Impacts of Wildfire in Clear Creek Watershed on the City of Golden's Drinking Water Supply

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Abstract

The Colorado School of Mines Environmental Engineering Pilot Plant class from the Spring of 2012 was tasked with determining how a wildfire could affect the water supply for the Golden Water Treatment Plant, located in Golden, Colorado, and developing treatment strategies that address wildfire-inflicted water quality changes. GWTP prides itself in not only meeting regulated drinking water standards, but exceeding these limits. Golden also faces the unique challenge of having a sole source of water, Clear Creek, to draw from. The Clear Creek watershed is heavily forested, mountainous and often lacking significant precipitation, making it highly susceptible to wildfires and subsequent flood and erosion events. In order to characterize the risk GWTP faces in the event of a wildfire, an extensive literature review was conducted examining forest fires in the Rocky Mountain region, as well as water treatment facilities that experienced wildfires in their watersheds. Following the literature review, the class performed GIS mapping of Flood and Erosion Risk using ESRI's ArcGIS software to determine the areas of the watershed facing the highest risk. Fire-affected soil was characterized using 3-D Fluorescence spectroscopy in order to produce a representative surrogate for experimentation. Once a surrogate was selected, bench scale testing and pilot scale testing commenced examining various treatment strategies including the addition of an acid feed, a pre-sedimentation coagulation feed, and granular activated carbon filtration. Finally, a list of suggested responses was compiled for GWTP based on fire intensity, precipitation intensity, flood and erosion risk following a forest fire and our bench and pilot scale test results. It was determined that GWTP is at risk if additional treatment strategies are not put in place.

I.   INTRODUCTION

The City of Golden Water Treatment Plant (GWTP) requested Colorado School of Mines students in the Civil and Environmental Engineering Department's Pilot Plant course to develop treatment strategies for the potential adverse effects on water quality due to wildfires in the Clear Creek Watershed. The GWTP is located at the mouth of Clear Creek Canyon, at the base of the foothills west of Denver, Colorado. Clear Creek [1] is one of the most over-appropriated streams in Colorado and several municipalities, including the City of Golden, rely on its waters [2]. In fact, Clear Creek is the GWTP's only source of drinking water, which makes the plant particularly vulnerable to water quality changes in the Clear Creek watershed. In addition to having only one drinking water source, the GWTP is part of the American Water Works Association (AWWA) and Environmental Protection Agency (EPA) Partnership for Safe Water program, which requires higher levels of treatment than state and federal standards. Therefore, it is extremely important that the GWTP is well-prepared for events in the Clear Creek watershed that may cause adverse water quality changes.

Much of the scientific literature regarding the effects of wildfires on watersheds and water quality stems from the sciences of forestry, biology, and hydrology. Few studies address the changes in surface water quality of major concern to drinking water utilities, such as turbidity, total organic carbon (TOC), metal concentrations, pH, and alkalinity [3]. However, since the year 2000 severe wildfires in the western United States, including the state of Colorado, have created diverse challenges for water treatment plants already faced with challenges related to water availability, reliability, and quality [4]. For these reasons, the research presented in this report is applicable to all communities relying on surface water resources faced with wildfire risk and the resulting consequences on water quality.

This report first addresses the goal and objectives of the research project followed by a literature review on wildfire risk, flood and erosion risk, and the effects of wildfire, flooding and erosion on water quality parameters. The materials and methods used in the desktop, bench and pilot-scale experiments are listed thereafter. The results, discussion, and conclusions follow, before closing with recommendations for the GWTP.

GOAL

The goal of the research project was to provide the GWTP staff with the necessary information to address the possibility of wildfire within the Clear Creek watershed and its effect on drinking water treatment.

OBJECTIVES

1) Ascertain the risk of wildfire in the Clear Creek watershed;
2) Establish the risk of runoff as a result of wildfire in the Clear Creek watershed;
3) Determine the potential changes to the following water quality parameters in Clear Creek following a wildfire:
   - Turbidity
   - Total Organic Carbon (TOC)
   - Color
   - Taste and Odor
   - Metal Concentrations
   - pH
   - Alkalinity
   - Radionuclide Concentrations;
4) Determine the potential effects of wildfire on existing infrastructure;
5) Propose alternative treatment strategies for the GWTP that may enhance treatment post-wildfire;
6) Validate existing and proposed treatment strategies through bench and pilot-scale testing;
7) Develop recommendations to the GWTP staff concerning infrastructural needs and response strategies for treating Clear Creek water impacted by wildfire.

II. BACKGROUND INFORMATION AND LITERATURE REVIEW

Due to the limited nature of published scientific literature concerning post-wildfire water quality, much of the background information was provided by firsthand accounts of water treatment plant operators and consultants. Furthermore, most of the obtained data emanates from a handful of severe wildfires in Colorado, Arizona, and California. The Hayman Fire (2002) and the Buffalo Creek Fire (1996), both southwest of Denver, Colorado, as well as the Fourmile Canyon Fire (2010) near Boulder, Colorado, were the wildfires studied closest in proximity to the Clear Creek watershed. In addition to these fires, the Missionary Ridge Fire (2002) outside of Durango, Colorado, the Rodeo-Chediski Fire (2002) in east-central Arizona, and the Zaca Fire (2007) in Santa Barbara County, California, were examined.

WILDFIRE RISK

The Clear Creek watershed is amidst areas that have experienced severe wildfires over the past two decades, and extends 575-square miles from the continental divide to where it drains into the Platte River north of Denver, Colorado (Figure 1). Two-thirds of the watershed is forested land west of Golden, Colorado, approximately half of which falls within the Arapaho and Roosevelt National Forests [5]. A large portion of the watershed is considered an urban-wildland interface, which greatly increases the risk of fire [4].
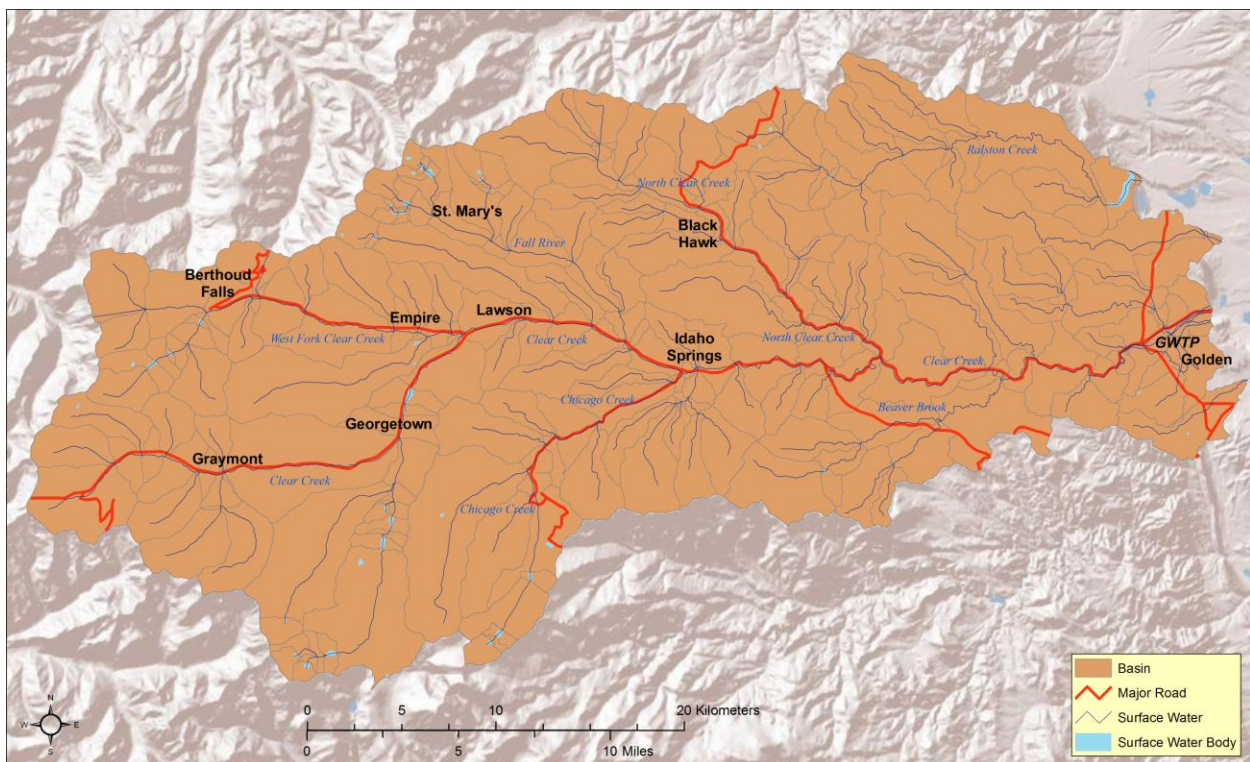
Figure 1: The Clear Creek watershed

Pine beetle kill has affected many pine stands in the watershed and is often thought to increase the likelihood of severe fires. Although no conclusive studies positively correlating beetle kill with an increase in fire danger exist, a theoretical risk assessment was conducted by a collaborative group including the Department of Forest, Rangeland and Watershed Stewardship and the Colorado Forest Restoration Institute at Colorado State University, as well as the Departments of Geography at the University of Idaho and the University of Colorado. Their assessment focused on the risk of crown fires, which tend to be the most spatially and destructively severe. The investigators concluded that during the first two years after a pine stand has been affected by pine beetle, there was a slight increase in the risk of crown fire initiation due to dead foliage remaining on the tree; this situation would not, however, increase the risk of spreading. Moreover, as needles eventually fall, canopy density is lowered, reducing the start and spread risks of a crown fire. Several years to decades later the crown fire risk may return due to fallen dead snags, which increase the heat and flame of a surface fire [6]. However, these risks may be mitigated by fire prevention strategies.

FLOOD AND EROSION

An increased risk of flood and erosion is a serious consequence of wildfire. Flood and erosion can dramatically affect surface water quality and damage nearby infrastructure. These effects are often magnified following a wildfire. High flow regimes can mobilize large volumes of debris and sediment, including heavier items such as tree trunks and boulders, which are later deposited downstream. Smaller debris consists of dissolved and particulate organic and mineral matter, which increase turbidity and alter water chemistry [1]. For example, Moody (2001) estimated sediment deposition in the summer of 1996 following the Buffalo Creek Fire to be 154,000 m^3, thereby significantly reducing the drinking water storage capacity of Strontia Springs Reservoir [7]. Aerial photographs of the reservoir show a carpet of floating debris on the water surface, which had to be manually removed. Additionally, major flood events with increased debris flow resulted in the destruction of water treatment plant intake structures [8].

One of the proposed mechanisms by which wildfires increase the potential for flood and erosion is that of the water repellent layer theory. During a fire, protective vegetation and organic litter covering the soil surface are incinerated, leaving the soil exposed to the full impact of raindrops and rainwater flows. As the organic matter is burned, hydrophobic compounds are volatilized at the soil surface. The compounds then travel down the steep temperature gradient present in the soil towards cooler layers where they condense on soil grains and organic matter. The water repellent layer that existed at the surface prior to the fire grows in thickness and relocates to a deeper position in the soil profile. Thereafter, precipitation easily saturates the wettable layer of soil left at the surface and is barred by the water repellent layer below. This facilitates erosion at the surface, followed by erosion of the water repellent layer beneath by turbulent water flow and finally erosion of the underlying wettable soil. Channels formed in this way are known as rill [9]. These findings imply an increased risk of sediment deposition from heavy precipitation events after wildfires.

However, Cerda and Doerr (2008) reported that 34 mm of ash deposition following a fire was sufficient for reducing runoff and erosion after a heavy precipitation event [10]. Fire-induced tree mortality deposited pine needles on the ash surface, which further reduced the ash layer's susceptibility to the impact of raindrops. Fire severity, wind during and after the event and precipitation intensity affect the level of ash deposition and should be considered when assessing the effects of a wildfire on flood and erosion potential.

EFFECTS OF WILDFIRE, FLOOD, AND EROSION ON WATER QUALITY

Turbidity

One of the most visible water quality effects of wildfires is an increase in turbidity [11]. After wildfire, surface water turbidity can increase due to the suspension of ash and silt-to-clay-sized particles. This effect is related to slope steepness and rainfall events that cause erosion [11]. Turbidity is typically treated using sedimentation, coagulation and filtration processes, and is regulated because it can indirectly represent the presence of microbial pathogens in water [12]. The EPA regulates turbidity as a primary drinking water standard requiring 95% of samples to be less than 0.3 Nephelometric Turbidity Units (NTU) while no samples should exceed 1.0 NTU [13]. In addition to federal regulations, the Partnership for Safe Water requires 95% of the samples to be less than 0.1 NTU while no samples exceed 0.3 NTU [14].

Total Organic Carbon

Total Organic Carbon (TOC) includes both particulate organic carbon (POC) and dissolved organic carbon (DOC). The presence of organic carbon in drinking water is a concern because of its capacity to transform into harmful products during disinfection. When exposed to oxidants, organic molecules can form disinfection by-products (DBP's), which can adversely affect human health and infrastructure [12]. The EPA regulates TOC as part of the Stage 1 Disinfectants and Disinfection Byproducts Rule. The requirements depend on alkalinity and TOC concentration in the source water. For example, 25% TOC removal is required for a source water with an alkalinity of >120 mg/L as $CaCO_3$ and TOC concentrations of > 4.0 mg/L - 8.0 mg/L [15].

TOC is ubiquitous in water sources and naturally varies in composition of its two primary constituents, humic and fulvic acid. The origin of natural organic carbon can be from within the water body or on land and mobilized via runoff [12]. Wildfire contributes to TOC concentrations in water by depositing consumed plant matter as organic carbon in the form of ash. Post-wildfire runoff mobilizes surface organic matter, thereby increasing TOC levels in surface waters up to 100 times above pre-fire levels during first major precipitation events and maintaining elevated levels thereafter [4, 11]. In addition, wildfire heat can induce transformations in the soil organic matter, resulting in alterations of the organic carbon composition [16].

Post-wildfire TOC in surface waters has been treated with conventional coagulation, flocculation, sedimentation and filtration with varying degrees of success [4, 8]. The use of activated carbon can reduce TOC levels through adsorptive processes but is not commonly available at water treatment plants.

Color, Taste, and Odor

Organic carbon in water can contribute to color, taste, and odor problems [12]. Although color, taste, and odor issues are not major health concerns, they have been common complaints by municipal customers following treatment of fire-affected drinking water in the past [4, 8, 17, 18]. The greatest concern with color, taste, and odor issues is losing consumer confidence in the treatment facilities' ability to supply safe drinking water. Although no treatment processes directly target color, taste, and odor, benefit could be gained by addressing these issues through optimization of existing processes aimed at TOC removal.

Disinfection Byproducts

DBP formation results from chemical oxidation of natural organic matter (NOM) by disinfectants and is directly proportional to the DOC present in water during disinfection [12]. The presence of DBPs can be predicted by ultraviolet light absorbance at 254 nm (UV_{254}) because the preferred sites for chemical reactions on NOM are carbon-carbon double bonds and aromatic rings, which also absorb UV_{254} [12].

Like TOC, DBP's are regulated under the Stage 1 and Stage 2 disinfection byproduct rules, which set federal requirements for TOC removal based on source water character and size of population served by individual municipalities. These rules are additive, meaning the latter of which builds upon the former with more stringent maximum contaminant levels (MCLs) for specific DBP components [15, 19]. The Stage 1 and 2 DBP rules also set MCLs for the DBPs total trihalomethanes (TTHM) and haloacetic acids (HAA5) of 0.080 and 0.060 mg/L, respectively [15].

Metals

Many metals are commonly present in organic complexes within soils and in forest vegetation. Therefore, metals such as magnesium (Mg) and manganese (Mn) can be mobilized in the ash flows following a wildfire [11]. Evidence points to ash in runoff as the source for increasing metal concentrations in surface waters following precipitation [11]. Contrarily, if a point source of metal contamination already exists, such as mine drainage, dilution by a storm event will decrease the concentrations of metals in surface waters [20]. With the exception of Mn and iron (Fe), most records of metal concentrations in surface waters following wildfires in mining regions similar to Clear Creek Canyon indicate that total metal concentrations, as well as dissolved metal concentrations, rarely exceed regulated limits [21, 22].

Historically, the GWTP has experienced naturally elevated concentrations of Mn that surpass the National Secondary Drinking Water Regulation of 0.05 mg/L [13]. For this reason, the GWTP treats Mn with the addition of the oxidant potassium permanganate [17].

Alkalinity and pH

Depending on the intensity, ash deposition after a wildfire can cause increases in pH and alkalinity in both soil and water [23]. This appears to be a result of carbonates and hydroxides leaching from the ash [24].

Alkalinity and pH are important and closely related drinking water treatment parameters. pH determines the solubility and biological availability of chemical constituents, such as nutrients and heavy metals, while alkalinity represents the capacity of water to resist a change in pH. More specifically, alkalinity measures resistance to changes in pH tending to make the water more acidic due primarily to the three ionic species of hydroxyls, carbonates, and bicarbonates. Measurements of alkalinity and pH are commonly used to determine the hardness and corrosiveness of water. Lower pH levels (pH<6.5) lead to softer, acidic and more corrosive water in which metals dissolve more easily, thereby increasing their toxicity. Higher pH levels (pH>8.5) do not pose an immediate health hazard but can cause bitter taste, pipe scaling and a decrease in the effectiveness of chlorine disinfection [25]. In contrast, alkalinity is regulated by the EPA and the standard is 500 ppm, indirectly measured in terms of total dissolved solids [13].

Water treatment facilities use lime softening to remove hardness and precipitate alkalinity [12]. Also, feeding a mineral acid, such as hydrochloric or sulfuric acid, can neutralize the alkalinity of water by converting bicarbonates and carbonates into carbonic acid and lower pH. However, there

are other ways to adjust pH. For example, the GWTP uses additional ferric-based coagulant in order to lower pH. However, this treatment strategy would not be financially feasible given the substantial amount of coagulant that would be needed to lower the high pH and alkalinity levels expected from wildfire affected water.

Radionuclides

Naturally occurring and anthropogenic radionuclides are a pertinent issue in regards to the treatment and distribution of drinking water because of their potential harmful effects to human health, especially concerning cancer and kidney problems [13]. Among the several known species of radioactive contaminants, combined radium (226 & 228), gross alpha, beta particle and photon radioactivity, and uranium are currently regulated under the EPA Radionuclide Rule [26]. These naturally occurring radionuclides occur as a result of the long-term weathering and erosion of rocks containing trace amounts of each element. Mobilization occurs through the weathering process, followed by leaching into adjacent surface waters or groundwater aquifers. Based upon historical MCL violations in Colorado, radium and uranium are of the highest concern in regards to radionuclides [13].

Despite the concern for radium and uranium, our literature review yielded no significant indication that wildfire directly increases radionuclide release. Considering the natural route of exposure for radionuclides, an increase in radionuclide concentrations in Clear Creek would only result from a substantial change in the watershed subsurface and rock formations, such as major rockslides or mudslides. In addition, a report prepared by Malcolm Pirnie, Inc. and the Colorado School of Mines demonstrated that coagulation and filtration processes can remove uranium from raw water sources [13]. Such processes are already in place at the GWTP and have proven effective against radionuclides in historical testing data. For these reasons, additional testing for radionuclides was not considered within the scope of this research.

