THESIS:

A Methodology for Estimating Detectable Change in Water Quality Due to Prescribed Fire in Northern Colorado

Submitted by

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We hereby recommend that the thesis prepared under our supervision by Robert William Lange entitled: A Methodology for Estimating Detectable Change in Water Quality Due to Prescribed Fire Northern Colorado be accepted as fulfilling in part requirements of the degree of Master of Science.

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Abstract of Thesis

A Methodology for Estimating Detectable Change in Water Quality Due to Prescribed Fire in Northern Colorado

Increases in nutrients and metals in receiving waters have been documented after wildfire. However, water quality impacts from prescribed fire are not well known. This research investigated the design of a post-fire water quality monitoring program using a pre-fire dataset to detect water quality changes from prescribed fire. Since water quality changes due to landuse practices are often difficult to detect due to high natural variability, a paired watershed approach was implemented. Two small watersheds were selected in the Cache la Poudre watershed in Northern Colorado and monitored for one year, resulting in 14 pre-fire water quality samples. A single station and paired approach, which consider statistical power are presented and the minimum detectable change is calculated for a range of post-fire sample sizes. Samples from the Bobcat Fire in the Big Thompson Watershed near Drake, Colorado are used to evaluate the results. These results show that with 16 post-fire samples a change of less than 1% of the difference between pre-fire water quality samples and samples from the Bobcat Fire can be detected for most parameters with a statistical power of 80%. The paired watershed approach is shown to reduce the minimum detectable change by half for parameters that are correlated between the two watersheds.

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It is with great humility and awe, that I consider the faithfulness of Jesus Christ whose living water has given me hope and purpose since 1987. The study of His creation has instilled me with deep respect and admiration for the complex processes at work to sustain physical and spiritual life.

Dedicated to Dr. Larry Douglas
who unconditionally accepted me as his son,
believing in my dreams and supporting my goals with love and sacrifice.

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Chapter 1: Introduction

One early writer noted, “Fire is more dreaded than any other destroying agent by those who are interested in forests” (Kinney, 1900). Even with the mounting evidence of the critical role fire plays in forest ecosystems, this attitude is still common today.

As early as 1890, fire was used to reduce pests in southeastern long leaf pine forests and benefits from fire were noted such as fuel reduction and improvements to wildlife habitat (Kinney, 1900). Fire was also used widely by European settlers in the West to clear land before farming or before mineral and timber extraction (Veblen et al., 1999). There is also evidence from personal accounts and from tree ring data that Native Americans set fires purposefully in the western United States to improve hunting grounds before Europeans arrived (McCord and Alexander, 1996).

The question of whether fire can be utilized for its benefits while minimizing the potential danger is the same today as for our predecessors. This is especially true in the foothills region of the northern Colorado Front Range between the Rocky Mountains and the plains of eastern Colorado. This area is characterized by a wildland/urban forested interface mostly contained within the Arapaho Roosevelt National Forest. The vegetation in this area is predominantly ponderosa pine (*Pinus pondersosa*) and shrubland (Hess and Alexander, 1986). This area has experienced fire suppression during the 20th century, which is believed to have created a high hazard for catastrophic fire (Veblen et al., 1999). Many of the Front Range forests are primed for severe wildfires due to dense vegetation and high fuel loading (Illg and Illg, 1997).

Front Range forested areas should be viewed in terms of when the last fire occurred and not if a fire occurred (Peet, 1981). Current conditions favoring homogenous stands of ponderosa pine, lodgepole pine, and Douglas fir with high fuel loads are most certainly a result of increased fire activity during the settlement period (1850-1905) followed by fire suppression after 1905 (Veblen et al., 1999). The fire return interval before European settlement has been conservatively estimated between 5 to 15 years for ponderosa pine ecosystems (Chandler et al., 1983). Although natural conditions are difficult to separate in fire-scar data, low severity fires before European settlement probably occurred frequently in ponderosa pine forests (2-10 years) and high severity, stand replacing fires probably occurred less frequently (40-100 years) (Veblen and Lorenz, 1986; Swetnam, 1997; Veblen et al., 1999).

Fire return intervals vary depending on site specific conditions such as location history, elevation, aspect, vegetation types, precipitation, and other variables. In a study of fire in Arizona, fire scar data showed that fires occurred as regularly as every two years in ponderosa pine sawtimber prior to 1876 (Harris and Covington, 1983). In general the fire return intervals for ponderosa pine forests in northern Colorado are longer than for ponderosa pine forests in the southern regions (Wright, 1978; Laven et al, 1980).

During the summer of 2000, after one of the most severe wildfire seasons in recent history, Congress appropriated substantial resources to improve the ability to fight fires and also to implement strategies to reduce fuels in wildland/urban interfaces. The foothill forests along the northern Front Range are primarily wildland/urban interfaces. These lands are of primary importance in efforts to protect increasingly valuable resources downstream. The value of these resources has increased with population growth along the Front Range, which has increased almost 14% between 1990-1995 (Colorado Department of Local Affairs, 1997). Municipalities in Northern Denver, Fort Collins, and Greeley are dependent on water supplies from the Cache la Poudre and Big Thompson Rivers that travel through or originate from northern Front Range forests (Monroe, 2000).

The June 2000 Bobcat and High Meadows Fires may be an omen of an increasing risk of large high-intensity wildfires in Front Range forests. The Bobcat Fire, at 10,600 acres, was nearly four times larger than the 2,800-acre Grace Creek Wildfire in 1988. The Grace Creek fire had been the largest wildfire in the Arapaho and Roosevelt National Forests since 1900. The Bobcat and High Meadows fires caused some flooding and impacts to water quality. However, the impacts could have been much worse given the history of localized convective thunderstorms common to this area (Jarrett, 2001).

For example, the Buffalo Creek Fire in 1996 burned nearly 12,000 acres of Pike National Forest and less than two months later a thunderstorm (2.5 inches in 45 minutes) caused severe flooding and loss of life (Illg and Illg, 1997). The combination of the Buffalo Creek wildfire and late summer storms resulted in the deposition of 15 years worth of sediment loads in Strontia Springs Reservoir during 1997. Water quality problems from increased nutrients and metals after the Buffalo Creek fire continue to present a major problem for the reservoir, a primary water source for Denver (Agnew et al., 1997).

One of the most widely utilized methods to reduce forest fuels is controlled or prescribed fires. Prescribed fires burn dead vegetation and ground fuels and consequently consume the fuel needed to sustain wildfires. Prescribed fire has been shown to reduce the impact from subsequent wildfires in ponderosa pine vegetation types (Wagle and Eakle, 1979). Additional benefits from prescribed fire are the return of the fire disturbance regime important for maintaining a natural successional processes, which in turn can improve the health of forests and the value to wildlife (Kozlowski and Ahlgren, 1974; DeBano et al., 1998). Prescribed fires can be managed for different intensities and typically occur at lower severities than wildfires.

Fires are part of the ecology of ponderosa pine creating variability in vegetation that is generally beneficial to herbs and shrubs, because it removes needle mats and creates gaps in the understory (Wright, 1978). Prescribed fires that cause tree scorching may have a beneficial effect on the overall health of the ponderosa pine stands (Harrington, 1993). Prescribed fire has been shown to reduce the severity of wildfires for 5 to 7 years following prescribed fire and increase the survivability of ponderosa pines during subsequent wildfires (Wright, 1978). Forage yields have been shown to improve after prescribed fire, and fire can be a beneficial process for forest health and possibly a necessary process to maintain natural disturbance regimes (Wright, 1978).

Federal agencies have increased the amount of acreage treated with prescribed fire from less than one million acres in 1995 to almost 2.5 million acres in 1999, which represents a 242% increase (National Interagency Fire Center, 2001). The cost of prescribed fire by all federal organizations in 1999 was nearly one billion dollars (National Interagency Fire Center, 2001). This same intensity of effort has been experienced in the northern Front Range of Colorado, where prescribed fires are currently in the thousands of acres per year and are expected to increase to tens of thousands of acres in the Arapaho and Roosevelt National Forests alone.

The severity of prescribed fire is managed by burning at times of the year with high soil moisture, high humidities, low temperatures, low wind, and during the dormant season for plants. This is done to control impacts on resources and to provide a safety margin during the burn. Prescribed burns in the northern Front Range of Colorado are primarily applied in light to medium fuel types. As managers begin to consider forested areas with heavier fuel types, the positive effects of prescribed fire increase proportionally with the potential impacts to other resources such as municipal water sources.

In addition to National Forests, prescribed fire is being applied in State, County, and private lands, as well as National Parks. With the expanding use of prescribed fires for forest management goals, it is important to study the potential impacts on water quality. Water managers in Northern Colorado are interested in determining how prescribed fire impacts water quality and quantity in rivers that serve Front Range treatment plants and reservoirs.

Potential increases in nutrients such as nitrogen and phosphorus are of concern to water managers due to possible increases in eutrophic conditions in water storage reservoirs, streams and canals. Total organic carbon, iron, and manganese can be very expensive to remove from drinking water sources and have been shown to increase after fires. Each can contribute to color, smell and taste issues. Total organic carbon has been shown to create carcinogens when water is treated with chlorine. Sediment production from burned areas can also decrease storage capacity in reservoirs and can cause changes in aquatic habitat in streams and rivers.

Water quality from prescribed burns is controlled by section 208 of Public Law 92-500, which specifically addresses non-point pollution as a result of silviculture practices. A categorical exclusion from this regulation was granted in 1999 for the Dadd/ Bennett and Lower Flowers Prescribed Fire Projects in the Cache la Poudre watershed located in northern Colorado (USDA, 1999). These prescribed fire projects are being implemented to reduce forest fuels and improve wildlife habitat. Specific instruction on how to conduct the fire have been formulated to reduce the potential impact to resources.

Determining the impacts on water resources from these prescribed fires must be considered on a landscape scale and is essentially a potential non-point pollution source. Therefore the paired-watershed approach was implemented to develop a predictive relationships between a burned and unburned watershed. This approach is recommended in areas with high natural variability (Ponce et al., 1982). In this research this paired approach is tested to determine improvement over single station approach that compares the pre- and post-fire means in one location. The result is a recommendation for the type of method that is most appropriate for each parameter, the number of post-fire sample to take to detect a water quality change, and how this detectable change compares to data from a wildfire.

Chapter 2: Thesis Hypothesis and Objectives

The hypothesis to be tested is that a minimum post-fire water quality sample size can be determined given the pre-fire dataset and within a selected statistical power to detect a minimum detectable change in water quality parameters of concern to water resources managers. This approach will be applied to a paired watershed study in the Cache la Poudre Watershed near Fort Collins, Colorado to measure several water quality parameters expected to change in response to a prescribed fire.

The objectives of this research were to:

1. Determine water quality parameters that are likely to be impacted by prescribed fire and are of concern to water resource managers.
2. Select water quality sampling and statistical analysis methods, and calculate a range of potential post-fire sample sizes needed based on the single station approach at an 80% statistical power.
3. Identify parameters that are correlated in the pre-fire dataset between the control and treated watershed and can be used for the application of the paired statistical approach. Calculate the improvement of the paired approach over a single station approach for the parameters identified at an 80% statistical power.
4. Calculate the Minimum Detectable Change (MDC) and the minimum number of post-fire samples needed to identify changes in water quality variables.
5. Recommend a post-fire sample size for all parameters and recommend a data analysis method for each parameter identified.

Chapter 3: Literature Review

There is a large body of literature documenting the effects of wildfire and prescribed fire on water resources. This literature base can be used to identify the potential effects of prescribed fire on water resources. Although the impacts of prescribed fire on water resources should not be expected to be as dramatic as wildfire, studying impacts from wildfire can be useful in identifying processes that contribute to water quality changes. This large body of fire research can be used to identify water quality parameters that may increase from the application of prescribed fire and parameters that could be of concern to water providers.

3.1 Watershed Scale Impacts from Fire

Fires can change rainfall interception, infiltration, soil moisture storage, and snow accumulation, thus changing watershed response to precipitation events (Tiedemann et al., 1979). For high severity wildfires, peakflows have been shown to increase up to 60 times above what would be expected for pre-fire conditions or compared to unburned watersheds (Tiedemann et al., 1979). Increases of 45% in peak flow in ponderosa pine watersheds have been measured (Anderson et al., 1976). One researcher in New Mexico found peakflows 100 times greater than pre-fire conditions from a watershed that was 60% burned in a wildfire (Bolin and Ward, 1987).

If fire decreases infiltration, an increase in overland flow often results (DeBano et al., 1998). The increase in overland flow depends on the fire severity, topography, vegetation and soil types (Chandler et al., 1983). A paired-catchment study in South

Africa measured higher storm flow responses due to overland flow (Scott and Van Wyk, 1990). Increased overland flow after fire is directly related to slope with the most dramatic increases in areas with slope of higher than 37% slope (Wright et al., 1976). Fire may also influence basic hydrograph parameters such as the time to peak runoff and baseflow amounts, however few studies have directly studied the timing of flows in areas burned by forest fires (Tiedemann et al., 1979; DeBano et al., 1998).

Fires have also been shown to increase suspended sediment loads (Troendle and Bevenger, 1996), and change the morphology of streams (Keller et al., 1997). A paired watershed study in Washington State found runoff and sediment production increases of 50% over pre-fire conditions with no change in the control watershed (Helvey, 1980). A study in a northern Californian watershed after an intense wildfire found that post-fire conditions can favor certain types of macroinvertebrates and may lead to changes in aquatic communities (Roby and Azuma, 1995).

The erosive impact of water on post-fire soils can be dramatic even after moderate precipitation events (Campbell et al., 1977; Helvey, 1980; Bolin and Ward, 1987; Williams, 1991). Debris flow potential may increase after fires causing sediment loss (Robison, 1990). Studies on sediment production from fire-related debris flows have measured increases of sediment concentrations of up to 60% by weight after moderate rainfalls (Weirich, 1987). A study on post-fire suspended sediment after the 1988 wildfires around Yellowstone National Park measured increases of up to 60% in snowmelt run-off and up to 473% in summer rainstorms above pre-fire conditions (Ewing, 1996).

3.2 Hillslope Processes During Fire

Fire has been studied on the hillslope scale to isolate specific processes such as nitrogen mineralization and the formation of hydrophobic soils, among others. These hillslope processes can lead to changes in water quality in receiving waters. Fire change the hillslope hydrologic processes by removing or reducing living vegetation and moisture as well as consuming forest litter. "Of all the ecosystem components, water is perhaps the most sensitive to the disturbance of vegetation and soils on the land surface," (Tiedemann, et al., 1979). The loss of vegetation and the underlying litter and duff layers during a fire decreases the amount of interception and thereby increases the potential for runoff (Tiedemann et al., 1979). The loss or reduction of vegetation canopies, litter, and soil organic matter can also greatly increase raindrop erosivity (Baker, 1990; Terry and Shakesby, 1993).

Fires can significantly alter soil properties due to soil heating, the removal of litter/duff layers, soil paving (small particles clogging macropores in the soil), and the formation of hydrophobic soil layers (Ralston, 1971). Heat-induced water repellency forms in soils when organic litter is consumed by fire and volatilized organic matter is transported into the soil profile by cooler temperature gradients (Savage, 1974). This process is more likely to occur in coarse and sandy textured soils (DeBano et al., 1970).

Hydrophobic effects are greatest in soils with high organic contents and low water contents (DeBano, 1971; Witter et al., 1991). A temperature range of 400-600^{o}F has been shown to cause hydrophobicity in soils (DeBano and Krammes, 1966). However, high organic contents alone have been shown to cause water repellency in unburned fine-grained soils (Barrett and Slaymaker, 1989). The organic substances that increase water repellency are most likely plant-derived hydrophobic acids with high concentrations of carboxyl and hydroxyl groups, and can eventually degrade to hydrophilic acids and carbon (Guggenberger et al., 1994). Hydrophobic conditions have been shown to reduce infiltration even in locations with macropores and preferential flow paths (Burch et al., 1989).

