected risk metrics should be interpreting cautiously, especially in high elevation forests.

In this study, we base risk measures on fire likelihood during a 25-year period of fuel treatment effectiveness. Over this time frame, FSim predicts 231,806 acres of fire activity within the full analysis extent and 156,871 acres within the Denver Water's source water collection system. The maximum pixel-level burn probability is 0.30, highlighting the relatively low likelihood that any individual unit of the landscape will encounter wildfire. However, wildfire exposure increases with watershed area, all other things being equal, so many of the water system components are predicted to experience non-trivial fire activity in the coming decades. Expected area burned within the undammed contributing area to each infrastructure component is reported in Table 6. Undammed was defined as any catchments with greater than 5% connectivity to the water infrastructure based on the channel sediment delivery ratio model, which is a liberal estimate of contributing area compared to the ZOC extent. Strontia Springs Reservoir has the highest predicted wildfire exposure at just under 54,000 acres, followed by Cheesman Reservoir at 16,000 acres, and Chatfield Reservoir at just over 11,000 acres. Predicted wildfire activity is very low for high elevation water infrastructure including Antero Reservoir, Dillon Reservoir, and the conveyance infrastructure in the Blue River and Upper Fraser watersheds.

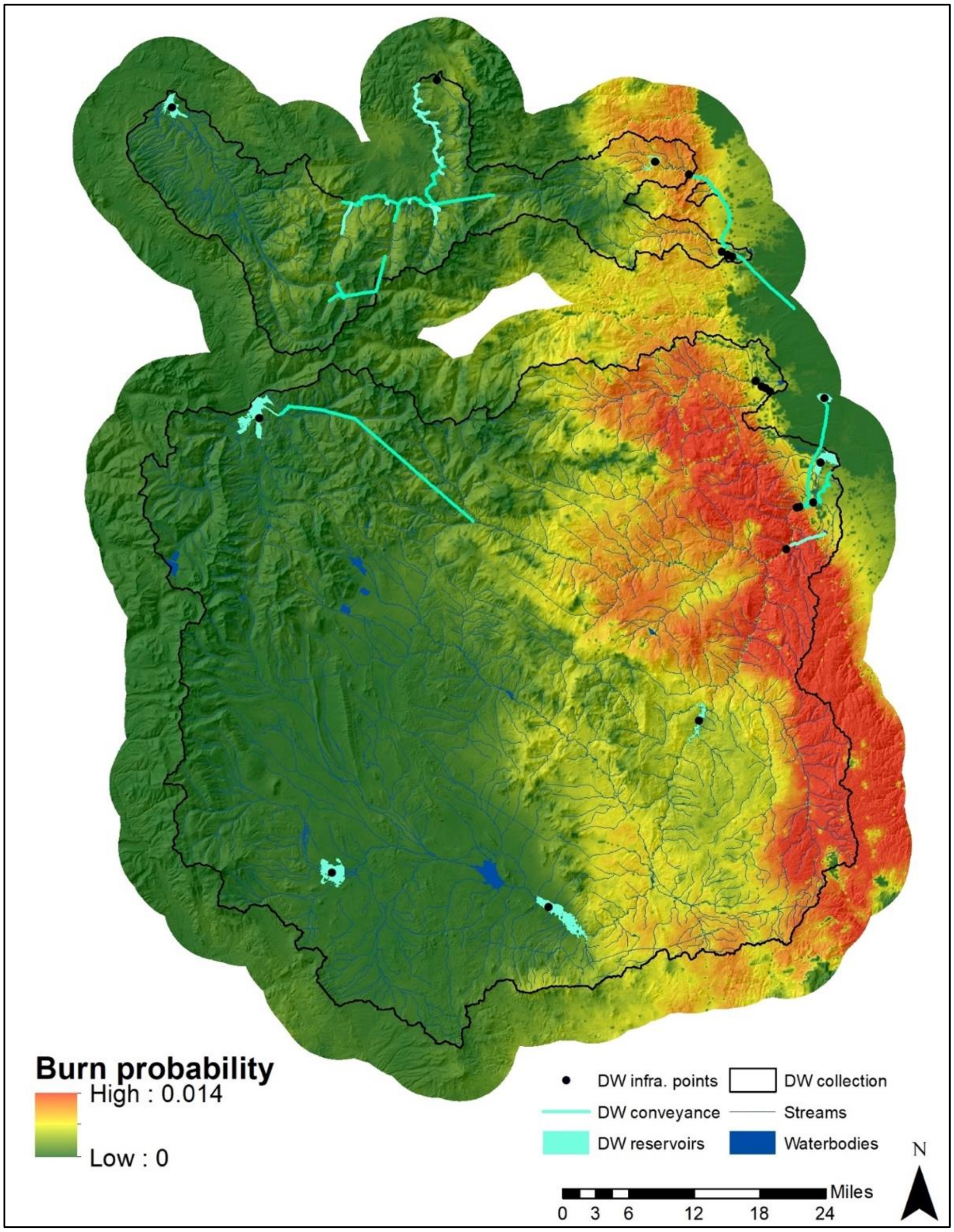

Figure 3: Mean annual burn probability for baseline conditions modeled with FSim from Short et al. (2020).

Table 6: Undammed contributing area and associated expected area burned over a 25-year time frame from FSim for infrastructure in Denver Water's collection system.

Reservoir and non-reservoir infrastructure	Contributing area (ac)	Expected Area Burned (ac)	Expected Percent Contributing Area Burned (%)
Antero Reservoir	113,710	430	0.38%
Bear Creek Diversion	44,934	7,516	16.73%
Chatfield Reservoir	64,837	11,168	17.22%
Cheesman Reservoir	183,685	15,989	8.70%
Dillon Reservoir	173,033	994	0.57%
Eleven Mile Canyon Reservoir	104,143	2,881	2.77%
Fraser Collection East	36,757	818	2.23%
Fraser Collection West	38,036	1,107	2.91%
Gross Reservoir	58,529	2,703	4.62%
Gumlick Tunnel Collection	8,402	67	0.80%
High Line Canal Diversion	12,879	3,034	23.56%
Marston Reservoir Diversion	12,879	3,034	23.56%
Meadow Creek Reservoir	4,532	162	3.57%
Ralston Reservoir	29,580	3,134	10.59%
South Boulder Canal	2,063	318	15.41%
South Boulder Canal Diversion	9,810	1,681	17.14%
Strontia Springs Reservoir	428,345	53,711	12.54%
Turkey Creek Diversion	32,593	6,406	19.65%
Vasquez Tunnel Diversion	3,934	20	0.51%
Williams Fork Reservoir	128,138	1,772	1.38%

