THESIS

OPTIMIZING THE NET BENEFITS FROM PRE-WILDFIRE TREATMENTS TO COLORADO-BIG THOMPSON HEADWATERS PARTNERSHIP WATER RECIPIENTS

Submitted by

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ABSTRACT

OPTIMIZING THE NET BENEFITS FROM PRE-WILDFIRE TREATMENTS TO COLORADO-BIG THOMPSON HEADWATERS PARTNERSHIP WATER RECIPIENTS

The vulnerability of water quality within Colorado's watersheds in the aftermath of wildfires has become palpable in light of recent wildfire events. The costs of damages and water treatment incurred by municipal water providers has exposed the need to take proactive measures to combat potential future wildfire impacts, especially when considering the susceptibility the surrounding forests have due to widespread Mountain Pine Beetle (MPB) impacts. The thrust of this research seeks to ascertain the cost-benefit tradeoffs associated with pre-wildfire treatments on areas where high-intensity wildfires are probable within the Colorado-Big Thompson Project (C-BT) boundaries through the resources of the Colorado-Big Thompson Headwaters Partnership. In particular, focus will be placed on determining the changes in water yields generated from applying hazardous forest fuel reduction treatments to forest stands using existing stand exam data. The stand exam data is then used to create a generalized model that is applied to individual units across the entire research area using regression data from a series of ArgGIS forest layers to predict water yield. These are then evaluated and compared in terms of the relative change in water yield given the application of three separate treatment approaches and a defined annual budget. At present, the water resources of the C-BT are entirely vulnerable to water quality degradation from potential wildfire events which could impose immediate reductions in available water and widespread economic damages to the C-BT and its nearly one million consumers.

The C-BT is a regional water transmission project that was approved by the U.S. Congress in 1937 to capture and direct water from the western slope of the continental divide to the growing population of business-owners, irrigators, and municipalities along Colorado's Front Range (eastern slope). Completed in 1957, the C-BT continues to operate via 12 reservoirs, 35 miles of tunnels, 95 miles of canals, three pumping plants, and six hydroelectric power plants to serve 860,000 people and 640,000 acres of irrigated land along the eastern slope (Gibbens, Johnson, and Piehl, 2013). With involvement from the U.S. Bureau of Reclamation, the Northern Colorado Water Conservancy District (Northern Water) manages the ongoing operation and distribution of water from the C-BT with the aid of local, state, and federal agencies as well as private landowners and businesses.

The C-BT exists across six watersheds and a range of landscapes, primarily composed of Lodgepole pine stands on the western slope and Ponderosa pine stands on the eastern slope of the continental divide (Colorado State University 2013). Given decades of ongoing fire suppression tactics and widespread infestation from the MPB that has left the forest littered with millions of standing dead and down trees (Leatherman, Aguayo, and Mehall, 2007), these regions are now rife with ladder fuels which can aid in producing higher-intensity wildfires that can then lead to greater negative watershed impacts such as high sediment loads, debris flows, and flooding. According to Daniel Neary, "Wildfire is the forest disturbance that has the greatest potential to change watershed conditions." Such wildfire impacts on watersheds are primarily the result of fire intensity and duration in combination with a fire's location, which can result in increased soil-water repellency, reduced water infiltration, increased debris torrents and erosion rates, and sediment pulses, as well as increased turbidity due to higher nutrient and sediment concentrations (Neary, Ryan, and DeBano, 2004). Such impacts occurred from the Buffalo Creek (1996) and

Hayman (2002) fires in which Denver Water spent $26 million on post-wildfire water treatment and watershed-related projects while the U.S. Forest Service spent $37 million on restoration and stabilization efforts (Denver Water, 2013). These costs were due to sedimentation and structural damages within Strontia Springs reservoir and the need to cleanse water that was being distributed to customers with a smoky-taste. Strontia Springs, which had annual sediment deposition of around 12,000 cubic yards per year, received over 160,000 cubic yards of sediment after a single rain event following the wildfire and was expected to accumulate 200,000 cubic yards of sediment per year thereafter until the watershed restabilized (Lynch, 2004). Given more recent wildfire events, the physical and financial threats from these impacts is readily apparent and has given rise to entities such as the Colorado-Big Thompson Headwaters Partnership, which is composed of stakeholders such as the U.S. Forest Service, Colorado State Forest Service, U.S. Bureau of Reclamation, and Northern Colorado Water Conservancy District. The C-BT Headwaters Partnership was developed to work with individuals and organizations to fund and restore forest and watershed health through pre-wildfire treatments that reduce wildfire impacts and preplan post-wildfire responses to protect C-BT facilities and municipal and rural water supplies.

The conditional burn probability for wildfire events in the C-BT watersheds has been constructed from U.S. Forest Service software for use within this research. With this knowledge, and the various jurisdictional and regulatory nuances of the C-BT Headwaters Partnership and its members, this study seeks to aggregate and generate a comprehensive model of pre-wildfire treatment locations that reduce the wildfire risk while increasing the changes in water yield. With the costs of such events considered, the crux of the model will be to optimize the extent to which pre-wildfire treatment methods can reduce the post-wildfire/watershed impacts, given a particular amount of financial input from the various stakeholders. Such scenarios will be optimized in order to provide a spectrum of outcomes for C-BT stakeholders to contemplate.

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Finally, I would be remiss in not expressing my most sincere appreciation to my family and friends who have been both accommodating and supportive throughout my graduate experience. My parents and family have unquestionably been a constant source of energy and encouragement throughout every one of my endeavors here, and for that I cannot thank them enough. I'm very thankful as well to graduate students of the department who themselves have been a source of motivation, knowledge, perspective and friendship.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

The allure of the American West has long been held in its dynamic landscapes, rich natural resources, and dramatic climatic and natural events. Over the past century, wildfires across public and private lands have been suppressed in support of human protection and preference. This dogma has interrupted cyclical wildfire events across landscapes and has led to increased fuel accumulation across numerous forests, making them more susceptible to high-severity fire events (Agee, 1993). Additionally, water resources of the western landscape have been altered and taxed to sustain agriculture, industry and growing western cities and communities as notably depicted in Mark Reisner's 1986 book, *Cadillac Desert: The American West and its Disappearing Water,* and subsequently researched by Sabo, et al. (2010). Despite conditions where climatic and topographic circumstances create water-scarce and wildfire prone regions, Americans have and continue to find appeal in livelihoods within and adjacent to these areas. Within the state of Colorado, along the eastern border of the Rocky Mountains commonly referred to as the "Front Range", such a scenario has played out with the establishment of numerous rural communities and urban cities. More than 80% (Colorado Department of Local Affairs, 2014.) of the state's nearly 5.3 million residents live within this area (U.S. Department of Commerce, 2014.), which is characterized by broad plains that are well-suited for agriculture, municipal and industrial uses (Western Resource Advocates, 2012). In order to meet the current and anticipated water demands of these sectors, a large share of surface water must be captured within the adjacent Rocky Mountains and delivered to water users along and within the Front Range through a system of reservoirs, pipes, canals, and tunnels.

An example of such a capture and delivery system is the Colorado-Big Thompson Project (C-BT), which captures water within five Colorado River Basin reservoirs that is then pumped across the continental divide to the eastern slope, where it is delivered for power generation and water use to more than 860,000 individuals and across 640,000 acres of agricultural land within the South Platte Basin (Northern Water, 2014.). The overall system operates through the use of 12 reservoirs, 35 miles of tunnels, three pump stations, six hydroelectric power plants and 95 miles of canals that traverse the continental divide, six watersheds, and various public and private lands (Gibbens, Johnson, and Piehl, 2013). Having begun in 1937, it was completed in 1957 and is operated through the Northern Colorado Water Conservancy District (Northern Water) in coordination with the United States Bureau of Reclamation.

1.1. Goals and Scope of the Study

The intention of this study is to acknowledge and identify the pre-wildfire treatment scenarios that would reduce the level of wildfire risk while best serving the water needs of Colorado-Big Thompson (C-BT) recipients through the formulation and application of models to express potential changes in water yield given particular forest characteristics and treatment methods. These scenarios will be applied to landscapes found within the six sixth-level[1] watersheds located in Grand County, Colorado whose runoff enters Lake Granby, Shadow Mountain Reservoir and Grand Lake, which serve as the most critical water bodies of the C-BT's West Slope Collection System (Figure 1.1). It was initially thought that water quality degradation from past wildfires could be ascertained by evaluating records of the water quality

[1] Sixth-level subwatersheds are categorized as 12-digit hydrologic units that generally range in size from 10,000 to 40,000 acres as discussed within the "Federal Standards and Procedures for the national Watershed Boundary Dataset (WBD)" (U.S. Geological Survey and the U.S. Department of Agriculture, Natural Resources Conservation Service, 2013).

impacts of these events on water providers and thus, measurable water quality improvements could be made given particular forest treatments to reduce the severity and extent of potential wildfire impacts. In conducting semi-structured interviews with C-BT water treatment facility members (summarized in "Appendix I"), it was found that such evidence of prior impact on water quality and the potential for future water quality impacts to water treatment facilities was not likely due to the existence of many C-BT reservoirs that serve as an intermediary for filtering degraded water from wildfire events. As a result, the impacts to Colorado-Big Thompson Headwaters Partnership (C-BTHP) recipients were evaluated, not on the basis of water quality, but on the basis of a change in water yield given a particular hazardous forest fuel treatment (fuel treatment). The optimal allocation of these fuel treatment scenarios will be a function of the expected return from fuel treatments with regard to water yield and reduced conditional wildfire probability within the C-BT given discrete budget constraints faced by the entities that comprise the C-BTHP.[2] Considering the financial implications and wildfire risks associated with the spatial distribution and application of various fuel treatments, the risk-return tradeoffs of such investments will be sought by considering treatments in terms of existing costs and annual budget allocations. The scope of this study will be primarily based on existing vegetative information available through the Arapaho-Roosevelt National Forest for the aforementioned watersheds which will be utilized to simulate present-day forest stand management scenarios and water yield and fire modeling outputs for a period of fifty years.[3] The dual objectives of protecting water quality by reducing wildfire potential around Shadow Mountain Reservoir and

[2] While additional gains in changes to water yield would be expected given widespread regional fuel reductions, such as those generated through regional clear cutting or wildfire events, it should be clarified that these events are not considered in the context of this research due to their impact on the utility currently derived from existing forest attributes and characteristics.
[3] This fifty year designation exists primarily due to model input requirements of the FVS-Suppose "WRENSS Post-Processor" as well as consideration for the potential for incremental reductions in changes in water yield across subsequent ten-year treatment cycle outputs.

Grand Lake prior to its transmission through the Alva B. Adams Tunnel while increasing water yield within these C-BT water bodies was pursued. This was primarily done by analyzing the changes in water yields to actual forest stands through the generation and application of a uniform "fishnet" grid system with similar stand attributes across the region.

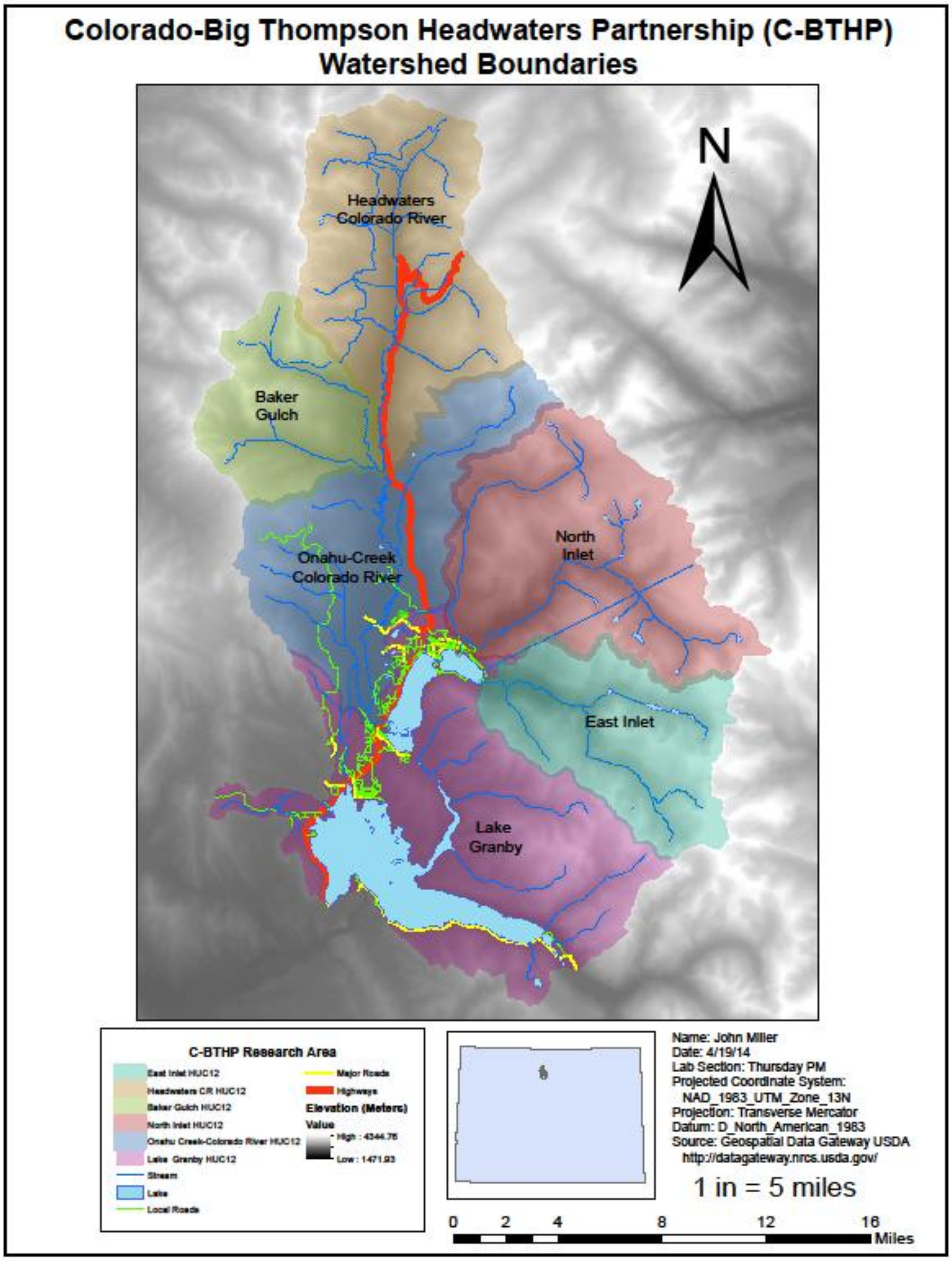

Figure 1.1 Colorado-Big Thompson Headwaters Partnership Watershed Boundaries

Through this approach, regression modeling was enabled across the entire study region to calculate changes in water yield. Once this was conducted changes in water yield were considered in conjunction with conditional wildfire probabilities to generate “Effective Burn-Free Water Yield” values that could then be evaluated in terms of a defined budget to express the regional changes in output generated given one of three treatment approaches. It is through this method of generating Water Yield Frontiers that water yield gains from a “Change in Water Yield” approach are found to be markedly greater than those under other approaches given a budget of $1,000,000. Despite this finding, it is made evident that treating forest units strictly for the purpose of generating changes in water yield is not substantiated when the costs of such an endeavor far outweigh the current investment necessary to purchase a comparable acre-foot of water under current market conditions. When this purpose is not sought, the mutual benefits of reducing wildfire risk simultaneously with generating changes in water yield can be considered to reflect more pragmatic efforts under particular budget constraints. that may aid C-BTHP decision-makers in better allocating their funds for pre-wildfire fuel treatments to best serve the multiple objectives that they seek.

1.2. Organization of the Study

Six chapters comprise this paper, each of which contains one or more sections. A literature review for the implications of fuel treatments on watersheds and fire effects, the Sharpe Ratio, and existing risk assessments for the Colorado-Big Thompson project are contained within Chapter 2. Within Chapter 3, the methodology and empirical specifications of the processes applied within this study are discussed as well as the measures used to acquire the study data and the models employed for data analysis with the results of these analyses outlined in Chapter 4. A summary of the study and its limitations, its contribution to the existing body of knowledge surrounding the Colorado-Big Thompson project, and the opportunities and suggestions for continued research within this area are presented in Chapter 5. Beyond this chapter are referenced tables and figures, as well as a synopsis of semi-structured interviews conducted with regional water treatment providers regarding wildfire-related water quality concerns and commentary.

CHAPTER 2: BACKGROUND

The focus of this section will be on reviewing literature and techniques that provide greater background information and insight into the various approaches taken within this study. An overview of pertinent Colorado-Big Thompson project features, forest conditions and fuel treatment effects relative to wildfire risk and watershed health, and discussion of the Sharpe ratio and recent C-BT wildfire-watershed assessments and analysis tools are conveyed to provide further context. These existing circumstances and prior research are presented to provide scope for the methods implemented and also serve to help define the objectives sought by the research.

2.1. Importance of the Project

The relevance of this research is considerable in light of recent catastrophic wildfire and flood events in and around the C-BT area and the threat that such future events pose to existing C-BT infrastructure and water quality. Local, state, and federal governments have also expressed their interest for preserving and enhancing existing forest and watershed conditions and through numerous collaborations, initiatives, and legislative gestures such as the Healthy Forest Initiative and the recently formed Western Watershed Enhancement Partnership, which identifies the C-BTHP as a pilot project for the program (U.S. Department of the Interior, 2014). From the management perspective, Northern Water must anticipate and address these concerns through expanded collaboration and efforts in order to continue providing its customers with the services they rely on today while preparing to meet the water demands they will have in the future. Discussions with representatives across many entities acknowledge the need for resolution of these and other concerns in a manner that is both comprehensive and effective in managing the issues at hand.

2.2. Background of Research

The impetus for research regarding pre-wildfire treatments for the purpose of watershed protection was borne through research carried out by Travis Warziniack and Matthew Thompson in a 2013 paper entitled, "Wildfire risk and optimal investments in watershed protection". Within this paper, Warziniack and Thompson acknowledged the growing interest in watershed protection relative to wildfire events through such efforts as the Healthy Forests Restoration Act and recently created Western Watershed Enhancement Partnership where multi-agency collaboration on watershed protection through efforts such as pre-wildfire treatments are utilized at a cost, without the benefits from such investments being known. Warziniack and Thompson postulated that such benefits could be derived through the application of the Sharpe ratio, which is a commonly used finance formula for determining the expected return on an investment per unit of associated risk. In terms of watershed protection, the following formula,

$$Max\ S = \frac{\sum_n w_n R_n}{\sigma}$$

was applied with regard to pre-wildfire treatments where S represents the Sharpe ratio, R_n is the expected return of fuel treatments in watershed n, w_n represents the percent of the overall budget spent on treatment efforts within each watershed, and σ is the standard deviation of the benefits in the portfolio. This approach was applied to recent wildfire events and subsequent regional flood events that occurred in and around the Cache la Poudre River and Horsetooth Reservoir near Fort Collins, Colorado. Their findings determined that sediment costs were high for water providers and that treatment efforts to prevent and mitigate sedimentation within and through a watershed would have large benefits (Warziniack and Thompson, 2013).

Using this approach, the research was expanded beyond the Cache la Poudre River and Horsetooth Reservoir to assess the impact of such treatment efforts across multiple agencies on water providers within the nearby Colorado-Big Thompson Project region through the Colorado-Big Thompson Headwaters Partnership. This partnership was signed in December of 2012 and has as its signatories the United State Forest Service, the Colorado State Forest Service, the United States Bureau of Reclamation, the Northern Colorado Water Conservancy District (Northern Water), the Western Area Power Administration (WAPA) and the National Park Service (NPS). The intentions of this partnership lie in working to restore forest and watershed health and preplan post-wildfire responses to protect C-BT facilities and water supplies (USDA, Forest Service, 2012).