Fire Retardants

Fire retardants have not been known to cause problems for drinking water treatment plants in the Rocky Mountain region [8, 22]. However, very little monitoring specifically targets the impacts of fire retardants in drinking water sources, which may explain the lack of supporting arguments. The major components of fire retardants are ammonium salts and sodium ferrocyanide [27]. Other elements are also found in fire retardants. For instance, boron and antimony levels both increased following the Four Mile Canyon fire [22]. Although the source is speculated, it is believed that fire retardants caused the increased concentrations. Despite the increased concentrations of antimony and boron, antimony concentrations never exceeded drinking water regulation standards and boron is not regulated [22]. Due to the lack of data and supporting documents, the effect fire retardants have on drinking water is inconclusive and was not included in this study.

Nutrients

Nutrient loading can increase following a wildfire due to the rapid mineralization and dispersion of plant nutrients. There is also less plant uptake of nutrients from soil following a wildfire, which creates long-term elevated nutrient loading [11]. Nitrogen, ammonium, and potassium are nutrients found to increase post-wildfire [4]. Although nutrient loading can cause eutrophication in reservoirs, the reservoirs owned by the GWTP do not support algae growth due to swift storage turnover [28]. Therefore, nutrient loading may not be a concern for the GWTP, but should be considered for communities with larger reservoirs that support algae growth.

SCOPE OF RESEARCH

Based upon the investigation of effects of wildfire, flood and erosion on raw water quality, and available budget, the following parameters were selected to examine during bench and pilot scale experiments.:

- Turbidity
- TOC
- Color, taste and odor
- DBP's
- Metals: Mn
- Alkalinity and pH

III.   MATERIALS AND METHODS

A desktop study was conducted using Geographic Information System (GIS) software in order to determine the flood and erosion risk in the Clear Creek watershed. This software and several bench-scale experiments were used in the evaluation of potential water quality changes due to wildfire, in addition to testing treatment strategies for those changes. Following the bench-scale experiments, numerous pilot-scale water treatment tests were established in order to validate suggested treatment strategies.

For each of the investigations, the conditions simulated were intended to represent one of three categories of severity: Spring Runoff-like, High, and Severe. The investigators determined the quantitative and qualitative values represented by these categories specifically for the GWTP. They were defined based on literature and professional experience.

DESKTOP STUDY: FLOOD AND EROSION RISK

Soil conditions and physical configuration within a watershed can be used to characterize the potential for flood and erosion. The relative intensity of runoff events with respect to surface water quality can be predicted per basin in a watershed by applying GIS mapping of Composite Risk, created from flood and erosion data, using ESRI's ArcGIS software [23]. Basin contribution to deterioration in water quality following a wildfire and prior to a heavy precipitation event can then be ranked. GIS data for this study was collected from a variety of sources including the EPA's BASINS 4 software, the National Resources Conservation Service (NRCS) database, and the Clear Creek County's GIS Program [29].

Risk maps were produced for Clear Creek according to methodology outlined by the Front Range Watershed Protection Data Refinement Work Group and are presented below [23]. Following their guidelines, Flood Risk is a factor of basin height, basin area, and road density. Slope steepness and the presence of impermeable surfaces influences the generation of debris flows [30]. Similarly, Erosion Risk was generated from slope and the soil K-factor, an erodibility value assigned to different soil types. The data was classified into five quantiles defining Low, Moderate, High, Very High and Severe risk categories. The equations and methods for calculating Flood, Erosion and Composite Risk are outlined in Appendix A. Importantly, evidence for less variation in soil erodibility after wildfires exists and may be predicted as a function of soil temperatures during fires, in which case a simple erosion model could be generated from visible and infrared radiation mapping of affected areas [31].

Several assumptions were made in producing these maps. Firstly, the sensitivity of paved and dirt roads to generating debris flow was treated equally. This leads to an overestimation of Flood Risk in urban areas or small basins containing paved roads. Flood Risk of most concern relates to dirt roads occurring on hill slopes vulnerable to wildfire effects [32], the result of which propagates debris flows, and less related to impermeable surfaces in urban areas that may propagate storm flows in general. Secondly, cover-management factor, related to the type and density of vegetative cover as indicated in the RUSLE analysis, was not included when calculating Erosion Risk [33]. This was done in order to maintain a boundary between the factors independent of forest fires and those depending on them. Vegetative cover depends on the intensity of wildfires and could therefore alter the Erosion Risk. This choice results in an overestimation of Erosion Risk in areas with dense vegetative cover, as vegetation reduces the intensity of raindrop impact on the soil surface, and

therefore the potential for erosion. However, this protective effect would be negated if a wildfire consumed all the vegetation. Finally, geological maps of the watershed displayed substantial areas of granitic soils, which can lead to underestimated soil erodibility when only using K-factors [23, 34]. Although there is some evidence against the effect of granitic soils on soil erodibility, erodibility rankings were increased for areas with granitic soils as suggested by the CDPHE report [31]. For cases where data was not available, worst case scenario values were chosen as conservative estimates. For example, soil K factor was unavailable for some survey areas so values of 0.43, the highest reported throughout the watershed, were used.

BENCH AND PILOT-SCALE STUDIES: WATER QUALITY PARAMETER CHANGES AND TREATMENT STRATEGIES

Analytical Methods

Several analytical methods were used in order to examine different water quality parameters. The details of each method are listed in table 1.

Table 1: Analytical methods used throughout project duration.

Parameter	Make	Model*	Sample location	Sample Type	Notes
Conductivity (μS/cm)	Science Workshop	500 Data Logging Interface	Mini-Pilot •Source Water •Sedim. Basin Water •Filter 1 and Filter 2 Combined Effluent	PC Readout	
Dose (mL)	Rainin	EDP1	Jar Testing •All Collected Data	Instrument Setpoint	
Dosing Rate (mL/min)	Master Flex	7519-06 L/S Standard Digital Drive	Mini-Pilot •Chlorine Dosing	Instrument Digital Setpoint	A bucket test was conducted prior to Mini-Pilot operations and verified flow readout to be within 5% of output flow.
Dosing Rate (mL/min)	Master Flex	7518-00 L/S Standard Digital Drive	Mini-Pilot •$FeCl_3$ Dosing •PEC Dosing	Instrument Digital Setpoint	A bucket test was conducted prior to Mini-Pilot operations and verified flow readout to be within 5% of output flow.
Dosing Rate (mL/min)	Master Flex	77202-60 L/S Standard Digital Drive	Mini-Pilot •$KMnO_4$	Instrument Digital Setpoint	A bucket test was conducted prior to Mini-Pilot operations and verified flow readout to be within 5% of output flow.
Free Chlorine	HACH	DR/2500 Spectrophotometer	•All Data	Grab	
Flow (GPM)	+GF+ Signet	2000 Microflow Rotor Sensor with 8550-1 Flow Transmitters	Mini-Pilot •Filter 1 Effluent •Filter 2 Effluent	Instrument Readout	A bucket test was conducted prior to Mini-Pilot operations and verified flow readout to be within 5% of output flow.
Flow (GPM)	King	0-1 GPM Inline Flowmeter	Mini-Pilot •Influent	Instrument Readout	

Parameter	Make	Model*	Sample location	Sample Type	Notes
3D-Fluorescence	Jobin Yvon-Horiba	FLUOROMAX-4 Spectro-fluorometer	•Soil Samples	PC Readout	
Manganese	HACH	DR/2500 Spectro-photometer	•All Data	Grab	
pH	Beckman	Φ255	Jar Testing •All samples Mini-Pilot •Source Water •Settled Water	Handheld Readout	
TOC/ DOC/ WSOC	Sievers	5310 C TOC Analyzer	•All Data	PC Readout	
Turbidity (NTU)	HACH	2100N Turbidimeter	Jar Testing •All samples Mini-Pilot •Source Water •Settled Water	Grab	
UV/Visible	Beckman Coulter	DU 800 UV/Vis Spectrophotometer	•All Data	PC Readout	

* Equipment was calibrated according to manufacturer specifications prior to sample runs unless otherwise noted.

Ash, Sediment, and Water Source

Raw Clear Creek water was used as the primary source of water throughout most of the experiments. Additional components, such as ash and sediment, were added to the water in order to represent post-wildfire High and Severe water quality conditions. The ash used was collected from burnt firewood and dosed by volume. Ash volumes were determined by comparing rainfall and runoff volume with quantities of ash removed following wildfires and precipitation events. Runoff volume from experiments estimating runoff was 45-75% of rainfall [35]. Based on one study, the removal of 36 mm of ash was observed after 153 mm of rain that fell over six days [10]. Using the runoff estimate and observed ash removal, the daily rainfall was averaged and 95% of the ash was assumed to have been removed within the first two days, simulating an ash-heavy, first-flush event. The remaining 1.8 L of ash would form 2% by volume of the 77 L of rainfall over the following 4 days. This is a rough estimate of ash concentration and it is expected that actual ash loading is unique to each situation. In order to magnify the potential effects of ash on sedimentation and taste and odor for experimental purposes, this estimate was increased to 10% by volume, which also resembled some literature values [35].

Sediment used was collected from two sources. The first sample was obtained from a deposit on the North shore of the first retention pond at the GWTP, created from a pond dredging operation in 2009 [17]. The second source of sediment came from forested land in the Clear Creek watershed, near Idaho Springs, Colorado. These sources of sediment were used to represent the best available character of sediment loading in Clear Creek.

In addition to sediment loading, understanding the character of organic matter in the sediment was important in creating representative surrogate waters for bench and pilot-scale testing. For this reason, the organic matter of soil samples from the Fourmile Canyon Fire (2010) and the Hayman Fire (2002) were characterized.

Organic Matter Characterization: Fourmile Canyon Fire (2010)

The composition of fire-affected soil organic matter is variable and should be determined on a site-by-site basis in order to simulate the correct character of TOC in runoff [6]. For this study, the Fourmile Fire (2010) was selected for soil sampling because of its close proximity to Clear Creek and because revegetation had not yet occurred since the fire. Sixteen samples were taken. Four samples were obtained from burned Lodgepole pine stands, four from burned Ponderosa stands, four from an ash-laden gully representing ash runoff, and four from an unburned Ponderosa pine site. Samples were taken from the uppermost organic (O) horizon and the organic-rich, fully-decomposed A horizon, to a depth of 2", and from different locations within a 20 ft radius. 50 mL plastic vials were filled with soil samples.

In order to determine the water-soluble organic carbon (WSOC), the samples were immediately transported back to CSM, refrigerated at 4ºC and, within a week, they were dried for 24 hours at 80°C prior to elution. Soil samples were then eluted using a 1:5 weight/volume ratio of soil to deionized water into 50 mL centrifuge tubes, placed horizontally and mechanically shaken for 30 minutes on a VWR shaker table for homogeneous mixing, and immediately centrifuged at 3000 rpm for 15 minutes using an Eppendorf 5810 centrifuge. The supernatant was decanted and filtered to 0.45 μm using ⊘25 mm Pall SUPOR® membrane filters and refrigerated. DOC (as WSOC) data was analyzed and recorded with a SIEVERS 5310C TOC Analyzer (adapted from [36]). UV absorbance at 254nm was determined with a Beckman Coulter DU 800 UV/Vis Spectrophotometer. Analysis was followed by 3-D fluorescence spectroscopy with a Jobin-Yvon Horiba FLUOROMAX-4

Spectrofluorometer for the generation of excitation-emission matrices (EEMs) that would speak to the character (humic acid, fulvic acid, biopolymers) of burned and control post-wildfire soil organic matter. For this method, samples that had previously undergone the WSOC determination were now adjusted to a pH between 6-8 and normalized through dilution to a TOC content of 1 mg/L, for them to be comparable among each other [37]. Once the character was determined to be mainly of humic nature, the addition of humic acid to the surrogate waters was used in order to represent a higher concentration of humic acid in post-wildfire organic matter.

Organic Matter Characterization: Hayman Fire (2002)

Soil samples from the Hayman Fire (2002) were used to confirm the characterization determined from the Fourmile Canyon Fire (2010) soil samples. The Hayman Fire (2002) soil samples were collected from the Center for Experimental Study of Subsurface Environmental Processes (CESEP) at CSM. These samples were taken on June 11th, 2011 from two different locations affected by the fire, along with two control samples, and preserved. The samples were obtained to a depth of up to 5 cm.

In order to determine the water-soluble organic carbon (WSOC) and the character of the soil organic matter of a burned and a control sample, the same preparation and analysis methods were used, as with the Fourmile Canyon Fire (2010) samples.

Surrogate Water Composition

Various compositions of water were used throughout the bench- and pilot-scale experiments. The constituents, and the water quality parameter they affect, are described in Table 2. References to water types presented in this report will be based on Table 2.

Table 2: Composition of water types used during experiments including components added and water quality parameters affected.

	Water Source	Ash (H₂O vol%)	Sediment (g/L)	Humic Acid (mg/L)ᵗ	CaCO₃ (mg/L)	HCl
Affected Parameter	Turbidity, TOC, Mn, Alkalinity, and pH	Turbidity and TOC	Turbidity	Turbidity and TOC	Alkalinity	pH
Type 1	Clear Creek	-	-	-		As Needed
Type 2	D.I.	10	-	-	-	-
Type 3	Clear Creek	-	133†	-	-	-
Type 4	Clear Creek	-	200†	-	-	-
Type 5	Clear Creek	10	17.0‡	-	-	-
Type 6	Clear Creek	-	17.0‡	-	-	-
Type 7	Clear Creek	2*	-	5.0	240	As Needed to lower to 6.8
Type 8	Clear Creek	2*	-	10.0	240	As Needed to lower to 6.8

ᵗ 25% Carbon

† Source 1 sediment from the west retention pond at the GWTP.

‡ Source 2 sediment from forested land in the Clear Creek watershed near Idaho Springs, Colorado.

*The ash in these waters was allowed to settle for approximately 24 hours and the supernatant was decanted before use.

Activated Carbon Selection

Sorption Test

Sorption isotherms were produced from two types of Norit activated carbon (HD 3000 and 300) in order to determine which carbon type provides optimal adsorption capacity for waters with elevated TOC. Both types of activated carbon were selected for their advertised ability to remove color, taste and odor, which are all associated with high TOC concentrations [12]. Since both types of activated carbon were provided in granular form, they were first ground into powder. Next, Type 8 water (Table 2) representing Severe TOC conditions was filtered first through a borosilicate glass filter, then through a 0.45 μm membrane filter and 200 mL each was poured into twenty-two glass jars with stoppers. Eleven concentrations (0, 20, 60, 120, 200, 400, 600, 800, 1000, 1500 and 2000 mg/L) each of Norit HD 3000 and Norit 300 powder activated carbon (PAC) were added to the jars. Immediately after the PAC was added, the solutions were mechanically shaken on a VWR shaker table for over 24 hours. The samples were then filtered through a 0.45 μm membrane filter and processed for DOC.

Taste and Odor Assessment

In addition to the isotherm, a taste and odor experiment was used to determine which of the two types of GAC offered better taste and odor removal. Six jars were filled with 200 mL of Type 2 water, in order to represent Severe TOC conditions. The flasks were secured in a box and mechanically shaken on a VWR shaker table for over 24 hours to ensure any soluble constituents would leach out. This water was added to six jars in addition to 20 mg/L each of Norit HD 3000 and

Norit 300 PAC in triplicate and placed on the VWR shaker table for 10 minutes. The samples were filtered using 0.5 µm filters prior to conducting a taste and odor assessment according to the Threshold Odor and Taste Test standard to determine threshold odor and taste numbers for the samples [38]. Each sample was warmed to be in the range of 40 to 60^0C and three sets of dilution series, composed of four dilutions (1x, 10x, 100x, 1000x), were prepared for each sample. Finally, three testers first smelled and then tasted a dilution series for each sample beginning with a blank and followed by the highest to lowest dilution. Testers were unaware of this order. If a tester detected an odor or taste, the sample was assigned a threshold number that corresponded to the dilution value. For example, if an odor was detected in the 10x dilution, the odor threshold number is 10. The final threshold numbers were averaged between the three testers for each sample.

Coagulation Optimization

Five sets of coagulant optimization jar tests were performed in order to first determine the optimal pH and later the concentration at which the coagulant would have optimal turbidity and DOC removal (Table 3). A Phipps-Bird 7790-901B jar testing system was used with six 2 L jars for each set of tests. The primary coagulant used was 5% ferric sulfate [$Fe_2(SO_4)_3 \cdot 9H_2O$] in addition to 0.01% cationic polymer solution (PEC) as a secondary coagulation enhancer. Turbidity and DOC by way of UV_{254} analysis was measured in the supernatant initially and at the end of the experiments. For each of the sets the jars were initially mixed for 1 minute at 150 rpm while the ferric sulfate was injected. Subsequently, the mixing was reduced to 30 rpm and PEC was injected. After 20 minutes of mixing at 30 rpm, settling occurred for 45 minutes. The optimal pH was based on lowest residual turbidity whereas optimal coagulant dose was a compromise between both turbidity and TOC removal.

Table 3: Jar tests performed for pH (set 1) and coagulant (sets 2 - 5) optimization using water types 0, 5 and 6 (Table 2).

Set	Water Type	pH	Ferric Sulfate (mg/L)	PEC (mg/L)
1	0	5, 5.5, 6, 6.5, 7, and 7.5	10, 20, 30, 40, 50, 60	0.4
2	5	6.5 - 7	10, 20, 30, 40, 50, 60	0.4
3	5	6.5 - 7	5, 10, 15, 20, 25, 30	0.4
4	6	6.5 - 7	2.5, 5, 7.5, 10, 15, 20	0.4
5	6	6.5 - 7	10, 15, 20, 25, 30, 35	0.4

Pre-Plant Sedimentation Evaluation

The pre-plant sedimentation study was used to quantify the reduction in turbidity that occurs within the retention ponds located after the intake from Clear Creek and to evaluate the effectiveness of adding a coagulant to enhance the pre-plant settling process. Three sets of test were performed. The first set of tests evaluated the kinetics of settling for Severe condition turbidity. The second set of tests assessed settling as a function of turbidity character for Severe condition turbidity. The last set of tests evaluated the effectiveness of a coagulant on Severe condition turbidity removal.

For the first set of tests, three plastic settling columns were each filled with 6 L of Type 3 water (Table 2), and three plastic settling columns were each filled with Type 4 water (Table 2). Samples were taken from the supernatant and turbidity was measured initially and at 1, 2, 3, 4, 5, 6, 10, 22.5, 30.5, and 39 hours. The final three samples represented the shortest possible retention time in the holding ponds (22.5 hours), the shortest historically recorded retention time (30.5 hours), and the average retention time during the summer months when demand is high (39.0 hours) [17].

The second set of tests was setup similarly with 6 L of Type 5 water (Table 2) in three columns and 6 L of Type 6 water (Table 2) in the remaining three columns. The effect of Severe condition ash on turbidity removal through settling was analyzed in these tests. Samples were taken from the supernatant and turbidity was analyzed initially and at 22.5 hours.

In the last set of tests, Type 8 water (Table 2) was used to represent Severe turbidity, alkalinity, and pH. All six settling columns were each filled with 6 L of water while rapidly mixed doses of different concentrations (0, 20, 30, 40, 50, 60 mg/L) of ferric sulfate were added. Turbidity, pH, and alkalinity were analyzed initially and after 22.5 hours.

