THESIS

A DEBRIS FLOW CHRONOLOGY AND ANALYSIS OF CONTROLS ON DEBRIS FLOW OCCURRENCE IN THE UPPER COLORADO RIVER VALLEY, ROCKY MOUNTAIN NATIONAL PARK, CO

Submitted by

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ABSTRACT

A DEBRIS FLOW CHRONOLOGY AND ANALYSIS OF CONTROLS ON DEBRIS FLOW OCCURRENCE IN THE UPPER COLORADO RIVER VALLEY, ROCKY MOUNTAIN NATIONAL PARK, CO

The role of debris flows along the Upper Colorado River was recently highlighted when the Grand Ditch, a 19^{th}-century water-conveyance ditch, overtopped from snowmelt in 2003 and triggered a large debris flow along Lulu Creek, a tributary of the Colorado. Historical aerial photographs indicate that at least two other debris flows have been triggered from the Grand Ditch over the last century. This study examines the natural regime of debris flows in the Colorado River headwaters to assess whether the Grand Ditch has increased magnitude and frequency of debris flow occurrence on the west side of the Colorado River valley. Ten distinct sites of debris flow deposition were mapped using aerial photographs and field exploration, dated from tree cores and tree scars, and analyzed for magnitude using field-estimated volumes of deposition. Six of these ten depositional sites are on the west side of the valley, and several of them have evidence of multiple debris flows. Forty scarred survivor trees and 38 cores from even-aged stands were dated, with corresponding dates of debris flow occurrence ranging from 1923 to 2003. At least 19 debris flows have occurred in this catchment over the last century, but only those at the across-from-Specimen Creek, Lady Creek, Lulu Creek, and Little Yellow sites appear to have been large enough to affect the Colorado River. There is not a substantial difference in the frequency of total debris flows catalogued at the ten sites of deposition between the east (8) and west (11) sides of the Colorado River valley over the last century, but three of the four largest debris flows originated on the west side of the valley in association with the Grand Ditch, while the fourth is on a steep hillslope of hydrothermally altered rock on the east side of the valley. Although ability to interpret the debris flow record is limited by frequent disturbance and burial of older deposits, and estimates of magnitude have high uncertainty, these data suggest that the Grand Ditch has altered the natural regime of debris flow activity in the Colorado River headwaters by increasing the frequency of debris flows large enough to reach the Colorado River. Likelihood of debris flow occurrence is augmented by steep slopes and hydrothermally altered rock, which are both common in the vicinity of the Grand Ditch. This study demonstrates the applicability of dendrochronology for dating geomorphic events in Rocky Mountain National Park and provides context for restoration following debris flows.

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1. Introduction

The Grand Ditch, a 19th-century water-conveyance ditch, flows parallel to and up-slope from the Upper Colorado River on the western side of Rocky Mountain National Park. The ditch bisects several smaller channels tributary to the Upper Colorado, and has the potential to send unnaturally large water flows down these channels when the ditch overtops or breaches. These large water flows can erode sufficient sediment along the tributaries to create debris flows capable of reaching the valley bottom along the Colorado River. In 2003, a large debris flow entered Lulu Creek, a tributary to the Colorado River, when the Grand Ditch overtopped from snowmelt (Rubin et al., 2012). Impacts of the 2003 event are still visible along the Colorado River, and include debris flows berms, a large sediment fan, lateral and mid-channel bars, and scarred trees. The Lulu City wetland, the most sensitive and ecologically valuable area of Rocky Mountain National Park impacted by the 2003 debris flow, was buried in up to 1 m of sand and gravel (Rubin et al., 2012). A lack of historical data makes it difficult to put the impact of this event in the context of previous natural and anthropogenic debris flows down tributaries in the Colorado River headwaters, but reference reaches and data from similar systems outside the basin provide useful information to assess channel recovery (Rubin et al., 2012).

The conceptual framework of historical range of variability (HRV) allows for a better understanding of the significance of the changes that have occurred along Lulu Creek and the Colorado River. HRV is defined as the range of environmental forms and processes that predate human use (Morgan et al., 1994). In the Colorado River headwaters, the appropriate time period defining the HRV is roughly constrained by the end of neoglaciation (3000 BP) and the start of logging and mining operations (200 BP) (Ellen Wohl, Colorado State University, pers. comm., 2012). While debris flow occurrence was undoubtedly an aspect of that time period, the HRV framework allows for consideration of whether the magnitude and frequency of debris flows has been shifted relative to the HRV by human influence. In general, HRV allows for recognition of the dynamic state of a landscape and its ecosystem, while acknowledging that there may be a limited range of processes to which the landscape is adjusted (Rubin et al., 2012). This makes HRV an effective tool for advising management and restoration decisions, as the existence of a process outside of its HRV can be used as a criteria for restoration. Based on monitoring of sediment regimes and channel morphology, three out of four reaches along Lulu Creek have step height-to-length ratios that are outside the HRV defined by reference channels, while the Colorado river is outside of the HRV for steep pool-riffle channels (Rathburn et al., in press). Given the National Park setting, the potential loss of ecosystem function associated with these changes motivates consideration of restoration and management options as well as further exploration of current and historical debris flow activity.

The primary goal of this research was to describe the debris flow regime in the Colorado River headwaters and the influence of the Grand Ditch on debris flow processes. Analysis of aerial photographs dating to 1937 suggests that other large debris flows have occurred in similar fashion to the 2003 event on Lulu Creek. The apparent triggering of multiple debris flows from the Grand Ditch (Rubin et al., 2009) provides an opportunity to compare events which are directly related to anthropogenic influences with those that occur as an intrinsic part of this steep-gradient, high elevation geomorphic system. Comparison of debris flows originating from both the east and west sides of the valley, and from potentially different source rocks, allows further evaluation of controls on debris flow occurrence. I used dendrochronologic records from trees bearing evidence of debris flows to systematically evaluate the age of debris flows large enough to reach the Upper Colorado River valley, and estimated debris flow volumes from preserved sites of deposition. These data were then used to evaluate whether debris flows have increased in magnitude and frequency since the ditch was built in the late 1890's. The null and alternative hypotheses pertaining to this question are:

$H1_0$: Debris flows triggered from the Grand Ditch and naturally occurring debris flows have equal frequencies and magnitudes.

$H1_A$: Debris flows triggered from the Grand Ditch have higher frequency and magnitudes than naturally occurring debris flows.

I also tested whether debris flow occurrence is related to the mapped distribution of hydrothermally altered rocks, which are present in portions of the Colorado River headwaters (Sanford, 2010). The null and alternative hypotheses related to hydrothermal alteration are:

$H2_0$: The spatial distribution of debris flows is not controlled by hydrothermal alteration of source rock.

$H2_A$: The spatial distribution of debris flows depends on the extent of hydrothermal alteration.

By placing the 2003 debris flow in the context of both previous events triggered by the Grand Ditch and natural events, this research adds to the understanding of landscape processes and evolution in Rocky Mountain National Park and contributes to a better understanding of what efforts are appropriate to restore affected areas of the Upper Colorado River to their natural functioning condition.

1.1 Study Area

This research was conducted in the headwaters of the Colorado River on the western side of Rocky Mountain National Park, in the drainages supplying the Lulu City wetland and 5 km of river directly upstream (Figure 1). The Colorado River flows south from the Continental Divide and is bordered by the Never Summer Mountains to the west and Front Range to the east. Mountain-building in this region began with the intrusion of the granitic Longs Peak-St Vrain batholiths during the Mesoproterozoic, but mostly reflects uplift during the Laramide Orogeny at the end of the Cretaceous (Braddock and Cole, 1990). The Never Summer Mountains are composed of late Oligocene and early Miocene intrusive volcanic rocks, while the Front Range contains mainly uplifted Proterozoic basement rocks (Braddock and Cole, 1990). Bedrock along the Upper Colorado River consists of Tertiary rhyolitic tuffs, with Pleistocene glacial till covering much of the valley bottom (Braddock and Cole, 1990). This stretch of the Colorado River has mainly pool-riffle planform (Montgomery and Buffington, 1997) and

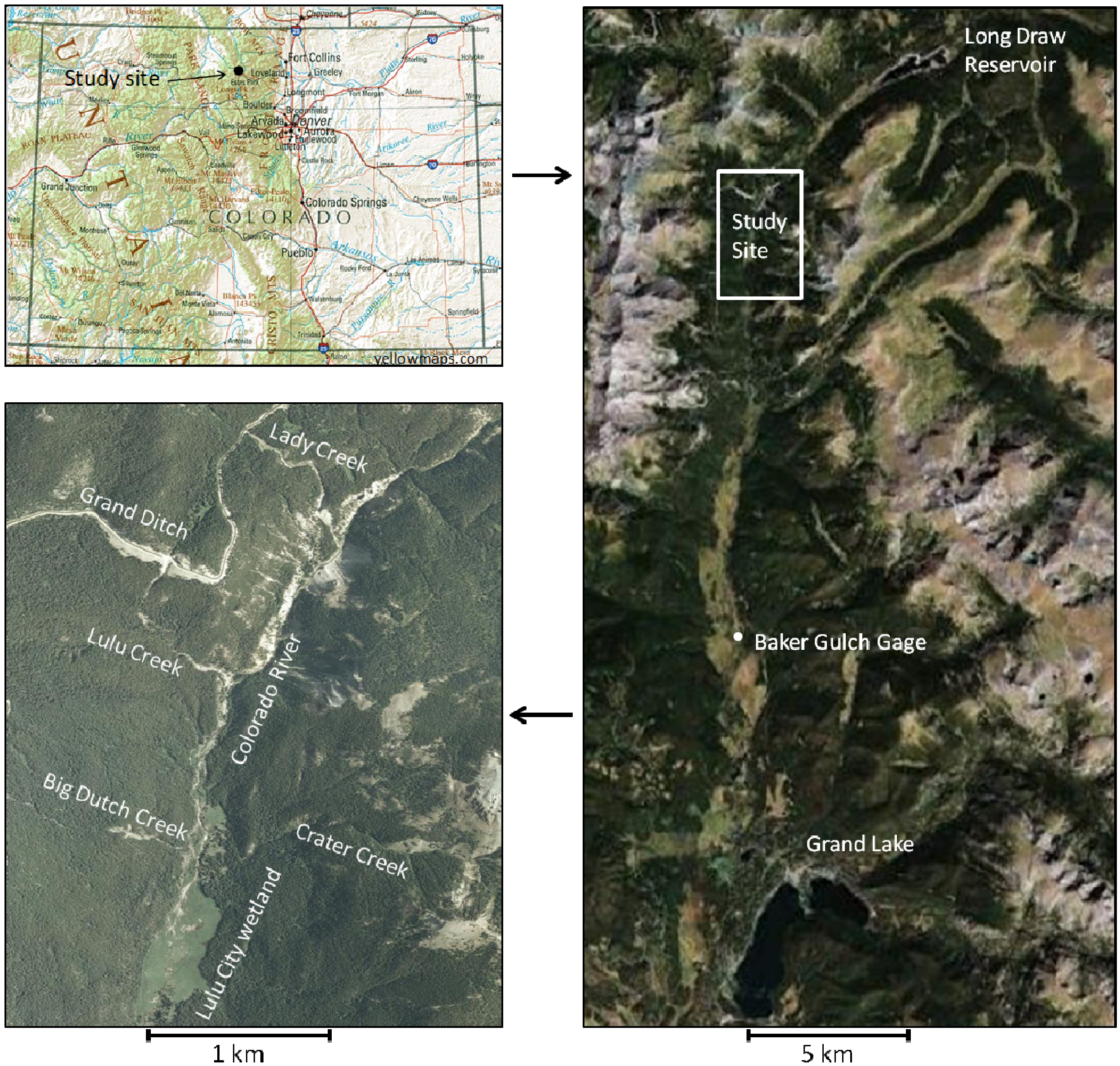

Figure 1: Location of the study site in Rocky Mountain National Park. Arrows show increasing resolution from the Colorado state map (top left), to the Upper Colorado River region (right), ending with the study site (bottom left). The location of the USGS Gage 09010500 Colorado River Below Baker Gulch, Near Grand Lake, CO is shown on the right image.

stream gradient varying from up to 4% to less than 1% in the Lulu City wetland. Elevations within the watershed as defined by the USGS Baker Gulch gage (USGS Gage 09010500 Colorado River Below Baker Gulch, Near Grand Lake, CO) range from 2670 m at the gage to 3944 m at the peak of Mount Richthofen, where the Colorado River heads (Braddock and Cole, 1990). Many of the tributaries to the Upper Colorado River originate in glacial cirques and have a steeper gradient than the main channel with largely step-pool planform (Woods, 2000). The runoff regime is snowmelt dominated, with roughly 80% of annual runoff occurring in May, June, and July (Woods, 2000) and an estimated 107 cm of average annual precipitation (Capesius et al., 2009).

Hillslope vegetation is largely composed of Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*), and subalpine fir (*Abies lasiocarpa*) (Woods, 2000). A recent mountain pine beetle outbreak has severely affected this area, resulting in many dead or dying mature pines. Subalpine wetlands are present along the valley bottom with willow, sage, and grass species common. These willows, along with aspen stands in the area, are subject to heavy grazing by elk during both winter and summer months (Suzuki et al., 1999).

The Grand Ditch diverts water across the Continental Divide from the Never Summer Mountains in the Colorado River watershed into the Cache la Poudre basin (Figure 2). The ditch starts above the USGS Baker Gulch gage and extends for over 25 km at near 3100 m elevation. Construction took place from 1890 to 1936, and diversions began in the late 1890's (Woods, 2000). Approximately 50% of annual flow is captured depending on the amount and timing of snowmelt (Woods, 2000). The Grand Ditch thereby alters the regimes of both flow and sediment in the Upper Colorado River. A second, smaller, shorter (2.7 km) ditch on the northwestern slope of Specimen Mountain parallels the Grand Ditch on the east side of the Colorado River, before feeding in to the Grand Ditch at La Poudre Pass (Figure 2). This offshoot of the Grand Ditch, sometimes referred to as the Specimen Ditch, has received less scientific and public attention because it is more concealed and diverts much less water (National Park Service, n.d.).