The independent consulting company JW Associates has performed numerous wildfire-watershed assessments along Colorado's Front Range and has been contracted by Northern Water and its affiliates to conduct a series of such assessments, including a recent "C-BT Small Watershed Targeting and Zones of Concern Prioritization Report" and a "Combined C-BT Wildfire-Watershed Assessment" report. The later assessment is a compilation of prior assessments that looked at prioritizing watershed-based risks to water supplies within particular C-BT basins. These assessments aggregated these risks based on a 0.5 to 5.5 composite hazard ranking scale (Lowest: 0.5-1.5, Low: 1.5-2.5, Moderate; 2.5-3.5, High: 3.5-4.5, Highest: 4.5-5.5) that was developed based on sixth level sub-watershed analysis of wildfire hazard, ruggedness, road density, flooding/debris flow hazard, and soil erodibility, as well as "Zones of Concern" which were those areas above important surface water diversion points/intakes/infrastructure/etc.

deemed of significance by stakeholders for transporting sediment and debris throughout the C-BT (JW Associates, Inc., 2014). These composite hazard rankings were then compiled to highlight those sub-watersheds that had the highest ranked wildfire hazards that could benefit from pre- and post-wildfire treatments to provide effective relief from negative impacts to C-BT water quality. These values were not directly correlated to wildfire intensity or severity, although given the attributes associated with their values, were presumed to be relatively indicative of having a higher risk for such occurrences. Such an assumption allowed these values to be adjusted for research to represent a scale of wildfire intensity from 0-5.0 (Lowest: 0-1, Low: 1-2, Moderate; 2-3, High: 3-4, Highest: 4-5). By identifying those values greater than 2 ("Low" Wildfire Intensity) within the Upper Colorado Headwaters basin, sixth-level watersheds were identified that fed into west slope collection reservoirs and lakes and would likely benefit from pre-wildfire hazardous fuel treatments by having reduced fuel availability.

2.3. Colorado-Big Thompson Project

The Colorado-Big Thompson Project (C-BT) was initiated in 1938 and completed in 1957 in an effort to secure water provisions and generate power for individuals living and working in and around northern Colorado. Today, the C-BT captures water within five Colorado River Basin reservoirs that is then pumped across the continental divide to the eastern slope, where it is delivered for power generation and water use among more than 860,000 individuals and across 640,000 acres of agricultural land within the South Platte Basin (Northern Water, 2014.). As aforementioned, the overall system operates through the use of 12 reservoirs, 35 miles of tunnels, three pump stations, six hydroelectric power plants and 95 miles of canals that traverse the continental divide, six watersheds, and various public and private lands (Gibbens, Johnson, and Piehl, 2013). The C-BT is operated through the Northern Colorado Water Conservancy District (Northern Water) in coordination with the United States Bureau of Reclamation

The C-BT project exists across eight counties on either side of the continental divide. Across these counties, the majority of C-BT infrastructure, including reservoirs and power plants, is situated within or near national forest system lands or forested private lands (USDA Forest Service, 2013a). Due to the scale and complexity of the C-BT project, along with the services it provides, many entities act both directly and indirectly to ensure the C-BT project maintains its ability to meet and protect the numerous obligations it has to its consumers and stakeholders across Colorado. Acknowledging the redundancy and specialization that these independent efforts can create, along with concerns borne from recent wildfire and flooding events, a number of public entities worked to create the Colorado-Big Thompson Headwaters Partnership to address these items and provide increased operational efficiency and effectiveness.

The Colorado-Big Thompson Headwaters Partnership (C-BTHP) was signed in December of 2012 and has as its signatories the United State Forest Service, the Colorado State Forest Service, the United States Bureau of Reclamation, the Northern Colorado Water Conservancy District (Northern Water), the Western Area Power Administration (WAPA) and the National Park Service (NPS). The C-BTHP exists largely on federal lands, namely those of the Arapaho-Roosevelt National Forest (ARNF) as well as the Rocky Mountain National Park. The intentions of this partnership lie in working to restore forest and watershed health and preplan post-wildfire responses to protect C-BT facilities and water supplies (USDA, Forest Service, 2012). Although it was identified by Warziniack and Thompson that the most current collaboration for watershed protection was via the newly formed Western Watershed

Enhancement Partnership (WWEP) which was signed on July 19, 2013, further consultation with individuals at Northern Water, the United States Forest Service (Forest Service) and the Colorado State Forest Service confirmed that no collaborative watershed protection efforts had yet been executed through the WWEP, but were being conducted through the C-BT Headwaters Partnership. Additionally, discussion with these entities revealed that the Forest Service was serving as the primary agency for executing such treatments and that, due to regional flooding in September of 2013, the vast majority of the areas sought for treatment along the eastern slope of the C-BT were made inaccessible by these events, which essentially isolated all treatment efforts in the near future to watersheds located within the Upper Colorado Headwaters basin on the western slope of the C-BT.

The west-slope collection system of the Colorado-Big Thompson Project is situated in Grand County, Colorado, adjacent to various public lands and the towns of Grand Lake and Granby. The surrounding landscape is characterized to the west by the low-lying, sparsely vegetated valley of the Colorado River that then transitions with elevation into dense conifer forest where the effects of the Mountain Pine Beetle (MPB) infestation have resulted in the death of nearly 90% of the county's dominant tree species, Lodgepole pine (Grand County Division of Natural Resources, 2008). It is within this landscape that three pump plants, five reservoirs, two canals and the Alva B. Adams Tunnel inlet are situated to collect and convey C-BT water from the western side of the continental divide to the eastern side.

2.4. Wildfire Characteristics

Beginning with the first settlers, the forested lands of the United States have been managed for multiple uses such as creating favorable pasturelands for grazing, performing selective tree harvesting for wood products, and excluding wildfires for the protection and control of resources (Covington and Moore, 1994.) The Forest Reserve Act of 1891 allowed for presidential designation of tracts of forested lands for public use. Following many such designations, the United States Department of Agriculture (USDA) formally established the Forest Service on February 1, 1905, to oversee, manage, and protect these national forest system lands. One notable aspect of this responsibility was the charge to prevent and control the spread of wildfires across the landscape (Snider, Daugherty, and Wood. 2006). Such a charge was quickly challenged in the summer of 1910, when wildfires raged across nearly three million acres of federal, state, and private lands within the northern Rockies and required the assistance of extensive federal personnel and resources as well as private individuals. As time progressed, so did support for increased fire suppression with Forest Service policy in 1935 stipulating that once a report of a wildfire was made, that fire was to be contained and controlled by 10 a.m. on the following day (USDA Forest Service2014.). These policies continued for nearly a century until in 2001, the "National Fire Plan" addressed objectives "to prepare to fight future fires, rehabilitate burned lands, actively reduce fuel loads in vulnerable areas, and assist local communities" (USDA U.S. Department of Agriculture, 2001.) Ongoing research, successive large-scale forest fire seasons, and widespread forest infestations since the 1990's (Grand County Division of Natural Resources, 2008) across much of the West prompted further action by the Bush Administration to outline implementation actions through the "Healthy Forests Restoration Act". This Act, signed into law in 2003, formally addressed hazardous fuels reduction on federal lands, utilization of woody biomass, watershed forestry assistance, forest inventory/monitoring and early warning systems and insect infestation and related diseases throughout U.S. public and private forested lands (Healthy Forests Initiative, 2003). While such efforts had been occurring for some time, this Act has served to promote and support the current range of recent projects and partnerships aimed at mitigating hazardous forest conditions through ongoing research, simulations, and modeling as well as restorative forest and ecosystem management across the United States.

In order to understand the impacts imposed by wildfire events, wildfire characteristics must first be understood to provide context for how they behave and what measures can be sought to control those behaviors. Wildfires occur for a number of reasons, yet essentially can be categorized into three separate types: ground, surface, and crown fires. Each of these types can be expressed in terms of their fire intensity (the rate at which fuels are consumed and heat is generated) and fire severity (the abiotic and biotic impacts to forest stands) and are influenced by available fuels, fuel arrangements, stand species, fuel moistures, physical settings and weather conditions (Brown and Davis, 1973). Various arrangements of these factors can result in different potential levels of fire severity and intensity, which can ultimately result in the extent to which landscapes are impacted by wildfire events. In terms of severity, crown fires have been found to have the potential for the greatest impact on landscapes as they involve the movement of fire through the crowns of a forest canopy which, given certain conditions, can then produce "firebrands[4]" that can drop on surrounding landscapes or be carried aloft to more distant fuel sources and propagate the fire behavior across a large area (Rothermel, 1991).

It is through the manipulation of these arrangements that methods such as fuel treatments can alter fire severity and intensity to more desirable levels. It should be acknowledged though that fuel treatments do harbor the potential to exacerbate fire behavior through the influence of reduced fuel moistures, intensified through-stand wind movement,

[4] "Firebrands" are defined as pieces of burning wood that can often be lofted upward from their source and carried aloft to more distant areas where unburned forest fuel resources exist. Through these actions, firebrands can serve as a significant mechanism for spreading wildfire (Williams 1982).

and/or increased nutrient availability and forest regeneration under certain conditions (Omi and Martinson, 2002 pg. 29). Forest “thinning” and “prescribed burning” are two of the primary means through which forest landscapes can be treated to influence stand characteristics. Thinning has been described as any kind of partial cutting such as cleaning, improvement, liberation, preparatory, sanitation, selection cutting or weeding within a forest stand. It is often employed through one of five methods: 1.) Low, or thinning from below 2.) Crown, or thinning from above 3.) Selection, or diameter-limit thinning, 4.) Free thinning, or 5.) Mechanical thinning (Brown and Davis, 1973 pg.2). Of these methods, “low” thinning will reduce the average forest canopy bulk density and increase the canopy base height (Agee and Skinner, 2005) through the removal of “ladder” fuels, which are smaller trees and brush that provide vertical continuity and allow a fire to burn from the ground level up into the branches and crowns of larger trees (Colorado State Forest Service, 2012 pg. 3). Mechanical treatments can thin to specified spatial arrangements, such as “low” thinning (Agee and Skinner, 2005) which can often provide economic and productivity advantages for treatment projects. It has been found that the effects of thinning, in conjunction with reductions in surface fuels, can result in decreased fire intensities (Agee, 1993).

Prescribed fire is another method for altering forest landscapes as it has been found to be effective in reducing surface fuels and increasing canopy base height through lower crown scorching (van Wagtendonk, 1996; Agee and Skinner 2005). In addition to these outcomes, prescribed burning can also consume snags and windfalls within a forest stand, which further reduce the fire hazard through ladder fuel reduction. Prescribed burning may also serve as an instrument for natural regeneration, especially for pyrophytic species, by consuming surface-level organic matter and creating microsites that have enhanced moisture and nutrient levels beyond those of unburned areas (Harrington and Sackett, 1990). As with natural fires, the effective consumption of fuels depends on both topography and weather conditions where prescribed fires are initiated (Pollet and Omi, 2002) as well as what ignition patterns are chosen by fire management personnel.

CHAPTER 3: DESCRIPTION OF DATA AND MODELING

This chapter presents the courses of action taken to acquire relevant data along with the unique processes and inputs used to evaluate this information. Additionally, the characteristics and rationale for many of the regional components used, including those later applied as regression variables, are discussed. The overall methodology used in acquiring the initial data necessary to determine changes in water yield, burn probabilities, and their integration for further modeling and investigation are discussed below.

3.1. Study Area

The region of interest for this research is isolated to the portion of the C-BT located west of the continental divide, within the Upper Colorado Headwaters basin. The C-BT maintains six reservoirs within this area, four of which are used to collect and distribute water from the western side of the continental divide to the eastern side via the 13.1 mile Alva B. Adams Tunnel. These reservoirs, from furthest-to-closest distance to the tunnel, include Willow Creek Reservoir, Lake Granby, Shadow Mountain Reservoir, and Grand Lake on the eastern edge of the west portal entrance of the Tunnel. With consultation from Jerry Gibbens, a Project Manager/Water Resources Engineer at Northern Water, it was determined that of these four reservoirs, Grand Lake and Shadow Mountain Reservoir are the two reservoirs to which wildfire events present the greatest immediate threat, due to their direct connectivity to the Tunnel and the increased likelihood that reduced water quality within these reservoirs would be transferred to the eastern slope (personal communication, January 28, 2014). With this consideration in mind, the isolation of treatment work to the C-BT's western slope, and in isolating those watersheds identified by JW Associates as having an adjusted composite hazard ranking above two, the pertinent sixth-level watersheds of concern were identified. The six identified sixth-level watersheds and their composite hazard rankings were identified as the following: Headwaters Colorado River – 5.4, East Inlet – 5.1, North Inlet – 5.0, Onahu Creek-Colorado River – 4.3, Baker Gulch – 4.2, and Lake Granby – 3.5. It was within these six sixth-level watersheds that subsequent fuel treatment considerations and constraints were applied in order to locate regions where the potential for applying fuel treatments was found to be possible (see Figure 1.1).

3.2. Spatial Model

The use of Geographic Information System (GIS) software was applied throughout the course of the research due to its widespread use and aid in spatially integrating "ground truth" data for isolating areas of interest, analyzing landscapes, and generating inputs and outputs for various simulations and modeling software. ESRI ArcGIS software (V.10.1) was used to integrate map layers sourced primarily from state and federal resources to construct the initial project areas. Through communications with the Arapaho-Roosevelt National Forest, additional layers, including project boundaries, vegetation management units, and stand exam polygons were received and applied to the project region (Arapaho-Roosevelt National Forest, 2014). Based on inputs from within the Arapaho National Forest "Forest Management Plan" and existing fuel treatment prescriptions, fuel treatment constraints were mapped across the project areas to isolate feasible fuel treatment regions. Having generated these locations, the vegetation polygon layer was then overlaid onto these areas. From here, those vegetation polygons for which stand exam data was available were then intersected with the feasible fuel treatment regions to isolate a layer of vegetation polygons with stand exam data that could be used in forest vegetation fuel treatment simulations (Figure 3.1). In this manner, both the feasible fuel treatment regions as well as locations of where existing stand data were located for management simulations were determined.

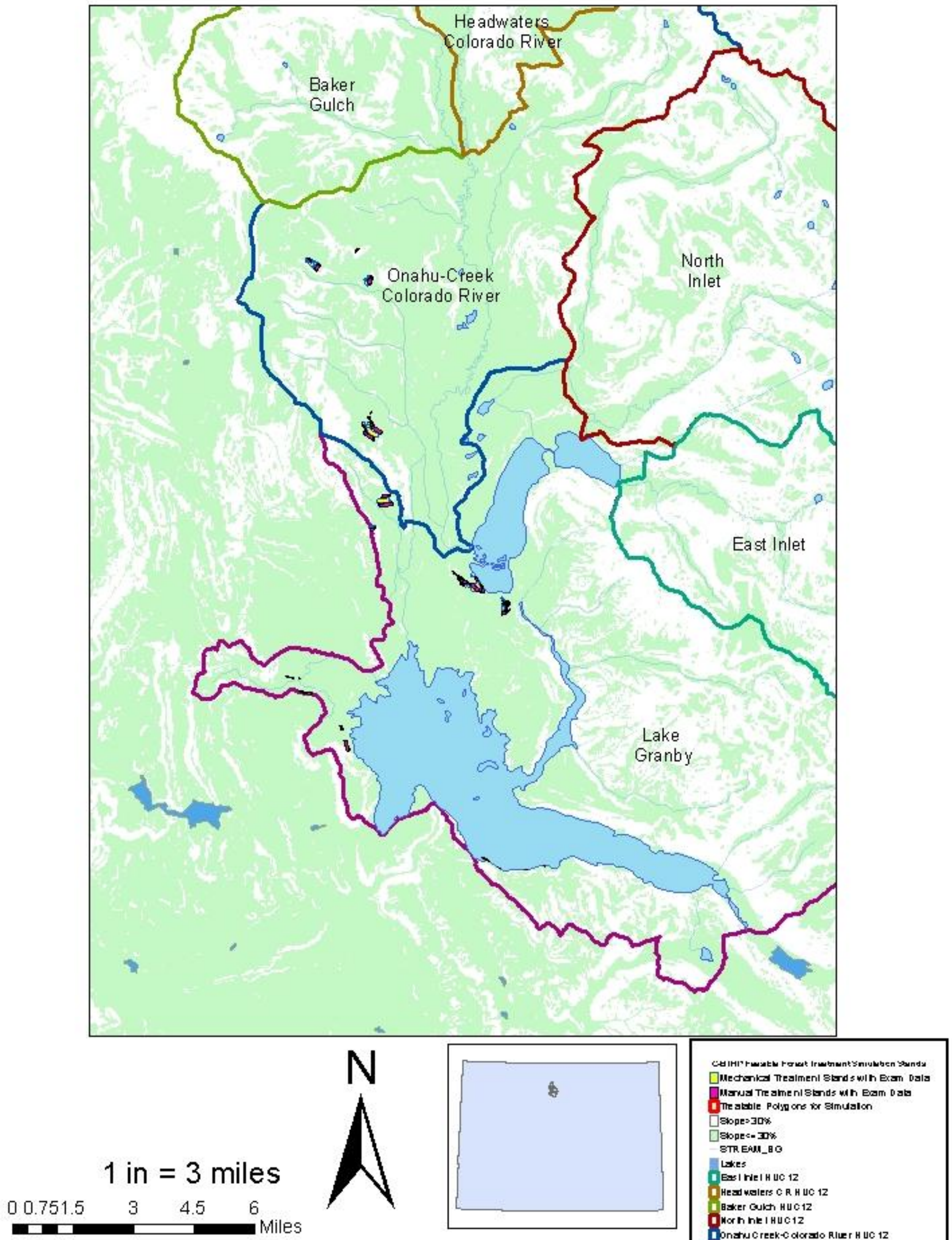

Figure 3.1 C-BTHP Feasible Forest Treatment Simulation Stands

3.3. Variables of Interest

Although there are numerous attributes that can be altered to influence forest, wildfire, and water management needs, a series of forest and landscape attributes were chosen from which existing stand exam data could be compared and future forest management outputs could be generated from across a large landscape. Aspect, Elevation, Precipitation, Slope, Canopy Bulk Density, Canopy Height, Canopy Cover, and Canopy Base Height were chosen as the variables with which to perform such analyses. These variables were chosen, in part, because of their availability as GIS "layers" which inherently means that they contain both attribute characteristics as well as spatial information that can be joined at any chosen location within the United States due to their national coverage. These layers have been used previously and have received endorsement by the U.S. Forest Service to model forest conditions and wildfire output through an ArcGIS software program known as the LANDFIRE Data Access Tool extension. In addition to this software, these attributes reflected characteristics generated through the processing of stand exam data using the FVS-Suppose interface and could be utilized through a variety of other U.S. Forest Service software programs, giving these variables broad applicability.

Initially, these layers were strongly considered for use based on their direct contribution to fire effects analysis and fuel loading modeling for wildfire behavior, before technical challenges with the associated LANDFIRE software made these roles less tangible. Nonetheless, these layers still held substantial information that could be captured and analyzed through other methods.

