Water Storage Opportunities in Headwater Catchment Areas in the Upper Cimarron Watershed, New Mexico

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Cover photo credit: View northeast of a forest meadow and spring just north of West Agua Fria Creek on American Creek Properties (J.W. Jansens)

Water Storage Opportunities in Headwater Catchment Areas in the Upper Cimarron Watershed, New Mexico: A Summary of Findings

The main sources of drinking and irrigation water for a considerable number of communities and ranches within and around the Cimarron watershed originate from mountain ranges around the Moreno Valley. The watershed's headwater sources are becoming increasingly less productive due to drought and large wildfire events. Rising summer temperatures annually lead to the loss of high amounts of summer precipitation due to evapotranspiration. Similarly, rising winter temperatures and high winds increasingly lead to earlier snowmelt, followed by early high peak runoff events and evaporation losses of melted ice and snow. Even moderate flow events in mountain streams carry large amounts of sediment and woody debris resulting from post-wildfire erosion. Inefficiencies in water harvesting, delivery, and storage exacerbate the water supply problems. Together, these factors greatly limit water diversion and use opportunities downstream.

Relevant water storage opportunities in the watershed include storage in lakes, ponds, and streams, groundwater storage in alluvial layers, storage in the unsaturated zone of the soil, and storage in snowpack and icepack. Any water stored in the watershed's deeper geologic layers, however, is not readily available for human use. The water storage volume in soil that is available for potential downstream use is the volumetric soil moisture content in excess of the volumetric soil moisture content that is retained by capillary forces and only available to plants. The most optimal soil types for water storage for downstream uses are thick, medium-coarsely textured forest soils with high organic matter content because these conditions provide high saturated hydrologic conductivity and the greatest protection from rapid runoff or evaporation.

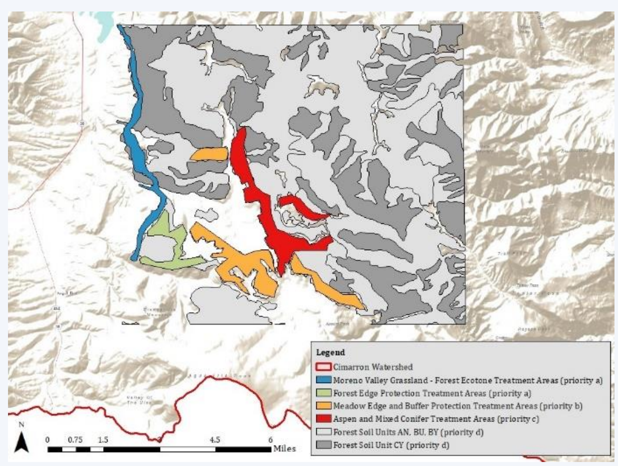
Research has shown that winter and spring precipitation account for around half of the total annual precipitation, but that it comprises the majority (68 to 88 percent) of groundwater recharge and streamflow in mountain streams in the Sangre de Cristo Mountains. Slow snowpack melting and deep percolation below the root zone when evapotranspiration demand is low is the foundation for annual groundwater recharge and streamflow. In specific locations, forest treatments could create small canopy openings that accumulate snow and provide protection against evaporation, sublimation, and melting. Therefore, protection and enhancement of water sources in the headwater catchments of the watershed must focus on winter precipitation, high elevation catchment areas, cool micro-climates on north- and east-facing slopes, forested areas with deep, organic soils, and large, rather flat drainages that can retain water longer than small, narrow, and steep drainages.

Long-term water source protection must be achieved primarily by protecting the headwater forests from high-severity wildfire impacts. Under specific thinning prescriptions, such treatments may also have short-term water storage benefits by improving soil conditions, reducing evapotranspiration, and spreading the runoff duration. Forest management strategies that prolong the melt out date and stretch the lag time between precipitation peaks and runoff peaks would minimize sediment and debris accumulation in concentrated runoff, increasing effective water use opportunities downstream. The cumulative effect of annual treatments across headwater catchment forests could thus lead to slight but sustained increases of water storage in the forest and downstream water yield.

Forest restoration treatments aimed at increasing forest resilience to the impacts of fire can be viewed at a landscape-level scale, a mid-level scale, and fine-level scale. At the landscape-level, comprising tens of thousands of acres, forest treatments would need to protect the forest edges of the Moreno valley from fire fronts and embers igniting fires in the Wildland-Urban-Interface and in higher elevation forests of the Cimarron Range. The forest lands of the Cimarron Range comprise a mosaic of aspen stands, and dry and moist mixed conifer stands, and some isolated spruce-fir stands, interrupted by large meadows and wetlands. These forest lands would need to be protected by breaking the continuity of the dense stand conditions across the landscape.

At the mid-level scale, specific locations must be selected and treated to reduce fire ignition sources and reduce chances for fire movement across the landscape. Warmer and drier mixed conifer forests on south-facing slopes are particularly sensitive to wildfire. These forests have a cycle of frequent, low-intensity fire, but have not burned for many decades. Treatments that mimic wildfire are of importance here, consisting of annual small thinning treatments that create irregular patterns of gaps in the dense canopy and many randomly spaced, small openings between groups of trees. These thinning treatments should be a priority to prevent high-severity fire and protect the water source ability of the forest soils.

Patch cuts in aspen and individual conifer removal in aspen stands would reduce the fire severity in these stands and increase snow accumulation, snow water equivalent, and water source capacity in this forest type. North- and east-facing, cool and moist mixed conifer stands would need to be treated by creating small patch cuts and by cutting small gaps in the dense canopy. Spruce-fir forests should only be treated with selective patch cuts to create small gaps at locations that are not exposed to high wind speeds. Only a small portion of the forest would need to be treated to achieve adequate landscape-level protection against high-severity fire impacts. Modeling can help locate and size appropriate treatment prescriptions.



At the fine-level scale, specific prescriptions would be applied to individual stand types and terrain conditions. Four preliminary prescriptions are presented which would need to be updated based on landowner objectives and terrain characteristics for selected treatment sites. The prescriptions offer details on leave trees, volumes of dead wood to be left, gap sizes for different stand types, and the size and orientation of forest openings for optimal snow accumulation and retention. Monitoring would need to support the evaluation and improvement of water storage results over time.

Cimarron Watershed Alliance

ECOTONE Landscape Planning LLC

1. INTRODUCTION

Project Background

The Cimarron Watershed Alliance is exploring ways to improve forest and watershed health in order to alleviate anticipated water supply shortages in the watershed (Figure 1). The Cimarron Watershed communities of Moreno Valley, Elizabethtown, Eagle Nest, Idlewild, Lakeview Pines, Taos Pines, Angel Fire, Rayado, Ute Park, Philmont Ranch Headquarters, Cimarron, Miami, and Springer, as well as communities outside the watershed, such as Black Lake, Black Lake Resort, and the City of Raton, and many ranches in the area, rely nearly exclusively on surface water from the mountain ranges around the Moreno Valley for drinking water and irrigation water. Many of these communities have expressed concern about water shortage projections. Recent wildfire impacts, periodic drought conditions, and inefficiencies in water harvesting, delivery, and storage have exacerbated this concern.

The 2016 Colfax Regional Water Plan (ISC-OSE 2016) lists several key collaborative projects identified by the water plan steering committee and area stakeholders. This study addresses the first item on this list, "Forest and Watershed Health," which was defined as:

> *Continued landscape-scale forest and watershed restoration in Colfax County is needed to limit catastrophic fires, mitigate negative effects of wildfire, and protect/restore water quality. The project includes logging/small-diameter timber extraction for forest health, invasive species treatment, stream and river restoration, rangeland health, and grazing management.*

This study addresses ways to improve water storage in headwater catchment areas in the Cimarron watershed through logging and small-diameter timber extraction for forest health. The study focuses on the questions:

1. How and where in the Cimarron watershed headwater catchment areas can water interception and storage be optimized through reduction of tree density; and

2. How and where would forest management measures increase ecosystem resilience against impacts of wildfire and other stressors that cause tree mortality and the associated loss of water storage capacity?

Purpose and Goals

The purpose of this study is to formulate detailed recommendations in support of a tangible land restoration proposal for forest interventions in selected headwater catchment areas in the Cimarron watershed in northern New Mexico. The study seeks to identify the most appropriate locations for forestry interventions and to propose detailed best practices and forest treatment prescriptions to achieve short-term, mid-long-term and long-term water conservation and water storage benefits originating from headwater catchment areas in the watershed.

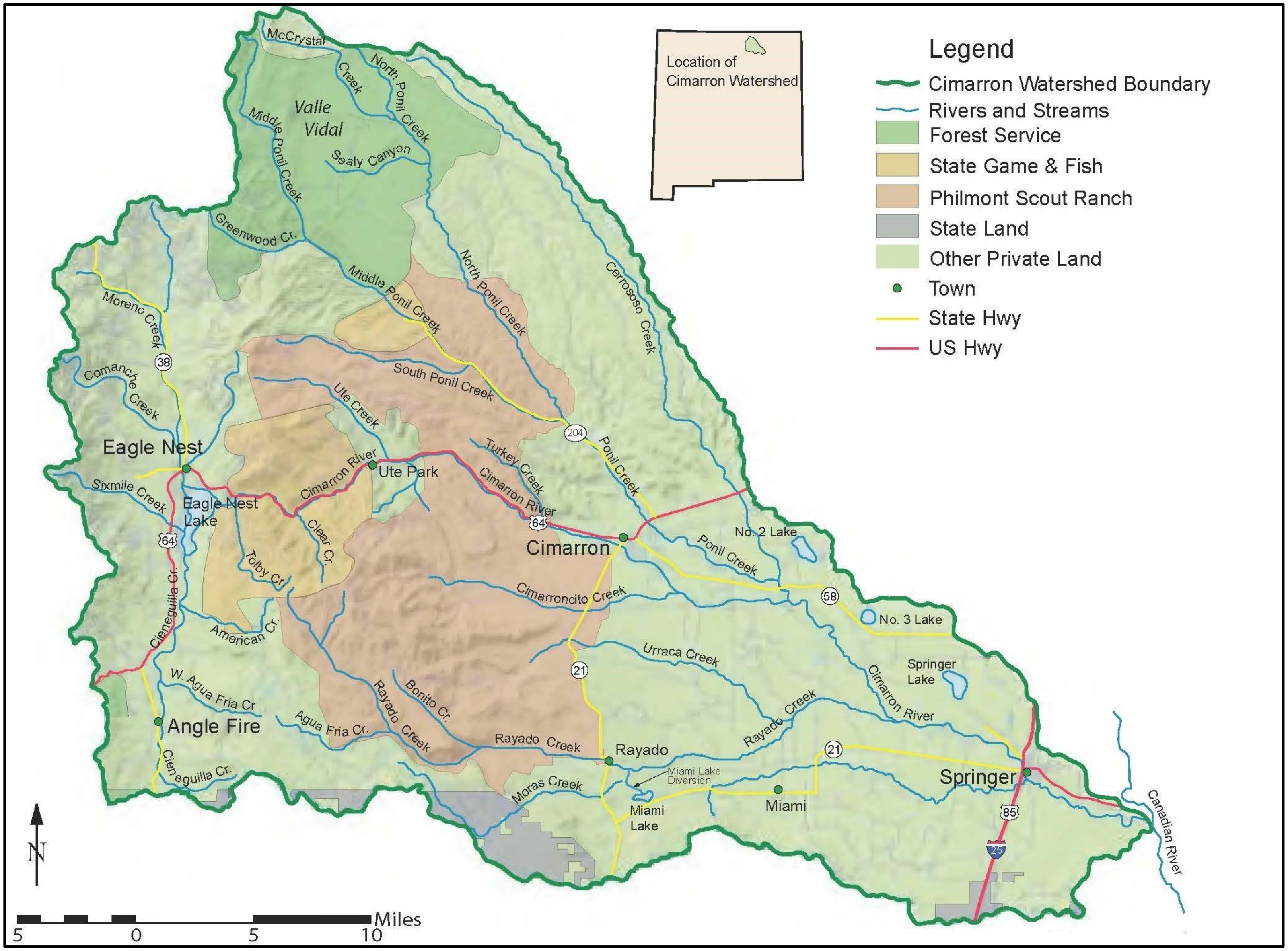


Figure 1. Landownership and location of towns in the Cimarron watershed (Hilton 2017)

2. WATER USER NEEDS AND INFRASTRUCTURE

Water User Needs

Beneficiaries of water storage improvements in the Cimarron watershed include the towns and communities of Raton, Springer, Cimarron, Ute Park, Eagle Nest, Agua Fria, and Angel Fire, as well as ranches in the area, such as American Creek Ranch, UU-Bar Ranch, Philmont Scout Ranch, and CS Ranch. During a field visit in November 2019, some representatives of these entities expressed the following needs regarding water supply (Community meeting participants 2019):

1. There is a need to stabilize slopes in burned areas, slow runoff volumes and energy, and reduce sediment transport. Participants suggested that drones could perhaps be used to explore specific target areas. Even relatively small precipitation events lead to rapid, torrential stream flow from burned forest areas with large amounts of sediment deposition.

2. Suggested forest management treatments include:

    a. Directional contour felling in places where treatment areas are accessible (only hand crews could feasibly get the job done, due to rugged terrain) and

    b. Log structures in drainages, such as palisade dams and sediment racks, appropriate for debris flow management and drainage restoration.

3. The development of a logging cooperative might leverage collaboration and economies of scale and coordinate marketing options for wood products to incentivize landowners to log or thin their forests.

The 2020 New Mexico Forest Action Plan (NMFAP) indicates that the Cimarron Watershed is an important source watershed for irrigators and municipalities downstream (NMEMNRD 2020a). The NMFAP ranks the Cimarron Watershed among the most important watersheds for source water supplies in the state, based on the number of downstream irrigators per acrefoot of water available. Numerically, much of the Cimarron Watershed headwaters ranks in the two highest map categories of downstream irrigators per acrefoot (the map class of 0.072 to 1 and of 0.017 to 0.071 irrigators per acrefoot, respectively) (NMEMNRD 2020a).

Water Diversion and Storage Infrastructure

The Colfax Regional Water Plan (2016) lists various limitations to the effective storage, delivery, and use of water to irrigators and municipalities (NMISC 2016). Both the Regional Water Plan (NMISC 2016) and water administrators from Raton, Springer, and Cimarron (Community meeting participants 2019) state that sediment and debris accumulation from flash floods in drainages, aggravated by the 2018 Ute Park wildfire and even the lasting impacts of the 2002 Ponil Complex fire, continues to wreak havoc on efficient water delivery and storage infrastructure (Figures 2 and

3). Water storage basins have become filled with sediment and in some instances need to be bypassed during flash floods, leading to decreases in mountain water made available. Seepage and evaporation losses in irrigation delivery systems also lead to inefficiencies in water delivery (NMISC 2016). The City of Raton faces major infrastructure limitations caused by the very small size of the spillway of Lake Maloya and funding reductions due to population declines (NMISC 2016).

Figure 2. Water diversion basin at the outflow of Turkey Creek (to the right) and sediment dredged from the basin and piled on the left bank, in the right side of the image (J.W. Jansens 2019)

Figure 3. Sediment and debris at the mouth of Turkey Creek (looking upstream onto State Road 64 and box culvert), resulting from flash floods after the Ute Park wildfire in 2018 (J.W. Jansens 2019)

3. PRINCIPLES OF WATER STORAGE

Hydrologic Cycle and Water Balance

This study concerns itself with water storage on the land surface and in subsurface components of the hydrologic cycle. However, according to the 2016 Regional Water Plan (NMISC 2016) and assertions from regional water managers (Community meeting participants 2019) the area's hydrogeology greatly limits the cost effective diversion of water from the saturated zone (also referred to as permanent groundwater in aquifers) by downstream communities. Therefore, this study does not focus on whether and how to enhance recharge to the saturated zone (groundwater recharge) of deeper, confined aquifers.

The study does consider recharge of shallow, unconfined aquifers in sediment layers (alluvial or water table aquifers that are in direct connection with the atmosphere) because they are often connected to surface storage bodies and contribute to runoff and base flow in streams. The groundwater inflow volume from outside the watershed area is unknown, and we assume that forest management impacts on such inflows conducted within the watershed are negligible. Therefore, this study focuses on water storage opportunities and a water balance based on soil storage and surface storage.

Definitions

Water storage in the context of this study is the portion of the water balance (water budget) that is retained on the land surface, such as in rivers, ponds, wetlands, reservoirs, snowpack and icepack, and in the subsurface, including the root zone, the unsaturated zone as a whole, the saturated zone, and different geologic units (Healy et al. 2007).

Water yield in the context of this study is the net increase in water storage resulting from one or more land management practices. (Note that this definition differs from *specific yield,* which is the storage coefficient for gravity drainage and filling of pores in sediments [Healy et al. 2007].)

The study's emphasis lies in optimizing the constituent water balance components of the available precipitation that are important for downstream water use. These water balance components are a positive change in annual water storage capacity (ΔS), an efficient (i.e., usable) increase in surface runoff (RO), and an increase in volume and duration of base flow (Q^{bf}), especially during dry seasons and drought periods. By the logic of the water balance equation, in order to increase the annual water storage capacity (ΔS), forest treatments will need to lead to a reduction of evapotranspiration losses (ET), assuming that total annual precipitation (P) remains unaltered. Simplified, such a water balance could be expressed in the following equation (Healy et al. 2007):

$$\mathbf{P = ET + \Delta S + RO + Q^{bf}}$$

where

P is precipitation

ET is evapotranspiration (the sum of evaporation from soils, surface water bodies, sublimation from snow and ice, and transpiration from plants)

ΔS is change in water storage

RO is surface runoff

Q^{bf} is base flow (groundwater discharge to streams).

The hydrologic cycle and water balance for the entire planet and for a defined place on the planet, such as the Cimarron watershed, is linked to the global energy budget (Healy et al. 2007). Precipitation and ET are the key components of the hydrologic cycle that interact with the energy cycle. Precipitation is a complex result of energy exchanges between Earth's surface and the atmosphere. ET follows the absorption of heat energy by plants, soil, and water surfaces. In energetic terms, the product of ET and latent heat of vaporization is the latent heat flux, or the energy used to evaporate water (associated with ET losses), effectively cooling Earth's surface (Healy et al. 2007).

Thus, climate change, which is largely expressed in increases of atmospheric temperature (potential energy), has direct effects on the hydrologic cycle and water budget by increasing ET. Because precipitation is not projected to increase in the region due to climate change (Robles and Enquist 2010, USGCRP 2018), by the logic of the water balance equation, ET increases would lead to decreases of water storage, runoff, and/or base flow.

Key Determinants

Water storage: Opportunities for increasing annual water storage have a bearing on storage in surface water through lake and pond capacity increases, groundwater storage in geologic strata of significant water holding capacity, storage in the unsaturated zone of soil, and storage in snowpack and icepack (Healy et al. 2017). Storage takes place when rain or snow meltwater enters the soil and a portion of it is retained in the pore spaces (Dunne and Leopold 1978; Healy et al. 2017). The remainder drains downward under the force of gravity into deeper geologic layers, eventually reaching the saturated zone (Dunne and Leopold 1978; Healy et al. 2017). A soil's porosity (the percentage of soil volume that consists of voids) determines the maximum amount of water that it can store. At maximum storage capacity, soil is said to be saturated, and its saturation moisture content is equal to its porosity (Dunne and Leopold 1978). Water storage in soil and in alluvial layers is effective because water loss due to evaporation from soil is relatively limited, compared to evaporation from surface water bodies. However, a certain amount of water storage in soil is made available to plants and may be lost through transpiration, which is explained below.

Soil's ability to absorb, hold, and release water depends on the complex interaction of a number of factors, such as:

- Infiltration rates,
- Soil porosity,
- Saturated hydrologic conductivity (Ksat), and
- Available Water Capacity (AWC).

The rate of infiltration depends on factors such as soil properties, vegetation cover and type, land use (e.g., compaction, amount of hardened terrain, etc.), slope length and steepness, and precipitation rates (Dunne and Leopold 1978, Healy et al. 2017).

The NRCS WebSoil Survey (2020) describes Ksat as a key indicator in the ability of a soil type to allow water to move through the soil. The survey also states that AWC is determined by capillary forces in the soil, which determine how much water remains in the soil at field capacity and are essential for water uptake by plants (NRCS 2020).

The water storage volume of a soil type that is available for potential downstream use is the volumetric soil moisture content in excess of the volumetric soil moisture content remaining at field capacity (i.e., AWC). The volumetric soil moisture content remaining at field capacity, specified in the custom WebSoil Survey for a particular area (NRCS 2020), is about 15-25 percent for sandy soils, 35-45 percent for loam soils, and 45-55 percent for clay soils (Cornell University 2020). The volumetric soil moisture content at the wilting point will have dropped to around 5-10 percent for sandy soils, 10-15 percent in loam soils, and 15-20 percent in clay soils (Cornell University 2020). Water in the soil above field capacity saturates soil layers and will drain away or evaporate.

Storage change (ΔS) occurs through gravity drainage and filling of pores. Field capacity numbers for the different soil types indicate that soil saturation is reached sooner for loamy and clay soils than for sandy soils (Figure 4). The percentage of storage in soil of a specific grain size is called the "storage coefficient" and expressed in what is called the "specific yield" of the soil type, with values ranging from 0.02 for fine-grained sediments to 0.35 for very coarse grained sediments (Healy et al. 2017).