PILOT-SCALE EXPERIMENTS: VALIDATION OF TREATMENT STRATEGIES

A previously constructed mini-pilot plant was used for validating treatment strategies at the pilot-scale (Figure 2). A submersible recirculation pump was used to pump water into the first of three flocculation basins containing variable speed mixers, succeeded by a sedimentation basin with eight settling plates. Following the sedimentation basin, two dual-media filtration columns were used. The first column (Column 1) consisted of sand and GAC, whereas the second column (Column 2) contained sand and anthracite. The Norit HD 3000 GAC selected for the first column was determined by the bench-scale *Taste and Odor Assessment*.
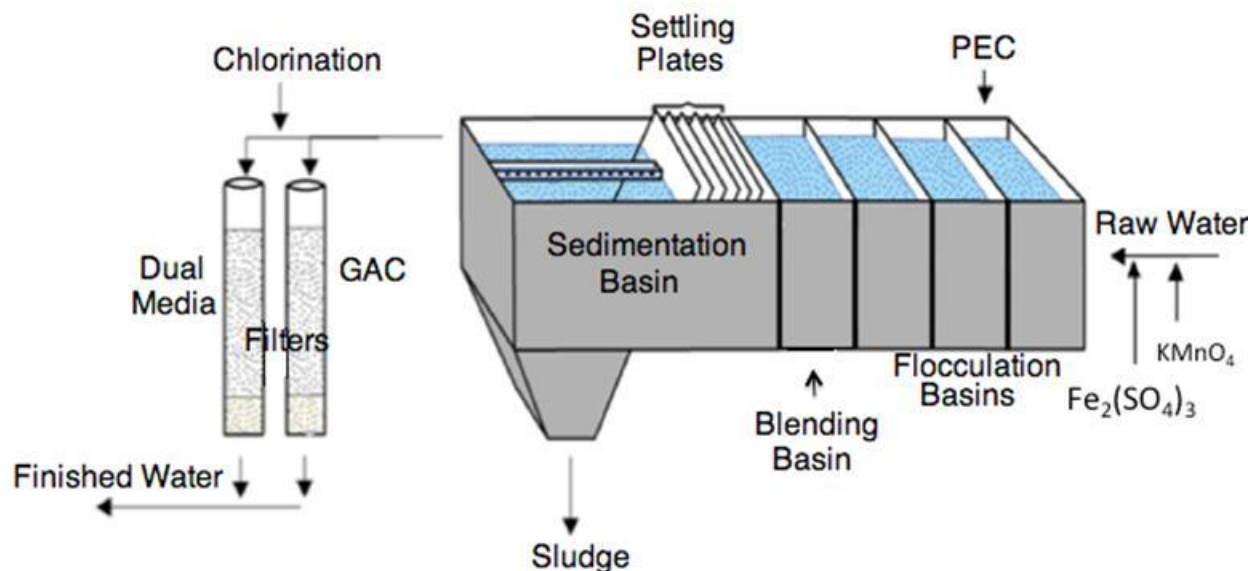
Figure 2: Process flow diagram of CSM Mini-Pilot Plant (adapted from [39]).

Potassium permanganate ($KMnO_4$) was dosed immediately after the surrogate water left the storage barrels to encourage adequate inline mixing and oxidation. Ferric sulfate was also dosed in the feed line, following the potassium permanganate, and finally polymer was dosed in the first flocculation basin. Dosing was performed using Masterflex L/S pumps, models 77202-60 and 7519-06. The dose was controlled electronically by adjusting the flow rate through the dosing pump. A flow meter consistently monitored water volume into the flocculation basins, which was adjusted

by using a valve immediately prior to the first flocculation basin. After leaving the sedimentation basin, Chlorine was dosed immediately prior to entering Column 2.

Influent samples were taken from the storage barrels for analysis. The barrels were continually mixed to ensure consistent influent water characteristics. Following treatment, finished water samples were taken from either Column 1 or Column 2.

Several experimental runs were organized with Type 7 and Type 8 water (Table 2) in order to represent High and Severe water quality conditions. Each run lasted approximately 5 hours or until finished water characteristics stabilized.

IV.   RESULTS AND DISCUSSION

WATERSHED RISK ASSESSMENT RESULTS[1]

Fire Risk

According to the Colorado State Forest Service (CSFS), the fire hazard in the Clear Creek watershed ranges from low to very high [40]. However, a substantial part of the watershed is considered to be in the high wildfire risk region (Figure 3). This risk assessment addresses the entire health of the forest, including insect kill [41]. As a large portion of the Clear Creek watershed is at high risk, the GWTP needs to be concerned about the potential of wildfire.
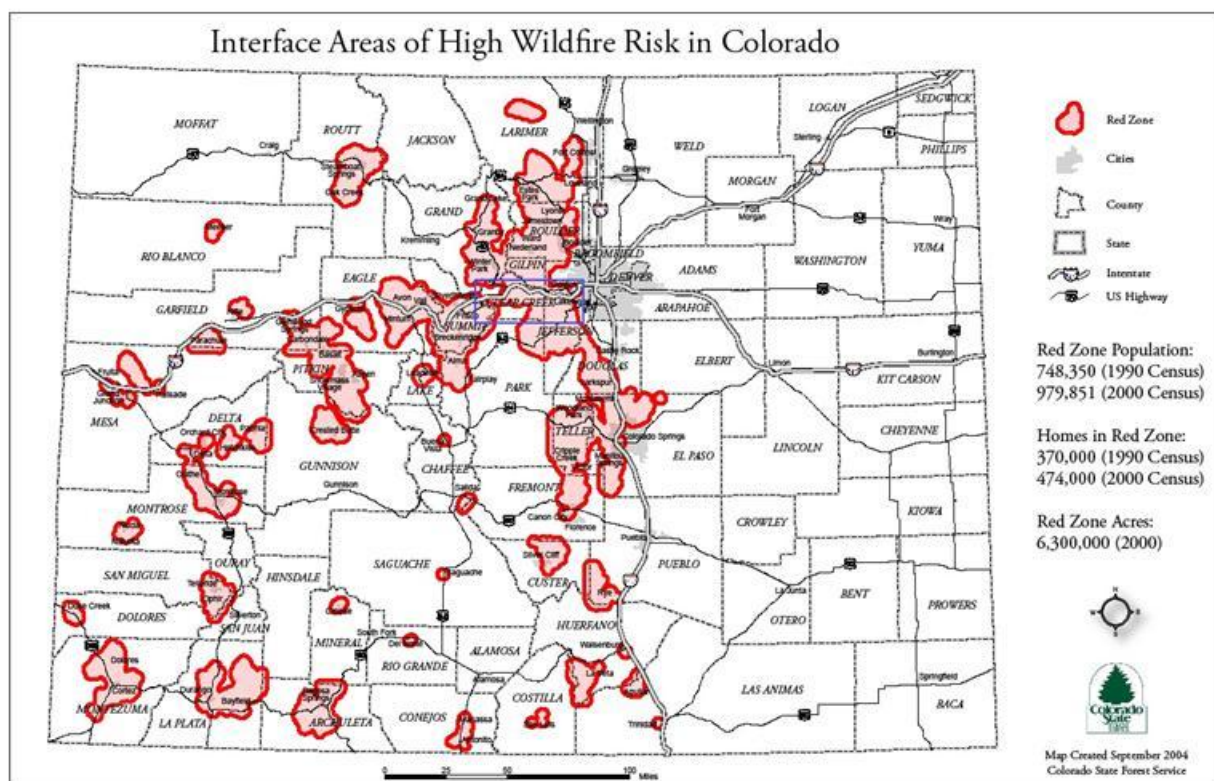
Figure 3: Interface Areas of High Wildfire Risk zones in Colorado [40]

Flood Risk

Flood risk exists to a varying extent throughout the Clear Creek watershed(Figure 4). Basins along the I-70 corridor between Graymont and Idaho Springs exhibit a consistently elevated flood risk, and municipalities with intake structures in this reach of Clear Creek should be wary of damaging debris flows during high intensity precipitation events. The Beaver Brook tributary, which is relatively close upstream of the GTWP, drains several basins with very High and Severe Flood Risk.

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[1] Objective 1. Ascertain the risk of wildfire in the Clear Creek Watershed and Objective 2. Establish the risk of runoff as a result of wildfire in the Clear Creek Watershed.

The upper most reaches of Ralston Creek, upper Fall River around St. Mary's, and the basins north and west of Black Hawk are also regions of concern. Flood Risk in these basins is strongly influenced by road density (Figure A - 1). Furthermore, these are urban areas with many paved roads, resulting in overestimated Flood Risk for these basins. If any of these regions are impacted by intense rainfall, the water quality in Clear Creek and the GWTP intake may be adversely affected.
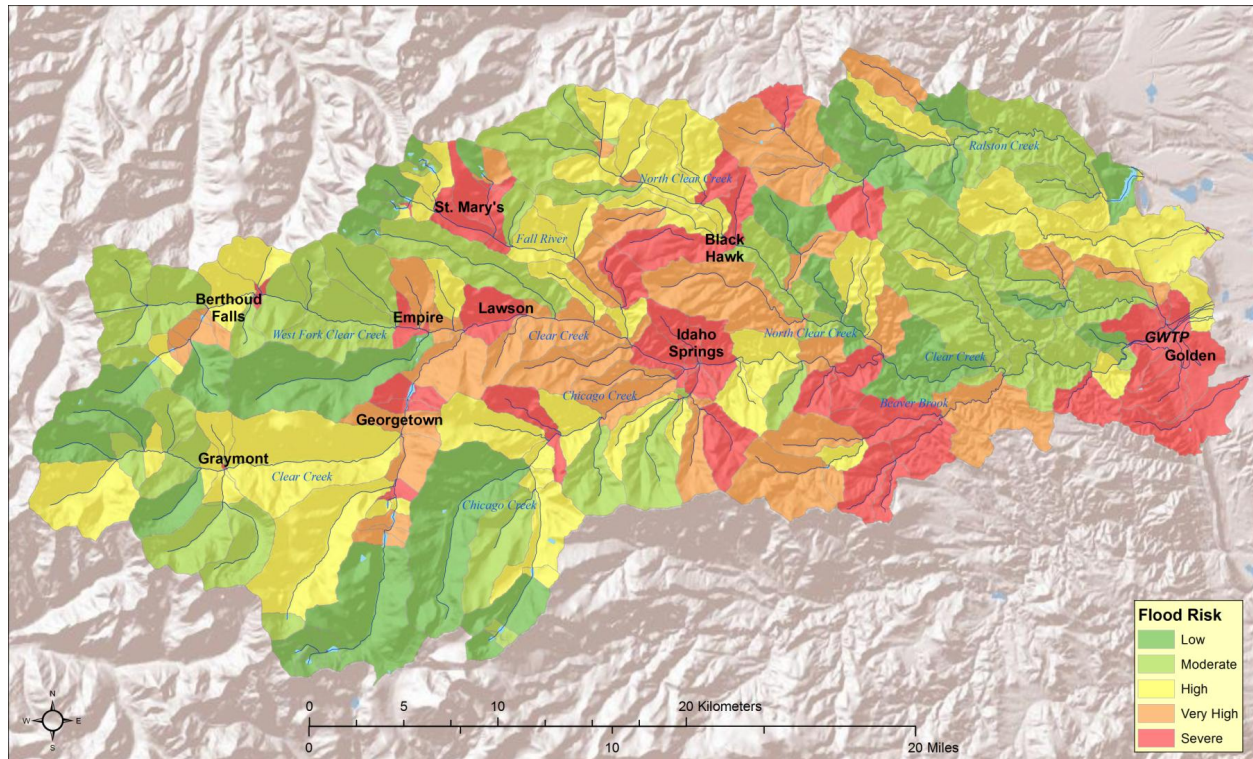
Figure 4: Flood Risk for Clear Creek Watershed, Colorado. Flood Risk is composed of basin height, basin area and road density.

Of particular interest to the GWTP are the upstream reservoirs that serve long-term water demand. Large debris flows in basins containing reservoirs will have negative impacts on water supply. The Georgetown Reservoir, Clear Lake, Lower Cabin Creek Reservoir (south of Georgetown), and the reservoir under control by the City of Golden at the Henderson Mine (southwest of Berthoud Pass) are in the highest two Flood Risk categories (Figure 5). Flood mitigation strategies would be most valuable in the aforementioned basins in order to protect long-term drinking water supplies.
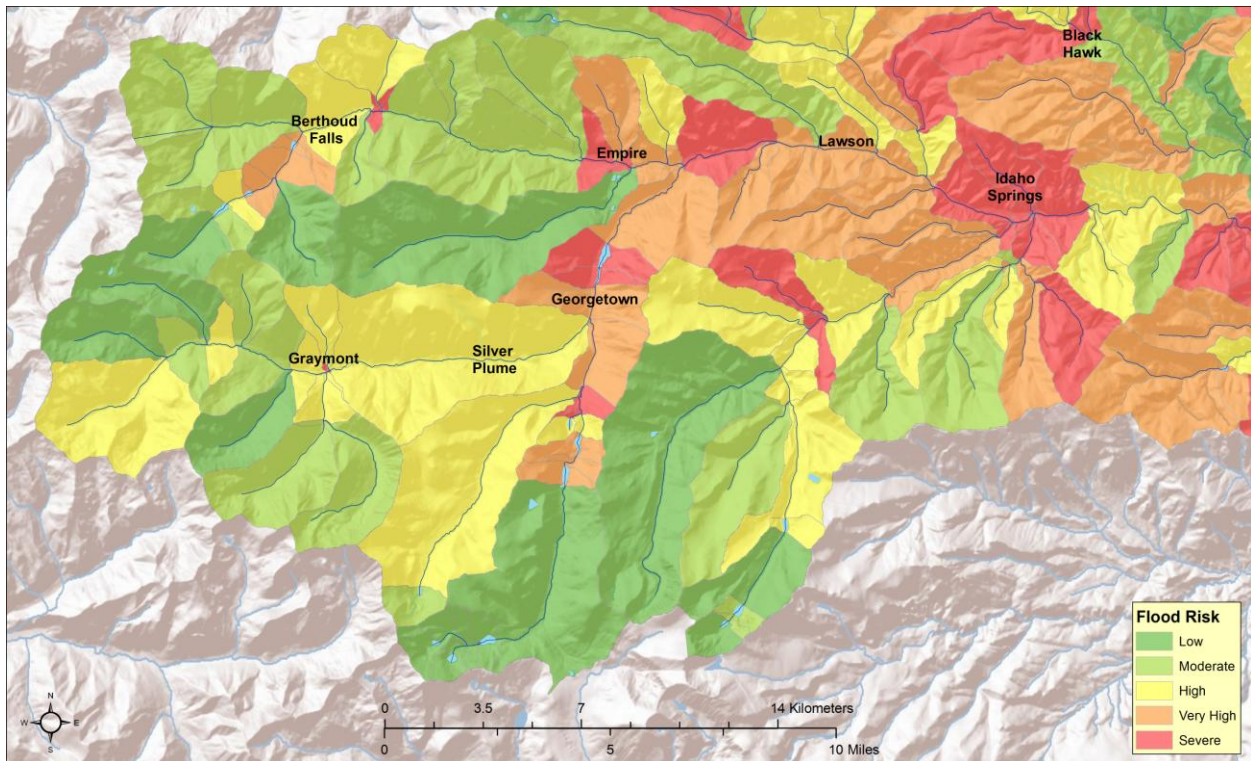
Figure 5: Flood Risk focusing on drinking water reservoirs in western Clear Creek Watershed, Colorado.

Erosion Risk

There are some clear patterns for Erosion Risk across the Clear Creek watershed. Most notably, Severe Erosion Risk is concentrated in the western region of the watershed, including the basins surrounding the municipalities of Graymont, Georgetown, Empire and Berthoud Falls (Figure 6). The basins draining into the West Fork of Clear Creek and all of Clear Creek south of Empire are among the areas very sensitive to erosion. As these basins are major headwaters for Clear Creek, extensive rainfall in these areas would result in severely deteriorated water quality at all downstream municipalities including the GWTP. The reservoirs at Henderson Mine and in Georgetown are also extremely vulnerable to erosion from the surrounding basins, in addition to flooding.
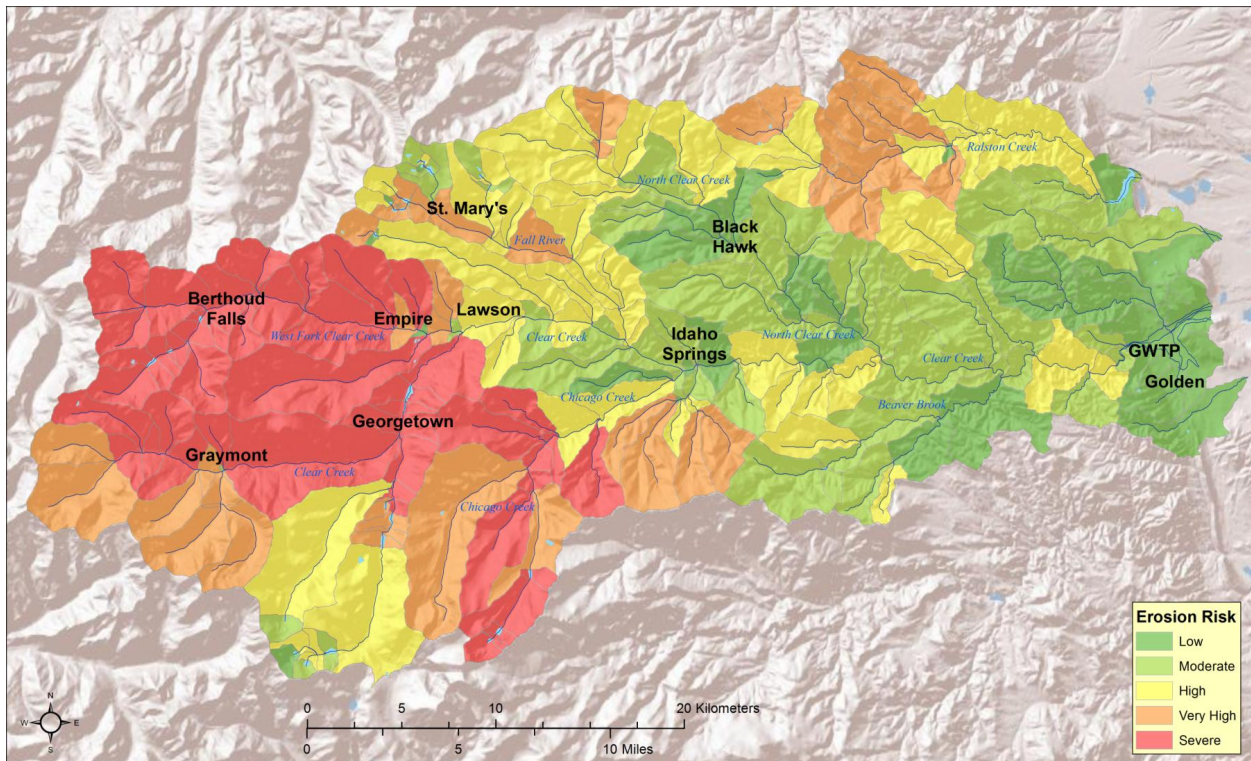
Figure 6: Erosion Risk for Clear Creek Watershed, Colorado. Erosion risk is composed of slope, soil K-factor and the presence of granitic soils.