4.2 Changes in Fire Behavior from Wildfire Mitigation Treatments

Crown fire activity, as predicted with FlamMap 5 for baseline conditions, is shown in Figure 4, which we use as a proxy for burn severity by mapping surface, passive crown, and active crown fire to low, moderate, and high burn severity respectively. Crown fire activity predictions under extreme fuel moisture and fire weather suggest that fire has potential to burn 48.9% of the analysis area at low severity, 24.5% at moderate severity, and 17.3% at high severity, and the remaining 9.3% is in a non-burnable state. These percentages do not vary substantially when limited to Denver Water's Collection System. Potential burn severity varies widely due to differences in fuels and topography across the landscape. Significant areas of the high mountain peaks have little to no fire potential due to sparse fuels. Areas with grass and shrub dominated vegetation are predicted to burn at low severity such as South Park, recently burned areas of the Upper South Platte, vegetated area of the alpine, and valley bottoms in the Upper Colorado basin. The greatest potential for active crown fire and high severity effects is in the montane zone, especially where forest density is high and slopes are steep, and subalpine spruce-fir forests, due to high vertical connectivity between surface and canopy fuels. A mix of moderate and high severity burning is predicted in areas dominated by lodgepole pine and aspen.

Conditional on modeled fire occurrence, wildfire mitigation treatments are predicted to reduce fire severity by moderating crown fire activity. When fuel treatment effectiveness is accounted for by modeling fuel treatment effects ("Modeled treatment effectiveness") on fuels and subsequent fire behavior, 21,037 acres of the 63,345 acres in the ALL analysis extent (Table 2) were improved. In contrast, 44,268 acres would be improved if all treatments reduce fire severity one level ("Assumed treatment effectiveness"). The assumed treatment effectiveness illustrates that approximately one third of the area treated was predicted to burn as surface fire with low severity effects before treatment and could therefore not be improved in our assessment model. Two caveats should be noted with these results: (1) baseline fuel conditions are represented with remotely sensed data products that may not match the exact conditions on the ground, and (2) fuel treatment effects were represented with stylized treatments that may not reflect the exact forest management actions. The most common canopy treatment type, thinning, often reduced modeled active crown fire to passive crown fire behavior but rarely changed passive crown fire to surface fire. This is primarily due to the relatively low starting canopy base height assigned to dry forests by LANDFIRE (2014) and the small proportional change we expect to this variable based on previous fuel treatment studies (Table 3). The modeled and assumed treatment effectiveness following treatments should be viewed as book ending the range of possible treatment benefits due to uncertainty in treatment effectiveness.

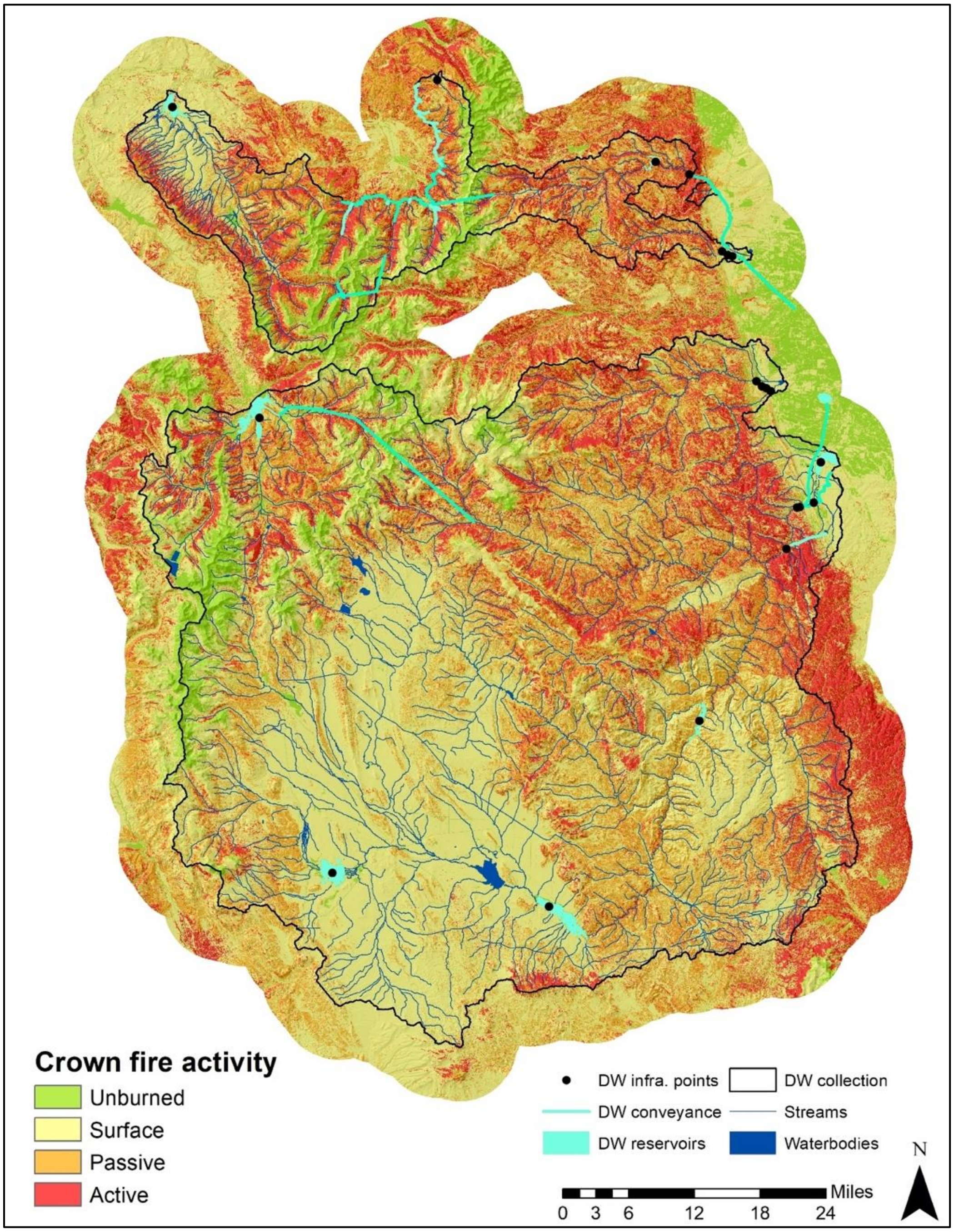

Figure 4: Crown fire activity modeled for baseline conditions in the full study extent.