3.4. Simulations Systems and Extensions: FVS-FFE, FVS-WRENSS, FlamMap

3.4.1. FVS-FFE

Information on the historic and current vegetative characteristics and conditions of forests and rangelands are of high importance to land managers. One of the primary means of assembling this information with regard to forests is through the execution of stand exams. A stand is defined as a spatially referenced polygon in which one or more points are referenced with actual tree data, vegetation composition, ground surface cover and down wood material records (NRIS FSVeg Field Guide/Common Stand Exam, 2014). The means through which this information is compiled and modeled is through the use of the U.S. Forest Service's Forest Vegetation Simulator (FVS) to which there are many extensions and post-processors. One extension, known as the Fire and Fuels Extension (FVS-FFE) is useful in modeling forest growth over time and also allows for alterations to stand conditions to predict future forest outputs. The FVS-FFE is widely used across the Forest Service by personnel of various professions to anticipate and model changing forest conditions (Reinhardt and Crookston, 2003).

3.4.2. FVS-WRENSS

Within the Forest Vegetation Simulator (FVS) are a series of post-processing programs that enable the user to conduct secondary stand analyses once the initial stand management objectives and outputs are conducted. Within this suite of programs is the Water Resources Evaluation of Non-Point Silvicultural Sources (WRENSS) program, which was initially developed by the U.S. Environmental Protection Agency and U.S. Forest Service in 1980 to estimate the hydrologic effects of various forest management practices and treatments on water yield and quality. The FVS-WRENSS program works by applying the stand and vegetative output data from simulated management processes generated through FVS with regional Hydrologic Province and State Climate Normals meteorological station information to predict water yield changes due to silviculture actions. FVS-WRENSS generates annual stand water balance information that integrates regional rain- and snow-dominated characteristics and evapotranspiration (ET) calculations for both pre- and post-treatment water balance values for the designated year of the 10-year treatment cycle. Adjustable inputs within the FVS-WRENSS post-processor generated interface include the meteorological station number, hydrologic province, rainfall lapse rate (in/1000ft), average daily snowfall rate (mm/day), average root depth (ft), snow method[5], and wind speed (km/hr). The outputs include both a detailed and summary report that include pre- and post-treatment information on the effective precipitation, evapotranspiration, water yield flow, basal area, WRENSS cover type, and water yield change (inches) for all stands within the simulation run.

In applying the FVS-WRENSS Post-processor to stand simulations, the "COLORADO.TXT" meteorological file was chosen from which the "075 GRAND LAKE 1 NW" station was selected to provide the appropriate weather information pertinent to the project area. These files were generated using State Climate Normals that originated from meteorological data that was acquired from the National Climatic Data Center (NCDC) (Oklahoma Climatological Survey Climate Information Group, 2006).

[5] 'Snow method' refers to the snow redistribution procedure used in calculating water yield for a particular snow-dominated geographic region or province. Using either the 'Modified Rocky Mountain' procedure (Snow Method=1) or the 'WRENSS Handbook' snow redistribution method (Snow Method=0), evapotranspiration and hydrologic values are calculated using different methods. For processing consistency, the WRENSS Handbook snow redistribution method (Snow Method=0) was applied for all water-yield calculations within the FVS-Suppose interface (USDA Forest Service, n.d.)

3.4.3. FlamMap

FlamMap 5 is a wildland fire behavior modeling program that integrates GIS raster inputs with a variety of modeling systems to calculate the landscape-level fire behavior that was utilized to generate a conditional burn probability map of the region. The program integrates eight base-input themes, along with user-specified criteria, to generate fire behavior and growth models under a constant set of environmental conditions across a landscape. Outputs from these processes include data on flame length, rate of fire spread, the direction of spread, minimum travel time (MTT), conditional burn probabilities, and fuel treatment optimization, among other options (Finney, 2006). This program has successfully been used to provide risk assessment, fuel treatment analysis, and fire behavior data to fire managers across the nation. A landscape (.LCP) file containing the regional elevation, slope, aspect, a Fuel Model 13[6], canopy cover, stand height, canopy base height, and canopy bulk density theme layers across the six watersheds was built using the LANDFIRE Data Access Tool extension for ArcGIS 10.1.

3.5. Forest Stand and Topographic Data

The primary observation forest stand data relevant to the research area was procured by directly contacting the GIS Coordinator with the Arapaho & Roosevelt National Forests (ANF) and represented actual tree stand exam data from within the Sulphur Ranger District. It was within this district that the initial, as well as the extended regional analysis, was conducted. This cross-sectional data included both vegetation data compatible with the FVS Suppose interface as well as Forest/District, Wilderness, and Ownership information for the research area, which was used to isolate the initial treatable stands. The FVS Data was contained in Microsoft Access and

[6] "Fuel Model 13" refers to the 13 original standard fire behavior fuel models that were developed by Hal Anderson in 1982 and represent distinct distributions of fuel loading among surface fuel components, fuel size classes, and fuel type (LANDFIRE, 2014).

other specialized file formats that could be read using the FVS Suppose interface. Through this interface, forest attributes of the "Central Rockies" variant, which was comprised of unique sub models, parameters, and major regional forest type attributes, could be referenced and used by FVS Suppose management and reporting processors to generate existing and forecasted conditional forest stand reports and outcomes as well as anticipated water yields via the WRENSS post-processor. This ANF data set was comprised of three tables representing observational and generated forest information for 1,130 forest stand records, 4,520 forest plot records, and 14,982 tree records, with each record containing a multitude of attributes with corresponding data. In order to isolate pertinent stand data located within the six watersheds from this dataset, a GIS shapefile provided by ANF that corresponded to the ANF FVS dataset was utilized to evaluate stands based on their treatment potential as defined by actual treatment specifications applied within this region. When this evaluation was performed, only 15 stands[7], located within two of the six watersheds, were found to meet these criteria. Acknowledging the limitations of evaluating regional forest changes based on a small sample, additional stands meeting the same criteria that were outside, but adjacent to these watersheds were incorporated. After this selection process, the number of potential records from which data was considered was reduced from 1,130 forest stand records to 47 stand records. This cross-sectional data, along with corresponding regional data acquired via the LANDFIRE Data Access Tool extension for ArcGIS 10.1, was interpreted using a variety of U.S. Forest Service software programs, ArcGIS 10.1 (GIS), GRETL, and STATA software programs and included a variety of variables beyond those directly outlined within the model, yet not available at the regional level. Detailed

[7] A "stand" is defined as a group of forest trees of sufficiently uniform species composition, age, and condition to be considered a homogenous unit for management purposes.

summary statistics of all of the attributes from these 47 stands are shown below in Table 4.1 and Table A.ii.1., respectively.

Table 4.1 Summary statistics for forest characteristics

Variable	N	Mean	Std. Dev.	Min	Max
ASPECT	47	141.4681	108.5331	1	359
ELEVATIONm	47	2824.66	163.9241	2538	3288
PRECIPmm	47	587.8936	124.2305	398	902
SLOPE	47	14	6.877816	1	30
CNPYBULKDNSTY	47	8.255319	3.172354	1	11
CANOPYHEIGHT	47	154.3617	55.43521	1	175
CANOPYCOVER	47	42.87234	16.85439	1	55
CNPYBASEHT	47	8.531915	13.87812	1	100
CNG_WY30m2	47	0.0045567	0.0057791	0.0000361	0.0210052

Additional vegetation and topographic data was acquired by downloading reputably-sourced ArcGIS layers primarily from the United States Department of Agriculture's Natural Resource Conservation Service's Geospatial Data Gateway, the United States Forest Service, and through the LANDFIRE Data Access Tool. Certain ArcGIS layers were selected for integration and manipulation within ArcGIS due to their applicability and relevance to FVS Suppose stand outcomes and their ability to aid in extending such findings across much of the area contained within the "Fishnet" grid area (explained in Section 3.7) to determine changes in water yield.

3.6. Treatment and Prescription Data

Treatment and prescription data was obtained through contact with the GIS Coordinator with the Arapaho & Roosevelt National Forests as well as through direct correspondence and documents received from a Forester on the Sulphur Ranger District (K. McLaughlin, personal correspondence, May 21, 2014). This information, primarily contained within prescription summary documents, expressed both past and current prescription and treatment details within the research area which took into regard the necessary environmental constraints relevant within the treatment stand areas. The repetitive and recurring treatment methods and prescription information were integrated into stand simulations and processed to generate stand and water yield outputs using the management action of "Fuel Treatments-Thin with fuel piled and burned", with a basal area target (residual densities) of 60 $ft.^2$. In addition to these parameters, the largest diameter-breast height (DBH) considered for removal was chosen to be eight inches or less, based on correspondence with the Forest Service. Considering the default 10-year treatment increment setting within FVS-Suppose, the date of collection for the most recent stand exam data, and the feasible time frame for future treatments to take place, a simulation time scale of 2007 to 2057 was chosen with the year 2017 selected as the year in which the stand simulation thinning treatments and the associated outputs for that treatment year would occur. In this manner, the existing stand exam data that was compiled up until 2007 for the selected stands could be processed to provide baseline conditions after which the simulation treatment in 2017 and the subsequent simulation treatments could be compared. The 50 year (2007-2057) time scale was chosen early on in the modeling process with the thinking that, in the event the effects of the treatment in 2017 were still present in the years 2027, 2037, 2047, and/or 2057, they would be reported, which they were not.

3.7. ArcGIS "Fishnet" Feature

In an effort to expand the initial FVS-Suppose water yield results beyond simply those stands to which stand exams had been performed, a technique available through ArcGIS known as creating a "fishnet" was employed in which a grid of rectangular cells of uniform dimension was created to be applied across an area of interest. Considering that the spatial resolution associated with GIS raster and vector data is commonly 30 square-meters, a fishnet grid was created of 30 square-meter cell units (units) within which all data from each of the layers could be contained, resulting in a fishnet of approximately 2.87 million cells. Using this fishnet, the attributes from each of the aforementioned layers of interest could be extracted from their respective layer to a cell with an associated cell identification number. The attributes for each cell identification number were then compiled into spreadsheets for further use in regression analysis. The "fishnet" grid technique has been applied to a variety of natural resource studies including one in which a series of fishnet grids of varying dimensions were overlaid on satellite imagery of a forested region in the southeast peninsula of Greece that experienced a severe wildfire in 2007. In this particular application, surface reflectance ratios were generated for each cell and analyzed to estimate pixel-level surface coverages for burned, unburned, and bare land following the fire (Pleniou and Koutsias, 2013).

3.8. Impacts to Water Quality/Yield

The FVS-Suppose interface was utilized to isolate the 47 stands that were found to be within the parameters for mechanical and manual fuel treatment. Simulated fuel treatment processes were then applied to each of these stands in the form of a "Thin from below" command that was based on the residual densities of stands relative to basal area. Through this application of the FVS-FFE program and the FVS-WRENSS post-processor, both existing water yields and changes in water yield were produced for all processed stands in the 2017 treatment year. Report outputs that conveyed any remaining changes in water yield in 2027, 2037, 2047, and /or 2057 from the treatment that took place in 2017 were generated, although none of the stands expressed any remaining changes in water yield responses to the forest treatment. While no components of water quality were available through this approach, the volumetric water values produced were compiled and utilized to aid in constructing the regression models to help determine the potential benefit in increased water yield from forest treatments within the C-BT region.

3.9. Budget Constrained Optimization

Through the analysis of feasible prescriptive forest fuel treatment regions, burn probability maps, and change in water yield maps, areas with the potential to express mutual benefits from forest fuel treatments can be identified. These areas can then be taken in conjunction with an annual budget to identify those areas that would provide the greatest annual gains from such treatment and allow for immediate and long-term forest treatment planning. The application of an annual budget provides context for the scale to which treatments can be allocated and their impacts generated, given pragmatic regional funding appropriations. Through this approach, the existing need and budget allocation for reducing wildfire risk will be effectively utilized, while simultaneously improving the water availability of the C-BT system, if only to a small degree, with little to no additional financial or logistic implications.

CHAPTER 4: RESULTS

Within this chapter, the methodology and components used in formulating a "base" and "variant" regression model are expressed. These models were constructed using actual stand exam attribute information from the 47 existing forest stands identified as relevant within the research area. An initial "base" regression model was first constructed and analyzed. Once this was performed, improvements to the "base" regression were sought with the process and outcomes of formulating a "variant" regression being discussed below. Establishing the "variant" regression model as more capable of predicting changes in water yield, this model was then exclusively used throughout the remainder of the research to conduct additional analysis as indicated at the regional level.

4.1. Formulation of Model

To address the question of "What is the influence of hazardous forest fuel treatments on changes in water yield?" we begin our assessment using a basic linear regression model based on the general equation below that includes the applicable forest variables as regressors:

$$(4.1)\quad CNG\_WY30m^2{}_i = \beta_0 + \beta_1 Aspect_{Degrees} + \beta_2 Elevation_{m.} + \beta_3 Precipitation_{mm.} + \beta_4 Slope_{\%} + \beta_5 CanopyBulkDensity + \beta_6 CanopyHeight_{m.} + \beta_7 CanopyCover + \beta_8 CanopyBaseHeight_{ft.} + u_i$$

The summary and detailed summary statistics of the individual variables chosen for use within this linear regression model are shown below in Table 4.1 and Tables A.ii.1 and convey a large degree of insightful information about each component and how and why it has relevance within the model. In addition to these outputs, scatter plots were generated for each of the regressors with respect to the dependent variable CNG_WY30m^2 for each of the 47 sample stands and are found in Figures 4.1 through 4.10.

In looking specifically at the change in water yield in Table 4.2, we can see that, on average, each stand saw a change of approximately 0.004557 inches of water per 30 square-meter surface unit given a forest treatment that reduced the basal area per unit to 60 square-feet (BA60), with a stand producing as little as 0.00003613 inches of change in water yield while another produced a change of 0.02101 inches of water per 30 square-meter surface unit. If we convert the changes of water yield to a more common unit, such as an acre, we find that between 0.0001625 and 0.09445 inches of water[8] is yielded when an acre of forest has its basal area reduced to 60 square-feet with the average change being approximately 0.0205 inches per year. To better understand the context in which these sample values were determined, it can be noted that the sample stand exam data involved treating 2,470 acres. The cumulative water yield across this area, prior to any treatment being performed, was found to be 4.22 acre-feet of water yield or an average of 0.1257 inches of water yield per acre. When a BA60 treatment was applied, the collective change in water yields across this area increased by 25.58 inches or 0.01036 inches per acre which converts to 2.1324 acre-feet across the entire 2,470-acre sample stand region. Relative to the base water yield prior to treatment, this change in water yield represents approximately an 8.24% increase in the overall water yield for the sample area. Evaluating this differently, if the average unit change in water yield (0.004557 inches) is considered in acre feet, we find through conversion that one additional acre-foot of water is made available for approximately every 2,633 forest units that receives a BA60 treatment. In terms of

[8] "'inches' of water" refers to the volumetric change in water yield determined by the FVS-WRENSS post-processor. While "'inches' of water" signifies a measure of distance rather than a volume, this is not the case as the author presents the units in this manner for simplicity with the belief that they will be taken in context with the area units ("stand", "acre", "unit") being referenced.

acres, this would convert to an increase of one acre-foot of water for nearly every 586 acres treated. If we consider the range of changes to water yield across the research area (low=0.00003613 inches, high=0.0201), it would take as many as 73,865 acres (332,134 units) or as few as 133 acres (597 units) of BA60 treatment to yield a change of one acre-foot of water. Presented differently, it would take a region approximately one-seventh the size of the gridded research area to produce a change in water yield of one acre-foot given the lowest yields or roughly one-quarter the surface area of Grand Lake given the highest levels of changes in water yield.

Table 4.2 Detailed summary statistics: Change in water yield per 30m² (Inches/unit)

VARIABLE NAME	CNG_WY30m2	
Percentage	Percentiles	Smallest
1%	0.0000361	0.0000361
5%	0.0001484	0.0001272
10%	0.0002526	0.0001484
25%	0.0005473	0.000156
50%	0.0020036	
		Largest
75%	0.0078784	0.0157315
90%	0.0135653	0.0182255
95%	0.0182255	0.00201206
99%	0.0210052	0.0210052
Observations	47	
Mean	0.0045567	
Standard Deviation	0.0057791	

The variable $Aspect_{Degrees}$ is an independent variable that expresses the orientation of a surface face using 360°. It was chosen due to its variability across the landscape, as well as the intuition that it may influence vegetative growth and density, wildfire potential, snowpack accumulation and evapotranspiration rates. In observing its summary statistics, we see that the average topographic surface across the region is oriented at nearly 141^{o}, which is to the southeast. If we consider the associated standard deviation, we can anticipate the majority of surface aspects to be oriented clockwise from the northeast to the southwest throughout the region. Another way of interpreting this information is that, in terms of precipitation, having a surface exposed to more sunlight has the potential to increase the amount of evapotranspiration that may occur on a surface as well as diminish the extent to which snowpack may exist, ceteris paribus. The $Aspect_{Degrees}$ variable, along with the $Slope_{\%}$ and $Elevation_{m.}$ variables, was drawn from digital elevation model data for the region.

The regressor $Elevation_{m.}$ represents the average elevation in meters, at which each unit is situated that, in the context of the research area, has been restrained to between 2,500 (8,300 ft.) and 3,300 meters (10,800 ft.) to reflect the elevation range from which the sample stand data used in the preliminary regression analysis was gathered. To provide some perspective, the area from which this data originates is directly west of the continental divide and at its highest extent, is roughly 700 feet below what is traditionally considered treeline, which is approximately 11,500ft. (Doesken, Pielke, Sr., and Bliss, 2003). The selection of the $Elevation_{m.}$ variable was done because of its regional fluctuations and its influence on vegetative species distributions (Peet, 1978). According to Doesken, Pielke Sr., and Bliss (2003), elevation gains within the mountains of Colorado generally cause a decrease in temperature and increase in precipitation, with modifications to these tendencies occurring due to mountain slope orientations and topographical features relative to prevailing winds and their influence on local air movements. If we interpret this variable with respect to “Changes in Water Yield”, which is expressed in Figure 4.1, we view a scatter plot matrix of the amount of change in water yield relative to the average elevations that were isolated in the dataset. This graph appears to express a horizontal or slightly negative linear trend. Removing outliers that express increases in water yield with elevation increases in Figure 4.2, the adjusted graph appears to express convex curvature due to the concentration of lower water yield in and around 2,900 meters, which gives even less of an indication of an ongoing increase in change in water yield when there is an increase in elevation. Such an observation does not provide as strong a support for elevation's influence on changes in water yield as it appears theory and intuition would suggest, although this lends support to incorporating the additional variables to help explain changes in water yield.