Organic matter in soil increases water infiltration and storage capacity (Elliott et al. 2020). Soils with coarser texture and a high volume of organic matter are therefore better able to absorb, store, and gradually release water into a watershed's drainages. Theoretically, this means that coarse textured soils with good vegetation cover and high organic matter content would have the highest infiltration and water storage capacity for future downstream use. However, more porous soils also have a higher potential evapotranspiration (PET) level because of the natural relationships between soil porosity, volumetric soil moisture, and ET. As mentioned above, sandy and stony, porous soils have low volumetric soil moisture levels at wilting point and at field capacity than finer textured soils, but a higher specific yield (capacity to store water between their pores) than finer textured soils. As a result, a larger volume of water is available to be lost due to evaporation and transpiration, if it does not percolate to below the root zone. Inhibitions to downward percolation include rock or clay layers, saturated or frozen soil, and finer particles and organic matter in the soil to which water will adhere.

In coarsely textured soils, summer ET is relatively high because there is a large volume of available water to draw from for evaporation and transpiration. However, when soils are not confined at depth by layers that prevent infiltration, a considerable amount of water is also stored beyond the root zone, if the volumetric soil moisture is plentiful. In dry summers, more water will be lost by coarse textured soil due to ET than from fine textured soils. However, in fine textured soils, the greater volume of water stored in the soil is not available to downstream users but only to plants, unless plants (e.g., trees) have just been removed and no new ones have replaced them. But in this case, exposed soil will likely lead to increased surface temperatures, which will increase evaporative losses despite the elimination of transpiration losses. Weather and other site-specific conditions would then determine whether evaporation losses exceed the storage gained by reduced transpiration or not. For these reasons, water storage for downstream use would be optimal in medium-coarse textured forest soils with a high percentage of organic matter content.

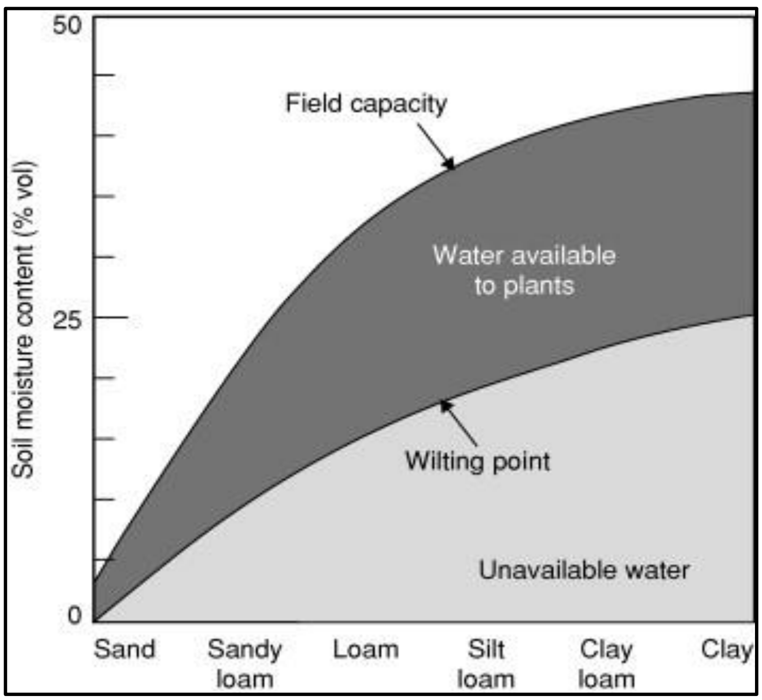


Figure 4. Graphic overview of soil water storage components (Cornell University 2020). The light gray area indicates water unavailable to plants and to downstream use; the dark gray area indicates water available to plants, but largely unavailable for downstream use; the white area indicates water available to plants and for downstream use. The graph indicates as well that water available for downstream use is in principle mostly found in the coarser textured soils (left side of the graph).

In order to increase water storage and downstream water yield, forest and landscape management initiatives would need to be designed in specific locations and in such a way as to help reduce both transpiration by plants and evaporation and sublimation losses, while increasing surface and sub-surface storage. Theoretically, this would require that treatments minimize temperatures and energy exchanges (i.e., heat fluxes) related to ET to maximize snow and ice accumulation and retention on land surfaces and increase soil porosity for optimal infiltration.

Recent modeling studies have identified several critical forest structure characteristics that affect specific micro-climate conditions that maximize snow retention on the forest floor (Essery et al. 2013, Sun et al. 2018, Mazzotti et al. 2020, Moeser et al. 2020). Forest gap shape, particularly gap width and orientation, in combination with forest edge characteristics play a role in reducing solar radiation and temperature, which helps determine locations of post-disturbance changes in snowpack (Moeser et al. 2020). The conclusions from these modeling findings regarding site conditions leading to post-disturbance snowpack retention can help design forest treatments in headwater forest stands for optimal water storage through snow retention.

Surface Runoff: Surface runoff consists of sheet flow and channel flow after precipitation events and snow melt. Seasonal weather patterns, climate trends, and land degradation due to fire and development tend to concentrate runoff volumes. Climate projections for runoff also indicate increases in early stream flow volumes and durations throughout the Southwest (Robles and Enquist 2010; DeBuys 2011; Gangopadhyay and Pruitt 2011; USDI 2011; Gutzler 2012; and Tolley et al. 2017).

When peak volumes are high and concentrated in time, downstream users will face capacity limitations to capturing, storing, and purifying large volumes of water for consumptive uses. As a result, increases in water expressed in increased annual runoff volumes due to deliberate land management interventions may not become effectively available to downstream users unless the runoff volumes are spread more evenly over time (i.e., by widening rather than heightening the peak curve of the hydrograph) and water source areas and drainage channels are protected against soil loss.

The modeling studies by Moeser et al. (2020) found that under certain forest structure conditions snow accumulation was not only higher than in other forest structural conditions, also the melt out date was later in the year. A later melt out date prolongs the period of runoff and can help lower the peak in the hydrograph. As a result, forest treatments aimed at forest structure modifications for snow retention can have a positive effect on prolonging the melt out period and the spread of the runoff volume, reducing the effects of a changing climate on flow regimes.

A study of peak runoff for flood management in Europe found that peak flows are highly related to pre-event soil moisture levels (Wahren et al. 2012). As well as pre-event saturation levels of soils in catchment areas, peak runoff volumes are related to the acreage of catchments areas, vegetation type and cover, and the presence of wetlands and wet meadows and their infiltration capacity. In a paired watershed study in the Andes, Roa-García et al. (2011) found that discharge volumes showed a "bursting" behavior of increased flood peaks after saturation of soils in high elevation wetland valleys. Yet, prior to saturation, wetlands and wet meadow areas provide a lag time to peak runoff, during which these areas accumulate and store water until saturation is reached (Roa-García et al. 2011). Wahren et al. (2012) noted that the need to spread peak flows is important to prevent flooding and to meet water quality and soil protection goals.

The phenomena prolonging the melt out date and lag time in peak runoff are particularly important in the Cimarron watershed and similar areas, where annual precipitation and runoff is concentrated in seasonal events, such as spring snowmelt runoff and monsoonal summer storms (Tolley et al. 2015). This is especially relevant for the study area, where recent forest fires have exposed soil, and soil particles are readily carried downstream during even mild runoff events, leading to water pollution and sediment deposits downstream (Community meeting participants 2019).

Effective management treatments in the Cimarron watershed should thus include slowing sheetflows and prolonging the time of concentration for stormwater runoff and snowmelt flows from high mountain drainages. Forest treatments would ideally need to take place in larger, forested catchment areas (drainages), preferably those with wetlands and wet meadows where grazing impacts are low (low compaction rates) and where soils have at least a moderate ability to absorb and store excess precipitation. Treatments would need to create carefully designed canopy gaps (patch cuts) that reduce heat fluxes and prolong the melt out date of snowpack on the forest floor. Treatments would also need to help increase surface water retention in moist forest soils and riparian, alluvial soils along first-order perennial, intermittent, and ephemeral streams.

Baseflow: Opportunities for increases in base flow (i.e., groundwater discharge to streams) relate to previously described factors and their suggested water storage improvement opportunities. The main determinant of concern for this study is the storage capacity and conductivity (flow volume and velocity) of alluvial aquifers. Therefore, it is important that as much precipitation and snow melt water as possible drain in surface and sub-surface flows into alluvial soils associated with drainages.

Potential benefits for available water downstream may particularly apply to the limestone geology around Angel Fire and the porous rock formations on the northeastern flanks of the Cimarron Range. However, in-depth hydrogeological research would be needed to define to what extent the aquifers associated with these geologic formations can be made accessible and water producing and to what extent particular forest management activities can help recharge them. Until more information is available, it is unlikely that forest management could do more than marginally influence baseflow originating from geologic aquifers in certain areas of the watershed. Therefore, water storage and hydrologic conductivity factors associated with deeper, confined aquifers in the area's geologic layers remain outside the scope of this study.

Evapotranspiration Loss Reduction: Opportunities for reducing evapotranspiration include lowering sublimation and ablation (melting) of snow and ice, decreasing evaporative loss from surface water bodies and exposed soil, and decreasing transpiration loss from living plants. In forest ecosystems, reductions in transpiration are typically achieved by reducing living plants (removing trees) and and/or by reducing air movement and radiative and turbulent heat fluxes by maintaining relatively dense canopy cover (Essery et al. 2003; Aron et al. 2019). Transpiration losses in high elevation forests are limited to the summer season (late May through September), and measures to reduce transpiration losses are temporary, with a measured maximum effect of five to ten years, because of rapid vegetation regrowth after tree removal (Evans et al. 2011; Reynolds et al. 2013; Mahan 2019).

Snow on tree canopies disappears through sublimation, ablation, and unloading (through-fall to the ground) (Essery et al. 2003). As with reduction in transpiration, reduction in evaporation and sublimation is achieved by reducing air movement and radiative and turbulent heat fluxes, which translates into providing wind shelter and preventing upward air mixing (Essery et al. 2003; Aron et al. 2019). Empirical wind and evaporation research revealed that wind speeds of 4 to 6 miles per hour (5.8 to 8.7 feet per second) readily absorb all the scant moisture released by the soil or water bodies (Jensen 1983). As a result, slight heat increases and moderate dry air movement contribute to increased evaporation rates and limit infiltration and water storage, especially in the summer period between May and September (Tolley et al. 2015; Aron et al. 2019). In summer, such a large portion of monsoon precipitation is lost to evapotranspiration due to canopy interception, bare soil evaporation, and uptake by vegetation that very little of it reaches the root zone (Tolley et al. 2015). As a result, evaporation loss reduction efforts much focus on reducing ablation and sublimation of snowpack during the winter precipitation season.

Scientific studies that describe sublimation of snow and ice show great variability in findings. Parmenter (2009) reports that in northern New Mexico's Valles Caldera, nearly 50 percent of the snow water equivalent (SWE) sublimates from canopies of trees in forest types and elevations like those in the headwaters of the Cimarron watershed. Field surveys in the Valles Caldera found that maximum snow accumulation occurred under canopy densities between 25 and 45 percent, corresponding to about 20 percent greater SWE than in open areas (Veatch 2008; Parmenter 2009). However, LaMalfa and Ryle (2008) found that snowpack sublimation is not much different between meadow, aspen, and conifer sites, and generally lower than 5 percent of winter precipitation volume.

Observational and modeling studies on the impacts of fire induced canopy changes on snow accumulation, snowpack ablation, and shortwave radiation also show a spread of different outcomes for SWE and melt-out dates (Moeser et al. 2020 and Goeking and Tarboton 2020). Moeser et al. (2020) notes, however, that most findings are from relatively coarse scale studies and advocates for the importance of fine scale modeling (1 meter precision). Moeser et al. (2020) indicate that their modeling studies for a burned forest site in the Valles Caldera indicate that change in canopy density is not a good predictor of snowpack response to canopy disturbance at a fine scale.

These findings indicate that when looking at forest structure, rather than canopy density, at a fine scale SWE increases can be achieved most effectively by reducing evaporative loss, ablation, and sublimation of winter precipitation. As described above, specifically shaped, small canopy gaps affect forest structure in headwater forests in ways that reduce evaporation and ablation (Moeser at al. 2020).

Only in specific locations might forest thinning (i.e., selective or group thinning from below) create openings that accumulate snow and protect it against sublimation and ablation (Parmenter 2009). Interpretation of findings by Woods et al. (2006), Evans et al. (2011), and Aron et al. (2019) indicates that an even stem distribution in aspen and pine stands may reduce air mixing and associated evaporative losses. Analysis of energy fluxes in areas where average winter temperature is more than -1° C indicates that it is important to maintain shading while managing for less dense forests to minimize total melt energy. As shading will block shortwave radiation and less dense stands emit less longwave radiation than denser stands, thinning in lower elevation, warmer stands, for example on south facing slopes, could help maximize snow retention (Goeking and Tarboton 2020).

In sum, maximizing water storage and water availability for downstream beneficiaries is largely dependent on:

- Increasing runoff volumes through snow retention,
- Spreading runoff over greater periods of time by prolonging the melt out date,
- Prolonging low flow in mountain streams into dry seasons and drought periods, and
- Reducing the sum of evapotranspiration losses in winter and spring by creating small canopy gaps with a very specific shape and orientation.

Snow retention and prolonged melt out dates can be achieved by reducing heat fluxes that drive evaporation and ablation of snow on the ground. This can be achieved covering bare soil, optimizing vegetation cover in alluvial areas and riparian zones, providing wind shelter to surface water bodies, and implementing site specific forest treatments that reduce evaporation losses during the winter season when most of the precipitation occurs in the Cimarron watershed area (NRCS 2019).

Many ecological factors associated with the water balance components are interrelated. Therefore, the cumulative short-term effects of many ongoing forest treatments will need to achieve a balance between ET reductions and efficient, usable runoff increases. Due to the complexity of the bio-physical environment of the headwater catchment landscape, a lack of scientific information pertinent to the watershed area, and many complexities in monitoring effects of forest treatments, much of the recommended work toward achieving this balance would need to be adaptive forest management, in which monitoring, evaluation, and ongoing research are essential.

4. LANDSCAPE CHARACTERIZATION

Hydro-Geology and Topography

The Cimarron watershed is located on the eastern slopes of the Sangre de Cristo Mountains in northern New Mexico. The watershed drains from the mountain divide, which forms the boundary between Taos and Colfax Counties, in an eastern direction to the Canadian River. The watershed is approximately 1,032 square miles in size (660,480 acres) (Hilton 2017). Roughly one third of the watershed area constitutes a high elevation mountain landscape, with headwater catchment areas that are relevant for this study (Figure 5). These areas are located between 8,400 feet in the Moreno Valley around Angel Fire and Eagle Nest and above 11,000 feet at Agua Fria Peak, five miles east of Angel Fire (BLM 1994).

Geology in the Cimarron watershed is diverse (Hilton 2017), which complicates the identification of optimally suited headwater catchments for water storage. In order to clarify the diversity of hydro-geologic features, the watershed's headwater catchment areas can be characterized by specific units from north to south (Figure 5), including:

a. The Valle Vidal, which is the headwaters of Ponil and Cerrososo creeks. The headwaters of this unit consist of sandstone, shale, mudstone, and claystone, and alluvial deposits in the valleys of the higher elevation headwater areas, which include wetlands, lakes, and ponds.
b. The northwestern ridgeline around the Moreno Valley and Red River pass, which consists of metamorphic rocks.
c. The most western ridge, including the southern end of the Moreno Valley around Angel Fire and lower West Agua Fria Creek, which constitutes the headwaters of several short drainages that empty in the Moreno Valley from the west and from the southeast. The geology of this unit consists of carbonates (limestone) and calcareous rocks.
d. The Moreno Valley, which is a north-south oriented, long and narrow mountain valley, with a broad bottom of grassland and former wetlands. It consists of alluvial deposits and drains from the south northward and from the north in a southerly direction to the center, where the streams empty into Eagle Nest Lake. The lake is the result of a dam in the headwaters of the Cimarron River, which flows eastward from there, down the mountain slopes. The Moreno Valley was formed as a result of faulting, which caused a rift valley (a syncline) that initially drained southward but was over time pirated by the breakthrough of the Cimarron Creek on its eastern side (Smith and Ray 1943).
e. On the northeast side of the Moreno Valley, a series of ridges and peaks run in a southeasterly direction, including Iron Mountain, Baldy Mountain, and Touch-Me-Not Mountain. This area constitutes the headwaters of a relatively dry and rugged landscape, underlain by intrusions of plutonic rock in the sandstones and shales of the northern part of the watershed. The area drains the Ute and Merrick creeks into the Cimarron River. Much of this landscape lies in the Colin Neblett Wildlife Area.

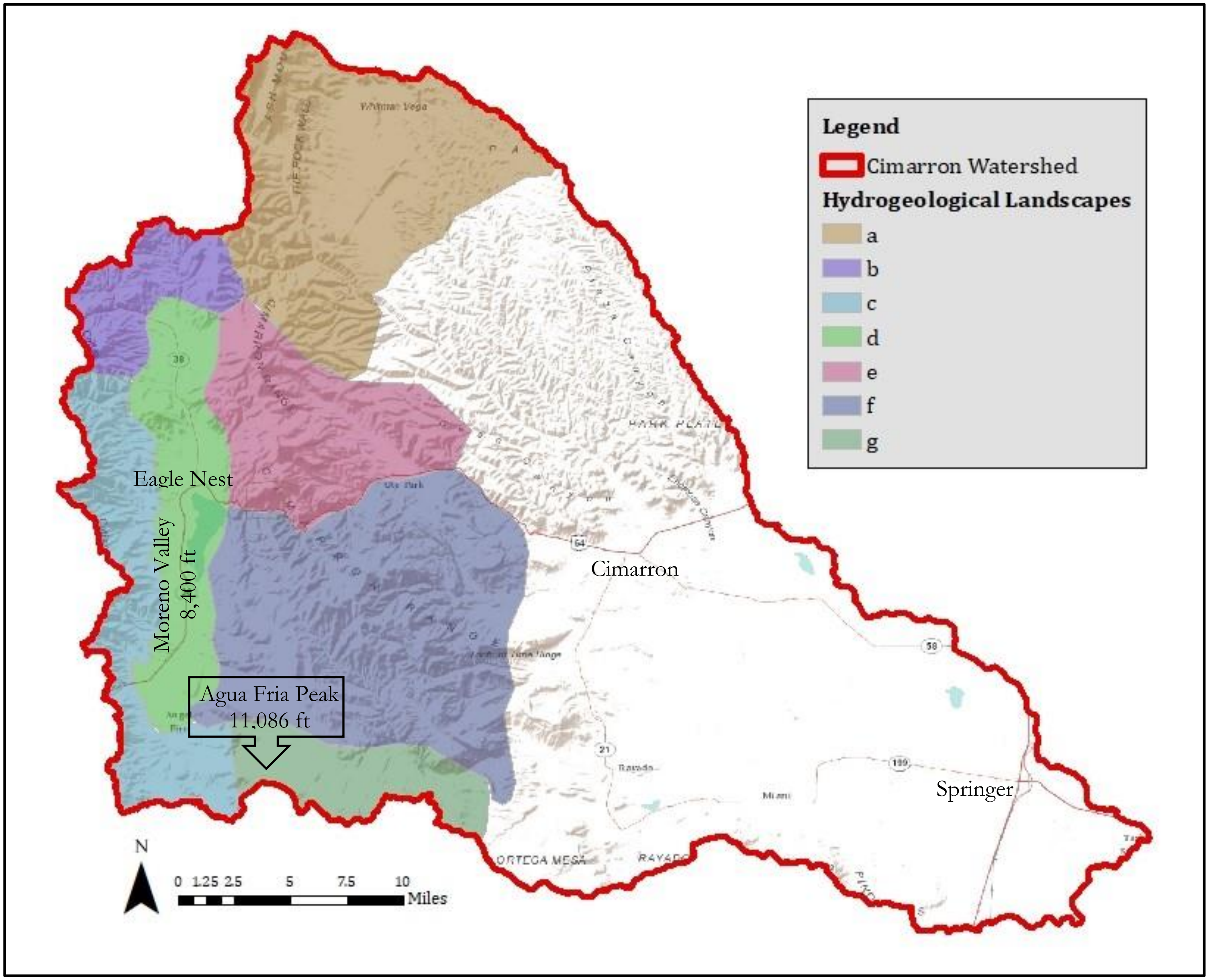


Figure 5. Land use / land cover map of the Cimarron watershed (Mollie Walton 2020)

f. The Cimarron Range extends to the southeast of Eagle Nest Lake and suddenly rises more than 5,000 feet above the adjacent Great Plains landscape (Smith and Ray 1943). Sedimentary rocks dip off a Precambrian core eastward into the Raton basin (Goodknight 1976). The core of the central and southern parts of the Cimarron Range consists mainly of vertically uplifted Precambrian metamorphic rocks (Goodknight 1976; Hilton 2017). Goodknight (1976) explains: "North of Cimarron Canyon the range consists mainly of a thick stack of igneous sills of mid-Tertiary age which spread apart Paleozoic and Mesozoic sedimentary rocks. The entire range was affected by late Tertiary high-angle faulting along its margins." Tertiary intrusions in the northern portion of the area and the lava flows to the south obscure regional relations of the range's geology. In the valley of Rayado Creek, a volcanic plug that fed some of the lava flows has been exposed by erosion (Smith and Ray 1943).
g. The southern part of the watershed, east of Angel Fire, consists of a high elevation plateau of mafic volcanic rocks, with a small felsic volcanic rock mass below Cieneguilla Mountain (Hilton 2017), the location of the Angel Fire ski area.

Analysis of the interactive New Mexico SFD Forest Treatments Map (NMEMNRD 2020) shows that the headwater catchment areas in the watershed comprise part or all of seventeen 12-digit HUC sub-watersheds. Eleven sub-watersheds have entirely the character of headwater catchments. Five of these stretch from Angel Fire north along the Moreno Valley; one comprises the high meadows and wetlands of the Agua Fria Creek sub-watershed; four are in the Cimarron Range (east of the Moreno Valley); and one comprises the headwaters of the Ponil Creek system in the eastern Valle Vidal. The other six sub-watersheds are mostly steep and narrow headwater valleys that extend eastward to the Cimarron River (Figure 6).