4.3 Changes in Values at Risk due to Wildfire Mitigation Treatments

In this section we present eight sets of predictions about changes in values at risk: four combinations of assumptions about burn probability and wildfire behavior following wildfire mitigation treatments for the two treatment extents, ALL and ZOC (Table 7). The four scenarios are ordered from highest to lowest in terms of their predicted impacts of wildfire mitigation on values at risk. The highest estimated benefits from wildfire risk mitigation are found under "Conditional fire occurrence + Assumed treatment effectiveness", which assumes that all treatments encounter wildfire during the 25-year time frame and are effective at reducing wildfire severity. The lowest estimated benefits from wildfire risk mitigation are found under "Expected wildfire occurrence + Modeled treatment effectiveness", which accounts for the likelihood of fuel treatments encountering wildfire and models treatment effectiveness based on their mean primary effects on fuels and resulting change in fire behavior predictions.

In Section 4.3.1 we present the predicted changes in values at risk (the avoided costs due to wildfire mitigation), and in Section 4.3.2 we present the results from the net benefit assessment without and with discounting.

Table 7: Variations considered in modeling the impact of the F2F project on values at risk.

Scenarios	**ALL Treatments:** treatments that were carried out in the full study area extent (Figure 1).	**ZOC Treatments**: treatments that were carried out in Denver Water's Zones of Concerns (Figure 2).
Conditional fire occurrence + Assumed treatment effectiveness	This scenario calculates treatment benefits assuming fire will occur and assumes that wildfire severity is reduced in all areas where treatments were carried out.	
Conditional fire occurrence + Modeled treatment effectiveness	This scenario calculates treatment benefits assuming fire will occur and models changes to wildfire severity based on the modeled change in fire behavior due to treatment type.	
Expected fire occurrence + Assumed treatment effectiveness	This scenario calculates the expected treatment benefits accounting for the probability of encountering wildfire over a 25-year effectiveness period (i.e., risk reduction) and assumes that wildfire severity is reduced in all areas where treatments were carried out.	
Expected fire occurrence + Modeled treatment effectiveness	This scenario calculates the expected treatment benefits accounting for the probability of encountering wildfire over a 25-year effectiveness period (i.e., risk reduction) and models changes to wildfire severity based on the modeled change in fire behavior due to treatment type.	

4.3.1 Avoided Costs from Wildfire Mitigation

4.3.1.1 Source Water Protection

Below we map the baseline predicted costs to reservoirs, diversions, and conveyance infrastructure (Figure 5) both conditional on fire occurrence (conditional) and accounting for the likelihood of fire occurrence (expected). Conditional on fire occurrence and 100-year rainfall, fire impacts to water infrastructure range from 0 to ~16,000 USD per acre and are concentrated in the watersheds most connected to the highest value infrastructure (Figure 5a). This shows that consequences could be high throughout much of the upper elevation watersheds if fire occurs. However, fire likelihood is estimated to be low in the high elevation watersheds (Figure 3); hence, the risk (expected impacts) to water infrastructure is more concentrated in the lower portion of the Upper South Platte above Strontia Springs Reservoir (Figures 5a and 5b). Accounting for the likelihood of fire occurrence, the baseline risk to water infrastructure (eNVC) for the 100-year rainfall ranges from 0 to 4,200 USD per acre (Figure 5b). This contrast highlights that wildfire impacts could be very expensive across a lot of the watershed, but the combination of high impacts and high burn probability suggest there is much greater benefit to wildfire mitigation treatments in the lower portion of the Upper South Platte.

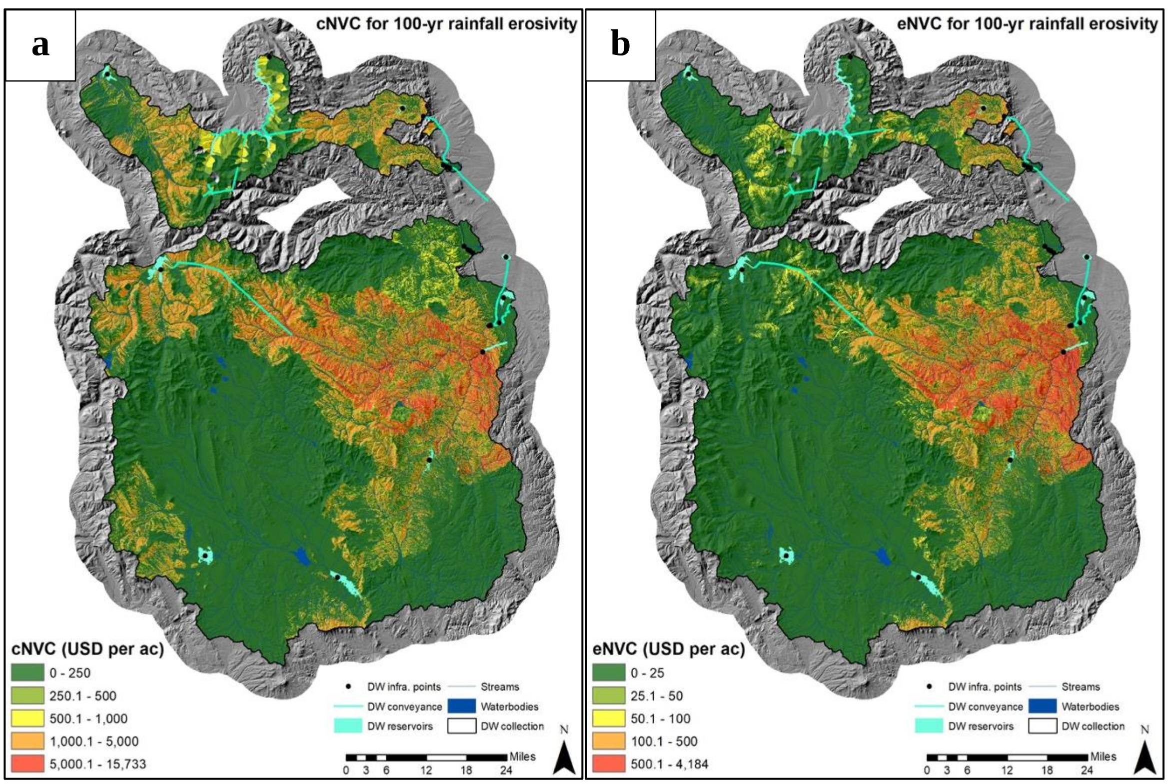

Figure 5: Baseline net value change (NVC) to water supply infrastructure under a) Conditional (cNVC) and b) Expected (eNVC) fire occurrence scenarios for 100-year return interval post-fire rainfall conditions.