Composite Risk

Patterns for Composite Flood and Erosion Risk for Clear Creek watershed closely resembles Erosion Risk. Of all areas within the watershed, the upstream western region of the watershed is most at risk from flood and erosion if a wildfire and heavy precipitation event were to coincide among the basins in the region (Figure 7). Again, the municipalities of Georgetown, Empire, Graymont and Berthoud Falls are most at risk to flood and erosion. It is important to note Golden's subsurface water supply near Empire may be protected from short-term sediment loading. Upper Chicago Creek also drains into sensitive basins, which is important for Idaho Springs and the reaches of Clear Creek downstream. Although the basin surrounding Idaho Springs is at Severe risk, this rating is attributed to Flood Risk, which in urban areas is overestimated by the high density of paved roads. The upstream reaches of Ralston Creek also fall under Very High risk, although Ralston Creek is a tributary to Clear Creek downstream of the GWTP.

Historical debris flow locations in Clear Creek Watershed [42] were superimposed on the Composite Risk map (Figure A - 5). This confirmed the methods used for calculating Composite Risk, as the locations for debris flows occur in Very High and Severe Risk Basins.
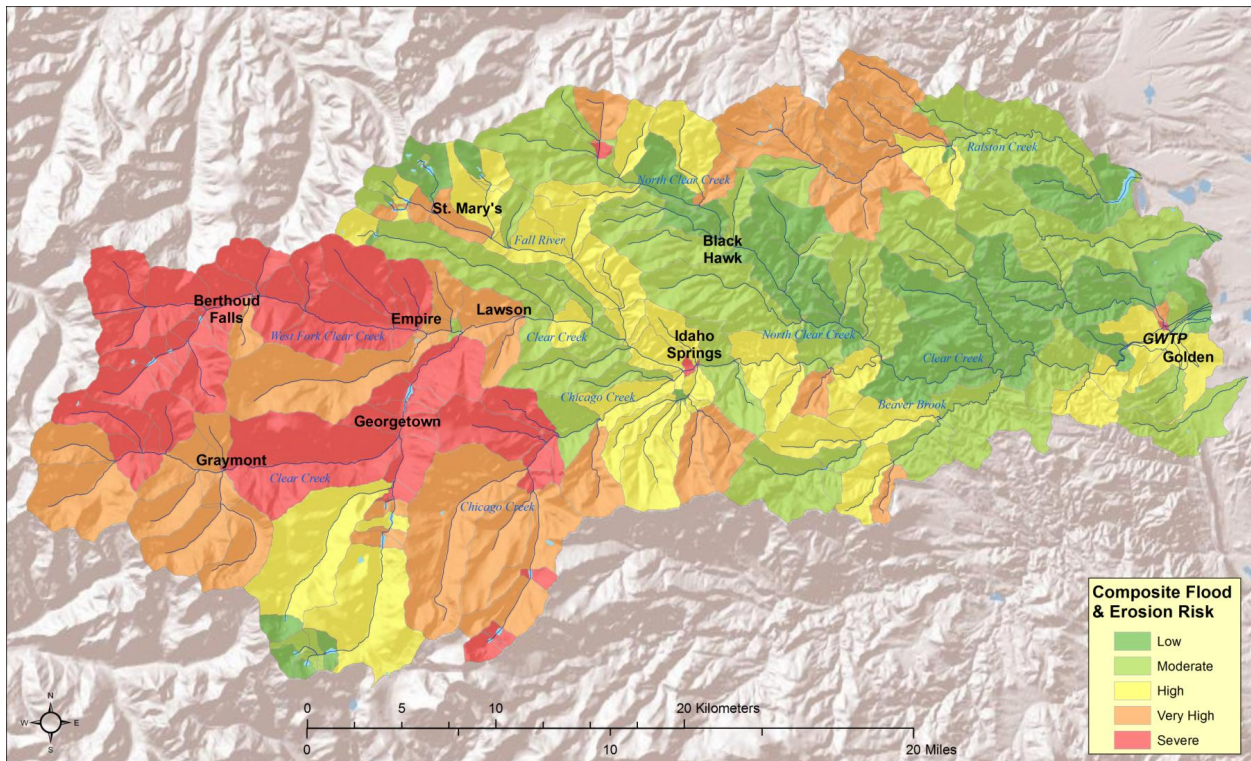
Figure 7: Composite Flood and Erosion Risk for Clear Creek Watershed, Colorado.

Caution should be used when evaluating risk maps. It is important to compare the Composite Risk map with each of the Flood and Erosion Risk maps to understand which factor is contributing more risk. Vegetation type and density can also have an impact on risk depending on fire severity and should be taken into account when analyzing an area under threat. For example, low intensity wildfire that only chars surface litter in highly vegetated areas will have less of an effect on erosion than in areas of low vegetation.

Precipitation Intensity and Fire Severity

In order to provide relative comparisons of rainfall events, precipitation intensity should be based on regional trends. The National Climatic Data Center (NCDC) provides access to weather gauges from which Lawson, Colorado, was chosen as the most representative location within the Clear Creek watershed. Albeit incomplete, hourly rainfall data from 1975 through 2011 [5] was tabulated to examine the frequency and intensity of rainfall events (Table 4). Assuming random sampling, the data was scaled to represent the entire time period. Based on the scaled values, *Low* precipitation intensity was defined by hourly events occurring most often. High intensity hourly events occur the least often at less than an average of 7 hours per year and the *Moderate* category covers the values between the former two. The *High* intensity cutoff value of 0.31 in/hr is supported by Coe and Godt (2003) [42] in their report on debris flows in Clear Creek County [42], where a debris flow following a 4 hour rainfall event with precipitation values close to 0.33 in/hr is documented. It is important to note that another 0.41 inches fell the following day, contributing to total rainfall for the event [42]. Event duration should also be considered when evaluating a given situation. Moderate precipitation lasting longer periods of time could have similar effects as heavy, short events.

Table 4: Frequency and Intensity of Rainfall Events measured at the Lawson, CO weather gauge between 1975 and 2011 [5] scaled to 36 full years. Cutoff hourly values for Low, Moderate and High precipitation intensities are defined by the dashed lines.

Precipitation (0.01 in/hr)	Frequency (hours)	Frequency scaled to 36 years (hours)	Hours per year	Intensity rating
0	66628	295774.3		
10	3957	17565.9	*8703.9*	Low
20	276	1225.2		
30	122	541.6	*49.1*	Moderate
40	26	115.4		
50	12	53.3		
60	6	26.6		
70	3	13.3		
80	5	22.2		
90	0	0		
100	1	4.4		
110	2	8.9		
120	0	0		
130	1	4.4		
140	0	0		
150	0	0		
160	0	0		
170	0	0		
180	1	4.4	*7*	High

Confusion often exists in the literature when using terminology to define fire intensity and severity. The US Forest Service (USFS) mentions the need to explain and define its use whenever it needs quantification. Keeley (2009) [43] suggests maintaining the original definitions for fire severity that are presented in Table 5 alongside precipitation intensity [43]. It is important to note that the fire severity definitions used by the US Forest Service's Burn Area Emergency Response assessment are similar and can be considered analogous to the ones presented herein. These definitions are used to classify a given situation and outline the suggested responses in the *Recommendations* section.

Table 5: Definitions of Fire Severity [43] and Precipitation Intensity for use in the situation assessment matrix (Table 10).

Fire/Precipitation Rating	Fire Severity	Precipitation Intensity (in/hr)
Light/Low	- Canopy trees with green needles although stems scorched - Surface litter, mosses, and herbs charred or consumed - Soil organic layer largely intact and charring limited to a few mm depth	0 - 0.10
Moderate	- Trees with some canopy cover killed, but needles not consumed - All understory plants charred or consumed - Fine dead twigs on soil surface consumed and logs charred - Pre-fire soil organic layer largely consumed	0.11 - 0.30
High	- Canopy trees killed and needles consumed - Surface litter of all sizes and soil organic layer largely consumed - White ash deposition and charred organic matter to several cm depth	> 0.31

POTENTIAL WATER QUALITY CHANGES[2]

Literature Review Results

Turbidity

Few post-wildfire values for turbidity can be found in the literature for reasons including the need to sample during sporadic flood events. Further, available documented turbidity values vary greatly [11, 44]. For example, in 2002 the turbidity at the intake of the Durango Water Treatment Plant was recorded at 3640 NTU during the first major storm event after the Missionary Ridge Fire (2002), compared to a typical pre-fire value of 1.8 NTU at the intake. Other turbidity values recorded range from 6.7 NTU to 38.5 NTU during the years following wildfire in the watershed [4]. In spite of these discrepancies, it can be expected that turbidity during the first major runoff flush following fire can reach the tens of thousands of NTUs [44]. In this case, targeted treatment strategies will be required to not exceed the allowable water quality standard set forth by the EPA, which is to be less than .3 NTU for 95% of the samples and never to exceed 1 NTU. In addition, the Partnership for Safe Water limit of less than 0.1 NTU for 95% of samples and never to exceed 0.3 NTU stresses the need for effective treatment [13, 14].

Total Organic Carbon (TOC)

After the Missionary Ridge Fire (2002), TOC concentrations increased to a maximum 18.7 mg/L immediately following the first major runoff event and stayed high during the following years. Other recent fires in the Southwestern US show similarly-elevated levels of DOC after the first major runoff event and DOC levels of 5-8 mg/L for years afterwards are common [4, 21].

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[2] Objective 3. Determine the potential changes to the water quality parameters in Clear Creek following a wildfire.

The character of TOC is also expected to change following a wildfire. Size-exclusion chromatography (SEC) of DOC performed on post-wildfire runoff from the Missionary Ridge Fire (2002) suggests that the organic carbon is primarily humic in nature [4]. This result matches other findings that indicate an increase in humic composition after fire [45]. Humic acids from recently burnt soils compared with unaffected soils (burnt 100+ years ago) were determined to be less aliphatic and more aromatic in nature [46]. An assessment of SUVA data (2000-2005) provided by Denver Water confirms an increase in aromaticity of DOC following fire (Figure 8) [8]. Almendros et al. [47] observed a reduction in aliphatic, carboxyl, and other oxygen containing functional groups during tests on humic substances and confirmed their results with field data [45]. These alterations had a detrimental effect on the colloidal properties and solubility of humins [45].

EEM spectra generated from the Fourmile Canyon Fire (2010) and Hayman Fire (2002) soil samples provide additional confirmation of these findings, particularly for the watershed of concern. The EEM spectra show the main components of the organic matter in the samples were formed of stable humic acids and biopolymers, as was expected. The organic character can be observed in Figure 8 and Figure 9, where two samples are shown: one from a burned area and another from a control area, for each of the soil sample origin locations. The organic makeup following fire is shifted to primarily humic in nature, validating the surrogates created for the pilot plant experimentation.
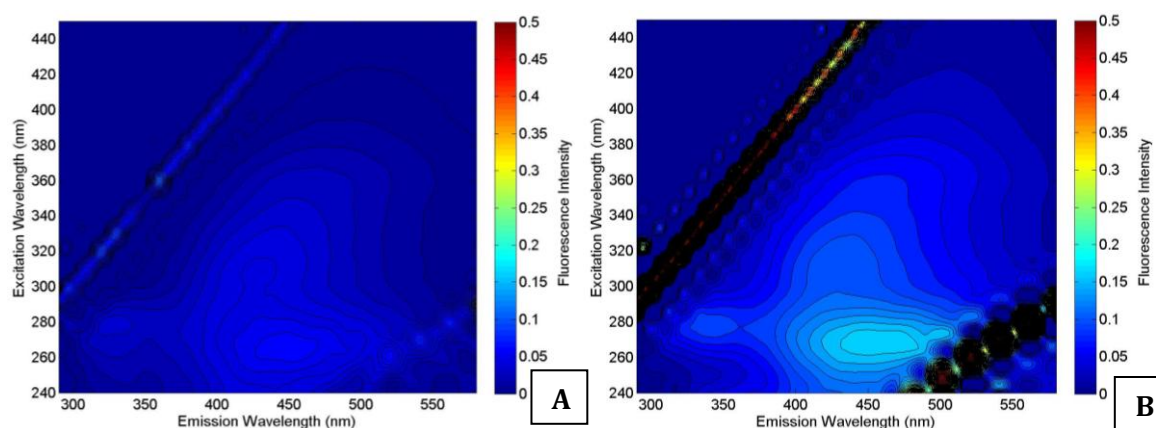
Figure 8: EEMs from A) a control sample and B) burned soil sample from the Hayman Fire.
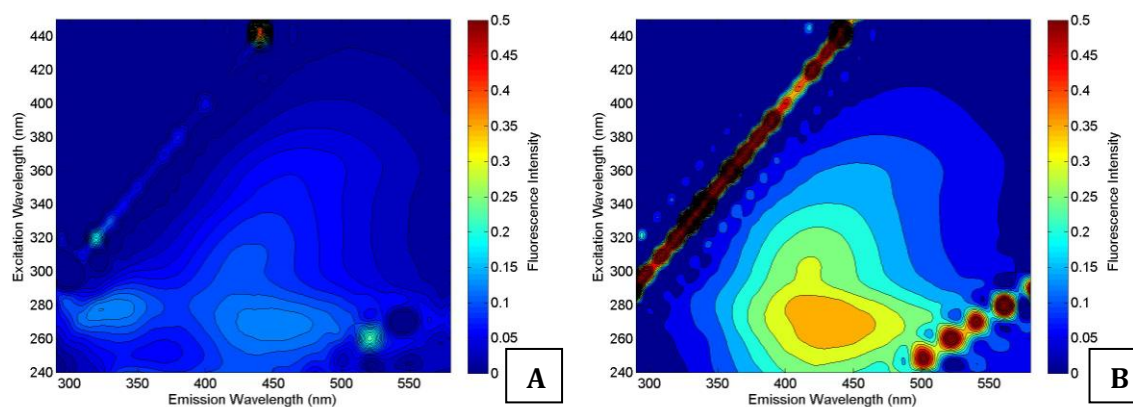
Figure 9: EEM spectra from A) a control sample and B) burned soil sample from Fourmile Canyon

Literature suggests color, taste and odor are directly related to the concentration and character of TOC in water. Elevated levels of TOC are known to turn water yellow-brown in color [12]. Furthermore, customers reported a "smoky" smell and taste in their tap water post-wildfire [4, 8, 17, 18]. Therefore, an increase in TOC concentrations should also indicate the potential for color, taste, and odor problems.

Disinfection By-products

Fire-affected TOC is more humic and aromatic in nature, making TOC in post-wildfire runoff more likely to serve as DBP precursors. Increases in DOC-normalized SUVA values, which are linearly correlated with TTHM formation potential, were recorded after the Hayman Fire (Figure 10). These results confirm that DBP formation potential is greater after fire. Thus, optimized TOC removal also is important for compliance with stage 1 and stage 2 disinfection byproduct rules.
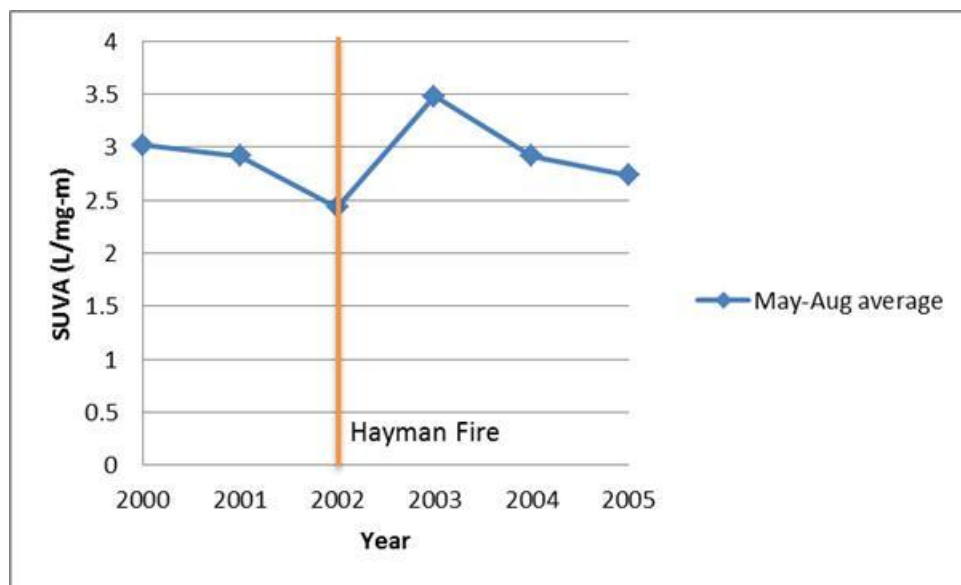
Figure 10: Average Raw Water SUVA (May-August, L/mg-m) recorded by Denver Water's Foothills plant from 2000 to 2005 [8]. Vertical line represents year of the Hayman Fire.

Metals

Of the contaminants tested following the Hayman Fire (2002), only Aluminum (Al), Fe, and Mn exceeded regulatory drinking water standards for total metal concentration at the Cheesman Lake Inlet. Of these three metals, only Mn exceeded secondary treatment standards for dissolved metal concentration as shown in Table 6 [21]. Following the Fourmile Canyon Fire (2010), no metals exceeded regulatory drinking water standards [22].

Table 6: Metal Concentrations at the Cheesman Lake Inlet Before and After Hayman Fire [21]

Contaminant	Average Pre-Fire Concentration (mg/L)	Average Post-Fire Concentration (mg/L)	Post-Fire Range (mg/L)	MCL (mg/L)
Aluminum - Dissolved	0.087	0.027	0.02 - 0.056	0.05 - 0.2 (S)
Aluminum - Total	-	2.2	0.065 - 20	0.05 - 0.2 (S)
Arsenic - Dissolved	-	0.001	0.0008 - 0.002	0.01
Arsenic - Total	-	0.0014	< MRL - 0.005	0.01
Barium - Dissolved	-	0.053	0.04 - 0.09	2
Barium - Total	-	0.1	0.055 - 0.41	2
Iron - Dissolved	0.044	0.069	0.03 - 0.14	0.3
Iron - Total	0.3	4.3	0.1-32	0.3
Lead - Total	-	0.005	< MRL - 0.01	TT5 Action Level: 0.015
Zinc - Dissolved	-	<MRL	< MRL	5 (S)
Zinc - Total	-	<MRL	< MRL	5 (S)
Cadmium - Dissolved	-	<MRL	< MRL	0.005
Manganese - Dissolved	0.01	0.086	0.013 - 0.42	0.05 (S)
Manganese - Total	0.052	0.3	0.02 - 1.7	S)

pH and Alkalinity

After a wildfire, depending on the intensity, ash deposition can cause an increase in pH and alkalinity in both soil and water. pH levels may range from 8.5 to above 10 [23], whereas alkalinity may increase to up to 300 mg/L, as it did after the Zaca Fire (2007) [4].

Summary of Expected Water Quality Changes

Increases in turbidity, TOC, Mn, pH, and alkalinity are expected after a wildfire in the watershed, especially immediately after precipitation events. The increase in TOC could also lead to issues with color, taste, and odor, along with increased potential for DBP formation. The results from the literature review suggest water quality changes post-wildfire as presented in Table 7.

Table 7: Expected Water Quality Changes for Spring Runoff-Like, High, and Severe Water Quality Conditions.