Research has confirmed that the size of drainage areas and sub-watersheds, along with the presence of wetlands and forested land, correlates positively with increased lag times (i.e., times of concentration) between peaks in precipitation and peaks in runoff (Roa-García et al. 2011). As a result, headwater catchment areas that comprise sub-watersheds with such characteristics are most suitable for water storage; they retain precipitation longer in the landscape, and appropriate management of the delayed peak runoff will likely increase opportunities downstream for effective water interception, diversion, storage, and use.

The 2016 Colfax Regional Water Plan describes the ways that the Cimarron watershed area's downstream hydrogeology greatly limits groundwater development (ISC-OSE 2016). This feature limits downstream communities to the use of surface water, which renders them vulnerable to drought conditions, as confirmed by administrators of the City of Raton, Springer and Cimarron (personal communication with field tour and meeting participants on November 13-14, 2019). The Cimarron watershed is underlain primarily by the Canadian River Declared Underground Water Basin (UWB), which stretches to the south and east beyond the watershed boundaries. The 2016 water plan states that development of groundwater resources has occurred almost exclusively in the Moreno Valley area around Angel Fire and Eagle Nest (NMISC 2016).

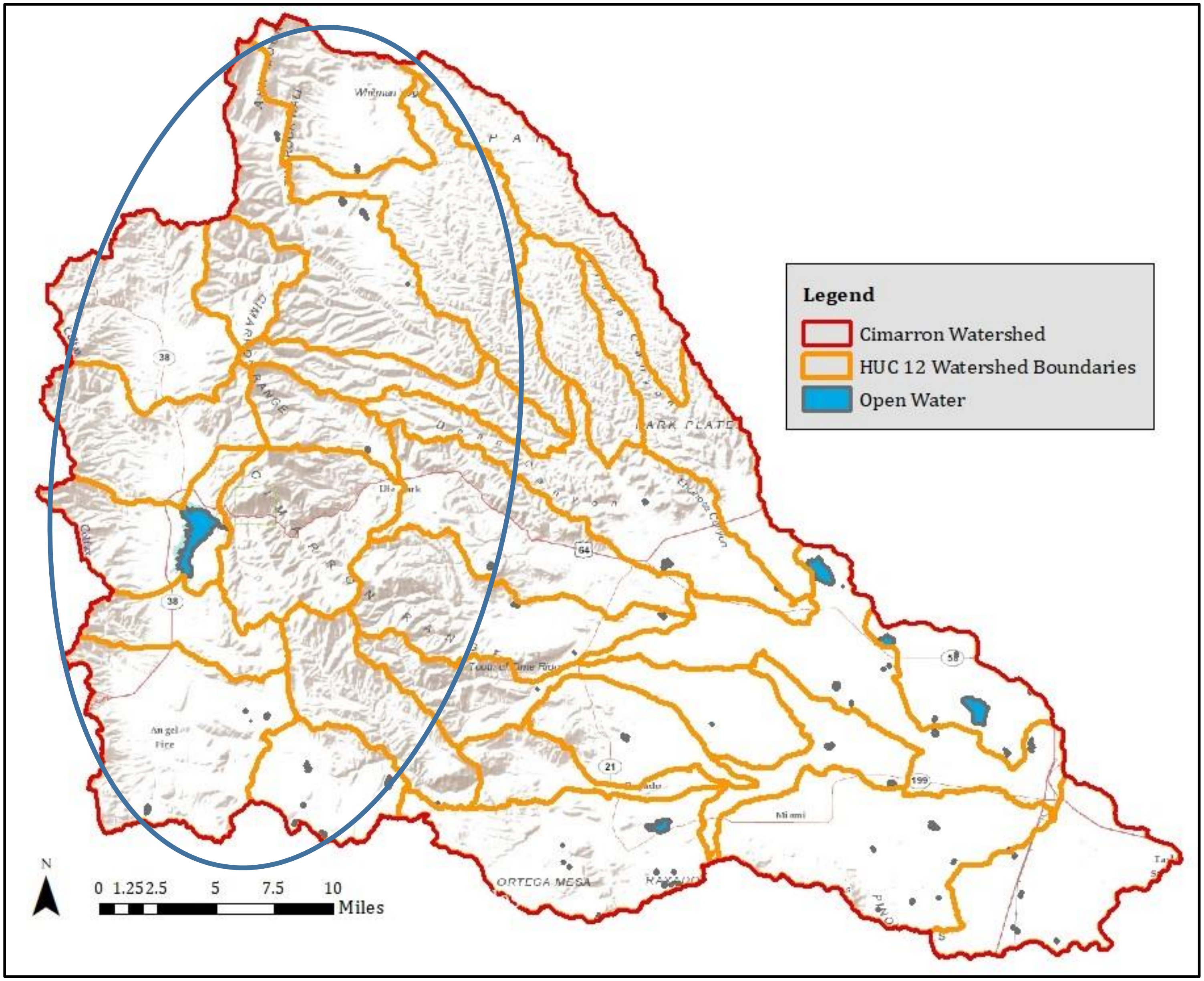


Figure 6. HUC-12 sub-watersheds of the Cimarron watershed (orange lines) and headwater catchment areas in 17 sub-watersheds (within blue oval) (Mollie Walton 2020)

Climate and Weather: Patterns and Trends

Terrain variability in Colfax County results in considerable climate and weather variations. According to the regional water plan (NMISC 2016), temperatures range from below 0 degrees Fahrenheit (ºF) in the mountains in the western part of the watershed to highs in excess of 100ºF in the eastern plains. Precipitation amounts and types vary also and are influenced by location and elevation. The long-term average annual precipitation for the higher elevations exceeds 30 inches (NMISC 2016).

Climate change projections for the Upper Canadian Basin and the Rio Grande Basin pertaining to the Cimarron Watershed indicate that average annual temperatures may increase between 0.5°F and 3°F until 2050 (USDI 2011), and up to 8.5°F by 2100 (USGCRP 2018). The most important climate change impact in relation to this study would be an increase in average winter temperatures, leading to reduced snowpack, reduced number of days with snow on the ground, and earlier and heavier snow melt runoff (USDI 2011; USGCRP 2018). Due to projected temperature increases in the summer, the potential evaporation rate would increase, extracting more moisture from soil and water bodies. The average annual precipitation amount is projected to stay more or less the same (USDI 2011). Overall, weather patterns and weather phenomena are expected to become more erratic, less predictable, and more extreme (USDI 2011; USGCRP 2018).

The USDA Natural Resources Conservation Service (NRCS) National Weather and Climate Center provides an online interactive mapping system with data, graphs, and tables relating to snowpack, precipitation, streamflow, reservoir storage, and soil moisture and temperature (NRCS 2019). Data for the nearest mountain in the area are for Tolby Peak (10,180 feet), which is located about five miles east from the southern point of Eagle Nest Lake.

The 30-year mean annual cumulative precipitation (1981-2010) for this location is 26.5 inches. Annual precipitation accumulation is nearly linear, with a brief increase around May 1 and a decline starting in the first week of May and extending until mid-July. The mean total winter precipitation between October 1 and May 1 comprises approximately 15 inches or 56.6 percent of the mean annual cumulative precipitation. However, by late February, the median snow water equivalent (SWE) is at most approximately 70 percent of the total precipitation. On an annual basis, the SWE is only about 8.1 inches or 30.5 percent of the total mean annual precipitation. Snow accumulation in the Cimarron watershed study area starts in mid-November and extends until late April. The snowmelt period extends from late March to late April. Stream flow is likely concentrated during late April and early May, due to snow melt, and between late June and September, due to summer storms. Precipitation and snow fall conditions in the winter of 2019-2020 appear to be well above the 30-year mean (NRCS 2019).

A recent study on streamflow in watersheds on the western slopes of the Sangre de Cristo Mountains cautions that water retention from snow melt is essential for stream flow and that climate change is likely to lead to reductions of snow accumulation (Tolley et al. 2015). The study documented the seasonal inputs of precipitation on groundwater recharge and streamflow in the Rio Hondo watershed, west of Taos, New Mexico. This watershed is believed to be broadly representative of the Sangre de Cristo Mountains for similar climatic and orographic conditions (Tolley et al. 2015)).

Tolley et al. (2015) also found that precipitation in the Sangre de Cristo Mountains shows a strong seasonal influence in water volumes that infiltrate and contribute to runoff. Winter precipitation due to slow melting of the snowpack and deep percolation below the root zone when ET demand is low is the foundation for annual groundwater recharge and streamflow (Tolley et al. 2015). The study shows that winter and spring precipitation accounts for about 68-88 percent of groundwater recharge and streamflow in the Rio Hondo, while it comprises only about 45-55 percent of the total annual precipitation (Tolley et al. 2015). Given that winter and spring precipitation amounts in the headwaters of the Cimarron watershed are at the upper end of this study's annual precipitation range, we may anticipate that the groundwater recharge potential is also toward the upper ranges mentioned, although much of this potential depends on soil and vegetation conditions (see below).

The Rio Hondo study clarifies that the seasonal correlations of isotopic composition in water samples with elevation can be explained by New Mexico's precipitation patterns (Tolley et al. 2015). Summer precipitation falls largely due to localized, mountain-induced lifting of water vapor originating from the Gulf of California, Gulf of Mexico, and to local recycling due to ET. Winter precipitation comes from more regional storm fronts that originate from the Pacific Ocean (Tuan et al. 1973 cited in Tolley et al. 2015). Summer monsoon precipitation is rapidly flushed from the system, consistent with a fast runoff process with residence times that can be measured in days. Because potential ET is greatest during the summer (Stewart et al. 1999), a large portion of monsoon precipitation is lost to canopy interception, bare soil evaporation, and uptake by vegetation. The study concludes that "as a result, very little of the precipitation that falls during monsoon storms, if any, makes it past the root zone" (Kurc and Small 2004 cited in Tolley et al. 2015). A combination of fast runoff and ET processes is most likely responsible for the lack of a significant isotope signature in surface water of monsoonal runoff events.

In sum, winter and early spring precipitation is a disproportionate source of groundwater recharge and streamflow in the Sangre de Cristo Mountains and by extension in the Cimarron watershed. This phenomenon is consistent with previous studies in the Saguache Creek watershed and the Rio Hondo watershed that used geochemistry, age-dating, and end-member mixing analysis techniques in fractured bedrock mountain watersheds (Tolley et al. 2015). Streamflow, and especially base flow in this type of watershed, appear to be significantly controlled by groundwater contributions, which in turn are heavily influenced by snowmelt-driven groundwater recharge processes. Therefore, reduction in the amount and duration of snowpack predicted by climate change will likely result in a disproportionate reduction of groundwater recharge and, ultimately, of streamflow in these types of mountain watersheds (Tolley et al. 2015).

In 2010, The Nature Conservancy published a climate vulnerability assessment of landscapes across the Four Corners States, with map details for each HUC-6 code watershed in the region (Robles and Enquist 2010). The assessment clarifies the climate change vulnerability levels of the northern Rio Grande Basin and the Upper Canadian Basin.

The study identifies four vulnerability categories based on temperature changes during the 55-year period of 1951-2006, a review of wildfire incidences in the region, a review of documentation about early stream flow and snowpack reductions, and an assessment of changes or decline in plant and animal species. Its results indicate that the Cimarron watershed falls in the lowest vulnerability category with only a mild (1°F) temperature increase during the 55-year period, a projection of only seven fresh-water species to be impacted, and an already documented snowpack reduction. The documented changes also include a temperature increase of 1.6°F in sub-alpine conifer forests (Robles and Enquist 2010).

The projected climate trends and impacts on the watershed's forest ecosystem underscore the importance of forest treatments that prolong snow and water retention and storage in the headwater catchment areas. They also offer the perspective that the Cimarron watershed may be at least somewhat less vulnerable to climate impacts than surrounding areas and may have some opportunities to curb current and projected ET losses toward temporary water storage gains.

Soils and Land Use

The ultimate purpose of this study is to recommend pilot land treatment projects on private properties in headwater catchment areas that are promising for water storage. The hydro-geological analysis of the study area, coupled with conversations with selected stakeholders in November 2019, led to a selection of high priority areas in the identified headwater catchment units. These include in descending order of importance (Figure 7):

a. The Agua Fria Creek sub-watershed, Headwaters Rayado Creek sub-watershed, and the upper part of the Urraca Creek sub-watershed, all located east of Angel Fire on the American Creek Ranch and UU Bar Ranch
b. The five sub-watersheds along the Moreno Valley, including the Headwaters Cieneguilla Creek sub-watershed (around Angel Fire), Outlet Cienguilla Creek sub-watershed (to the north of the previous one), Eagle Nest Lake sub-watershed, Outlet Moreno Creek sub-watershed (to the north of the previous one), and the Headwaters Moreno Creek sub-watershed (at the northern end of the Moreno Valley)
c. The Ute Creek and Ute Creek-Cimarron River sub-watersheds and the upper part of the Cimarroncito Creek sub-watershed, at the heart of the Cimarron Range; the majority of this priority area is located on the Colin Neblett Wildlife Area, managed by the NM Department of Game and Fish, while the northern and southern parts are owned by the Philmont Scout Ranch.

The six sub-watersheds, including the Greenwood Canyon sub-watershed, the four Ponil Creek sub-watersheds and the Headwaters Cerrososo Creek sub-watershed, are either located on national forest lands or constitute steep, narrow, rocky headwaters that have limited water storage ability. As a result of these limitations these sub-watersheds have been further ignored in this study (Figure 7).

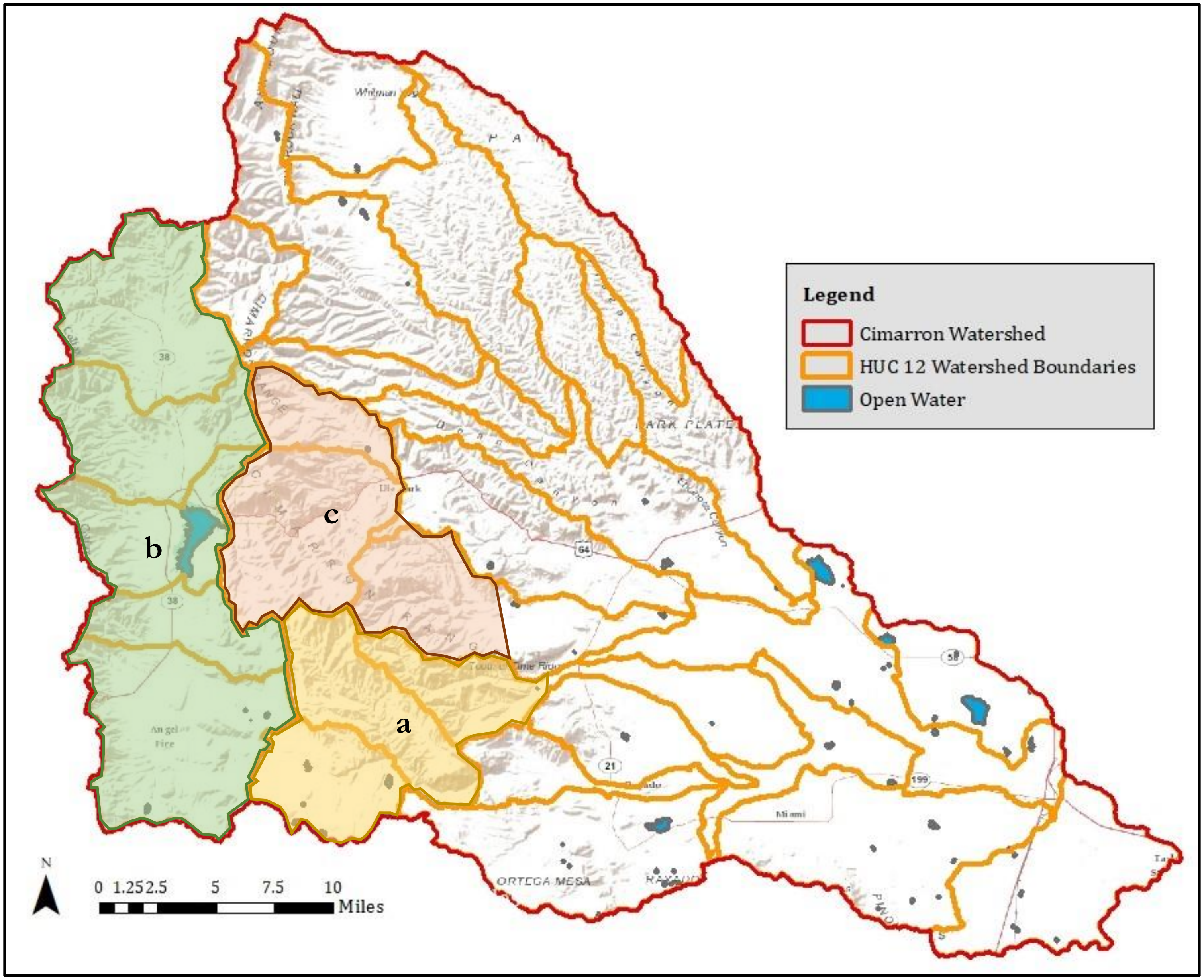


Figure 7. High priority sub-watershed areas (Mollie Walton 2020)

For purposes of the Cimarron watershed study, a description of soils is of interest in relation to the varying ability of specific soil types to absorb water through infiltration, retain it in the soil matrix, and release it, either through percolation into a (shallow) aquifer that supports base flow or by surface runoff into water bodies. Therefore, using the WebSoil Survey (NRCS 2020), the study's authors prepared a custom soil survey for the most important parts of the three selected areas with the greatest management potential.

The WebSoil Survey does not provide explicit information about water storage sources for downstream use. Therefore, a compilation of relevant factors was used to approximate the most important soil groups on which forest management could be considered to optimize downstream water yield. Important factors that play a role in determining whether land can be managed to increase water infiltration, storage and gradual release include a soil type's subsurface outflow water quality limitations (such as erosion risk, pesticide/nutrient movement, and acidity), liquid limit (the amount of water soil can hold before it liquefies), drainage class, hydrologic soil group, and erosion rating. Table 1 provides an overview of the eight most important soil groups in the study area with numerical values for the most important factors regarding infiltration and drainage.

An evaluation of the values that together generate the most favorable conditions for infiltration, water storage, and drainage for downstream use leads to the following prioritization of soil types for consideration of land management treatments to optimize water storage. In descending order:

1. The soil groups of the Angostura-Tolby association (AN), Bundy association (BU), and Burnac-Hillery association (BY)
2. The soil group of the Cypher-Bundo association (CY)
3. The soil groups of the Etoe-Etown association (EE) and the Fuera-Burnac association (FD)
4. The soil group of Hillery stony loam (HrD) and any miscellaneous soil groups

Another important soil group, the Saladon mucky silt clay association (SaC), is unsuitable for water storage development. The soil groups are briefly described in Table 2 and illustrated in a map in Figure 8.

Table 1. Overview of soil groups and numerical values for key water storage indicators, based on NRCS WebSoil Survey analysis

Code	Outflow Water Quality[1]	Liquid Limit[2]	Ksat[3]	Drainage	AWC[4]	Hydrologic Soil Group[5]
AN	Very limited (e, n, a)	30.9%	13.98 = High	Well drained	0.11	B
BU	Very limited (e, n)	24.4%	28.23 = High	Well drained	0.08	A
BY	Somewhat limited (e, n)	43.6%	7.15 = Mod. High	Well drained	0.12	D
CY	Very limited (e, n)	25%	19.66 = High	Well drained	0.09	D
EE	Very limited (e)	28.4%	9.17 = Mod. High	Well drained	0.11	B
FD	Very limited (e)	45%	3.42 = Mod. High	Well drained	0.11	C
HrD	Not limited	46.7%	2.92 = Mod. High	Well drained	0.14	D
SaC	Somewhat limited (n)	47.7%	0.38 = Mod. Low	Very poorly drained	0.16	D

1) Subsurface water outflow quality limitations include the following causes: erosion (e), nutrient movement (n), and acidity (a).

2) Liquid limit is the amount of water that soil can hold before it liquefies and loses integrity.

3) Ksat is saturated hydraulic conductivity (expressed in standard classes), which is the ease with which pores in a saturated soil transmit water (in micrometers/second). Ksat is dependent on soil structure, porosity, and texture.

4) Available water capacity (AWC)

5) Hydrologic soil groups (HSG):

A = Soil with a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils also have a high rate of water transmission.

B = Soil with a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.

C = Soils with a slow infiltration rate when thoroughly wet. These consist chiefly of soils with a layer that impedes the downward movement of water or soils of moderately fine or fine texture. These soils have a slow rate of water transmission.