In Table 8 we present the economic benefits (avoided costs) from the eight sets of results for avoided sediment delivery to reservoirs and other water infrastructure for three rainfall intervals. We present results for all relevant source water infrastructure (Table 6) and separately for Strontia Springs Reservoir since the potential benefits to source water protection from avoided sediment are highest for this feature. Focusing on all infrastructure protection and the full study area extent, conditional on fire occurrence and under a 100-year rainfall interval, the potential economic benefits range from USD 26 million to USD 41 million under modeled and assumed treatment effectiveness, respectively. Expected benefits when factoring in burn probability (expected fire occurrence) are lower, and under 100-year rainfall are between USD 4 million to USD 7 million for all infrastructure. When we focus in on treatments made within the ZOC the total economic benefits are slightly lower, because of the smaller number of acres treated.

The economic benefits from reduced sedimentation for Strontia Springs Reservoir account for >60% of all source water protection benefits. Conditional on fire occurrence, wildfire mitigation treatments around Strontia Springs lead to as much as USD 31 million in benefits when treatment effectiveness is assumed and USD 17 million when treatment effectiveness is modeled, under a 100-year rainfall. The predicted economic benefits when accounting for expected fire occurrence range between USD 4 and USD 7 million depending on how treatment effectiveness is modeled, following a 100-year rainfall.

Table 8: Economic benefits (avoided costs) from reduced sediment to reservoirs and other water infrastructure over 25-year timeframe at different post-fire rainfall intervals (RI).

	All Reservoir and Non-Reservoir Water Infrastructure (1,000 USD)		**Strontia Springs Reservoir (1,000 USD)**	
	ALL Treatments	ZOC Treatments	ALL Treatments	ZOC Treatments
	Conditional on Fire Occurrence + Assumed Treatment Effectiveness			
RI=2	9,500	7,800	6,700	6,000
RI=10	20,300	16,600	15,100	13,300
RI=100	41,100	32,100	31,00	26,300
	Conditional on Fire Occurrence + Modeled Treatment Effectiveness			
RI=2	7,300	5,900	4,800	4,200
RI=10	15,500	12,400	10,700	9,400
RI=100	25,600	19,400	17,200	14,300
	Expected Fire Occurrence + Assumed Treatment Effectiveness			
RI=2	1,500	1,400	1,500	1,300
RI=10	3,400	3,100	3,300	3,000
RI=100	6,900	6,000	6,600	5,800
	Expected Fire Occurrence + Modeled Treatment Effectiveness			
RI=2	1,100	1,1000	1,100	1,000
RI=10	2,400	2,200	2,400	2,100
RI=100	3,900	3,300	3,700	3,200

In Table 9 we present the economic benefits (avoided costs) from the eight sets of results for avoided debris flows to canals and pipelines for each rainfall interval. We present results for all relevant source water infrastructure (Table 6) and separately for Fraser Collection East since the potential benefits from reduced debris flow are highest for this feature. Benefits to conveyance infrastructure from reduced debris flow range from USD 7 thousand under "Expected Wildfire Occurrence and Modeled Treatment Effectiveness" with 100-year rainfall interval, to USD 491 thousand conditional on fire occurrence and assuming treatment effectiveness at a 100-year rainfall interval. The Fraser Collection East system accounts for >25% of all benefits from reduced debris flow due to wildfire mitigation treatments.

Table 9: Economic benefits (avoided costs) from reduced debris flow to water infrastructure over 25-year timeframe at different post-fire rainfall intervals (RI).

	All Reservoir and Non-Reservoir Water Infrastructure (1,000 USD)		**Fraser Collection East (1,000 USD)**	
	ALL Treatments	ZOC Treatments	ALL Treatments	ZOC Treatments
	Conditional on Fire Occurrence + Assumed Treatment Effectiveness			
RI=2	230	194	123	63
RI=10	315	277	155	84
RI=100	491	459	178	106
	Conditional on Fire Occurrence + Modeled Treatment Effectiveness			
RI=2	175	108	91	59
RI=10	230	153	115	82
RI=100	321	244	148	121
	Expected Wildfire Occurrence + Assumed Treatment Effectiveness			
RI=2	5	4	2	1
RI=10	7	6	3	2
RI=100	11	10	3	2
	Expected Wildfire Occurrence + Modeled Treatment Effectiveness			
RI=2	4	3	1	1
RI=10	5	4	2	1
RI=100	7	6	2	2

Combining the economic benefits (avoided costs) to source water protection from avoided sediment and avoided debris flow due to wildfire risk mitigation activities shows the total value to source water protection on the federal lands included in this assessment (Table 10). The majority of this benefit is from reductions in hillslope erosion (Table 8) versus reduced debris flows (Table 9).

Assuming treatments encounter wildfire (conditional on fire occurrence) results in between USD 26-42 million in benefits to source water protection for the full study extent (ALL), depending on the assumptions around treatment effectiveness, and between USD 20-33 million within the ZOC, under a 100-year rainfall event. Accounting for the likelihood of treatments encountering wildfire over the 25-year time period (expected fire occurrence) the predicted economic benefits to source water protection range between USD 4-7 million for the full study area (ALL) and USD 3-6 million for treatments carried out within the ZOC, following a 100-year rainfall event.

Table 10: Total economic benefits (avoided costs) to source water protection from avoided sedimentation and debris flow due to wildfire mitigation over 25-year timeframe at different post-fire rainfall intervals (RI).

	All Reservoir and Non-Reservoir Water Infrastructure (1,000 USD)	
	ALL Treatments	ZOC Treatments
Conditional on Fire Occurrence + Assumed Treatment Effectiveness		
RI=2	9,700	8,000
RI=10	20,600	16,800
RI=100	41,600	32,600
Conditional on Fire Occurrence + Modeled Treatment Effectiveness		
RI=2	7,500	6,000
RI=10	15,700	12,600
RI=100	25,900	19,600
Expected Wildfire Occurrence + Assumed Treatment Effectiveness		
RI=2	1,500	1,400
RI=10	3,400	3,100
RI=100	6,900	6,000
Expected Wildfire Occurrence + Modeled Treatment Effectiveness		
RI=2	1,100	1,000
RI=10	2,400	2,200
RI=100	3,900	3,300

4.3.1.2 Community & Environmental Stewardship

The benefits to community and environmental stewardship values from wildfire mitigation on federal lands as part of the F2F program are presented in Table 11. The total benefit to these values at risk is around USD 100 million for the full study extent (ALL) conditional on fire occurrence, regardless of the assumptions around treatment effectiveness. For the ZOC study extent, conditional on fire occurrence, the economic benefits are closer to USD 60 million. When burn probability is factored in (expected fire occurrence) the economic benefits to community and environmental stewardship values are closer to USD 25 million for the full study area (ALL) and USD 16 million for the ZOC areas.