Parameter	Notes	Spring Runoff	High	Severe
Turbidity (NTU)	Into retention ponds	2 - 10	1 - 500	> 500
	Into treatment facility	< 10	10 - 150	> 150
TOC (mg/L)		< 4	5 - 10	> 10
Taste and Odor	Qualitative	Normal	Normal to Smokey	Smokey
	Threshold #	0	0 - 10	> 10
Color	Qualitative	Normal	Normal to Yellow/Brown	Yellow/Brown
DBP Potential*		Normal	Moderately elevated	Highly elevated
Mn (mg/L)		< 0.05	0.05 - 0.3	> 0.3
pH		6.5 - 8	8 - 10	> 10
Alkalinity as CaCO$_3$ (mg/L)		80 - 130	131 - 300	> 300

*DBP formation potential has been linearly correlated to SUVA. However, correlations from the literature are water-specific and cannot be applied to water differing in composition. It can be expected that DBP formation potential will increase during post-fire runoff according to changes in water severity as indicated by increased SUVA.

EFFECTS ON EXISTING INFRASTRUCTURE[3]

Literature Review Results

Extreme total suspended solids (TSS) values seen in Brush Creek following the Hayman Fire (2002) were as high as 4,600 mg/L from baseline values of 16 mg/L [48]. If these elevated levels of suspended solids are allowed into the GWTP retention ponds, it is expected that the capacity of the retention ponds will quickly be reduced. This is confirmed in the literature by the accumulation of over 154,000 m^3 of sediment in the Strontia Springs Reservoir that had to be dredged following the Buffalo Springs Fire (1996) [7]. In addition, debris flows can carry boulders as large as 50 cm in diameter [48], which along with flood events are capable of damaging infrastructure, especially the intake into the retention ponds [18].

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[3] Objective 4. Determine the potential effects on existing infrastructure post-wildfire.

PROPOSED TREATMENT STRATEGIES[4]

Turbidity

In order to treat High and Severe condition turbidity, several strategies were proposed. First, the two retention ponds located before the plant intake could be managed as settling ponds. In order to test the approach, column settling tests were performed.

Using column settling tests, turbidity kinetics were determined by recording turbidity over a 39 hour period. Figure 11 indicates that a substantial amount of turbidity settles in the first 10 hours, suggesting that the retention ponds could be effectively used as settling ponds and would experience a 98.9% reduction in turbidity after 22.5 hours, which is the minimum retention time in GWTP's ponds. Although a substantial amount of turbidity was reduced, the results also indicate a reduction in storage volume, which is important to consider. Despite these results, the turbidity was still at 20.1 NTU after 22.5 hours, which is higher than typical pre-fire values.
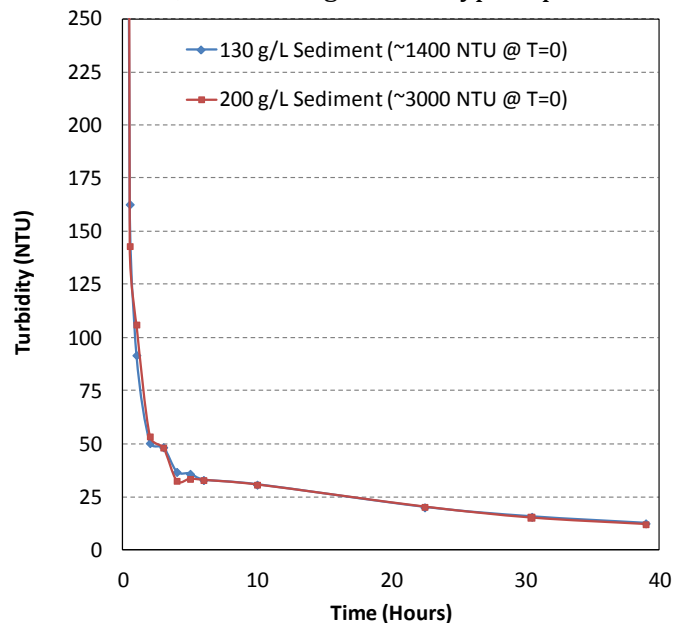
Figure 11: Turbidity reduction over time in column settling tests using 6 L Type 3 and 4 water.

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[4] Objective 5. Propose alternative treatment strategies for the GWTP that may enhance treatment post-wildfire.

The addition of ash did not substantially reduce the turbidity removal efficiency. Removal was 89.8% and 87.8 % with and without ash, respectively (Figure 12).
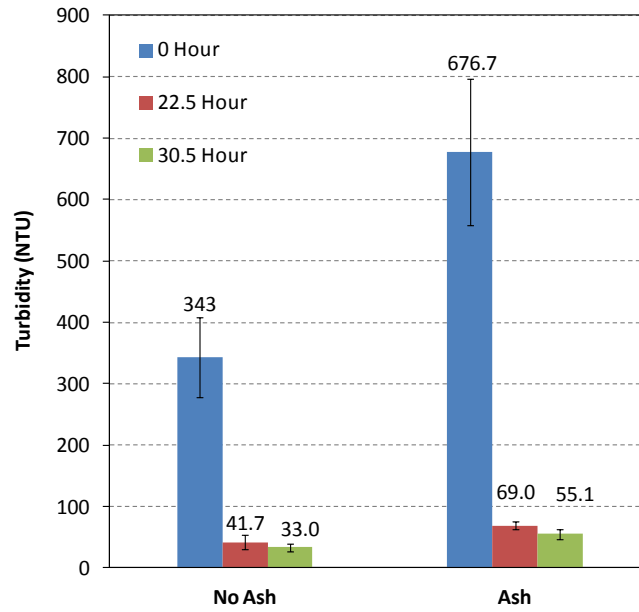
Figure 12: Turbidity reduction at specified intervals in column settling tests using 6 L of 5 and Type 6 water.

Figure 13 demonstrates that short-term settling improved with the addition of coagulant. After 22.5 hours of settling, the turbidity in all columns was in the range of 3 to 10 NTU.
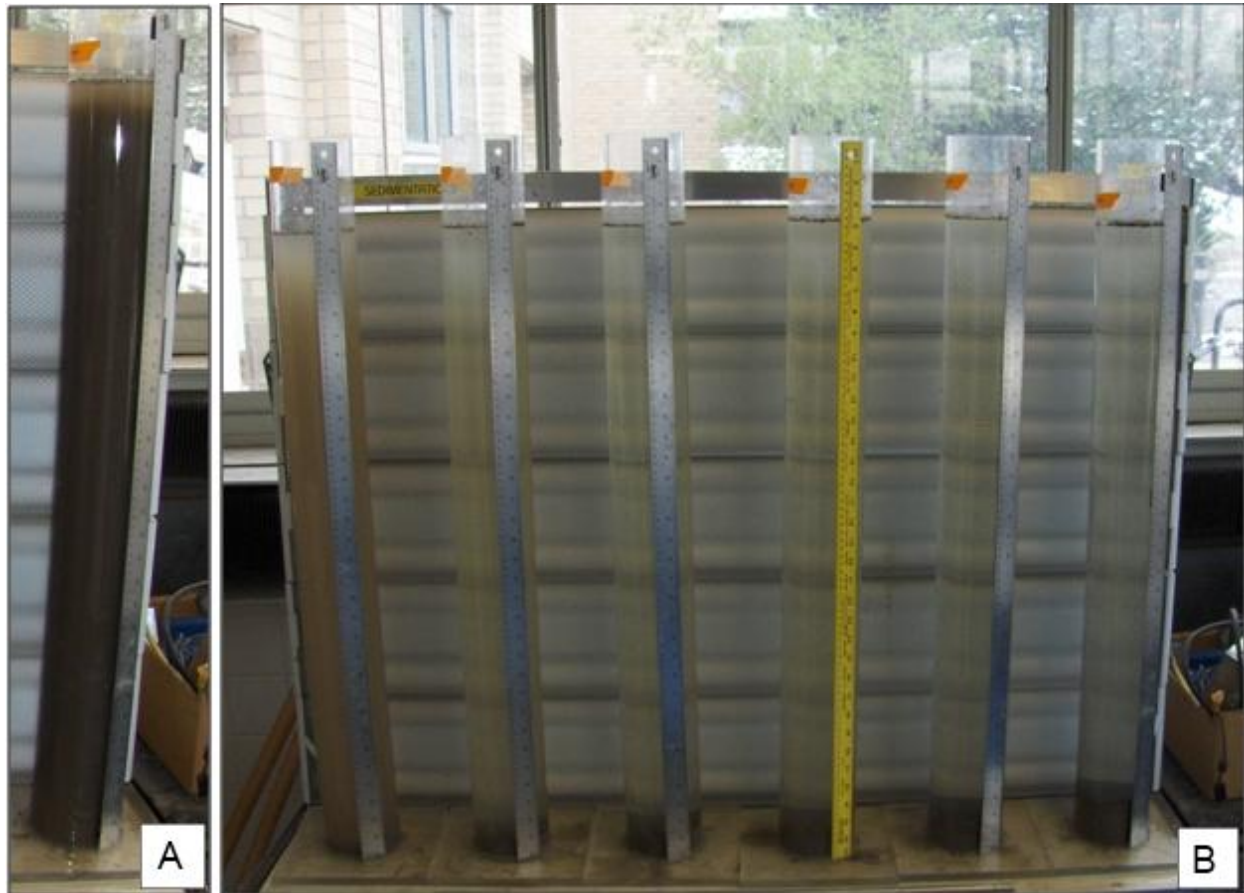
Figure 13: Pre-Sedimentation Coagulation Column Settling tests at (A) t = 0 minutes with 6 L of Type 8 water, and (B) t = 20 minutes with 6 L of Type 8 water and 0, 20, 30, 40, 50, 60 mg/L (left to right) Ferric Sulfate.

The second treatment process proposed for treating turbidity was standard coagulation, which is a treatment process the GWTP currently practices. In order to find the optimal coagulation dose within the ranges tested, pH and coagulation optimization tests were performed. Results suggested an optimal pH between 7 and 7.5. Turbidity reduction was greatest using a coagulant dose of around 10 mg/L for Type 7 and around 20 mg/L for Type 8 water.

Table 8: Summary of coagulation jar testing results.

Set	Water Type	Optimal pH	Optimal Dose (mg/L)	Initial Turbidity (NTU)	Turbidity at Optimal Dose (NTU)	Initial TOC as UV$_{254}$ Absorbance (1/m)	TOC as UV$_{254}$ Absorbance at Optimal Dose (1/m)
1	0	7	-	10	6.5	-	-
2	5	-	10	150	1.9	-	-
3	5	-	30	-	-	15.04	4.46
4	6	-	20	28	0.84	-	-
5	6	-	35	-	-	27.15	2.67

Total Organic Carbon (TOC)

To address the increase in concentration and the unique characteristics of TOC post-wildfire, standard coagulation was used to remove TOC. In addition to coagulation, the use of activated carbon was tested.

The optimal pH of 7 used in the turbidity removal coagulation optimization tests was used for the TOC removal optimization. Within the range of coagulant doses tested, the optimal coagulant dose for TOC removal was 30 mg/L for Type 7 water and 35 mg/L for Type 8 water. In both cases, the optimal dose was at the highest end of the range. However, further tests were not employed to improve coagulant dosing for TOC removal because turbidity removal would have suffered. A compromise between the optimal dose for turbidity and TOC removal was decided upon at 20 mg/L.

The use of activated carbon was proposed to remove TOC and its related components of taste, odor, and color. A sorption test was performed in order to determine sorptive capacity of two types of activated carbon. Sorption isotherms for Norit HD 3000 and 300 indicate that Norit HD 3000 displayed better sorption of TOC than Norit 300, although both carbon types substantially reduced TOC (Figure 14). It is assumed that the reduction of TOC would also reduce DBP's; therefore, the use of activated carbon as a treatment strategy for DBP's is also valid.
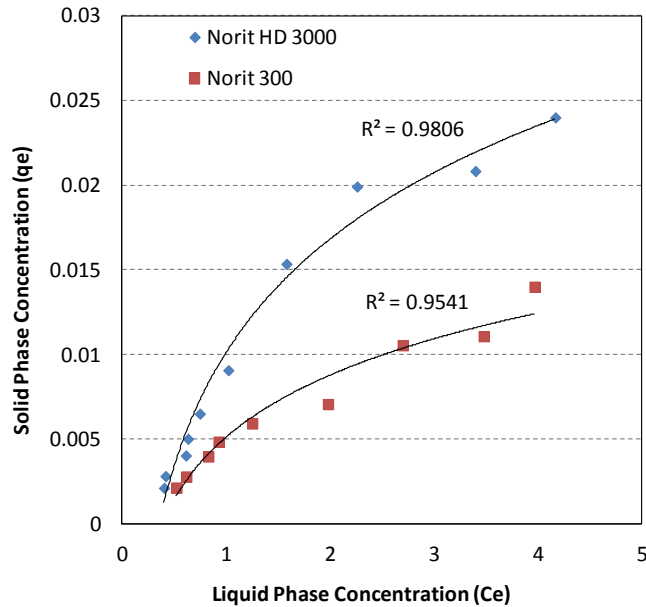
Figure 14: Sorption Isotherms for Norit HD 3000 and
300 activated carbon using type 8 water.

A taste and odor assessment was also conducted to specifically address activated carbon's ability to remove taste and odor issues associated with increased TOC. The results confirmed that the Norit HD 3000 was more efficient at removing taste and odor (Table 9).

Table 9: Taste and Odor Assessment Results.

Carbon Type	Odor	Taste
	0.33*	7
Norit HD 3000	0.00	7
	0.00	10
Average	0.11	8
	0.33	10
Norit 300	3.33	10
	0.00	7
Average	1.22	9

*Taste and odor values are threshold numbers [38].

Manganese, pH, and alkalinity

Treatment strategies to address Mn, pH, and alkalinity were not tested because GWTP is equipped with potassium permanganate pre-oxidant, so the plant is capable of effectively treating the expected ranges for these parameters during post-wildfire precipitation events. The methods used by GWTP were validated at the pilot scale and the results are discussed in the *Validation of Treatment Strategies* section below.

VALIDATION OF TREATMENT STRATEGIES[5]

Turbidity

Regardless of the initial turbidity, the mini pilot plant was capable of reducing turbidity to below Partnership for Safe Water limits (Figure 15). There was no substantial difference between the GAC column and the standard dual-media column. However, it is important to note that all mini-pilot-scale treatment of turbidity assumes the addition of an acid feed. In the case of extreme alkalinity and high pH, it may be unfeasible to treat turbidity to these levels with existing infrastructure at GWTP.
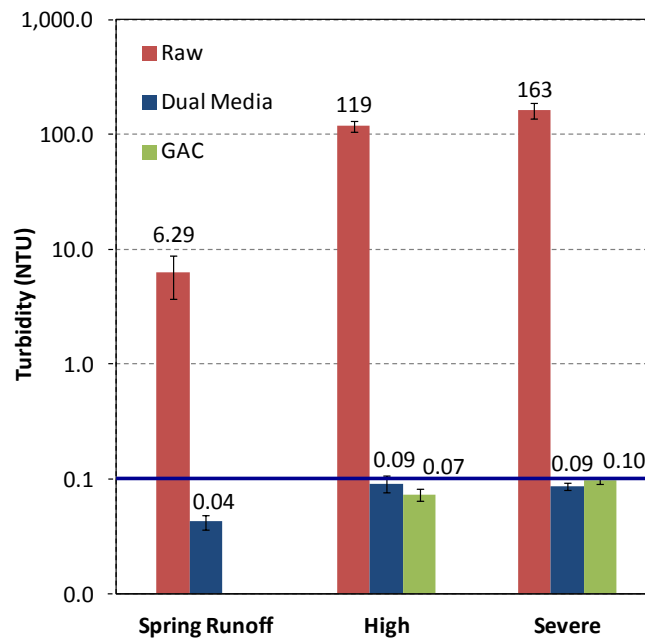
Figure 15: GWTP turbidity during spring runoff compared to mini pilot plant turbidity using Type 7 water (high) and Type 8 water (severe), before and after treatment.

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[5] Objective 6. Validate existing and proposed treatment strategies through bench and pilot-scale testing.

Total Organic Carbon

Under spring runoff conditions, GWTP typically removes an average 52% of TOC, exceeding regulation (Figure 16). Under high conditions, the mini-pilot plant was able to meet regulations, but removal was limited due to issues with coagulant optimization. In spite of this, the GAC filter was able to exceed TOC removal by traditional dual-media filtration under all conditions. With optimized coagulant dosing and type 7 severe water, the mini-pilot was able to match GWTP's removal, but was surpassed by GAC filtration which removed 87% of TOC (Figure 16). In extreme alkalinity conditions, the addition of an acid feed may be necessary for GWTP to exceed regulatory standards with conventional treatment.
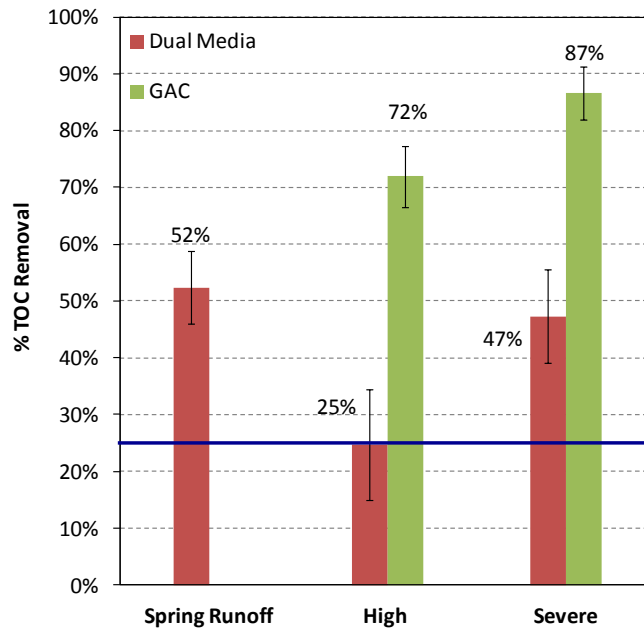
Figure 16: Percent TOC removal (as 1-C/Co) during spring runoff at GWTP compared to mini-pilot plant using Type 8 water (high) and Type 7 water (severe). Horizontal blue line represents EPA Stage 1 disinfection by-products rule for minimum TOC removal of 25% (Source water TOC = 4 to 8 mg/L. Source water alkalinity > 120 mg/L as CaCO3 [15]).

Near-complete reduction of color, as represented by visible absorbance at 436 nm, was achieved in finished water from both the dual media and GAC columns (Figure 17). Therefore, the GWTP should be able to treat color with existing infrastructure as well, assuming proper coagulant functionality in the presence of alkalinity.
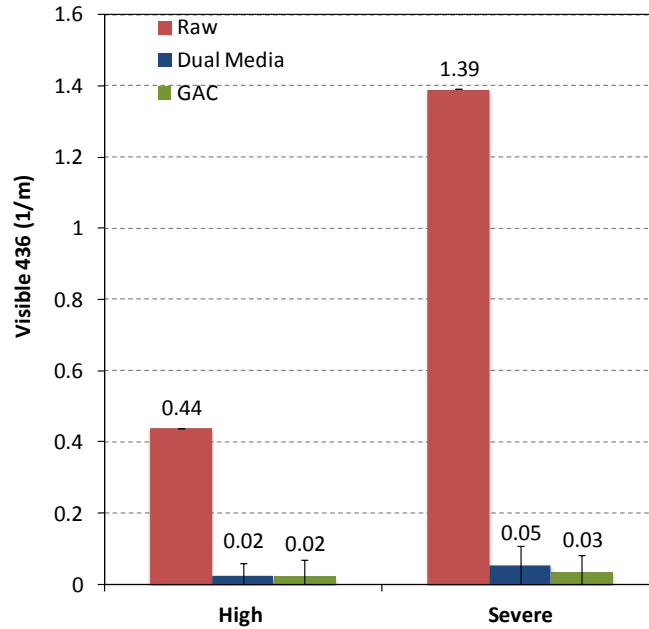
Figure 17: Visible absorbance at 436 nm (1/m) before and after treatment with Type 8 (high) water and Type 7 water (severe), representing reduction in yellow-orange color.