D = Soils with a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have high shrink-swell potential, soils with a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

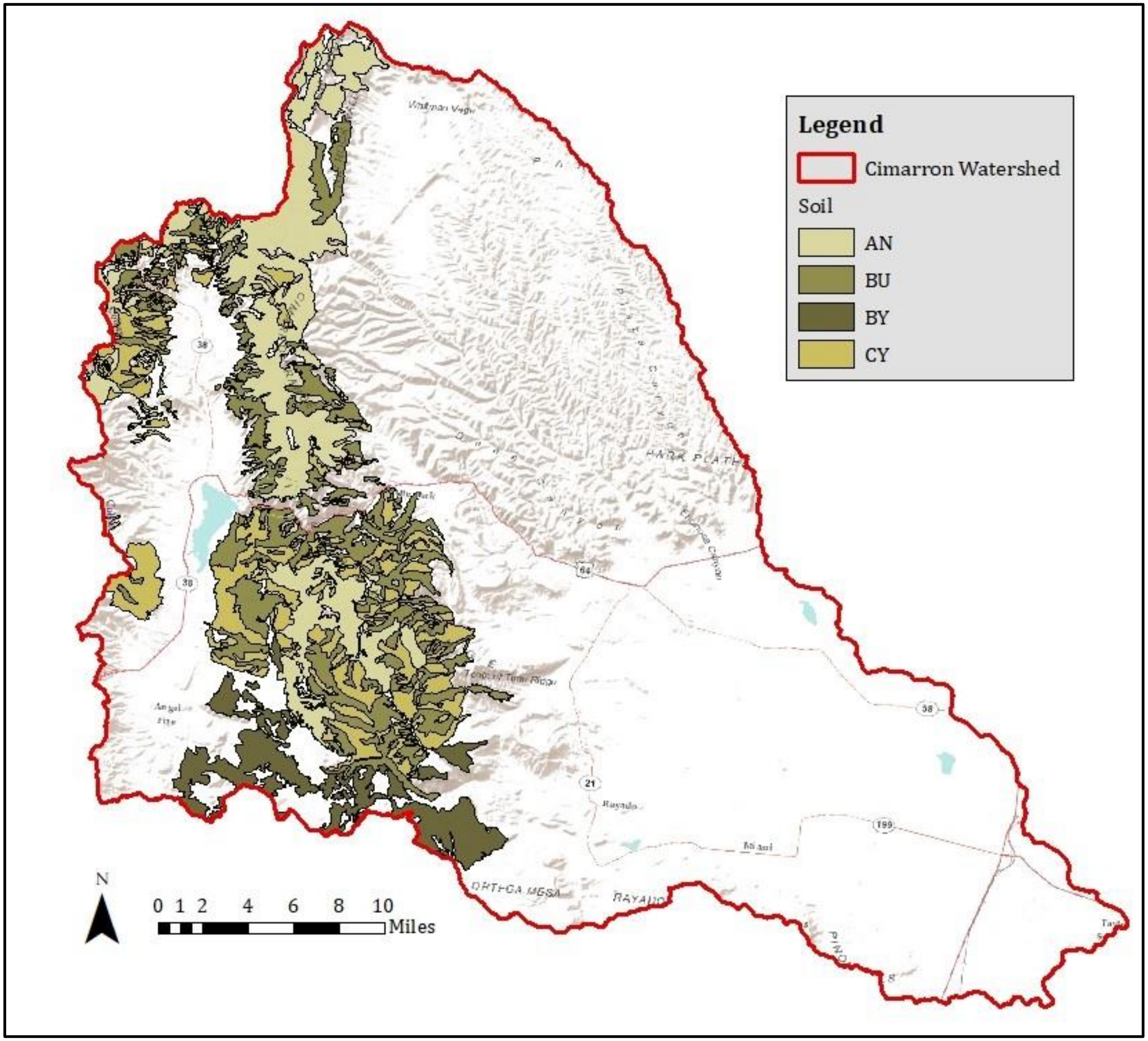


Figure 8. Soil map showing the four most important soil groups for the purpose of water storage in the watershed (Mollie Walton 2020)

Table 2. Characterization of key soil groups in the study area, based on NRCS WebSoil Survey analysis

Code	Name	Slope	Site Description
AN	Angostura-Tolby association	Steep	Southwest-facing slopes of the Cimarron Range, east of the large mountain meadow areas; aspen and dry and wet mixed conifer forest
BU	Bundy association	Steep	The forested north- and northeast-facing slopes of most of the Cimarron Range; cool, moist mixed conifer forest
BY	Burnac-Hillery association	Steep	The forested north- and south-facing slopes at the higher elevations of the central parts of West Agua Fria Creek sub-watershed and around meadows; dry and moist mixed conifer forest
CY	Cypher-Bundo association	Steep	The forested south- and west-facing slopes of most of the Cimarron Range; dry mixed conifer forest and some aspen
EE	Etoe-Etown association	Steep	The forested, north- and south-facing lower slopes of the western part of the West Agua Fria Creek sub-watershed; dry to moist ponderosa pine and mixed conifer forest
FD	Fuera-Burnac association	Steep	Forested north-facing slopes of the Saladon Creek sub-watershed; cool, moist mixed conifer forest
HrD	Hillery stony loam	1%-7% slopes	Grassland and wetland meadows of the West-Agua Fria and western Cimarron Range sub-watershed units with some mixed conifer tree encroachment
SaC	Saladon mucky silt clay	0%-5% slopes	Riparian and wetlands and drainage areas in the wet meadow areas of the West Agua Fria and western Cimarron Range sub-watershed units

Land use usually alters soil's natural ability to absorb and retain water because of changes to soil structure and related infiltration ability, such as through compaction, and impacts to topsoil texture, organic matter content, and vegetation cover. Land use also alters soil's ability and speed with which it releases water through ET or runoff. Research has found that forested lands support soil conditions that increase infiltration (Roa-García et al. 2011). This study also noted that grazing can lead to increased compaction of soils, limiting infiltration and increasing immediate water losses through evaporation and short-delay runoff. Shortened lag times between precipitation peaks and runoff peaks may increase bulk runoff amounts and reduce opportunities for downstream users to capture these high water volumes (Roa-García et al. 2011). Land management practices, such as stem reductions and prescribed fire, also influence soil's infiltration capacity (which will be described more in depth below and in section 5 of this report).

Key factors considered in this study are compaction, erosion rating, suitability of the use of harvesting equipment, the risks of fire impact on soils, and the risk of wind throw of trees after stem reductions. Trees that have grown in dense conditions in spruce-fir, aspen, and mixed conifer stands and that have become exposed after fire or timber harvests are generally susceptible to wind throw due to elevated wind speed at higher elevations and shallow root systems on rocky soils (Smith et al. 2008). The WebSoil Survey offers mostly qualitative indications for these values (Table 3).

Table 3. Qualitative overview of indicators of soil group suitability for terrain treatments aimed at stem reductions for water availability increase downstream, based on NRCS WebSoil Survey analysis (NRCS 2020)

Soil Type	Compaction Risk	Erosion Hazard	Harvest Equipment Operability[1]	Damage Risk of Soil by Fire	Windthrow Hazard Rating	Suitability for Forest Treatment
AN	High	Moderate	Moderate	Low	Slight	Moderate
BU	Medium	Moderate	Poor	Low	Slight	Moderate
BY	Medium	Slight	Moderate	Low	Slight	Moderately High
CY	Medium	Severe	Poor	High	Moderate	Low
EE	Medium	Severe	Poor	Low	Slight	Moderately Low
FD	High	Severe	Poor	Low	Slight	Low
HrD	High	Slight	Moderate	Low	Slight	Moderately Low
SaC	Low	Slight	Moderate	Moderate	Moderate	Moderate

1) NOTE: Harvest equipment operability is the suitability of soils for the use of forest harvesting equipment.

A review of the hydrological soil characteristics and the potential land use impacts related to water storage development has resulted in a prioritization of soil groups in order of their declining ability to absorb, store, and drain water and the ease with which the land can be managed to optimize the volume and use of water downstream. Table 4 lists the relative water infiltration and storage potential, limitations, and a summary of land treatments to be considered.

Table 4. Prioritization of soil groups to be targeted for forest management treatments aimed at water storage development

Soil	Water Storage Potential	Limitations	Treatment
AN	Moderately High	WQ outflow; HSG=B; compaction; some erosion	Selective cuts by hand, conifer removal from aspen, L&S/SC
BU	Moderately High	WQ outflow; some erosion; dry ecosystem; rugged; equipment use	Selective thinning by hand
BY	Moderately High	HSG=D; surface runoff	Use of harvesting equipment, thinning by hand, possible use of prescribed fire, SC
CY	Limited	WQ outflow; HSG=D; mud flow; surface runoff; erosion; equipment use	Selective thinning by hand, fuel reduction, SC
EE	Limited	WQ outflow; erosion; HSG=B	Very selective thinning by hand, SC
FD	Limited	WQ outflow; erosion; HSG=C; compaction	Very selective thinning by hand, SC
HrD	Slight	Compaction; low Ksat; HSG=D	Encroachment removal by hand
SaC	Poor	HSG=D; no water storage capacity	No action

WQ = water quality	HSG = Hydrologic Soil Group
L&S = Lop and scatter of slash	SC = Soil conservation techniques

Vegetation, Fire, and Succession

There is a data gap regarding specific information about vegetation communities in the headwater catchment areas of the Cimarron watershed. Field observations, WebSoil Survey information, and general forest ecosystem information for the area confirm that vegetation communities consist of aspen stands, cool and moist mixed conifer forests, relatively warm and dry mixed conifer forest, meadows, wetlands, and riparian zones. There are also stands of spruce-fir forest on ridges and north-facing slopes above 10,000 feet. The vegetation communities are strongly related to elevation, aspect, slope steepness, and soil type (see Table 2).

The spruce-fir type typically consists of blue spruce (*Picea pungens*), Engelmann spruce (*Picea engelmannii*), sub-alpine fir (*Abies lasiocarpa*), and limber pine (*Pinus flexilis*). The moist mixed conifer stands include sub-alpine fir, Douglas fir (*Pseudotsuga menziesii*), and white fir (*Abies concolor*), and the dry mixed conifer type is mostly made up of Douglas fir and ponderosa pine (*Pinus ponderosa*) (Smith et al. 2008) (Figures 9 and 10). Aspen (*Populus tremuloides*) stands occur as part of the dry and moist mixed conifer stands and as independent groups (Figures 11 and 12). Detailed stand exams and field assessments will have to confirm the dominance of each species in their forest type and at specific locations in the watershed area.

Meadows and wetlands occur mostly on the slightly sloping and nearly flat mountain plateaus and broader valley bottoms, and are typically devoid of trees except small clumps or solitary fir and aspen trees (Figures 13 and 14). Riparian zones meander through the meadows and run along the streams in valley bottoms and consist of white fir, Douglas fir, alder, and willow species. The vegetation types form a mosaic across the landscape, with patch sizes and shapes dependent on terrain variations and past disturbances, such as fire, grazing, and mechanical tree removal.


Figure 9 (left): Meadow and south-facing, dry mixed conifer forest; and
Figure 10 (right): Meadow and west- and south-facing dry mixed conifer and aspen forest
Both photographs were taken on the American Creek Properties (J.W. Jansens 2019).

Fire, a natural disturbance factor in these forest types (Evans et al. 2011, Reynolds et al. 2013), occurs at irregular intervals but within a range of predictability (Evans et al. 2011). In dry mixed conifer forests, recurrent surface fires of relatively low to moderate severity maintain a relatively open stand structure with a mixture of small tree groups and areas with random spatial patterns of trees (Reynolds et al. 2013). Occasionally, small areas of high severity crown fires tend to occur as well. Cool and moist mixed conifer stands undergo a more mixed-severity fire regime, which causes larger openings, less spatial heterogeneity, and coarser patterning of age groups than in the warm, dry mixed conifer type (Reynolds et al. 2013).


Figure 11 (left): View east of the grassland-forest ecotone with dry mixed conifer and aspen forest on the property boundaries of American Creek Properties and UU-Bar Ranch (J.W. Jansens 2019)
Figure 12 (right): View northeast of the same area (J.W. Jansens 2019)


Figure 13 (left): View southeast across high elevation meadows and wetlands
Figure 14 (right): View north across meadows and wetlands
Both photographs were taken on the America Creek Properties (J.W. Jansens 2019).

Little information exists for estimating the mean number of trees per acre in the mixed conifer forests in the headwater catchment areas of the Cimarron watershed. Reynolds et al. (2013) offer wide ranging stem counts between 20 and 100 trees per acre and 40-125 square feet basal areas per acre. A comparison of sites in Reynolds et al. (2013) suggests that the San Francisco Peaks (9,200 feet) in Arizona, which has a mean of 65.1 trees per acre, may be a comparable area. However, on cooler and moister sites in the Cimarron watershed, stem densities are likely to be on the higher end of the suggested range (Reynolds et al. 2013).

Using regional statistics of mean fire return intervals (MFRI) for mixed conifer stands in the Central and Southern Rocky Mountains, Evans et al. (2011) found that the MFRI for low-severity fire in stands above 9,000 feet could be as low as 4.8 years in the Jemez Mountains and as much as 30 years in the San Juan Mountains, with a combined occurrence range of 1 to 89 years (average 16 years) for the various data sites. The MFRI for higher severity fire (scarring at least 25 percent of the stems) for the same data samples ranges between 12.67 in the Jemez Mountains and 36 years in the San Juan Mountains, with a combined range of 1 to 66 years (average 24 years) for the various data sites (Evans et al. 2011).

Reynolds et al. (2013) conclude that departures from historical compositions, structures, and spatial patterns are likely greater on the warmer and drier slopes than on the cooler and moister sites due to a more severe disruption of the characteristic fire regime on the drier sites. The presence and distribution of snags, logs, and coarse woody debris is variable over time and across different sites (Reynolds et al. 2013). Compared with ponderosa pine stands, mixed conifer forests typically have a larger abundance of snags, logs, and woody debris, and include in the order of 5-35 snags per acre for dry mixed conifer forest (Moore et al. 2004, cited in Reynolds et al. 2013). Although little data are available, it is likely that in mature conditions, cool and moist mixed conifer forests would have an even larger abundance of such structural forest elements.

It is reasonable to conclude from the frequency intervals of natural fires in mixed conifer forests that it is important to develop a program of treatments to produce changes in stand characteristics with spatial and temporal variability and frequency that mimic the natural fire dynamics (Evans et al. 2011). This would lead to many, diversely sized, small openings on the dryer south- and west-facing slopes, and larger openings in the moist, north- and east-facing slopes (Figures 15 and 16). Additionally, treatments need to be prioritized on the drier sites to prevent the occurrence of uncharacteristic, high intensity wildfire when these sites show signs of a greater departure from historic conditions.

Limited fire history data have been found for the headwater catchments of the Cimarron watershed. However, the widespread occurrence of tree species that are susceptible to death from fire, such as white fir, sub-alpine fir, and aspen (Reynolds et al. 2013), throughout much of the higher elevation plateaus, forest edges, and ridges of the Cimarron Range points to an absence of frequent fire.

Known wildfires in the area include the 2002 Ponil Complex Fire in the northern part of the watershed and the 2018 Ute Park Fire in the center of the watershed. The 2002 Ponil Complex Fire, reportedly caused by lightning, erupted on June 1, 2002, and burned nearly 92,000 acres (143 square miles), including 28,000 acres affected and 14,000 acres actually burned on the Philmont Scout Ranch (RememberSchiff 2018). The fire burned across the rugged canyons and ridges with mid-elevation slopes of ponderosa pine and piñon-juniper woodland, north of Highway 64, and up to the eastern Valle Vidal. The 2018 Ute Park Fire erupted on May 31, 2018 and burned approximately 36,740 acres. The cause of the fire remains undetermined. The fire burned large parts of the central drainages and ponderosa pine forests on the Philmont Scout Ranch and a considerable acreage of the ranch north of Highway 64, as well as other private property around Ute Park and parts of the Colin Neblett Wildlife Area.

Figure 15 (left): View west of forest edge of (left) dry and (right) moist mixed conifer forest at the ridgeline edge of a large meadow on the American Creek Properties (J.W. Jansens 2019)
Figure 16 (right): View north across a forest opening with a stock tank and dense, moist mixed conifer forest with aspen at the northern edge of the American Creek Properties and southern edge of the Colin Neblett Wildlife Area (J.W. Jansens 2019)

The relative scarcity of wildfire in the watershed in comparison with the theoretical fire frequency for the area's forest types may be related to weather patterns that bring few dry lightning storms over the area and a low frequency of anthropogenic sources (Gibson 2020). Lightning strikes account for about half of the acres burned across the Rocky Mountains and the Southwest United States (Evans 2018). The most common human sources of fire are campgrounds, followed by "miscellaneous human sources," such as powerlines, burning vehicles, fireworks, highways, stove fuel sparks, and slash burns in timber harvesting operations (Evans 2018). Fire Chief Scott Gibson of Eagle Nest confirmed that ignitions in the upper Cimarron watershed are caused about half of the time by lightning and half of the time by humans. Human causes include chimney fires in cabins, campfires, sparking during woodcutting, and pile burns of construction debris. Lightning fires are usually followed by rain that readily extinguishes them (Gibson 2020).

As a result of the relative low frequency of fire in the watershed, and pending detailed stand exam reports, it should be expected that stem densities and live and dead biomass fuel loads in the forests are relatively high. As in other areas of the Sangre de Cristo Mountains, high stem density conditions in the high elevation forests may also result from a lack of fire linked to the area's grazing history and active wildfire suppression (Johnson and Margolis 2019). This increases the risk of fires with high intensity (fires that are hot or release high amounts of energy) and with high severity (fires that are highly damaging). Climate trends exacerbate the fire risk for the area (Westerling et al. 2006), which is also factored into the projection.

Once ignited in sufficiently dry or windy conditions, fires burning in sub-alpine forests exhibit a high-severity crown-fire behavior that poses extreme risks to human life and infrastructure. Quaking aspen stands generally burn with a lower intensity than adjacent conifer forests and may be used strategically in fire suppression efforts. However, under extreme drought and fire weather conditions, aspen forests may also sustain crown fires. Recent high-severity fires in sub-alpine forests of the region have also shown that post-fire flooding and debris flows can pose as much risk to human lives, infrastructure, and ecosystems services as fire itself (Johnson and Margolis 2019). The 2018 Ute Park fire (Figure 17) and the 2002 Ponil Complex fire are good cases in point.

The upper Rio Hondo watershed, west of Taos, described earlier as a representative model for many mountain watersheds in the Sangre de Cristo Mountains (Tolley et al. 2015), contains extensive sub-alpine conifer and aspen forests similar to those in the headwaters of the Cimarron watershed. The Rio Hondo forests historically burned with large (>640 hectares) patches of high-severity fire (Johnson and Margolis 2019). The authors quote various sources that used tree-ring records to confirm similar high-severity fire behavior in the sub-alpine conifer and aspen forests in northern New Mexico, including the Columbine-Hondo wilderness, the Valle Escondido, the Santa Barbara drainage, and the west slopes of Santa Fe Baldy, and sub-alpine forests in Colorado and Arizona (Johnson and Margolis 2019).

Natural fire would usually burn large areas in high elevation forests, such as those in the Cimarron watershed, leading to stand replacing regeneration of the ecosystem (Johnson and Margolis 2019). Typically, fire impacts are of mixed severity, which include small patches as well as larger areas encompassing hundreds or even thousands of acres (Evans et al. 2011; Johnson and Margolis 2019). After such fires, natural succession would start at the herbaceous level and regenerate a forest in the shade of the herbaceous cover, the layers of shrubs, and lesser shade tolerant trees, such as Douglas fir, and shade intolerant species, such as aspen and limber pine. Spruce and fir trees have a high shade tolerance and eventually grow in such shady conditions after other species have grown back (Smith et al. 2008). At lower elevations and on south-facing slopes dominated by ponderosa pine and Douglas fir, which are more fire adapted, fire would likely remove most of the smaller trees and scar the larger ones. Regeneration of pine and Douglas fir would then occur in larger openings between trees in nearly full sun, as required by these tree species (Smith et al. 2008).

Management of the sub-alpine forests in the Cimarron watershed is complicated by the need to balance the ecologically important occurrence of high-severity fires against the assets at risk in the wildland-urban interface of nearby towns (Cimarron, Angel Fire, Eagle Nest) and the need to optimize water storage for these communities and prevent erosion and downstream sediment deposition and flooding (Johnson and Margolis 2019; Community meeting participants 2019).

Projected Climate Impacts on the Forest Ecosystems

The predicted effects of a warmer, drier climate in the Southwest include reduced tree growth and increased tree mortality in mixed conifer forests (Evans et al. 2011; Reynolds et al. 2013; Field et al. 2020). The effects of warmer winter temperatures and earlier spring runoff also include increased occurrence and severity of wildfire (Westerling et al. 2006; Hurteau et al. 2014; Sun et al. 2018; Field et al. 2020), declining stem volume growth and increased bark beetle impacts (Williams et al. 2010; Evans et al. 2011; Reynolds et al. 2013; Melillo et al. 2014). Research findings of historical links between severe drought and high severity fire occurrences in sub-alpine forest and wet mixed conifer forest project that fire risk will continue to increase with projected increases in drought severity and duration due to climate change in this region (Hurteau et al. 2014; Johnson and Margolis 2019).

Mantgem et al. (2018) concludes that prior to fire biotic and abiotic changes that affect growth negatively (e.g., drought stress) or positively (e.g., growth releases following thinning treatments) may influence expressed fire severity, independent of fire intensity (e.g., heat flux, residence time). Even if fire behavior remains constant, these relationships suggest that tree mortality may increase under stressful climatic or stand conditions (Mantgem et al. 2018).

Moeser et al. (2020) describes how these climate induced forest disturbances change biophysical processes (e.g., interception and transpiration) and how they are important drivers of hydrological variation in headwater forest ecosystems. Forest disturbance caused by bark beetle and fire has affected large areas with seasonal snow in the coniferous forests of the headwaters of the Rio Grande. Yet, there is limited understanding of how climate change impacts on forest disturbances will affect downstream water resources (Sexstone et al. 2018; Moeser et al. 2020). Modeling studies and field observations confirm that forest disturbance reduces canopy cover (density) and increases the prevalence of canopy gaps and edges (canopy structure heterogeneity), which, in turn, affect snow accumulation and ablation. The reduction of forest cover decreases interception, which is a primary driver of heterogeneous snow accumulation patterns in forests, resulting in increased snow accumulation on the ground because less snow is intercepted and subsequently sublimated (Moeser et al. 2020; Goeking and Tarboton 2020). However, modeling shows that canopy cover and leaf area index have little influence on SWE in headwater forest disturbances. As a result, thinning from below in these ecosystems is not very useful (Moeser et al. 2020). In New Mexico's headwater forests, which have a relatively low number of cloudy days in comparison with more temperate climate zones, the factor of solar radiation, and therefore aspect, is relatively important in relation to other factors influencing SWE (Sexstone et al. 2018; Moeser et al. 2020). Hence, deliberate forest treatments in headwater forest ecosystems that mimic natural forest disturbances resulting in small openings may hold an opportunity for snow retention and water storage.