The economic benefits from individual values at risk vary considerably in the community and environmental stewardship category. Suppression costs are the same for all four scenarios since they are based off total area burned estimates that do not vary by scenario. Avoided suppression costs are around USD 17 million for the full study area extent (ALL) and USD 6 million within the ZOC. Property loss values are the largest economic benefit under conditional fire occurrence, at about USD 100 million for the full study extent (ALL) and USD 60 million for the ZOC area. Recovery and rehabilitation costs are around USD 5 million for the full study area (ALL) and USD 3 million for the ZOC under conditional fire occurrence. Recreation values are slightly lower at USD 3 million for the full study extent (ALL) and USD 1 million for the ZOC areas. Avoided costs to endangered species habitat are about USD 200 thousand conditional on fire occurrence. The economic benefits to community and environmental stewardship values from wildfire mitigation drop considerably under expected fire occurrence, since the probability that treatments encounter wildfire is reduced.

Table 11: Total economic benefits (avoided costs) to community and environmental stewardship values over 25-year timeframe.

Value at Risk	Value of Co-Benefits (1,000 USD)	
	ALL Treatments	ZOC Treatments
	Conditional on Fire Occurrence + Assumed Treatment Effectiveness	
TOTAL	**109,400**	**59,400**
Property loss	81,300	41,800
Suppression costs	17,000	6,000
Recovery & rehabilitation costs	5,600	3,100
Recreation	2,900	1,100
Endangered species habitat	233	214
	Conditional on Fire Occurrence + Modeled Treatment Effectiveness	
TOTAL	**103,100**	**57,600**
Property loss	75,800	40,400
Suppression costs	17,000	6,000
Recovery & rehabilitation costs	5,100	2,800
Recreation	2,600	1,000
Endangered species habitat	222	203
	Expected Fire Occurrence + Assumed Treatment Effectiveness	
TOTAL	**24,700**	**15,700**
Property loss	4,100	1,900
Suppression costs	17,000	6,000
Recovery & rehabilitation costs	867	534
Recreation	299	115
Endangered species habitat	52	49
	Expected Fire Occurrence + Modeled Treatment Effectiveness	

TOTAL	**24,100**	**15,500**
Property loss	3,600	1,800
Suppression costs	17,000	6,000
Recovery & rehabilitation costs	800	500
Recreation	270	101
Endangered species habitat	49	46

Of the co-benefits considered in this assessment, property loss represents the largest economic benefit (avoided cost) from wildfire mitigation treatments under conditional fire occurrence. Figure 6 presents the spatial patterns of baseline risk to built structures (private homes and Denver Water buildings) taking into account burn probability as the expected net value change (eNVC) per acre. Most of the risk to structures is concentrated in the Upper South Platte between Highway 285 and Interstate I-70 corridors, Woodland Park, and the Boulder County foothills due to the combination of high housing density, high proportion of the landscape predicted to burn as crown fire, and the high burn probability. Risk of structure loss is lower in Summit County, South Park, the Fraser Valley, and Divide due to lower burn probability. There is relatively low risk of structure loss where treatments were placed to protect Strontia Springs Reservoir due to the low housing density and the reduced fuel conditions from the Buffalo Creek, Hi Meadow, and Hayman fires.

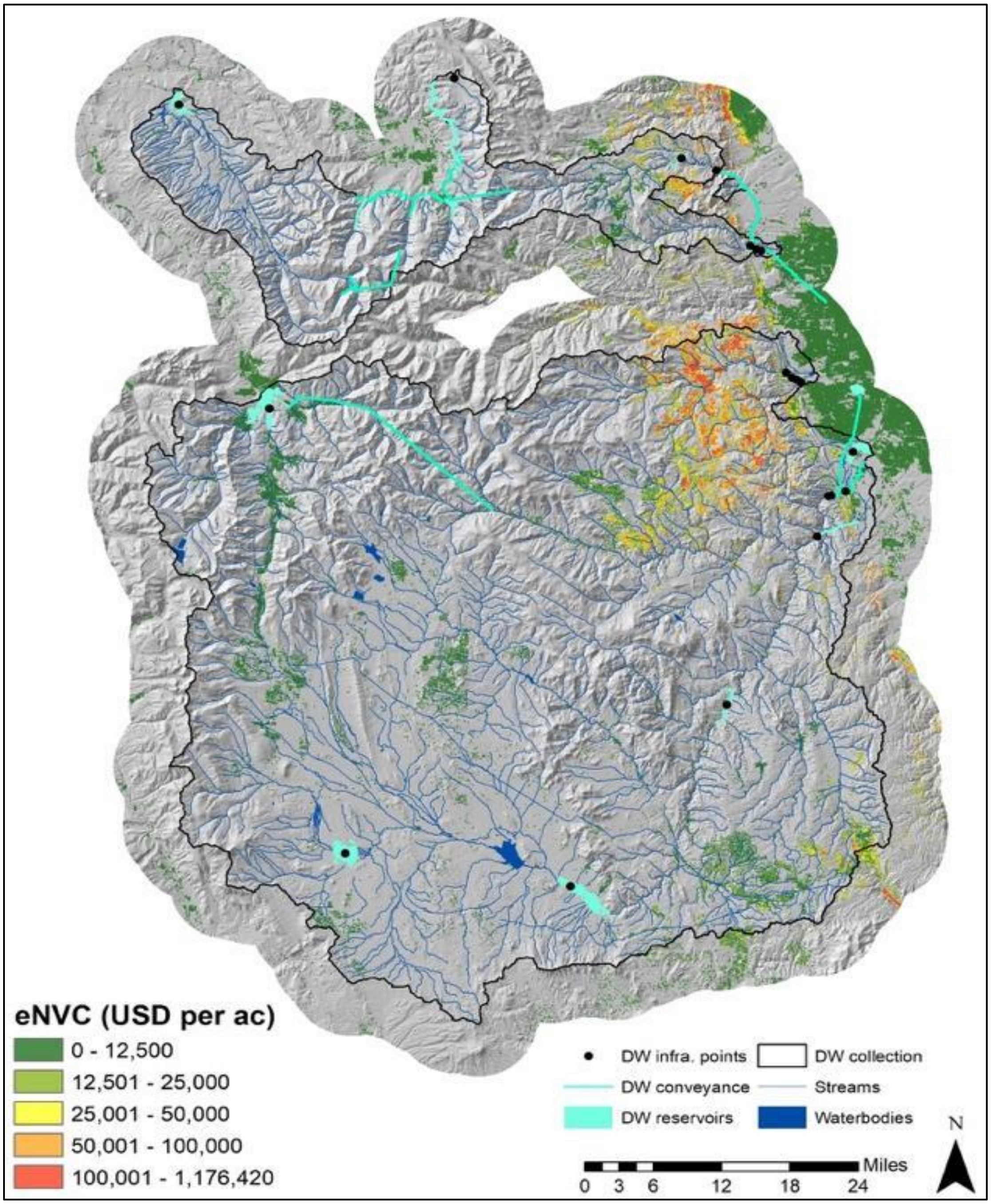

Figure 6: Baseline risk of property loss value. Results were rasterized and smoothed with a 90m radius filter for display purposes.