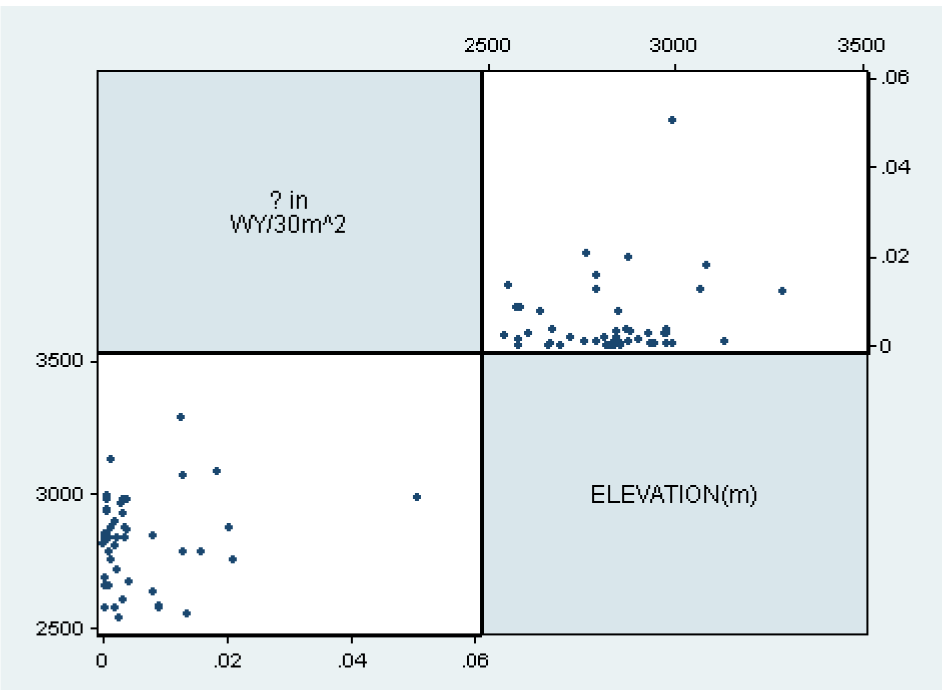

Figure 4.1 Change in Water Yield vs. Elevation

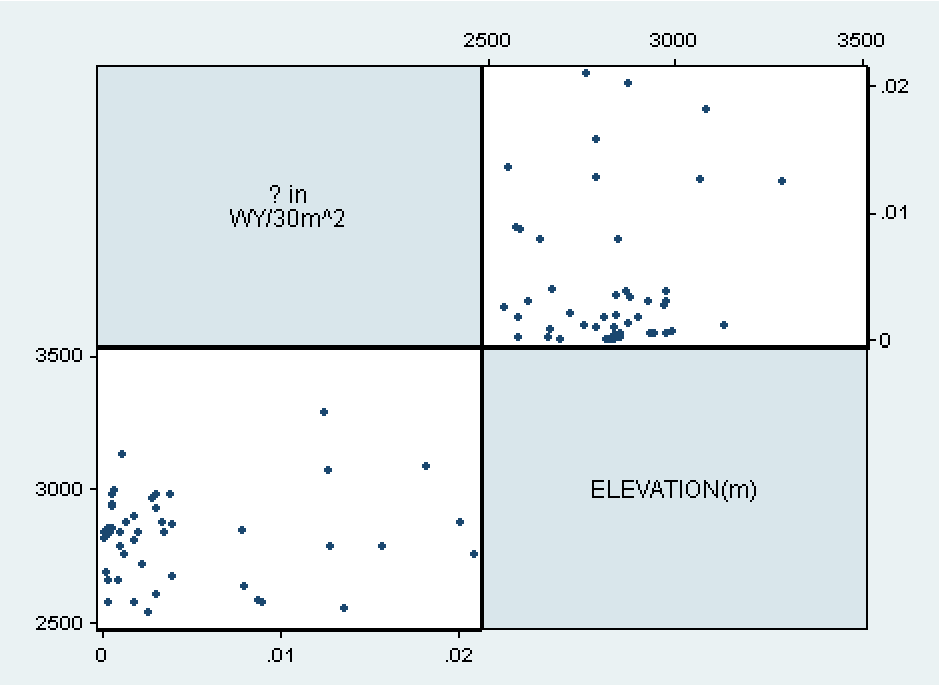

Figure 4.2 Adjusted Change in Water Yield vs. Elevation (Outliers Removed)

The $Precipitation_{mm.}$ independent variable represents annual average 30-Year precipitation normals in millimeters from 1981 through 2010 across the region. Its role in the water cycle and the assumption that the exogenous nature of precipitation and its impact on botanic features has a large influence on the change in water yield form the basis for its inclusion. The summary statistics for this variable express an average annual rate over the 30-year period that was 588mm (23.16 inches) with the standard deviation being approximately 124mm (4.87 inches) and minimum and maximum values of 398mm (15.67 inches) and 902mm (35.51 inches), respectively. These average annual values, as expected based on their elevation alone, express that they tend to be greater than the statewide annual average precipitation of approximately 432 mm (17 inches) (Doesken, Pielke, Sr., and Bliss, 2003).

The $Slope_{\%}$variable expresses a standard deviation of approximately 6.88 percent and dominant slopes between 0 and 30 for each unit. This layer was chosen in light of its role in surface water runoff, tree density, and evapotranspiration. In terms of the 0 to 30 percent slope range values,   in the context of a mountainous region, these are expected to potentially act as a highly restrictive constraint to the amount of area capable of receiving forest fuel treatments as well as the method of labor employed to perform such treatments.

$CanopyBulkDensity$, $CanopyHeight_{m.}$, $CanopyCover$, and $CanopyBaseHeight_{ft.}$ are representative of vegetation characteristics where $CanopyBulkDensity$ expresses the density in kg/m^3 of available canopy fuel in a forest stand (Reeves, Kost, and Ryan, 2006) and had an average density of approximately 8.26 kg/m^3, a standard deviation of roughly 3.17 kg/m^3, and a range of between zero and 11 kg/m^3. It is believed that the $CanopyBulkDensity$ layer may express a considerable change in its density value given a fuel treatment due to the composition of the many other tree and stand attributes that contribute to its value.

For the variable $CanopyHeight_{m.}$, it conveys the average height in meters multiplied by ten (meters*10[9]) to the top of the vegetated canopy (LANDFIRE, 2014b) and was found to have an average value of approximately 15.4 meters with a standard deviation of about 5.5 meters and a range of between 0.1 and 17.5 meters. This variable was considered due to its use as an input to many forest vegetation simulation processors as well as its likely relevance in terms of forest characteristics associated with canopy height.

The $CanopyCover$ independent variable explains the percentage of the forest floor that was covered by the vertical projection of the tree It was included as an independent variable due to its generalized application, which may or may not be altered by a fuel treatment, depending on the tree species. The influence of such a regressor intuitively does not seem substantial with regard to changes in water yield, although there could be an inconspicuous degree of influence

[9] The multiplication of the average height in meters by 10 is a specification set by the developers of the LANDFIRE Data Access Tool extension. No explanation for this specification was available.

that corresponds to its influence on evapotranspiration rates, wildfire probability, or other notable forest characteristics. Across the region, $CanopyCover$ was found to cover on average about 43% of the forest floor, with some stands expressing no canopy cover (adjusted to one (1) for calculation purposes) while others had 55% forest floor coverage. There was a relatively wide spread within this range as the standard deviation was found to be nearly 17% canopy cover. In general terms, these statistics give the sense that the forest stands may not have been as densely packed as described or may have had trees with narrow canopies.

The $CanopyBaseHeight_{ft.}$ states the average height from the ground to the forest stand's canopy bottom in feet (LANDFIRE, 2014b.) and is believed to have a relatively large influence on changes to water yield due to its correlation with changes to the basal area of a stand and association with ladder fuels and vertical fuel continuity relative to fire propagation (Colorado State Forest Service, 2012 pg. 3). In looking at the summary statistics, we see that the average canopy base height was approximately eight feet, with a range of between zero (adjusted to one (1) for calculation purposes) and 100 feet, and a standard deviation of nearly 14 feet.

Basal area, which is the cross sectional area in square-feet of a tree stem that includes the bark and is measured at breast height (4.5 feet (1.37 meters) above the ground) (USDA Forest Service, 2013[2]), serves as the primary measure against which hazardous forest fuel treatments are applied. While tree stand "basal area" would have been an ideal independent variable and was available from each of the sample tree stand exams performed, this information was not provided in a manner that was conducive to thorough understanding and application within this research, nor was there a "basal area" layer that covered the entire study area that was available for integration into the analysis. Nonetheless, understanding this attribute as a measure of forest treatments helps to provide an understanding of how and to what extent forest treatments are performed. The variable u_i in the model is the error term that is assumed to be normally distributed.

Given the empirical findings for the effects of elevation in Colorado, along with the range of values it expresses across the region, it was presumed that elevation could exert a disproportionate amount of influence on changes in water yield across the study area. With this consideration in mind, a univariate linear regression model between the dependent CNG_WY30m^2 variable and the independent $Elevation_{m.}$ variable was performed with the results located in Table A.ii.3.. Prior to performing this though, the regression was considered to see if it would meet the Ordinary Least Squares assumptions that the conditional distribution of the error term has a mean of zero, that large outliers are relatively rare, and that due to the unidentifiable attributes of the sample data, that the dependent and independent variables are independently and identically distributed. In evaluating these criteria, it was seen in viewing Figure 4.1 and in analyzing the data that there appeared to be only one stand that had a change in water yield well beyond those of other samples. In light of this, that sample was excluded from the change in water yield value since this outlier could cause the regression line to bias the relationship between increases in elevation and increases in the change in water yield. As seen in Figure 4.2, the removal of this outlier provides a scatter plot graph with data that appears to fit better around the mean values at each elevation. With the Ordinary Least Squares assumptions met, a linear regression was performed with the dependent CNG_WY30m^2[10] variable and our independent $Elevation_{m.}$ variable selecting for "robust" standard errors, which was applied throughout the research to account for heteroskedasticity and potential OLS standard error bias.

[10] Unless otherwise indicated, all references to forest fuel treatments are with regard to a "BA60" treatment level, which is a reduction in a unit's basal area down to 60 square-feet.

The results of the regression express that, based on the R^2 value (0.0043), the $Elevation_{m.}$ regressor provides relatively low explanatory power for how much change in water yield occurs as a function of elevation. In analyzing the t-statistic, we find that it is less than the 5% critical value (|0.42|<1.96) and implies that we must fail to reject the null hypothesis that our $Elevation_{m.}$ regressor is equal to zero. If we look at the correlation coefficient values in Table 4.3, we see that the linear relationship strictly between CNG_WY30m^2 and $Elevation_{m.}$ is positive with a correlation coefficient of 0.0653. Having discussed each of the regressors in terms of their value, likely contribution to the model, and relevance with regard to the dependent variable CNG_WY30m^2, the basic linear regression model was applied to the 47 sample stands.

4.2. Empirical Results

4.2.1. Base Regression

To see to what extent a combination of all of the eight regressors influence a change in water yield, the multiple linear regression model was run selecting for "robust" standard errors with the data for the base regression shown below in Table 4.3. The correlation coefficient values in Table 4.3 were again referenced in order to evaluate whether or not multicollinearity was present between the independent and dependent variables. In evaluating the results of this table, we note that the correlation value between $CanopyCover$ and $CanopyHeight_{m.}$ (0.8892) is the greatest amongst all the variables, expressing that they have a high degree of correlation. $Precipitation_{mm.}$ and $Elevation_{m.}$ (0.7546), $CanopyCover$ and $CanopyBulkDensity$ (0.6503), and $CanopyHeight_{m.}$and $CanopyBulkDensity$ (0.5070) also show an appreciable amount of correlation. The correlations found amongst these latter variables are intuitively sensible as changes within these variables, such as from a forest fuel treatment, tend to cause an appreciable degree of change to the corresponding variable, hence the high correlation value. Correlation seen between the variables $Precipitation_{mm.}$ and $Elevation_{m}$ of 0.7546 seems justified due to the tendency for there to be increased levels of precipitation as elevation increases as indicated by Doesken, Pielke, Sr., and Bliss. These findings express that multicollinearity is present within the model. Acknowledging this, considerations to mediate multicollinearity, such as dropping variables, obtaining more data, or transforming variables were considered, with regressions omitting variables with high correlation coefficients.

Table 4.3 Correlation coefficient table

Variable	ASPECT	ELEVATIONm	PRECIPmm	SLOPE	CNPYBULKDNSTY	CANOPYHEIGHT	CANOPYCOVER	CNPYBASEHT	CNG_WY30m2
ASPECT	1.0000								
ELEVATIONm	0.1677	1.0000							
PRECIPmm	0.2518	0.7546	1.0000						
SLOPE	0.1657	0.0712	0.0822	1.0000					
CNPYBULKDNSTY	0.0139	0.2778	0.2324	0.2182	1.0000				
CANOPYHEIGHT	0.0171	0.2507	0.0735	0.0553	0.5070	1.0000			
CANOPYCOVER	0.1489	0.1571	-0.0076	0.1294	0.6503	0.8892	1.0000		
CNPYBASEHT	-0.0580	-0.0450	-0.1072	0.0303	-0.2555	0.2064	0.2457	1.0000	
CNG_WY30m2	-0.1846	0.0653	-0.0209	-0.0085	0.2171	0.1426	0.2230	-0.0655	1.0000

Table 4.4 Results of the base and variant regression models applying unit-level forest attributes

	Base	*Variant*
Dependent Variable	**CNG_WY30m2**	**CNG_WY30m2**
ASPECT	-1.23898E-05 *	
	(0.00000730253)	
ELEVATIONm	4.94872E-05	5.38193E-04 **
	(0.00000790074)	(0.000209669)
PRECIPmm	-1.44332E-06	
	(0.0000106466)	
SLOPE	-1.48825E-05	
	(0.000125179)	
CNPYBULKDNSTY	-1.59575E-04	
	(0.00036536)	
CANOPYHEIGHT	-4.20040E-05 *	
	(0.0000224623)	
CANOPYCOVER	2.31073E-04 **	2.51925E-04 *
	(0.0000857841)	(0.000133352)
CNPYBASEHT	-7.50508E-05 **	-4.90050E-05 ***
	(0.0000324546)	(0.0000176415)
SpecialASPECT		2.43371E-05
		(0.0000152793)
sqrtELEVATION		-5.73763E-02 **
		(0.0224284)
LnCNPYCVR		-2.17656E-03
		(0.00161452)
Intercept	-0.00807728	1.52757 **
	(0.0186384)	(0.599366)
N	47	47
R^2	0.138538	0.210752
adj. R^2	-0.42822	0.092365
F-statistic	2.619142	5.221992
Robust standard errors in parentheses		*p<0.10, **p<0.05,***p<0.01

In assessing the "goodness-of-fit" results of this multiple linear regression model, the R^2 value is 0.1385 while the F-statistic is 2.619142 and the regression P-value is 0.021754. The root mean square error of the regression is found to be 0.005901 which relates the spread of the distribution of CNG_WY30m^2 around the regression line. Interpreting the t-statistics and p-values, we find that four of the eight independent regressors ($Aspect_{Degrees}$, $CanopyHeight_{m.}$, $CanopyCover$ and $CanopyBaseHeight_{ft.}$) are statistically significant at the 10% significance level while two ($CanopyCover$ and $CanopyBaseHeight_{ft.}$) are greater than the critical level values at the 5% significance level for a two-tailed test and we can therefore reject the null hypothesis that their coefficients are equal to zero at those levels. For $Aspect_{Degrees}$, we find that the absolute value of the t-statistic is |-1.6966|>1.64 and has a p-value of 0.09794, which provides that we can reject the null hypothesis that the coefficient is equal to zero at the 10% level. The $CanopyHeight_{ft.}$ coefficient is found to be statistically different from zero at the 10% level. This finding could be warranted on the basis that as a tree's height increases, the impact of applying a fuel treatment to the tree has less relative influence than if the tree received a treatment at a shorter height and therefore, more water may be intercepted by the tree and transported via evaporation/transpiration away from the landscape, thus resulting in a decreased change in water yield, ceteris paribus. The $CanopyCover$ variable is found to be statistically significant for the 5% critical level (|2.694|>1.96) and has a p-value of 0.0105 indicating that we can reject the null hypothesis at the 5% level that the coefficient is equal to zero. The $CanopyCover$ coefficient expresses that, ceteris paribus, for every percent decrease in canopy cover we get a 0.00003348 decrease in water yield, which implies that treating a parcel that has a lower initial canopy cover will result in lower changes in water yield than a parcel that is treated with an initially higher canopy cover. Additionally, the measured canopy cover values found within these stands aligned with similar values determined along the Front Range (Gensuo, et. al. 2006). For $CanopyBaseHeight_{ft.}$, we find that the t-statistic is greater than the 5% critical value (|-2.3125|>1.96) and has a p-value of 0.02626, which allows us to reject the null hypothesis that the coefficient is equal to zero at the 5% level. The 95% confidence interval for $CanopyBaseHeight_{m.}$ explains that, with 95% confidence, we would expect to find the regressor value between the values of -0.0001408 and -0.000009350. The $CanopyBaseHeight_{m.}$ regressor conveys that treating a stand with a higher canopy base height of one meter would result in a decrease in the expected change in water yield of 0.00007505, ceteris paribus. This finding aligns with intuition, since given a treatment of a stand with a higher base height, we would expect a lower yield than from a treated stand with an initially lower base height. Although none of the remaining regressors have t-statistics that were found to be significant at the 10%, we are able to see in Table 4.3 that seven of the nine coefficients, including the intercept term, would have a negative relationship with changes to water yield. With regard to $Elevation_{m}$, for whose influence on change in water yield it was thought to be substantial, we find it to not be significantly different from zero.

4.2.2. Variant Regression

While the original regression model serves to facilitate some understanding of the relationship between changes in water yield and the forest attributes, it is likely that the relationship between these variables is much more dynamic and therefore can be better expressed through the application of a linear regression model that uses a differentiated functional form. One method of determining whether a regression model should include variables that have non-linear functional forms is by applying intuition as well as academic acumen to make pragmatic adjustments to variables. Another method of assessing the likelihood that a linear regression model with an altered functional form can better explain the relationship between the dependent and independent variables is by evaluating their graphical relationship, as in Figures 4.3 through 4.10 which express scatter plots of the changes in water yield against each of the independent variables, to see if a particular regression function captures a better fit of the data than another. Interpreting these graphs involves the consideration of whether the data expresses a linear trend, suggesting a linear relationship, or if there appears to be some curvature in the data, which would suggest a nonlinear relationship may exist between a dependent and independent variable. If it appears that a nonlinear relationship may exist, then polynomial or logarithmic functions may be applied to variables to improve the fit of the data. This same approach can be performed when applying instinct or research-based knowledge to variables. To make this appraisal for each potential model component, logarithmic and polynomial variants using the base data were generated for each of the variables to assess their fit to the data and influence on the overall regression, with the findings discussed below.