Relatively little research has been conducted on debris flows in the Colorado Rocky Mountains. The activity level of mass wasting in subalpine zones of the Indian Peaks area has been described as slight (Caine, 1984). Small debris flows have been observed in conjunction with intense rainfall and flooding (Costa and Jarrett, 1981). Costa (1984) has also described levees and boulder berms caused by

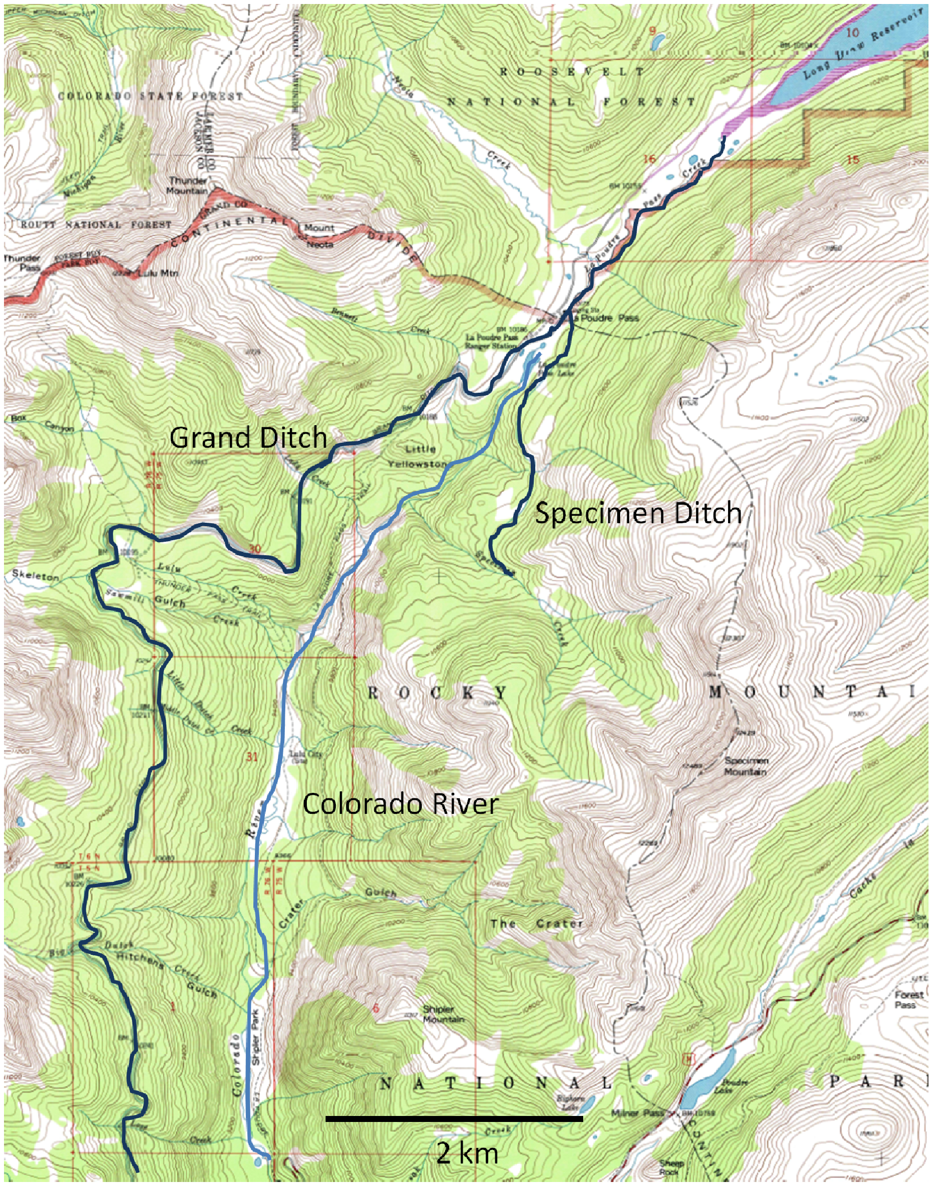

Figure 2: Positions of the Grand Ditch and Specimen Ditch relative to the Colorado River. The Colorado River flows south, while both ditches flow north into Long Draw Reservoir.

debris flows along steep mountain channels in the Southern Rocky Mountains. Larger debris flows have mostly been observed to occur in association with wildfire (Cannon et al., 2001; Wondzell and King, 2003) or extreme rainfall (Godt and Coe, 2007). Landslide deposits are widespread in the Williams Fork Mountains to the west of Rocky Mountain National Park, although they are mostly inactive except above timberline (Kellogg, 2001). Coarse sediment deposition from ground penetrating radar surveys in the wetland suggest that debris flows in the Colorado River headwaters did occur before construction of the

Grand Ditch (Rubin, 2010), but aggradation rates have been elevated over the last century (Rubin et al., 2009). David Cooper (Colorado State University, pers. comm., 2011) observed establishment of conifer trees in the 1920's and 1950's below the Grand Ditch and along the Colorado River, indicating debris flow disturbance prior to that time period. There is also evidence of debris flows from the Grand Ditch in Baker Gulch, a tributary south of the study site on the west side of the Colorado River. Occurrence of the Holzwarth debris flow along Baker Gulch is documented on June 16, 1978, and another debris flow with a similar path is reported to have occurred there between 1969 and 1974 (Braddock and Cole, 1990).

1.2 Debris Flows

In high gradient environments, debris flows are commonly a dominant source of sediment transport and erosion (Benda, 1990; Stock and Dietrich, 2006). However, the complexity of their structure and interaction with the ground surface makes it difficult to model and anticipate their impact on the landscape and human structures (Stock and Dietrich, 2006). Given this importance to landscape evolution, and the expensive, hazardous, and unpredictable consequences that debris flows commonly have on human populations, research on occurrence and history of debris flows is an increasingly relevant topic (Baumann and Kaiser, 1999; Bollschweiler and Stoffel, 2010).

Debris flows are mass movements that are defined by the interaction of solid and fluid forces (Iverson, 1997). High concentrations of suspended sediment cause debris flows to act as non-Newtonian fluids, allowing for high destructive potential and transport of large sediment clasts (Whipple, 1997). While other distinguishing factors such as sediment distributions and shear properties have been used to differentiate debris flows from the related processes of avalanches and floods, this mechanical complexity is the broadest and most consistently unique element (Iverson, 1997). Debris flows tend to have high sediment concentrations, often greater than 60%, and velocities ranging from roughly 1 m/s up to 3 m/s depending both on the characteristics of the hillslope and the composition of the debris flow (Costa, 1984).

Debris flows tend to occur where loose rock and soil on steep hillslopes are subjected to substantial inputs of moisture such as intense rainfall or snowmelt (Costa, 1984). Sites most conducive to debris flow origination are steep, sparsely vegetated hillslopes mantled with unconsolidated sediment and subject to sporadic periods of wetness, such as much of Japan, the mountainous semi-arid western United States, and the Pacific Northwest (Costa, 1984). Small debris flows may occur much more frequently than larger ones and not travel as far downstream or be as destructive (Hupp et al., 1987), and may therefore be undetected in some cases.

The regularity with which intense rainfall acts as a trigger for debris flows has motivated case studies investigating the connections between the two processes. Researchers in the central Alps did not observe a strong correlation between debris flows and precipitation records, but interpreted a threshold of 20-30 mm of rain over the course of a few hours that consistently triggered debris flows (Pelfini and Santilli, 2008). Such a threshold is necessarily sensitive to site conditions such as slope, soil properties, and vegetation, as well as antecedent moisture. In other cases, debris flows have been more successfully linked to rainfall records (Hupp et al., 1987; Rebetez et al., 1997; Szymczak et al., 2010). Connections between precipitation and slope failure may become increasingly relevant if climate change leads to more frequent severe weather, as suggested by many studies (Pelfini and Santilli, 2008).

In forested catchments, debris flow initiation from rainfall is often greatly augmented by forest fires due to destabilization of hillslopes by removal of vegetation (Wohl and Pearthree, 1991; Cannon et al., 2001; Wondzell and King, 2003). While strong correlations between timing of stand-replacing fires and subsequent debris flows have been observed, not every large fire is followed by a debris flow. Wohl and Pearthree (1991) interpret this as the time interval needed for loose sediment to accumulate in the upper portion of a catchment after being denuded by a debris flow. Attempts to quantify recharge rates of debris flow source areas have been made in British Columbia (Jakob et al., 2005), but have not yet been expanded to apply to other regions. Research in the French Alps has found that the number of days below freezing, which strongly influences production of debris, may also be a good predictor of debris flow occurrence (Jomelli et al., 2003). In regions where stand-replacing fires are a key process, debris flow recurrence intervals can then be related to climatically controlled slope weathering and erosion rates, and fire frequencies (Wohl and Pearthree, 1991). Even more extreme rainfall is commonly necessary to initiate debris flows in locations where large forest fires are less frequent, such as the Appalachian Mountains in central Virginia, where tropical air systems are needed to generate sufficient rainfall (Kochel, 1987).

In a landscape affected by debris flows, zones of erosion and deposition are typically divided by breaks in slope (Stock and Dietrich, 2006). Degradation therefore tends to occur high on slopes, where gradients are often steepest, while aggradation occurs lower on the slope (Hupp et al., 1987). In erosive zones, where slopes are typically greater than about 0.03 - 0.10, bedrock scour and altered valley morphology are commonly observed, suggesting that debris flows can dominate geomorphic work in those areas (Stock and Dietrich, 2006). In depositional zones, debris flows may provide the majority of sediment input, especially of larger clasts that exceed fluvial transport thresholds.

Debris flow deposits have a characteristically lobate shape, especially along upstream reaches (Hupp et al., 1987). Along the margins of debris flow deposits, mounded sediment berms are commonly present with a high concentration of boulders and decreasing thickness down-slope (Costa, 1984). Debris flow deposits tend to be poorly sorted with large clasts supported in a mud or silt matrix. At the distal end of deposition, debris flow material tends to spread out and can often lead to formation of alluvial fans. Interpretation of old debris flows is often complicated by the reworking of deposits by water flows (Costa, 1984).

Debris flow runout distances are difficult to determine as they depend on the complex interaction of the slope and topography of the surface as well as the characteristics of the debris flow material. Debris flows often form temporary channel-blocking dams as they slow down in low slope areas, but these may be breached by the arrival of subsequent sediment and down-slope movement may continue (Costa, 1984). One promising approach to calculating runout distance has been mass-change models, which account for the changing velocities of debris flows as mass is lost or gained during travel (Cannon and Savage, 1988). However, these models remain at a theoretical stage due to the impracticality of calibration to specific debris flows.

The earliest known record of a debris flow is from Rubble Creek, British Columbia in 1858, while first-hand accounts date back to 1872 (Skermer and VanDine, 2005). The history of awareness and knowledge of debris flows is difficult to assess due to lack of documentation predating the early 1900's (Skermer and VanDine, 2005). One of the first scientific works on debris flows is from the Austrian geologist Stiny, who authored the book *Die Muren* in 1910 (Skermer and VanDine, 2005). The risk of debris flows was appreciated even earlier in the French Alps, where the consequences of deforestation were acknowledged as early as 1870.

Detection and management of debris flow hazards has become increasingly important with the ongoing expansion of human population and infrastructure (Jakob, 2005). As of 1979, 70,000 debris flow channels with five or more structures in the runout zone had been documented in Japan. Jakob (2005) outlines a six-step approach for debris flow hazard analysis that begins with recognition of hazards and culminates in development of magnitude-frequency relationships and maps of hazard potential. The hazards that debris flows pose are often a motivating force for research, and therefore many studies treating debris flows in this framework have been conducted (Lin et al., 2002; Glade, 2005; Hurlimann et al., 2006).

Reconstruction of debris flow volume is an important step for understanding the role of debris flows in an environment and the potential hazards they might pose, but it is not a simple or consistent process and is typically limited by small sample size (DAgostino and Marchi, 2001). Volumes of sediment deposition have been successfully estimated using field surveys which analyze potential sediment sources or preserved deposits, especially in combination with historical records (DAgostino and Marchi, 2001). However, most studies are only able to constrain debris flow volumes within broad ranges, making accurate magnitude-frequency relationships difficult to construct (van Steijn, 1996).

Approaches for predicting debris flow magnitudes and recurrence intervals in a catchment can be separated into two categories: empirical methods, in which basin morphometry and geology are used to model debris flows, and probabilistic methods, in which historical data are used to make statistical interpretations of debris flow occurrence (Wrachien and Mambretti, 2011). A case study in the Val Gola catchment of the eastern Italian Alps comparing both categories of prediction tools found that there were limitations to each approach, and recommended comparing methods to reduce the associated error (Wrachien and Mambretti, 2011). The best results for empirical models have been found when considering only debris flows in recently burned basins (Gartner et al., 2008), while probabilistic models are most effective when abundant data on past debris flows at a site are available.

1.3 Hydrothermal alteration

Hydrothermal alteration refers to a variety of scenarios in which the chemistry and structure of rocks are altered through contact with high temperature fluids (Taylor, 1974). Multiple authors have cited a relationship between hydrothermal alteration and slope failure (Crowley and Zimbelman, 1997; Reid et al., 2001; Lopez and Williams, 1993). Hydrothermal alteration tends to lower shear strength of rocks (Watters and Delahaut, 1995) and facilitate debris flow occurrence in combination with steep slopes (Reid et al., 2001). In the Upper Colorado River valley, bands of altered rhyolitic tuff are weaker than the surrounding rock. Changes in mineralogy, especially production of clay minerals, alter both the appearance and strength properties of these rocks (Sanford, 2010). Clasts of altered rhyolitic tuff are observed to crumble *in situ* or in transport (Figure 3), and represent a large fraction of debris flow deposits in the northern areas of the study site. The median grain size of degrading tuff clasts is coarse sand (Rubin et al., 2012). Research on the extent and potential impacts of hydrothermal alteration in this region supports a heightened risk of slope failure (Sanford, 2010) in the shaded areas (John Ridley, Colorado State University, pers. comm., 2012) (Figure 3).

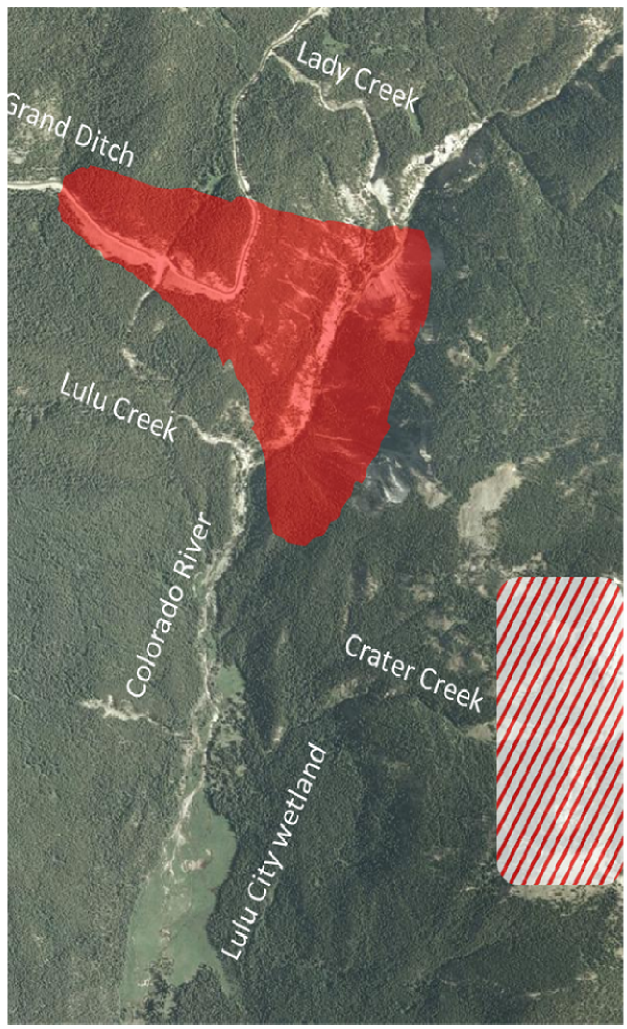

Figure 3: Left: A cobble of rhyolitic tuff from the 2003 debris flow that is degrading *in situ* into gravel- and sand-sized fragments. Right: Two zones of hydrothermal alteration in the Colorado River headwaters. Alteration in the vicinity of the Grand Ditch (solid shading) has been mapped and studied. Alteration at the top of Specimen Mountain (hatched shading) is interpreted from remote observations.

1.4 Conifer Growth

Implicit in using trees as a geomorphic tool is an understanding of tree growth and structure. Characteristics of trees vary greatly with species and climate, but only temperate conifers are considered here as the three species sampled in this study, Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*), and subalpine fir (*Abies lasiocarpa*), all fall under that category. Tree growth can be broadly separated into a vegetation period, typically consisting of spring and summer months during which cell formation occurs, and a period of dormancy during the rest of the year (Stoffel and Bollschweiler, 2008). The dormancy period is responsible for the clear distinction between annual growth rings. Tree ring formation occurs as the vascular cambium, a tissue located between the xylem (wood) and phloem (bark) contributes new cells to both the xylem and phloem (Stoffel and Bollschweiler, 2008). In conifers, the vegetation period consists of first the production of earlywood, which has larger, thin-walled cells that are well-suited to nutrient transport, followed by latewood, in which denser cells contribute to the stability of the tree (Stoffel and Bollschweiler, 2008). Tree ring growth is controlled both by biotic factors, such as the genetics and aging of trees, as well as abiotic factors, including light, temperature, water, and nutrients, among others (Bollschweiler and Stoffel, 2010). Tree ring series can therefore preserve both the changes in these growth factors as well as mechanical disturbances such as debris flows.