Despite the opportunities that climate induced and anthropogenic forest disturbances may generate for snow accumulation, many studies indicate that the impacts of a changing climate severely undermine efforts toward water storage development resulting from forest treatments. Leading literature indicates that climate disturbance contributes to declining snow accumulation, increased winter temperatures and greater evapotranspiration losses (USDI 2011; Melillo et al. 2014; Tolley et al. 2015; USGCRP 2018). As a result, over time, the conditions for water storage produced by forest disturbances will further decrease and will likely also diminish opportunities for treatments supporting water storage increases in higher elevation forests in the CWA study area.

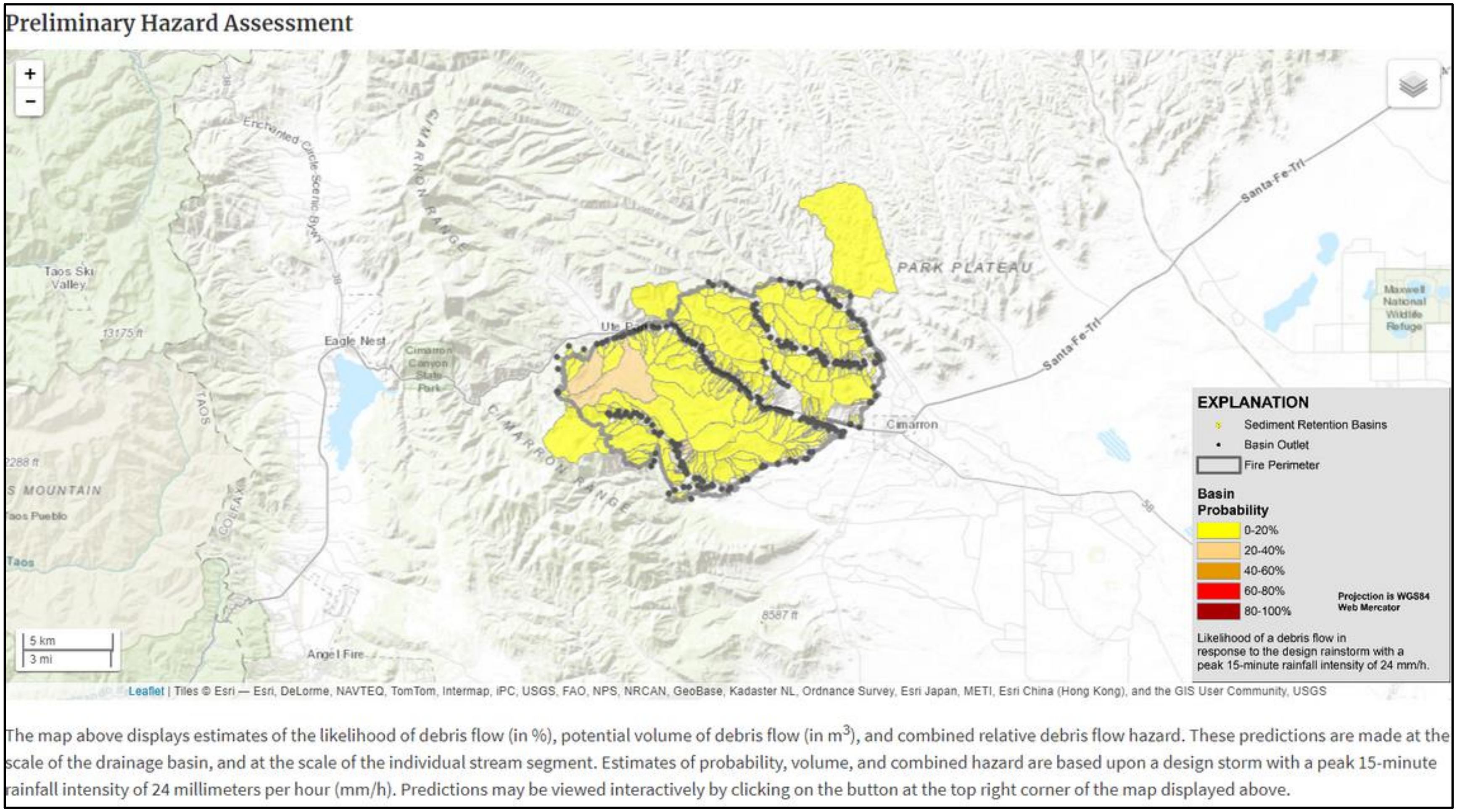


Figure 17. Footprint of the 2018 Ute Park fire and likelihood of debris flows in response to stream runoff events (usgs.gov/media/images/ute-park-fire-map-nmwsc)

5. LANDSCAPE MANAGEMENT PRACTICES

Forest Management Practices and Water Storage

Scientific and experiential data on the relationship between forest management practices and long-term water storage improvements are limited, despite a recent increase in modeling studies (Sexstone et al. 2018; Goeking and Tarboton 2020; Mazzotti et al. 2020; Moeser et al. 2020). Because no specific information exists on these relationships for the Cimarron watershed, this study evaluates and interprets findings on mixed conifer forests in the Southwest, partially related data from other areas (such as Field et al. 2020), and the findings from the recent modeling studies, mentioned above.

A 2008 New Mexico Forest and Watershed Restoration Institute (NMFWRI) Working Paper (Smith et al. 2008), a 2011 joint report by the USDA Forest Service (USFS) and Forest Guild (Evans et al. 2011) and a 2013 USFS General Technical Report (Reynolds et al. 2013) provide general best practices recommendations for future forest management in mixed conifer forests and include some comments about forest treatments aimed at increasing water storage. All three reports note an absence of any publications that evaluate the long-term effects of forest restoration on hydrologic function and water storage in frequent-fire forests in the Southwest. The studies reviewed in the reports present only short-term results.

In the course of 2020, several papers on fine scale modeling and forest management treatments provided new insights in relationships between forest structure and snow accumulation (Goeking and Tarboton 2020; Moeser et al. 2020) and fine scale rapid response treatments and increased forest resilience to climate change and megadroughts (Field et al. 2020). In the current climate crisis, short-term, rapid response solutions aimed at fine-scale, high intensity management are the focus of the recommendations offered (Field et al. 2020).

The more recent referenced publications (after 2013) on potential water availability resulting from forest treatment at locations across the U.S. are all reporting short-term outcomes. Snow accumulation and water yield appear to be largely dependent on forest type and elevation, aspect, post-disturbance forest structure (tree spacing, tree grouping, opening shapes and orientation, and edges), seasonal precipitation variation (winter-spring vs. summer-fall precipitation), and annual precipitation patterns (high vs. low). Small openings that allow for shading, higher elevations, winter and spring precipitation, and high annual precipitation appear to have some positive effects on increasing water storage, while the converse conditions have negative effects. It is therefore essential to differentiate between forest types when specifying forest management practices aimed at water storage.

Warmer, lower elevation ecosystems: ponderosa pine and dry mixed conifer forests. Reynolds et al. (2013) report that, despite initial increases of 15-45 percent in ponderosa pine forest on basalt-derived forests soils when high basal area in current forests is reduced, increases can be expected to decline with time as new vegetation establishes and develops. Despite some studies that indicate positive effects of stem reduction on stream flow, observed annual variation in stream flows shows that the amount and timing of precipitation have greater overall effect on stream flow than tree removal (Reynolds et al. 2013; Sun et al. 2018).

In addition, meta-analysis of 26 studies shows that in general forest harvesting has little to no effect on soil carbon and nitrogen (Evans et al. 2011). This is relevant because other studies have shown elevated soil carbon and nitrogen levels as important factors in relation to soil health and soil moisture retention (Evans et al. 2011, Elliott et al. 2020).

A recent evaluation of monitoring data from forest restoration projects conducted in New Mexico between 2003 and 2018, with USFS funding under the Collaborative Forest Restoration Program (CFRP), found that thinning treatments in eight CFRP projects in mixed conifer stands did not have a lasting effect on forest conditions (Mahan 2019). In dry mixed conifer stands, thinning impacts on stand characteristics (such as basal area, stems per acre, average height of live trees, average live crown base height, live saplings per acre, live seedlings per acre, live shrubs per acre, sick trees per acre, snags per acre, overstory canopy cover percent, tons per acre total surface fuels, and tons per acre 1000-hour fuels) lasted generally less than ten years.

Cooler, higher elevation ecosystems: moist aspen, mixed conifer and spruce fir forests. The same CFRP project evaluation indicates that in moist mixed conifer stands thinning had a significant impact over ten years only on basal area reduction, while it had no impact on other stand characteristics (Mahan 2019). Modeling by Moeser et al. (2020) confirms that changes in canopy density are not a good predictor of snowpack response to canopy disturbance (e.g., due to forest thinning) at a fine scale, as opposed to increases in seasonal temperature and higher insolation which heighten post-disturbance changes in snow variability. The effects of inter-annual variations in climate are also found to be more important on changes in annual river flow than the influence of areas with high or moderate burn severity impacts (Sun et al. 2018). Wildfires and prescribed fires affecting less than 20 percent of a watershed are unlikely to produce any lasting impact on annual river flow in basins larger than 10 square kilometers (3.86 square miles) (Sun et al. 2018). Conversely, as a rule of thumb, at least 20 percent of basal area must be removed in a sub-watershed by thinning and/or fire to produce any significant change in river flow (Sun et al. 2018).

Studies in aspen indicate a greater peak snow accumulation and greater stream flow gains than in conifer stands (LaMalfa and Ryle 2008; Evans et al. 2011). LaMalfa and Ryle (2008) states that potential snow water equivalent (SWE) in early succession aspen averaged 34 percent higher (in an average snow year) to 44 percent higher (in an above average snow year) than in adjacent late succession conifer stands. Snowmelt nearly doubled in aspen stands (21 mm/day in aspen vs. 11 mm/day in mixed conifer) (LaMalfa and Ryle 2008). Aspen also showed a greater potential water yield of 42-83 percent for runoff and groundwater recharge, but 33 percent higher summer ET rates. Evans et al. (2011) confirm that increases in available water for runoff and groundwater recharge in aspen stands are partially offset by greater evapotranspiration than in conifer stands. Conifer canopies intercept a larger portion of snowfall, and snow caught in canopies sublimates at higher rates than ground-level snow (Smith et al. 2008; Parmenter 2009).

Using and Mimicking Wildfire for Snow Accumulation

Evans et al. (2011) reason that treatments will need to be repeated with time intervals similar in frequency to those of natural fire disturbances in these ecosystems. Under the pressure of increasing risk of catastrophic wildfire and insect damage, publications appear to move toward a consensus that forest treatments aimed at restoring natural (wild) fire regimes and preparing for managed wildfire practices will have the greatest potential to restore forest ecological conditions, including soil conditions, that are beneficial for snow and rainfall interception and retention (Evans et al. 2011; Reynolds et al. 2013).

Warmer, lower elevation ecosystems: ponderosa pine and dry mixed conifer forests. In ponderosa pine and dry mixed conifer forest, stem reduction treatments that mimic natural fire could create ecological conditions that improve overall forest resilience, increase forest resilience to high severity wildfire, and maintain forest moisture conditions (Smith et al. 2008; Evans et al. 2011). Increased soil moisture levels and longer durations of moist forest soils could further reduce fire intensity and severity. Reestablishing fire as an active ecological process is, therefore, important to increase forest ecosystem resiliency to the negative effects of an altering climate. In mixed conifer forests management that increases heterogeneity of forest structure and fuels will help maintain resilience (Evans et al. 2011). Restoring natural fire regimes could help maintain—and under some conditions or in some years—increase water storage (Reynolds et al. 2013).

One study shows a slight (5 percent) increase in modeled water storage from restoring natural fire regimes (Boisrame et al. 2019; Cook 2019). The authors describe the effects of changing fire management on Yosemite National Park's Illilouette Creek Basin, a snowmelt dominated catchment in California's Sierra Nevada, on changes in the area's water balance. Modeling shows that restoring natural fire regimes reduces forest water stress and increases the availability of water downstream. The simulations suggest that water balance changes have been most pronounced during wet years and are due to small increases in snowpack and belowground water storage, coupled with ET reductions. These factors result in earlier snowmelt runoff and a roughly 5 percent increase in annual stream flow (Boisrame et al. 2019; Cook 2019).

By modeling fire behavior across the landscape, Conver et al. (2018) found that the grassland-forest ecotone is a primary corridor for fire growth on the landscape of the Valles Caldera, New Mexico. Regular fires that spread along the grassland-forest ecotone may help stabilize the boundary zone between these two dynamic ecological communities by preventing forest encroachment into the grassland and maintaining an open stand structure that prevents fires from advancing to higher elevations (Conver et al. 2018). Identifying potential dominant fire corridors in the Cimarron watershed would help land managers prioritize treatment areas where the natural fire regime can be mimicked in space and in certain intervals of time.

A recent literature study of the effects of forest thinning, prescribed fire, and a combination of both treatments found that in a large majority of cases, the combined treatment approach leads to the most optimal restoration of soil function in frequent-fire forests of the western United States

(Sánchez Meador et al. 2017). Results of meta-analysis showed that mean differences in macronutrients and nitrogen cycling were consistently higher in composite treatments when compared to thin-only and burn-only treatments. The most significant effects were observed following treatments that were both thinned and burned for nitrogen and carbon responses, net mineralization and nitrification, ammonium availability, and soil respiration rate (Sánchez Meador et al. 2017). Given that elevated soil carbon and nitrogen levels are important factors in relation to soil health and soil moisture retention (Evans et al. 2011), it is reasonable to posit that the paired treatment approach would eventually be most beneficial for a potential increase of soil water storage.

Cooler, higher elevation ecosystems: moist aspen, mixed conifer and spruce-fir forests. In high elevation forest ecosystems stem reduction treatments through mechanical tree removal are preferred. While most research on canopy cover reductions on SWE in headwater forests used relatively coarse-scale studies (Goeking and Tarboton 2020; Moeser et al. 2020), recent fine-scale modeling studies offer new windows of opportunity for snow accumulation and water storage in headwater forests for the next few decades (Moeser et al. 2020). The fine-scale modeling suggests that appropriate treatments that mimic fire and create small openings may include patch cuts, shelterwood systems, small patch (conifer) thinning in aspen stands, and patch coppicing of aspen stands. Thinning from below is not very useful because modeling for canopy cover and leaf index area shows little influence on SWE (Moeser at al 2020). Creating openings through prescribed fire is complicated and bears certain risks (Evans et al. 2011; Johnson and Margolis 2019). The use of fire in headwater forests where snow accumulation is key to water storage also bears the risk of producing blackened debris and logs that increase albedo and heat fluxes (i.e., elevated temperatures) that lower the SWE and precipitate the melt out date (Moeser et al. 2020).

Inferring from the diversity of findings on the effects of treatments in mixed conifer and aspen forests, it is important to observe that treatment impacts have a limited duration and that it is important to repeat treatments to renew changes in stand characteristics that improve water storage. If we figure that stand disturbances (i.e., treatments or fire) in wet mixed conifer forest have a potential increased snow accumulation effect of at most ten years, and if we need to achieve at least 20% disturbance in the forest (as per Sun et al. 2018), disturbance planning would require five ten-year cycles of 20% disturbance to achieve at least an average of 20% disturbance across an entire target area. A disturbance regime with a return cycle of 50 years appears to fall in the range of the observed fire frequency (MFRI) for the moist mixed conifer forest type in this region. In addition, the presence of permanent forest openings and grassy meadows and wetlands is important in the landscape structure of the headwater forests to achieve the target percentage of areas without forest cover that could increase snow accumulation and to create buffers against landscape-scale wildfire.

Best Practices for Fire Adaptation: Forest Resilience Strategies

Treatments aimed at improving long-term forest resilience to the impacts from natural disturbance regimes and a changing climate, such as fire, insects, and drought, are central to restoring the natural processes, functions and characteristics of the ecosystem that support water storage (Smith et al. 2008; Evans et al. 2011; Field et al. 2020). Forest treatments would need to take into consideration a broad spectrum of guidelines offered by the cited literature (Smith et al. 2008; Evans et al. 2011; Reynolds et al. 2013; Field et al. 2020; Moeser et al. 2020). Some key aspects for the purpose of this study (not to the exclusion of other topics) include:

a. ***Increasing forest heterogeneity:*** in species composition, patch sizes, gap sizes, tree groups and individual trees, grass-forb-shrub interspaces, and snags-logs-woody debris (Evans et al. 2011; Reynolds et al. 2013)
b. ***Reducing and distributing remaining fuels*** to levels commensurate with reintroduction of frequent surface fire regimes
c. ***Conducting frequent treatments with controlled burns in lower elevation forests***, including low-severity fire in dry mixed conifer stands and slightly less frequent mixed-severity fire in moist mixed conifer stands (where possible and safe)
d. ***Prioritizing aspen protection and regeneration*** and its representation across the landscape; and
e. ***Ensuring in all treatments that soil health is improved***.

(a) Forest heterogeneity is typically identified at three different levels (Evans et al. 2011; Reynolds et al. 2013):

1. Landscape-level: 1,000-10,000 acres, but typically more than 50,000 acres, with assemblages of mid-level scales (e.g., total scale of the proposed cumulative treatments in the headwaters of the Cimarron watershed east of the Moreno Valley or total scale of proposed treatments in and at the edges of the Moreno Valley);
2. Mid-level: 100-1,000 acres in size, with assemblages of fine-level scales (project scale or soil type scale); and
3. Fine-level: up to 100 acres in size, with individual trees, groups, and aggregates of groups (single treatment scale, as part of a mid-level and landscape-level scale plan).

Treatment planning should address these different scales to optimally impact fire behavior and break up stands that could cause high-severity fire impacts on the landscape. Landscape-level and mid-level heterogeneity would lead to differences in densities, ages, and species mixes, based on different aspect and terrain conditions. Fine-level heterogeneity would include creating canopy gaps within stands, which would help reduce fire severity and transition the risk of crown fire behavior to increased opportunities for surface fire. Such gaps would also provide openings for snow accumulation and shading, which provide opportunities for water storage.

Landscape-level planning relates to the scale of landscape units and sub-watersheds described in relation to the area's hydrogeology, geomorphology, and topography. For example, landscape-scale planning would benefit from fire behavior simulation modeling to identify where and how much land to treat for creating optimal protection and resilience at the highest scale (Evans et al. 2011). Modeling also helps to optimize project efficiency and treatment effectiveness by focusing the intervention areas. It is likely that modeling will conclude that only as little as 10 percent of the landscape might need treatment to achieve desired results in reducing projected wildfire impacts (Evans et al. 2011). A dispersed treatment plan with strategically placed treatments is two to three times more effective than randomly placed treatments, in that strategically placed treatments require two to three times less acres to be treated to produce the same fire hazard reduction (Evans et al. 2011).

Mid-level planning relates to the scale of soil groups and soil types and their characteristic stands (a.k.a. patches) of forest (Table 2) (Reynolds et al. 2013). Patch structure and size are important for wildfire management (Evans et al. 2011), and forest gap size, aspect, and orientation are important for influencing water storage (see below).

Fine-level planning relates to the scale of individual vegetation groups that mimic low- and mixed-severity wildfire and create a distinct spatial structure, age distribution, and species composition (Reynolds et al. 2013). It is at this level that specific prescriptions are implemented that alter the spatial, age class, and species mix characteristics toward desired conditions. At this scale, forest thinning strategies are implemented that reduce stem densities and canopy gaps in spatial configurations that reduce high-severity fire risk, increase snow accumulation, and reduce evaporative losses.

The literature provides a variety of fine-scale treatment recommendations, which must be specified by forest type. Treatment principles that apply to all forest conditions (Field et al. 2020) include:

- Contouring (where possible and desirable) of slopes to slow overland flow, increase infiltration and enhance soil water storage, including contour felling, and distributing thinning debris in contour strips (where appropriate from a fuel load perspective)
- Slash redistribution or reduction and in some cases mulching residual thinning debris to enhance soil water storage and reduce erosion
- Fuel load reduction by removing thinning debris or (pile) burning debris
- Retention of large trees to improve shading in openings and to serve as seed trees
- Monitoring and adaptive management are important because there is insufficient field knowledge and information on how forest treatments influence increases in SWE and the prolonging of the melt out date. More must be learned over time about the extent to which research findings are transferrable between different areas.

Ponderosa pine and dry mixed conifer stands

- Departure from historical fire conditions has been observed mostly on the drier, south-facing mixed conifer slopes rather than on moister sites (Evans et al. 2011; Reynolds et al. 2013). Therefore, treatments on south-facing slopes would need to be prioritized for fire management purposes (Evans et al. 2011; Reynolds et al. 2013). Live standing biomass fuel in warm, dry mixed conifer forests will need to be treated to reduce the overgrown canopy to the historic cover of at most 30 percent (Smith et al. 2008).
- This is best accomplished in a rather random pattern of stem removals to optimize stand diversity in space and age groups. In addition, it is important to select for maintaining more fire-resistant trees, such as ponderosa pine, Douglas fir, and Southwestern white pine, and to a lesser extent, limber pine, blue spruce, and Engelmann spruce (Smith et al. 2008).

- Selective thinning from below and thinning to create tree groups and clumps will be the preferred treatment techniques (depending on site conditions and additional goals, such as tree selection and wildlife habitat improvement) (Reynolds et al. 2013).
- Managed wildfire and prescribed fire play a role in stands where creating fire adapted forests rather than snow accumulation is the main goal.