The effects of fires on soil organisms can cause increases in some populations and decreases in others, recovery can occur quickly in burned areas if they are adjacent to unburned areas (Ahlgren, 1974). Some types of fungi and bacteria can increase after fire and may be a factor in increased mineralization of nitrogen species observed in ponderosa pine forests burned by fire (Harris and Covington, 1983).

3.3 Water Quality Impacts from Fire

Post-fire effects can include impacts to both water quantity and quality (DeBano et al., 1998). Researchers have reported the potential for impairing the quality of surface water (Kozlowski and Ahlgren eds, 1974; Tiedemann et al, 1979; DeBano et al., 1998). Depending on the characteristics of the element (nitrogen, phosphorus, carbonates, organic carbon, manganese, and iron), it may volatilize in a fire and escape from the system, move into the soil profile, be transported by erosion to the stream channel, or be deposited in a more soluble form as ash (Tiedemann et al., 1979; Chandler et al., 1983). Alkalinity and pH of receiving waters can increase from ash deposition as a consequence of burning, however one study did not find a significant change in pH in response to prescribed fire (Williams and Melack, 1997).

Both burning and natural decomposition release mineral elements from organic matter into the soil. Leaching from burned material in a coniferous ecosystem can increase soil nutrients (Grier, 1975). A study in ponderosa pine forests found evidence that nitrogen in the form of ammonium is more available for transport after a fire (White, 1996). Concentrations of nitrogen, potassium, magnesium, and other cations in the form of carbonates have been shown to increase in receiving waters after fires (Viro, 1974).

Mineral elements released from organic matter by combustion may enter the soil during burning through volatilization or by percolation through surface ash layers. A study measuring nutrient concentrations in burned and unburned plots found significant increases in potassium and nitrogen in a ponderosa pine forest in Arizona as measured in the understory as well as the soil (Harris and Covington, 1983).

Fire may also change the form of nitrogen to one that is more available for plants due to increases in mineralization after the fire (Tiedemann et al., 1979; Freeman, 1984; Ryan and Covington, 1986). Ash has higher concentrations of mineral elements than unburned vegetation and are soluble in this form (Soto and Diaz-Fierros, 1993). In a lab study using ponderosa pine litter, Gillion et al. (1995) measured increases in the concentration of potassium, manganese and calcium by a factor of 15 and nitrogen, carbon and sulfur by a factor of 2 in burned organic material. Ash with high nutrient concentrations can be easily transported to stream channels via overland flow and wind (Hauer and Spencer, 1998).

McCord and Alexander (1996) found elevated concentrations of calcium, iron, bicarbonate, manganese, lead, and phenol concentrations in streamflow after a wildfire. Hauer and Spencer (1998) found changes in total nitrogen and total phosphorus of 5 to 60 fold over background conditions in the first flushes after a wildfire near Glacier National Park. This study was in high elevation steep watersheds and found the highest concentrations measured were in response to increased streamflow. Streams were sampled during the fire and for two seasons after the fire. Background conditions were determined by monitoring unburned areas nearby. A water quality comparison of two watersheds in mixed conifer forests in California found elevated concentrations of multiple nutrients (Williams and Melack, 1997). This study occurred during a drought period which elevated the production of nutrients from the control watershed. Pre-fire data were available for this study, however a paired statistical approach was not attempted.

3.4 Potential Water Resource Impacts from Prescribed Fire

Wildfires can cause dramatic impacts on water quality and quantity, but the impacts of prescribed fire are less defined. For prescribed fire, streamflow responses are generally smaller than for wildfires and can be nonexistent in areas of low severity (DeBano et al., 1998). However, increases in surface runoff and erosion have been measured as related to prescribed burning (Biswell and Schultz, 1957).

Studies have measured impacts from prescribed fires on receiving waters in mixed-conifer forested streams of the Sierra Nevada in California (Chorover et al., 1994; Williams and Melack, 1997). In the tropical savanna in northern Australia, Townsend and Douglas (2000) measured changes to total suspended solids, volatile suspended solids, nitrogen, phosphorus, iron, and manganese from different fire conditions in low gradient watersheds and found changes in receiving waters of 2-5 times unburned conditions.

When a forest burns, soil is heated and produces changes in surface ground cover. The effects are directly related to the severity of the fire, properties of the forest vegetation, and geology. Removing the litter layer exposes mineral soil and makes it more susceptible to erosion from rain drops. However prescribed fires will typically not remove the entire litter layer and light burning is not likely to change the organic amounts in the surface soil (Ralston, 1971). Prescribed fires are likely to have a negligible impact on soil properties compared to mechanical methods of logging and wildfires (Ralston, 1971).

A study based on 20 years of research on prescribed burning in South Carolina found that organic material in the soil increased in locations with periodic burning (Wells, 1971). Soils have been found to have higher amounts of ammonium with prescribed fires, but two studies in the same location in Arizona found no change in nitrate and nitrite concentrations after prescribed fire in ponderosa pine forests (Covington and Sackett, 1984; Ryan and Covington, 1986). Ammonium in soil increases with burn severity and may be attributed to leaching of nutrients from ash as well as increases in microbial mineralization (Harris and Covington, 1983; Chorover et al., 1994).

The conversion of nitrogen stored in living and dead plant material to ammonium has been observed with light fires and the historical use of this method for making agricultural land more productive has been documented (Kozlowski and Ahlgren, 1974). Phosphorus, potassium, and magnesium showed a significant increase in the soil and pH increased in locations with periodic burning due to greater abundance of cations after a prescribe fire in South Carolina (Wells, 1971).

Changes in water quality as a result of prescribed fire can be expected to be more pronounced in the first year following a fire. McColl and Grigal (1977) found that increases in water quality parameter concentrations were highest in the first year for a prescribed fire in Minnesota and the values were expected to reduce with time. In another study, spikes in water quality parameter concentrations were measured mostly in the first year, but increases were also measured in subsequent years in response to snow melt events (Hauer and Spencer, 1998). Soil nutrient contents in burned plots was been shown to increase significantly with light and moderate forest fires without causing a marked difference in soil runoff and erosion (Kutiel and Inbar, 1993). This increase in soil nutrients may be caused by the stimulation of microbial activities in the soil following the fire (Jorgensen and Hodges, 1971). A study of soil and stream chemistry after a prescribed fire showed increases in most nutrients. A dramatic increase in ammonium was measured in the soil, but there was not a corresponding increase in the streamflow chemistry. However cations such as calcium, manganese, and potassium were increased in stream chemistry (Chorover et al., 1994).

Studies of changes in water quality at the watershed scale from prescribed fire for forest management are rare, and few studies have been done in ponderosa pine ecosystems at the watershed scale. One conclusion common to researchers is that studies should be area and fire type specific to analyze the watershed response (Parminter et al., 1983). Researchers have pointed out there is a need for focused studies on the effects of prescribed fires in wildlands, specifically on the effects of typical prescribed fire on soil and water that can be done in a controlled environment to limit confounding variables (Omi and Laven, 1982).

3.5 Procedures for Evaluating Changes in Water Quality due to Fire

This research investigated the design of a post-fire water quality monitoring program using a pre-fire dataset to detect potential water quality changes. This design requires the application of statistical techniques that can define the ability to detect potential changes in water quality parameters.

Only a few studies have had pre-fire datasets (Williams and Melack, 1997; Hauer and Spencer, 1998). A common procedure in studies that address water quality changes from wildfires is to locate an unburned watershed nearby and assume it represents background conditions. These studies typically use a significance test for means to compare the fire and no-fire conditions. Rarely is an evaluation of the possible error due to background variability in these watersheds presented. With large changes in some parameters common to wildfire studies this is probably not an issue, since it is not uncommon to measure changes of 1-60 times background conditions. However, not considering watershed scale differences in a fire/no fire comparison can lead to uncertain conclusions even when pre-fire data is available (Ewing, 1996).

For any given two-parameter statistical test a minimum detectable change (MDC) can be calculated, this is sometimes referred to the as the minimum detectable effect or MDE (Bunte and MacDonald, 1999). The MDC is the smallest magnitude for which a two-sided confidence interval about the mean does not contain the possibility of no change between the datasets. The MDC is then a threshold value for which all larger changes are considered statistically significant. The MDC along with an estimate of the variability of the dataset can be used to evaluate the minimum number of samples needed for the statistical test to detect a change (Loftis et al., in review).

3.5.1 Single Station Approach

The single station approach compares the means of the water quality parameters of the pre and the post-treatment dataset. For the single station approach, the MDC can be calculated using Equation 1, as described by Loftis et al., (in review).

$$MDC = \frac{Z_{1-\alpha/2}\sqrt{2}\sigma}{\sqrt{k}} \tag{1}$$

where:

MDC = is the minimum detectable change, referred to MDE in Loftis et al. (in review),

Z = $Z_{(1-\alpha/2)}$, standard normal deviate, $Z = 1.96$ for a 95% confidence level, two-sided interval,

σ = standard deviation for pre-treatment mean,

k = is the minimum sample size assuming equal sample sizes.

The statistical power (the probability of detecting a given change that has occurred) of the above approach can be no greater than 50%, meaning that Equation 1 can only be expected to have a 50% chance of detecting a given change (Loftis et al., in review). Therefore, it is important to consider the power of the procedure when selecting a minimum sample size for a monitoring program.

3.5.2 Single Station Approach Considering Power

Zar (1999) presents a method to calculate a two-sample hypothesis using the Student's t-test for comparison of means. For the single station approach the population represented by the pre-fire dataset is compared to the post-fire dataset and tested to see if the means are significantly different. The advantage of this method is that the MDC can be calculated at a selected statistical power for the single station approach (Loftis et al., in review).

3.5.3 Paired Watershed Approach

The paired approach for determining the water quality impacts can be used to improve the ability to detect changes after a treatment (Ponce et al., 1982). This is achieved by including predictive information from the relationship of the pre-treatment paired watersheds. This procedure uses a change in slope and/or intercept for the post-fire linear regression to represent a change in the relationship. Changes in this relationship between the treated and control watersheds can be tested for significance.

Ponce et al. (1982) presents the paired watershed method used by the Forest Service for most wildland water quality studies. For this method to work effectively the paired watersheds should be as nearly alike as possible and the water quality parameter of concern should be normally distributed and correlated for paired samples from the treatment and control watersheds. This method has been successfully applied to general water quality parameters such as annual sediment yields, suspended solids, turbidity, and electrical conductivity. However, Ponce et al. (1982) states that there are "no procedures available to the hydrologist to determine a specific sample size which will permit a comparison test at a predetermined level of statistical reliability." The authors go on to recommend a minimum of 15 observations to be collected per station per year, but give no rationale for this number.

Chapter 4: Methods

Beginning in August 1999 background water quality samples were collected for paired watersheds located within the Dadd/Bennett Project Area in the Cache la Poudre Watershed in Northern Colorado. A total of 14 sample trips yielded 10-14 paired values, depending on the parameter, for each watershed (Appendix I).

4.1 Site Description

The Dadd/Bennett Prescribed Fire Project area is approximately 30.4 km^2 acres with 28.3 km^2 proposed for treatment, the project goals are to improve wildlife habitat by increasing grass, shrub, and aspen growth and reducing fuels (USDA, 1999). The project boundaries are roughly the Pingree Park road on the East, Dadd Gulch Trail on the West, Crown Point road on the South (with the Lower Flowers area to the south of this road) and Highway 14 on the North. The study site is 2-3 miles East of Rustic, Colorado on the South side of Highway 14 in the Cache la Poudre canyon (Figure 1).

4.1.1 Watershed Selection

Mom Gulch (2.58 km^2) and Dadd Gulch (3.63 km^2) watersheds were selected since they have similar area, elevation, topography, and vegetation types (Table 1). Mom Gulch will be burned as part of a prescribed burn in the spring of 2001 if weather conditions are favorable.

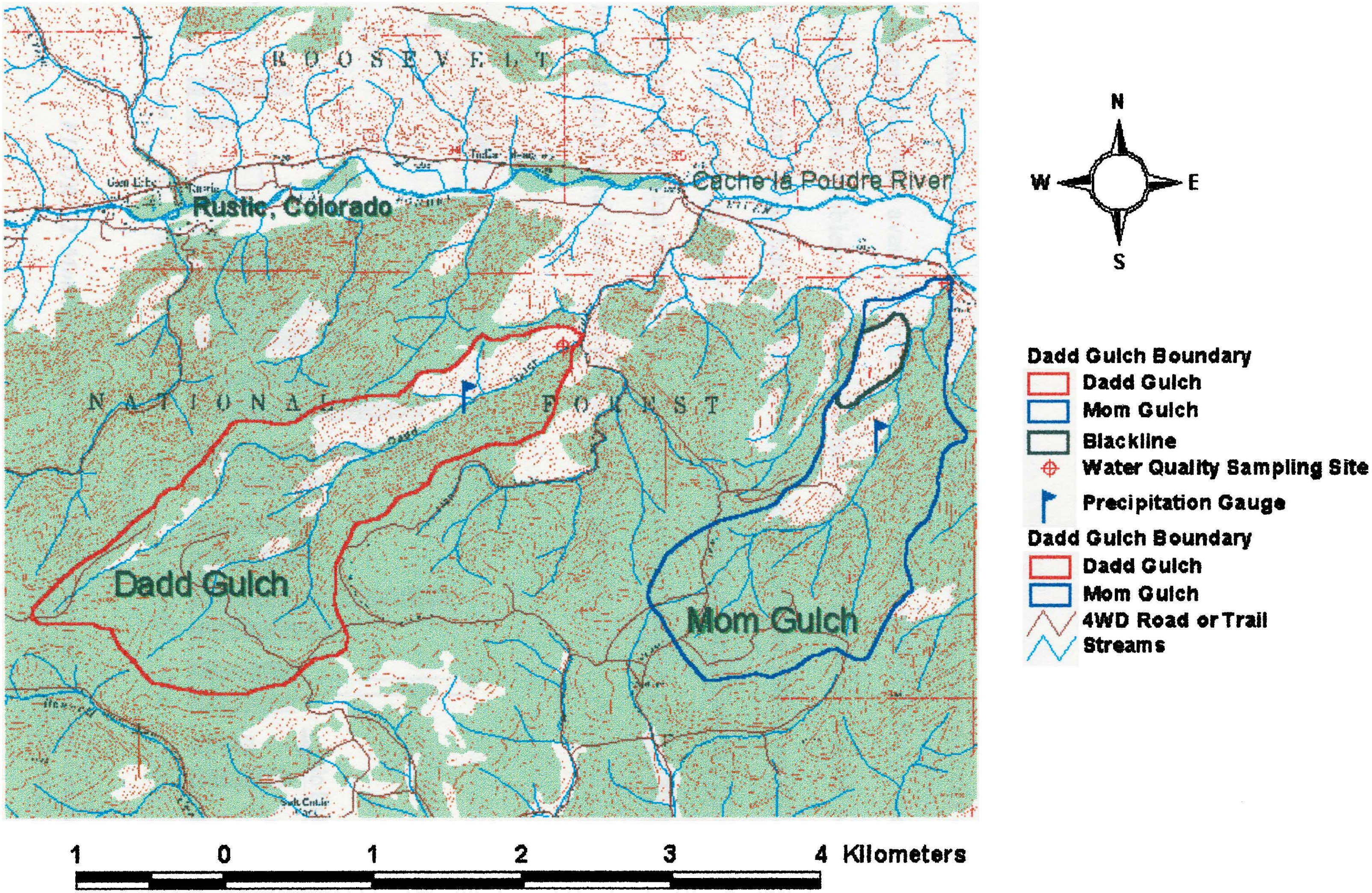


FIGURE 1. Paired watershed study area in the Cache la Poudre Watershed in Northern Colorado.