1.5 Dendrogeomorphology

Dendrochronology uses the variation in annual tree growth rings to make inferences about the site conditions affecting growth over time. Use of the term “dendrogeomorphology” to describe the application of tree growth properties to questions pertaining to geomorphology was coined by Alestalo (1971). Trees may preserve a remarkable amount of information on the timing and frequency of debris flows, as well as indicators of relative magnitude (Bollschweiler and Stoffel, 2010). Trees are an especially valuable data source for debris flow research due to the lack of direct observations of debris flows because of their unpredictable and destructive nature. Dendrogeomorphology has been applied to debris flow research most heavily in the Swiss and Italian Alps (Baumann and Kaiser, 1999; Fantucci and Sorriso-Valvo, 1999; Bollschweiler et al., 2008; Pelfini and Santilli, 2008; Arbellay et al., 2010), but also in the Cascade mountains of the western United States (Hupp et al., 1987; Pierson, 2007), and northwestern Argentina (Grau et al., 2003), among other locations. Conifers have been most frequently used for dating debris flows due to their abundance in mountain regions and simple wood structure, but broad-leaved deciduous trees have also been used successfully (Grau et al., 2003; Arbellay et al., 2010; Szymczak et al., 2010).

Dendrogeomorphic evidence of debris flows can be preserved either through the age of an entire stand or through the characteristics of individual trees (Butler et al., 1987). When no trees survive a debris flow, the age of trees on the disturbed surface corresponds to a minimum age of the most recent disturbance (Bollschweiler et al., 2008). However, this approach contains uncertainties due both to the difficulty in determining the oldest trees on a surface and in estimating the time elapsed between a debris flow and tree germination and growth. Typically, the trees with largest diameters are assumed to be the oldest, but this may not always be the case and trees may surpass one another in girth as growth rates fluctuate (Cherubini et al., 1998).

Assuming the oldest trees have been sampled, two time corrections, which are jointly referred to as the colonization time gap, must be accounted for to accurately represent the age of a surface (Pierson, 2007). These corrections are (1) the time for trees to germinate on the freshly disturbed surface, known as germination lag time or ecesis, and (2) the time needed for trees to grow to the sampling height after germination (Pierson, 2007). Researchers are typically unable to sample at the base of trees due to space needed above the ground surface to rotate the increment borer, and samples are often collected at breast height for consistency. Pierson (2007) documented a germination lag time of 5±5 years for the mean age of the largest five Douglas firs growing on the surfaces of volcanoes in the Cascade Range. When trees were cored at breast height, a total colonization time gap of 11±7 years occurred. Ecesis times on disturbed surfaces also vary greatly with tree species and climatic setting, as documented by case studies in which *Alnus acuminata* (alder) thoroughly recolonized a hillslope in northern Argentina only 2 years after a landslide (Grau et al., 2003), while conifers on glacial forefields in British Columbia take 5 to 25 years to excise (McCarthy and Luckman, 1993).

When survivor trees are present in the disturbed area, they can preserve evidence of impacts or other stresses through a variety of mechanisms. The connections between mechanical disturbances and the corresponding responses of tree growth were framed in the context of process-event-response systems by Shroder (1980). The process-event-response concept is used to link geomorphic processes with observed results in a systematic way. In this case, the process of debris flows is linked to potential events affecting trees, including injury, decapitation, stem burial, root exposure, and stem tilting (Shroder, 1980). Four common responses of trees to these events are (1) growth decrease, (2) callus tissue, (3) reaction wood, and (4) traumatic resin ducts (Bollschweiler and Stoffel, 2010). Traumatic resin ducts only occur in certain species of trees and can result from non-geomorphic process such as insect attacks (Stoffel, 2008), and are therefore less often used in dendrogeomorphic research.

Growth decreases are typically quantified using an anomaly index as described by Fantucci and Sorriso-Valvo (1999). While growth decreases reflect high levels of stress, sustained growth increases, also known as releases, can also be used to make inferences about disturbances in certain cases (Rubino and McCarthy, 2004). In particular, the removal or damaging of surrounding trees frees up additional resources for surviving trees to use, which may then be reflected in release events. Limitations of using release events to assess disturbance include potential difficulties of separating out climatic fluctuations and distinguishing between closely spaced successive disturbances (Rubino and McCarthy, 2004).

Where a tree is wounded severely enough to damage the cambium, annual ring growth ceases in the wounded area and instead compartmentalization and callus tissue growth occur (Stoffel and Bollschweiler, 2008). Depending on the size of the scar and health of the tree, overgrowth of callus tissue may eventually fully cover the wounded area. In a study of scars from ice floods, nearly 50% of scars were from closed wounds and only discovered after samples were collected (Tardif and Bergeron, 1997). This can be detrimental to sampling success of trees impacted by debris flows, as older scars may not be detected during surveying. Additionally, trees at the distal end of debris flow deposition are frequently unscarred due to the lowered impact force as the velocity decreases (Costa, 1984).

By sawing out a thin wedge through the discontinuity in the cambium at the edge of a scar, warped tree rings can be counted to precisely date scarring events (McBride and Laven, 1976). This technique has been demonstrated to not destroy sampled trees and can have seasonal dating accuracy based on earlywood and latewood growth (Hupp et al., 1987). While potentially very accurate, the use of tree scars still relies on counting growth rings, and is therefore susceptible to errors due to false or missing rings. These errors can be minimized by cross-dating tree scar samples with each other and with core samples from the same site or nearby locations. The application of tree scars to the study of debris flows has become increasingly prevalent in recent research (Hupp et al., 1987; Benda, 1990; Baumann and Kaiser, 1999; Fantucci and Sorriso-Valvo, 1999; DAgostino and Marchi, 2001; Grau et al., 2003; Rubino and McCarthy, 2004; Bollschweiler et al., 2008; Stoffel and Bollschweiler, 2008; Arbellay et al., 2010).

Tree scars have also been successfully used to estimate flood magnitude (Yanosky and Jarrett, 2002). Gottesfeld (1996) surveyed scars from a 1990 flood along the Skeena River in British Columbia and found that the mean height of the top of sampled scars was 20±3 cm below peak stage, while scars from a 1996 flood along Buffalo Creek in Colorado were an average of 21 cm above peak stage (Yanosky and Jarrett, 2002). However, floods tend to leave scars that are more conducive to magnitude estimation because most impact wounds form by abrasion of logs transported at the water surface at peak flow (Gottesfeld, 1996). Applying this technique to historical events also assumes an improbably static channel position and morphology. Debris flow scars may be less consistent indicators of magnitude because their steep surge fronts and turbulent nature (Costa, 1984) cause high uncertainty of the position of impactors within the flow at the time of collision.

Stem tilting is most commonly observed in response to slow mass-movement processes, but also occurs due to the forces exerted by debris flows and other rapid mass movements (Stoffel and Bollschweiler, 2008). Trees respond to tilting by producing reaction wood, which in conifers results in larger, darker rings that help the tree resume vertical growth. The timing of reaction wood and corresponding growth decrease can be used along with geomorphic context to date disturbance (Stoffel and Bollschweiler, 2008). However, on geomorphically active hillslopes, stem tilting is a common result of other processes and it may therefore be difficult to isolate tilted trees that are related to debris flows.

Debris flows and avalanches may have overlapping runout zones in high altitude catchments and can produce similar tree damage (Szymczak et al., 2010). The seasonality of the damage can commonly be used to distinguish between processes based on the position of earlywood and latewood (Stoffel et al., 2006). The spatial distribution of damaged trees, meteorological records, and geomorphic context can provide additional indication of the active process (Szymczak et al., 2010).

The length of dendrogeomorphic records is highly variable at different sites, ranging from less than 50 years (Arbellay et al., 2010), to 500 years (Baumann and Kaiser, 1999). Record length is dependent both on the longevity of tree species and site conditions. Regions with frequent debris flows may be prone to the removal of dendrogeomorphic evidence from later disturbance (Hupp et al., 1987; Jomelli et al., 2003). Even where trees bearing evidence of old debris flows have survived, they may be difficult to detect for sampling due to eventual wound closure (Tardif and Bergeron, 1997) or degradation of even-aged stands as other processes lead to variation of ages within the stand.

There is often a sampling bias toward more recent disturbances in dendrochronologic studies due to the prevalence of younger trees as mature trees experience mortality (Hupp et al., 1987) or the removal of dendrogeomorphic evidence in areas of high debris flow activity (Jomelli et al., 2003). Some studies use circumstantial evidence to downplay the importance of this bias (Tardif and Bergeron, 1997), and it may be less of an issue in situations with a low forest turnover rate. Potentially inflated rates of recent debris flow occurrence have also been attributed to increased human populations and awareness of debris flow hazards (Rapp and Nyberg, 1988). The tendency to overemphasize the frequency of recent debris flows can be averted by considering the trajectory of site conditions and other forms of geomorphic evidence.

2. Methods

Debris flow location, timing and magnitude within the study area were constrained using multiple approaches including field mapping, aerial photograph analysis, and dendrochronology. All identifiable major debris flow deposits that reached the valley bottom of the Colorado River were cataloged and mapped, as these flows tend to be large enough to scour channels and deposit large amounts of sediment along tributaries to the main stem Colorado River. Mapping extended from the downstream end of Lulu City wetland (Figure 1; 427720 E, 4476560 N) to just upstream of Specimen Creek (429100 E, 4479600 N), as prior observations suggested that this was a key area of debris flow activity, and the wetland is of particular ecological and geomorphologic interest.

Field mapping was conducted by traversing the valley bottom at a distance of 100 to 400 m parallel to and on each side of the active channel, depending on the topography, and attempting to locate berm deposits (Figure 4) along tributaries or valley wall concavities where debris flows are most

Figure 4: A debris flow berm on the left bank of the Colorado River above the junction with Lulu Creek. The berm is roughly 1 m high and clasts are predominantly rhyolitic tuff.

likely to occur. These potential debris flow deposits were then followed up- and down-slope to verify their origin and make observations. Source location, flow direction, rock type, soil cover, and lichen growth were noted where relevant and available. Lichen growth was assessed visually based on size and coverage, and given an ordinal classification from 1-5, where '1' represents sparse growth and lichen diameters less than 1 cm, and '5' represents thick growth with diameters of at least 3 cm (Table 1).

Table 1: Lichen growth classification.

Class	Maximum Diameter	Surface Coverage	Description
1	1 cm	< 25%	sparse, small-sized growth
2	3 cm	< 25%	sparse, medium-sized growth
3	3 cm	25-50%	common, medium-sized growth
4	6 cm	25-50%	common, large-sized growth
5	6 cm	> 50%	dense, large-sized growth

Even-aged stands and wounded trees were sampled and dated, as described later in this section. These processes were repeated for each of ten distinct located sites of debris flow deposition, several of which had evidence of multiple debris flows. Estimation of debris flow magnitudes was originally attempted by measuring the elevations of the top of debris flow scars relative to the active channel. Distance of wounded trees from the active channel was also recorded. Measurements were carried out using a measuring tape and hand level. Unfortunately, this technique provided little insight into debris flow magnitudes due to several limiting factors. Most significantly, the potential for variation among impact heights from a given debris flow is large owing to the stochastic nature of particle movement within a debris flow. In addition, a low number of samples per debris flow, high mobility of channels in the study area, and variation in other factors such as channel confinement at the sample site render this approach ineffective. Scar heights have successfully been used to constrain the maximum stage of floods (Smith and Reynolds, 1983; Yanosky and Jarrett, 2002), but have not been widely used in debris flow research.

Instead, coarse field estimation of deposition volume was used as a proxy for debris flow magnitude. Beginning at a break in slope where large-scale deposition was evident, width and depth measurements of deposition were taken perpendicular to the flow direction. Width was recorded using a handheld Garmin GPS unit to record endpoints and a measuring tape to verify the corresponding measurements. Average depth for each transect was extrapolated from points where stream incision had exposed the stratigraphy of deposition below the surface. Down-slope intervals between measurements were chosen to correspond with significant changes in either width or depth. Measurements were continued down-slope to the Colorado River or an end to discernible debris flow deposition.

ArcGIS software was used to evaluate deposit volumes. Boundary coordinates from the GPS unit were imported onto a Digital Elevation Map (DEM) and used to create a polygon shapefile. A separate point shapefile of deposit depths was then interpolated into a continuous surface of depths and cropped to the extent of the boundary coordinates. Finally, the cut/fill tool was used to calculate deposit volume. While this approach is useful for assessing first-order approximations of debris flow magnitudes, it has several inherent limitations. First, it is a calculation of storage rather than debris flow magnitude or even volume of material deposited. Therefore, differences in confinement of the Colorado River valley may lead to limited preservation of debris flows at the junctions of certain tributaries, causing underestimation of magnitudes. Accuracy is limited both by DEM resolution (10 m) and the validity of the interpolation. Another difficulty arises where multiple debris flows have occurred in the same location. Except in cases where source rock or other factors vary, it is difficult to distinguish the material deposited by an individual debris flow, and therefore, to ascertain contributions to the total volume of deposition. This issue can be partially overcome using historical aerial photography, as discussed below.

Aerial photographs provide a useful remote sensing supplement for determining the spatial and temporal occurrence of debris flows. Large debris flows often remove patches of trees from the landscape, and therefore leave scars on hillslopes that are visible in aerial photographs. By delineating scarred areas on several images and comparing the results, time periods containing the most significant debris flow activity were determined. Aerial photographs for the Upper Colorado River valley are spaced on approximately a decadal interval. The results for this technique were used both to confirm source locations and assess recent debris flow activity.

Where even-aged stands were observed, trees were cored using an increment borer (Grissino-Mayer, 2003). Cored species included lodgepole pine, Douglas fir, and Engelmann spruce. Cores were taken as close to the ground surface as possible to minimize the underestimation of the germination age (Grissino-Mayer, 2003). In most cases, the largest four trees at the site were selecting for sampling. Tree species, diameter at breast height, and core height from ground surface were recorded. Core samples were stored in paper straws and dried.

Debris flow ages were also evaluated by sampling scarred trees (Figure 5). Only trees that were located within or on the fringe of debris flow berms with an appropriate scar shape and orientation were sampled to reduce the risk of including false data from trees that were wounded from other processes such as fire or tree fall. Samples were collected by using a 61-cm bow saw to make two cuts into the cambium of the tree, one horizontal and one slightly dipping, through the center of the scar. While this technique is damaging to the tree, trees have typically been observed to survive this procedure (Hupp et al., 1987), and most of the trees sampled in this study were already afflicted by the pine beetle. Death dates of beetle-kill trees were determined using cross-dating and therefore did not create a source of uncertainty in debris flow ages. One scarred tree that was dying from pine beetle along Sawmill Creek was too thick to saw by hand and was therefore felled by a trail crew using a chainsaw (Figure 5).

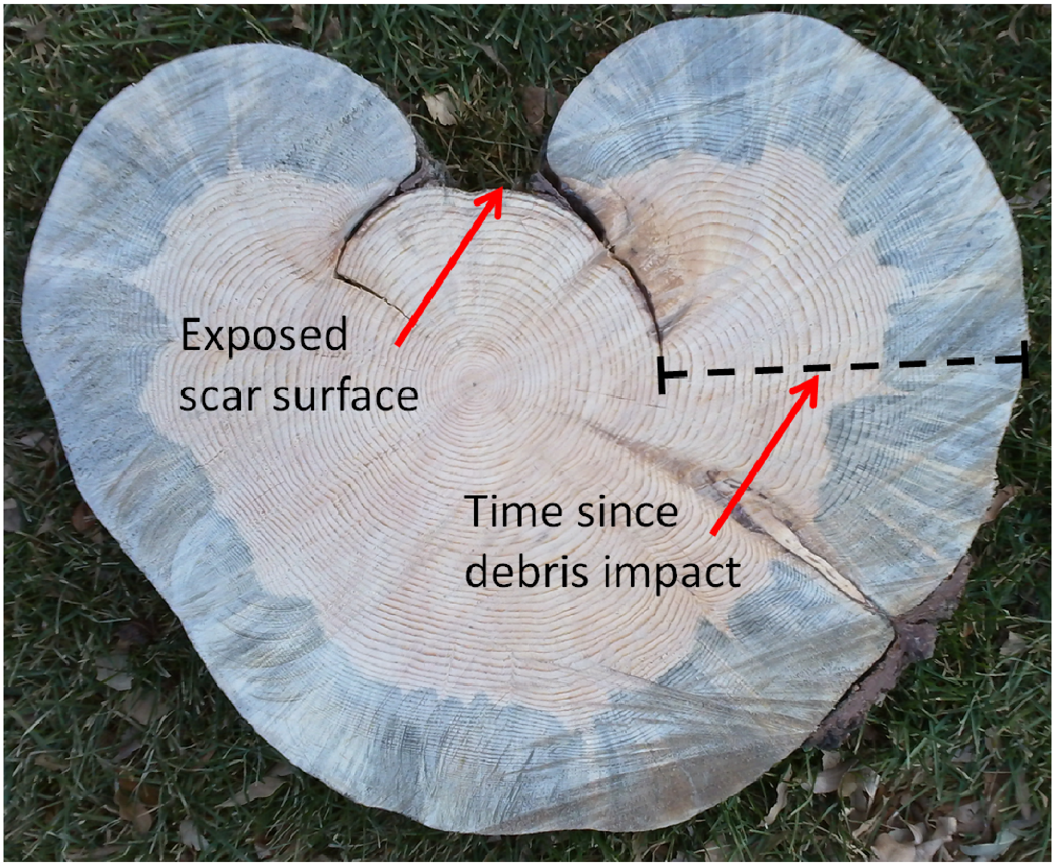

Figure 5: A scar sample collected with a chainsaw from a berm along Sawmill Creek. The blue coloration on the outer portion of the wood is a result of pine beetle infestation.