Conventional dual-media filtration reduced SUVA for both water types, but GAC SUVA reduction surpassed conventional treatment in both cases (Figure 18). GAC filtration demonstrated near-complete SUVA reduction, indicating that GAC should exceptionally decrease DBP formation potential.
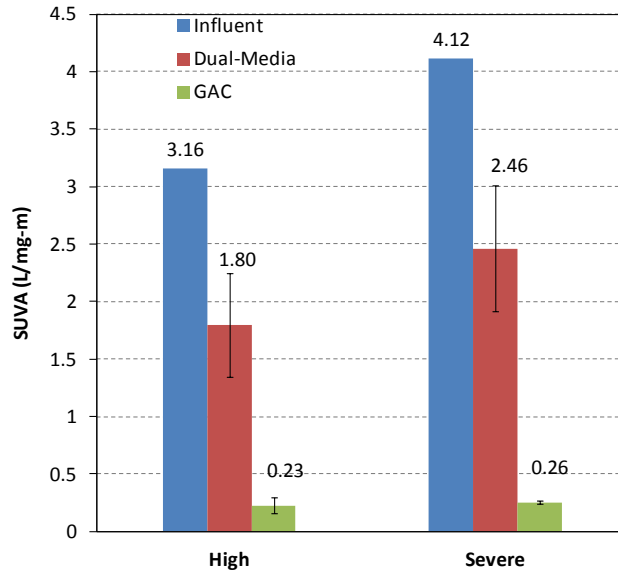
Figure 18: SUVA values for Type 7 (Severe) and Type 8 (High) influent water, as well as after dual-media and GAC filtration.

Manganese

Mn in Type 7 and Type 8 water was higher than typical Spring Runoff conditions because Mn is diluted during Spring Runoff (Figure 19). As Mn was not dosed in either surrogate water types, the higher concentrations in Type 7 and Type 8 water are natural occurrences. The minimum Mn removal limit of 0.05 mg/L, as indicated by the EPA, was achieved under all conditions. It is believed that the dual media filter outperformed the GAC filter due to a residual artifact of previous Pilot Plant classes' use of activated green sand in the filtration column.
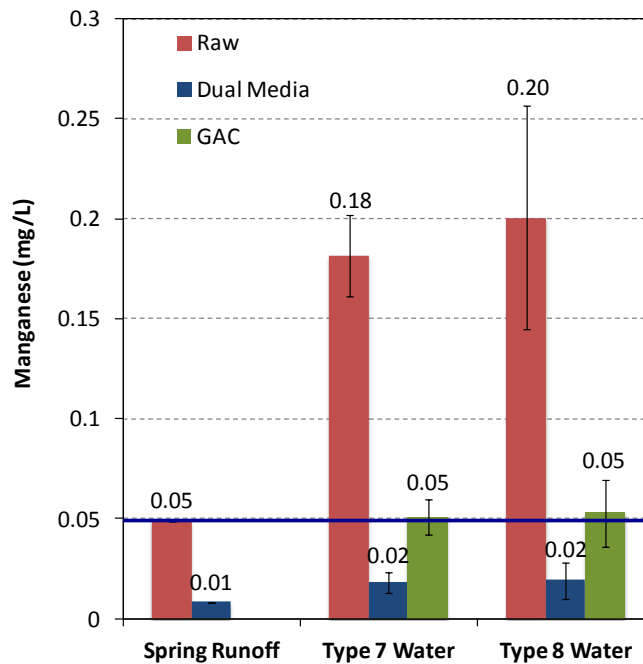
Figure 19: Manganese before and after GWTP and mini pilot plant treatment.

pH and Alkalinity

Results from the mini-pilot plant exhibited little change in pH in either the flocculation basin or in column effluent where pH values remained within 10% of influent pH, previously adjusted to 7 - 7.5 (Appendix Table C- 2Table C- 6).

V.   CONCLUSIONS

The Clear Creek watershed is at risk for wildfire and subsequent flood and erosion. After interviewing industry representatives and staff from municipal treatment plants affected by fire, as well as reviewing forest service reports and conducting a thorough literature review, it was determined that several water quality parameters of concern to drinking water treatment facilities are affected by wildfire-influenced flood and erosion. Turbidity, TOC, color, taste, odor, DBPs, Mn, pH, and alkalinity were found to be of most concern for the GWTP. Based on these results, it is likely that wildfire will have an effect on GWTP's drinking water quality. Techniques used to treat surrogate wildfire-affected water comprised of High and Severe intensity water quality parameters require operations and infrastructure that the GWTP is currently not using or does not have. For example, all of the treatment strategies were validated assuming the use of an acid feed in order to lower the pH. To achieve the high quality water standards that the GWTP provides today, it is recommended that the GWTP implement operational and infrastructural improvements.

VI.   RECOMMENDATIONS[6]

Based upon desktop, bench, and pilot-scale testing, as well as treatment recommendations, the project team respectfully recommends the following operational and capital improvements for review by the City of Golden and the GWTP.

OPERATIONS AND STAFF RECOMMENDATIONS

Monitoring Team

Monitoring of a wildfire situation is crucial for understanding the potential effects on GWTP water quality and supply. During and after a fire and prior to precipitation events, watershed monitoring would be beneficial. Two levels of monitoring are suggested and referred to in the *Response Strategy* section (Table 11):

- Level (1): In-house monitoring consists of information gathering at a distance through appropriate sources and contacts, such as upstream municipalities or members of the USFS or CSFS. The purpose is to obtain details on the location, severity, and extent of the wildfire, in addition to the local vegetation type and density and a wildfire's effect thereon. Furthermore, weather forecasts and events should be monitored for precipitation that coincides with burned areas. Regular updates should be obtained as situations progress.

- Level (2): Field monitoring confirms the information gathered from Level (1) and specifies details concerning relevant water resources. This is achieved through deployment of a monitoring team into the watershed. The team should be composed of a watershed, a water quality technician, and a member of the City of Golden Fire Department. Most importantly, confirming weather information with observations, such as the location of a storm cell and where precipitation is subsequently delivered, is crucial to validate potential concerns.

Call-Down System

The GWTP, along with other water treatment facilities in the Clear Creek watershed, have a call-down system in place, which is initiated by public safety agencies. This system is designed to address emergency situations, such as accidents involving a vehicle entering Clear Creek. A similar call-down system addressing other severe water quality issues, such as a major runoff event, could also be effective at giving plant operators advance warning. For this reason, a fully integrated call-down system is recommended to help both the GWTP and other treatment facilities in the watershed. The call-down system should include the following:
- Incorporation of all water treatment facilities in the Clear Creek watershed;
- An agreed upon set of maximum values for specified water quality parameters, such as turbidity or pH, that when violated would trigger the call down system.

Employing an integrated call-down system would help the GWTP be more prepared to potentially close the intake, to increase storage prior to closure, and to prepare any changes to traditional treatment trains.

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[6] Objective 7. Develop recommendations to the GWTP staff concerning infrastructural needs and response strategies for treating Clear Creek water influenced by wildfire.

Fire Retardant Discourse

Preventative measures should be implemented whenever possible to reduce the effects of wildfires on drinking water treatment. It is our recommendation that GWTP organize a joint meeting with Jefferson County Fire Department, Clear Creek County Fire Department, the USFS, and CSFS to discuss preventative measures related to fire retardants. Although fire retardants historically have not been shown to cause problems for drinking water treatment plants, it is advised that fire retardants should not be dispersed directly over surface waters [11] and that fire retardants be jointly selected by the aforementioned agencies [4]. By doing so, GWTP will be able to inform these agencies which fire retardants are the most difficult to remove.

CAPITAL UPGRADES

Intake Structure

Currently, GWTP's intake structure may be at risk for severe damage or may become overwhelmed in the event of severe post-fire runoff yielding large volumes of sediment and large debris. To mitigate such dangers and increase operational flexibility during such events, the following capital improvements would be beneficial to the water treatment facility:

- Permanent or standby heavy equipment for debris removal;
- An engineering review of the intake and diversion structure with the possibility of structural reinforcement;
- Chemical dosing and storage capabilities for coagulant addition to influent raw water.

Without stated improvements, the GWTP risks losing function of the intake and could be forced to stop water treatment until the damage to the intake is repaired.

Retention Ponds

During periods of elevated turbidity in Clear Creek, it may be necessary to accept water into the facility retention ponds with turbidity levels higher than previously accepted. We recommend managing the retention ponds as settling basins and adding coagulant dosing capabilities to the intake structure. The following specific enhancements are recommended:

- A metered chemical dosing pump, similar to those already used by GWTP, at the Clear Creek intake structure;
- Chemical storage for coagulant.

Coagulation addition at this point in the treatment train would target early turbidity removal. This increases the facility's ability to accept lower quality water, reduces the potential of overloading flocculation and sedimentation basins, and limits filter loading and backwashing.

Acid Feed

High pH and alkalinity pose a substantial threat to the coagulation and flocculation process by increasing chemical demand in order to provide sufficient charge neutralization. To increase operating flexibility during expected post-wildfire conditions, acid dosing is recommended. The following improvements are suggested:

- Installation of a metered dosing pump and a predetermined junction for acid addition upstream of the flocculation basins;
- Purchase and storage of acid.

In 2006, CSM ESGN 530 Environmental Science and Engineering students conducted a detailed cost analysis of installing an acid feed at the GWTP and found installation costs to be neither burdening nor beneficial [49]. However, in the event of a wildfire in the Clear Creek watershed, the flexibility

that an acid feed offers is advantageous for optimal treatment in the presence of increased alkalinity and pH.

GAC

Based on the taste and odor results recorded during the preliminary and pilot plant tests, we recommend the conversion of at least one of the GWTP's finishing filters from anthracite coal to GAC. Use of activated carbon is the only method for addressing the taste and odor issues directly associated with increased levels of ash from post-wildfire precipitation events. Importantly, the installation process this modification would require means it cannot be applied to the treatment train at short notice. The planned replacement of the GWTP's filters later this year (2012) would be an advantageous time to convert one or two of the dual media filters to GAC. The filters' use is not required to meet peak summer water demand and they would be ready in the case of a severe taste and odor issue.

Powdered activated carbon (PAC) is a second type of activated carbon for addressing severe taste, odor and color issues. Unlike GAC, extensive infrastructure is not required for its delivery. PAC could be added as a slurry at the point of coagulant dosing before the flocculation basins. However, its use would be labor intensive and it is not recoverable once applied, which could lead to high costs during treatment of large volumes of affected water. This option allows some treatment flexibility as a reaction to fire-impacted waters.

Precipitation Gauges

The addition of precipitation gauges at key locations within the watershed could provide GWTP with advance warning of precipitation events likely to cause detrimental runoff. In fact, a reliable form of precipitation monitoring within the watershed has proven to be a beneficial investment for Denver Water to track large-flush flows following wildfires [8]. Remote rainfall monitoring with rain gauges and increased stream flow monitoring are often more accurate than weather radars. To prevent unnecessary dispatch of the field monitoring crew, the following procurements are recommended:
- Installation of flow monitors on the West Fork Clear Creek, below Georgetown Lake, and below the confluence of Clear Creek and West Fork Clear Creek.;
- Installation of remote rain gauges in all major basins within the watershed.

All equipment should be capable of real time monitoring, remote information delivery to GWTP and alarm signaling in the event of high flows. Precipitation monitoring allows GWTP to close the intake from Clear Creek only when needed in order to avoid untreatable water and capitalize on valuable clean water preceding the flush.

Erosion Control

Erosion control techniques exist to mitigate the effects of heavy precipitation events on erodible post-wildfire forest soils [50]. If used as a cautionary measure in high risk areas, such as on the slopes around the Henderson Mine Reservoir, and prior to precipitation in areas affected by wildfire, erosion control techniques may protect vital water resources by mitigating sediment deposition and the detrimental water quality characteristics associated with ash-laden surface runoff. Therefore, the following erosion control techniques are suggested:
- Reestablish vegetation post-wildfire;
- Mulch burned areas with straw to promote colonization of the soil surface grasses;
- Use contour log terraces and straw wattles to reduce runoff velocity;
- Install water bars and culverts to divert runoff from bare soils if necessary.

The use of erosion control techniques in high risk areas and immediately after a wildfire offers the most proactive protection possible to the GWTP's drinking water supply.

SITUATION ASSESSMENT MATRIX

A situation assessment matrix was created to rank a given fire and precipitation situation in Clear Creek watershed. For its use, fire severity and precipitation intensity have been defined according to literature (Table 5). After attributing a fire severity and precipitation intensity to a given situation and determining the composite flood and erosion risk level from the GIS maps (Figure 7) the situation assessment matrix (Table 10) can be used to assign a color code to a particular situation (Table 11).

Table 10: Situation assessment matrix comparing fire severity, precipitation and composite risk to determine suggested response.

Fire Severity	Composite Risk					Precipitation Intensity
	Low	Moderate	High	Very High	Severe	
Light	green	green	green	green	orange	Low
	green	green	orange	orange	orange	Moderate
	orange	orange	orange	red	red	High
Moderate	green	green	orange	orange	orange	Low
	orange	orange	orange	red	red	Moderate
	orange	orange	red	red	red	High
High	orange	orange	orange	red	red	Low
	orange	orange	red	red	red	Moderate
	red	red	red	red	red	High

RESPONSE STRATEGIES

Table 11 defines the expectations and suggested action items we recommend the GWTP undertakes based on the situational color code. Proactive measures are undertaken before precipitation events occur, while reactive measures are employed immediately following precipitation in the affected area.

Table 11: Suggested response based on situation assessment matrix (Table 10).

Color Code	Surface Water Quality Expectations	Suggested Action	
		Proactive	Reactive
(green)	• Turbidity: up to 100's NTU; • Elevated TOC similar to Spring Run-Off conditions; • No taste and odor problems; • No substantial fluctuations in manganese and other metal concentrations; • No substantial fluctuations in pH and alkalinity; • Possible fluctuations in flow regimes.	• Employ monitoring level 1.	• Review *Moderate* action level recommendations as event progresses; • Review monitoring level 2.
(orange)	• Turbidity: 100-1,000's NTU; • TOC: 5-10 mg/L; • Possible but unlikely taste and odor problems; • Fluctuations in manganese and other metal concentrations depending on dilution by precipitation; • Fluctuations in pH and alkalinity depending on dilution by precipitation; • Increased flow regimes.	• Employ monitoring levels 1 and 2; • Prepare for closure of intake; • Possibly reinforce intake structure • Prepare to use acid feed; • Prepare to switch to GAC filter.	• Prepare heavy equipment in case of damage; • Review *High* action level recommendations as event progresses.
(red)	• Turbidity: 500 - 10,000's NTU; • TOC: >10 mg/L; • Taste and odor problems likely; • Large fluctuations in manganese and other metal concentrations; • High pH and alkalinity; • High Total Suspended Solids and large debris flows; • High flow regimes.	• Employ monitoring levels 1 and 2; • Prepare for closure of intake; • Reinforce intake structure; • Increase flow rate through plant to fill finished water reservoirs and impose water restrictions.	• Mobilize heavy equipment for repairs; • Employ sedimentation pond coagulation to mitigate turbidity after initial event; • Employ acid feed to mitigate pH and alkalinity spikes; • Employ GAC filter to control taste and odor problems.

VII.   REFERENCES

1.   Smith, H. G.; Sheridan, G. J.; Lane, P. N. J.; Nyman, P.; Haydon, S., Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology* **2011,** *396*, (1-2), 170-192.
2.   The Clear Creek Watershed Foundation. http://www.clearcreekwater.org (March 1),
3.   Clark, S.; Fuller, G.; Rogers, J.; Huston, T.; Amato, M., Scorched-Earth Policy. *Civil Engineering* **2004**.
4.   Clark, S., 2012, CSM Presentation - Water Quality and Treatment Impacts of a Watershed Forest Fire Personal Communication with ESGN 530, in Golden, CO.
5.   NOAA NCDC. Precipitation Data, hourly, for COOPID 054877, Lawson, CO. http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.cdobystn?dataset=DS3240&StnList=054877
6.   Romme, W. H.; Clement, J.; Hicke, J.; Kulakowski, D.; MacDonald, L. H.; Schoennagel, T. L.; Veblen, T. T. *Recent Forest Insect Outbreaks and Fire Risk in Colorado Forests: A Brief Synthesis of Relevant Research*; Colorado Forest Resoration Intitution, Colorado State Forest Service, Colorado State University, University of Idaho: Fort Collins, 2006.
7.   Moody, J. A.; Martin, D. A., Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* **2001,** *26*, (10), 1049-1070.
8.   Lohman, S., 2012, CSM Presentation - Fire Impacts on Denver Water Quality   Personal Communication with ESGN 530, in Golden, Colorado.
9.   DeBano, L. F., The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* **2000,** *231, 232*, (0), 195-206.
10.   Cerda, A.; Doerr, S. H., The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. *CATENA* **2008,** *74*, (3), 256-263.
11.   Neary, D. G.; Ryan, K. C.; DeBano, L. F. *Wildland fire in ecosystems: effects of fire on soils and water*; Department of Agriculture, Forest Service, Rocky Mountain Research Station: Ogden, 2005 (Revised 2008).
12.   Edzwald, J. K., *Water Quality and Treatment: A Handbook on Drinking Water*. 6 ed.; McGraw-Hill Professional 2010; p 1696.
13.   Malcolm Pirnie Inc.; Colorado School of Mines. *Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS) Bench and Pilot Testing Report*; CDPHE: Denver, Colorado, January 2009, 2009; p 62.
14.   AWWA et al. *Partnership For Safe Water: Annual Reporting Requirements*; American Water Works Association, US Environmental Proteciton Agency, American Water Works Associaiton Research Foundation, Association of Metropolitan Water Agencies, Association of State Drinking Water Administrators, National Association of Water Companies: Denver, Colorado, December 2007, 2007; p 22.
15.   US EPA. Fact Sheet on the Federal Register Notice for Stage 1 Disinfectants and Disinfection Byproducts Rule (EPA 815-F-98-010). http://water.epa.gov/lawsregs/rulesregs/sdwa/stage1/factsheet.cfm
16.   Knicker, H.; Almendros, G.; González-Vila, F. J.; Martin, F.; Lüdemann, H. D., 13C- and 15N-NMR spectroscopic examination of the transformation of organic nitrogen in plant biomass during thermal treatment. *Soil Biology and Biochemistry* **1996,** *28*, (8), 1053-1060.
17.   Dalton, A., 2012, Personal Communication with ESGN 530, in Golden, Colorado.
18.   Haas, B. d., 2012, Personal Communication with Boerner, C., in Boulder, Colorado.
19.   US EPA. Stage 2 Disinfectants and Disinfection Byproducts Rule: A Quick Reference Guide For Schedule 3 Systems (EPA 816-F-06-003).
20.   US EPA and CDPHE. *Clear Creek State of the Watershed Report*; 1997.
21.   Gill, D. D., 2004, The Impacts of Forest Fires on Drinking Water Quality. Unpublished.
22.   Montgomery, D.; McClain, T.; Love, E.; Erlenbach, B.; Casella, A.; Bogdanova, T. *Results of the Four Mile Canyon Fire on Chemical Water Quality of Fourmile Creek*; Metropolitan State College of Denver: Denver, 2010.
23.   Front Range Watershed Protection Data Refinement Group. *Protecting Critical Watersheds in Colorado from Wildfire: Technical Approach to Watershed Assessment and Prioritization* Denver, Colorado, 2009; p 19.
24.   Battle, J.; Golladay, S. W., Prescribed Fire's Impact on Water Quality of Depressional Wetlands in Southwestern Georgia. *American Midland Naturalist* **2003,** *150*, (1), 15-25.
25.   Ziemkiewicz, P.; Vandivort, T.; Saville, D.; Mack, B.; O'Neal, M. *Development and Presentation of Current Monongahela River Water Quality Data for the Public*; WRI-119; West Virginia Water Research

Institute, National Research Center for Coal and Energy, West Virginia University: Morgantown, West Virginia, May 31 2011, 2011; p 67.