TABLE 1. Comparison of physical parameters for Mom and Dadd Gulch, located in the Cache la Poudre Watershed in Northern Colorado.

Parameter	Mom Gulch	Dadd Gulch
Watershed Area (km^2)	2.58 (638 acres)	3.63 (897 acres)
Average Elevation (m)	2,347 (7,700 ft)	2,451 (8,041 ft)
High and Low Elevations (m)	2109 to 2585 (diff. 1,562 ft)	2170 to 2733 (diff. 1,847 ft)
Length of Streams (km)	3.5	5.3

4.1.2 Precipitation

A National Weather Service (NWS) station located at Rustic, Colorado (Figure 1) was used to characterize the precipitation for the monitoring period. Daily total precipitation were available from 1975 to 2000. The year 1991 was omitted from the analysis due to problems with data for that year. The total annual rainfall was higher for both 1999 and 2000 than the average for the combined data, which was 10.5 inches. The total precipitation in 1999 was 11.8 inches and the total for 2000 was 11.7 inches. The monthly distribution showed that 1999 had higher early season precipitation and 2000 had higher than normal late season precipitation (Figure 2).

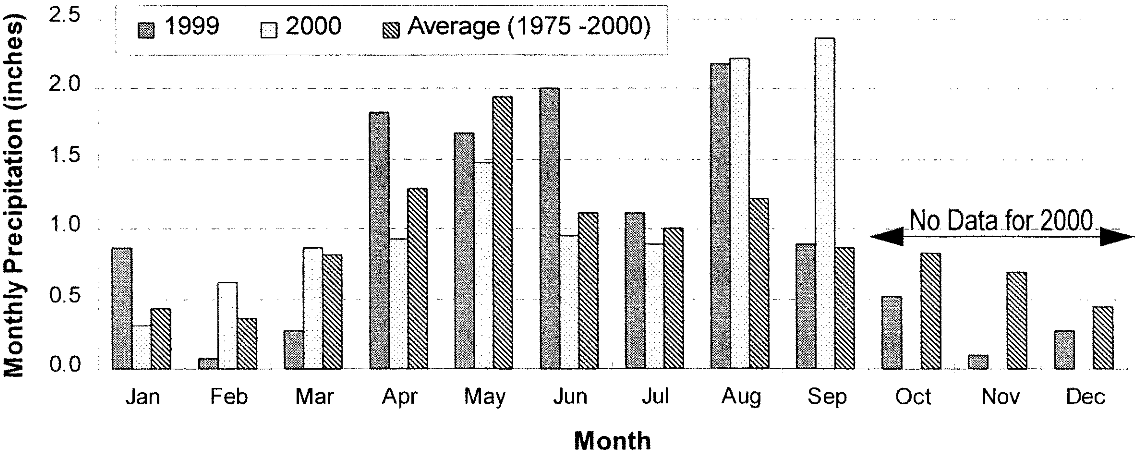
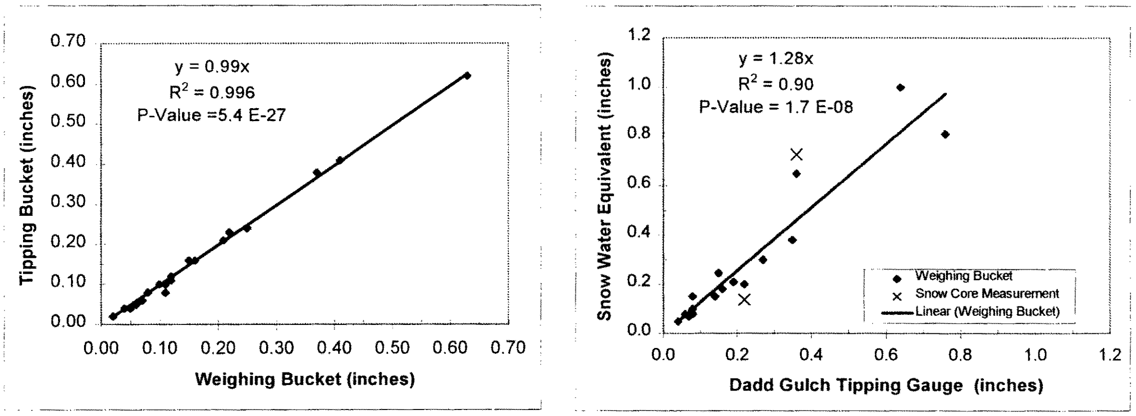


FIGURE 2. Monthly precipitation for NWS gage near Rustic, Colorado (1975-2000). Data available through September 2000.

Precipitation was measured in Mom and Dadd Gulch using 8-inch diameter tipping bucket rain gages attached to Onset Hobo Event Loggers. The capacity of the collection buckets for the rain gages was 0.01 inches. The rain gages were installed approximately 5 feet from the ground surface in small openings. The largest error in precipitation measurements can result from wind and has been estimated to range from -5% to -80% depending on the location. Other factors including evaporation, adhesion, color, inclination, and splash account for an additional -1.5% error (Brakensiek et al., 1979). Therefore, the locations were selected in openings protected by vegetation and topography from direct wind. Care was taken to locate the gages so that the tops of surrounding trees were less than 45^0 in relation to the top of the collection bucket.

Snow measurements using the tipping buckets raingages are subject to error. Therefore, to estimate winter precipitation a Belfort weighing bucket gage was installed near the tipping bucket rain gage in Dadd Gulch. The weighing bucket gage was filled with automobile antifreeze and oil to reduce evaporation and sublimation and monitored from November 1999 to December 2000. On two occasions snowfall was measured by taking core samples and measuring the weight, which was then converted to the snow water equivalent. The weighing bucket gage was also monitored during the summer of 2000 to compare rainfall between the two gages.

The relationships between snow and rainfall data for Dadd Gulch was used to estimate a correction factor to apply to winter precipitation to account for the undercatchment for the tipping bucket gage. Although the weighing buckets probably did not measure the full snowfall (Brakensiek et al., 1979), the limited number of snow core measurements did not provide enough data to evaluate this possibility. Figure 3 shows the regression equations, correlation coefficients, and graphs for rainfall and snowfall during the measurement period. A total of 23 rainstorms and 16 snowstorms were used for the comparisons. The slope of the regression for rainfall was nearly 1.00 for rainfall and 1.28 for snow.



(a) Comparison of rainfall, 23 data points.

(b) Comparison of snowfall, 16 data points.

FIGURE 3. Linear regression for rainfall (4/7/00 - 8/18/00) and snowfall (11/22/99 - 12/10/00) in Dadd Gulch, located in the Cache la Poudre Watershed near Rustic, Colorado.

Based on this relationship the winter precipitation tipping bucket measurements were multiplied by 1.28 to compensate for their lower snow catch efficiency. Data from August 1999 to January 2001 is presented in Appendix II for Mom and Dadd Gulch.

4.1.3 Discharge

A 6-inch Parshall flume was installed at the mouth of each watershed to measure discharge. Each flume was equipped with a stilling well and stage recorder. For the summer of 1999, Stevens chart recorders were used. In the fall of 1999 punch-tape Fisher Porter recorders were used due to problems with the clocks and insensitivity to changes in stage for the Stevens recorders. Flows at both gulches stopped in June 2000 and resumed for a short period in October 2000. From November to April for both 1999 and 2000 flows were not measured due to ice forming in the stilling well and also in the flume. A staff gage was installed in each of the flumes and observations of stage were recorded for each water quality sampling trip (Figure 4).

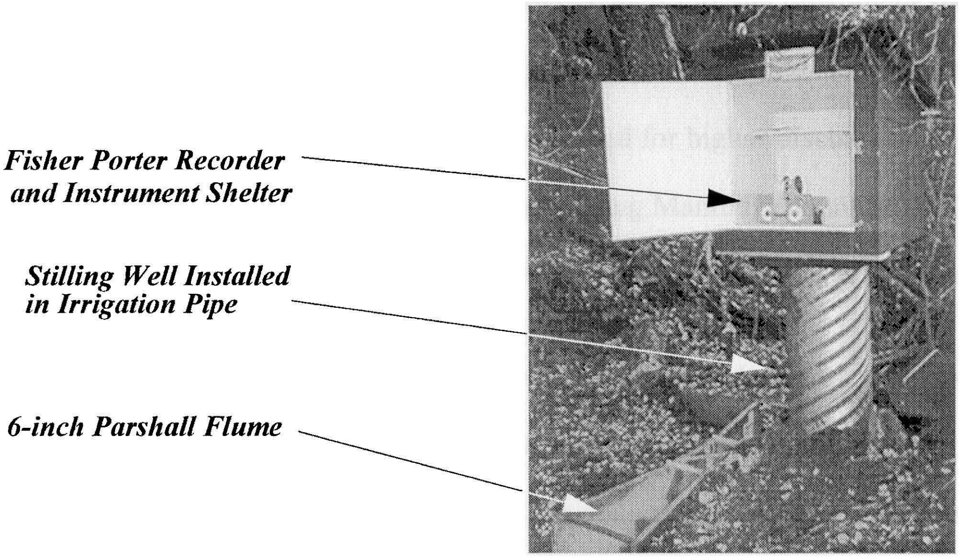


FIGURE 4. Parshall flume and continuous stage recorder at Dadd Gulch in the Cache la Poudre Watershed near Rustic, Colorado.

The bottom of the inlet into the stilling well for Mom Gulch was 0.01 feet and for Dadd Gulch it was 0.006 feet. The maximum upstream head that can be measured with the flumes is 1.25 feet. Therefore the discharge and the capacity of the flumes can be determined from Equation 2 assuming free-flow conditions (USBR, 1984).

$$Q = 2.06 \ H_a^{1.58} \tag{2}$$

where,

Q = the discharge in cubic feet per second,

H_a = the upstream head of the flume measured in feet.

The capacity of the flumes is 0.0014 to 2.93 cfs for Mom Gulch and 0.00063 to 2.93 cfs for Dadd Gulch. Fisher Porter recorders were used for the majority of the study period and could measure changes of 0.01 feet stage change, therefore discharge could be reliably measured to 0.001 cfs.

The largest anticipated discharge was 5-10 cfs, therefore the instrument shelters were mounted on 5-foot tall 2-foot diameter irrigation pipes that could serve as a stilling wells for larger discharges. The stage could be measured for higher discharges using this method and the stream discharge could be estimated using Mannings equation. Roughness coefficients were selected from Van Haveren (1986).

A localized thunderstorm on 8/15/00 caused flooding in Mom Gulch and exceeded the capacity of the flume. Discharge was estimated from a cross-section and stage measurements recorded during the storm event. The main portion of the rainfall fell from 7:05 to 7:35 p.m., and resulted in 1.4 inches of rain. The maximum 5-minute intensity was from 7:25 to 7:30 p.m. and resulted in over one-half inch of rain during this time period. There was evidence of erosion and changes were observed in the bed composition and geomorphology of the stream channel in Mom Gulch. The discharge and precipitation for the storm is shown in Figure 5 and the daily average discharge is shown in Appendix III.

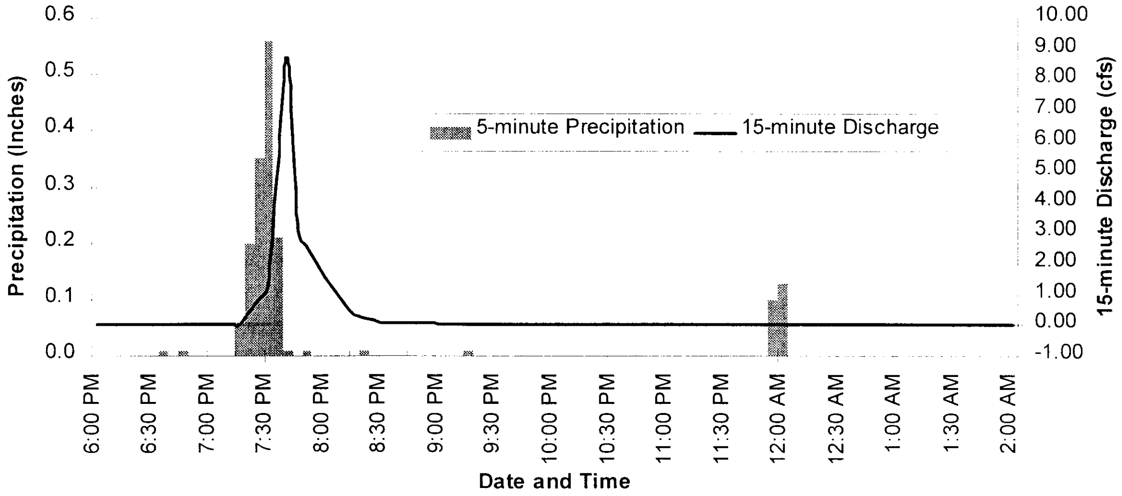


FIGURE 5. Precipitation and stream discharge on the evening of 8/15/00 for Mom Gulch located in the Cache la Poudre Watershed near Rustic, Colorado.

4.1.4 Soils and Vegetation

Soils in this area are generally shallow and of coarse texture derived from colluvial and residual parent material from igneous and metamorphic geology (Bashkin, 1999). Metamorphic gneisses and schists are common and associated with severe geological forces that formed dykes of quartz, monzonite, diorite and granite evident in this area. No sedimentary rocks are present (USDA, 1980). The slopes are steep, over 30% in most areas with exposed rock outcrops.

Forest habitat types are defined by the topography and vegetation and are in the ponderosa pine (*Pinus ponderosa*) series and Douglas fir (*Pseudotsuga menziesii*) series on the north facing slopes, mountain juniper series (*Juniperus scopulorum*) with grass/ shrubland on the south facing slopes, and mixed aspen stands (*Populus tremuloides*) in the *Populus Aungustifolia* series in the riparian areas (Peet, 1981; Hess and Alexander, 1986). Shrubs include sagebrush (*Artemisia tridentata*) and mountain mahogany (*Cercocarpus montanus*), among others.

4.1.5 Land Uses

According to the Canyon Lakes District Ranger the Dadd/Bennett project area has experienced grazing with high intensity as late as the 1940s. Currently 140 cow/calf pairs are in a grazing allotment which includes both Mom and Dadd Gulch from July to October. Logging has been extensive in some parts of the project area, which include both Mom and Dadd Gulch, with some wildlife cuts and clear-cuts as late as the 1980s and selective harvesting since the early 1900s. The watersheds do not have significant impacts from recreation and have experienced some minor amounts of mineral extraction, but they are fairly undisturbed.

4.1.6 Expected Burn Conditions

The North Fork of Dadd Gulch was selected as the control watershed and will not be burned in the near future. The lower watershed (Mom Gulch) with its outlet to the Cache la Poudre River near USGS benchmark number 6908 will experience moderate to high burns in the upper portions of the reach and low severity burns near the mouth. The burn plan includes a buffer strip along riparian areas and the fire can be expected to vary in severity depending on fuel types and random effects of the burning process. Some areas will not be proactively ignited based on concerns about the danger of canopy fire spread and/or steep slopes with highly erodible soils (USDA, 1999).

4.2 Water Quality Sampling

Water quality samples were taken from Mom and Dadd Gulch from August 1999 to October 2000 on a monthly basis with one intensive four week long weekly sampling period. A total of 14 paired samples were taken from the thalweg just above the location of the stream gauges in each watershed. Water quality samples were measured for temperature, pH, and specific conductivity in the field. Total dissolved and total suspended solids were measured in the Earth Resources Water Quality Laboratory using gravimetric analysis (Stednick, 1991). All other water quality parameters were analyzed by the City of Fort Collins Water Quality Laboratory with the exception of total organic carbon which was analyzed by the City of Greeley.