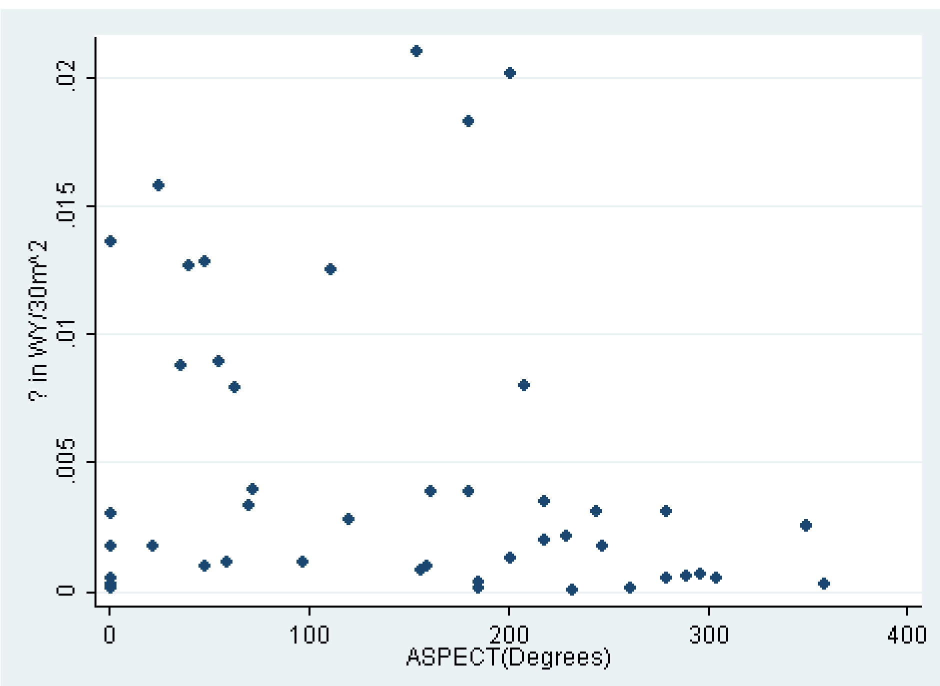

Figure 4.3 WY30m2 vs. ASPECT(Degrees)

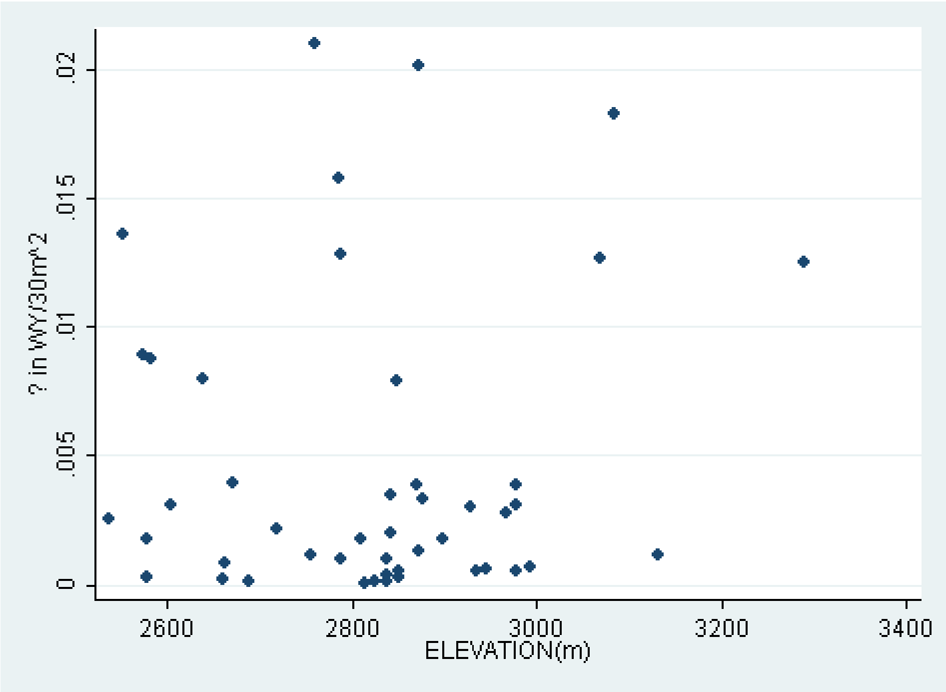

Figure 4.4 WY30m2 vs. Elevation(m)

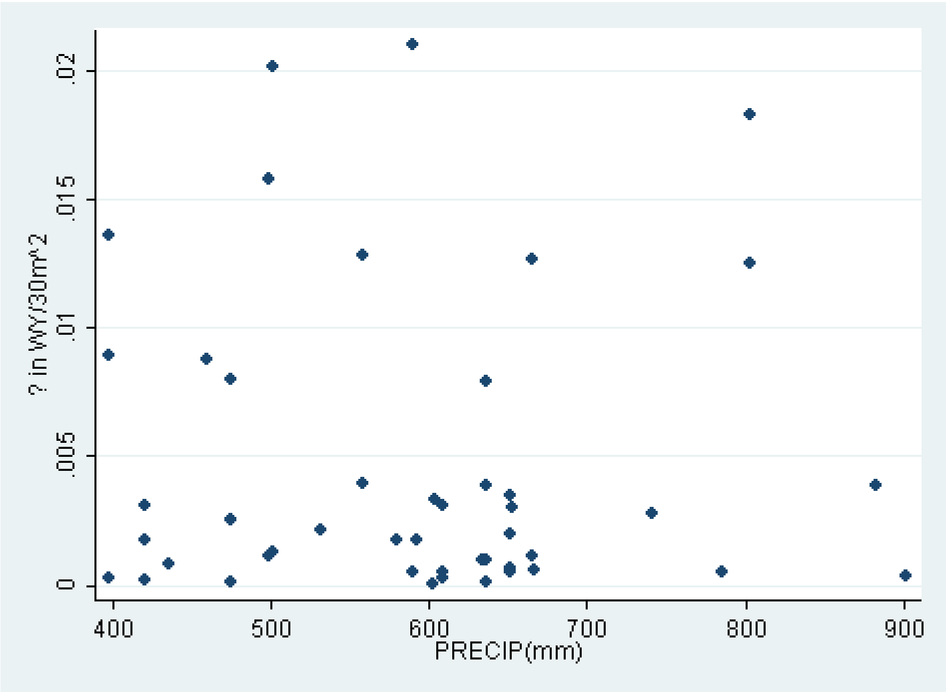

Figure 4.5 WY30m2 vs. Precipitation(mm)

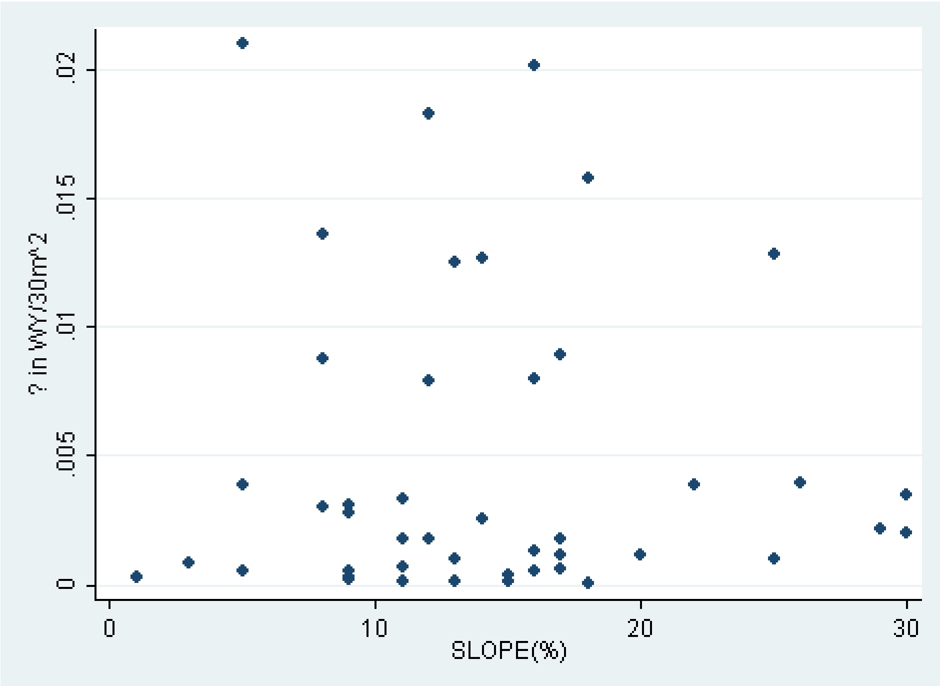

Figure 4.6 WY30m2 vs. Slope(%)

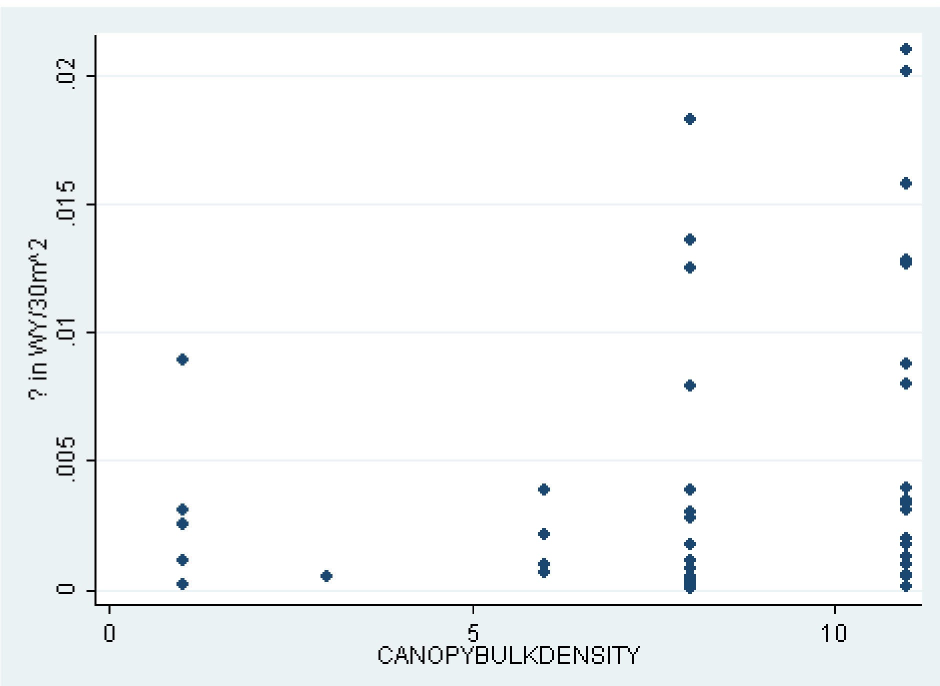

Figure 4.7 WY30m2 vs. Canopy Bulk Density

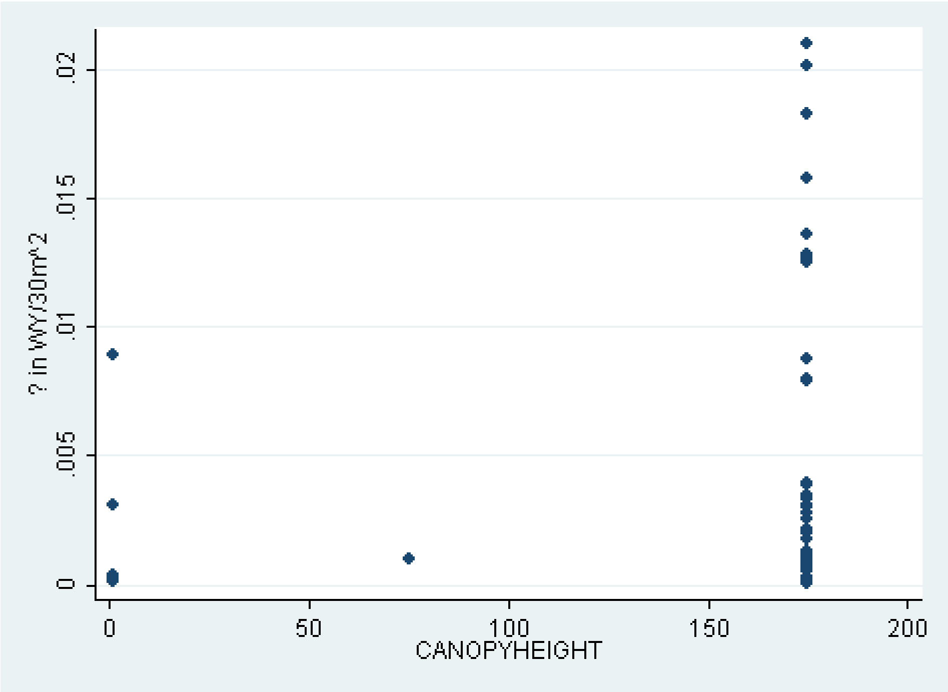

Figure 4.8 WY30m2 vs. Canopy Height(ft.)

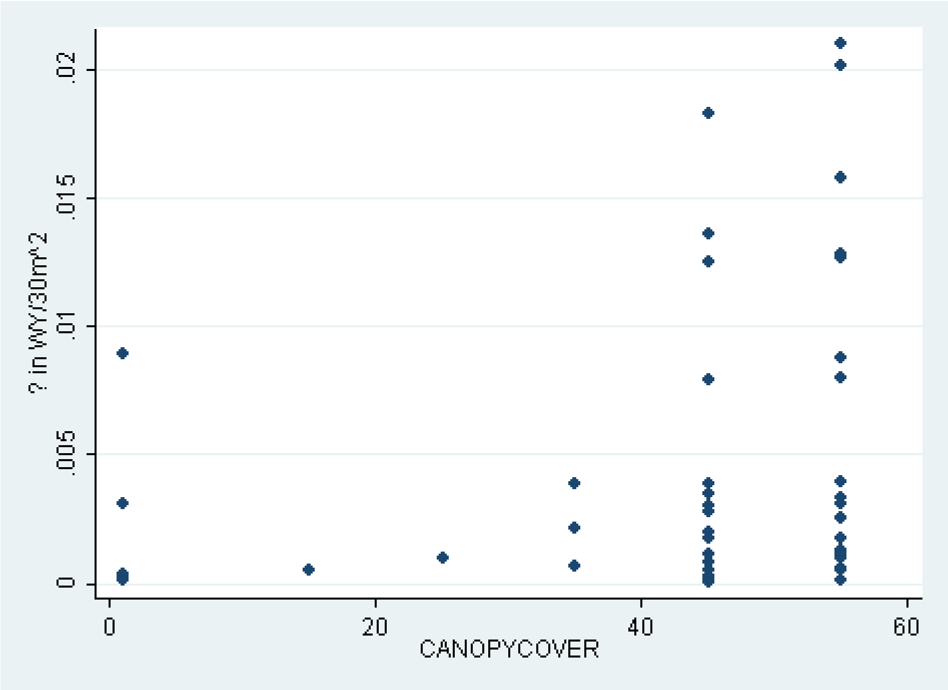

Figure 4.9 WY30m2 vs. Canopy Cover

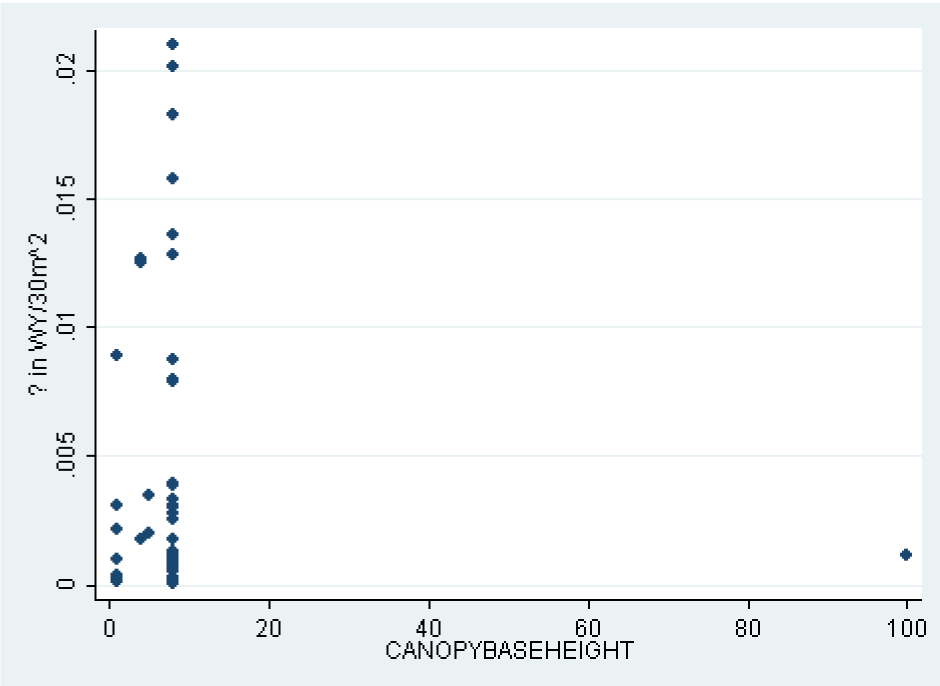

Figure 4.10 WY30m2 vs. Canopy Base Height (ft)

Across the dependent and independent variables, intuition and prior research directed the application of various functional forms to create new quadratic variable values from the base data. Additionally, exponential and logarithmic functions were generated to reflect percentage changes amongst variables. These values, along with the base data, were compiled within a spreadsheet and utilized via STATA and GRETL to assess their ability to improve the existing regression model. The result of this assessment is provided in the following multiple linear regression model with the associated statistical results located in Table 4.4:

$$(4.2)\ CNG\_WY30m^2{}_i = \beta_0 + \beta_1 SpecialAspect + \beta_2 Elevation_{m.} + \beta_3 sqrtElevation + \beta_4 CanopyCover + Ln\beta_5 CanopyCover + \beta_6 CanopyBaseHeight_{ft.} + u_i$$

where all variables represent those characteristics first expressed in the basic linear regression model with the following exceptions. $SpecialAspect$ represents $Aspect_{Degrees}$, but in a manner that resolves the apparent over-valuation of orientations that were beyond 180° by expressing all those values between 180° to 360° as inverse positive values between 0° and 180°. In this way, all $Aspect_{Degrees}$ values fall within the pragmatic influential range such that, for example, a 345° aspect no longer has more model influence than the assumed 180°, and instead now shares the same influence and value as its counterpart of 15°. The variable $sqrtElevation$ was generated and applied as it was thought it could help explain some of the curvature found when change in water yield was graphed against elevation. The $LnCanopyCover$ variable was applied as canopy cover is expressed as a continuous value as it is often a product of various combinations of tree and forest characteristics. By applying the logarithm to this variable, it is now being assessed within the model as the impact on changes in water yield given a percentage change in the overall canopy cover percentage.

The results from applying this regression model are located in Table 4.4 and express improvements to the base regression. Comparing the results, we see that the R^2 value conveys improved model prediction with values adjusting from 0.1385 to 0.2108 between the base and variant regression. We find that when accounting for degrees of freedom from the regressors involved, the adjusted R-squared values have improved from -0.04282 to 0.09237, despite decreasing the number of regressors thus indicating model improvement. In comparing the standard error of the regression values, we also see that the precision of the model has improved from 0.005901 to 0.005506, expressing a decrease in the standard deviation of the estimates from the regression line. The F-statistic, which was 2.6191 and above the 10% critical value (2.30) for the base regression, improved to 5.2220 and above the 1% critical value (4.61) for the variant regression and allowed us to reject the null hypothesis that all of the coefficients in the variant regression are equal to zero at the 1% critical level. While the base regression had four of eight regressors express statistical significance (two above the 10% critical value and two above the

5% critical value for the two-tailed test), the variant regression has four of six regressors expressing statistical significance (one above the 10% critical level, three (including the intercept term) above the 5% critical level, and one above the 1% critical level for a two-tailed test). This statistical significance is also expressed through the decrease in individual regressor p-values (with the exception of $CanopyCover$) conveying that the regressors serve as meaningful additions to the model whose changes are reflected in changes to the dependent variable.

Between the two regressions, the direction of influence adjusted from six of the eight regressor coefficients having negative influence on the dependent variable in the base regression, to only three of the six regressors expressing this effect within the variant regression model. Exploring this further, in the base regression, the $Aspect_{Degrees}$ variable seemed objective to the environment, and therefore the coefficient sign did not seem to necessarily represent an understood effect on water yield. The $Elevation_{m.}$ and $CanopyBulkDensity$ coefficients did have signs that corresponded with expected effects on change in water yield, given independent changes to their values, ceteris paribus. This yielded three coefficients whose rationale for influence on changes to water yield was either inconclusive or contrary to expectations given previous research and/or intuition. The variables $Elevation_{m.}$, $CanopyCover$, and $CanopyBaseHeight_{ft.}$, were included in both regression equations and expressed changes in their values that supported the direction of change seen between the base and variant sample regressions.

4.2.3 Regression Grid Application

The findings from both of these regression models as they pertain to the sample stand data, have served to help explain the predictive capabilities of the available attributes on changes in water yield. Having assessed and improved upon these models, they were then applied on a significantly larger scale to these same attributes as they were found to exist across the research region. As aforementioned, a grid composed of 30-square meter "units" was draped over the research area across which individual layers representing each of the attributes were applied and the discrete or dominant value was identified and associated with the corresponding unit to generate eight unique attributes for nearly 2.87 million units. The overall results from applying the base and the variant regression models are discussed below and are located within Table 4.5 and correspond to Figures 4.11 and 4.12. Due to the scale and complexity of this attribute gridding approach, these resulting values represent a rectangular research region that encompasses all six sixth-level watersheds as well as adjacent lands. They represent a "first-cut" at applying the regression models and assessing the implications of modeling potential changes in water yield across a regional landscape.