Tree cores and scar samples were processed in the USGS dendrochronology lab at the Natural Resources Research Center in Fort Collins, CO. Tree cores were mounted on routed 1.25 cm by 2 cm lengths of wood, while scar samples were mounted on 2.5 cm cm by 10 cm blocks, in each case to provide stability while sanding. Samples were then clamped down and sanded with a handheld orbit sander using three levels of increasingly finer grain until a flat, smooth surface was attained. Tree rings were counted and measured using a Velmex microscope setup in the USGS dendrochronology lab.

Ring widths were compared to nearby existing chronologies from the National Climatic Data Center's International Tree-Ring Data Bank (ITRDB), as well as a site-specific chronology developed from the tree cores sampled in this study. Cores were used for the chronology because: they record a longer growth record in this case; they are presumably less significantly disturbed than scarred trees; and they also have less potential for providing a precise age than scarred trees, thus making it advantageous to use the cores to more accurately date the scar samples. The computer program Arstan was used to normalize and detrend individual samples with first a negative exponential curve and then a cubic spline, as suggested in Cook and Holmes's Arstan guide (1986). The resulting ring width indices were cross-dated based on years of very low growth using skeleton plots, according to Stokes and Smiley (1996), and shifted where appropriate. The finalized individual chronologies were then averaged to create a representative chronology for the study area. Ring width series from scar samples were checked against the representative chronology using visual comparison and the Cofecha software to improve dating accuracy. Determination of years of debris flow occurrence was based on evidence from multiple scars and cores, with the exception of the debris flow along Sawmill Creek from which only one scar sample was available.

The representative ring width chronology was compared to local records of snowpack and discharge to evaluate climatic trends. Snow course sites at Grand Lake and Long Draw Reservoir (National Park Service, n.d.), with continuous records from 1949 and 1971, respectively, were averaged for the comparison. Annual peak discharges at the Baker Gulch gage from 1953 were also used. In addition, debris flow ages were overlain on both the snowpack and discharge records to analyze the role of those factors in contributing to debris flow initiation.

Rock type and degree of hydrothermal alteration were mapped to analyze the roles of source rock strength and weathering characteristics in controlling debris flow occurrence. A lithology layer from the USGS Mineral Resources Online Spatial Data website was imported into ArcMap, while zones of hydrothermal alteration were mapped using field observations and information from Dr. John Ridley (Colorado State University, pers. comm., 2012). Additional basin characteristics were evaluated remotely in ArcGIS. Slope of each contributing basin, as defined by the beginning of debris flow deposition, was calculated using the Spatial Analysis tools and averaged for use in statistics. Basin area was also calculated, with the expectation that larger areas might provide more weathered surface material and therefore have potential for larger debris flow volumes. This expectation is supported by a study from the Oregon Coast Range which attributed greater debris flow activity of basins with larger drainage area to the availability of more potential source areas (May and Gresswell, 2004).

Multivariate regression was used to compare debris flow volumes to basin characteristics. The strength of the statistical analysis was limited due to the small sample size of only 10 distinct sites of deposition. A further complication is the uncertainty of what proportion of the volume of deposition at a site should be attributed to a specific debris flow. The necessary approach is, therefore, to consider total debris flow deposition at each site and ignore the potential temporal changes in debris flow frequency and magnitude. Given these limitations, the aim of this section is to achieve a qualitative understanding of which variables best predict debris flow volume at the study site, rather than to develop quantitative relationships.

Assumptions of normality, linearity, and homoscedasticity were addressed to test the validity of using multivariate regression. Normality was evaluated using histograms and normal quantile plots for each variable. Quantile-quantile plots are a comparison of the quantiles, or percentiles, of two distributions that graphically demonstrate dissimilarities in the distributions (Wang and Bushman, 1998). Normal quantile plots are a special case of quantile-quantile plots in which the observed quantile values of a distribution are plotted against the theoretical quantiles from a standard normal distribution (Wang and Bushman, 1998). Normal quantile plots therefore provide a simple graphical test of normality, as nonlinearity represents deviation of the observed values from the standard normal distribution.

The histogram and normal quantile plot for volume show strong non-normality (Figure 6 a, b), with most of the data points concentrated at low values. After logarithmic transformation, the volumes were much more normally distributed (Figure 6c, d). The logarithmically transformed values are used

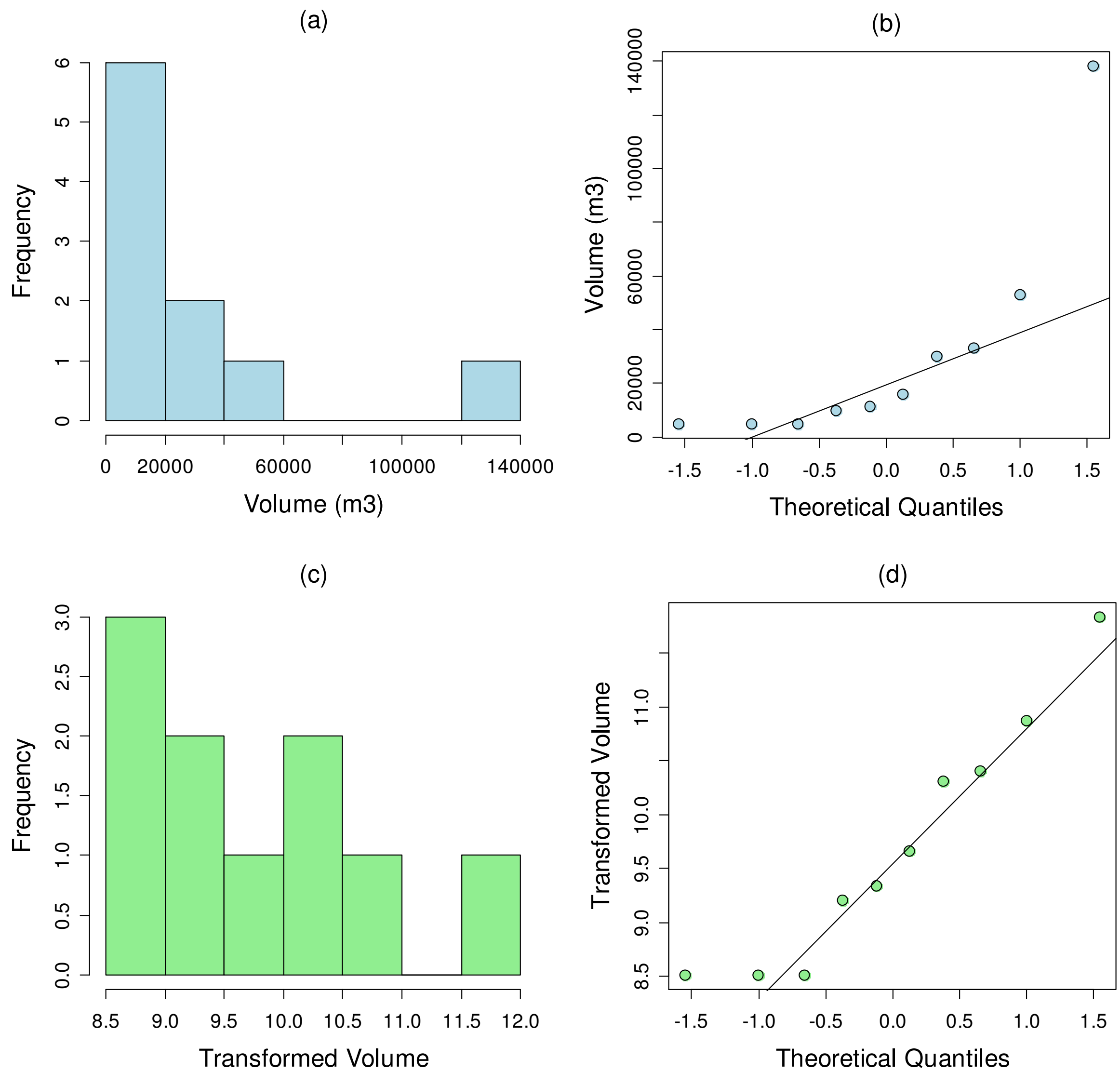

Figure 6: Plots testing normality for debris flow volumes: (a) histogram before transformation, (b) Q-Q plot before transformation, (c) log-transformed histogram, and (d) log-transformed Q-Q plot. The logarithmic transformation results in a more normal distribution for the volume series.

for the remainder of the statistical analysis as their approximate normality makes them more appropriate for multivariate regression.

Similarly, the normality of the basin areas was improved using a square root transformation (Figure 7), and the transformed values were carried forward for the remainder of the analysis. Slopes were already normally distributed, while the variables 1) presence of the Grand Ditch and 2) hydrothermal alteration were represented categorically.

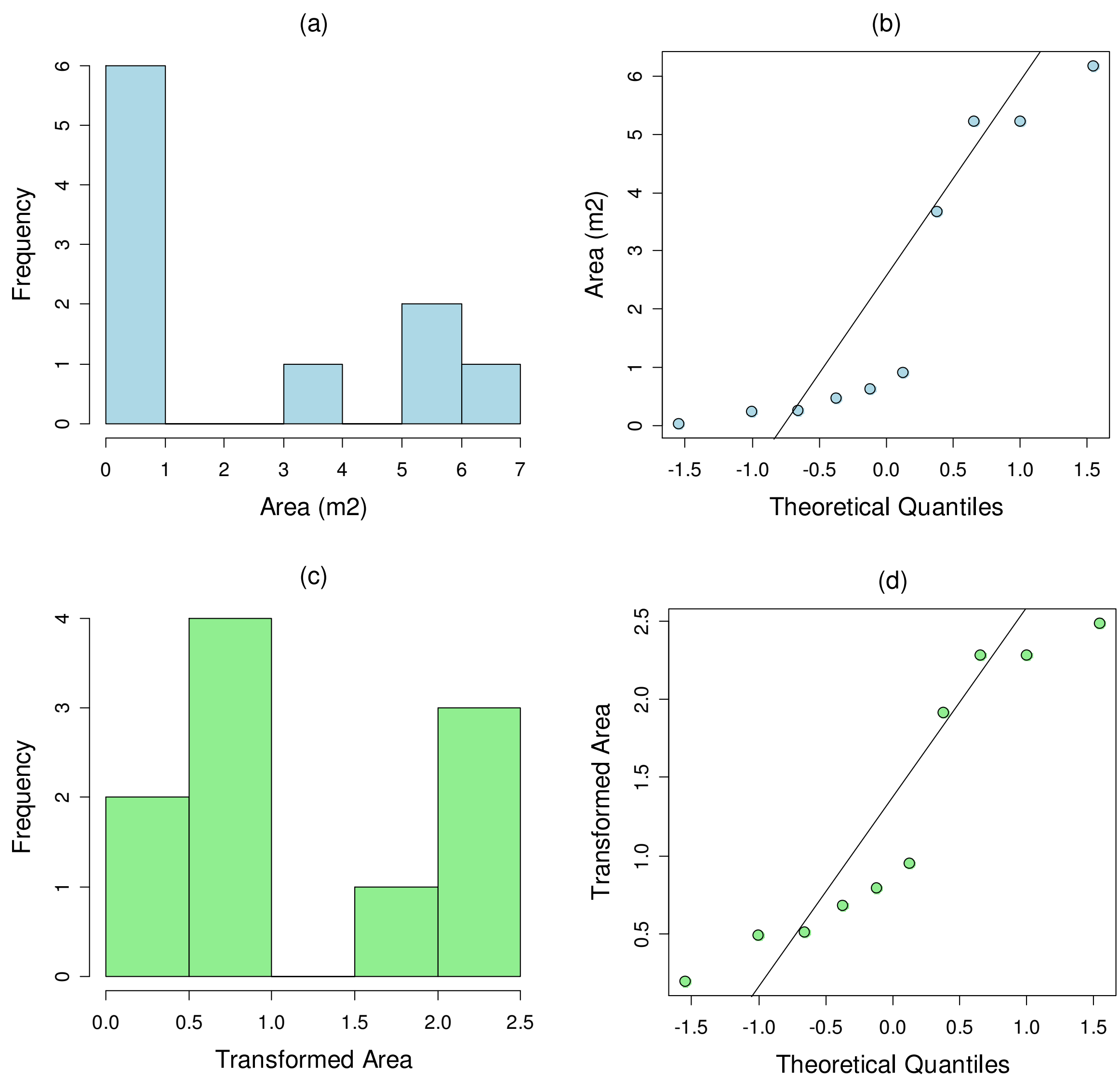

Figure 7: Plots testing normality for basin areas: (a) histogram before transformation, (b) Q-Q plot before transformation, (c) square-root-transformed histogram, and (d) square-root-transformed Q-Q plot. Square-root transformation results in a slightly more normal distribution of areas.

The linear dependence of the independent variable on the dependent variables was tested using bivariate scatter plots of log-volume versus slope and square-root-area (Grand Ditch and hydrothermal alteration were excluded due to being categorical). The resulting plots have a large amount of scatter (Figure 8), but linearity is moderately satisfied.

Homoscedasticity was tested using residual plots of the independent variables, where uniform distribution of residuals indicates equality of variance. Residual plots for slope and area show fairly

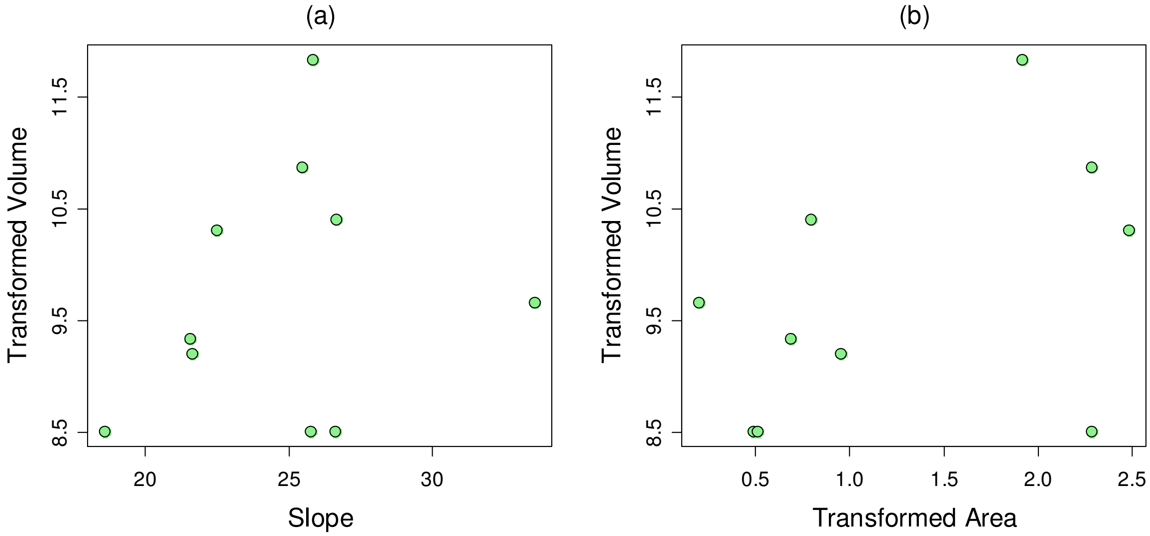

Figure 8: Scatter plots testing linear dependence of log-transformed volume on (a) slope and (b) square-root-transformed area. Concentration of points about the line x = y indicates linearity.

equal variance; the categorical variables were once again excluded (Figure 9). After concluding that the assumptions of normality, linearity, and homoscedasticity were reasonably well met, multivariate regression was performed on debris flow volume as a function of mean slope, basin area, presence of the Grand Ditch, and presence of hydrothermal alteration.