4.3.2 Cost-Benefit Analysis of F2F Program

The benefits (avoided costs) from wildfire risk mitigation presented above do not account for the costs of implementing fuel treatments. Based on the reported acres treated (Table 2) and a USD 1000 per acre average treatment cost, the total treatment costs are just over USD 63 million for the full study area extent (ALL) and USD 22 million for treatments within ZOC between the years 2011-2019. For the forested area impacting Strontia Springs Reservoir we estimated the total treatment costs at

USD 14 million for the full area (ALL) and USD 7 million for treatments made within the ZOC. It is important to note that the total treatment costs (ALL) used in this analysis (USD 63 million) are higher than the total reported budget of the F2F partnership during phase I and phase II combined (USD 62 million for the years 2011-2021, with known expenditures on non-wildfire mitigation activities). However, these costs reflect the larger number of wildfire mitigation acres we used in this analysis (Table 2), rather than the acres accounted for in F2F project reporting.

Below we take the difference between the benefits reported in Section 4.3.1 and the treatment costs, to show the net economic returns on federal lands from F2F investments in wildfire mitigation treatments. Table 12 shows the difference in benefits and costs from **source water protection and community and environmental stewardship values** under a 100-year rainfall return interval without discounting and using a 3% discount rate. With no discount rate, our bookends around net benefits for ALL treatments range between USD 85 million for "Conditional fire occurrence + Assumed treatment effectiveness" and negative 38 million for "Expected fire occurrence + Modeled treatment effectiveness". For the ZOC area, the range is between USD 63 million and negative USD 11 million. Using a 3% discount rate, the net benefits from ALL fuel treatments range between USD 52 million under "Conditional fire occurrence + Assumed treatment effectiveness" and negative USD 38 million for "Expected fire occurrence + Modeled treatment effectiveness". Within the ZOC, the range is between USD 42 million and negative USD 12 million.

Table 12: Net benefits (benefits minus costs) of F2F program on federal lands from avoided costs to source water protection (following 100-year rainfall return interval) and community & environmental stewardship values. Results presented using no discount rate and a 3% discount rate.

	All Reservoir and Non-Reservoir Water Infrastructure (1,000 USD)	
	ALL Treatments	ZOC Treatments
	Conditional on Fire Occurrence + Assumed Treatment Effectiveness	
No discount rate	85,400	62,600
3% discount rate	52,300	42,400
	Conditional on Fire Occurrence + Modeled Treatment Effectiveness	
No discount rate	63,400	47,800
3% discount rate	36,100	31,500
	Expected Fire Occurrence + Assumed Treatment Effectiveness	
No discount rate	-33,900	-7,600
3% discount rate	-35,600	-9,300
	Expected Fire Occurrence + Modeled Treatment Effectiveness	
No discount rate	-37,600	-10,500
3% discount rate	-38,300	-11,500

In Table 13 we show the net present value (with no discount rate and with a 3% discount rate) of the F2F program on federal lands over the 25-year time period for just **source water protection** under a 100-year rainfall return interval. Results are presented separately for Strontia Springs ZOC. Similar to Table 12 findings, net benefits tend to be positive under conditional fire occurrence, especially for the treated areas around Strontia Springs Reservoir, but are negative under expected fire occurrence.

Table 13: Net benefits (benefits minus costs) of F2F program on federal lands from avoided costs to source water protection values (following 100-year rainfall return interval). Results presented using no discount rate and a 3% discount rate.

	All Reservoir and Non-Reservoir Water Infrastructure (1,000 USD)		**Strontia Springs Reservoir (1,000 USD)**	
	ALL Treatments	ZOC Treatments	ALL Treatments	ZOC Treatments
	Conditional on Fire Occurrence + Assumed Treatment Effectiveness			
No discount rate	-21,800	10,400	16,700	19,500
3% discount rate	-26,600	4,000	9,900	13,200
	Conditional on Fire Occurrence + Modeled Treatment Effectiveness			
No discount rate	-56,400	-2,500	2,900	7,500
3% discount rate	-38,200	-5,600	-200	4,400
	Expected Fire Occurrence + Assumed Treatment Effectiveness			
No discount rate	-56,400	-16,100	-7,600	-1,000
3% discount rate	-52,200	-15,600	-8,000	-1,800
	Expected Fire Occurrence + Modeled Treatment Effectiveness			
No discount rate	-59,500	-18,800	-10,500	-3,600
3% discount rate	-54,400	-17,600	-10,100	-3,800

Because there is uncertainty in both our estimated treatment costs and in the monetary values assigned to values at risk, we also conducted a sensitivity analysis around our expected benefits and costs estimates of wildfire mitigation treatments (Table 14). If the expected monetary benefits from reducing wildfire severity to values at risk were double what we estimated above, the net benefits from the F2F program would be positive for three of the four scenarios within the ZOC area extent and positive for two of the four scenarios within the full study area (ALL). The range of net benefits would be between USD 234 million for "Conditional fire occurrence + Assumed treatment effectiveness" and negative USD 12 million for "Expected fire occurrence + Modeled treatment effectiveness" for ALL treatments with no discount rate. Within the ZOC area, the bookends of our predicted net benefits would be USD 147 million for "Conditional fire occurrence + Assumed treatment effectiveness" and USD 1 million for "Expected fire occurrence + Modeled treatment effectiveness" with no discount rate. Similarly, halving treatment costs to an average of USD 500 per acre leads to positive expected net benefits of F2F investments on federal lands in most scenarios when ZOC area extent is considered, and positive net benefits in two of the four scenarios within the full study area.

Table 14: Sensitivity analysis around net benefits (benefits minus costs) of F2F program on federal lands from avoided costs to source water protection (following 100-year rainfall return interval) and community & environmental stewardship value. We double the economic benefits and halve the treatment costs. Results presented using no discount rate (0%) and a 3% discount rate.