26.   Pierson, F. B.; Robichaud, P. R.; Spaeth, K. E., Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. *Hydrological Processes* **2001,** *15*, (15), 2905-2916.

27.   Gimenez, A.; Pastor, E.; Zarate, L.; Planas, E.; Arnaldos, J., Long-term forest fire retardants: a review of quality, effectiveness, application and environmental considerations. *International Journal of Wildland Fire* **2004,** *13*, (1), 1-15.

28.   Stambaugh, W., 2012, Clear Creek Watershed Tour Personal Communication with ESGN 530, in Golden, Colorado.

29.   Clear Creek County. Mapping and GIS Department Products and Services. http://www.co.clear-creek.co.us/index.aspx?nid=353

30.   Cannon, S. H.; Reneau, S. L., Conditions for generation of fire-related debris flows, Capulin Canyon, New Mexico. *Earth Surface Processes and Landforms* **2000,** *25*, (10), 1103-1121.

31.   Moody, J. A.; Smith, J. D.; Ragan, B. W., Critical shear stress for erosion of cohesive soils subjected to temperatures typical of wildfires. *J. Geophys. Res.* **2005,** *110*, (F1), F01004.

32.   Piehl, B., 2012, Email "Protecting watersheds in colorado from wildfire report - questions" Personal Communication with Roux, V., in Golden, CO.

33.   Renard, K. G.; Foster, G. R.; Weesies, G. A.; Porter, J. P., RUSLE: Revised universal soil loss equation. *Journal of Soil and Water Conservation* **1991,** *46*, (1), 30-33.

34.   Pannkuk, C. D.; Robichaud, P. R., Effectiveness of needle cast at reducing erosion after forest fires. *Water Resour. Res.* **2003,** *39*, (12), 1333.

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

36.   Lu, X.; Fan, J.; Yan, Y.; Wang, X., Soil Water Soluble Organic Carbon Under Three Alpine Grassland Types in Northern Tibet, China. *African Journal of Agricultural Research* **2011,** *6*, (9), 2066-2071.

37.   Reche Research Group. *Protocol for Fluoromax-4 Spectrofluorometer*; University of Granada, Spain, Colorado School of Mines: Granada, Spain

Golden, Colorado, 2008; pp 1-6.

38.   Lin, S. D. *Tastes and Odors in Water Supplies-A Review*; ISWS/CIR-127/77; Illinois State Water Survey: Urbana, Illinois, 1977; pp 20-24.

39.   Colorado School of Mines, 2010, A Pilot Scale Investigation to Guide in Start up of the Aurora Reservoir Train of the Prairie Waters Project. Golden, CO, Unpublished.

40.   Colorado State Forest Service, Interface Areas of High Wildfire Risk in Colorado. In 2004.

41.   USDA Colorado State Forest Service. *Colorado Statewide Forest Resource Assessment*; Fort Collins, 10-28-2008, 2008.

42.   Coe, J. A.; Godt, J. W., Historical debris flows along the Interstate-70 corridor in Clear Creek County, Central Colorado. In *Engineering Geology in Colorado: Contributions, Trends and Case Histories*, Boyer, D. D. S. P. M. R. W. P., Ed. Association of Engineering Geologists Special Publication No. 15 and Colorado Geological Survey Special Publication 55¬†: Denver, CO, 2003.

43.   Keeley, J. E., Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire* **2009,** *18*, (1), 116-126.

44.   Murphy, S., 2012, Oral interview with Sheila Murphy (U.S. Geological Survey, Water Mission) Personal Communication with Boerner, C., in Boulder.

45.   Almendros, G.; González-Vila, F. J.; Martín, F.; Fründ, R.; Lüdemann, H. D., Solid state NMR studies of fire-induced changes in the structure of humic substances. *Science of The Total Environment* **1992,** *117–118*, (0), 63-74.

46.   Golchin, A.; Clarke, P.; Baldock, J. A.; Higashi, T.; Skjemstad, J. O.; Oades, J. M., The effects of vegetation and burning on the chemical composition of soil organic matter in a volcanic ash soil as shown by 13C NMR spectroscopy. I. Whole soil and humic acid fraction. *Geoderma* **1997,** *76*, (3,Äì4), 155-174.

47.   Almendros, G.; Gonzalez-Villa, F. J.; Martin, F., Fire-Induced transformation of soil organic matter from an oak forest: an experimental approach to the effects of fire on humic substances. *Soil Science* **1990,** *149*, 158-168.

48.   Kershner, J. L.; Macdonald, L.; Decker, L. M.; Winters, D.; Libohova, Z. *Ecological effects of the Hayman Fire: fire-induced changes in aquatic ecosystems.* ; USDA Forest Service

Rocky Mountain Research Station: Ogden, UT, 2003.

49.   Bauer, E. H.; Burgermeister, G.; Chamberlain, K.; Jeffers, J.; Johnson, B.; Savage, A. *Enhanced Coagulation with Acid Feed*; Colorado School of Mines: Golden, CO, 2006.

50.   Moench, R.; Fusaro, J., Fact Sheet No. 6.308: Soil Erosion Control after Wildfire. In *Natural Resources Series-Forestry*, USDA NRCS: Fort Collins, CO, 2002.

51.   Melton, M. A. *An analysis of the relations among elements of climate, surface properties and geomorphology.*; Technical Report 11; Department of Geology, Columbia University: New York, NY., 1957; p 102.

VIII.   APPENDIX

APPENDIX A: GIS INFORMATION

Calculating Risk

Flood Risk

Melton [51] defines ruggedness by:

$$R = \frac{H_b}{\sqrt{A_b}} \qquad \text{(Equation 1)}$$

Where,
H_b = Basin Height
A_b = Basin Area

Flood Risk is defined in the Front Range workgroup report as:

$$F_r = 2R + D_r \qquad \text{(Equation 2)}$$

Where,
F_r = Flood Risk
R = Ruggedness
D_r = Road Density

Erosion Risk

Table A- 1: Criteria for determining soil erodibility [23]*.

	K factor			
Percent Slope	< 0.1	0.1 - 0.19	0.2 - 0.32	> 0.32
0 - 14	Slight	Slight	Slight	Moderate
15 - 34	Slight	Slight	Moderate	Severe
35 - 50	Slight	Moderate	Severe	Very Severe
> 50	Moderate	Severe	Very Severe	Very Severe

* Presence of granitic soils increases soil erodibility by one ranking.

Composite Risk

Composite Risk is simply an average of Flood Risk and Erosion Risk scaled to 1

Maps

Higher resolution maps of roads (Figure A - 1), Flood Risk (Figure A - 2), Erosion Risk (Figure A - 3) and Composite Risk (Figure A - 4) are provided here.
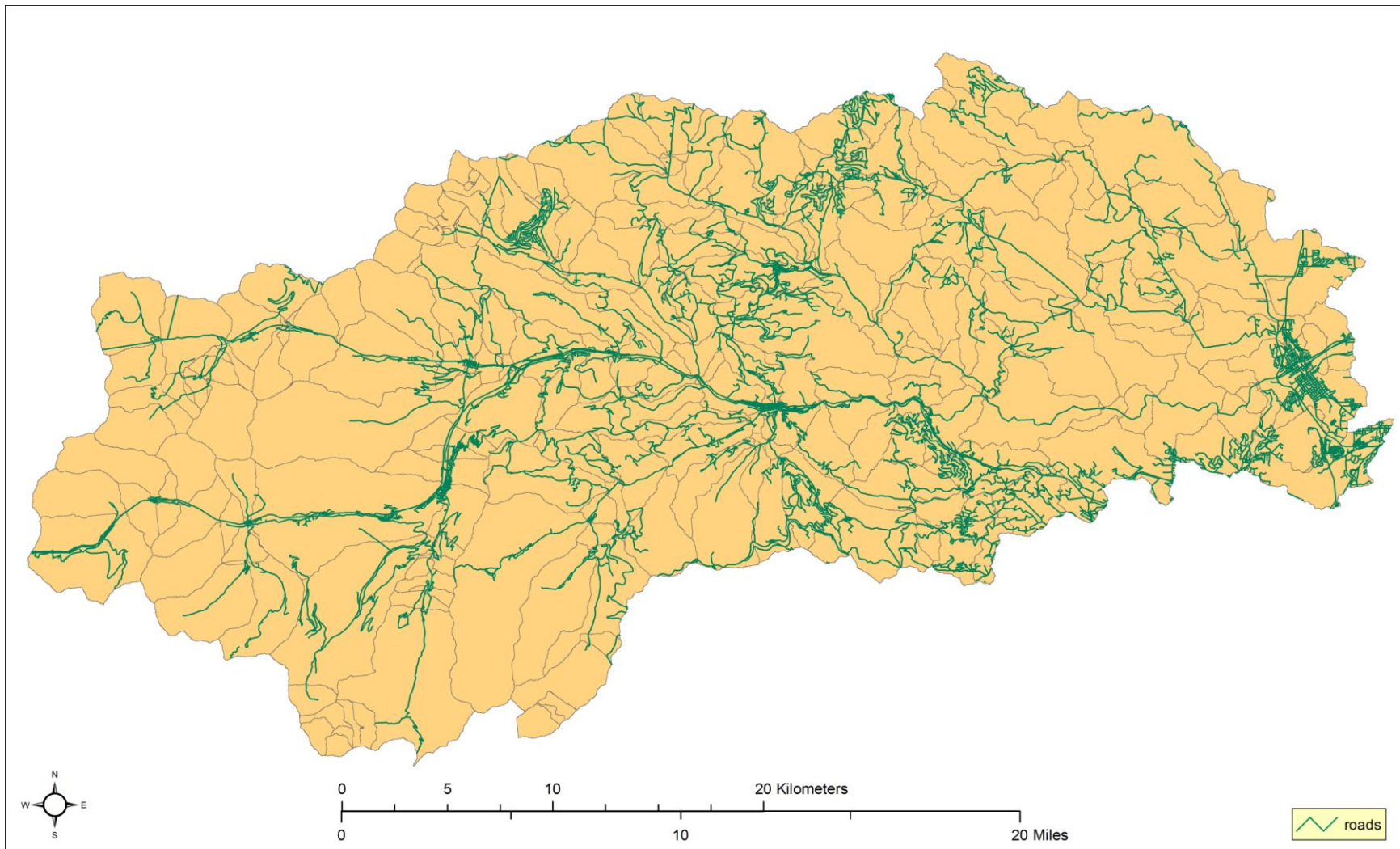
Figure A - 1: Roads in Clear Creek Watershed, Colorado used to calculate road density.
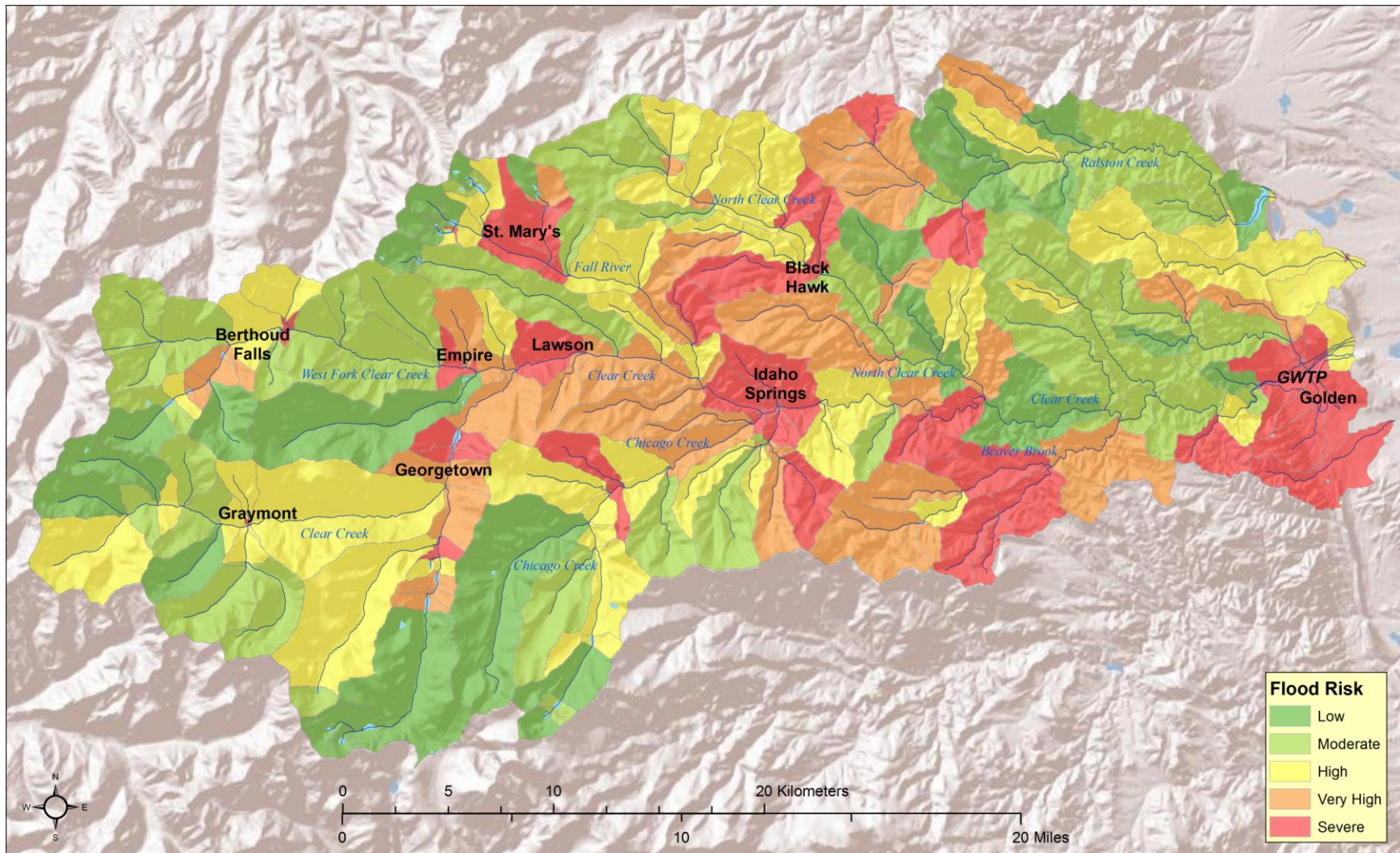
Figure A - 2: Flood Risk in Clear Creek Watershed, Colorado.
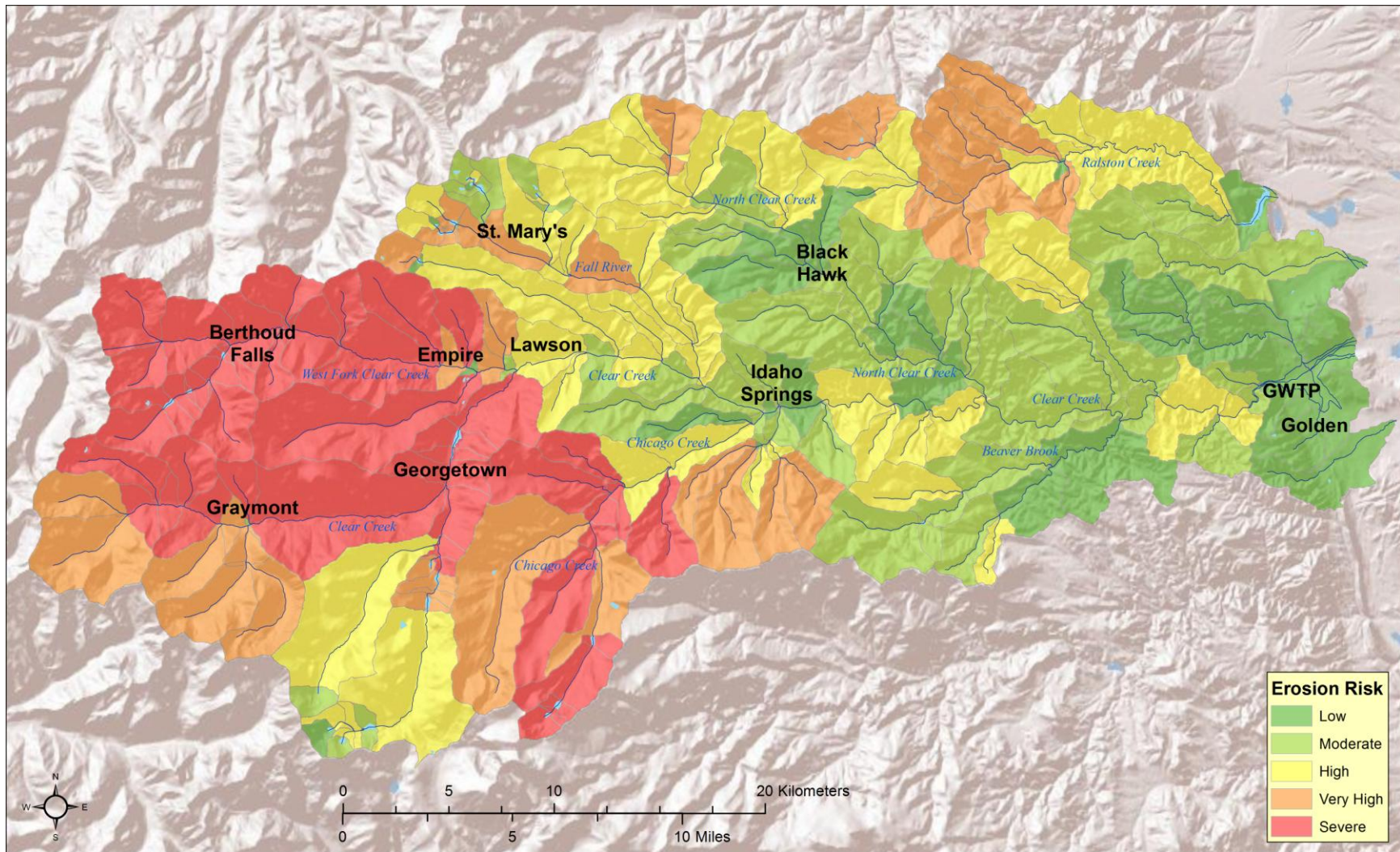
Figure A - 3: Erosion Risk in Clear Creek Watershed, Colorado.
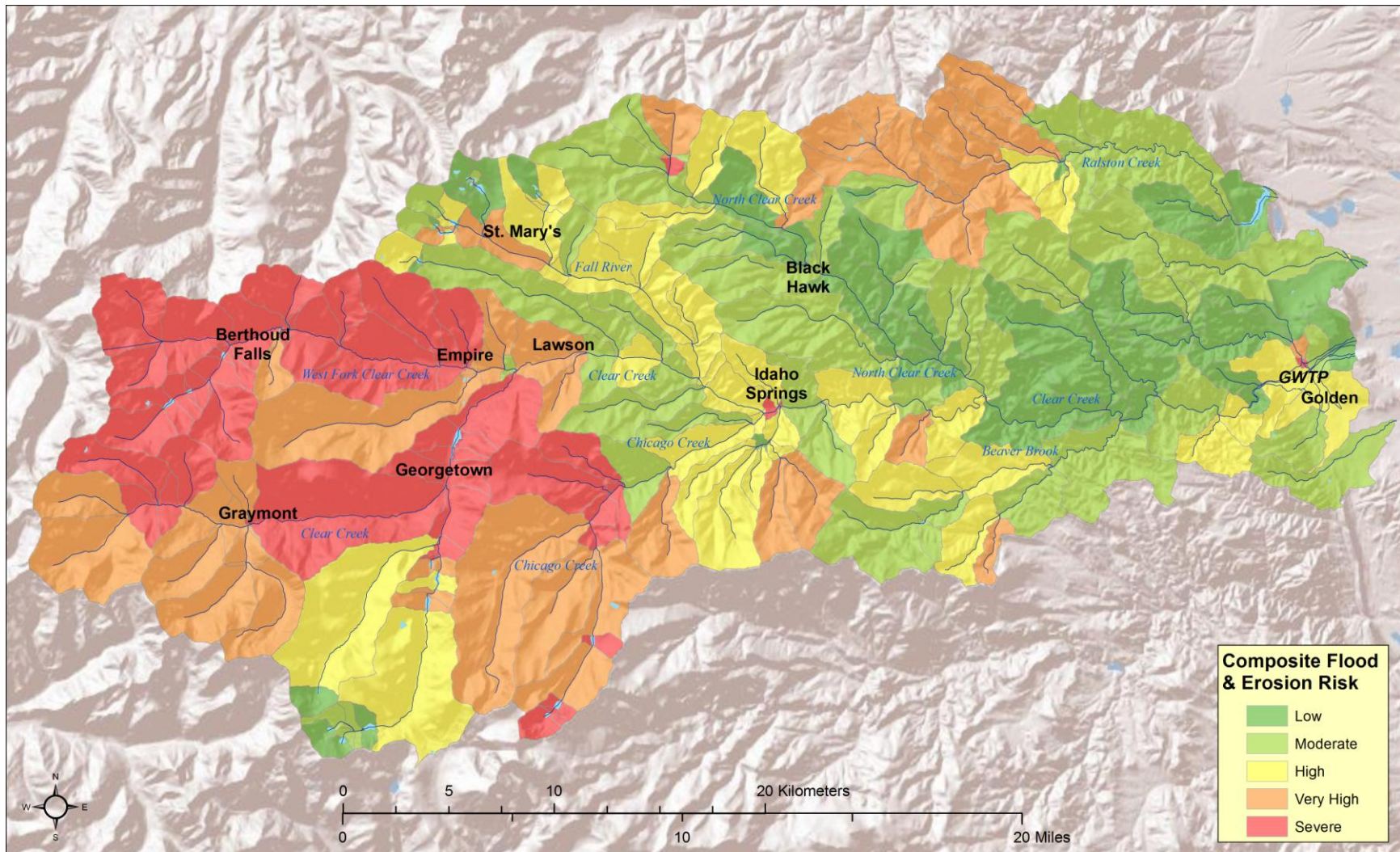
Figure A - 4: Composite Flood and Erosion Risk in Clear Creek Watershed, Colorado.
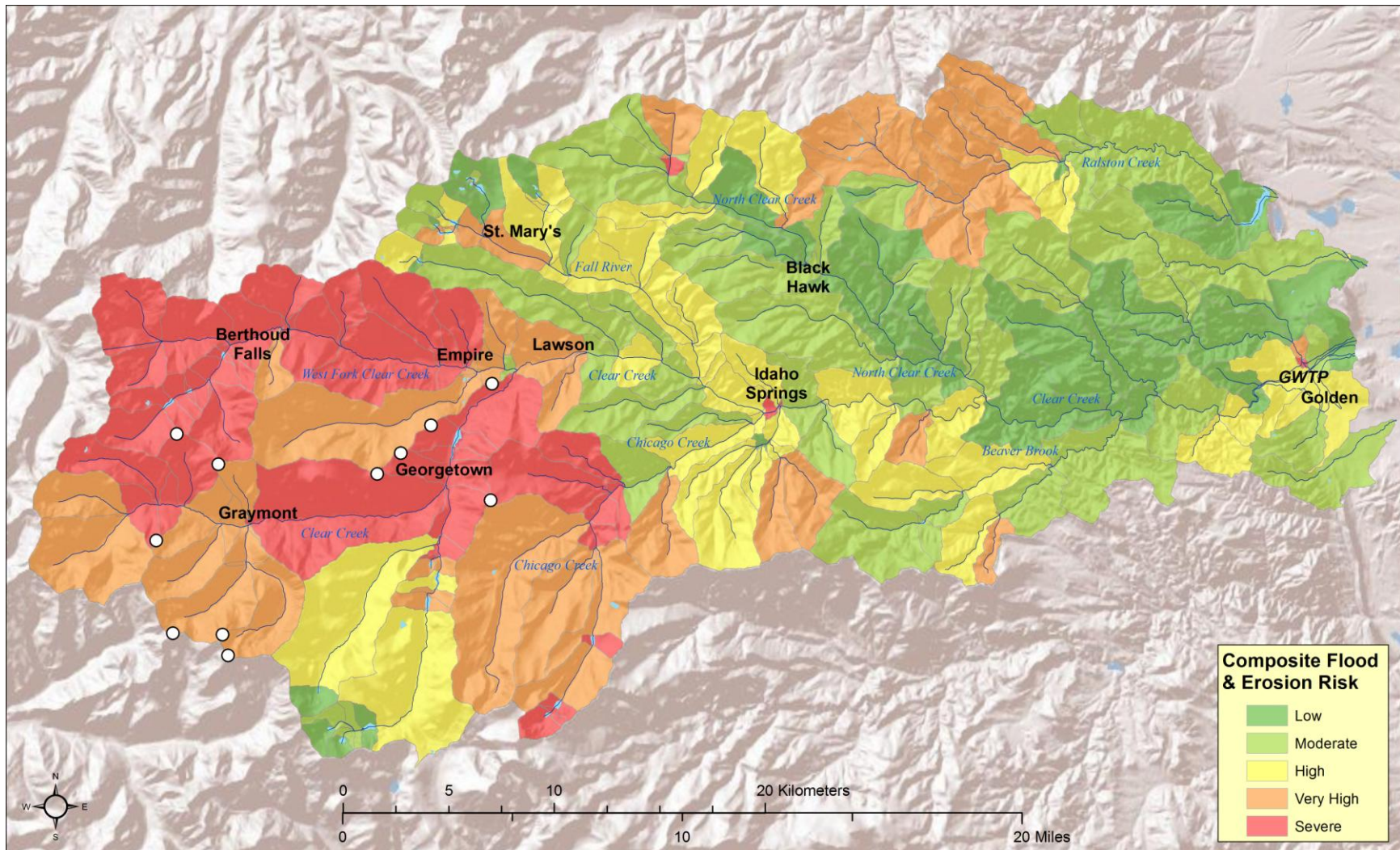
Figure A - 5: Composite Flood and Erosion Risk for Clear Creek Watershed, Colorado, with locations of mountains on which debris flows were generated as indicated by [42].