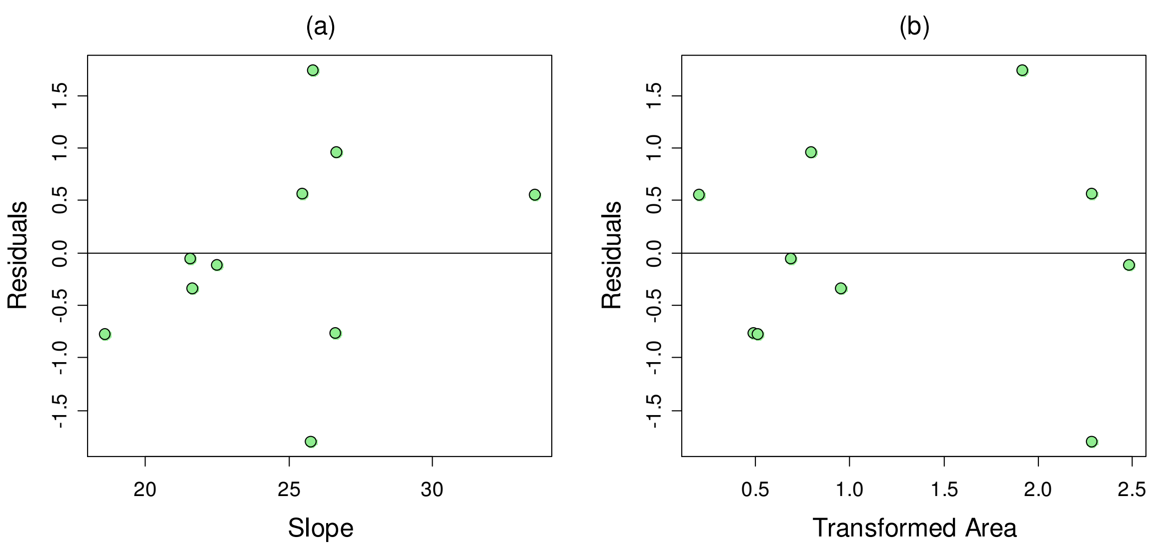

Figure 9: Residual plots testing equality of variance for slope and square-root-transformed area. An even distribution of residuals about the line y = 0 indicates homoscedasticity.

3. Results

3.1 Debris Flow Mapping

Nineteen mappable debris flows at ten sites were located within the survey area. Six of these sites, with 11 age-constrained debris flows, are on the west side of the Colorado River valley, while the remaining four sites are on the east side of the valley. Deposition along the active channel of the Colorado River is observed from only three sites on the west side (Specimen Creek, Lady Creek, and Lulu Creek) and one site on the east side (Little Yellow), suggesting that that these areas have had more significant recent debris flow activity. Almost all deposition occurred within 100 m elevation and 400 m perpendicular distance of the Colorado River, reflecting the more gradual hillslopes along the valley bottom. Each site is described below, starting with the west side at the upstream end of the study area, with the site abbreviation and the valley side shown in parentheses. Some relevant basin characteristics are given for both the entire basin and the basin below the Grand Ditch (btGD), as the latter may be more relevant in cases where debris flows originate from the Grand Ditch (Table 2).

The deposit on an unnamed tributary across from Specimen Creek (SC, west) (Figure 10) appears to originate from the Grand Ditch. Remnants of the debris flow are present both just below the ditch, where channel scour and a small area of deposition and even-aged stand growth are visible, as well as along the Colorado River. The drainage area of the basin is 0.91 km^2 (.30 km^2 btGD) and mean slope is 39.7% (29.1% btGD). Debris flow clasts here have minor lichen growth (ordinal value of '2'), suggesting that the majority of deposition occurred recently. Both the tributary channel and the nearby downstream reaches of the Colorado River are highly confined, resulting in limited preserved deposition.

The Lady Creek site (LC, west) (Figure 10) is similar to that across from Specimen Creek in that it also appears to originate from the Grand Ditch, with evidence of scour and deposition fairly high along the channel. Deposits are again sparse and mainly preserved along the Colorado River, due to the steep

Table 2: Basin characteristics for study sites with debris flow deposits that reached the Colorado River valley.

	Site	Basin Area (km^2)	Mean Slope (%)	Area btGD (km^2)	Slope btGD (%)
West	Big Dutch Cr.	5.22	47.6	0.35	33.9
	Lady Cr.	0.47	39.5	0.17	23.7
	Lulu Cr.	6.17	41.4	0.71	23.6
	Sawmill Cr.	5.22	48.3	0.48	22.9
	Misc. West	0.26	33.7	0.13	29.9
	Specimen Cr.	0.91	39.7	0.30	29.1
East	Little Yellow	0.04	66.4	N/A	N/A
	Ellen's Trib	0.63	50.2	N/A	N/A
	Crater Cr.	3.67	48.4	N/A	N/A
	Misc. East	0.24	50.1	N/A	N/A

gradient and confinement of both the tributary and the Colorado River. The drainage area is 0.47 km^2 (0.17 km^2 btGD) and mean slope is 39.5% (23.7% btGD). Lichen growth is moderately well developed (ordinal value of '3') on coarse clasts here, suggesting that the main slope failure occurred earlier than that across from Specimen Creek. Distinctive material from this site is also observed much further downstream, indicating that the corresponding debris flow was particularly large.

Lulu Creek (LU, west) (Figure 10) is dominated by the dramatic after-effects of the 2003 debris flow from the Grand Ditch, including unconsolidated sediment berms up to 2 m high, abundant downed or scarred trees, and altered channel position and morphology. Coarse sediment is profuse, extending down to the Lulu City wetland on the Colorado River, and the wetland itself remains buried in fine sediment. Hydrothermally altered rhyolitic tuff is a major component of the 2003 coarse sediment, which itself is prone to crumbling and in-situ degradation. Paired scars on several mature trees on both sides of Lulu Creek just above its junction with the Colorado River indicate that at least one older debris flow has occurred there since completion of the Grand Ditch. No corresponding sediment deposits are distinguishable, and a rain-on-snow flood may be another possible explanation for these scars. However, rain-on-snow events tend to be minor at elevations above 2450 meters in this part of the

Rocky Mountains (Nolan Doesken, Colorado State Climatologist, pers. comm., 2012). The drainage area of the basin is 6.17 km^2 (0.71 km^2 btGD) and mean slope is 41.4% (23.6% btGD).

Exposed deposition at the Sawmill Creek (SM, west) (Figure 10) is limited due to valley confinement, but there are a few fairly well defined berms of debris flow material roughly 1 m high on both sides of the channel. There also appears to be some debris flow deposition from Sawmill Creek at the edge of the Colorado River valley bottom, but this is mostly covered by sediment from the 2003 Lulu Creek debris flow. One old, partially healed tree scar was sampled from one of the berms, and another similar scar was located but not sampled. Thick vegetation and lichen growth (ordinal value of '4') suggest that this site has been less active than those to the north. The drainage area of the basin is 5.22 km^2 (.48 km^2 btGD) and mean slope is 48.3% (22.9% btGD).

Deposition at the Miscellaneous West site (MW, west) (Figure 10) occurs on the western hillslope between Sawmill Creek and Big Dutch Creek and is characterized by a lack of well defined major drainage. Berms and scarred trees along small channels indicate minor debris flow activity, but it is unclear whether these deposits are dispersed from a single source or represent small individual slope failures. Lichen growth is low to moderate (ordinal value of '2'), the estimated drainage area is 0.26 km^2 (0.13 km^2 btGD) and the mean slope is 33.7% (29.9% btGD).

Big Dutch Creek (BD, west) (Figure 10) has a multithread channel pattern in the vicinity of the heaviest deposition, and it appears that debris flow activity may have played a factor in controlling this channel morphology. Typically only one or two of the up to four channel threads have active flow, and those with no flow are aggraded with debris flow material. Big Dutch Creek joins the Colorado River just below the end of Lulu City wetland, where the valley bottom once again narrows. Lichen growth is low to moderate (ordinal value of '2'), the estimated drainage area is 5.22 km^2 (.35 km^2 btGD) and the mean slope is 47.6% (33.9% btGD).

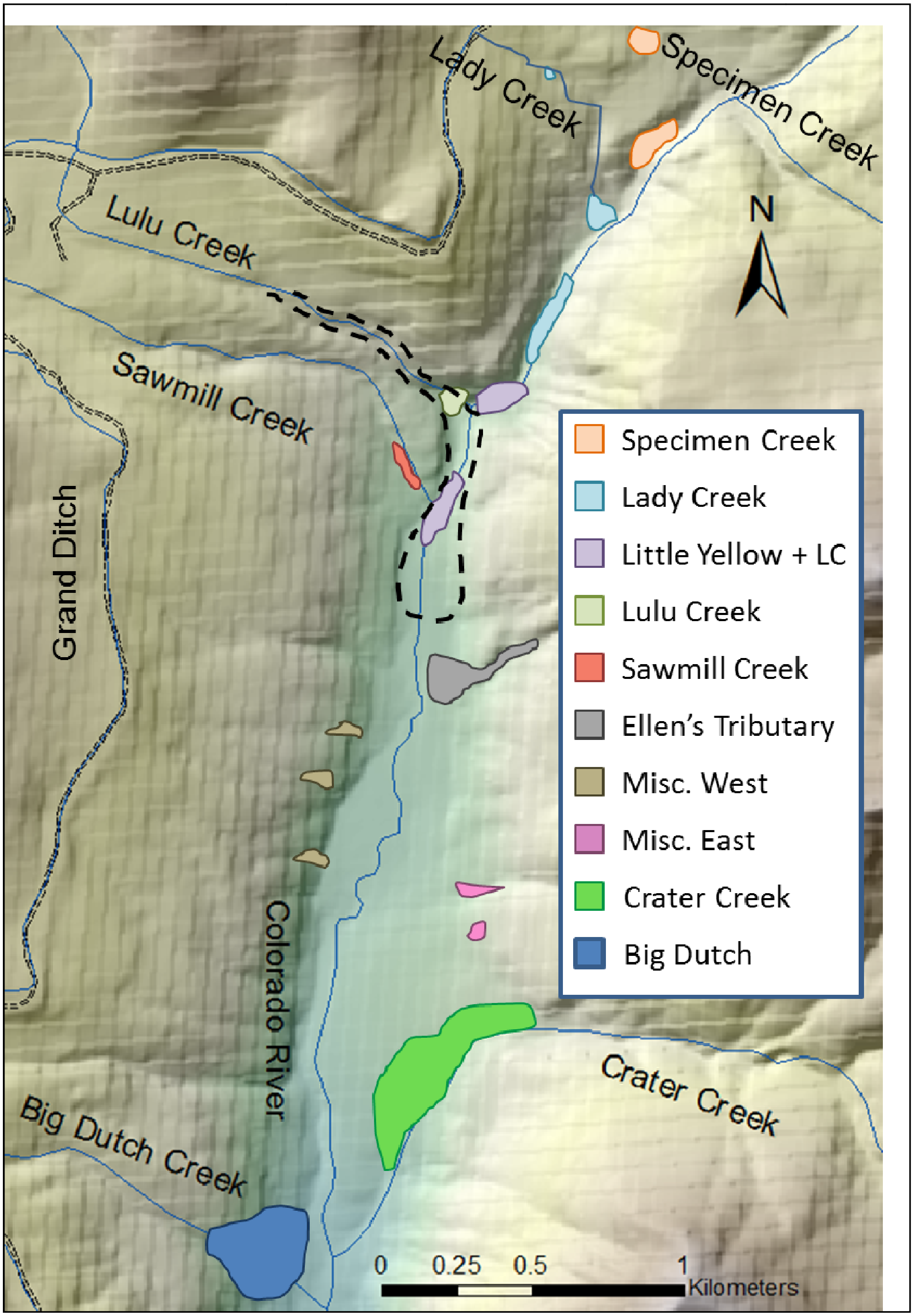

Figure 10: Mapped debris flow deposits extending to the valley floor along the Upper Colorado River. Approximate extent of deposition from the 2003 Grand Ditch debris flow along Lulu Creek is indicated with a dashed black line for comparison. The "Little Yellow + LC" label is used for locations where Little Yellow and Lady Creek deposits are both present.

Debris flow material at the Little Yellow site (LY, east) (Figure 10) originates from a steep hillslope on the east side of the Colorado River. The catchment is very small 0(.04 km^2) and too steep (66.4%) for consistent vegetation growth, making it the only entirely barren basin included in the study. Deposition is limited to open areas along the Colorado River, where it frequently overlies Lady Creek deposits. The downstream extent of deposition suggests that this was a relatively large debris flow. The Little Yellow debris flow is younger than that from Lady Creek, based on superposition and supported by sparse lichen growth (ordinal value of '2').

The depositional zone along Ellen's Tributary (ET, east) (Figure 10) has two distinct sections. Where the break in slope first occurs, roughly 0.5 km from the Colorado River, the channel is partially confined and the debris flow material is coarse but narrowly deposited. Within 0.25 km of the Colorado River, the slope decreases and the valley is unconfined, resulting in fan-like deposition of finer sediment. No deposition is observed along the active Colorado River, although this is unsurprising given the wide, flat valley bottom. Debris flow surfaces appear relatively inactive and lichen growth is moderate to heavy (ordinal value of '4'). The drainage area of the basin is 0.63 km^2 and the mean slope is 50.2%.

The Miscellaneous East site (ME, east) (Figure 10) includes the eastern hillslope between Ellen's Tributary and Crater Creek (the western side of Specimen Mountain), and exhibits similar characteristics to the Miscellaneous West site, although the deposits are more localized and the gradient is steeper. Lichen growth is moderate (ordinal value of '3'), the corresponding drainage area is 0.24 km^2 and the mean slope is 50.1%.

The Crater Creek site (CC, east) (Figure 10) has an expansive area of deposition, but minimal indication of recent debris flow activity. As with Ellen's Tributary, deposition can be divided into a steeper area of boulder and cobble sized clasts and a more gently sloping fan of finer sediment. The transition occurs near the position of the Poudre Pass trail, which is roughly 0.5 km from the Colorado River at that point. The fan is finely mantled with soil and grass, while the upper depositional area has well developed forest and lichen growth (ordinal value of '4'), suggesting that neither region has experienced significant recent disturbance. Where channel incision has occurred, debris flow material is observed to be up to 4 m deep. The drainage area of the basin is 3.67 km^2 and the mean slope is 48.4%.

3.2 Debris Flow Volume

Reported volumes represent an estimate of the total preserved deposition at a site based on field surveying and GIS interpolation. Volumes are minimum estimates of total debris-flow deposition, because of the potential for erosion of material following the debris flow, burial of deposited material below levels evident from stream cutbanks, and deposition upslope of the mapped area. Mapped surface area of debris flow deposits ranged from a few thousand m^2 (Miscellaneous East and Miscellaneous West) to approximately 85,000 m^2 (Crater Creek), while estimated volumes ranged from a few thousand m^3 (Miscellaneous East and Miscellaneous West) to 135,000 m^3 (Crater Creek) (Table 3).

Table 3: Debris flow deposit volumes for tributaries of the Colorado River. Volumes are surveyed estimates of the total preserved deposition. Because the majority of deposition at some sites appears to predate the tree-ring record presented here, based on lichen cover, forest maturity, and lack of deposits reaching the Colorado River, the reported volume may not reflect recent debris flow activity.