For each sampling trip one field blank was prepared by using deionized water and a duplicate sample was taken at one location during each sample trip for quality assurance (Table 2). Parameters were selected for analysis based on the literature review (Chapter 3), for their likelihood to change with fire and importance to water providers.

TABLE 2. Water quality parameters sampled from August 1999 to October 2000 from Mom and Dadd Gulch located in the Cache la Poudre Watershed near Rustic, Colorado.

Variable Name	Detect Limit	Units	Paired Values	Description
Alkalinity	2.0	mg/L CaCO$_3$	12	Capacity to neutralize acid.
Lab pH	n/a	units	14	The pH is a measure of the hydrogen ion activity, which in dilute solutions is approximately equal to the hydrogen ion concentration.
Field pH	n/a	units	13	
Discharge	0.001	cfs	14	Stream discharge, measured at sampling time and every 15 minutes.
Specific Conductivity	n/a	uS/cm	12	The ability of water to conduct an electric current depends on the amount of ions in the water.
Nitrite (NO2)	0.03	mg/L	14	Unstable intermediate stage of the nitrogen cycle, formed in water by the oxidation of ammonia or the reduction of nitrate.
Nitrate (NO3)	0.02	mg/L	12	Most highly oxidized form of nitrogen, common in surface waters as the end product of decomposition of organic matter.
Ammonia (NH3)	0.02	mg/L	11	Produced when organic matter is consumed by microbiological activity.
Kjeldahl Nitrogen (TKN)	0.10	mg/L	11	Sum of ammonia nitrogen and other nitrogen compounds released when the sample is digested.
Total Organic Carbon (TOC)	0.01	mg/L	12	Carbon present as organic matter dissolved and/or suspended in the water.
Total Phosphorus (TPHOS)	0.018	mg/L	11	Phosphorus from soil, plants, and microorganisms dissolved and/or suspended in the water.
Copper (Cu)	3.0	ug/L	14	Typically unaffected by fire, dissolved fraction.
Iron (Fe)	5.0	ug/L	14	Shown to increase with fire, dissolved fraction.
Manganese (Mn)	1.0	ug/L	14	Shown to increase with fire, dissolved fraction.
Suspended Solids (TSS)	n/a	mg/L	12	Material as collected by a Whatman paper filter with a 40 rating.
Dissolved Solids (TDS)	n/a	mg/L	12	Material left after evaporation from sample passing through Whatman filter.
Bedload	n/a	g/day	7	Sediment collected in sediment traps, typically for one week.

4.3 Background Water Quality from the Cache la Poudre River

Mom Gulch drains directly into the Poudre river below Rustic and before the confluence with the Little South Fork of the Cache la Poudre River. The City of Fort Collins has been monitoring water quality along the length of the Poudre River since 1997. Two sites above and below Mom and Dadd Gulches on the Poudre River were selected to compare the background water quality data for parameters measured in this study. The locations are above the confluence with the Little South Fork and the Poudre River and below the confluence of Sheep Creek above Rustic. Two samples were available for each summer at each site, and the mean of all the values was calculated for comparison (Table 3). the full datasets for these two sites is presented in Appendix I.

TABLE 3. Comparison of mean values for water quality parameters from the Cache la Poudre River Watershed in Northern Colorado. Samples are from above the confluence of the Little South Fork of the Cache la Poudre River (Little South), Mom Gulch, Dadd Gulch, and below the confluence of Sheep Creek.

Parameter/ Location	Sheep Creek Mean (1997- 2000)	Dadd Gulch Mean (1999-2000)	Mom Gulch Mean (1999-2000)	Little South Mean (1997- 2000)
Number of sample trips	7	14	14	7
Alkalinity (mg/L as $CaCO_3$)	14	89	108	15
Lab pH (units)	7.2	7.9	7.9	7.3
Conductivity (uS/cm)	32	18.7	22.5	34
Nitrite (mg/L)	<0.03	<0.03	<0.03	<0.03
Nitrate (mg/L)	0.060	0.049	0.021	0.019
Ammonia (mg/L)	-	0.017	0.019	0.023
Kjeldahl Nitrogen (mg/L)	-	0.20	0.20	0.30
Organic Carbon (mg/L)	3.94	2.86	3.42	4.17
Phosphorus (mg/L)	-	0.027	0.022	0.028

The most dramatic differences between Mom and Dadd Gulches and the samples from the Cache la Poudre River are the alkalinity, specific conductivity, and pH measurements (Table 3). Alkalinity is seven or eight times higher in the study area and both specific conductivity and pH are higher, which may be related to higher amounts of cations from Mom and Dadd Gulch. The nutrients tend to be slightly lower in the Mom and Dadd Gulch samples than for the Poudre River samples.

4.4 Water Quality Samples from the Bobcat Fire

Although many researchers have quantified changes in water quality parameters some of the parameters identified for this study have not been reported in other research, have not been measured in a comparable ecosystem, or have been measured only in relation to wildfire. Therefore, there is a need to estimate realistic changes in variables based on data from a comparable location that has experienced a fire.

The June 2000 Bobcat Fire in the Big Thompson Watershed near Drake, Colorado burned 10,600 acres in mostly ponderosa pine and Douglas fir. The same water quality parameters selected previously were measured from June to September 2000 in two watersheds located in the burned area. Bobcat Gulch (2.2 km^2) and Jug Gulch (3.6 km^2) were selected for monitoring (Table 4). These watersheds have similar vegetation and are of similar size as those in the Poudre watershed. These data are used to evaluate potential water quality changes due to the Dadd/Bennett prescribed fire.

TABLE 4. Water quality parameter mean values for the paired watersheds located in the Cache la Poudre Watershed (Mom and Dadd Gulches) and from the Bobcat Fire (Bobcat and Jug Gulches) in the Big Thompson Watershed, both located in Northern Colorado. Samples collected from August 1999 to August 2000.

Parameter	Mom Gulch Mean	Dadd Gulch Mean	Jug Gulch Mean	Bobcat Gulch Mean
Number of sample trips	14	14	3	7
Alkalinity (mg/L as $CaCO_3$)	108	89	158	84
Conductivity (uS/cm)	225	187	344	262
Nitrite (mg/L)	0.015	0.015	0.023	0.054
Nitrate (mg/L)	0.021	0.050	1.203	2.608
Ammonia (mg/L)	0.019	0.020	0.079	0.841
Kjeldahl Nitrogen (mg/L)	0.20	0.20	1.86	9.47
Organic Carbon (mg/L)	3.42	2.86	21.22	30.98
Phosphorus (mg/L)	0.023	0.024	0.238	0.105
Copper (mg/L)	2.9	2.4	4.0	3.6
Iron (mg/L)	126	76	803	1500
Manganese (mg/L)	3.9	2.5	313	184
Suspended Solids (mg/L)	5.3	4.7	308	97
Dissolved Solids (mg/L)	156	136	333	249

As can be seen from Table 4, all the parameters are at least an order of magnitude higher for the Bobcat Fire data than they are for Mom and Dadd Gulch for most parameters. The Bobcat Fire burned at a higher intensity than what can be expected from the prescribed fire. However, since parameters measured in this study have not been measured in other studies and since literature recommends site specific studies these data will be useful in evaluating expected changes in water quality parameters expected due to the prescribed fire.

4.5 Data Analysis

For the statistical analysis, the precision of the full reported value was used and significant figures for reporting were selected individually based on an estimate of the precision of the measurement (Appendix I). Means of the field duplicate and primary sample were used for the statistical analysis when available. For parameters with more than 10% of the values below the detection limit, the probability plotting method (Gilbert, 1987) was used to fill data values for the calculation of mean, standard deviation, and variance. For parameters with one or two values below the detection limit 1/2 the detection limit was used for data filling before calculating statistical parameters.

Increasing the sample size increases the ability for monitoring programs to detect change, but will also increase the monitoring time and expense needed for the study. Therefore, there is a need to determine the most efficient sample size required to detect a given change. For this study, the number of pre-fire samples is fixed and therefore the number of post-fire samples is selected such that an expected amount of change can be detected. The first step in this process is to calculate the mean, standard deviation, and variance for the pre-fire dataset. The minimum detectable change (MDC) can then be calculated using the single station approach by considering the variability in the treatment watershed. Next each parameter can be evaluated individually to determine if they are correlated between the control and treatment watersheds, in this case Dadd and Mom Gulch, respectively. If they are correlated, the paired watershed approach can be evaluated. Finally, a recommendation for an analysis method and a final sample size can be selected to calculate MDC values.

4.5.1 Quality Assurance and Treatment of Non-Detect and Censored Data

A typical standard for field blank quality assurance is to censor data for which the field blank was above the detection limit selected by the laboratory. However, for the pre-fire dataset there were several cases where field blanks were above the detection limit and yet samples on the same trip were measured below the detection limit. It may be the case that the deionized water was not free of ions, the lab detection limit was too high, or sample bottles were contaminated. Regardless of which of these possibilities is the case, field blanks above the detection limit indicate a general problem that may be present in all samples. Removing data points for individual sample trips would not improve the results and could remove valuable information from the analysis. Therefore, the standard adopted for this research was any field blanks that showed a value higher than one standard deviation (calculated for all values) greater than the zero triggered the removal of parameter values collected.

The quality assurance analysis of the sample duplicates used the Upper Concentration Limit (UCL) method as described by Bartram and Ballance (1996) to determine what sample duplicates were outside the "control" of the study. The UCL is 3.67 x the mean of the *R* value, where *R* is the relative range value and is calculated using the first duplicate, *1st Dup*, and second duplicate, *2nd Dup*, by Equation 3.

$$R = \frac{|(1st\ \ Dup - 2nd\ \ Dup)|}{((1st\ \ Dup + 2nd\ \ Dup)/2)} \tag{3}$$

A summary of the quality assurance outcomes, the original number of paired samples, the number of samples removed because of blanks or duplicates, and the final number of samples used for the water data analysis are shown in Table 5.

TABLE 5. Pre-fire quality assurance summary table for water samples from Mom and Dadd Gulches in the Cache la Poudre Watershed near Rustic, Colorado. Samples were collected from August 1999 to September 2000.

Parameter Name	Units	Lab Detect Limit	# Paired	# < DL	# Removed		# Analysis	Non Detect Method[a]
					Blank	Dups.		
Alkalinity	mg/L $CaCO^3$	< 2.0	14	0	0	1	13	n/a
Lab pH	units	-	14	n/a	0	0	14	n/a
Nitrite (NO^2)	mg/L	< 0.03	14	14	0	0	14	n/a
Nitrate ($N0^3$)	mg/L	< 0.02	14	6	1	0	13	prob.
Ammonia (NH^3)	mg/L	< 0.02	14	6	3	1	10	prob.
Total Kjeldahl Nitrogen (TKN)	mg/L	< 0.10	14	0	1	0	13	1/2 DL
Total Organic Carbon (TOC)	mg/L	< 0.01	14	0	0	3	11	n/a
Total Phosphorus (TPHOS)	mg/L	< 0.01	14	1	1	1	12	1/2 DL
Copper (Cu)	ug/L	< 3.0	14	8	0	0	14	prob.
Iron (Fe)	ug/L	< 5.0	14	0	0	0	14	n/a
Manganese (Mn)	ug/L	< 1.0	14	n/a	0	0	14	1/2 DL
Total Suspended Solids (TSS)	mg/L	-	12	n/a	0	1	11	n/a
Total Dissolved Solids (TDS)	mg/L	-	12	n/a	1	1	10	n/a

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a. **prob.** - Uses probability plots to estimate mean and variance.
1/2 DL - For less than 10% non detects, 1/2 the detection limit was used.

4.5.2 Post-Fire Sample Size Range

The cost of taking individual water quality samples in terms of time and money should be considered when determining the sample size (Gilbert, 1987). In the case of fires, researchers have found the water quality impacts are highest in the first year after the fire and may be non-existent after 5 years, especially in low severity fires (McColl and Grigal, 1975; Tiedemann et al., 1979; Hauer and Spencer, 1998). Therefore the water quality samples should be taken in the year following the fire for the best chances of detecting a change.

Equations for calculating the minimum sample size assume the sample size for the pre and post-treatment periods are equal. Since the pre-fire sample size is set, if additional samples are needed to achieve a desired detectable change the post-fire sampling period will be lengthened or shortened accordingly. Since this will most likely make the pre-fire and post-fire sample size unequal, special consideration should be given to calculating the sample size. Loftis et al. (in review) states, "When the sample sizes are not equal, it does not matter whether the calibration or treatment period has the larger sample size".

Zar (1999) gives an equation to calculate the minimum sample size, *k*, in the case of unequal sample sizes:

$$k = \frac{2n_1 n_2}{n_1 + n_2} \tag{4}$$

The notation "*k*" is used to denote the sample size calculated assuming equal sample sizes or corrected for unequal sample sizes. The fixed pre-fire sample size is denoted by n_1 and the variable post-fire sample size to be determined is denoted by n_2.

There is a diminishing return for adding additional post-fire samples, when the sample sizes are unequal. For this study the pre-fire sample size after considering quality control ranges from 10-14 (Table 5). Therefore, the *k* value can be calculated for different choices of the post-fire sample size n_2. Assuming $n_1 = 10$ for the lowest number of pre-fire samples, Figure 6 can be constructed.

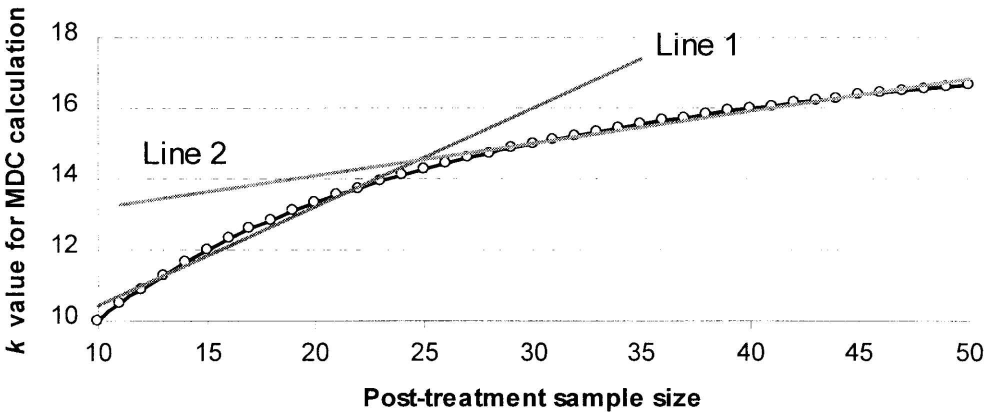

FIGURE 6. k values used for MDC Calculation based on post-treatment sample sizes.

In Figure 6, the slope of the relationship diminishes as n_2 increases as can be seen from a comparison of Line 1 and Line 2. Therefore, the advantage of taking 16 samples over 15 is better than the advantage of taking 45 over 44 samples, yet the increase in time and effort for each additional sample trip is the same. Notice that for an increase in the post-fire sample size from 40 to 50 only increases the *k* value from 15 to 16, whereas a change in post-fire sample size from 10 to 15 increases the *k* value from 10 to 12.