Table 4.5 Base and variant regression grid summary statistics

BASE REGRESSION ATTRIBUTES AND SUMMARY STATISTICS															
OBJECTID	**Y**	**ASPECT(Degrees)**	**-1.23898E-05**			**ELEVATION(Meters)**	**4.94872E-06**			**PRECIP(mm)**	**-1.44332E-06**	**SLOPE**	**-1.48825E-05**		
TOTAL	**4335.990931**	213834300	-2649.36421			4839491732	23949.28952			1132861793	-1635.082083	26930132	-400.7876895	CONTINUED	
AVERAGE	**0.002666007**	127.6344793	-0.001581366			2914.470494	0.014422898			689.0015402	-0.00099445	16.12175198	-0.000239932	BELOW	
COUNT	**1668662**	1668662	1668662			1668662	1668662			1668662	1668662	1668662	1668662		
VARIANT REGRESSION ATTRIBUTES AND SUMMARY STATISTICS															
OBJECTID	**Y**	**ASPECT(Degrees)**	**-1.23898E-05**	**SpecialASPECT**	**2.43371E-05**	**ELEVATION(Meters)**	**0.000538193**	**sqrtELEVATION**	**-0.0573763**	**PRECIP(mm)**	**-1.44332E-06**	**SLOPE**	**-1.48825E-05**		
TOTAL	**4317.926473**	213834300	-2649.36421	107730876	2621.857102	4839491732	2604580.574	89792335.32	-5151951.969	1132861793	-1635.082083	26930132	-400.7876895	CONTINUED	
AVERAGE	**0.00263712**	127.6344793	-0.001581366	63.72536091	0.00155089	2914.470494	1.568547618	53.94345868	-3.095076068	689.0015402	-0.00099445	16.12175198	-0.000239932	BELOW	
COUNT	**1668661**	1668662	1668662	1668661	1668661	1668662	1668662	1668661	1668661	1668662	1668662	1668662	1668662		
		CNPYBULKD	**-0.000159575**	**CNPYHT**	**-0.000042004**	**CNPYCVR**	**0.000231073**				**CNPYBASEHT**	**-7.50508E-05**	**CONSTANT**	**-0.00807728**	**R^2=0.138538**
TOTAL		12108344	-1932.188994	984250	-41.342437	2633345	608.4949292				1129607	-84.77790904		-13478.2502	
AVERAGE		7.299621508	-0.001164837	0.564156817	-2.36968E-05	1.620705499	0.000374501				0.663972453	-4.98317E-05		-0.00807728	
COUNT		1668662	1668662	1668662	1668662	1668662	1668662				1668662	1668662		1668662	
		CNPYBULKD	**-0.000159575**	**CNPYHT**	**-0.000042004**	**CNPYCVR**	**0.000251925**	**SpecialCNPYCVR**	**LnCNPYCVR**	**-0.00217656**	**CNPYBASEHT**	**-0.000049005**	**CONSTANT**	**1.52757**	**R^2=0.210752**
TOTAL		12108344	-1932.188994	984250	-41.342437	2633345	663.4054391	4232812	247452.6724	-538.5955887	1129607	-55.35639104		2548998.011	
AVERAGE		7.299621508	-0.001164837	0.564156817	-2.36968E-05	1.620705499	0.000408296	2.57817826	0.152140489	-0.000331143	0.663972453	-3.2538E-05		1.52757	
COUNT		1668662	1668662	1668662	1668662	1668662	1668662	1668661	1668661	1668661	1668662	1668662		1668662	

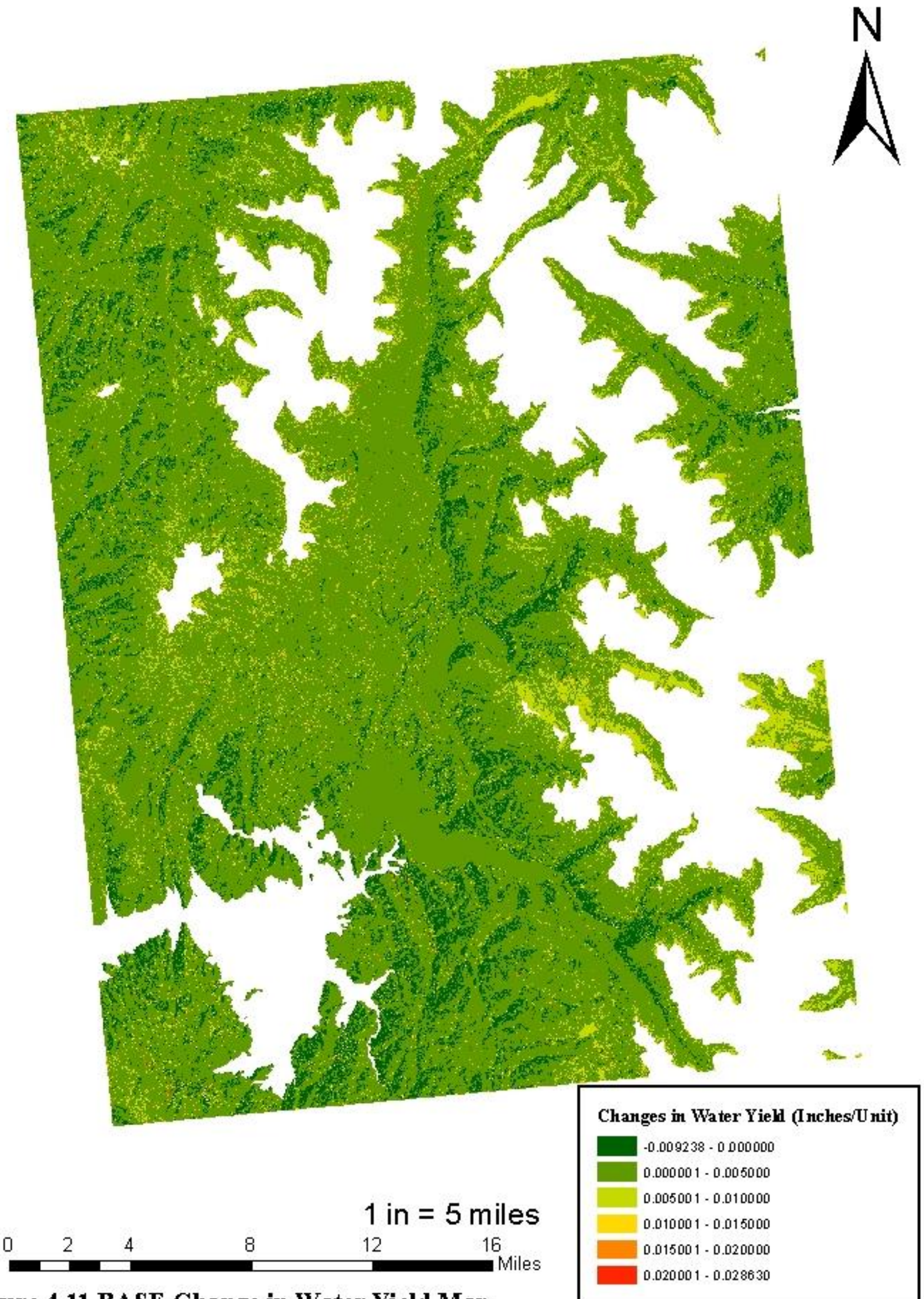

Figure 4.11 BASE Change in Water Yield Map

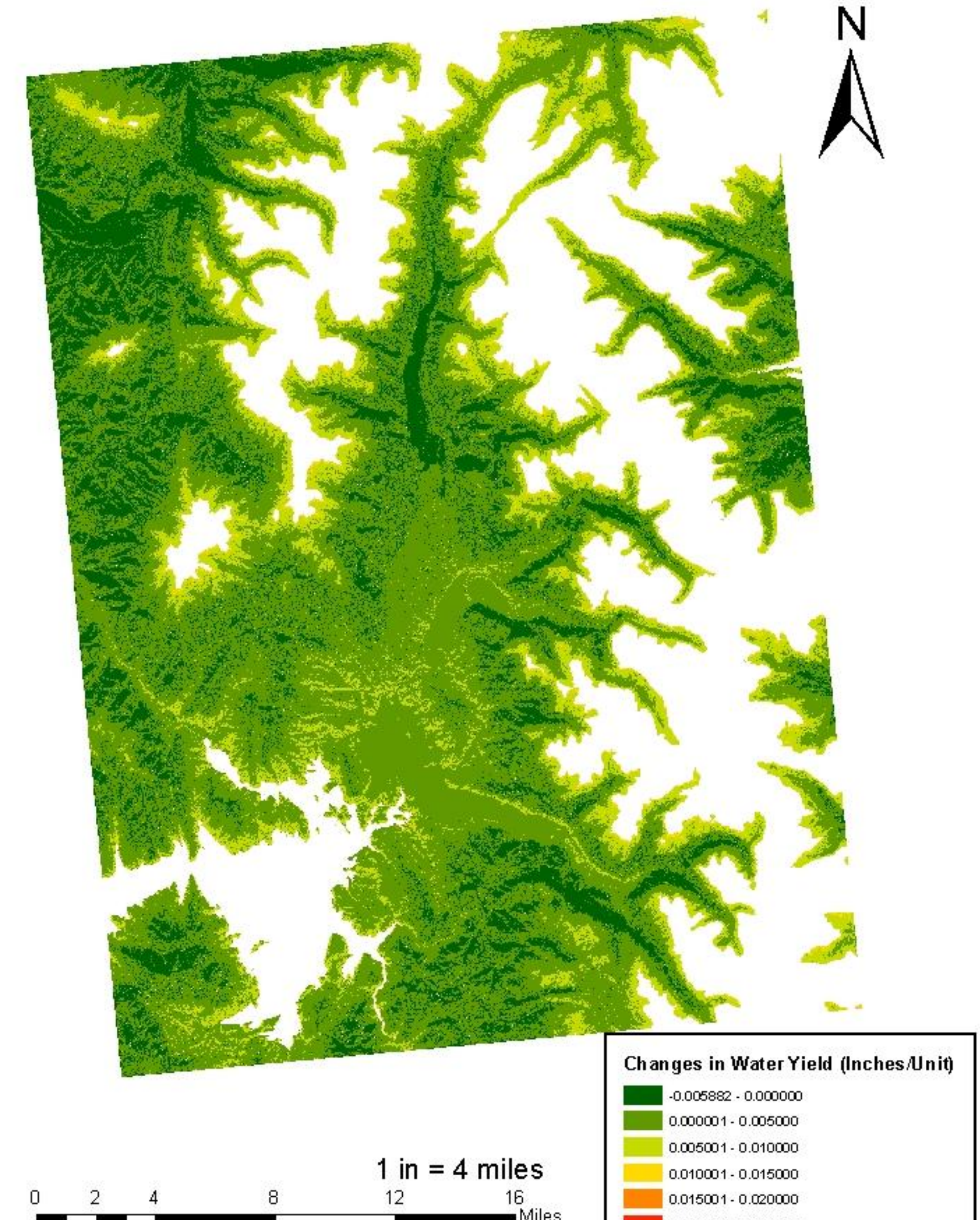

Figure 4.12 VARIANT Change in Water Yield Map

In applying the base regression that utilized all eight attributes in their basic form, it was determined that across approximately 1.67 million units[11] (638,000 acres), if forest fuel treatments that reduced unit characteristics to a basal area of 60 square-feet per unit were applied to the entire landscape, this action would result in changes in water yield of nearly 4,336 inches, or 361 acre-feet across the area, with an average change in water yield of approximately 0.002598 inches. The minimum change in water yield was found to be a unit producing 0.025073 less water in light of a treatment being performed whereas the maximum positive change in water yield a unit produced was 0.02863 inches. If we once again look at these values in a different light, we find that an acre-foot of water would be produced due to the average change in water yield for nearly every 4,619 units or 1,027 acres treated. In assessing all of the attributes isolated for each of the 1.67 million units, while there is no direct explanation, many of the regional observations (Table A.ii.3) appear to express a limited range of integer values, including zero values, which likely serve as a default or null measurement of those variables.

When the variant regression coefficients were applied to their respective attributes, it was determined that the change in water yield for the entire grid area diminished by less than one percent (-0.42%) from 4,336 to 4,318 inches (relative to the base model) despite there being a slight increase (0.38%) in the average change in water yield to 0.002588 annually. Such findings could be the result of there being a number of large outlying changes in water yield generated using the variant regression that influence the overall average, but there being a collective reduction in changes to water yield relative to the base regression that resulted in there being a diminished overall water yield for the variant regression. The minimum change in water yield remained as a decrease in water yield of 0.008654 inches per unit, while the maximum change in

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[11] The overall number of grid units generated was approximately 2.87 million. This value was restricted to the 1.67 million unit value indicated through the application of an elevation restriction between 2,500 (8,200 ft) and 3,300 meters (10,800 feet), which reflects the elevation range within which the sample data was found to exist.

water yield on a unit was relatively larger at 0.291091 inches. Solving for acre-feet, we were able to determine that nearly 4,637 units or 1,032 acres would need to be treated in order to expect a change in water yield equivalent to one acre foot. Conversely, the potential increase in water yield across the region under the base regression has the capacity to produce 80.34 additional acre-feet of water while the variant regression predicts that 80.03 acre-feet of water could be produced. Overall, the variant regression indicated that changes in water yield would be less than expected through the application of the base regression.

4.3. Treatment Costs

Performing forest fuel treatments begins with a considerable amount of preparatory efforts in order to assess the feasibility of performing fuel treatments and then working with internal resources and contractors to ensure that treatments are performed adequately and within all regulatory boundaries. All of these efforts result in the costs that are ultimately associated with performing forest fuel treatments. In the case of the research area, such considerations have in the past been formally acknowledged in the *Arapaho National Recreation Area Forest Health Project* plan (USDA Forest Service, 2004) which outlines a number of issues and proposed resolutions as well as within the forests' *Schedule of Proposed Actions* (SOPA) (USDA Forest Service, 2014) which are published quarterly. With the acknowledgement of such issues, a variety of planning efforts ensue that, in the case of federal lands, treatments follow items such as the National Environmental Policy Act (NEPA) guidelines to ensure environmental impacts are properly considered and appropriate actions and alternatives are proposed and public scoping and review processes are performed (United States Environmental Protection Agency, 2014).

According to Forest Service personnel, the process to fully conduct NEPA assessments for forest fuel treatments tends to take between one and two years to conduct, depending on the complexity and scale of the area being assessed . The costs to perform these and other procedures (administrative, preparatory, stand exam, and prescription), including annual accounting for items such as fuel costs, cost-of-living, and market timber value, are all factored into the final price that the Forest Service is willing to pay for the treatments to be performed (P.Motley, personal communication, April 25, 2014). As is often the case, the Forest Service executes fuel treatments by preparing fuel treatment contracts with set prices to be paid per acre that independent contractors then bid on, much like would be done for a forest timber sale. Despite the fact that some forest fuel treatments are conducted by Forest Service crews and personnel, the scale and consistency of such activities do not substantiate their consideration relative to treatments performed by independent contractors.

While often discussed, access to documents conveying forest fuel treatment costs and accounting records were not found to be available, either via the Forest Service nor independent contractors. Through a number of interviews with Forest Service personnel and an independent contractor, a range of costs for forest fuel treatment components were compiled and are provided below in Table 4.6. Preparatory costs, barring undisclosed personnel fees, were conveyed to be approximately $30 per acre for contract preparation and $60 per acre for each stand[12] exam. For actual treatment costs, the price the Forest Service would pay for manual treatments were mentioned to be between $300 and $600 per acre, while for mechanical treatments, $600 to $800 were often indicated as approximate costs. Mechanical treatments appeared to harbor the largest range of costs, with $200 per acre being the price when the harvested timber is in demand and treatments were in close proximity to a timber mill; upwards of $2,000 per acre when treatments were required in and along roadsides where various hazards and obstacles were present. In

[12] See Footnote "5" for "stand" definition.

addition to these costs, it was conveyed that the associated treatment time varied as well, from one to two acres per day when mechanical treatments occurred along roadsides, up to eight or ten acres within Ponderosa pine stands. A quantity of acres treated per day was not provided with regard to hand crews, although it was relayed that they were responsible for working either in "sensitive" areas as well as those areas where the slope exceeded 35%.

Table 4.6 Forest fuel treatment costs

FOREST FUEL TREATMENT COSTS			
PREPARATORY COSTS	**Contract Preparation ($/Acre)**	$30.00	
	Stand Exams ($/Plot)	$60.00	
	Timber Cruising/Timber Sale/Etc. ($/Hr.)	$48.00	
TREATMENT COSTS	**Treatment Costs/Acre**	**Low**	**High**
	MANUAL	$300.00	$600.00
	MECHANICAL	$1,000.00 $400.00 $600.00	$1,500.00 $500.00 $700.00
	Mech with nearby Mill	$200.00	
	Roadside Hazard		$2,000.00
FOREST SERVICE	**Treatable Acres/Day**	**Low**	**High**
*USFS makes adjustments to account for diesel, cost-of-living, timber prices, etc.	Roadside	1	2
	Forest	8	10

4.4. Treatment Funding

The need to address both immediate and long-term resource needs as they pertain to wildfire events and overall forest health relies upon a number of local, state, and federal programs and funding mechanisms. At the federal level, these may involve programs such as the Emergency Watershed Protection Program (EWP) in which $216 million was allocated in 2012, $244 million in 2013, and $0 proposed in 2014, America's Great Outdoors (AGO) Initiative, the Farm and Foreign Agricultural Services (FFAS), the Natural Resources and Environment (NRE) mission area in which $15 million dollars was enacted in 2012, $15 million proposed for 2013, and $0 proposed in 2014, State and Private Forestry programs in which $240 million dollars is proposed for 2014, the National Forest System (NFS) that in 2014 has a proposed budget of $1.556 billion, the U.S. Department of the Interior's (DOI) Forest Legacy ($25 million) and Land Acquisition ($34 million) programs, as well as a portion of the nearly $25 billion in 2014 that is associated with discretionary programs that include management of national forests. In 2012, the United States Forest Service allocated $317 million dollars towards hazardous fuel reduction activities with estimating the same funding in 2013 and a decrease in funding to $201 million in 2014. To get a sense of how these funding allocations relate to the magnitude and expenses associated with wildfires, the 2014 Forest Service Budget Authority allocated nearly $2.36 billion dollars or 42.7% of their overall budget in 2014 to wildland fire management. In 2014 alone, funding was appropriated with the intent to reduce the risk of catastrophic fire to nearly 700,000 acres of land designated as being within the wildland urban interface (WUI). Performance measures for the Forest Service indicate an overall downward trend in the number of acres of hazardous fuels treated to reduce the risk of wildfire in WUIs from 2.189 million acres in 2009 to 685,000 acres in 2014 (USDA, 2014). Given the entities, budgets, and trends in spending noted above, the Colorado-Big Thompson Headwaters Partnership (C-BTHP) currently acts as the forum through which synergistic treatment efforts and funds are appropriated to reduce hazardous fuel loads within the research region.