	Site	Volume (m^3)
West	Big Dutch Creek	53,000
	Lady Creek	11,000
	Lulu Creek	36,000
	Sawmill Creek	< 5000
	Miscellaneous West	< 5000
	Specimen Creek	10,000
East	Little Yellow	16,000
	Ellen's Tributary	33,000
	Crater Creek	138,000
	Miscellaneous East	< 5000

The smallest and more spatially fragmented of the deposits are labeled as 'Miscellaneous' as they were associated with small unnamed tributaries on poorly channelized hillslopes and are otherwise indistinctive. The mapped Lulu Creek deposit (Figure 10) is from the older debris flow, as the deposited sediment volume of the 2003 debris flow along Lulu Creek is already well constrained at 36,000 m^3 (Rubin et al., 2012). Since no deposition from the older potential Lulu Creek debris flow is visible, a minimum area of deposition was estimated based on the position of tree scars, while the approximate extent of the 2003 debris flow is shown for comparison (Table 3). The implications and caveats associated with these data are considered in the discussion.

3.3 Aerial Photography

Annotated aerial photographs for Lulu Creek, Crater Creek, Sawmill Creek, Lady Creek, Specimen Creek, and Big Dutch Creek are shown in Appendix A. The primary evidence of debris flows is the destruction or re-growth of trees on disturbed surfaces. Photographs of Lulu Creek (**Error! Reference source not found.**) just below the Grand Ditch from 1999 and 2007 show the change from nearly solid forest cover to a path of exposed ground caused by the 2003 debris flow. Lulu Creek provides a useful example from a recent event where the characteristics of the associated debris flow are known, and therefore allows for comparison with debris flow scars evident on older photographs. Removal or recovery of trees along Crater Creek (**Error! Reference source not found.**), Sawmill Creek (**Error! Reference source not found.**), Lady Creek (**Error! Reference source not found.**), Specimen Creek (**Error! Reference source not found.**), and Big Dutch Creek (Figure) confirm the occurrence of debris flows within the time periods constrained between or before images. Note that the Lulu Creek debris flow appears to most dramatically alter the landscape.

3.4 Debris Flow Chronology

The record of mapped debris flows extends back 89 years, with the oldest debris flow along Sawmill Creek in 1923 (Figure 11). The remaining 18 documented debris flows all took place in the past

65 years. The length of this record is limited by a combination of deposit mobilization or burial by the Colorado River and tree recovery. These dendrochronologic results are supported by previous tree

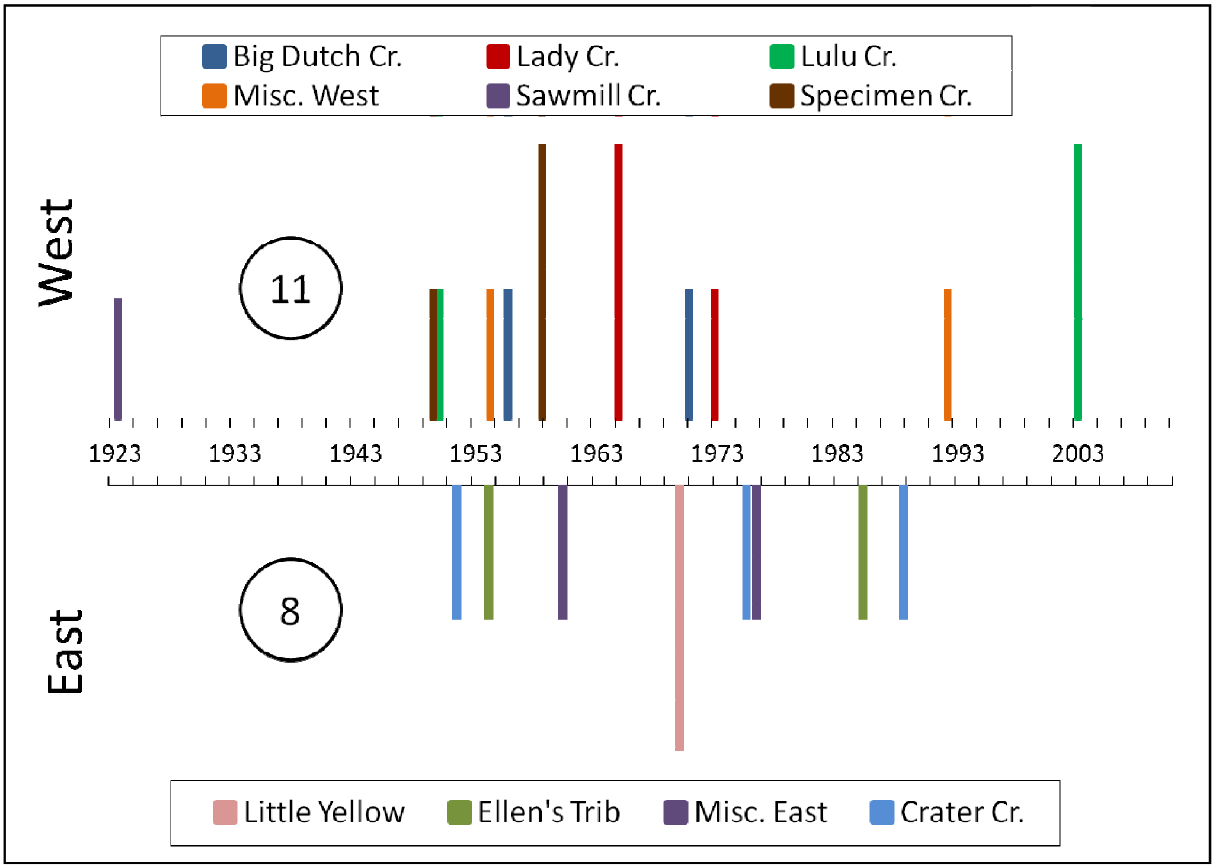

Figure 11: Timing of debris flow occurrence on the west (above axis) and east (below axis) sides of the Colorado River valley. Height of vertical bars distinguishes between 'large' debris flows (tall bars), that result in widespread deposition along the Colorado River, and 'small' debris flows (short bars), that do not. Circled numbers 11 and 8, on the west and east side of the Colorado River, indicate the total number of debris flows documented during this study.

cores collected by David Cooper of Colorado State University. Cooper (pers. comm., 2011) collected a total of 26 tree cores from three sites: (1) in a gully below the Grand Ditch along Lady Creek, (2) on the Colorado River above Lulu Creek, and (3) on the Colorado River below Lulu Creek. Tree establishment in the gully dated to the 1920's and 1960's, while tree establishment on the Colorado River was mostly in the 1960's (David Cooper, pers. comm., 2011). A 1920's debris flow along Lady Creek was not detected in this study, but is not infeasible. The 1960's tree establishment observed by Cooper matches the Lady Creek debris flow reported here and could also be related to the Specimen Creek and Little Yellow debris flows, which entered the Colorado River valley.

Debris flow ages were predominantly derived from tree scar samples, with core samples used to validate scar ages and develop the ring width chronology. Use of this technique under favorable circumstances is often able to achieve exact year accuracy or even seasonality of disturbance. In this case, ages are assumed to be correct to within plus or minus one year, due to slightly increased uncertainty associated with the inconsistency of ring growth after trees are impacted by debris flows. Based on these data, multiple debris flows occur within one year or consecutive years (to account for uncertainty) four times: 1949-50-51, 1954, 1970-71, and 1975-76, accounting for 10 of the 19 documented debris flows. Prior work in different basins suggests that coincidental occurrence of multiple debris flows reflects a site-wide influence on triggering mechanisms such as weather (Hupp et al., 1987). Measured and detrended tree ring width series from core and scar samples are displayed in Appendices B-E. Ring width series from this site do not correspond well with reported chronologies in the International Tree-Ring Data Bank from nearby sites in the Rocky Mountains (Appendix F).

3.5 Snowpack and Peak Flow

High levels of runoff and hillslope saturation resulting from either snowmelt or heavy rainfall are the most common triggering mechanism for debris flows (Rebetez et al., 1997). Considering both the snowpack and peak flow records for the study area gives a sense of the total water availability during the snowmelt season as well as the largest flow achieved through either snowmelt or intense summer thunderstorms. While thunderstorms are typically of secondary importance to snowmelt for causing high discharges at subalpine elevations of the Colorado Rocky Mountains, they may occur with local intensities that are sufficient to trigger debris flows (Jarrett and Costa, 1988). Historical snowpack data are available from USDA snow course sites at Grand Lake and Long Draw Reservoir, while discharge measurements are from the USGS Baker Gulch gage. Snow courses are sites of snow depth and snow water equivalent measurement maintained by the USDA's Natural Resources Conservation Service. Measurements are collected manually on a monthly basis during winter and spring months from wind-sheltered areas (United States Department of Agriculture, n.d.). The snow course and peak discharge correlate fairly well here in most years (Pearson's r = 0.53), as expected for a snowmelt-dominated hydrograph (Figure 12). Exceptions are likely due either to unusual temperature patterns or to water demands from the Grand Ditch. It is also possible to get a large peak discharge with a smaller-than-average snowpack if very warm temperatures occur early in the melt season. Regression results show a weak correlation of the ring width series with discharge (r = 0.31), while no correlation is observed with snowpack (r = 0.02) (Figure 12). Other factors such as temperature, light, and nutrient availability also influence the annual tree ring width. In addition, the trees sampled in this study were typically near active river channels and therefore may not react as clearly to moisture availability stresses.

Debris flow ages were compared to snow depth and discharge records (Figure 13). Cross-correlation between years of debris flow occurrence on (1) the east, (2) west, and (3) total on both sides of the valley with snowpack and with peak discharge indicates little correlation in most cases (Table 4).

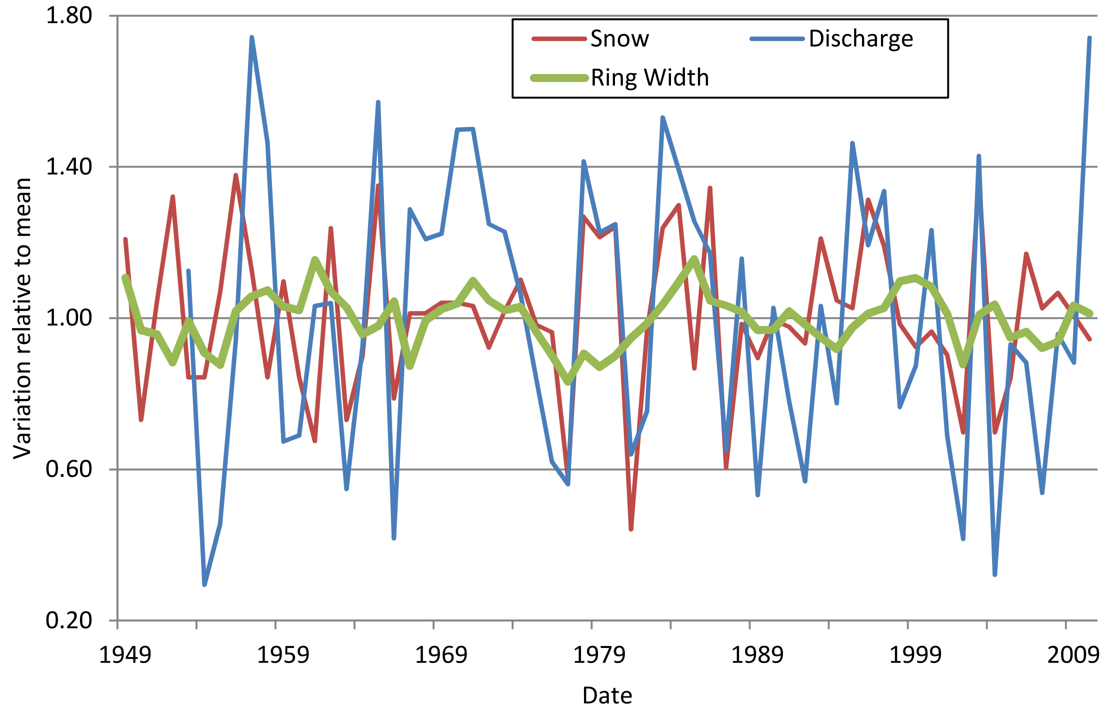

Figure 12: Annual snow depth records (averaged from Long Draw and Grand Lake Snowtel sites), annual peak discharge (from Baker Gulch USGS gage), and site-representative ring widths derived from tree core samples collected during the study.

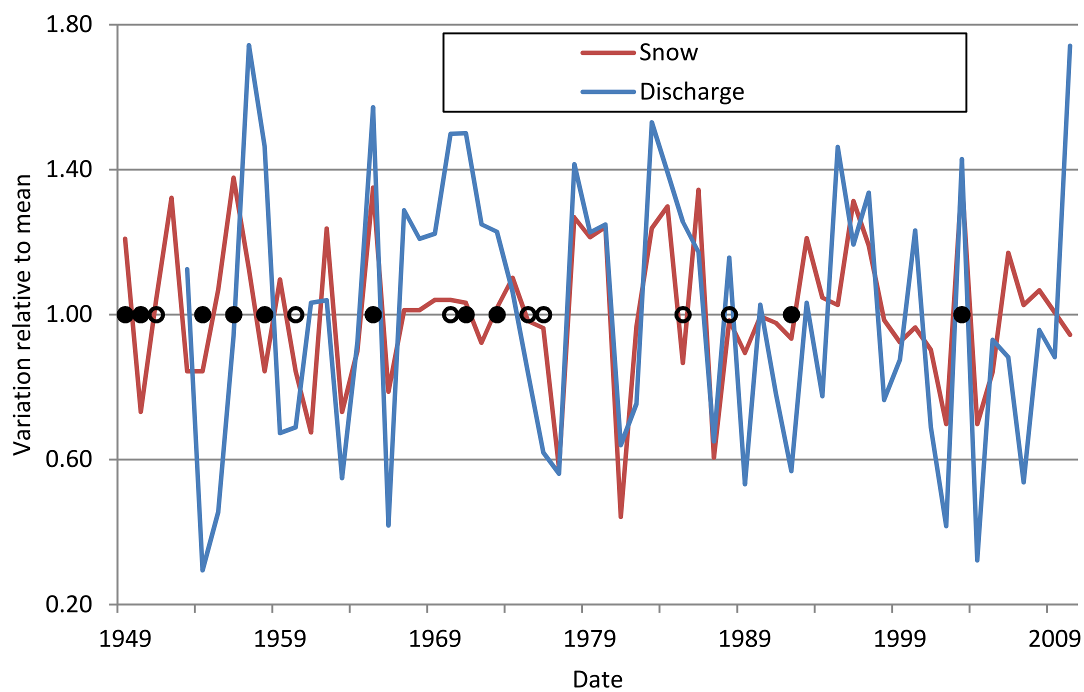

Figure 13: Years of debris flow occurrence on the east and west sides of the Colorado River valley overlain on snow depth and annual peak discharge records.

The strongest correlation, and the only one significant at the .05 level, is observed between debris flow occurrence on the west side of the valley and snowpack (r = 0.28). The apparent lack of a relationship between measures of wetness and debris flow occurrence may reflect the small magnitude

Table 4: Pearson's product moment correlation coefficients and corresponding p-values for debris flow records vs. snowpack and peak discharge.