Aspen stands

- Treatments in aspen stands should produce a scattering of trees that concentrate snow on north-facing (and northwest- and northeast-facing) slopes and increase cumulative wind shelter and shading to keep snow and ice longer on the land, optimizing SWE levels. Such thinning configurations could create local micro-climate effects (i.e., reducing upward air mixing) to reduce warming of the snowpack and forest soil (Aron et al. 2019).
- Canopy cover of at least 30 percent aspen forest must be maintained (Smith et al. 2008).

Moist mixed conifer and spruce-fir stands

- In cool, moist mixed conifer forest, natural disturbance can be mimicked by creating small canopy openings (e.g., with small patch cuts in conifer stands and thinning in aspen). This would support increased heterogeneity of snow mass densities and variability in space of SWE, etc., contributing to increased potential spread over time and in space of SWE differences and melt out date (Field et al. 2020), which benefits downstream water use (because water flows will not all come at the same time, lowering peak flows and flow energy, and therefore mobilizing less sediment). An open canopy (<30% cover) must be maintained in patches of shade intolerant conifers, such as Douglas fir. In mature, moist mixed conifer stands with older trees, it would be best to create or maintain a mosaic of gaps and tree groups with overall a more closed canopy (>30% canopy cover) consisting of white fir, sub-alpine fir, and blue spruce (Smith et al. 2008). Target trees to remove could include locally large numbers of small trees and trees affected by disease or insects (Smith et al. 2008; Evans et al. 2011).
- It is important to take into consideration that with the creation of small opening (patch cuts) patch shape and north-south width are critical as opposed to patch size (Moeser et al. 2020).
- On southern aspects (south-facing slopes), the north-south width of canopy gaps and patch cuts should be less than three times tree height (3H) and creating south-facing edges must be avoided to reduce insolation and associated evaporation (Moeser et al. 2020). Therefore, gaps should ideally have a triangular shape or heart shape (chevron shaped with the apex to the south). On southern aspects it is also important to maintain large trees to optimize shading and reduce the expansion of canopy gaps stretching toward the south leading to a reduction of shaded area (Moeser et al. 2020).
- On northern aspects, creating larger forest openings, mimicking gaps created by wildfire, would likely optimize snow accumulation and a more gradual melting process, which could add to the water storage capacity of the forest in areas where soil conditions allow.

- While in general openings are beneficial to SWE and later melt out dates compared to dense canopy (e.g., on north aspects), in areas known for high winds, wind throw (blow down risk) and wind scour of snow may lead to snowpack reduction and reduced SWE (Goeking and Tarboton 2020).
- Prioritizing tree removal over the use of fire avoids generating blackened debris and logs that increase albedo and heat fluxes that lower the SWE and precipitate the melt out date (Moeser et al. 2020).

For purposes of maximizing snow accumulation, SWE, and water storage in headwater forests, the structure, orientation, and sizes of tree patches and gaps would need to achieve optimal ET reductions. This could be achieved by implementing treatments that maintain cumulative wind shelter of scattered trees or longitudinal patches of trees that separate small gaps perpendicular to prevailing summer-fall and winter-spring winds. Additionally, it would be important to keep the soil covered at optimal levels with remaining woody biomass, ground covering vegetation, and plant litter. Such treatments would minimize sublimation and evaporation of snow, ice, and melt water and evaporation from bare soil, lakes, ponds, wetlands, and streams.

Approximation of forest gap size and shape: In the Cimarron watershed, the prevailing summer wind direction is from the west and southwest (Gibson 2020), and the prevailing winter wind direction is from the east and southeast (Rackley 2020). As a result, gaps would ideally be more or less V-shaped (or heart- or kidney-shaped) with the apex facing south. This shape avoids immediate south-facing edges and orients the lengths of the openings away from prevailing winds. Wind speeds are reduced to about 50 percent in a wind sheltered space of up to 10 times the height of a shelterbelt with about 40 percent transparency (Jensen 1983). Estimated average mixed conifer tree heights in northern New Mexico are 37.5 feet (Mahan 2019). For just reasons of wind impacts, gap size should be no more than 375 feet in diameter, and ideally around 200 feet in diameter to compensate for slope impacts and to optimize wind shelter effects.

Around the date of the winter solstice, the insolation angle at noon at this latitude (36.5°N) is approx. 13°, casting a shaded area of approx. 4.2 times the height of any shading object (e.g., a tree). With an approximated average conifer tree height of 37.5 feet, the shaded area is approximately 157 feet for flat terrain. It would be half this length (78 feet) for a south-facing slope of 13° (23 percent) and infinite for a north-facing slope of that angle. As a result, it would be best to maintain small gaps of up to 80 feet wide in sloped terrain and up to 100 feet wide (less than approximately 3H) on nearly flat terrain on south-facing slopes to optimize snow shading. Larger gaps are possible on north-facing slopes and to a lesser extent on east-facing and west-facing slopes slopes.

Around the time of the summer solstice, the sun angle at noon would be approx. 60°, casting a shadow of 50 percent of a tree's height, which is less than 19 feet on flat terrain behind conifers. This confirms that it is difficult to design forest treatments aimed at reducing evaporation losses during the summer, other than by maintaining high tree densities, which does not meet the requirements for fire risk reduction and the more effective winter ET loss reduction.

(b) Reduction and distribution of remaining fuels to levels commensurate with reintroduction of frequent surface fire regimes is essential to meet the goals of reducing fire severity and reintroducing frequent low- or mixed-severity fires (Smith et al. 2008). As described above, it is important to maintain a presence of large woody debris on the forest floor and as standing snags, especially large snags in various stages of decay, for biodiversity, wildlife habitat, and forest soil improvement (Smith et al. 2008; Evans et al. 2011). Roughness on the forest floor also creates micro-climates conducive to snow retention, water infiltration, and evaporation reduction. Dry mixed conifer forests have in the order of 5-35 snags and 8-16 tons per acre of dry fuel on the forest floor (Moore et al. 2004, cited in Reynolds et al. 2013; Evans et al. 2011), with higher numbers (10-20 tons per acre) for the cool and moist mixed conifer forests (Evans et al. 2011). Wildfire or prescribed fire will over time remove the dead woody material, especially the smaller pieces (Evans et al. 2011). In forest stands with a shortage of surface fuels, leaving the thinned woody material would help carry low-intensity fire through the landscape (Reynolds et al. 2013). In denser stands, however, especially on cooler aspects and during dry years, high fuel loads on the forest floor could lead to high severity fire (Johnson and Margolis 2019).

(c) Treatment frequency should ideally mimic that of natural low and mixed-severity fire in the region (Evans et al. 2011). As we have seen, fire frequencies in mixed conifer ecosystems were high (between 1 and 24 years, depending on conditions and severity standards, with 16 years as a mean for low-severity fire and 24 years for fire scarring at least 25 percent of trees. However, stand-replacing fire was the rule in moist, cool mixed conifer forest (Evans et al. 2011) and no signs of recent fire have been found in the headwater forests of the Cimarron Watershed. Therefore, to mimic wildfire and to preserve soil cover, frequent entries are necessary at any given site. This can be achieved for the selected target area in the upper Cimarron watershed with a rotational forest treatment plan consisting of annual treatments on different sites and returning to the same treatment sites after approximately 16-24 years. Such a rotational scheme would ensure frequent disturbances, which would create a mosaic of diverse age groups, structural diversity, high biological diversity associated with young successional forest, and permanent opportunities for optimal snow accumulation in small forest openings and water storage on a landscape scale.

(d) Aspen protection and regeneration are desirable because in the last few decades drought, disease, and insects have led to a regional decline of aspen stands (Smith et al. 2008; Evans et al. 2011). Aspen decline is also thought to be caused by the lack of mixed-severity fire disturbances, the regeneration of white fir and other conifers underneath mature aspen clones, and heavy elk browsing of young aspen plants (Smith et al. 2008). Yet, aspen stands are part of the mixed conifer ecosystems in the headwater catchment landscape of northern New Mexico and the Cimarron watershed. Moreover, aspen stands have the capacity to accumulate more snow, and in some cases help store snowmelt water more efficiently than other forest types (LaMalfa and Ryle 2008; Smith et al. 2008; Evans et al. 2011). Therefore, it is of value to maintain pure aspen stands and conifer stands that include scattered aspen trees.

On warm, dry mixed conifer sites, aspen occur in small clonal groups as a sub-dominant species mixed in with species such as Douglas fir (Smith et al. 2008). At high elevations and in a mosaic of cool and moist mixed conifer stands, aspen develop as independent patches (Smith et al. 2008; Evans et al. 2011). Aspen can also dominate a site after a stand-replacing fire in mixed conifer or spruce-fir forest (Smith et al. 2008). In time, the aspen will be replaced by conifer species, but reestablishment of mixed-severity fire would support the recovery of aspen as part of the landscape over time (Smith et al. 2008; Evans et al. 2011).

Aspen can be protected and regenerated in the Cimarron watershed by selective stem cutting or group removal (whole stem coppicing). On sites where aspen are invaded by shade tolerant trees, such as white fir and sub-alpine fir, selectively removing the conifers along with old and diseased aspen clumps would open the aspen stand, providing light for the shade-intolerant aspen to regenerate. Additionally, the micro-climate created between the remaining aspen trees would be conducive to snow accumulation and retention, while reducing evaporative loss, if the remaining aspen stems were sufficiently dense to maintain effective regional wind shelter.

(e) Healthy soils would need to be an important outcome of all forest treatments in the Cimarron watershed to improve moisture retention as part of general ecosystem health and as the goal of the forest's enhanced water storage ability. Forest treatments that maintain soil integrity (minimal erosion and high levels of organic matter) (Elliott et al. 2020), slow sediment transport, and effectively prevent wildfire and their inevitable ash and sediment flows into water bodies would at least help maintain surface water storage capacity. Soil health and future low- to medium-intensity natural fire would benefit from any remaining coarse woody fuels on the forest floor. Conversely, a restored fire regime can improve soil nutrient conditions (Reynolds et al. 2013), which in turn creates important conditions for water storage in the soil (Evans et al. 2011). Despite an initial decline in soil nitrogen after high intensity fire, forest soil conditions will recover rapidly, and fire tends to release valuable trace metals that boost plant regeneration and soil development (Reynolds et al. 2013; Sánchez Meador et al. 2017; Smith et al. 2017; Hart et al. 2018; Elliott et al. 2020).

Forest treatments that maintain and build forest soils, spread surface flows, and help retain moisture after precipitation events might gradually and slightly expand storage in the unsaturated zone and in some places boost aquifer recharge. However, it is unlikely that forest management initiatives would increase the inflow of groundwater for storage into deeper aquifers. Table 5 summarizes different treatment concepts for a variety of water storage types.

Recommended Prescriptions

The general guidelines described above have been used to develop preliminary prescription templates for four forest types in the Cimarron watershed: dry mixed conifer, moist mixed conifer, pure aspen patches, and spruce-fir patches. These prescriptions are included in Appendix B. They are preliminary because they will have to be modified based on specific terrain conditions, landowner objectives, and other forest management goals.

Specific terrain conditions may include existing stand structure and stem densities, tree species variability, age class variability, herbaceous and shrub components, and tree health and vigor. Landowner objectives may include wood product harvesting, hunting and grazing uses, scenic considerations, maintenance and access conditions, and wildlife and bird habitat considerations. Other management goals may include cost aspects, timing, disease management, erosion control, management requirements for the protection of listed plant or animal species, cultural resource preservation requirements, road building or road closure, educational purposes, project-related collaboration aspects, and monitoring and adaptive management goals (Evans et al. 2011). All these forest management aspects will need to be considered for each specific treatment site and each landowner, and prescriptions will need to be adapted to meet the additional objectives. The final prescriptions to be used to guide treatments for selected treatment sites will need to serve multiple purposes and represent the best possible reconciliations for a given set of management objectives.

Finally, managers should be concerned with harvesting impacts, site preparation disturbances, the amount of tree material that is removed, and the accumulation of fuel from fire suppression. Soil compaction and erosion, in combination with other site factors, and particularly after fire, work to degrade productivity on the scale of decades and centuries (Elliott et al. 2020). Erosion reduces forest productivity mainly by decreasing soil water availability. This is a result of changing the water holding capacity and thickness of the root zone. On erosion-sensitive sites (see Table 3), managers need to carefully evaluate such management factors in order to not adversely affect water storage potential as a result of degrading effects of tree removal (Elliott et al. 2020).

Forest Products Supplies, Industry, and Markets in the Area

Available timber in the watershed and surrounding area is spread between multiple jurisdictions, including national forest lands in the Valle Vidal and to the west and south of the Moreno Valley, extensive State Trust Lands southeast of Angel Fire and Black Lake (north of State Road 120), State lands in the Colin Neblett Wildlife Area, and private lands on various large ranches across the watershed. However, over the last three decades, the regional forest industries sector and wood markets have been heavily impacted by fluctuating wood availability. Many businesses were laid down in the mid-1990s as a result of national forest closures due to region-wide litigation over the protection of listed bird species. Subsequent budget reallocations and budget cuts in the USFS reduced the agency's capacity to complete the necessary planning for timber harvesting in the area. Additionally, wildfires led to forest closures and loss of standing timber resources. As a result, most of the forestry operations in the Cimarron watershed took place on private lands and have been coordinated through the State Forestry Division's Cimarron District office in Ute Park.

Supply needs in the area continue to be a serious problem for local operations. Between early October 2019 and late 2020, a new injunction on timber harvesting on national forest lands shut down all commercial logging and pre-commercial thinning activities on national forest lands throughout the Southwest, including the Cimarron watershed. Some thinning and timber harvesting on private lands has been continuing and is aimed at improving forest health and wildfire prevention

(Friedt 2019). Private land operations included some woodland restoration work on the Philmont Scout Ranch, timber sales on the American Creek Properties, a salvage sale in the Moras Creek drainage of the UU-Bar Ranch, and several small sales and thinning activities in the Moreno Valley and around Angel Fire. The New Mexico Game and Fish Department also conducted some thinning activities in the Tolby Meadows area (Figure 18). These activities total approximately 2,500 acres when completed (Friedt 2019).

As of January 2019, the Las Vegas District contractor list for forest industries that have operated in the local area between Las Vegas and Raton included nine sawmill or wood products operations, eight of which were located in the local area and one in Chama. The list also included five timber harvest contractors, of which three are located in Mora County and two are located a significant distance outside the local area, and seventeen thinning contractors, of which twelve are located in the local area. This indicates that the local market experiences competition from operators that are willing to travel from great distances to work in this area.

As a result of the fluctuating supplies and work opportunities, markets for wood processing remain in a fledgling state. Recent news that a California sawmill is planning to establish a mill operation in Cimarron represents a positive sign in the current flat timber economy. The available and possibly growing wood manufacturing capacity would respond well to a gradual increase of wood made available from forest treatments to increase water storage suggested in this plan. However, the recommended forest treatment activities in this study must initially be developed at a small scale to ensure a steady supply rather than high volume, which might not find any ready markets.

Responsible Parties and Collaboration Opportunities

Forest management for fire resilience improvements and water storage will involve a diversity of stakeholders who would have to collaborate to achieve success for all involved. Landowners would likely be the driving force and decision-making entities for forest management treatments. However, the New Mexico State Forestry Division, and particularly the Cimarron District office (District 2) would play a critical role in assisting with technical and regulatory information and oversight. The District would oversee project planning and implementation to ensure that state guidelines, Best Management Practices, and when necessary the state's Commercial Timber Harvesting Requirements (NMAC 19.20.4) are followed (NMEMNRD 2002).

Other stakeholders could include tribal entities with interests in the area, the State Historic Preservation Office in relation to cultural resource conservation requirements, New Mexico Department of Game and Fish—especially related to treatments in the Colin Neblett Wildlife Area—Colfax County, and the Colfax Soil and Water Conservation District regarding runoff management. If outside funding is involved, funding agencies would play a role as well (see also section 8). Additionally, either as funders or as interested parties, certain conservation groups, such as the Mule Deer Foundation, Rocky Mountain Elk Foundation, or Trout Unlimited may be invited to participate in proposed projects and could potentially complement project activities with technical assistance and financial support.

In the Wildland Urban Interface (WUI) areas of the Moreno Valley, an important new form of collaboration could be established through a local Fire Adapted Communities (FAC) partnership in collaboration with the regional FAC network (https://fireadaptednetwork.org/). In New Mexico, the FAC network is coordinated by the Forest Stewards Guild and The Nature Conservancy to mobilize landowners, local fire departments, counties, local businesses, and other institutional and private partners with a stake in improving community and landscape fire adaptation. Additionally, there is an urgent need to update the 2008 Colfax County Community Wildfire Protection Plan (CWPP). The Cimarron Watershed Alliance has begun an initiative in early 2021 to acquire funding and a network of partners to undertake this update process and boost collaboration toward strengthened FAC capacity in the Cimarron Watershed. These initiatives will greatly support the suggested fire risk reduction treatments in the forest and are critical to the long-term protection of water storage opportunities in the watershed's headwater forests.

Table 5. Overview of Forest Treatment Concepts for different water storage types

Storage Type	Critical Factors	Critical Forest and Tree Roles	Beneficial Locations and Conditions	Forest Treatment Concept
All storage: indirect and long-term	Fire adaptation; resilience to impacts from fire, drought, and insects	Tree health and vigor	Heterogeneity of forest structure at fine-, mid- and landscape scale	Multiple, ongoing selective thinning activities to increase/maintain tree and forest health and vigor and increase/ maintain heterogeneity at all scales
Icepack	Temperature (prolonged low)	Shade and wind shelter	S side (SE and SW sides) of high elevation ponds, tanks, and lakes; S side of streams; East- and West-facing high elevation slopes	Maintain (through thinning or protection) tree stringers in E-W direction (especially on E, W, N slopes and flat terrain)
Snowpack	Ground contact + Temperature (prolonged low): sharing, low wind	Openings between trees + shade, wind shelter: small canopy gaps	Wide spacing in aspen and other narrow canopy trees; small canopy gaps in conifer forest; and as above	Thin conifers and crowded aspen in aspen stands; conduct patch cuts in moist mixed conifer and selected spruce-fire stands; maintain natural opening (meadows)
Surface water (ponds, tanks, lakes, streams)	Wind reduction, temperature	Wind shelter, shade	S side (SE and SW sides) of high elevation ponds, tanks, and lakes; S side of streams	Maintain (through thinning or protection) tree stringers in E-W direction
Sub-surface: topsoil and litter (O-horizon)	Infiltration, absorption, and retention in OM	Needle cast, roots, and soil microbiome support; tree health	All stands; especially on soils with low porosity and conductivity where O-horizon plays a key role in water retention and delayed runoff	Maintain diverse and resilient forest ecosystems and optimize O-horizon thickness: minimal tree removal or at best small openings (OM retention; lop and scatter; coarse woody debris)
Sub-surface: soil (A-B-C horizons)	Soil porosity, absorption, and retention in soil	Roots and soil microbiome support; tree health	All stands	Maintaining diverse and resilient forest ecosystems; minimal tree removal or at best small openings
Sub-surface: saturated zone	Soil porosity and conductivity	Rooting depth and density; tree health	All stands, especially riparian areas (alluvial aquifers)	Maintaining diverse and resilient forest ecosystems

6. OPPORTUNITY AREAS FOR TREATMENT

The landscape analysis of section 4 identifies various key factors for the selection of opportunity areas for forest management aimed at increasing water storage. These factors include hydrogeology, soil type, vegetation cover, land use, fire management strategies, and runoff outflow into areas with high erodibility, such as burned areas.

These selection factors lead to the identification of three key opportunity areas for intervention:

1. The forest edges of the Moreno Valley;
2. The forest land in the mountains east of the Moreno Valley; and
3. The canyons and slopes burned in the 2018 Ute Park fire.

The forest edges of the Moreno Valley constitute the Wildland Urban Interface (WUI) areas in the grassland-forest ecotones, along roads, and in the forested subdivisions of Idlewild, Lakeview Pines, Agua Fria, and Angel Fire in the southern half of the Moreno Valley. Local stakeholders have stated that wildfire prevention and establishing Fire Adapted Communities is of great importance on the western and southwestern side of the Moreno Valley (Overby 2019; Gibson 2020). They point out that subdivisions of Idlewild and Lakeview Pines are precariously located at the forest edge of the west side of the Moreno Valley, with very limited access for fire emergency equipment. Wildfire originating along the western side of the valley, fanned by western or southwestern winds, would likely destroy the two subdivisions and drive embers through the air across the valley toward Eagle Nest and the grassland-forest ecotone on the eastern side of the valley.

Forest treatments in this area would need to target multiple jurisdictions of private lands, USFS land, and Taos Pueblo lands. Treatment planning and financing would fit best in a strategy of WUI interventions and promoting Fire Adapted Communities.

Forest treatments in this opportunity area support the goal of water storage improvements in the watershed by responding to the need of preventing water quality degradation in Eagle Nest Lake from ash and debris flows caused by wildfire and the strategic need protect areas for water storage in the mountains east of the lake. Treatments in this opportunity area would need to reduce the risk of ignitions that might blow embers across the valley in case of a high severity fire and western winds.

The forest land in the mountains east of the Moreno Valley constitutes a prime opportunity area for forest treatment because of its water storage abilities and fire risk. The area is defined by the Moreno Valley in the west with a corner point at Eagle Nest Lake; from there the area boundary follows the northern divide of the American Creek watershed along the southern part of the Colin Neblett Wildlife Area to Tolby Peak, and from there along Clear Creek Mountain to the southeast to Comanche Pass and Black Mountain, Trail Peak, and Rayado Peak. Agua Fria Creek and West Agua Fria Creek define the southern boundary. This area is about 39,900 acres in size (Figure 18).