The Northern Colorado Water Conservancy District currently provides $340,000 annually for hazardous fuel treatments, with $250,000 originating through the Northern Water General Fund (O&M) with an additional $90,000 from its Municipal Sub-District (Windy Gap) budget. Looking forward, Northern Water has expectations that this allocation will continue through 2018 after which time the forest conditions will be reassessed to determine further funding needs. It acknowledges that funding for this and other programs will likely require increases to existing customer water assessment rates, with the potential to set up a one-time special water assessment which could also help create a reserve fund specifically for hazardous fuel treatments. In terms of the existing $340,000 Northern Water has been appropriating, this has gone towards supporting hazardous fuel reduction efforts implemented by the U.S. Forest Service due to their expertise in this area and their management of the majority of public lands adjacent to resources managed by Northern Water. In addition to this reasoning, hazardous fuel reduction funding channeled through the Forest Service ensures that all treatments are performed on lands that meet necessary regulations, as through NEPA assessments performed by the Forest Service. Annually, Northern Water has provided funding for more than 1,000 acres of hazardous fuel treatments (personal communication, March 10, 2014). In 2013 and 2014, Northern Water was the recipient of grant funding from the Wildfire Risk Reduction Grant Program, created by Senate Bill 13-269 and provided by the Colorado Department of Natural Resources. These awards were in the amount of $133,780 in 2013 and $131,000 in 2014 and involved a 50/50 cost share between the grant recipient and the grant awarded (Colorado Department of Natural Resources, 2014). With the 2013 award, Northern Water disseminated the funding directly to homeowner's associations (HOAs) in and around the three lakes region (Lake Granby, Shadow Mountain Reservoir, and Grand Lake) to help mitigate hazardous fuel loads to a number of residences in high priority WUI regions with help from the Colorado State Forest Service. Discussion with Northern Water relayed that future Northern Water award funding will likely be distributed to counties in order to help maximize the impacts of hazardous fuel treatment applications

The U.S. Department of the Interior's Bureau of Reclamation (USBoR), which manages the Alva B. Adams Tunnel within the study area, allocated $22,000 in 2013 and $130,000 in 2014 to hazardous fuel reduction treatments within the Colorado-Big Thompson project area. With the establishment of the Western Watershed Enhancement Partnership (WWEP) in 2013, the Colorado-Big Thompson Headwaters Partnership has become one of six pilot projects for the WWEP and as such, receives funding from the USBoR through this program (P. McCusker, personal communication, September 29, 2014). In terms of the overall funding allocated to the C-BTHP, Northern Water also indicated that, due to ongoing federal budget situations and program priorities, uncertainty remains as to the contribution provided for such efforts from the Forest Service despite the federal spending mentioned above. Additionally, it was conveyed that the National Park Service, which has a considerable amount of land in and around the study area, has expressed that its policies provided little support to fund efforts at reducing hazardous fuel loads within its jurisdiction (personal communication, March 10, 2014). In light of these funding realities and the federal distribution of lands within the study area, forward-looking, conservative estimates of annual hazardous fuel treatment budgets within the study area are likely to fall within the range of $495,000 to $600,000 annually. In considering potential treatments, not simply within feasible treatment areas, but across the regional landscape a conservative $1,000,000 annual budget (budget) will be applied to consider funding availability for hazardous fuel treatments and the outcomes that are generated under such a funding scenario.

4.5. Burn Probability

This research grew out of the intention to evaluate, at depth, the multiple benefits of hazardous fuel treatments, which included understanding the components that contribute to wildfire risk and burn probabilities. In pursuing the determination of changes in water yield and acknowledging the complexity and degree of understanding necessary to independently determine, let alone evaluate, unconditional burn probabilities, it became readily apparent that time and resource constraints were prohibitive in allowing for this attainment of knowledge and analysis to occur. While still yielding fairly rudimentary information, FlamMap 5.0 software was utilized to generate conditional burn probabilities for a large portion of the study area. Using this software, ArcGIS shapefiles representing each of the eight regression attributes, along with an additional "Fuel Model" themed ArcGIS shapefile, were input into the software in order to assemble a landscape file of the study area. Once this procedure was complete, forest inputs, fire behavior calculations and outputs, fire ignition sequences, behavior, and outputs, including "Burn Probabilities", were selected. While the vast majority of default calculation methods and environmental input settings were preserved, the number of random fire ignitions allowed across the region was set to "10,000" and the resolution of calculations were set to "30" meters to coincide with the information generated for and from the grid analysis. Allowing for such a large number of random ignitions to occur was done to ensure that, across the entire landscape, there could be expected some number of differentiated burn probability values generated to coincide with the maps of changes in water yield. The output of this simulation can be found in Figure 4.13 with burn probabilities (BPs) represented below in Table 4.7. Given these outputs generated from forest characteristics, we can observe that approximately 5% of the landscape is more susceptible to carrying fire if an ignition occurs on or near that unit than is found throughout the rest of the forest region. Provided the assumption is made that for an area with a burn probability designation above that of 0.00008 (Green designation), a forest fuel treatment will reduce the burn probability by one class, this map can then be used to represent areas where forest fuel treatments would be beneficial. Intuitively, forest fuel treatments would best be applied by prioritizing treatments to those units with the highest burn probability levels. In looking at the Burn Probability Map in Figure 4.13, we can observe that higher burn probability units exist in and around roads and populated areas. These units are often grouped with units of similar or lesser burn probabilities, allowing for the opportunity to access and treat numerous units of concern within a given area while efficiently employing available funds. By integrating the Burn Probability Map with the Variant Change in Water Yield Maps (Figure 4.12), we can observe burn probabilities in conjunction with units expressing positive changes in water yield given forest fuel treatments.

Table 4.7 Burn probability class map

BURN PROBABILITY CLASS MAP			
Burn Probability (%)	**Number of Gridded Units**	**Frequency**	**Color Class**
0.008	2,000,142	95.540%	
0.016	86,544	4.134%	
0.024	6,452	0.031%	
0.032	369	0.018%	
0.04	13	0.001%	

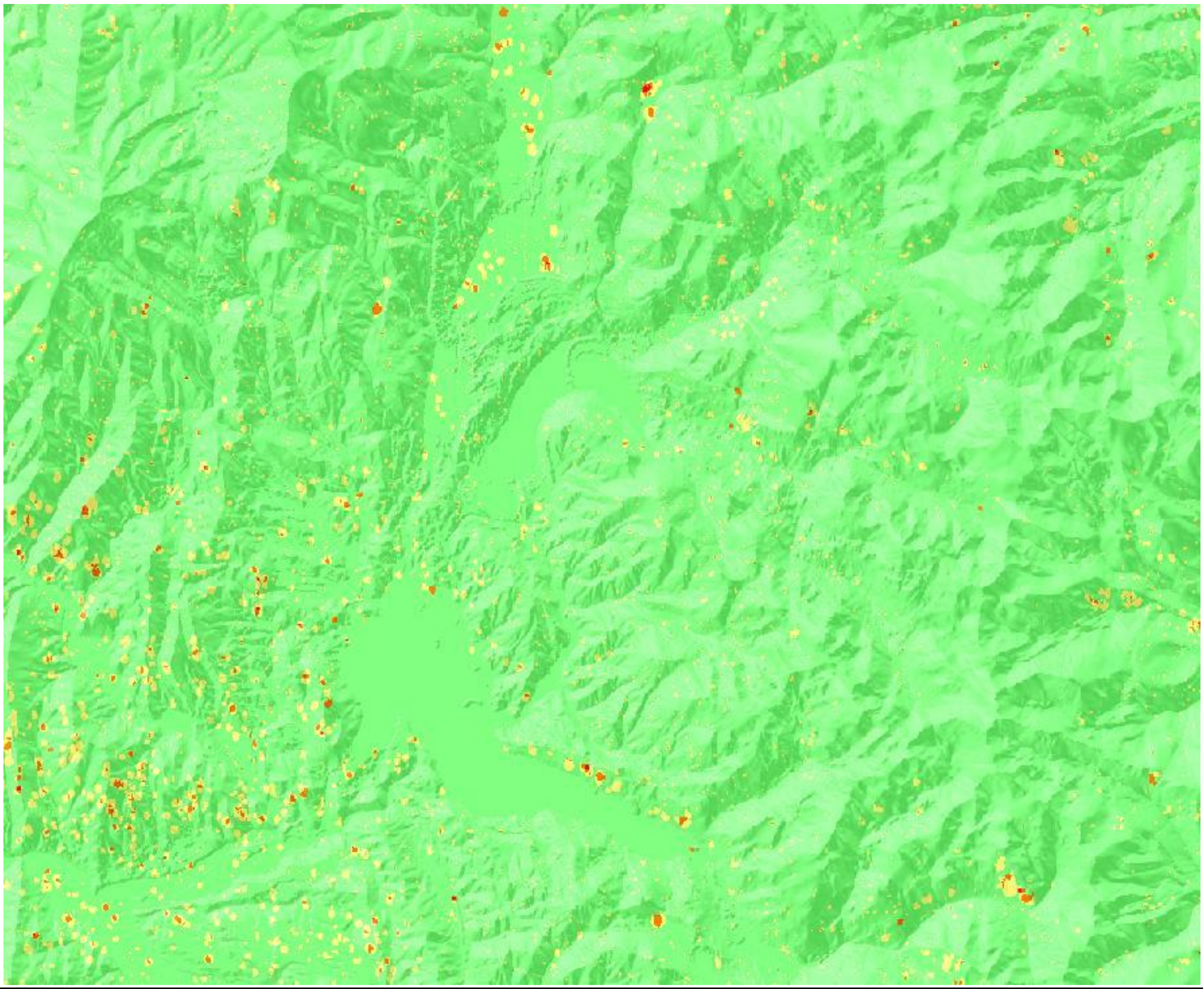

Figure 4.13 FlamMap: Burn Probability Map

In this manner, we can isolate those locations that, through forest fuel treatments, are most likely to express the greatest overall reductions in burn probability while simultaneously expressing gains in changes in water yield to the C-BT system. These measures can be performed such that the $1,000,000 annual budget is effectively allocated to produce the greatest systematic gains across both areas of interest.

4.6. Water Yield Frontier

Being cognizant of the treatment costs along with the budget, it was determined that a "Water Yield Frontier" could be constructed to express the changes in water yield across the region given treatment costs on providing forest fuel treatments up to the defined budget of $1,000,000. This frontier illustrates the relationship between the budget allocated to forest thinning and the expected changes to water yield that result. In addition to showing changes in marginal benefits of treatment, the frontier can also highlight instances where financial investment is not being allocated in the most cost-effective manner, depending on the outcome sought and the spatial region(s) being considered for treatment..

In an attempt to understand the region-wide water yield, a water yield frontier was created to represent values across the entire study region to assess the changes in water yield produced when treatments were applied to serve particular interests. Those interests were presented in terms of three separate treatment approaches:"Random Sorting", "Changes in Water Yield", and "Burn Probability". The "Random Sorting" approach represented forest fuel treatments that were applied to a randomly chosen collection of units within the study region. The "Change in Water Yield" approach represented treatments that sought out the greatest modeled changes in water yield in the region. The final approach, "Burn Probability", looked at seeking out the regional units that had the highest burn probabilities and choosing to treat those units. For all of these treatment approaches, the "Expected Burn-Free Water Yield" value was calculated by multiplying the existing "change in watery yield" value associated with each unit by the difference between one and the burn probability value associated with each unit. This approach streamlined the water yield frontier analyses by incorporating burn probabilities directly into the "Change in Water Yield" values to better represent forest fuel treatment outcomes in terms of one comprehensive output value[13]. This was conducted by first

[13] It should be noted that despite the regional summary statistics indicating "change in water yield" values upwards of 0.0210052, when these values were isolated with the overall highest "change in water yield" values, they appeared as a limited number of outliers whose truncated distance from other "change in water yield" values resulted in their absence from use within the "Water Yield Frontier" analyses.

establishing the approximate cost per $30m^2$ unit of forest fuel treatments to be $177.92, based on the most common cost values provided by each of the numerous forest professionals consulted and representative of the fractional value that a unit represents for an $800/acre treatment. The "Expected Burn-Free Change in Water Yield" (EBF Water Yield) value in inches per unit was then calculated from the existing "Change in Water Yield" and "Burn Probability" values across the entire region as recently described. This "EBF Water Yield" data then utilized the "Random Number Generator" command within Microsoft Excel to associate a unique random number value between 0 and 1 to every regional unit and its associated attribute values. To determine those units used within the "Random Sorting" treatment approach, the randomly generated numbers were sorted with their associated unit information from largest to smallest, with the largest 5,621 units, which represent the number of units capable of being treated with a budget of $1,000,000, being isolated for use within the Water Yield Frontier analyses. The largest 5,621 "Change in Water Yield" and "Burn Probability" values were sorted in the same manner across all the regional units and their unit information was isolated as well for Water Yield Frontier analyses. Having identified and segregated those treatment units sought for comparison, their "EBF Water Yield" values were first applied graphically to express the incremental change in water yield produced as investments in fuel treatments were applied up to their $1,000,000 budget allocation as seen in Figure 4.14. They were expressed in a manner that showed the change from the greatest to least change in water yield across the units.

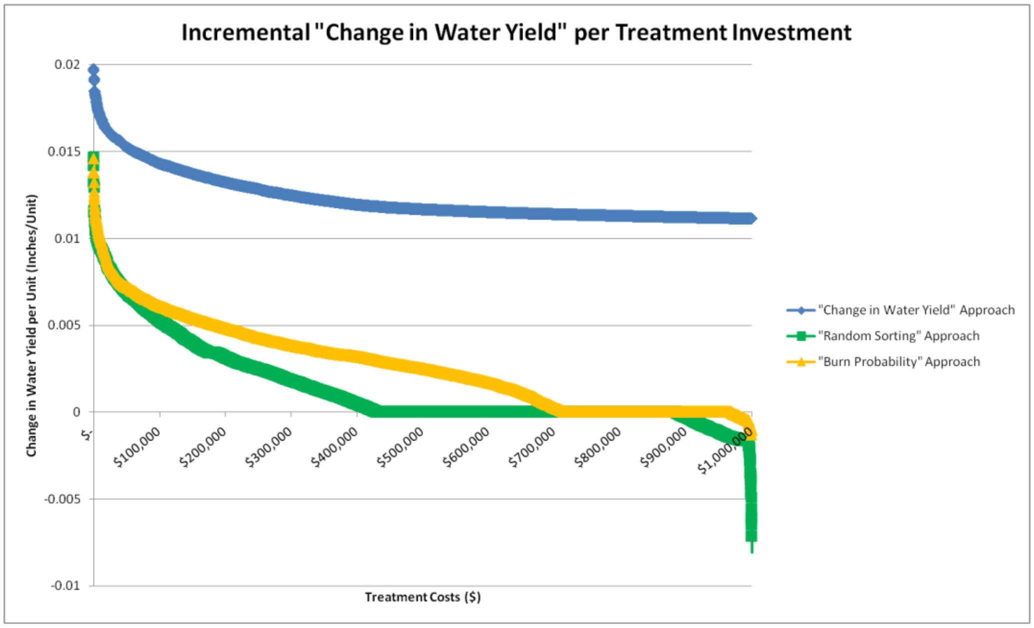

Figure 4.14 Incremental "Change in Water Yield" Map

Presented in this manner, it can be observed that the "EBF Water Yield" values were found to have higher , entirely-positive values and express less overall variability when the "Change in Water Yield" approach was sought versus the "Random Sorting" or "Burn Probability" approaches. The "Burn Probability" approach was seen as having the next best "EBF Water Yield" outcomes, although these outcomes convey relatively little differentiation from the outcomes observed under the "Random Sorting" approach, suggesting a relatively low correlation between burn probabilities and water yield. It is worth noting that although the initial "EBF Water Yield" values were quite similar, the "Burn Probability" approach resulted in much less "EBF Water Yield" outcomes that were negative than observed for the "Random Sorting" approach. Relative to the other two approaches, the "Burn Probability" approach outcomes reflect changes that appear acceptable in light of there being an understood, if still non-definitive, degree of associated increased "Change in Water Yield" values related to areas with higher burn probabilities.

Given the outcomes conveyed when changes in water yield were graphed for incremental treatments, the cumulative changes in water yield were considered for the same budget in terms of acre-feet of water generated and are expressed in Figure 4.15.

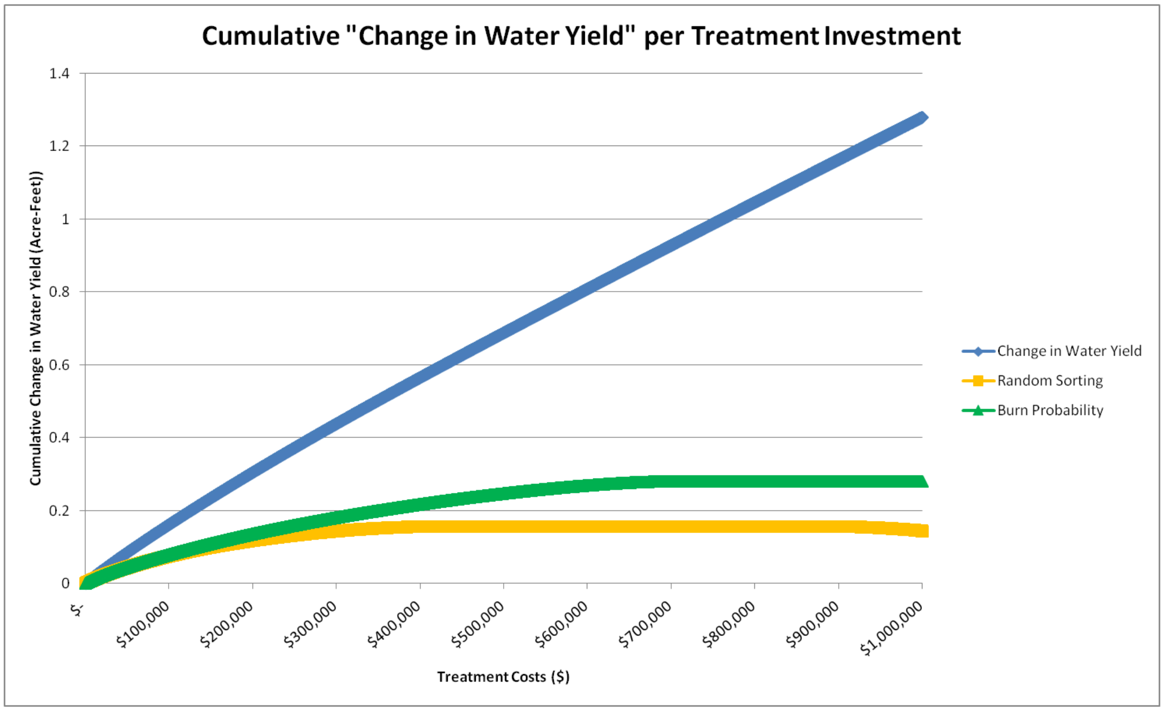

Figure 4.15 Cumulative “Change in Water Yield” Map

Within Figure 4.15, it can be observed that when applying regional treatments solely for generating the greatest “EBF Water Yield”, there appears to be a negligibly diminished marginal increase in “EBF Water Yield” as budget expenditures continue up to their $1,000,000 limit. In other words, at budgets up to $1,000,000, the relationship between expenditures and cumulative water yield is essentially linear. Much like what was seen in terms of the incremental “EBF Water Yield”, the “Burn Probability” approach once again generates “EBF Water Yield” quantities that lie between the “Change in Water Yield” and “Random Sorting” approaches, with the overall values trending much like those expressed for the “Random Sorting” approach. To provide context, the “Change in Water Yield” approach generates one acre-foot of water at the point where approximately $761,000 are invested in fuel treatments, whereas neither of the other two approaches express gains that would produce an acre-foot of water across 5,621 units. Overall, the cumulative “EBF Water Yield” in acre-feet when the entire budget is expended appears to be approximately seven times the yield of applying either the “Burn Probability” or the “Random Sorting” approach, indicating a marked difference in outcomes depending on the approach taken. The fact that the slope for the ‘Change in Water Yield” approach is positive and expresses little change as the budget is expended relative to the other approaches, suggests that with continued expenditures, the gains generated for “EBF Water Yield” may continue at a similar rate for some time prior to diminishing. For both the “Burn Probability” and “Random Sorting” approaches, increased expenditures would appear to only marginally increase the cumulative gains in “EBF Water Yield”, presuming the positive changes continue to occur at greater rates than those of negative changes in “EBF Water Yield”, as is seen in Figure 4.15. Overall, the “EBF Water Yield” gains generated from the “Change in Water Yield” approach appear to outweigh those gains generated through either of the alternative approaches.