Snowpack			Peak Discharge		
Debris flows	r	p	Debris flows	r	p
east	-0.13	0.33	east	0.09	0.49
west	0.28	0.03	west	0.08	0.56
total	0.16	0.23	total	0.07	0.60

of many of the debris flows represented in this chronology. When only the four largest recent debris flows that have significant deposition along the Colorado River are plotted (Figure 14), a much stronger association with discharge is observed, with debris flows only occurring in years with at least 140% of mean discharge. No such relationship is observed between the four large debris flows and snowpack, which is somewhat surprising. However, peak discharge may be a better proxy in this case for the

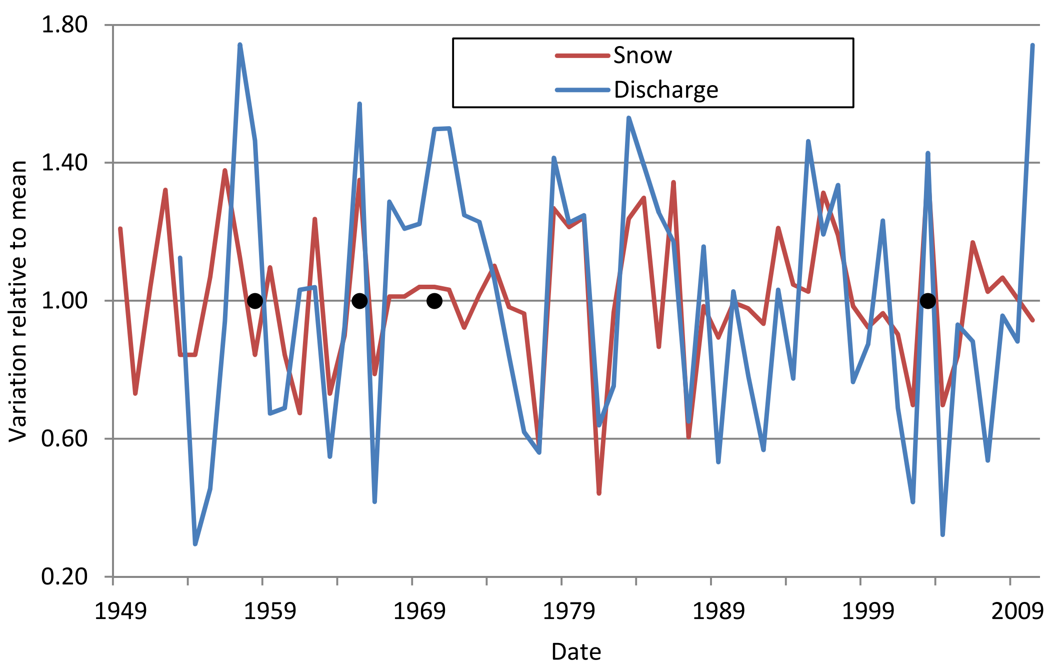

Figure 14: The four most significant recent debris flows along Specimen Creek (1958), Lady Creek (1965), Little Yellow (1970), and Lulu Creek (2003) overlain on snow depth and annual peak discharge records.

amount of moisture available to the hillslope during the wettest conditions, and could therefore better reflect the likelihood of slope failure and debris flow occurrence.

3.6 Fire History

Debris flows are also often associated with increased sediment mobility after fires. However, fires tend to be stand-replacing but infrequent in subalpine forests (Veblen et al., 1994), and there is a history of larger but less frequent fires on the west side of the continental divide as compared to the east in the southern Rocky Mountains (Sibold et al., 2006). Fire mapping in Rocky Mountain National Park has been carried out by Sibold et al. (2006) (Figure 15). The study site along the Upper Colorado

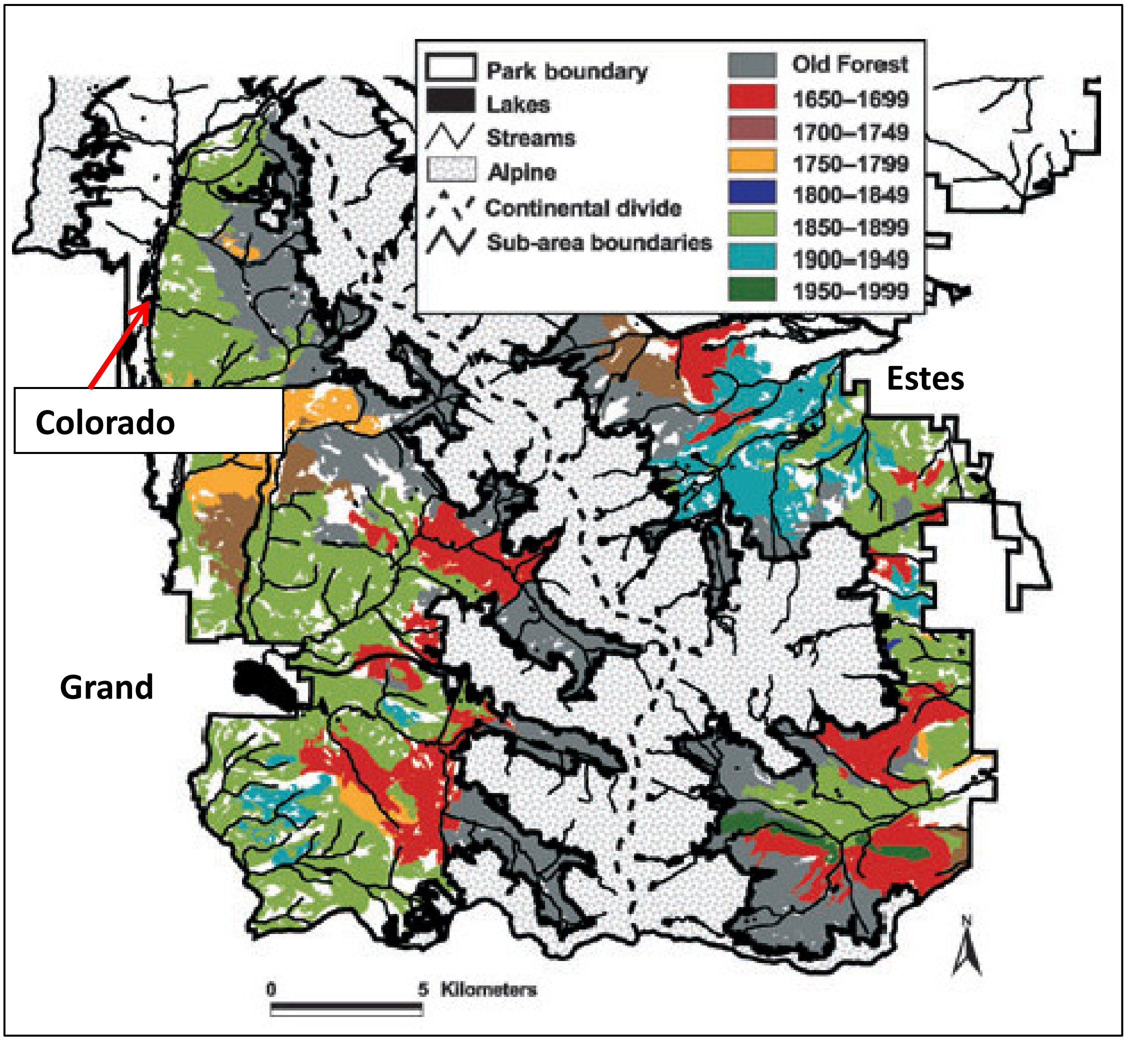

Figure 15: Fire history map of Rocky Mountain National Park, annotated from (Sibold et al., 2006). The study area is off the map but would be located above the top left corner.

River is off the top edge of the map and does not have a documented fire history. However, the most recent stand-replacing fire along nearby downstream areas of the Colorado River occurred between 1850 and 1899 (Sibold et al., 2006). In combination with a lack of observed evidence of major fire in recent history, this suggests that fire has not played a significant role in debris flow occurrence at this site over the last century. Additionally, soil pits in the Lulu City wetland found only a few scattered pieces of charcoal contained in sediments deposited over the past several thousand years (Rubin, 2010).

3.7 Regression Analysis

After concluding that the assumptions of normality, linearity, and homoscedasticity were reasonably well met, multivariate regression was performed on debris flow volume as a function of mean slope, basin area, presence of the Grand Ditch, and presence of hydrothermal alteration (Table 5).

Table 5: Results of multivariate regression for debris flow volume.

Regressor	p-value	
mean slope	0.011	Multiple R^2 = 0.711
basin area	0.561	
Grand Ditch	0.084	Adjusted R^2 = 0.546
alteration	0.154	

While limited by sample size, regression does suggest that mean slope (p = 0.011) and presence of the Grand Ditch (p = 0.084) are significant factors controlling debris flow volume, such that steeper slopes and presence of the ditch both correlate with larger volumes. These factors also explain 71% of the variance in debris flow volumes.

Analysis of best subsets for the regression reveals that two- and three-variable models can explain almost as much variance as the model with all four variables (Figure 16). In particular, the model

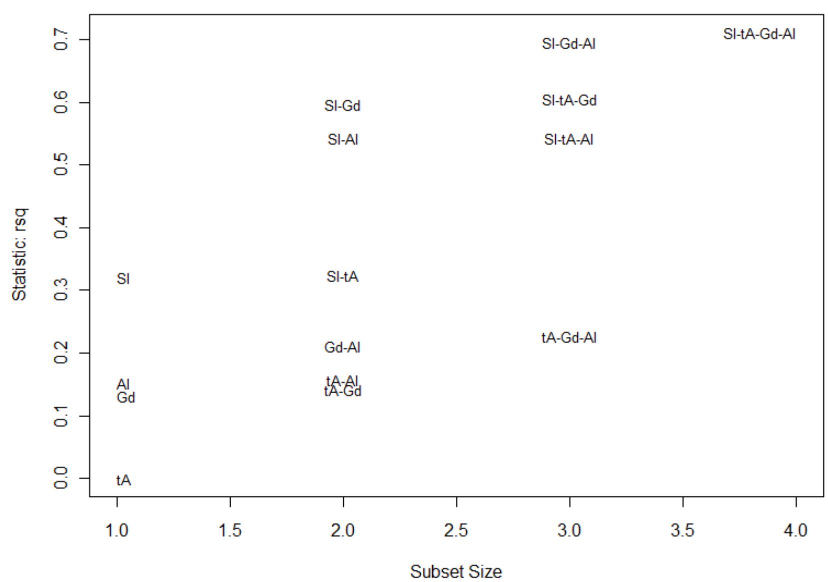

Figure 16: R-squared values for all possible subsets of the four variables used in the regression analysis.

including slope, Grand Ditch, and alteration explains 70% of the variance in debris flow volumes, while the model including just slope and the Grand Ditch explains 60% of the variance (Table 6).

Table 6: The three-variable model 'Sl-Gd-Al' and two-variable model 'Sl-Gd' which were selected through best subsets analysis.

Three-variable model		Two-variable model	
Regressor	p-value	Regressor	p-value
mean slope	0.007	mean slope	0.010
Grand Ditch	0.080	Grand Ditch	0.035
alteration	0.146		
Multiple R^2 = 0.696		Multiple R^2 = 0.597	
Adjusted R^2 = 0.582		Adjusted R^2 = 0.508	

4. Discussion

4.1 Role of the Grand Ditch

Anthropogenic disturbances are inevitable in places where humans interface with the environment. However, when these disturbances occur outside the historic range of variability - or range of environmental forms and processes that predate human use (Morgan et al., 1994) - dramatic changes in the landscape can occur (Rubin et al., 2012). A major aspect of understanding debris flow processes in the Colorado River headwaters is determining whether debris flows related to the Grand Ditch fall within the historical range of variability.

Along Lulu Creek, changes caused by the 2003 debris flow include up to tenfold increase in channel width, loss of step-pool morphology, and debris flow berms up to 2 m high (Rubin et al., 2012). Along the Colorado River, the large pulse of coarse sediment caused infilling and overbank deposits, but these processes and the associated transport-limited conditions are consistent with sedimentary records of debris flow deposition in the valley over the past 3,000 years (Rubin, 2010; Rubin et al., 2012). While none of the older sites of debris flow deposition are as visually evident as Lulu Creek, the recovery of channels and dispersion of debris flow material over time makes such a comparison of differently aged debris flows inaccurate. The tools provided by dendrogeomorphology and remote sensing, therefore, become critical for deciphering temporal changes in the debris flow regime.

The east side of the Colorado River valley is used as a proxy for pre-ditch conditions because the length of the dendrochronologic debris flow record does not extend prior to the installation of the Ditch. This design requires the assumption that hillslope aspect is not a key factor affecting debris flow processes. Solar insolation is comparable on both sides of the valley as the hillslopes face predominantly east and west, while the difference in sunlight is most significant between north- and south-facing slopes. Wind conditions may be unequal, but observations of vegetation and hillslope morphology suggest that aspect generally plays a minimal role. In the Front Range of the Colorado

Rocky Mountains, aspect-related differences in channel head location were most prominent at lower elevations, while aspect did not appear to impact hillslope topography at subalpine elevations (Henkle et al., 2011).

Initial comparison of frequencies and volumes of deposition shows only small differences between the east and west hillslopes. The west side has six sites of preserved debris flow deposition, with 11 age-constrained debris flows, while the east side has four sites and eight dated debris flows. Similarly, there is no readily apparent difference in volumes, with the largest volume of deposition occurring at the Crater Creek site on the east side of the valley. However, multiple pieces of evidence suggest that debris flow sites on the west side of the valley have had more significant recent activity. First, the only deposits currently visible along the main channel of the Colorado River are those from Specimen Creek, Lady Creek, Little Yellow, and the 2003 Lulu Creek debris flow. Of these, only Little Yellow is from the east side of the valley, and it has a steep catchment with hydrothermally altered rock. Recent, larger debris flows are more likely to be preserved than older or smaller events. The lack of debris flow material from the southern and eastern catchments therefore indicates that the northern portion of the study area – where the Grand Ditch coincides with hydrothermally altered rock – has recently been more prone to slope failure.

Aerial photography also supports this interpretation. The aerial photographs from before and after the 2003 debris flow along Lulu Creek show a level of channel and forest disturbance that is unmatched in images of any other tributaries in the study area over the past 75 years. While this can partially be attributed to improved imaging quality, it strongly suggests that the 2003 debris flow from the Grand Ditch was unusually large relative to other debris flows in the time period of human observation.

Forest growth provides additional evidence for inferring timing of debris flows. For example, the largest volume of deposition was observed along Crater Creek, along with a few tree scars located on berms. However, the advanced soil development and mature forest age are indicative of a relatively undisturbed environment. Well-developed forest structure, with a wide range of tree ages including some trees that have reached or are approaching old growth age (> 200 years), suggests that at least a few centuries have passed since major stand removal along Crater Creek. The dating range of this study is limited to evidence preserved in the dendrogeomorphic record if the past 90 years, so the ages of older debris flows could not be definitely constrained. Smaller mass movements have occurred recently along Crater Creek, as indicated by tree scars along berms, a small even-aged stand, and aerial photography, but not of sufficient quantity to account for the amount of debris flow material present.

The high volume of deposition along Crater Creek, as well as Big Dutch Creek and Ellen's Tributary, must therefore be attributed to larger, older debris flows. The cause for an earlier period of more intense debris flow activity is uncertain, but may be related to a shift in climate or to one or more catastrophic events. One viable explanation is the triggering of debris flows from glacial outburst floods during glacial retreat around 14,000 years ago (Rubin, 2010). This mechanism has been used to explain debris flows in the Canadian Rockies (Jackson Jr, 1979), the Alps (Chiarle et al., 2007), and other high mountainous regions (Kaab et al., 2005). While the topography in the upper drainages of tributaries in the Colorado River headwaters is not conducive to the formation of lakes, outburst floods down the main valley of the Colorado River could have caused instability by eroding toe deposits along side-slopes (Ellen Wohl, pers. comm., 2012).

The possible existence of an earlier period of more intense debris flow activity is supported by a study of sediments deposited in Sky Pond, an alpine lake in the Colorado Front Range (Menounos, 2000). Menounos (2000) documented 1-5 debris flows per century over 1600 years of record, significantly fewer than the 19 debris flows documented in the Colorado River headwaters over the last 90 years. However, the drainage area of the catchment that feeds Sky Pond (2 km^2) is also much smaller than the combined drainage area of the basins sampled in this study (23.8 km^2, 6.7 km^2 if drainage areas are limited to below the Grand Ditch). Menounos (2000) also interpreted heightened frequency and magnitude of debris flows during the period of regional climatic amelioration from 8000 – 4500 years BP. Elevated debris flow rates have also been reported in the High Tatra Mountains of South Poland during the Little Ice Age (Kotarba, 1992). Local factors may vary greatly between these sites, but the concept of phases of altered debris flow activity in relation to climate shifts is overarching.

Summation of the available evidence of debris flow activity in the study area indicates that the Grand Ditch has altered the natural regime of debris flow activity in the Colorado River headwaters. The comparable frequency of debris flows between the east (8) and west (11) sides of the Colorado River valley is outweighed by aerial photography, multivariate regression, and the origination from the Grand Ditch of three out of four large recent debris flows. These results demonstrate that the Grand Ditch has shifted the debris flow regime of the Colorado Headwaters toward more frequent occurrence of large debris flows.