A somewhat arbitrary choice can be made for a maximum post-fire sample size of 20 based on the diminishing returns illustrated in Figure 6. As mentioned previously, samples should be taken in the year following the fire. More than 20 samples would significantly increase the sampling intensity for the post-fire sampling period. Therefore, any samples beyond this range should be considered carefully to determine if time and funding would be justified. By using a range of 10 to 20 post-fire samples, the values for *k* can be determined for different pre-fire sample sizes using Equation 6, a range of sample sizes is displayed in Table 6

TABLE 6. Calculated *k* values for pre-fire sample size (n_1) and post-fire sample size (n_2).

n_1 →

n_2 ↓

	10	**11**	**12**	**13**	**14**
10	***10***	10	11	11	12
11	10	11	11	12	12
12	11	11	12	12	13
13	11	12	12	13	13
14	12	12	13	13	14
15	12	13	13	14	14
16	12	13	14	14	15
17	13	13	14	15	15
18	13	14	14	15	16
19	13	14	15	15	16
20	13	14	15	16	***16***

Recall n_1 is the pre-fire dataset and n_2 is the post fire dataset. According to Table 6, with a minimum of 10 and a maximum of 14 pre-fire samples, the minimum and maximum *k* value needed for calculating MDC needed for 10 to 20 post-fire samples is 10 to 16 (see the entries in italics in Table 6).

4.5.3 Single Station Approach

The single station approach without power is presented in Chapter 3: Literature Review. This section describes a methodology to calculate the single station approach considering power. Power is the probability of detecting no difference when in fact there is a difference, commonly known as the Type II error. In this example a Type II error would be to have a significant change between the two watersheds after the fire, but not be able to detect it. Since it is the goal of this research to detect a change in water quality variables, this possibility should be minimized. The minimum sample size for a Student's t-test can be calculated considering power using the following equation (Zar, 1999):

$$n_{min} = \frac{2S_p^{\,2}(t_{\alpha,\,2(n-1)} + t_{\beta((1),\,2(n-1))})^2}{\delta^2} \qquad (5)$$

Where n_{min} is the sample size before and after the treatment (assuming sample sizes are equal, $2n_{min}$ = total samples taken), $S_p^{\,2}$ is the estimate of pooled variance among the two groups and δ is the MDC, typically calculated between the post and pre-treatment means $(\mu_2 - \mu_1)$. Values from the t-distribution used for the term $t_{\alpha,\,2(n-1)}$ are for a two-tailed distribution with an $\alpha = 95\%$. The $t_{\beta((1),\,2(n-1))}$ is the power term, which is the probability of detecting no difference when in fact there is a difference.

The water quality data from the Bobcat Fire area is used to estimate the expected MDC after the prescribed fire in Mom Gulch. The sample size was then calculated using the Environmental Protection Agency's sample size estimator. The *Sample Size & Sampling Frequency Estimator* is a 32-bit Windows application. The program performs iterative calculations to arrive at an estimate based on statistical distributions (EPA, 1998). This program was used to calculate the number of samples needed to detect a change equal to 100%, 50%, and 5% of the difference between the mean values measured for the Poudre and the Bobcat wildfire samples. For each of the percentages the Mom Gulch pre-fire variance was used and the number of samples were estimated at a 90%, 75%, and 50% statistical power using Equation 5. This process is used to identify a range of possible sample sizes needed to detect an expected change.

By substituting the MDC notation for δ and k for n_{min} in Equation 5 and then solving for MDC, the following equation can be used to calculate a MDC based on a selected sample size and statistical power. This equation is the same as equation 8.23 in Zar (1999):

$$MDC = \sqrt{\frac{2S_p^{\,2}(t_{\alpha,\,2(n-1)} + t_{\beta((1),\,2(n-1))})^2}{k}} \tag{6}$$

4.5.4 Paired Watershed Approach

The paired watershed approach requires the parameters be linearly correlated and normally distributed (Ponce et al., 1982). For the paired watershed approach, it is beneficial to include an explanatory variable when the correlation is as low as R = 0.3 (Loftis et al., in review), where R is the Pearson correlation coefficient. Therefore R > 0.3 is used as the criteria to determine for which parameters the correlation is significant.

The paired watershed approach has an advantage over Equation 6, since it considers the relationship of the two watersheds as a predictive variable. The linear regression equation which defines this relationship is well known:

$$y = mx + b \tag{7}$$

Where y is the parameter value from the treated watershed (in this case the burned watershed or Mom Gulch), x is the parameter value from the pre-fire control watershed, m is the slope of the line, and b is the y-axis intercept. The paired watershed approach can consider differences in the slope of the before and after treatment linear regression lines and/or it can consider differences in the intercept values. Therefore instead of considering the mean and the variances for independent datasets, the paired approach considers the distribution about the regression lines from the pre- and post-treatment datasets.

Detecting change between the slopes of the before and after treatment relationship is beyond the scope of this research, however the magnitude represented by b is of interest since we are most interested in determining a change in the magnitude for water quality variables. This methodology assumes that the slope will not significantly change. However, a caution should be noted for the post-fire analysis that regression lines should have a similar slope. If not, the slope of the regression should be included as recommended in Loftis et al. (in review). Recommendations for the use of slope are given in Chapter 5: Results.

Assuming that the slopes stay constant for the comparison the equation for the paired approach is:

$$y = mx + (B_1 - B_2) \tag{8}$$

Where in Equation 8, B_1 is the pre-fire treatment intercept value and B_2 is the post-fire intercept value. The difference between the intercepts is $(B_1 - B_2)$ and is analogous to a change in means for the single station approach. The sample size required to detect a change can be estimated based on Equation 9 (Loftis et al., in review):

$$\sigma_d^2 = \frac{2\sigma_y^2}{k}(1 - \rho^2)\left(1 + \frac{1}{2(k-2)}\right) \tag{9}$$

where

σ_y = variance of the treated watershed,

k = or n_{min}, the minimum sample size for both pre and post-treatment,

ρ = R, Pearson's correlation coefficient for the pre-treatment and control watersheds.

Equation 9 can be calculated interatively until $\sigma_d \leq d/Z$, where σ_d is the variance of the adjusted means, and *d* is the minimum detectable change or MDC. The MDC in this case is the average intercept value equal to the difference in the adjusted means for the linear regression between the two watersheds, and *Z* is 1.96 for a 95% confidence interval.

By rearranging the equation and substituting the notation MDC for *d*, the equation can be solved for an MDC associated with a minimum sample size:

$$MDC = Z\sqrt{\frac{2\sigma_y^2}{k}(1-\rho^2)\left(1+\frac{1}{2(k-2)}\right)} \tag{10}$$

Where MDC is the minimum change that can be detected for $(B_1 - B_2)$ with the given sample size *k*, assuming equal pre- and post-fire sample sizes or adjusting for unequal sample size using Equation 4. Calculating the MDC using Equation 10 is analogous to calculating the MDC for the single sample size approach. The power of Equation 10 is 50%. Twice the MDC value calculated for the sample size *k* can be used as an estimate of the minimum sample size needed for an 80% statistical power (Loftis et al., in review). Therefore one-half the *k* value can be used in Equation 10 as an estimate of the MDC at an 80% statistical power at the *k* value selected.

Chapter 5: Results

Determining the post-fire sample size is of primary concern in this chapter, however it is also important to understand the ability of the data analysis procedures presented in Chapter 4 to detect change, to determine the magnitude of this change, and also to see how this change compares to water quality data from the Bobcat Fire area. This chapter will accomplish these goals by calculating the minimum detectable change (MDC) for post-fire sample sizes using the single station approach with and without power and by employing the paired watershed approach with and without power for parameters that are correlated between the two watersheds. The MDC values calculated are evaluated using water quality data from the June 2000 Bobcat Fire in the Big Thompson Watershed near Drake, Colorado. Recommendations based on these calculations will be presented in Chapter 6.

5.1 Estimates of Means and Variance

The means and variances for Mom Gulch were estimated based on the pre-fire dataset and are used in the single and paired approaches for calculating MDC and sample size. Data are presented in Appendix I. The pre-fire variance from Mom Gulch was used as an estimate of the pooled variance for the pre and post-fire datasets. Nitrate, ammonia, and total phosphorus had more than 10% of their values listed as non-detects by the laboratory, therefore probability plotting was used to estimate the values below the detection limit before the statistical parameters were calculated. The mean calculated from the combined data from Bobcat and Jug Gulch was used for the initial selection criteria for minimum sample sizes and to evaluate MDC values.

Table 7 summarizes the means and variances used for the calculations in the rest of the results, the full datasets are presented in Appendix I.

TABLE 7. Summary table for pre-fire statistical parameters calculated from the paired watersheds located in the Cache la Poudre Watershed (Mom and Dadd Gulch) and from the post-fire dataset from the Bobcat Fire located in the Big Thompson Watershed (Bobcat and Jug Gulch) collected from August 1999 to August 2000.

Parameter (units)	Mom Variance	Mom Mean	Dadd Mean	Paired Mean	Jug Mean	Bobcat Mean	Wildfire Mean	Paired - Wildfire Difference
Number of sample trips	-	14	14	28	3	7	10	-
Alkalinity (mg/L as $CaCO_3$)	254	108	89	98	158	84	106	8
Conductivity (uS/cm)	1301	225	187	206	344	262	289	83
Nitrite (mg/L)	0.000	0.015	0.015	0.015	0.023	0.054	0.044	0.029
Nitrate (mg/L)	0.00031	0.021	0.050	0.036	1.203	2.608	2.187	2.151
Ammonia (mg/L)	0.00019	0.019	0.020	0.019	0.079	0.841	0.612	0.593
Kjeldahl Nitrogen (mg/L)	0.0080	0.20	0.20	0.20	1.86	9.47	6.20	6.01
Organic Carbon (mg/L)	0.21	3.42	2.86	3.14	21.22	30.98	28.54	25.39
Phosphorus (mg/L)	0.000094	0.023	0.024	0.023	0.238	0.105	0.162	0.139
Copper (ug/L)	4.8	2.9	2.4	2.7	4.0	3.6	3.8	1.2
Iron (ug/L)	4180	126	76	101	803	1500	619	518
Manganese (ug/L)	5.2	3.9	2.5	3.2	313	184	262.0	258.8
Suspended Solids (mg/L)	50.5	5.3	4.7	5.0	308	97	55.5	50.5
Dissolved Solids (mg/L)	114	156	136	146	333	249	259	114

Although Mom and Dadd Gulch were very similar in terms of elevation, aspect, soils, vegetation and size as presented in Chapter 4, the streamflow response during the monitoring period was very different (Appendix III). Dadd Gulch had more of a response to snow melt in the spring 2000 and Mom Gulch experienced an intense localized thunderstorm on 8/15/00 (Appendix II). It may be that the differences in mean water quality parameters presented in Table 7 are a result of these differences in streamflow response. Also, the 1999 and 2000 season showed a difference in summer streamflow response between the two years. In 1999 both gulches had streamflow throughout the summer, but in June 2000 both gulches dried up. Mom Gulch experienced the highest streamflow response to the storm on 8/15/00. The average daily discharge on 8/15/00 was nearly 5 times greater than the highest discharge measured during rest of the monitoring period (Appendix III).

An intense thunderstorm on 8/16/00 in Bobcat Gulch may account for the difference in response measured in Bobcat and Jug Gulch as can be seen from the difference in the mean values for each (Table 7), however this cannot be assumed without a pre-fire dataset for the Bobcat Fire.

5.2 Selection of Ranges to Calculate Statistical Power and Sample Size

The EPA program Sample Size and Sampling Frequency Estimator (EPA, 1998) was used to estimate the post-fire sample size needed. This program calculates sample size using Equation 5. The difference between the mean values for water quality samples obtained from the Bobcat Fire and the mean values from the pooled data from the paired watersheds were used to select the MDC values (Table 7). The pre-treatment variance for Mom Gulch is used as an estimate of the pooled variance. A two-tailed 95% confidence level was selected for the α term in the calculations.

Sample sizes were calculated for 100%, 50%, and 5% of the difference between the wildfire and paired mean (Table 7), along with a the statistical power of 50%, 75% and 90% are shown in Table 8. These ranges were selected to evaluate the improvement in sample sizes using different powers and evaluate the range of post-fire sample sizes to calculate MDC directly presented in Chapter 4: Methods.

TABLE 8. Minimum number of samples required to detect change for water quality parameters based on MDC values, calculated using the difference between the wildfire mean values and the paired mean values.

Variable	100% Value	Number of Samples (k) for Selected Statistical Power and MDC *Note - Lowest possible value for k is 5.*								
% Diff. Wildfire-Paired		100% Diff.			50% Diff.			5% Diff.		
Statistical Power		50%	75%	90%	50%	75%	90%	50%	75%	90%
Alkalinity (mg/L as $CaCO_3$)	8	33	58	87	127	228	345	12591	22747	34438
Conductivity (uS/cm)	0.27	5	5	6	8	13	19	628	1134	1716
Nitrite (mg/L)	83	5	5	5	7	11	17	579	1045	1582
Nitrate (mg/L)	2.2	5	5	5	5	5	5	5	5	5
Ammonia (mg/L)	0.6	5	5	5	5	5	5	5	5	6
Kjeldahl Nitrogen (mg/L)	6.0	5	5	5	5	5	5	5	5	5
Organic Carbon (mg/L)	25	5	5	5	5	5	5	5	5	5
Phosphorus (mg/L)	0.14	5	5	5	5	5	5	5	25	>50
Copper (ug/L)	1.2	28	49	73	107	193	291	10573	19101	28918
Iron (ug/L)	518	5	5	5	5	5	5	49	88	132
Manganese (ug/L)	259	5	5	5	5	5	5	5	5	5
Suspended Solids(mg/L)	50	5	5	5	5	5	5	16	28	41
Dissolved Solids (mg/L)	114	5	5	5	5	5	5	130	233	352

Recall that in Chapter 4: Methods, the feasible range of post-fire samples was 10-20. This range results in a *k* value, or minimum combined sample size, between 10 to 16. Table 8 shows that most of the parameters can detect 50% of the difference between the wildfire and paired means with a *k* value of less than 16 at a power of 90%. To detect 5% of the difference 6 samples at 90% power could be taken to detect nitrate, ammonia, total kjeldahl nitrogen, and manganese. These five parameters have been shown to increase with fire in previous studies (Chapter 3: Literature Review), with the exception of total organic carbon which has not been measured with fire.

For several of the variables the number of samples is prohibitive at 90% power, for example alkalinity would require almost 3,500 samples to detect a 5% difference and almost 350 samples to detect even a change equal to 50% of the difference between the paired and wildfire values. Therefore, more sensitive statistical methods are employed to determine changes in alkalinity, pH, specific conductivity, iron, total dissolved solids and total suspended solids.

5.3 Single Station Approach with Power

Given the range of post-fire samples that would be feasible, using Equation 6 the MDC can be calculated for selected statistical power. For this analysis, a statistical power of 80% is considered (Table 9).

TABLE 9. MDC for 80% power using the single station approach for Mom Gulch located in the Cache la Poudre Watershed near Rustic, Colorado for *k* = 10 - 16.

Parameter (units)	Minimum Detectable Change for Values of *k* = *10-16*						
	10	11	12	13	14	15	16
Alkalinity (mg/L as $CaCO_3$)	21	20	19	18	18	17	16
Lab pH (units)	0.17	0.16	0.15	0.14	0.14	0.13	0.13
Conductivity (uS/cm)	48	45	43	41	40	38	37
Nitrate (mg/L)	0.025	0.024	0.023	0.022	0.021	0.020	0.019
Ammonia (mg/L)	0.020	0.019	0.018	0.017	0.016	0.016	0.015
Kjeldahl Nitrogen (mg/L)	0.118	0.112	0.107	0.102	0.098	0.095	0.091
Organic Carbon (mg/L)	0.61	0.58	0.55	0.53	0.51	0.49	0.47
Total Phosphorus (mg/L)	0.013	0.012	0.012	0.011	0.011	0.010	0.010
Copper (ug/L)	2.9	2.7	2.6	2.5	2.4	2.3	2.2
Iron (ug/L)	86	81	77	74	71	69	66
Manganese (ug/L)	3.0	2.9	2.7	2.6	2.5	2.4	2.3
Suspended Solids (mg/L)	4.7	4.4	4.2	4.0	3.9	3.7	3.6
Dissolved Solids (mg/L)	31	29	28	27	26	25	24

The Bobcat wildfire samples can be used to evaluate the MDC values calculated in Table 9, by expressing the values as a percentage of the difference between the mean values measured for the Wildfire and for the Paired values (Table 10).