To express the findings of Figures 4.14 and 4.15 in relation to their quantitative distribution, the histogram in Figure 4.16 was generated.

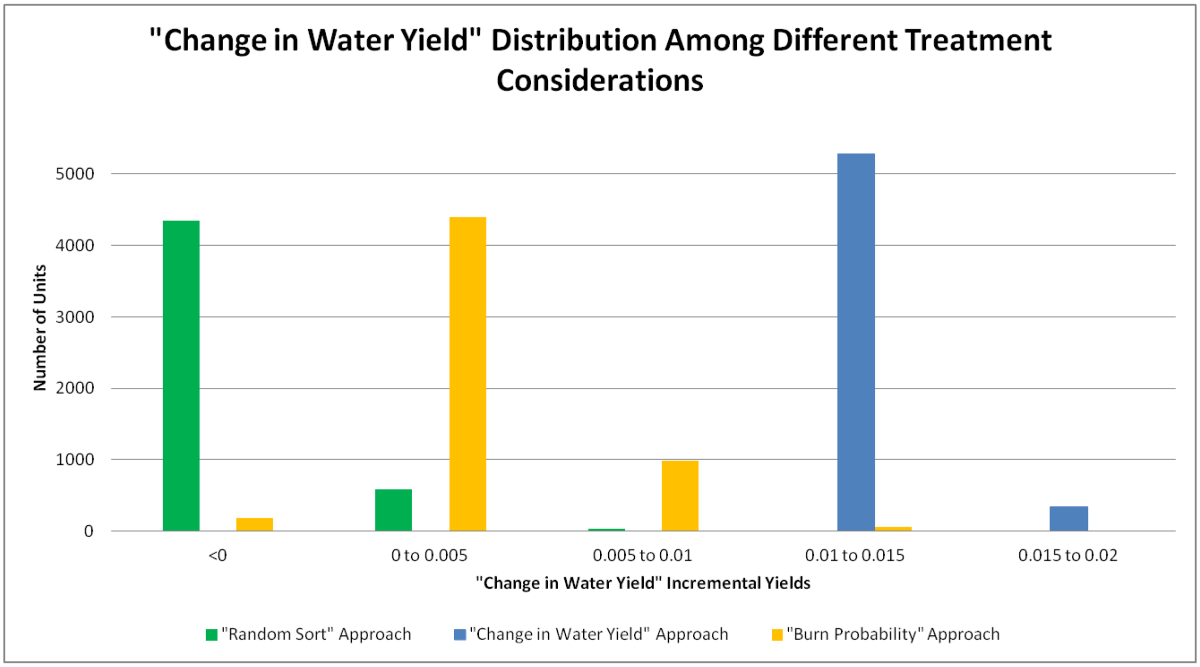

Figure 4.16 "Change in Water Yield" Distribution Map

The histogram relates that the approach with the least quantitative gains across the range of possible gains was for that of the "Random Sort" approach. The greatest quantitative gains across the 5,621 units was for the "Change in Water Yield" approach while the same rationale as expressed in Figures 4.14 and 4.15 can be used to justify the gains seen using the "Burn Probability" approach. These findings coincide with those seen within Figures 4.14 and 4.15 and align with intuition regarding expected changes for particular treatment techniques applied.

To provide context, within the Colorado-Big Thompson project area, seasonal water lease rates averaged $24.43 per acre-foot in 2012 through the Northern Water's Regional Pool Program (RPP) composed of extra quota water not utilized in a prior year by allottees. In terms of C-BT water unit sales, in March of 2014, forfeited units were sold on average for $21,020 per acre-foot. More historic data shows that the price per acre-foot of water sold by municipalities and irrigators was approximately $1,500 from 1990-1996, with dramatic increases in 2000 to $16,000. After this spike, prices had a declining trend to approximately $10,000 per acre-foot as of 2011 (Leonard Rice Engineers, Inc. 2011). Given these rates and the rates determined from our regional data, we see that the average treatment costs necessary to generate an acre-foot increase in water yield ($761,000) is more than 36 times the current (March, 2014) purchase price for a forfeited unit of C-BT water when the "Change in Water Yield" approach is applied. As can be observed, it would require modeling such cumulative "Changes in Water Yield" per treatment investment for a substantially larger budget to ascertain the costs of generating an acre-foot of water for either the "Random Sorting" or "Burn Probability" approach.

CHAPTER 5: CONCLUSION

The results of this study show that in the application of forest fuel treatments to reduce the threat of wildfires amongst unique combinations of forest attributes, there exists the opportunity to significantly change forest water yields depending on the treatment approach applied while simultaneously accounting for the effects of burn probability on changes in water yield. Through the techniques of extracting and compiling forest attribute data using the "fishnet" grid to then generate "Water Yield Frontiers" it was determined that, on a regional level, changes in water yield are highest when that is the objective for which a treatment is applied. Relative to this approach, when either "Random Sorting" or "Burn Probability" approaches are sought, there is a negligible difference in the change in water yield outcomes generated relative to the overall amounts of investment made. In this manner, treatment applications can also be applied such that preferred treatment benefits are maximized relative to treatment budget constraints.

The application of the eight specified forest attributes serve as a critical component between detailed forest stand data, forest and water modeling software, and landscape level remote geographic data resources. Based on the regression analysis performed, these variables add to the statistical strength and explanatory power of the predictive regression formulas applied across the landscape. These variables are essential in expressing the synergy and correlation between forest characteristics, wildfire fuel components, and forest water yield. Through the analysis of the variant regression outputs and correlation tables, the variable "Precipitation" did not appear to model changes in water yield nearly as well as the "Elevation" variable. Despite this conclusion, "Precipitation" remains an objective variable defined primarily by climactic factors that has considerable impacts on the change in water yield in any given year due to its ongoing role in delivering water to the region. This observation brings to light the complexity of basing such broad-scale findings on a limited number of available resources.

5.1. Findings of the Study

Results of the research conclude that the expense of applying forest fuel treatments for the sole intention of creating increasing changes in water yield would be high relative to the current costs associated with purchasing available units of water through a traditional market transaction. This affirms the pragmatic approach of coupling such gains with those already sought through the application of forest fuel treatments for the reduction of wildfire risk. Through this approach, it is likely that gains through reduced wildfire risk and increased changes in water yield will occur with little to no increase in expenditures across an area for treatment consideration.

5.2. Limitations of the Study

The study was susceptible to limited data resources, complex wildfire risk and water estimation theories and software, and extensive and challenging data set issues. The region of interest is remote and has a limited number of roadways from which existing mechanical work can be performed. Once the policy processes of applying forest fuel treatments was made apparent, the opportunities for considering the original watershed regions for treatment was greatly restricted to those regions likely adjacent to roadways. The opportunity to consider integrating temporary roads into the landscape is possible, although this would elicit temporal, financial, and policy constraints that were undertaken within this analysis. Additionally, budgetary considerations were not able to be vetted to the extent initially intended due to a lack of access to hazardous forest fuel treatment accounting information and the large variance in the values provided from personal interviews.

5.3. Suggestions for Further Research

Future research into the relationship between burn probabilities, changes in water yield, and budget constrained conditions could improve by seeking and obtaining additional forest records and datasets at the same scale. While no additional, constructive resources were readily available at the time of this research, it is likely that additional forest attribute information via GIS and other formats will be available in the near future that will have the potential to contribute greatly to the existing research. Beyond new datasets being available, another avenue for improvement would be to combine existing forest attributes to represent other forest components, such as "Basal Area" or "Ruggedness" much like what was done by JW Associates, or establish a more defined understanding of the contribution existing variables provide to estimating water yield. This could be done by delving into the formulation of water yields within the WRENSS post processor at greater length, or by adopting and/or comparing other water yield prediction programs and their outputs. Through this approach, the method employed to determine changes in water yield could be readily exposed and from that, a "Change in Water Yield Optimization" model could be constructed to isolate stands from which the greatest increased changes in water yield would occur given a particular treatment or method of approach. As it stands, this same approach was attempted on behalf of this research, but insufficient knowledge of the determining components and formulation for changes in water yield was known, which prohibited conclusive results from being found. The same vetting could be done for understanding the effect in reducing burn probabilities given particular forest fuel treatments. This component of the research, while tedious, has been given substantial consideration globally by researchers and wildfire professionals.

An aspect of the research that could be expanded upon is the procedural method developed and applied within this research. While the interplay of the components themselves can be challenging, the melding of forest attributes via a GIS grid helped to compartmentalize forest attributes in a manner that allowed them to readily be considered in the context of changes to water yield and reduced wildfire risk. More accurate depictions of forest attributes, for instance "slope", could be better differentiated at the "unit" level to help increase the accuracy of predictions regarding water yield. A third water yield frontier could also be developed that could incorporate a variable cost component based on the distance of a treatment from an existing road as well as a change in the grade of the unit (acre) being treated. In this manner, the marginal benefits could be determined by creating a change in water yield-to-cost ratio.

Additional work could also be performed with regard to sectional treatments to refine inputs and better determine relational causation from seeking particular treatments. In this way, the outcomes discussed above can be explored and, in the event these findings are supported, can be refined to allow for more effective funding allocation of treatment applications down the road. Such an outcome could then be used to publically convey the joint benefits gained from applying strategic forest fuel treatments, which in turn could result in additional funding allocations as well as greater collaboration efforts between the public, private, and governmental sectors regarding hazardous fuel treatments.

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APPENDIX I

The Colorado-Big Thompson Headwaters Partnership was formed to identify mutual watershed protection needs and opportunities between local, state and federal agencies and effectively employ resources to address these items. While the Colorado-Big Thompson project (C-BT) ultimately works to serve the water and energy production needs of customers and entities on the eastern slope, the municipal water treatment providers are the ones who ensure that the water meets the necessary water quality requirements for consumptive use. In this capacity, the water treatment providers were initially seen as the recipients of raw water from the C-BT, which often originates far from these treatment locations and whose quality could be compromised by events such as flooding, erosion and wildfires. It was with the concern of compromised water quality, particularly from wildfire events within the C-BT region that initial efforts were taken to contact and determine if, and to what extent, water quality had been compromised and impacted the water treatment efforts and costs to those water treatment facilities served by the C-BT. It was thought that the responses of the water treatment facilities would support the hypothesis that wildfire events within the C-BT area have a negative effect on water quality and require increased treatment processes and costs.

In discussing this consideration with the Northern Colorado Water Conservancy District (Northern Water), a list of 26 water treatment facilities served by the C-BT was provided. The extent of where these facilities were located spanned the eight Colorado counties of Boulder, Broomfield, Larimer, Logan, Morgan, Sedgwick, Washington, and Weld. Contact information for each of these facilities was sought and email and telephone correspondence was initiated to explain the scope of research and locate an appropriate individual with whom to schedule and discuss water quality questions with. Two attempts to make initial contact with each of these entities were conducted, after which it was presumed contact could not be made or the entity was choosing to not engage in conversation. The response rate from these efforts was fruitful with 10 of the 26 water treatment providers agreeing to discuss their water quality issues either over the telephone or in person.

For each correspondence with a water treatment facility employee, a series of pertinent water quality and operating questions were crafted, based on both existing knowledge of their facility and operations as well as questions derived through the interview correspondence. These questions and responses were then recorded and aggregated as a sample of the water treatment facilities of the C-BT. Some questions, regardless of whether or not they were discussed with every water treatment facility employee, were not able to be answered by the individual with whom the discussion was taking place.

The results of the interviews were first thought to be provided in a manner that would be uniform and conducive to a qualitative write-up and quantitative analysis. It became readily apparent from the initial interviews that such uniformity and access to water treatment facility data varied greatly in terms of availability, precision, and certainty. Acknowledging this, the author chose to qualitatively summarize his findings in order to address the voids and inconsistencies in the interview data as well as convey the unique commentary that many of the interviews elicited.

Analysis of these responses provided a range of feedback. In terms of the number of shares of C-BT water owned by each of the water treatment facilities, it was found that six out of the ten water treatment facilities relied on owning a majority of the C-BT water they used and leasing C-BT shares for the remainder of their demands.

Overall characteristics across the water treatment facilities can be expressed as follows. Of the ten water treatment facility (WTF) operations discussed, six conveyed ownership of C-BT water that resulted in a range of as few as 919 shares to as many as 6750 shares, with an overall average of approximately 3800 shares owned across these providers. In terms of leasing shares, one WTF had a lease agreement with a ditch company of nearly 2800 shares, while the remaining WTF's acknowledged the existence of agreements and opportunities to lease given levels of demand. Distribution of C-BT water by WTFs appeared to largely be dictated by the proximity of adjacent forest surface water sources, with those WTFs in close proximity distributing as little as 10% C-BT water while those WTFs furthest from these sources relying entirely on C-BT water. For a few of the WTF's, additional water was sourced from groundwater resources and/or ditch companies. Approximately 70% of the treated water was distributed to residences, with roughly 15% going to the commercial/industrial sector and 15% to the agricultural sector.

All of the WTF's received their C-BT water via pipelines or ditches originating from Carter Lake, Grand Lake, Green Ridge Glade, or Horsetooth Reservoirs. Conventional water treatment methods were commonly used, with some WTFs using membrane filtration and one applying ultraviolet treatment. Average daily water treatment was approximately 8.4 million gallons per day (MGD) with the average treatment capacity across the facilities being approximately 14 MGD. These values were found to fluctuate significantly depending on the season as well as the sector distribution demands on a WTF.

Inquiring of raw water quality, nearly all of the WTFs conveyed that they received relatively clean water. Turbidity and total organic compounds (TOCs) were issues that the majority of the WTFs were consistently treating for. Two water treatment facilities conveyed the increasing need to treat for Geosmin, which is a byproduct of dead blue-green algae within the reservoirs that is not harmful, but had been eliciting complaints from customers as it can generate an unpleasant odor and taste.

The WTFs quantify the number of households they served in terms of "taps" with as few as 2500 and as many as 19,000 taps being provided for, with the average amount per WTF being approximately 7000. Water treatment costs per thousand gallons ranged from $0.20 to $2.50 per thousand gallons of water treated, with the average cost being $1.60. It was unknown if these values represented fixed and/or variable costs.

When asked whether any facility had ever been impacted by wildfire events within the C-BT project area, two water treatment providers conveyed that their facilities were threatened and responded to this threat by bypassing incoming water around their plant intakes to alleviate potential issues associated with treating the water. For the other eight facilities, regardless of their proximity to wildfire events, none expressed an impact at any point from wildfires, but some did express that turbidity would likely be an anticipated issue if a wildfire occurred in the future and impacts were seen. Many of the facilities had seen escalated turbidity levels from the flood events in September 2013, with a few facilities noting that this water did appear to contain "carbony" material from nearby wildfire events. During the floods, some facilities experienced structural and/or water quality issues from incoming water that caused them to rely on backup water sources to meet demand needs. One facility expressed that it had to pump water from an adjacent storage site for six months at a rate of $8000-9000 per month. It was found that for nearly every facility, an emergency water plan had been created with an adjacent municipality or water source to supplement water supplies in an emergency, which could sustain the water needs for a minimum of a few days. For the majority of WTFs, the additional costs for impaired water quality would be primarily for increased chemical treatment, as agreements for emergency water often dictated the water would be provided at the present rate, with no additional markup.

Despite the above generalizations, the characteristics and size of each WTF and the sectors they served were found to vary. Of growing concern among many water treatment providers, was the issue of Geosmin, which is caused by the decay of blue-green algal growth found in Shadow Mountain Reservoir, Carter Lake, and Horsetooth Reservoir. With the exception of a few WTFs, a consensus was made among water treatment providers that the effects of prior and future wildfire events will be negligible due to the buffering effect that the reservoirs provide by allowing sediments and solids from incoming C-BT water to fall out of suspension prior to being transported to the WTF. In this way, the direct impact of wildfire events on WTFs will likely remain negligible. The cumulative effects of wildfires will therefore be imposed primarily on the reservoirs, which have the potential to absorb much of the effects over time with the greatest potential impacts likely being comparable to the water quality and structural impacts as seen at Strontia Springs reservoir from flooding events following the Buffalo Creek Fire in 1996. It is from this understanding of the reservoir buffering effects on wildfire impacts to water quality that the subsequent thesis research has focused on the available water from changes in water yield across treatment areas.

APPENDIX II

Table A.ii.1 Detailed summary statistics:Base regressors

VARIABLE NAME	ASPECT		ELEVATIONm		PRECIPITATIONmm		SLOPE		CANOPYBULKDENSITY		CANOPYHEIGHT		CANOPYCOVER		CANOPYBASEHEIGHT	
Percentage	Percentiles	Smallest	Percentiles	Smallest	Percentiles	Smallest	Percentiles	Smallest	Percentiles	Smallest	Percentiles	Smallest	Percentiles	Smallest	Percentiles	Smallest
1%	1	1	2538	2538	398	398	1	1	1	1	1	1	1	1	1	1
5%	1	1	2574	2553	398	398	5	3	1	1	1	1	1	1	1	1
10%	1	1	25878	2574	421	398	5	5	1	1	1	1	1	1	1	1
25%	40		2689	2578	475	421	9	5	8	1	175	1	45	1	5	1
50%	156		2837		602		13		8		175		45		8	
		Largest		Largest		Largest		Largest		Largest		Largest		Largest		Largest
75%	229	296	2935	3069	651	803	17	26	11	11	175	175	55	55	8	8
90%	289	304	2994	3083	785	803	25	29	11	11	175	175	55	55	8	8
95%	304	350	3083	3132	803	882	29	30	11	11	175	175	55	55	8	8
99%	59	359	3288	3288	902	902	30	30	11	11	175	175	55	55	100	100
Observations	47		47		47		47		47		47		47		47	
Mean	141.4681		2824.66		587.8936		14		8.255319		154.3617		42.87234		8.531915	
Standard Deviation	108.5331		163.9241		124.2305		6.877816		3.172354		55.43521		16.85439		13.87812	

Table A.ii.2 Linear regression: *CNG_WY30m2* on *ELEVATIONm*

Independent Variable	***ELEVATIONm***	***INTERCEPT***
Coefficient	2.30E-06	-1.95E-03
Standard Error	(0.00000547)	(0.0153548)
T-statistic	0.42	-0.13
p-value	0.676	0.900
N	47	47
R^2	0.0043	0.0043
F-statistic	0.18	0.18
Root MSE	0.00583	0.00583

Robust standard errors in parentheses *p<0.10, **p<0.05,***p<0.01

Table A.ii.3 Summary statistics of regional forest characteristics

Variable	N	Mean	Std. Dev.	Min	Max
ASPECT	1668662	127.6344793	119.4239522	-1	359
ELEVATIONm	1668662	2914.470494	208.2226198	2532	5838.666667
PRECIPmm	1668662	689.0015402	179.5811974	127	1176.866667
SLOPE	1668662	16.12175198	5.779828842	0	63
CNPYBULKDNSTY	1668662	7.299621508	4.165510989	0	45
CANOPYHEIGHT	1668662	0.564156817	9.380545315	0	375
CANOPYCOVER	1668662	1.620705499	8.131370181	0	95
CNPYBASEHT	1668662	0.663972453	6.257448381	0	100