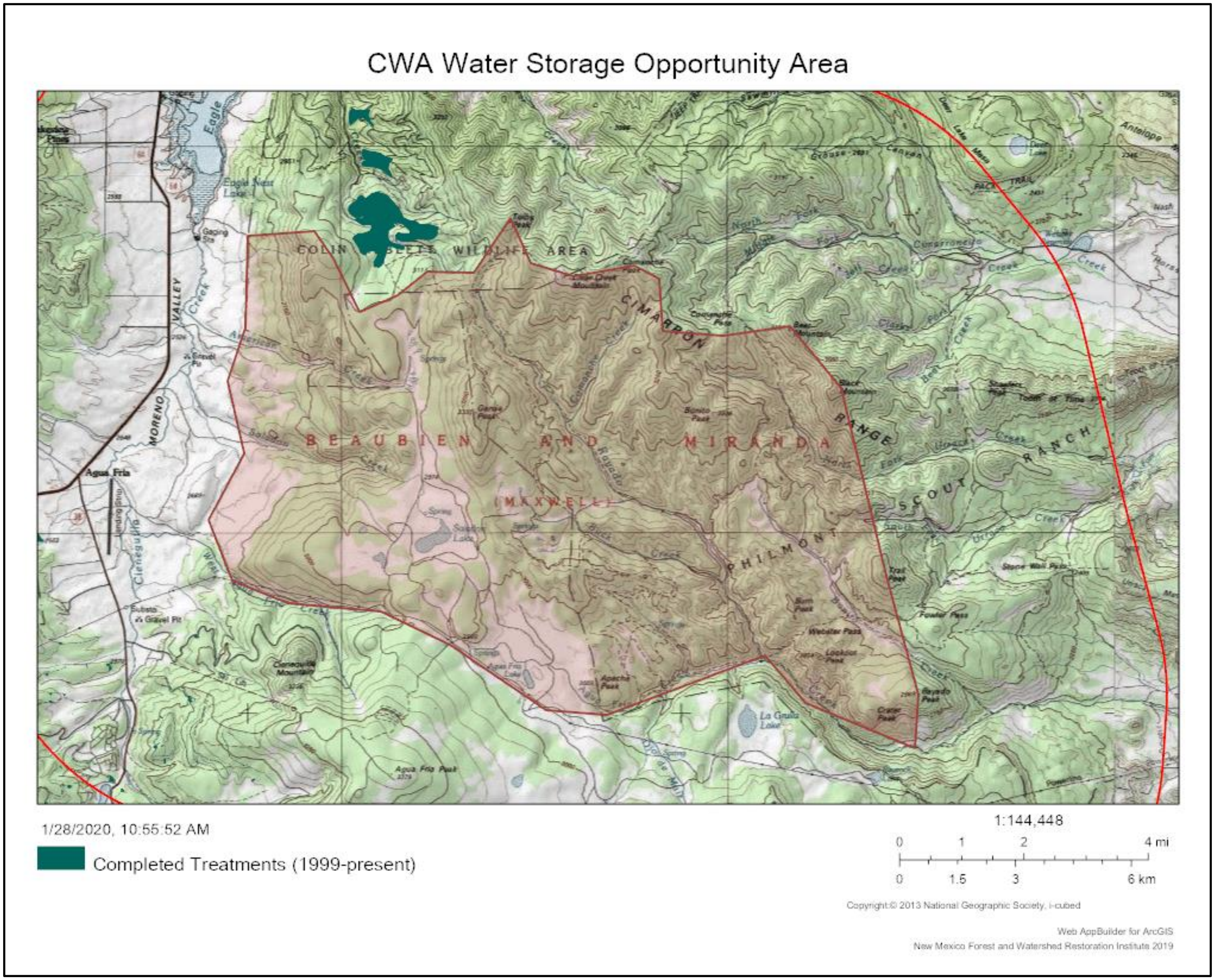


Figure 18. Selected forest management opportunity area (red) with indication of recently completed forest treatment areas (green) in a 4-mile radius around the opportunity area (red line) (NMEMNRD 2020 and J.W. Jansens 2020)

This opportunity area is largely located across the American Creek Properties, UU-Bar Ranch, Philmont Scout Ranch, and several private properties on the west-facing slopes of the Moreno Valley, and it also includes the southern part of the Colin Neblett Wildlife Area. The area is surrounded by a number of completed and planned treatment areas on private and federal forest lands and State Trust Lands. A search through the interactive New Mexico Vegetation Treatments website (NMEMNRD 2020) identifies 1,517 acres of treated lands and 5,455 acres of planned treatments within a 4-mile radius of the opportunity area, for the time frame between 1999 and 2018. This means that the proposed treatment area complements forest management work across jurisdictional boundaries in a wider area and would contribute to increased protection against catastrophic wildfire at a landscape scale.

The canyons and slopes burned in the 2018 Ute Park fire are a third opportunity area for intervention. This area is not of direct importance for water storage improvements, but is essential to be treated to improve water quality in the drainages originating in the northern part of the headwater catchment areas east of the Moreno Valley. Watershed constituents identified that there is a need to treat the drainages burned in the 2018 Ute Fire area for soil conservation purposes (Community meeting participants 2019). Area constituents identified that the target areas for soil conservation treatments include the Cimarron Canyon watershed and tributaries above and around Ute Park, the Ute Creek sub-watershed, the slopes around mile post 302 in the Cimarron River canyon, Harlan Creek (2-3 miles upstream from Raton intake point), and the burned slopes of Turkey Creek and Turkey Roost Mountain (Community meeting participants 2019).

Criteria for Strategic Area Selection

Criteria for the selection of treatment locations and treatment strategies typically follow guidelines established in forest landscape stewardship plans. In the absence of such plans they follow landowner objectives. Forest stewardship plans combine landowner objectives with considerations for desired ecological conditions, considerations regarding the commercial sale of forest products, enhancement of wildlife habitat, maintenance of cultural resources, and protection of water resources (Evans et al. 2011).

Most considerations listed extend beyond the boundaries of a single owner. As a result, collaboration opportunities and strategies including multiple owners play into criteria for the selection of treatments locations and treatment strategies. Larger-scale area plans and collaborative groups, such as Community Wildfire Protection Plans, Fire Adapted Community network programs, watershed-based plans, and watershed coalitions, such as the Cimarron Watershed Alliance (CWA), come into play at this level. This report aims to stimulate a collaborative approach across property boundaries and to inform the above listed planning instruments and forms of collaboration.

Based on findings described in previous sections, the cross-boundary criteria considered for this study include:

a. The strategic locations to reduce ignitions from distant fires and fire sources, such as

- Embers carried by wind from the west and southwest to the forests on the east side of Moreno Valley
- Fire fronts originating in the Moreno valley (e.g., grassfires and structural fires) to the forests around the Moreno Valley
- Embers and fire fronts from the west, north, east, and south affecting the higher elevation catchment area forest land east of the Moreno Valley.

These locations are the grassland-forest ecotones around the Moreno Valley, especially on the east side, and the slopes and ridgelines on the west, north, east, and south around the CWA Water Storage Opportunity Area (Figures 18 and 19).

b. Interrupting continuity of biomass fuels in conifer stands between and around the large meadow areas on the American Creek Properties, so as to increase the fuel break function of the meadows across the headwater landscape

c. Reducing fuel loads and increasing moisture in aspen and mixed conifer stands by creating more distance between stems and clumps on the American Creek Properties and UU-Bar Ranch

d. Increasing forest heterogeneity by reducing fuel densities, interrupting continuity of stand densities, and creating small forest openings in suitable stands (based on soil characteristics); these interventions would be most effective across relatively large headwater catchment areas with gentle slopes, with large forested areas, wetlands, and soil types with relatively high infiltration levels and soil characteristics that accommodate forestry activities.

Treatments in these areas would be limited to higher elevation forest types, such as spruce-fir forest, moist mixed conifer forest, dry mixed conifer forest, and aspen stands, including riparian areas and grassland-forest ecotones. In these forest types, treatments would focus on stands with conditions that have significantly departed from historical stand conditions in terms of stem densities, basal area, age class distribution, fuel loads, and tree species diversity. Additionally, stands with poor understory ground cover and understory diversity would also need to be considered.

Critically, treatment area selection depends on landowner interest and agreement. Furthermore, it is important that identified treatment areas are accessible by vehicle and for the use of tree harvesting equipment. In this phase of the study, CWA is exclusively targeting privately owned forest lands. Finally, when laying out forest treatment prescriptions that would include commercial timber harvesting, it is essential that the treatment area include marketable timber for which there are nearby markets in the region. Details on the wood products harvesting and manufacturing capacity identified for the region is described in section 5.

Priority Area Description

The consideration of landscape-wide opportunity areas for treatment, the identification of strategic locations for intervention (landscape-level analysis), and the selection of the most suitable areas for treatment based on a soil analysis (mid-level analysis) led to the selection of tentative priority areas for treatment. These tentative priority areas will need be evaluated in more detail regarding landowner interest, access, regulatory requirements and limitations, and site-specific conditions, which must be verified through stand exams and site analyses (fine-level analysis). The tentative priority areas are illustrated in Figure 19.

The priority areas include:

1. ***Short-term priority areas (years 1-5)***, based on the criteria listed above:

   - Moreno Valley Grassland – Forest Ecotone Treatment Areas (priority a; blue polygons in Figure 19)
   - Forest Edge Protection Treatment Areas (priority a; green polygons in Figure 19)
   - Meadow Edge and Buffer Protection Treatment Areas (priority b; orange polygons in Figure 19)
   - Aspen and Mixed Conifer Treatment Areas (priority c; red polygons in Figure 19)

2. ***Mid-long-term priority areas (years 6-20)***, based on the analysis of a custom soil survey (see Table 4):

   - Forest Soil Units AN, BU, BY (priority d; light gray polygons in Figure 19)
   - Forest Soil Unit CY (priority d; dark gray polygons in Figure 19)

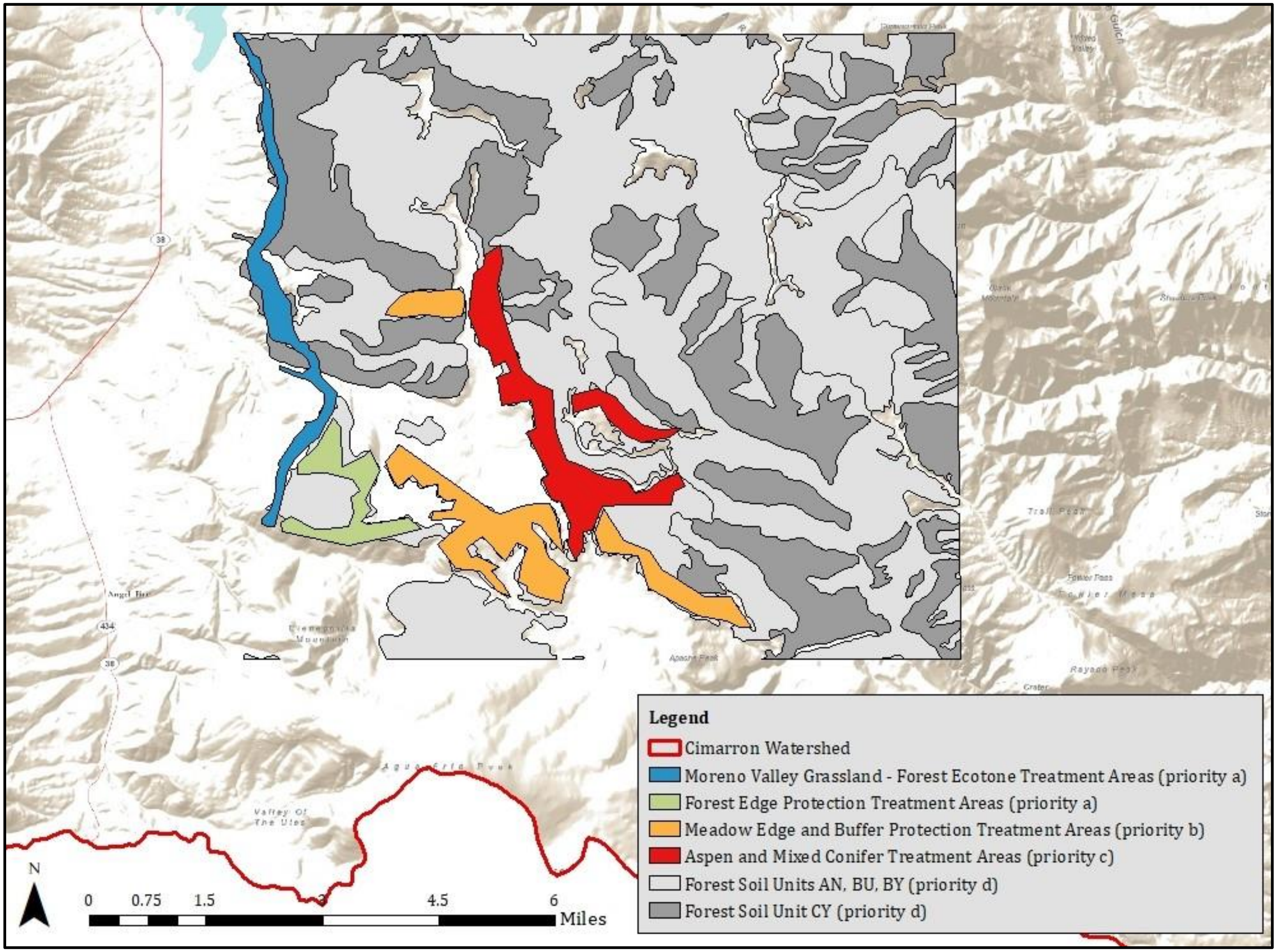


Figure 19. Map of tentative priority treatment areas for years 1-5 (priority areas a, b, and c), and tentative priority treatment areas for years 6-20 (priority areas d) (Mollie Walton 2020)

7. POTENTIAL FUNDING SOURCES

Table 6. Funding Sources by Type, Purpose and Focus, Funding Cycles, Eligibility Requirements, and Amount Range and Match Requirements

PRIVATE LANDS

Funding Source: Entity and Program	Funding Purpose/Focus	Funding Cycle	Eligibility Requirements	Amount Range and Match Requirement
NM Forest and Watershed Restoration Act (FAWRA) – annual projects	State FAWRA Board-selected projects for forest and watershed restoration, based on criteria TBD	TBD; possibly first RFP in fall 2020	TBD	TBD; $2.7M made available for FY2020
NM State Forestry (NMSF) – Hazardous Fuels	Reduce fire threat for communities at risk adjacent to federal land; restore fire adapted ecosystems	Applications due in March each year	Local and tribal governments; political sub-divisions of the state	<$300,000; 10% non-federal match
NMSF – WUI grants	Planning and implement-ation of hazardous fuels mitigation to reduce fire threat in WUI areas; within boundaries of approved CWPP	Applications due in March each year	Local and tribal governments; political sub-divisions of the state	<$300,000; 1:1 non-federal match
NMSF – Forest Health Initiative	Reduce insect and disease risk; improve degraded (including over-stocked) forest land	Varies depending on funding	Landowners who own at least 10 acres of forest land and have a steward-ship plan	<$100,000; 30% non-federal match
NRCS – Environmental Quality Incentives Program (EQIP)	Implementation of measures to protect soil, water, plant life, etc., including thinning and riparian restoration	Throughout the year; long process (decisions early in year)	Landowners of nonindustrial forest lands; tribes and pueblos	Varies (reimbursements made after work completion and approval)
Soil and Water Conservation District (SWCD)	Dependent on funding programs pursued by the SWCD	Varies, depending on funding	Landowners	Varies

Funding Source: Entity and Program	Funding Purpose/Focus	Funding Cycle	Eligibility Requirements	Amount Range and Match Requirement
North-Central NM Watershed Restoration Project (coordinated by Deirdre Tarr)	Dependent on funding programs pursued by the NCNMWRP, based on NRCS Regional Conservation Partnership Program	Varies depending on funding (allocated >$7M between 2014-2018)	Landowners (in collaboration with SWCD and NRCS)	Varies; projects with high match are more competitive
NM Forest and Watershed Restoration Act (FAWRA) – annual projects	State FAWRA Board selected projects for forest and watershed restoration, based on criteria TBD	TBD; possibly first RFP in fall 2020	TBD	TBD; $2.7M made available for FY2020
Coalitions and Collaboratives Inc. (COCO) AIM Grants	Capacity building for fire risk reduction and for increasing Fire Adapted Communities concepts in WUI areas next to USDA FS land	Annually in January-February and June	Communities, non-profits, fire departments, counties, SWCD	$10K - $50K; 1:1 match
NM Finance Authority - NM Water Trust Board – Water Project Fund	Loans and grant programs for rehab of (1) water conservation and recycling; (2) flood prevention; (3) ESA collaborative projects; (4) water storage, conveyance and delivery; (5) watershed restoration and management	Annual cycle announced by NMFA; subject to detailed regulations (see nmfa.net website)	Mostly water management institutions, local and state government entities	Varies; often part loan and part grant funding

PUBLIC LANDS

Funding Source: Entity and Program	Funding Purpose/Focus	Funding Cycle	Eligibility Requirements	Amount Range and Match Requirement
NM Game & Fish Department	Various programs aimed at protection of listed species and habitat restoration	TBD; depending on funding program	Non-profit organizations and/or private landowners	Variable

Funding Source: Entity and Program	Funding Purpose/Focus	Funding Cycle	Eligibility Requirements	Amount Range and Match Requirement
USDA Forest Service – Collaborative Forest Restoration Program (CFRP)	Public forest land restoration, wildfire prevention, planning, wood utilization, public education, and multi-party collaboration	Annually in January	Non-profit organizations, businesses, tribes, SWCDs, local govern-ment agencies	Up to $360,000 for 4 years with a required $90,000 (25%) non-federal match
National Forest Foundation	Collaborative and innovative programs on national forest lands: Matching Awards Program (for on-the-ground restoration work); Ski Conservation Funds (SCF) and Forest Stewardship Funds (FSF)	MAP: January and June (in 2 phases); SCF and FSF by invitation only (in December)	Non-profit organizations, universities, and tribes	Average award: $25,000 with a 1:1 match

PRIVATE AND PUBLIC LANDS

Funding Source: Entity and Program	Funding Purpose/Focus	Funding Cycle	Eligibility Requirements	Amount Range and Match Requirement
Private Donors	Mostly unrestricted	N/A	N/A	N/A
Volunteers	N/A	N/A	N/A	N/A
Trout Unlimited	Determined in collaboration with TU	TBD	TBD	TBD
Mule Deer Foundation	Determined in collaboration with MDF	TBD	TBD	TBD
New Mexico Counties - Wildfire Risk Reduction Program for Rural Communities	Grants to assist NM communities in reducing wildland fire risk on non-federal lands in Wildland -Urban Interface (WUI) areas and with a relation to wildfire protection on BLM lands	Annual cycle announced in January-February and due in March	Municipalities and counties, non-profit or community organizations; BLM letter of support	Up to $50K for hazardous fuel reduction work; up to $10K for wildland fire education; up to $15K for CWPP updates; at least 10% match

Funding Source: Entity and Program	Funding Purpose/Focus	Funding Cycle	Eligibility Requirements	Amount Range and Match Requirement
Rocky Mountain Elk Foundation	Determined in collaboration with RMEF	TBD	TBD	TBD
National Fish and Wildlife Foundation	Various grant programs that sustain, restore and enhance fish and wildlife habitat	Dependent on grant program	Dependent on grant program	Dependent on grant program
Wildlife Conservation Society – Climate Adaptation Fund	Competitive grants for on-the-ground actions focused on implementing priority conservation actions for climate adaptation at a landscape scale, with a focus on implementing priority actions and strategies identified in State Wildlife Action Plans	TBD	Nonprofit conservation organizations	Variable

The New Mexico State Forestry (NMSF) Hazardous Fuels program and NMSF's new Forest and Watershed Restoration Act (FAWRA) funding (starting in FY 2021) appear at this time to be the most appropriate funding sources in support of the recommendations in this report. In future years, individual landowners may want to pursue NRCS-EQIP, New Mexico Department of Game & Fish (NMDGF) grants, and Soil and Water Conservation District funding. The Cimarron Watershed Alliance would be well positioned to start negotiations with NCNMWRP for future funding for a landscape-wide project. NCNMWRP uses NRCS, NMFA-WTB/WPF, and other state funds to support large-scale projects conducted by SWCDs and other entities. The CWA would also be well positioned to negotiate forest restoration work in collaboration with NMDGF on the Colin Neblett Wildlife Area to complement work on private lands in the area. Private initiatives, contributions, and support from conservation groups such as Trout Unlimited, the Mule Deer Foundation, and the National Fish and Wildlife Foundation would also be an important component of a comprehensive, multi-donor funding strategy for the area.

8. CONCLUSIONS AND RECOMMENDATIONS FOR PROJECT DEVELOPMENT

Conclusions

This study concludes that water interception and storage in the headwater catchment areas of the Cimarron watershed can be optimized by (1) creating small forest openings (canopy gaps) with particular shapes, dimensions, and orientations in moist mixed conifer stands and spruce-fir stands and selectively thinning aspen stands at specific locations in the headwater forests to increase snow accumulation, and (2) treating the larger forest landscape, including the headwater forests, lower elevation ponderosa pine and dry mixed conifer forests, and forest lands in Wildland Urban Interface areas, in ways that improve the forest's adaptation to wildfire. Specific conclusions include:

A. Improved water storage and water availability for downstream beneficiaries is largely dependent on increasing runoff volumes, spreading runoff over greater periods of time, and prolonging low flow in mountain streams into dry seasons and drought periods, while reducing net evapotranspiration (ET). Because many ecological factors associated with these water budget components are interrelated, the cumulative short-term effects of many ongoing forest treatments and the long-term effects of individual treatments will need to achieve a balance between ET reductions and efficient, usable runoff increases.
B. It is essential to plan and implement forest treatments aimed at improving forest resiliency to wildfire as a strategy for maintaining long-term water storage in the face of climate change impacts on the forest ecosystem.
C. Preventing winter evaporation likely holds the greatest potential for optimizing water storage in the high elevation forests in the watershed.
D. Evaporation losses can be reduced by reducing evaporation losses during the winter season when most of the precipitation in the area occurs, covering bare soil, optimizing vegetation cover in alluvial areas and riparian zones, and providing wind shelter to surface water bodies. An even spatial distribution between stems in aspen and spruce-fir stands may reduce air mixing and help reduce evaporative losses.
E. In select locations in moist mixed conifer and spruce-fir stands, specific patch cut prescriptions (small gaps no wider than 3H and in shapes of hearts or chevrons with the apex to the south) aimed at creating shaded canopy gaps and small forest openings could increase snow accumulation and protect the snow from ablation, sublimation, and evaporation. Evaporation can also be reduced by reducing air movement and radiant and turbulent heat exchanges, which translates into providing wind shelter and preventing upward air mixing.
F. By increasing water storage in the watershed, forest management should result in a postponement of the melt out date and an increase of the time lag between precipitation peaks and runoff peaks. This is important because concentrated runoff accumulates sediment and debris, which complicates water harvesting of streamflow and increases the cost of water diversion and water purification infrastructure downstream.