TABLE 10. MDC at 80% Power expressed as a percentage of the difference between the mean values from the Bobcat Fire located in the Big Thompson Watershed (10 samples) and the mean values measured at Mom and Dadd Gulch in the Cache la Poudre Watershed (28 samples). Both sets of watersheds are located in Northern Colorado.

Parameter (units)	Difference	Percentage of Difference between Bobcat and Paired for Values of *k (10-16)*						
		10	11	12	13	14	15	16
Alkalinity (mg/L)	8	268%	254%	242%	232%	223%	214%	207%
Lab pH (units)	0.27	60%	57%	55%	52%	50%	48%	47%
Conductivity (uS/cm)	83	57%	54%	52%	50%	48%	46%	44%
Nitrate (mg/L)	2.151	1%	1%	1%	1%	1%	1%	1%
Ammonia (mg/L)	0.592	3%	3%	3%	3%	3%	3%	3%
Kjeldahl Nitrogen (mg/L)	6.005	2%	2%	2%	2%	2%	2%	2%
Organic Carbon (mg/L)	25.39	2%	2%	2%	2%	2%	2%	2%
Total Phosphorus (mg/L)	0.139	9%	9%	8%	8%	8%	7%	7%
Copper (ug/L)	1.2	243%	231%	220%	210%	202%	195%	188%
Iron (ug/L)	51	17%	16%	15%	14%	14%	13%	13%
Manganese (mg/L)	259.8	1%	1%	1%	1%	1%	1%	1%
Suspended Solids (mg/L)	50.5	9%	9%	8%	8%	8%	7%	7%
Dissolved Solids (mg/L)	114	27%	26%	24%	23%	22%	22%	21%

Table 10 shows that there is only a small improvement for additional samples for most parameters. For example nitrate, kjeldahl nitrogen, ammonia, and manganese can all detect changes below 1% of the difference with the water quality data from the Bobcat Fire using only 10 post-fire samples. Most of the parameters can detect an MDC that is equivalent to at least 25% of the change measured between the wildfire and the paired study for 16 post-fire samples. However, for alkalinity and pH, which have been shown to change in fire studies (Tiedemann et al., 1979), 16 post-fire samples would be inadequate to detect the change measured for the Bobcat Fire using the single station approach. However, the paired watershed approach may yield a more sensitive test for change.

5.4 Paired Watershed Approach

The paired watershed approach requires the parameters to be linearly correlated and be normally distributed (Ponce et al., 1982). If the Pearson's correlation coefficient

(R) is greater than 0.3, the correlation was considered significant (Loftis et al., in review). Normality was evaluated using probability plots and the Shapiro-Welk test; values and plots were calculated using the SPSS statistical software package.The Shapiro-Welk test was only used as a guide since the performance of the test is adversely affected in the common situation when data values are tied (Zar, 1999). For nitrate, ammonia, and copper, more than 33% of the values were non-detects; therefore the normality was not evaluated.

TABLE 11. Correlation coefficients for linear regression on pre-fire dataset from Mom and Dadd Gulch located in the Cache la Poudre Watershed in Northern Colorado, significance and normality for Mom Gulch dataset from pre-fire dataset collected from August 1999 - August 2000.

Parameter Name	Pearson R	P-Value	Significant?	Normal?
Alkalinity	0.90	0.000024	Yes	Yes
Lab pH	0.84	0.00015	Yes	Yes
Discharge	0.31	0.29	Yes	No
Specific Conductivity	0.62	0.033	Yes	No
Nitrite (NO2)	Below Detection Limit for all Mom Gulch Samples			
Nitrate (N03)	0.74	0.0036	Yes	n/a
Ammonia (NH3)	0.08	0.82	No	n/a
Total Kjeldahl Nitrogen (TKN)	0.04	0.89	No	Yes
Total Organic Carbon (TOC)	0.90	0.00014	Yes	Yes
Total Phosphorus (TPHOS)	0.27	0.37	No	Yes
Copper (Cu)	0.41	0.15	No	n/a
Iron (Fe)	0.26	0.36	No	Yes
Manganese (Mn)	0.15	0.62	No	No
Suspended Solids	0.71	0.02	Yes	No
Dissolved Solids	0.77	0.010	Yes	Yes

From Table 11, the parameters that are correlated and normal are alkalinity, lab pH, total organic carbon, and total dissolved solids. As shown in Table 9, all four of these parameters would require large sample sizes to detect a MDC that could be expected after the fire at an 80% statistical power. Therefore the paired approach is used to determine the number of samples needed based on the predictive information provided by the relationship between Mom and Dadd Gulch.

As described in Chapter 3: Literature Review, the single station approach without power given by Equation 1 has been commonly used to calculate the sample size needed for paired watershed studies (Table 12). The MDC values calculated with this approach will be used to evaluate the improvements of the paired approach for alkalinity, lab pH, total organic carbon, and dissolved solids, which were shown to be correlated and have a normal distribution.

TABLE 12. MDC calculated for values of the adjusted sample size, *k*, from 10 to 16 using the single station approach with power = 50%, calculated with Equation 1.

	MDC for values of k 10-16						
Parameter (units)	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Alkalinity (mg/L)	13.98	13.33	12.76	12.26	11.82	11.41	11.05
Lab pH (units)	0.11	0.10	0.10	0.10	0.09	0.09	0.09
Organic Carbon (mg/L)	0.41	0.39	0.37	0.36	0.34	0.33	0.32
Dissolved Solids (mg/L)	20.38	19.43	18.61	17.88	17.23	16.64	16.11

The MDC values for the paired approach can be calculated according to the Equation 9 and for values of *k* of 10 -16, to evaluate the improvement over the paired approach.

TABLE 13. MDC calculated for values of the adjusted sample size, *k*, from 10 to 16 using the paired approach with a power = 50%, calculated with Equation 9.

		MDC for Values of k						
Parameter (units)	**R**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Alkalinity (mg/L)	0.90	6.28	5.97	5.70	5.46	5.26	5.07	4.90
Lab pH (units)	0.84	0.06	0.06	0.06	0.05	0.05	0.05	0.05
Organic Carbon (mg/L)	0.90	0.18	0.17	0.17	0.16	0.15	0.15	0.14
Dissolved Solids (mg/L)	0.77	13.41	12.74	12.17	11.66	11.22	10.82	10.46

Table 11 and Table 13 show roughly a 50% reduction in the MDC values by using the paired approach for most of the parameters, however Equations 1 and 9 do not take into account a Type II error by including power. Loftis et al. (in review) states that in order to calculate power the change in slope in the pre-treatment and post-treatment relationships and the true change in the post-fire relationship must be known. However, a general relationship was presented by Loftis et al. (in review), in which the sample size should be at least twice the sample size calculated using the paired approach at 50% to estimate the sample size at a power of 80%. Therefore, it follows that the MDC values calculated for half the *k* value will be approximately equal to the MDC value for an 80% power (Loftis et al., in review). For example, the MDC value calculated for a *k* value of 5 using Equation 9 at 50% power would be approximately equal to the MDC value for *k* =10 at an 80% power.

This approach is employed here to estimate the MDC for given post-fire sample sizes. The pre-fire sample size for pH was 14 so the *k* values based on a post-fire sample size of 10 to 20 would be 10 to 16 (Table 14). The MDC can now be calculated for half of these ranges (5-8) as an estimate of the MDC that could be detected at a 80% power.

TABLE 14. Calculation of MDC using paired approach for values of k = 5 to 8 at 50% statistical power and values of *k* = 10 to 16 at 80% power.

	MDC for Values of k (50%) / k (80%)			
Parameter (units)	**5/10**	**6/12**	**7/14**	**8/16**
Alkalinity (mg/L)	9.31	8.34	7.64	7.09
Lab pH (units)	0.09	0.08	0.07	0.07
Organic Carbon (mg/L)	0.27	0.24	0.22	0.21
Dissolved Solids (mg/L)	19.87	17.81	16.30	15.13

The values in Table 14 can be compared to values of MDC calculated using the single station approach with a power of 80% (Figure 7).

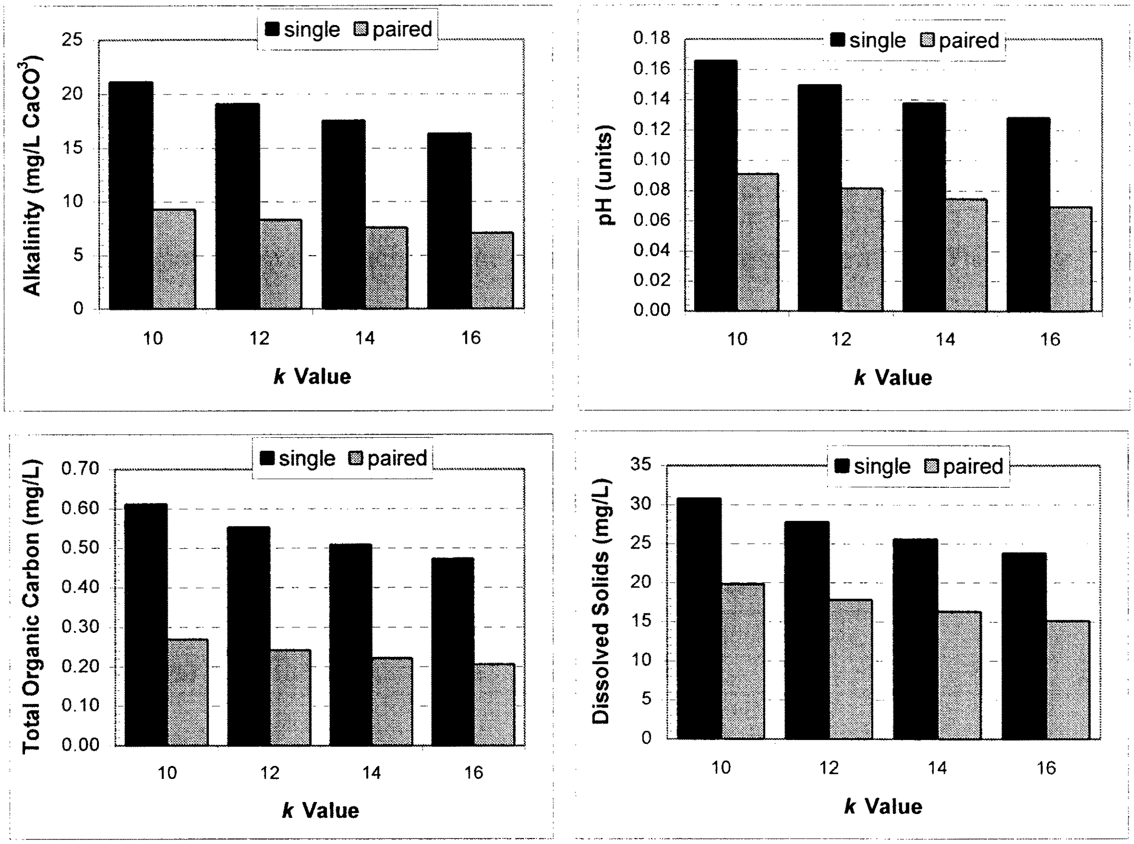

FIGURE 7. Comparison of MDC for Single and Paired Approach using k values of 10 to16 and Statistical power of 80% for Mom and Dadd Gulch near Rustic, Colorado.

The paired approach shows an improvement in the MDC values depending on the parameter, alkalinity and total organic carbon showed the most improvement, being able to detect half the change for the paired approach compared to the single station approach for most parameters. The results of the paired approach can be compared to the wildfire dataset to put these values in context.

TABLE 15. Paired approach MDC values at 80% power as a percentage of the difference between the Bobcat Fire in the Big Thompson Watershed and mean values from Mom and Dadd Gulch near Rustic, Colorado.

	MDC as a Percentage of the Difference for *k* = 10-16				
Parameter (units)	**Diff.**	**10**	**12**	**14**	**16**
Alkalinity (mg/L)	7.9	118%	106%	97%	90%
Lab pH (units)	0.3	33%	30%	27%	25%
Organic Carbon (mg/L)	25.00	1.1%	1.0%	0.9%	0.8%
Dissolved Solids (mg/L)	110	17%	16%	14%	13%

5.5 Selecting a Post-Burn Sample Size

The paired approach had an advantage for the parameters that were correlated and normally distributed, being able to detect half the change of the single station approach. Therefore, a final table can be constructed that takes into account the unequal sample sizes using the single station approach and the paired watershed approach at an 80% power. The values for the MDC are given in Table 16 and the values in relation to the wildfire data are given in Table 17.

TABLE 16. Estimated MDC values for post-fire sample sizes (n_2) using the single station and the paired watershed approach at 80% power for Mom and Dadd Gulch near Rustic, Colorado.

Parameter (units)	# Pre-fire Samples	Paired/ Single	MDC for Post-fire Sample Size, n_2 = 10-20					
			10	12	14	16	18	20
Alkalinity (mg/L as $CaCO_3$)	12	Paired	9.0	8.3	8.0	7.6	7.4	7.1
Lab pH (units)	14	Paired	0.08	0.08	0.07	0.07	0.07	0.07
Conductivity (uS/cm)	12	Single	53	50	48	46	45	44
Nitrate (mg/L)	12	Single	0.028	0.026	0.025	0.024	0.023	0.022
Ammonia (mg/L)	11	Single	0.023	0.021	0.020	0.020	0.019	0.019
Kjeldahl Nitrogen (mg/L)	11	Single	0.130	0.124	0.119	0.114		0.106
Organic Carbon (mg/L)	12	Paired	0.25	0.24	0.23	0.22	0.22	0.21
Phosphorus (mg/L)	11	Single	0.015	0.014	0.013	0.013	0.012	0.012
Copper (ug/L)	14	Single	3.1	3.0	2.9	2.8	2.7	2.6
Iron (ug/L)	14	Single	94	90	86	82	79	77
Manganese (ug/L)	14	Single	3.3	3.2	3.0	2.9	2.8	2.7
Suspended Solids (mg/L)	12	Single	5.1	4.9	4.7	4.5	4.4	4.3
Dissolved Solids (mg/L)	12	Paired	19.0	17.8	17.0	16.3	16.3	15.0

TABLE 17. Comparison of MDC and wildfire values for post-fire sample sizes (n_2) using the single station and the paired watershed approach at 80% power expressed as a percentage of difference measured for Mom and Dadd Gulch near Rustic, Colorado.