APPENDIX B: BENCH- SCALE TESTING RESULTS

Jar Testing Results

Table B- 1: Clear Creek Raw Water pH Optimization

Jar	$Fe_2(SO_4)_3$ (mg/L)	pH (Initial)	pH (Final)	Turbidity (NTU)
Raw	-	7.05	-	10
1	30	5	3	32.7
2	30	5.5	2.98	32.5
3	30	6	3	22
4	30	6.5	3.09	10.4
5	30	7	3.16	6.5
6	30	7.5	3.24	6.6

Table B- 2: Jar Testing Results Optimized for Turbidity using 5 mg/L Humic Acid.

Jar	$Fe_2(SO4)_3$ (mg/L)	Dose as PEC (mg/L)	pH	Turbidity (NTU)
Raw	-	-	-	150
1	2.50	0.4	6.6	12.5
2	5.00	0.4	6.6	5.57
3	7.50	0.4	6.6	2.16
4	10.00	0.4	6.6	1.9
5	15.00	0.4	6.6	2.05
6	20.00	0.4	6.6	2.95

Table B- 3: Jar Testing Results Optimized for Turbidity using 10 mg/L Humic Acid.

Jar	$Fe_2(SO_4)_3$ (mg/L)	Dose as PEC (mg/L)	pH	Turbidity (NTU)
Raw	-	-	7.05	8.6
1	10	0.4	7	0.85
2	20	0.4	7	3.4
3	30	0.4	7	13.5
4	40	0.4	7	56
5	50	0.4	7	85.8
6	60	0.4	7	96.6

Table B- 4: Jar Testing Results Optimized for Turbidity and DOC using 5 mg/L Humic Acid.

Jar	$Fe_2(SO4)_3$ (mg/L)	pH (Initial)	Turbidity (NTU)	UV_{254} Absorbance (m^{-1})
Raw	-	7.2	180	15.04
1	5	7.2	1.5	9.32
2	10	7.2	0.6	7.71
3	15	7.2	0.8	6.45
4	20	7.2	0.83	5.35
5	25	7.2	1.2	4.94
6	30	7.2	1.3	4.46

Table B- 5: Jar Testing Results Optimized for Turbidity and DOC using 5 mg/L Humic Acid.

Jar	$Fe_2(SO_4)_3$ (mg/L)	pH (Initial)	Turbidity (NTU)	UV_{254} Absorbance (m-1)
Raw	-	-	80.1	27.15
1	10	7	1.27	7.14
2	15	7	0.78	5.3
3	20	7	0.77	4.31
4	25	7	0.95	3.38
5	30	7	0.85	3.08
6	35	7	0.89	2.67

Column Settling Result

Table B- 6: Turbidity reduction over time in column settling tests using 6 L Type 3 and 4 water.

Sediment added (g)		800			1200	
Column	1	2	3	4	5	6
Time			Turbidity (NTU)			
0	1500	1100	1460	3430	2700	2240
0.5	241	130	117	153	118	158
1	129	64.5	81.4	115	104	99.2
2	71.9	43.2	35.6	61.8	54.3	44.1
3	65.1	45.2	34.6	58.9	52.9	32.6
4	49.0	28.5	32.5	32.3	31.0	34.2
5	41.7	29.8	35.8	36.3	34.3	29.6
6	48.2	24.7	25.7	34.0	32.0	32.5
10	48.0	22.0	22.0	31.0	30.0	31.0
22.5	28.0	15.4	16.6	19.9	18.4	22.4
30.5	22.4	12.2	12.0	15.5	15.3	14.4
39	17.3	9.85	10.2	11.3	13.5	11.3

Table B- 7: Turbidity reduction at specified intervals in column settling tests using 6 L of Type 5 and Type 6 water.

Ash (mL)		-			7.5	
Soil Mass (g)		100 (75 mL)			100 (75 mL)	
Time (hr)			Turbidity (NTU)			
Column	1	2	3	4	5	6
0	399	359	271	540	760	730
22.5	30.4	52.7	42.2	65.3	65.9	75.7
30.5	28.1	41.2	29.8	50.1	50.7	64.5

Table B- 8: Pre-Sedimentation Coagulation Column Settling tests with 6 L of Type 8 water.

Column	$Fe_2(SO_4)_3$ (mg/L)	Turbidity (NTU) Initial (± 500)	23.5 hrs	pH 23.5 hrs
1	-	3000	10.2	10.6
2	20	3000	5.13	10.2
3	30	3000	4.04	10.0
4	40	3000	3.23	9.8
5	50	3000	3.89	9.8
6	60	3000	10.8	10.3

APPENDIX C: PILOT-SCALE TESTING RESULTS

Test 1- 4/4/2012

Table C- 1: Initial dosing.

Humic	5	mg/L
Ferric	20	mg/L
Polymer	0.4	mg/L
Bleach	0.07	mg/L
KMnO4	0.5	mg/L
Flow Rate	0.2	gal/min

Table C- 2: Raw Water Parameters.

Initial Raw Water	Time (hr)	Manganese (mg/L)	Turbidity (NTU)	UV$_{254}$ Absorbance (1/m)	Visible$_{436}$ Absorbance (1/m)	DOC (mg/L)	pH	Alkalinity (mg/L as CaCO$_3$)	Conductivity (μS)
Barrel 1	0	0.167	180	10.15	0.44	3.21	7.5	180	478
Barrel 2	4	0.196	146	-	-	4.30	7.9	180-240	960

Table C- 3: GAC Column Finished Water Parameters.

Time (hr)	Manganese (mg/L)	Turbidity (NTU)	UV$_{254}$ Absorbance (1/m)	Visible$_{436}$ Absorbance (1/m)	DOC (mg/L)	SUVA (L/mg-m)	pH	Alkalinity (mg/L as CaCO$_3$)	Conductivity (μS)
0	0.085	0.220	0.950	0.125	0.418*	0.227*	6.2	40	259
0.5	0.064	0.130	0.085	0	0.374*	0.227*	6.2	80	511
1	0.055	0.092	0.180	0	1.170	0.154	6.5	80	514
1.5	0.043	0.100	0.210	0.025	0.924*	0.227*	6.5	120	594
2	0.045	0.094	2.200	0	1.220	0.180	6.7	120	504
3	0.04	0.105	0.280	0	0.900	0.280	6.7	120	890
5.5	0.038	0.091	0.230	0	0.779	0.295	7.0	120	515

* = Calculated – See appendix C-5

Table C- 4: Dual-Media Column Finished Water Parameters.

Time (hr)	Manganese (mg/L)	Turbidity (NTU)	UV_{254} Absorbance (1/m)	$Visible_{436}$ Absorbance (1/m)	DOC (mg/L)	SUVA (L/mg-m)	pH	Alkalinity (mg/L as $CaCO_3$)	Conductivity (µS)
0	0.012	0.14	4.74	0	2.638*	1.797*	6.7	120	1678
0.5	0.018	0.11	5.025	0.0003	2.797*	1.797*	6.6	120	2367
1	0.005	0.087	4.88	0.01	3.300	1.479	6.7	120	2181
1.5	0.021	0.092	47.59	0.08	26.490†	1.797†	8.4	0	2862
2	0.034	0.081	50.23	0.04	27.959†	1.797†	8.5	0	1525
3	0.019	0.093	16.05	0.11	8.934†	1.797†	8.3	0	1375
5.5	0.024	0.08	5.18	0.13	2.450	2.114	7	180	1068

* = Calculated – See appendix C-5
† = Outliers due to chlorine oxidation of organic matter
Notes: Head loss around 4 hours run time, and around 4.5 hours the pump shut off, causing the flow meter to stick, which shut off the intake. Intake was taken apart and hour # 4 was pushed back to hour #5.5.

Test 2 - 4/5/2012

Table C- 5: Initial dosing.

Humic	10	mg/L
Ferric	20	mg/L
Polymer	0.4	mg/L
Bleach	1	%
KMnO4	50	mg/L
Flow Rate	0.2	gal/min

Table C- 6: Raw Water Parameters.

Initial Raw Water	Time (hr)	Manganese (mg/L)	Turbidity (NTU)	UV_{254} Absorbance (1/m)	$Visible_{436}$ Absorbance (1/m)	DOC (mg/L)	pH	Alkalinity (mg/L as $CaCO_3$)	Conductivity (µS)
Barrel 1	0	0.161	109	17.41	1.39		6.8	240	1021
Barrel 2	1	0.240	129	-	-	-	7.0	180	604

Table C- 7: GAC Column Finished Water Parameters.

Time (hr)	Manganese (mg/L)	Turbidity (NTU)	UV_{254} Absorbance (1/m)	$Visible_{436}$ Absorbance (1/m)	DOC (mg/L)	SUVA (L/mg-m)	pH	Alkalinity (mg/L as $CaCO_3$)	Conductivity (µS)
0	0.033	0.109	0.155	0.095	0.608*	0.255*	6.2	120	509
0.5	0.050	0.099	0.170	0.000	0.667*	0.255*	6.1	120	1062
1	0.054	0.086	0.330‡	0.030‡	0.456‡	0.724‡	6.3	120	637
1.5	0.060	0.063	0.120	0.000	0.471*	0.255*	6.3	120	1009
2	0.051	0.068	0.210	0.110	0.798	0.263	6.3	120	939
3	0.058	0.083	0.190	0.000	0.452	0.420	6.4	120	1062
5.5	0.050	0.077	0.220	0.000	0.891	0.247	6.4	120	657

* = Calculated – See appendix C-5
‡ = Possible contamination of UV sample

Table C- 8: Dual- Media Column Finished Water Parameters.

Time (hr)	Manganese (mg/L)	Turbidity (NTU)	UV$_{254}$ Absorbance (1/m)	Visible$_{436}$ Absorbance (1/m)	DOC (mg/L)	SUVA (L/mg-m)	pH	Alkalinity (mg/L as CaCO$_3$)	Conductivity (μS)
0	0.015	0.188	8.350	0.095	3.392*	2.462*	7.1	120	792
0.5	0.022	0.103	6.240	0.015	2.535*	2.462*	6.9	120	1202
1	0.023	0.095	5.260	0.000	1.770	2.972	6.8	120	1137
1.5	0.025	0.116	5.065	0.040	2.057*	2.462*	6.7	120	1092
2	0.013	0.084	5.380	0.000	2.130	2.526	6.5	120	1062
3	0.014	0.081	6.505	0.000	2.642*	2.462*	6.9	120	1138
4	0.013	0.081	5.080	0.020	2.690	1.888	6.6	120	1038

* = Calculated – See appendix C-5

Calculations for Appendix C

Calculating SUVA and DOC

For this report, DOC was measured instead of TOC in order to be used for SUVA correlations. This allows the use of UV_{254} to be measured in place of TOC, which is expensive and time-consuming to measure in comparison to UV. DOC was measured for influent and at least three finished-water samples per water type. SUVA was then calculated as follows:

$$SUVA\ (L \cdot mg^{-1}m^{-1}) = \frac{UV_{254}(m^{-1})}{DOC\ (mg \cdot L^{-1})}$$

Unmeasured DOC values were then back-calculated from UV_{254} absorbance via the SUVA correlation.

Calculating TOC:

TOC was calculated in order to compare measured mini-pilot DOC results to regulatory standards. As TOC is comprised of POC and DOC, the portion which is DOC was calculated as

$$\%DOC = \frac{DOC}{TOC} X\ 100$$

for a sample from influent and finished water for each water type, and was then applied to the rest of the DOC values to get TOC:

$$TOC = \frac{DOC}{\%DOC}.$$