G. Larger high elevation catchment areas with wet meadows and wetlands help prolong the lag time between precipitation and runoff and would be most suitable for forest treatments aimed at improving water storage in deep soils.
H. Selective thinning in ponderosa pine and dry and warm mixed conifer stands could in certain circumstances slightly increase water storage and water yield downstream and will contribute to regional protection against spread of wildfire to higher elevation forest ecosystems.
I. There is no scientific and empirical evidence for long-term (more than 10-year) water interception and storage benefits resulting from tree density reduction treatments. Theoretically a continuous treatment regime at a scale that covers approximately 2% of the forest per year (or at least 20% over ten years) would generate optimal conditions for snow accumulation, postponed annual melt out dates, and long-term water storage increases.
J. The following areas, in descending order, represent the most important forest management areas from the perspective of improving wildfire resiliency and water storage:
    a. The Agua Fria Creek sub-watershed, Headwaters Rayado Creek sub-watershed, and the upper part of the Urraca Creek sub-watershed, all located east of Angel Fire on the American Creek Ranch and UU Bar Ranch
    b. The five sub-watersheds along the Moreno Valley, including the Headwaters Cieneguilla Creek sub-watershed (around Angel Fire), Outlet Cienguilla Creek sub-watershed (to the north of the Cieneguilla Creek sub-watershed), Eagle Nest Lake sub-watershed, Outlet Moreno Creek sub-watershed (to the north of the Eagle Nest Lake sub-watershed), and the Headwaters Moreno Creek sub-watershed (at the northern end of the Moreno Valley)
    c. The Ute Creek and Ute Creek-Cimarron River sub-watersheds and the upper part of the Cimarroncito Creek sub-watershed, at the heart of the Cimarron Range. The majority of this priority area is located on the Colin Neblett Wildlife Area, managed by the NM Department of Game & Fish, while the northern and southern parts are owned by the Philmont Scout Ranch.
K. The southwestern watershed area, including the Moreno Valley and the mountain landscape to the east of the valley, is most suitable for forestry activities that aim at water storage improvements. Other areas are less suitable due to their varied geology and steep slopes.
L. Theoretically, effective water retention in the soil to protect it from rapid runoff or evaporation is most optimal in thick, medium-coarse textured forest soil layers with a high organic matter content.
M. Based on an analysis of landforms and soil types, the mountain area to the east of the Moreno Valley should be the principal target area for forest treatments aimed at improving water storage conditions for the watershed's downstream communities. Only a select group of soil types have a sufficient ability to store water and are sufficiently resilient to forest treatments. These soil group areas include:
    a. Soils with aspen and dry and moist mixed conifer forests on southwest-facing slopes of the Cimarron Range, east of the large mountain meadow areas (the Angostura-Tolby association – AN)

b. Wet mixed conifer and spruce-fir forests on north- and northeast-facing slopes of most of the Cimarron Range (the Bundy association – BU)
c. Dry and moist mixed conifer forests on north- and south-facing slopes at the higher elevations of the central parts of West Agua Fria Creek sub-watershed and around meadows (the Burnac-Hillery association – BY)
d. Dry mixed conifer forest and some aspen on south- and west-facing slopes of most of the Cimarron Range (the Cypher-Bundo association – CY).

N. The impacts of a changing climate are projected to work against the opportunities to increase effective water storage in high elevation forests in New Mexico. However, increases in water storage can be a significant incidental benefit to forest restoration approaches that reestablish natural fire regimes. The headwater forests of the Cimarron Watershed are among the ones least affected by climate change impacts in New Mexico, and therefore, have a relatively higher likelihood to show some positive effects of the recommended forest treatments for water storage.
O. Due to the complexity of the bio-physical environment of the headwater catchment landscape, a lack of detailed scientific information and forest modeling data pertinent to the watershed area, and many complexities in the monitoring of forest treatments, much of the recommended forest management work toward achieving this balance would need to be adaptive. Monitoring, evaluation, and ongoing research would be essential.

Recommendations

A. Forest treatments aimed at increasing fire resiliency in high elevation forest stands—particularly a combination of thinning and prescribed fire in lower elevation stands—would increase the ability of forests in the Cimarron watershed to sustain natural, low-severity fire regimes, in such ways that the forest ecosystem would naturally reestablishes itself. Such a treatment approach would be the most likely strategy to maintain or potentially improve water storage for some uncertain period of time, while reducing the risk of sudden water storage reductions due to the impacts of high-severity wildfire.
B. Wildland Urban Interface thinning treatments would be critical around the edges of the Moreno Valley to (1) reduce the fire threat to the area's communities, (2) reduce the risk of fire that would blow embers into the forests to the east, and (3) to prevent fire fronts from moving into the mountain landscape to the east of the valley.
C. Based on the frequency intervals of natural fires in mixed conifer forests, it is important to develop a program of treatments to affect changes in stand characteristics with spatial and temporal variability and frequency that mimic the natural fire dynamics.
D. Under the pressure of the increasing risk of catastrophic wildfire and insect damage, it is important to conduct forest treatments that aim to restore natural (wild) fire regimes and to prepare for managed wildfire practices. These management practices will likely have the greatest potential to restore forest ecological conditions, including soil conditions that are beneficial for snow and rainfall interception and retention.

E. Reestablishing natural low and mixed severity fire regimes as an active ecological process is important to increase forest ecosystem resiliency to the negative effects of an altering climate.
F. Management that increases heterogeneity of forest structure and fuels in mixed conifer forests will help maintain resilience. Restoring natural fire regimes may lead to possibilities for maintaining—and under some conditions or in some years—increasing water storage.
G. Forest thinning, patch cuts, shelterwood systems, patch cutting (coppicing) aspen stands, prescribed fire, and managed wildfire are among the most effective treatment strategies for mimicking wildfire.
H. Key components of treatment prescriptions include:
    a. Thin conifers and diseased or weak trees amid aspen stands to increase inter-canopy spacing and create small openings for snow penetration.
    b. Create small heart- or chevron-shaped canopy gaps and forest openings of up to 80 to 100 feet in diameter on south- and west-facing slopes and up to 200 to 375 feet in diameter on north- and east-facing slopes to increase snow accumulation, reduce ablation, wind impacts, and evaporation, and interrupt the continuous forest canopy for fire risk reduction purposes (the given range pertains to sloped vs. flatter terrain).
    c. Thin grassland-forest ecotones to remove trees that have encroached in the grassland and to reduce stem densities in the forest stands to maintain an open stand structure that prevents fires from advancing to higher elevations.
    d. Develop final prescriptions based on landowner objectives, specific site conditions, site objectives and opportunities, and the preliminary prescriptions in this document.
I. Managers should be concerned with harvesting impacts, site preparation disturbances, the amount of tree that is removed, and the accumulation of fuel from fire suppression. Soil compaction and erosion, in combination with other site factors, and particularly after fire, can have long lasting degrading effects on forest productivity and water storage potential.

9. APPENDICES

A. REFERENCES CITED
B. PRELIMINARY TERRAIN MANAGEMENT PRESCRIPTIONS

APPENDIX A. REFERENCES CITED

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APPENDIX B. PRELIMINARY TERRAIN MANAGEMENT PRESCRIPTIONS

Preliminary Prescription for Warm and Dry Mixed Conifer Units

Objectives

1. Restore historical forest structure and processes to improve the resilience of the forest to disturbances such as wildfire, insect infestation, drought, and climate change.
2. Prepare the treatment units for the reintroduction of fire in 2025.
3. Create canopy gaps and small openings that provide optimal shading and wind shelter to accumulate snow and reduce evaporation by insolation and wind.

Existing conditions

To be determined. It is expected that a mixture of even-aged and mixed-aged, young to middle-aged trees exist in dense stands and dense clumps with some canopy gaps. Old and large trees may be rare. Stands will mostly occur on west-, southwest-, south-, and southeast-facing slopes.

Restoration prescription

- ☐ Utilize existing terrain and vegetation features to guide implementation by creating V- or kidney-shaped, small openings with the apex toward the south, and with the length oriented more or less from east to west, separated by closed-canopy groups of trees (canopies touching). Openings are at most 375 feet long and no more than 160 feet wide on flat terrain, narrowing to about 120 feet for slopes of around 15 percent and 80 feet wide for slopes of around 30 percent.
- ☐ Primarily remove concentrations of small (<5-8 inch diameter) vegetation.
- ☐ Improve forest health by removing stress, damage, and mortality agents, such as dwarf mistletoe and spruce budworm.
- ☐ Strive to maintain around 30 percent canopy cover per acre, with a random pattern of canopy gaps and larger forest openings (as described above).
- ☐ Favor ponderosa pine, Douglas fir, and limber pine. Use existing ponderosa and Douglas fir groups as anchor points for action. Where ponderosa pine or Douglas fir groups exist, thin from below to create more space around leave trees.
- ☐ Leave mid-size and larger ponderosa pine (>14 inches) and Douglas fir (>16 inches).
- ☐ On more productive sites, more discretion is required to create openings. Look for depressions, flat areas, and high densities of small diameter trees as potential openings. As with other areas, use large/old trees as anchor points for openings.
- ☐ Within groups of trees, strive for a diversity of age, height, and size classes.
- ☐ Do not limb leave trees.
- ☐ Openings can include sparse individuals or groups of 8-16 trees of varying size and age classes.

- ☐ Maintain at least 8 and as much as 16 tons per acre of coarse woody debris on the forest floor. Redistribute the debris to avoid piles. Remove all debris from beneath driplines of leave trees.
- ☐ Retain at least 5 and possibly as many as 35 dead standing trees (snags) with DBH >10 inches and height >15 feet. (DBH is diameter at breast height)
- ☐ Select to fell snags <10 inches DBH and <15 feet in height. Fell trees parallel to contours to help minimize erosion and optimize soil and water retention.

Slash

- ☐ Slash height should not exceed 24 inches.
- ☐ Stump heights should not exceed 6 inches.
- ☐ Felled trees should be bucked to lengths to maximize contact with the ground.
- ☐ Limbs and tops should be separated from the bole.
- ☐ To the greatest extent possible, spread slash evenly across exposed soil in forest openings and inter-canopy gaps. For example, when moving between cut trees, drag slash with you.
- ☐ Do not place slash under the dripline of leave trees.
- ☐ Avoid piling slash on or within 3 feet of existing large diameter dead and down logs and standing snags greater than 12 inches in diameter.

Preliminary Prescription for Cool and Moist Mixed Conifer Units

Objectives

1. Restore historical forest structure and processes to improve the resilience of the forest to disturbances such as wildfire, insect infestation, drought, and climate change.
2. Prepare the treatment units for the reintroduction of fire after 2040.
3. Create canopy gaps and small and larger openings that provide optimal shading and wind shelter to accumulate snow and reduce evaporation by insolation and wind.

Existing conditions

To be determined. It is expected that a mixture of even-aged and mixed-aged, young to middle-aged trees exist in dense to very dense stands and dense clumps with some canopy gaps. Old and large trees occur. Stands will mostly occur on northwest-, north-, northeast-, and east-facing slopes.

Restoration prescription

- ☐ Utilize existing terrain and vegetation features to guide implementation by creating more or less heart- or chevron-shaped openings with the apex facing south (avoid south-facing forest edges), separated by dense, closed-canopy groups of trees (canopies touching and intertwined). Openings on slopes are between 80-100 feet wide in a north-south direction and at most 375 feet in size in an east-west direction, and at most 200 feet in diameter in areas exposed to wind.
- ☐ Retain large, tall trees (for optimal shading and for future seed sources), especially on the south side of canopy gaps.
- ☐ Using patch cuts, primarily remove concentrations of small (<5-8 inch diameter) vegetation, groups of white fir, and stressed and diseased trees.
- ☐ Improve forest health by removing stress, damage, and mortality agents, such as dwarf mistletoe and spruce budworm.
- ☐ Thin out aspen and conifer stands by removing white fit, small Douglas fir, and any diseased and stressed trees by selectively removing individual trees or small clumps to generate a more or less regularly spaced stand of aspen and conifer stems.
- ☐ Strive to maintain around 30 percent canopy cover per acre, with a random pattern of canopy gaps and larger forest openings (as described above) in Douglas fir and limber pine stands. Strive to maintain at least 30 percent canopy cover and upwards to 60 percent canopy cover in moister fir stands and in small aspen patches.
- ☐ Favor aspen, Douglas fir, limber pine, and sub-alpine fir. Use existing Douglas fir and sub-alpine fir groups as anchor points for action. Where Douglas fir groups exist, thin from below to create more space around leave trees.
- ☐ Leave aspen of >12 inch DBH and mid-size and larger Douglas fir and sub-alpine fir of >16 inch DBH. Do not cut in any spruce stands.

- ☐ On more productive sites, do not create openings and maintain natural density (thinning would lead to a proliferation of small trees).
- ☐ Within groups of trees, strive for a diversity of age, height, and size classes.
- ☐ Do not limb leave trees.
- ☐ Openings can include individuals or dense groups of 8-24 trees of varying size and age classes.
- ☐ Maintain at least 10 and as much as 20 tons per acre of coarse woody debris on the forest floor. Redistribute the debris to avoid piles. Remove all debris from beneath driplines of leave trees.
- ☐ Retain at least 6 and possibly as many as 40 dead standing trees (snags) with a DBH >10 inches and height >15 feet.
- ☐ Select to fell snags <10 inches DBH and <15 feet in height. Fell trees parallel to contours to help minimize erosion and optimize soil and water retention.

Slash

- ☐ Slash height should not exceed 24 inches,
- ☐ Stump heights should not exceed 6 inches.
- ☐ Felled trees should be bucked to lengths to maximize contact with the ground.
- ☐ Limbs and tops should be separated from the bole.
- ☐ To the greatest extent possible, spread slash evenly across exposed soil in forest openings and inter-canopy gaps. For example, when moving between cut trees, drag slash with you.
- ☐ Do not place slash under the dripline of leave trees.
- ☐ Avoid piling slash on or within 3 feet of existing large diameter dead and down logs and standing snags greater than 12 inches in diameter.

Preliminary Prescription for Pure Aspen Units

Objectives

1. Restore historical forest structure and processes to improve the resilience of the forest to disturbances such as wildfire, insect infestation, drought, and climate change.
2. Prepare the treatment units for the reintroduction of fire in 2025.
3. Create small canopy gaps and small openings that provide optimal shading and wind shelter to accumulate snow and reduce evaporation by insolation and wind.
4. As much as possible, maintain even distribution and spacing between stems within patches that have a more-or-less closed canopy.

Existing conditions

To be determined. It is expected that a mixture of even-aged and mixed-aged, young to middle-aged trees exist in dense to rather open stands and groups. Old and large trees may occur. Stands will mostly occur on higher elevation grassland-forest ecotones and on southwest-, west-, northwest-, east-, and southeast-facing slopes.

Restoration prescription

- ☐ Utilize existing terrain and vegetation features to guide implementation by creating small, more-or-less circular openings, separated by dense, closed-canopy groups of trees (canopies touching). Openings should be no more than 200 feet in diameter.
- ☐ Using patch cuts, primarily remove concentrations of small (<5-8 inches in diameter) vegetation of conifers and over-mature aspen, groups of white fir, and stressed and diseased trees.
- ☐ Improve forest health by removing stress, damage, and mortality agents.
- ☐ Strive to maintain at least 30 percent canopy cover per acre and upwards to 60 percent for denser stands with an even spacing between stems. Create a random pattern of canopy gaps and small forest openings (as described above).
- ☐ Favor mid-aged and mature aspen, Douglas fir, limber pine, and sub-alpine fir. Use existing clumps of aspen, Douglas fir, and sub-alpine fir groups as anchor points for action. Where Douglas fir groups exist, thin from below to create more space around leave trees.
- ☐ Leave mid-size and larger aspen, Douglas fir and sub-alpine fir of >16 inches DBH. Do not cut in any spruce stands.
- ☐ On more productive sites more discretion is required to create openings. Look for depressions, flat areas, and high densities of smaller diameter trees as potential openings, especially if grass cover is likely between the aspen. As with other areas, use large/old trees as anchor points for openings.
- ☐ Within groups of trees, strive for homogeneity in age, height, and size classes.
- ☐ Do not limb leave trees.
- ☐ Openings can include individuals or dense groups of 6-24 trees.

- ☐ Maintain at least 10 and as much as 20 tons per acre of coarse woody debris on the forest floor. Redistribute the debris to avoid piles. Remove all debris from beneath driplines of leave conifer trees.
- ☐ Retain at least 6 and possibly as many as 40 dead standing trees (snags) with a DBH >10 inches and a height >15 feet.
- ☐ Select to fell snags <10 inches DBH and <15 feet in height. Fell trees parallel to contours to help minimize erosion and optimize soil and water retention.

Slash

- ☐ Slash height should not exceed 24 inches.
- ☐ Stump heights should not exceed 6 inches.
- ☐ Felled trees should be bucked to lengths to maximize contact with the ground.
- ☐ Limbs and tops should be separated from the bole.
- ☐ To the greatest extent possible, spread slash evenly across exposed soil in forest openings and inter-canopy gaps. For example, when moving between cut trees, drag slash with you.
- ☐ Do not place slash under the dripline of leave trees.
- ☐ Avoid piling slash on or within 3 feet of existing large-diameter dead-and-down logs and standing snags greater than 12 inches in diameter.

Preliminary Prescription for Spruce-Fir Units

Objectives

1. Restore historical forest structure and processes to improve the resilience of the forest to disturbances such as wildfire, insect infestation, drought, and climate change.
2. Prepare the treatment units for the reintroduction of fire after 2035.
3. Create many small canopy gaps that provide optimal shading and wind shelter to accumulate snow and reduce evaporation by insolation and wind.

Existing conditions

To be determined. It is expected that a diverse mixture of even-aged and mixed-aged, young to middle-aged trees exist in dense to very dense stands and dense clumps with some canopy gaps. Old and large trees may occur. Stands will mostly occur in rather isolated patches on northwest-, north-, northeast-, and east-facing slopes, ridgelines, and crests at elevations above 10,000 feet.

Restoration prescription

- ☐ Utilize existing terrain and vegetation features to guide implementation by creating small irregularly shaped or heart- or chevron-shaped canopy gaps and small forest openings (avoid creating south-facing forest edges), separated by dense, closed-canopy groups of trees (canopies touching and intertwined). Openings should be 80-100 feet in diameter in a north-south direction on southern aspects and at most 200 feet in diameter at other aspects.
- ☐ Do not cut any trees in wetlands, on wet or saturated slopes (seep and spring areas), or in wind exposed locations.
- ☐ Retain all large, tall trees, especially on the southern sides of canopy gaps.
- ☐ Using small patch cuts, primarily remove concentrations of small (<5-8 inch diameter) vegetation, groups of white fir, and stressed and diseased trees.
- ☐ Improve forest health by removing stress, damage, and mortality agents, such as mistletoe and spruce budworm.
- ☐ Strive to maintain at least 30 percent canopy cover per acre in stands with natural openings and up to 70 percent canopy cover in dense stands. Strive to maintain or optimize spatial diversity. Maintain a random pattern of canopy gaps and small forest openings (as described above) in spruce and sub-alpine stands.
- ☐ Favor aspen, sub-alpine fir, blue spruce, and Engelmann spruce. Use existing aspen, fir, and spruce groups as anchor points for action. Where aspen groups exist, thin from below to create more space between the aspen stems.
- ☐ Leave mid-sized and larger sub-alpine fir and spruce of >14 inches DBH.
- ☐ On more productive sites do not create openings and maintain natural density (thinning would lead to a proliferation of small trees).
- ☐ Within groups of trees, strive for a diversity of age, height, and size classes.
- ☐ Do not limb leave trees.

- ☐ Openings can include individuals or dense groups of 8-24 trees of varying size and age classes.
- ☐ Maintain at least 10 and as much as 20 tons per acre of coarse woody debris on the forest floor. Redistribute the debris to avoid piles. Remove all debris from beneath driplines of leave trees.
- ☐ Retain at least 6 and possibly as many as 40 dead standing trees (snags) with a DBH >10 inches and a height >15 feet.
- ☐ Select to fell snags of <10 inches DBH and <15 feet in height. Fell trees parallel to contours to help minimize erosion and optimize soil and water retention.

Slash

- ☐ Slash height should not exceed 24 inches.
- ☐ Stump heights should not exceed 6 inches.
- ☐ Felled trees should be bucked to lengths to maximize contact with the ground.
- ☐ Limbs and tops should be separated from the bole.
- ☐ To the greatest extent possible, spread slash evenly across exposed soil in forest openings and inter-canopy gaps. For example, when moving between cut trees, drag slash with you.
- ☐ Do not place slash under the dripline of leave trees.
- ☐ Avoid piling slash on or within 3 feet of existing large diameter dead and down logs and standing snags greater than 12 inches in diameter.