Parameter (units)	# Pre-fire Samples	Paired/ Single	100% Diff.	MDC as a Percentage of Wildfire Differences for Post-fire Sample Sizes n_2 = 10-20					
				10	12	14	16	18	20
Alkalinity (mg/L as $CaCO_3$)	12	Paired	8	114%	106%	101%	97%	94%	90%
Lab pH (units)	14	Paired	0.27	30%	30%	27%	27%	25%	25%
Conductivity (uS/cm)	12	Single	83	64%	60%	58%	55%	54%	53%
Nitrate (mg/L)	12	Single	2.151	1%	1%	1%	1%	1%	1%
Ammonia (mg/L)	11	Single	0.592	4%	4%	3%	3%	3%	3%
Kjeldahl Nitrogen (mg/L)	11	Single	6.005	2%	2%	2%	2%	2%	2%
Organic Carbon (mg/L)	12	Paired	25.39	1%	1%	1%	1%	1%	1%
Phosphorus (mg/L)	11	Single	0.139	11%	10%	9%	9%	9%	9%
Copper (ug/L)	14	Single	1.2	263%	254%	246%	238%	229%	221%
Iron (ug/L)	14	Single	51	18%	17%	17%	16%	15%	15%
Manganese (ug/L)	14	Single	259.8	1%	1%	1%	1%	1%	1%
Suspended Solids (mg/L)	12	Single	50.5	10%	10%	9%	9%	9%	9%
Dissolved Solids (mg/L)	12	Paired	114	17%	16%	15%	14%	14%	13%

Chapter 6: Conclusions and Recommendations

Pre-fire water quality samples were collected for paired watersheds located within the Dadd/Bennett Project Area in the Cache la Poudre Watershed near Rustic, Colorado. A total of 14 sample trips yielded 10-14 paired values, depending on the parameter, for each watershed (Appendix I). Using both single and paired watershed data analysis methods the Minimum Detectable Change (MDC) was calculated for a range of possible post-fire sample sizes (Chapter 3: Methods).

A recommendation of 16 post-fire sample trips is given based on the need to obtain water quality samples in the year following the fire and the ability of the data analysis methods to detect change. The MDC values were compared to water quality data from similar watersheds in the Bobcat Fire near Drake, Colorado in the Big Thompson Watershed and background water quality data from the Cache la Poudre River. For most of the parameters less than 20% of the difference observed for the wildfire can be detected (Chapter 4: Results).

At a statistical power of 80%, nitrate, ammonia, total Kjeldahl nitrogen, total organic carbon, total phosphorus, manganese, and suspended solids can be detected if the changes after the fire are 10% of those observed from the Bobcat Fire. These parameters have all been shown to increase with fire and/or are of concern to water providers downstream (Chapter 3: Literature Review).

The paired approach improves the ability to detect changes, for total organic carbon, the paired approach allows for the detection of changes less than 1% of the changes observed for the Bobcat Fire. The paired approach improved the ability to detect changes in alkalinity to 97% of the change that was observed from the Bobcat fire, and 27% of the change observed for pH can be detected using the paired approach.

Copper has not been shown to change with fire and therefore a change should not be detected. In deed, the MDC for copper is 2.8 ug/L for 16 samples and represents 238% of the difference measured between the wildfire and paired values for copper. Therefore, the difference in copper concentrations measured in the Bobcat fire area and Mom and Dadd Gulch were less in relation to the variability of copper. Therefore, any change in copper after the prescribed fire should be less than the detectable change calculated for copper. It is recommended that the analysis for copper continue since it appears to be a good indicator of the quality of the data analysis methodology.

Some studies have not found significant changes in alkalinity or pH with fire and the relatively small differences between the paired and wildfire data may be an indication that these parameters will not change after the prescribed fire. However, the values for alkalinity measured in Bobcat Gulch were very low and may have influenced the averages for wildfire disproportionately (Appendix I). Although pH would have to change 27% of what it changed for Bobcat fire, this represents a change of only 0.1 units.

The post-fire data analysis should consider potential slope changes in the linear relationship for the parameters that use the paired approach. If there is not a change in slope in the post-fire samples, the methodology described here should be used. The criteria to determine if slope should be considered could be to determine if the pre- and post-fire linear regression lines cross. If so, slope should be considered in the analysis and applied according to Loftis et al. (in review).

A localized thunderstorm on 8/15/00 caused a dramatic flow event that resulted in significant erosion in Mom Gulch (Chapter 4). Dadd Gulch in contrast experienced no measurable flow during the same period and no signs of erosion (Appendix III). No water quality samples were available for the peak discharge event in Mom Gulch, and it is uncertain if the water quality relationship between Mom and Dadd Gulch will change. The impact of this storm on water quality in Mom Gulch will be difficult to determine and it should be noted, that some of the erosion observed in response to the storm was in the small area burned in February 2000 as part of the "black-line" for the prescribed fire, see Figure 1.

Variability should be expected for small watersheds in Northern Front Range Forests and cannot be determined by readily measured variables during the watershed selection process for water quality studies. Therefore using a nearby watershed for post-fire water quality monitoring and assuming the watershed represents baseline conditions should be employed with caution where pre-fire datasets are not available. For example the differences in alkalinity measured in the Bobcat Fire area shown in Appendix I, could be a result from the 8/16/00 storm (54 mm in 5 hours) that caused flooding in Bobcat Gulch but only moderate rises in Jug Gulch with only 11 mm of precipitation from the same storm. The possibility of this precipitation variability masking the true response to fire should be considered carefully in post-fire data analysis. In this study, the streamflow responses to localized thunderstorms in August 2000 for the Poudre and Bobcat sites impacted the watersheds differently and therefore this difference should be considered in the post-fire analysis.

This research has shown that the pre-fire sample size and the proposed 16 post-fire samples is adequate to determine expected changes due to prescribed fire in water quality parameters of interest to water providers.

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Appendix I: Water Quality Data

TABLE 18. Water quality data from Mom Gulch near Rustic, Colorado in the Cache la Poudre Watershed for sampling dates 9/6/99 - 9/26/00.

Parameter	Alka	Cu	Fe	NO_2	NO_3	Mn	NH_3	pH	TKN	TPhos	TOC	Flow	S. Cond.	TSS	TDS
Units	mg/L as $CaCO_3$	ug/L	ug/L	mg/L	mg/L	ug/L	mg/L	units	mg/L	mg/L	mg/L	(cfs)	uS/cm	mg/L	mg/L
Reporting Limit >	<2.0	<3.0	<5.0	<0.03	<0.02	<1.0	<0.02	-	<0.10	<0.01	<0.01	<0.001	-	-	-
9/6/99	111.2	2.98	63.2	<0.03	0.020	3.16	<0.02	7.89	0.17	0.018	4.11	0.038	218	-	-
9/12/99	115.8	<3.0	65.1	<0.03	0.018	2.94	0.032	8.08	0.32	0.026	*D-4.04	0.031	271	4.0	164
9/19/99	113.2	<3.0	151.0	<0.03	<0.02	2.99	*B-0.052	8.02	0.16	0.005	3.92	0.031	260	3.4	139
9/26/99	107.6	<3.0	113.0	<0.03	*B-0.029	3.13	0.052	7.85	0.18	*D-0.047	4.07	0.018	276	4.7	179
10/20/99	106.5	2.83	96.6	<0.03	<0.02	3.12	<0.02	7.93	0.26	0.020	3.79	0.031	-	2.0	159
10/31/99	102.0	8.32	170.0	<0.03	<0.02	2.32	<0.02	8.00	0.21	0.013	3.45	0.027	215	2.0	162
11/28/99	102.8	6.15	173.0	<0.03	<0.02	2.05	0.021	8.10	0.20	*B-0.024	3.01	0.031	207	4.4	158
1/2/00	91.5	5.40	239.8	<0.03	0.015	5.45	<0.02	7.95	B - 0.216	0.023	2.73	0.031	206	6.2	159
1/30/00	92.0	<3.0	185.0	<0.03	0.038	5.59	<0.02	7.88	0.15	0.019	2.96	0.024	185	-	-
2/27/00	88.0	<3.0	197.5	<0.03	<0.02	5.52	*B-0.042	7.79	0.19	0.020	2.91	0.024	184	10.3	139
3/26/00	98.0	3.56	160.0	<0.03	<0.02	5.28	<0.02	7.68	0.16	0.033	3.70	0.024	182	13.1	149
4/30/00	*D-117.5	<3.0	58.7	<0.03	0.031	1.77	*D-0.074	7.77	0.13	0.017	3.15	0.004	225	3.0	166
6/4/00	139.0	<3.0	55.6	<0.03	0.023	9.89	*B-0.032	7.82	0.41	0.042	3.42	0.001	274	8.1	194
9/26/00	138.0	<3.0	32.7	<0.03	0.072	1.05	0.021	8.03	0.05	0.034	3.32	0.0005	-	2.3	100
Minimum	88.0	<3.0	32.7	<0.03	<0.02	1.05	<0.02	7.68	<0.10	<0.01	2.73	<0.001	182	2.0	100
Average	108.1	3.06	125.8	<0.03	0.020	3.88	0.018	7.91	0.20	0.02	3.42	0.02	225	5.3	156
Maximum	139.0	8.32	239.8	<0.03	0.072	9.89	0.052	8.10	0.41	0.04	4.11	0.04	276	13.1	194
S. Deviation	15.9	2.16	64.7	-	0.019	2.28	0.015	0.13	0.09	0.01	0.46	0.01	36	3.5	23
Variance	254.4	4.68	4179.8	-	0.00036	5.21	0.00022	0.016	0.0080	0.00010	0.21	0.0001	1301	12.4	541
Coef. Variation	0.15	0.71	0.51	-	0.96	0.59	0.82	0.02	0.45	0.45	0.13	0.54	0.16	0.67	0.15
# of Paired	12	14	14	14	12	14	11	14	11	11	12	14	12	12	12

* = Sample removed for quality assurance due to the field blank reading high (B), or a large difference between duplicates (D).

TABLE 19. Water quality data from Dadd Gulch near Rustic, Colorado in the Cache la Poudre Watershed for sampling dates 9/6/99 - 9/26/00.

Parameter	**Alka**	**Cu**	**Fe**	**NO_2**	**NO_3**	**Mn**	**NH_3**	**pH**	**TKN**	**TPhos**	**TOC**	**Flow**	**S. Cond.**	**TSS**	**TDS**
Units	mg/L as $CaCO_3$	ug/L	ug/L	mg/L	mg/L	ug/L	mg/L	units	mg/L	mg/L	mg/L	(cfs)	uS/cm	mg/L	mg/L
Reporting Limit >	<2.0	<3.0	<5.0	<0.03	<0.02	<1.0	<0.02	-	<0.10	<0.01	<0.01	<0.001	-	-	-
9/6/99	93.6	<3.0	35.3	<0.03	0.03	4.53	<0.02	7.95	0.25	0.005	2.51	0.031	169	-	-
9/12/99	93.4	<3.0	77.4	<0.03	0.03	2.72	<0.02	8.11	0.15	0.022	*D-2.85	0.031	230	4.0	164
9/19/99	91.0	<3.0	259.5	<0.03	0.05	8.75	*B- 0.054	8.08	0.51	0.039	3.49	0.038	248	13.9	144
9/26/99	94.4	<3.0	86.9	<0.03	*B-0.021	2.62	0.023	7.89	0.14	*D-0.005	3.00	0.038	180	2.0	147
10/20/99	86.5	3.2	57.0	<0.03	<0.02	1.29	<0.02	7.93	0.17	0.018	3.25	0.038	-	0.6	125
10/31/99	84.0	<3.0	99.2	<0.03	<0.02	1.48	<0.02	8.01	0.12	0.005	2.54	0.031	180	0.8	130
11/28/99	89.7	5.4	51.7	<0.03	0.02	1.71	<0.02	8.05	0.20	*B-0.023	2.13	0.031	170	0.5	140
1/2/00	78.0	4.9	103.0	<0.03	0.06	2.32	<0.02	7.78	B - 0.341	0.023	1.72	0.031	190	3.2	146
1/30/00	84.0	<3.0	22.3	<0.03	0.09	<1.0	0.026	7.79	0.21	0.017	2.10	0.031	185	-	-
2/27/00	77.0	<3.0	27.2	<0.03	0.08	<1.0	*B-0.039	7.69	0.05	0.018	2.26	0.038	184	2.0	139
3/26/00	71.5	<3.0	127.0	<0.03	0.07	5.73	0.036	7.65	0.39	0.124	6.06	0.072	145	17.2	122
4/30/00	*D-72.0	<3.0	32.8	<0.03	0.04	1.12	*D-0.058	7.74	0.12	0.016	2.76	0.054	162	2.4	132
6/4/00	102.8	<3.0	50.8	<0.03	0.03	0.77	*B-0.030	7.99	0.22	0.016	2.86	0.008	202	5.0	149
9/26/00	110.0	3.8	38.8	<0.03	0.14	1.36	0.018	8.04	0.05	0.020	2.54	0.005	-	5.2	89
Minimum	71.5	<3.0	22.3	<0.03	<0.02	0.50	<0.02	7.65	<0.1	<0.01	1.72	0.005	145	0.5	89
Mean	88.9	2.5	76.3	<0.03	0.05	2.53	0.027	7.91	0.20	0.027	2.86	0.034	187	4.7	136
Maximum	110.0	5.4	259.5	<0.03	0.14	8.75	0.036	8.11	0.51	0.124	6.06	0.072	248	17.2	164
S. Deviation	10.1	1.4	59.4	-	0.04	2.25	0.007	0.15	0.12	0.030	1.03	0.016	27	5.1	18
Variance	111.0	1.9	3802.0	-	0.00	5.46	0.00005	0.02	0.02	0.0010	1.16	0.0003	811	28.5	346
Coef. Variation	0.11	0.54	0.78	-	0.78	0.89	0.26	0.02	0.63	1.13	0.36	0.46	0.15	1.08	0.13
# of Paired	12	14	14	14	12	14	11	14	11	11	12	14	12	12	12

* = Sample removed for quality assurance due to the field blank reading high (B), or a large difference between duplicates (D).

TABLE 20. Water quality samples from Bobcat Fire in the Big Thompson Watershed near Drake, Colorado for sampling dates 6/27/00 - 9/26/00.

Location	Date	Alka.	Cu	Fe	NO_2	NO_3	Mn	NH_3	pH	TKN	TPhos	TOC	S. Cond.	TSS	DSS
Units		mg/L as $CaCO_3$	ug/L	ug/L	mg/L	mg/L	ug/L	mg/L	units	mg/L	mg/L	mg/L	uS/cm	mg/L	mg/L
Reporting Limit >		2.0	3.0	5.0	0.03	0.02	1.0	0.02	-	0.10	0.01	-	-	-	-
Jug Gulch	6/27/00	104	2.96	1138	0.015	0.001	264	0.018	7.6	1.83	0.010	-	344	40.2	257
Jug Gulch	8/17/00	132	1.88	326	0.015	3.430	303	0.171	7.9	0.79	0.118	-	-	3.1	345
Jug Gulch	9/26/00	237	7.12	946	0.039	0.178	374	0.049	7.5	2.95	0.587	21.22		8.9	311
Lower Bobcat Gulch	6/27/00	216	4.62	-	0.015	0.010	353	0.036	8.0	3.83	0.166		264	314.2	327
Lower Bobcat Gulch	8/16/00	46	-	-	0.100	3.121	-	1.480	7.5	-	-	-	-	26.6	257
Lower Bobcat Gulch	9/1/00	74	-	-	0.067	2.977	-	0.945	7.4	18.49	0.117	28.94		63.8	200
Upper Bobcat Gulch	8/16/00	56	-	-	0.063	2.901	-	0.888	7.4	14.86	0.036		260	50.8	226
Upper Bobcat Gulch	9/1/00	60	-	-	0.050	2.961	-	1.260	7.6	-	-	33.32	-	23.9	230
Upper Bobcat Gulch	9/1/00	66	-	-	0.046	2.799	-	1.240	7.6	-	-	30.67	-	21.8	225
Upper Bobcat Gulch	9/26/00	73	2.59	66	0.035	3.488	16	0.036	7.9	0.69	0.101	-	-	1.5	216
Minimum	-	46	1.88	66	0.015	0.001	16	0.018	7.4	0.69	0.010	21.22	260	1.5	200
Average	-	106	3.83	619	0.044	2.187	262	0.612	7.6	6.20	0.162	28.54	289	55.5	259
Maximum	-	237	7.12	1138	0.100	3.488	375	1.480	8.0	18.49	0.587	33.32	344	314.2	345
S. Deviation	-	68	2.09	506	0.027	1.482	144	0.604	0.2	7.31	0.195	5.20	47	93.1	51

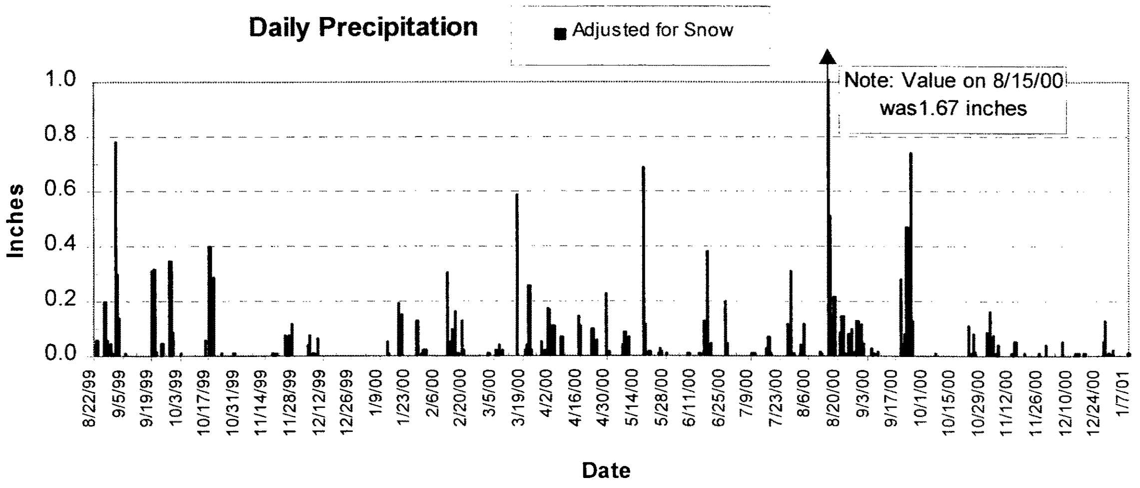
TABLE 21. Water quality data from the Cache la Poudre River above the confluence of the Little South Fork from 6/3/97 to 6/6/00.