	All Reservoir and Non-Reservoir Water Infrastructure (1,000 USD)	
	ALL Treatments	ZOC Treatments
	Conditional on Fire Occurrence + Assumed Treatment Effectiveness	
Doubling benefits (0%)	234,100	147,400
Doubling benefits (3%)	161,800	104,800
Halving treatment costs (0%)	117,00	73,700
Halving treatment costs (3%)	81,000	52,400
	Conditional on Fire Occurrence + Modeled Treatment Effectiveness	
Doubling benefits (0%)	190,100	117,800
Doubling benefits (3%)	129,400	83,100
Halving treatment costs (0%)	95,100	58,900
Halving treatment costs (3%)	64,700	41,500
	Expected Fire Occurrence + Assumed Treatment Effectiveness	
Doubling benefits (0%)	-4,600	6,900
Doubling benefits (3%)	-14,00	1,300
Halving treatment costs (0%)	-2,300	3,400
Halving treatment costs (3%)	-7,00	1,000
	Expected Fire Occurrence + Modeled Treatment Effectiveness	
Doubling benefits (0%)	-11,900	1,100
Doubling benefits (3%)	-19,400	-2,900
Halving treatment costs (0%)	-6,000	500
Halving treatment costs (3%)	-9,700	-1,500

5. Discussion

5.1 Main Findings

This cost-benefit analysis of the F2F program between the years 2011-2019 should be interpreted considering the assumptions and sources of uncertainty that enter the fire, erosion, and economic modeling. To account for this uncertainty, we have presented eight sets of results that take different approaches to modeling likelihood of wildfire occurrence (conditional vs expected wildfire occurrence) and treatment effectiveness (assumed vs modeled treatment effectiveness), for the treatment areas Denver Water prioritized that contribute most directly to source water protection (ZOC treatments), as well as a larger study extent around Denver Water's source watersheds that represent our best approximation of all F2F program investments on federal lands (ALL treatments). Additionally, we conducted a sensitivity analysis around our economic benefit and cost estimates to account for uncertainty in these monetary valuations.

The expected total benefits for source water protection and community and environmental stewardship from the >60,000 acres of fuel treatments in the study area (not considering treatment costs) are around USD 149 million under "Conditional Fire Occurrence + Assumed Treatment Effectiveness" and closer to USD 26 million under "Expected Fire Occurrence + Modeled Treatment Effectiveness", the two bookends of our modeling assumptions, when considering 100-year rainfall events (Table 10 + 11). Within the >22,000 acres treated in the ZOC, the economic benefits to values at risk (not considering treatment costs) range from USD 85 million under "Conditional Fire Occurrence + Assumed Treatment Effectiveness" and closer to USD 12 million under "Expected Fire Occurrence + Modeled Treatment Effectiveness" when considering 100-year rainfall events (Table 10 + 11). Wildfire treatment costs in the two study area extents are USD 63 million (ALL) and USD 22 million (ZOC), respectively.

With 57% and 45% of total treatment benefits realized within the ZOC under each bookend scenario, Denver Water and the USFS are realizing the bulk of their ROI by focusing treatments in a small, prioritized area. There are clearly additional benefits to active forest management that weren't considered in this study and occur outside the ZOC, but our analysis demonstrates the high concentration of diverse values at risk within the ZOC beyond delivering water to the Denver region. The ZOC appear to be an area of high ROI for wildfire risk reduction activities where strategic, prioritized investments can protect multiple values at risk to high severity wildfire, aligning with the USFS Shared Stewardship targeted investment approach and Denver Water's prioritization.

The largest single economic benefit from fuel treatments in our assessment was the potential replacement costs of built structures, which included private homes and Denver Water buildings. Home loss is one of the largest expenses in the US following wildland fires. In this study, we only assessed the impact of fuel treatments on federal lands, so the benefits to private property would likely have been higher if fuel treatments on non-federal lands under F2F were included. Since 2011, Denver Water and the USFS have increased their funding of treatments on non-federal lands through partnerships with the Colorado State Forest Service, Natural Resources Conservation Service, and many other organizations to compliment the investments on federal lands. Given that the majority of built structures in the study area are not on USFS lands, supporting fire risk reduction activities on non-federal lands should have greater average benefit. Following the USDA cohesive wildfire strategy to create more fire resilient landscapes, develop fire adapted communities, and enhance safe and effective fire response would likely yield a high ROI if effective at protecting structures.

We find a positive ROI from the F2F investments in the full study area extent (ALL) and the ZOC areas in terms of the quantified economic benefits to source water protection and community and environmental stewardship versus treatment costs conditional on fuel treatments encountering wildfire over the 25-year time period ("Conditional fire occurrence"). The high end of estimated net benefits from the F2F program are USD 85 million under "Conditional fire occurrence + Assumed treatment effectiveness" for ALL acres treated and USD 63 million for ZOC acres, using no discount rate and with the 100-year rainfall scenario. Thus, similar to the benefit estimations (not considering costs), we find a relatively higher ROI for the number of ZOC acres versus the full treatment area (ALL), reflecting the larger contribution to values at risk from treatments made in these areas relative to treatment costs. We do not find a positive ROI for the F2F investments when the probability of treatments encountering wildfire ("Expected fire occurrence") are modeled, reflecting low burn probability in many areas treated, which we return to below.

Our sensitivity analysis around our estimated economic benefits (doubling the value of these benefits) and our estimated treatment costs (halving these costs) shows a positive ROI on F2F investments under both "Conditional" and "Expected" fire occurrence in the ZOC areas. For the full study extent (ALL), benefit estimates would need to be 2.5 times higher than what we estimated in our analysis to show a positive ROI under "Expected fire occurrence". Thus, if all the values at risk excluded from this study were able to be quantified (e.g., human health impacts, carbon storage, additional tourism and recreation impacts, etc.), it is likely that the results of this ROI would be positive for all eight sets of results presented.

When we focus in on just source water protection values, a major motivator for the F2F program, we find that the most beneficial impact of fuel treatments comes from investments located within the contributing area to Strontia Springs Reservoir. The high end of the estimated ROI from treatments made to the contributing area of Strontia Springs are USD 20 million under "Conditional Fire Occurrence + Assumed Treatment Effectiveness", with no discount rate and the 100-year rainfall scenario. In other parts of the collection system, fuel treatments are predicted to cost more than the avoided impacts under all the tested scenarios due to a combination of the lower biophysical potential for reducing fire and erosion impacts and the lower protection value assigned to the infrastructure. The negative ROI when considering only the risk reduction to source water protection is similar to findings of avoided cost work from wildfire mitigation in the Sierra Mountains of California (Buckley et al., 2014).

A main finding from this analysis is that limitations on the biophysical potential for fire and erosion in the study area directly influence the cost-benefit results. In our post-fire watershed modeling for reservoirs and diversions, we assumed hillslope erosion rates were limited to 200 Mg ha^{-1} y^{-1} based on results presented in Moody and Martin (2009). For an area of the landscape with this maximum erosion potential that contributes its sediment with 100% efficiency to the most expensive infrastructure (USD 150 per m^3 for Strontia Springs), we estimate the maximum source water impacts at 15,934 USD ac^{-1} conditional on fire occurrence. Considering that the FSim burn probability modeling from Short et al. (2016) predicts a maximum 25-year planning period burn probability of 0.30, the highest baseline risk from sedimentation possible in our framework is 4,780 USD ac^{-1}.

Erosion rates approaching the maximum value allowed in this study are rare. The combined average rate of rill and inter-rill erosion during the first year after the Buffalo Creek fire was estimated at 72.0 Mg ha^{-1} by Moody and Martin (2001) (converted from their volume estimates using a sediment bulk density of 1.6 Mg m^{-3}). This is a fire-wide average, so some areas of the fire undoubtedly exceeded this rate. The first-year erosion rate observed at Buffalo Creek was more than three times greater than the highest annual erosion rate of 22.0 Mg ha^{-1} observed from hillslope erosion after the Hayman fire (Robichaud et al., 2013a, 2013b). Most forest within the analysis area has predicted post-fire erosion rates far lower than the assumed maximum value. The median predicted first-year erosion rate for forests when exposed to the 100-year return interval rainfall is 63.9 Mg ha^{-1}, which is reasonable in comparison to the 72.0 Mg ha^{-1} observed by Moody and Martin (2001) in response to similar rainfall. Furthermore, we expect substantial sediment storage on hillslopes, such that the net delivery to streams will average about half of the gross erosion (see Technical Report). Therefore, wildfire risk to water infrastructure approaches the maximum of 4,780 USD ac^{-1} only in areas with the highest burn probability, steepest slopes, forests predicted to burn at high severity, and closest to Strontia Springs (Figures 5a and 5b). Baseline risk and the risk reduction benefits of fuel treatments diminish with decreasing burn probability, slope, hazardous forest fuel conditions, and increasing distance from the highest value infrastructure.

The wide variability in risk to source water (Figures 5a and 5b) and associated benefit of mitigation means that treatment placement is critical for source water protection. The actual spatial distribution of F2F treatments was not as optimal as analyses of hypothetical treatments prioritized in the highest risk areas (e.g., Jones et al., 2017). For example, the steep slopes directly adjacent to Strontia Springs Reservoir did not receive treatment, but lower-gradient, more accessible areas further from the reservoir did. We suspect that treatments were not located in the highest wildfire and erosion risk areas due to a number of factors including accessibility, operability, and land ownership. Despite treatments not being located in the highest risk areas, our analysis showed that the ROI to the Strontia Springs ZOC for source water protection was positive under conditional fire occurrence (Table 13). High resolution maps of risk (Figure 5) highlighting where forest management interventions can make the biggest risk reduction may help to improve future placement decisions.

Finally, as mentioned earlier in this report, burn probability is modeled based on recent historical fire activity (Finney et al., 2011; Short et al., 2016), which leads to predictions of very little future wildfire activity in the high elevation forests (Figure 3). This translates to low estimates of wildfire risk and the risk reduction benefits of fuel treatments around Dillon Reservoir and the conveyance infrastructure in the Blue and Fraser River Watersheds. The short historical record of fire activity used to calibrate the burn probability modeling and the possible increase in fire activity in the study area due to climate change may mean that our estimates of future wildfire activity are likely conservative. Still, it is important to recognize that it is unlikely that all fuel treatments will encounter wildfire over their effective lifespans (assumed to be 25 years in the study) to avoid wildfire impacts on source water protection and other values at risk.

5.2 Program Recommendations

Moving forward, future assessments of the F2F program could be improved through better accounting of forest management actions to document pre- and post-treatment canopy and surface fuel conditions. In this analysis, treatment effectiveness was modeled using remotely sensed data on canopy and fuel conditions to represent baseline conditions with stylized treatment effects to approximate the post-treatment outcomes (Section 3.4). F2F and FACTS databases did not provide detailed information on the intensity of treatment. Because of sparse attribute information, we had to make several assumptions about how reported fuel treatments might modify fire behavior. It is for this reason that we added the "Assumed treatment effectiveness" scenario. As mentioned before, assumed and modeled treatment effectiveness scenarios should be considered as bookends of the range of possible fuel treatment benefits. Clear documentation of when the work was completed would also aid in future modeling of fuel treatment effectiveness. Treatment completion data is difficult to judge from FACTS for stewardship contracts and when there are multiple management actions in the stand. We included the FACTS data in this assessment because Forest-level spatial accounting of F2F accomplishments fell short of the Regional non-spatial accounting. We suspect this is due to a delay in reporting from the Forests, but it may also be a discrepancy between the sum of annual area treated and the cumulative area treated accounting for overlapping actions or between planned and implemented treatment extents. Finally, better information on the costs of treatments is needed to evaluate their cost-effectiveness at reducing risk. We assumed a uniform cost per acre for this assessment due to the lack of consistent and spatially-explicit accounting of treatment costs. Better documentation of program expenditures that clearly document costs by canopy and fuel treatment types would lead to a more precise cost-benefit analysis in the future.

Only a handful of cost-benefit analyses have been conducted for watershed investment programs in the US and the majority of these are prospective analyses (e.g., Flagstaff Watershed Protection Project Monitoring Committee, 2014, Buckley et al., 2014, Kruse et al., 2016, Jones et al., 2017). Prospective evaluations have the advantage of targeting fuel treatments to the most effective places on the landscape (e.g., Jones et al., 2017). However, on-the-ground realities can alter where fuel treatments are implemented. In the case of the F2F program, wildfire treatment placement may have been constrained by accessibility, divergent priorities across partners, bureaucratic requirements, and land tenure status (USDA, N.D.), limiting the impact of treatments on wildfire risk or protection of values at risk. It is important to keep in mind that the operational costs of treating in high priority areas may not always outweigh the additional benefits, and it may not be safe to conduct fuel treatments in some areas. Even where the highest priority areas are cost-effective (and safe) to treat, finding contractors that have the skills and tools to work in remote locations can be a limitation. Another constraint to treatment location is finding mutually-beneficial projects that all partners agree to and procuring the appropriate approvals. While Denver Water concentrated its treatments in ZOC areas that contribute most directly to source water protection, >40,000 treated acres considered in this assessment fell outside of those areas. Additionally, NEPA requirements and timelines can limit where treatments can be implemented on federal lands, and it has been recommended in watershed partnerships that non-federal partners could help pay for NEPA in order to accelerate where wildfire treatments can be implemented on the landscape (USDA, N.D.). Moving forward, prioritizing fuel treatments to benefit source water protection in advance and using this information to negotiate mutually-beneficial projects that remain cost-effective will be important to improve source water protection outcomes of the F2F program. Improving coordination of fire mitigation activities to align with fire suppression strategies would also increase the likelihood treatments are leveraged to help reduce impacts from fire events, and increase benefits to protecting prioritized values at risk.

Supplementary Files

- **Technical Report.** The technical report provides additional detail on the modeling and data used in this assessment, including modeling assumptions and uncertainties.

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