Parameter	ALKA	Spec. Cond.	Fe-Total	NO_2	NO_3	Ammonia	TOC	pH	Total N	TPHOS
Units	mg/L as $CaCO_3$	uS/cm	ug/L	mg/L	mg/L	mg/L	mg/L	units	mg/L	mg/L
Reporting Limit >	-	-	5 ug/L	0.03 mg/L	0.02 mg/L	0.02 mg/L	0.5 mg/L	-	0.1 mg/L	0.01 mg/L
6/3/97	11	28	1197	-	0.021	0.024	6.35	7.2	0.350	0.054
9/30/97	19	44	159	-	0.010	0.010	-	7.5	0.430	<0.01
6/2/98	11	28	542	<0.03	0.020	0.063	5.39	7.2	0.311	0.023
9/22/98	22	45	114	<0.03	0.010	0.020	1.68	7.5	0.104	<0.01
6/15/99	12	29	569	<0.03	0.026	0.010	5.73	7.3	0.352	0.026
10/5/99	24		67	<0.03	0.010	0.027	1.81	7.3	0.220	0.017
6/6/00	10	30	271	<0.03	0.036	0.010	4.05	7.0	0.326	0.021
Minimum	10	28	67	<0.03	0.010	0.010	1.68	7.0	0.104	0.017
Mean	15	34	417	<0.03	0.019	0.023	4.17	7.3	0.299	0.028
Maximum	24	45	1197	<0.03	0.036	0.063	6.35	7.5	0.430	0.054
S. Deviation	6	8	398	--	0.010	0.019	2.02	0.2	0.106	0.015

TABLE 22. Water quality data from the Cache la Poudre River below the confluence of Sheep Creek from 6/3/97 to 6/6/00.

Parameter	ALKA	Spec. Cond.	Fe-Total	NO_2	NO_3	TOC	pH
Units	mg/L as $CaCO_3$	uS/cm	ug/L	mg/L	mg/L	mg/L	units
Reporting Limit >	-	-	< 5	< 0.03	< 0.02	< 0.5	-
6/3/97	10	28	668	-	-	6.65	7.2
9/30/97	16	38	200	-	-	2.08	7.4
6/2/98	11	28	353	<0.03	0.020	5.63	7.2
9/22/98	18	38	182	<0.03	0.010	1.92	7.5
6/15/99	11	30	8605	<0.03	0.036	5.40	7.1
10/5/99	19		186	<0.03	0.193	1.74	7.1
6/6/00	10	32	247	<0.03	0.043	4.17	6.8
Minimum	10	28	182	<0.03	0.010	1.74	6.8
Mean	14	32	1492	<0.03	0.060	3.94	7.2
Maximum	19	38	8605	<0.03	0.193	6.65	7.5
S. Deviation	4	5	3141	-	0.075	2.03	0.2

Appendix II: Precipitation



Note: Value on 8/15/00 was1.67 inches

FIGURE 8. Daily Precipitation for Mom Gulch located near Rustic, Colorado. Collected from August 22, 1999 to January 8, 2001.

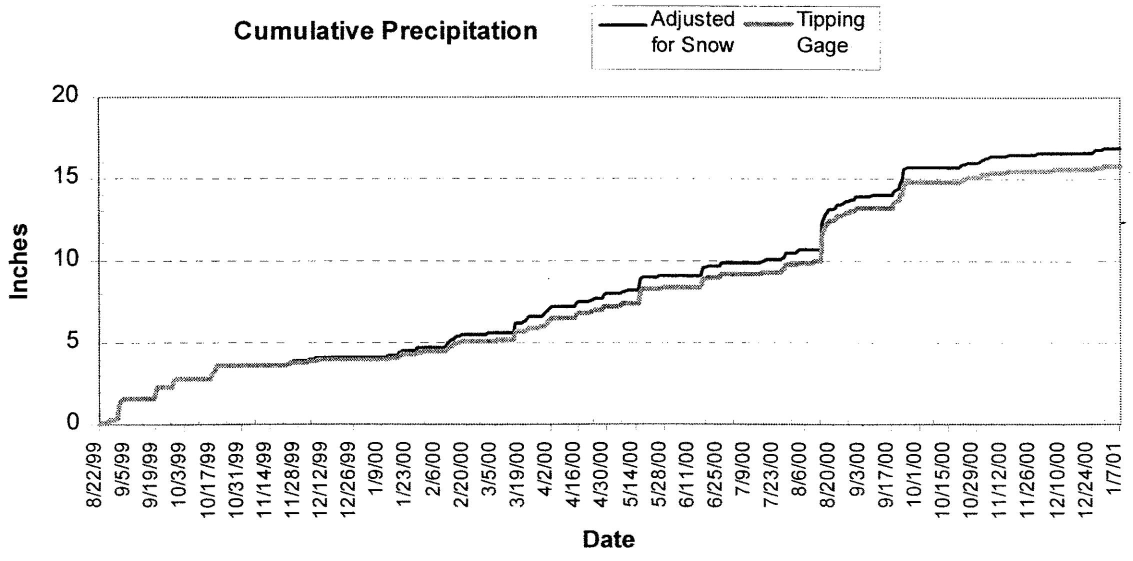


FIGURE 9. Cumulative Precipitation for Mom Gulch located near Rustic, Colorado. Collected from August 22, 1999 to January 8, 2001.

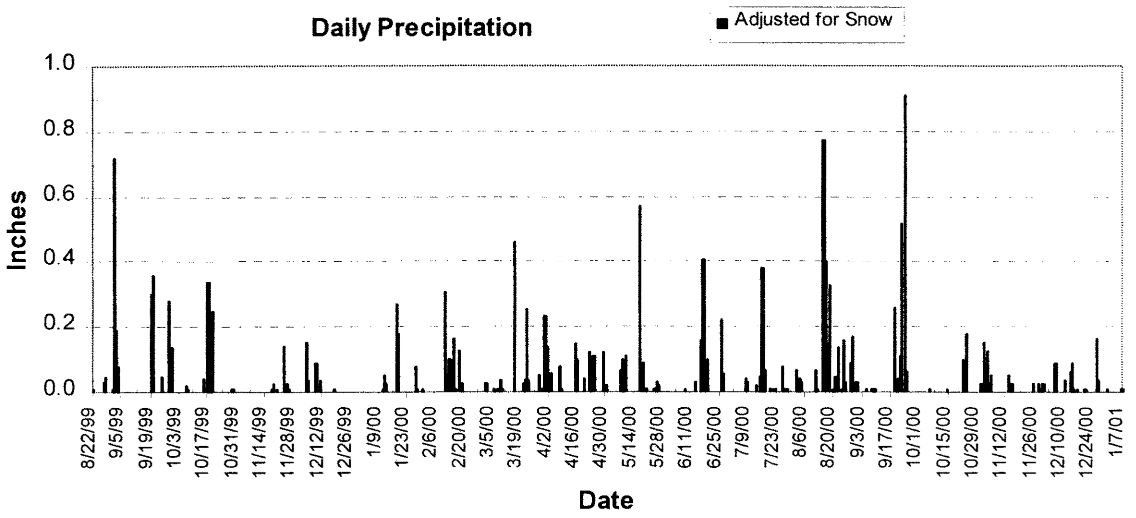


FIGURE 10. Daily Precipitation for Dadd Gulch located near Rustic, Colorado. Collected from August 22, 1999 to January 8, 2001.

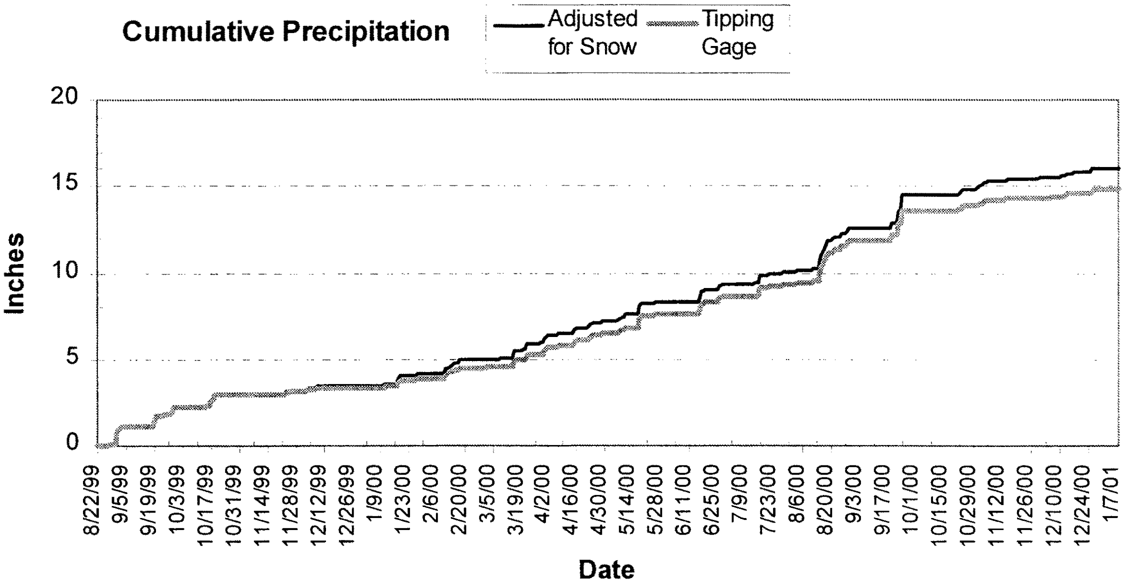


FIGURE 11. Cumulative Precipitation for Dadd Gulch located near Rustic, Colorado. Collected from August 22, 1999 to January 8, 2001.

Appendix III: Streamflow

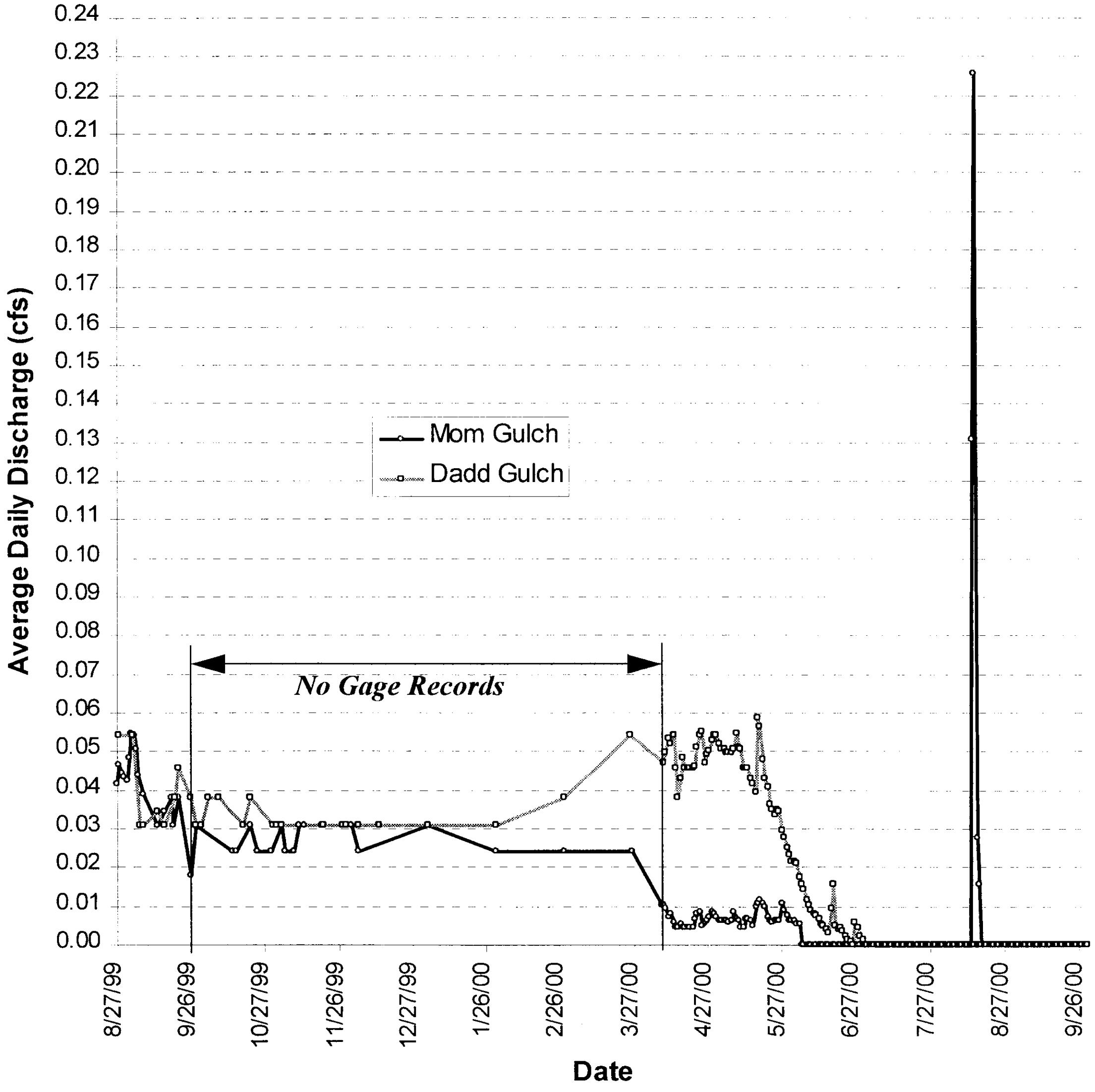


FIGURE 12. Average Daily Streamflow for Mom and Dadd Gulch located near Rustic, Colorado from 8/27/99 to 9/30/00. Values from 9/26/99 to 4/8/00 are from Field Visits and May not Represent Daily Averages.