4.2 Regional Debris Flow Rates

Another implication of the results of this study is the higher than expected rate of debris flows based on limited work on other subalpine sites in the region. Morphodynamic zonation based on active geomorphic processes and sediment transport rates has been qualitatively evaluated for the Colorado Front Range, which is underlain primarily by crystalline intrusive and metamorphic rocks (Caine, 1984). The subalpine forest zone is described as being the least geomorphically active, and having only 'slight' mass wasting activity, except infrequently after catastrophic events such as forest fires when hillslope erosion is elevated (Caine, 1984). Assuming that these inferences can be extrapolated to the west side of the Continental Divide, one would not expect debris flows to be an important geomorphic agent in this study area. The occurrence of at least 19 debris flows over the last century along tributaries in the Colorado River headwaters suggests that they may play a larger role in shaping hillslopes and transporting sediment in subalpine forests than previously thought. However, the majority of these debris flows appear to have been minor events that did not greatly alter the landscape. The exceptions are debris flows that took place across from Specimen Creek, along Lady Creek, at Little Yellow, and at Lulu Creek. All of these are in areas of hydrothermally altered rock and all but Little Yellow are subject to the influences of the Grand Ditch. The other large, older debris flow deposits may be associated with infrequent events such as deglaciation or wildfire, and therefore fit in with Caine's description of the subalpine zone in the Front Range of the Rocky Mountains. The Colorado River headwaters may represent an exception to the typical behavior of debris flows in subalpine areas due to the Grand Ditch and hydrothermally altered rhyolitic tuff.

4.3 Limitations

The results of this project were constrained by several limiting factors. First, the dendrochronologic record of debris flows along this portion of the Upper Colorado River is limited to the last century. The short length of this record can be attributed to three factors, including: (1) riparian areas in the Colorado River headwaters are dynamic and therefore trees are unlikely to persist to old-growth status (> 200 years), (2) logging for both the Lulu City mining camp and construction of the Grand Ditch removed much of the older forest, and (3) debris flow scars eventually heal over and are no longer readily visible on the outer surface of the tree, so trees that survived both of the previous fates may have been missed in sampling. This short record length adds to the difficulty of isolating the impact of the Grand Ditch on debris flow occurrence, as diversions began in the late 1890's.

Cross-dating is difficult due to the complacency of tree ring series at the study site. The usefulness of annual tree rings for dendrochronology is generally dependent on two properties of the climate and tree species including: (1) a single environmental factor such as precipitation or temperature must strongly limit growth, and (2) tree rings must reflect annual variation in this limiting factor (Stokes and Smiley, 1996). Ideally, the growth limiting factor should be consistent across a fairly large area so that tree ring records and nearby sites can be compared and compiled (Stokes and Smiley, 1996). Most of the trees sampled in this study were growing along channel margins, where evidence of debris flows is most often preserved. This led to greater complacency (less variation as controlling factors change) in ring widths of samples, because trees growing close to a river tend to experience less year-to-year variation in growth as precipitation becomes less of a limiting factor (Dudek et al., 1998). Growth of trees in the Colorado River headwaters is also probably limited by some combination of temperature, precipitation, and stand conditions that may shift yearly, making patterns in ring growth less apparent. Furthermore, tree ring chronologies from nearby sites (Milner Pass, Onahu Creek, and Cameron Pass) do not correspond well with each other or the representative site chronology developed in this study (Appendix F), which may reflect the sensitivity of ring growth to elevation, aspect, and other site conditions of trees in the region (Oberhuber, 2004). The determination of years of debris flow occurrence therefore included potential uncertainty both in the form of possible cross-dating inaccuracies and the judgment-based combination of scar and core ages, which are separated by a colonization time gap.

Differences in confinement of the Colorado River valley lead to a disparity in the preservation of debris flow deposits, with limited preservation along northern tributaries such as Specimen, Lulu, and Sawmill creeks, but relatively good preservation of debris flow deposit volumes along southern tributaries such as Big Dutch and Crater Creeks, where the Colorado River valley is up to 1000% wider than confined reaches. The role of valley width in controlling fan formation from debris flow deposits at tributary mouths has been previously recognized in the Oregon Coast Range (May and Gresswell, 2004). Without detailed sediment profiles and corresponding ages of deposit layers at each debris flow site, which have not been collected at this time, it is currently infeasible to separate volumes of deposition corresponding to a given time period. These differences in debris flow deposit preservation hampered the statistical analysis and the general picture of debris flow activity on the east and west sides of the

Colorado River valley. However, historical aerial photographs and comparison of deposit characteristics was sufficient to make inferences about the extent of debris flow activity within the last century.

Remobilization of debris flow sediment has the potential to cause additional channel change and either add or remove sedimentary signals from the dendrochronologic record. On July 8th, 2011, peak flow remobilized sediment deposited by the 2003 Grand Ditch debris flow, causing burial of a footbridge along the La Poudre Pass trail on the Colorado River, channel avulsion, as well as displacement of previously scarred trees and scarring of new trees. Events that are not true debris flows but are capable of scarring trees as well as destroying evidence of original debris flows have potential to complicate the debris flow chronology. Analysis of the snow pack and discharge data suggests that a similar remobilization event may have occurred on Lady Creek following the 1965 debris flow.

5. Conclusions

Dendrogeomorphic approaches can be effective tools for dating debris flows in the Rocky Mountains, but may be limited to recent time periods in highly disturbed areas. Dendrogeomorphology is unique in its ability to precisely determine the age of debris flows to within seasonal accuracy. In catchments where no historical records of debris flow activity are available or are limited, this is a particularly valuable resource for developing chronologies of disturbance. Dendrogeomorphic techniques are most effective when paired with evaluation of debris flow deposit characteristics, historical aerial photographs, and any other observations which may provide additional context.

At least 19 debris flows have occurred along the Upper Colorado River over the last century. This is considerably higher than typical predictions for levels of mass wasting activity in subalpine forests in the Colorado Rocky Mountains (Caine, 1984), or than documented in another alpine catchment on the east side of the Continental Divide (Menounos, 2000). However, the majority of these debris flows appear to be small based on aerial photographs and lack of deposition along the Colorado River. The few large debris flows that have definitively occurred here within the last century – at Specimen Creek, Lady Creek, Little Yellow, and Lulu Creek – are associated with the Grand Ditch and rhyolitic tuff that is weakened from hydrothermal alteration. The relative importance of the Grand Ditch versus hydrothermal alteration is difficult to distinguish, because both are present at most of the recent sites of large debris flow activity in the study area.

There is not a substantial difference in the frequency of total debris flows from the east (8) and west (11) sides of the Colorado River valley over the last century, but, as discussed above, most of these seem to be small mass movements. When considering only the largest recent debris flows, there is a readily apparent difference, with three of the four largest debris flows occurring on the west side of the valley. The amount of debris flow material stored on the east side of the valley can be attributed to older slope failures.

Snowpack and peak flow records show weak to no correlation with general debris flow occurrence over the last century. However, when the comparison is restricted to the four major recent debris flows along Specimen Creek, Lady Creek, Little Yellow, and Lulu Creek, a threshold of 140% of mean annual discharge is observed. Older large debris flows in the Colorado River headwaters may have a similar threshold, while smaller debris flows may be more sporadic. High snowpack and peak flow are therefore observed to correlate well with occurrence of major debris flows, especially from the Grand Ditch.

Likelihood of debris flow occurrence is augmented by steep slopes and hydrothermally altered rock, which are both common in the vicinity of the Grand Ditch. Although regression results (Table 5) don't indicate hydrothermal alteration as a controlling factor for debris flow occurrence, the recent large debris flows in areas of high alteration suggest that the second alternative hypothesis $H2_A$, that the spatial distribution of debris flows depends on the extent of hydrothermal alteration, is valid. Additionally, rock type and degree of alteration appear to be important factors affecting debris flow occurrence along nearby tributaries of the Colorado River that are not impacted by the Grand Ditch (Sara Rathburn, pers. comm., 2012), which may provide an important opportunity for future research.

The Grand Ditch has altered the natural regime of debris flow activity in the Colorado River headwaters. The first alternative hypothesis $H1_A$, that debris flows triggered from the Grand Ditch have higher frequency and magnitudes than naturally occurring debris flows, is supported by the results of multivariate regression (Table 5), aerial photography, and deposit characteristics. Before the construction of the Grand Ditch, infrequent large debris flows were likely associated with catastrophic changes such as deglaciation and stand-replacing fires, while more frequently occurring debris flows were small and probably did not reach the Colorado River in most cases. Since that time, large debris flows on at least three tributaries suggest a strong association with the Grand Ditch.

5.1 Future Work

One key aspect of future research will be extending the debris flow mapping from this study to nearby areas that are not affected by the Grand Ditch. Initial inspection of two catchments south of the Grand Ditch reveals multiple recent debris flows on Bowen Gulch (west side, no Ditch influence), and only a few small, very old debris flows on North Inlet (east side, no Ditch influence) (pers. comm. Sara Rathburn, 2012). These areas have similar igneous and metamorphic lithologies, but mineralization is much more prevalent on Bowen Gulch relative to North Inlet. Study of debris flows in these and other nearby catchments would help to distinguish the roles of the Grand Ditch, hydrothermal alteration, and aspect in controlling debris flow occurrence.

Another valuable addition to this work would be the collection of augered soil cores in areas of extensive debris flow deposition and use of appropriate soil dating techniques to constrain the ages of layers within these deposits. This would extend the debris flow chronology for the Colorado River headwaters and would provide more concrete evidence for the hypotheses presented here about the timing of deposition for major debris flows on the west versus east sides of the valley. Finally, thorough mapping and testing of hydrothermally altered rock in the region would be beneficial. Testing of rock properties may indicate how much more susceptible this variety of altered rock is to slope failure, while additional mapping would help bring attention to other sites where risk of slope failure is elevated.

5.2 Management Implications

The finding of this research that the Grand Ditch has altered the natural debris flow regime toward more frequent occurrence of debris flows large enough to reach the Colorado River suggests that an active management strategy for impacted areas may be appropriate. When the destruction of trees, alteration of channel morphology, and sediment load associated with debris flow are outside of the historical range of variability, the landscape, in particular the Lulu City wetland, may not be able to sufficiently recover from disturbance to maintain its natural functions. However, most options for directly counteracting the results of debris flows are expensive and would cause further disruption to the landscape. The preferred option based on this study is, therefore, to focus on minimizing the future impacts of the Grand Ditch on the Colorado River headwaters. This could include stabilizing vulnerable hillslopes and the Ditch itself to reduce the risk of another breach and resulting debris flow, as well as other initiatives such as more gradually adjusting headgates to provide more natural patterns of discharge. It may also become necessary to assist key areas of the Colorado River in recovering from the 2003 Lulu Creek debris flow. For example, elevated aggradation rates in the Lulu City wetland have caused parts of the wetland to fill in and the Colorado River itself to shift from its natural position on the valley floor (Rubin et al., 2012). Therefore, removal of sediment and realignment of the Colorado River may be desirable. However, there are abundant sources of sediment upstream from the exposed debris flow deposits, so efforts to forcibly adjust the form of the river may not be long-lasting unless they are combined with upstream mitigation and the aforementioned efforts to reduce future impacts of the Grand Ditch.

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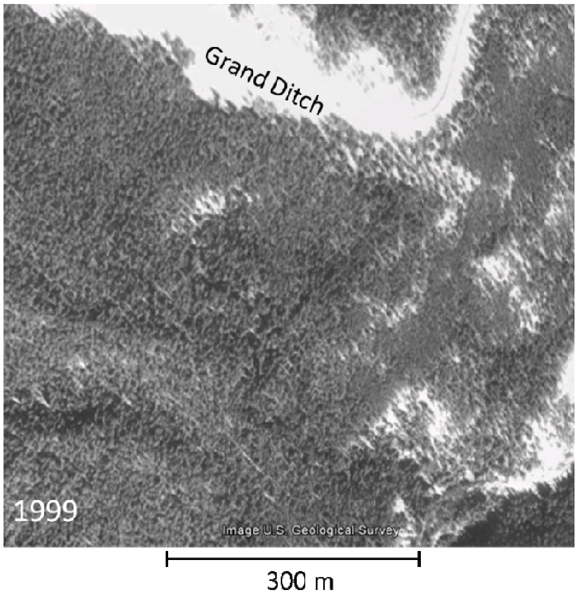
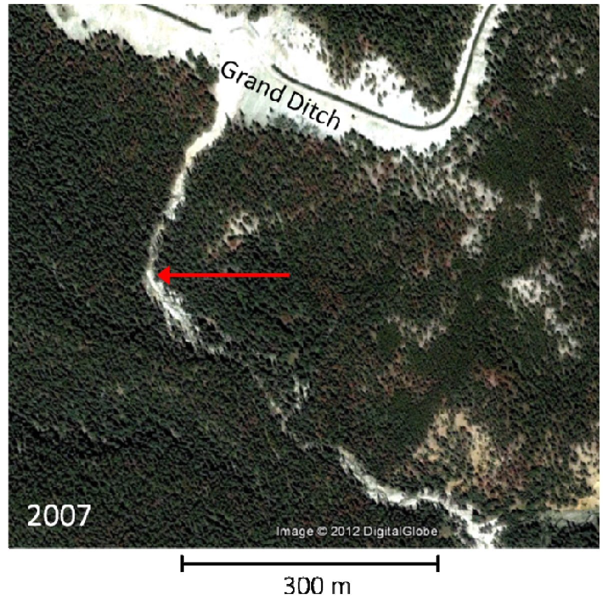
Appendix A: Aerial Photographs

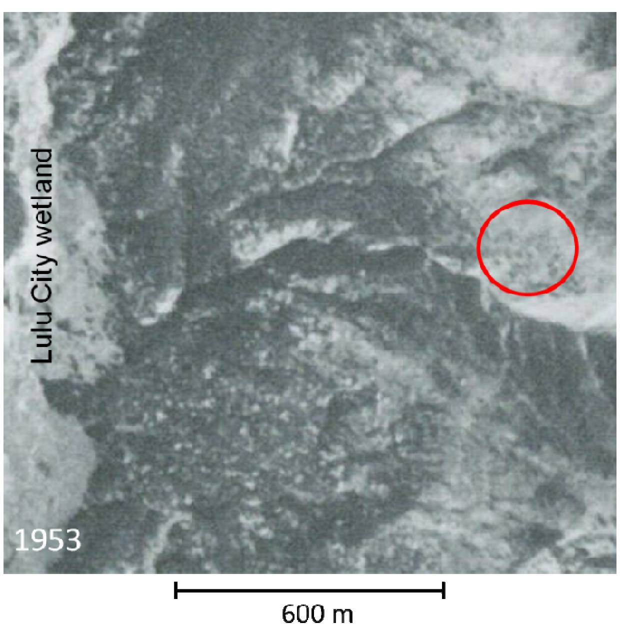
Lulu Creek

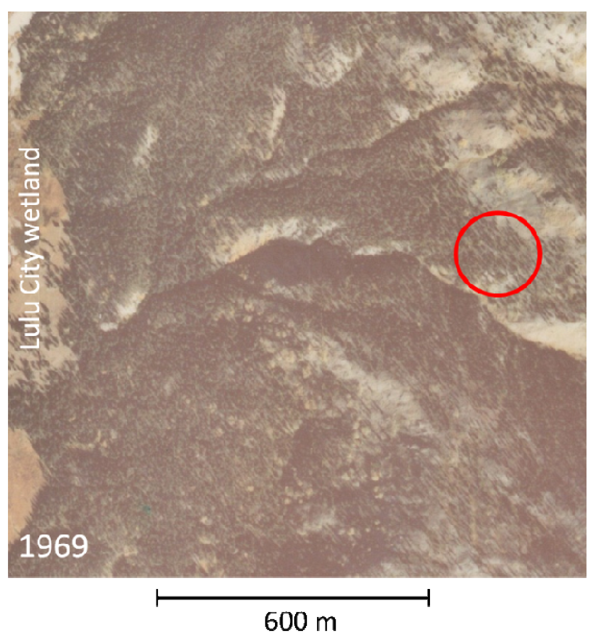




on the 2007 image

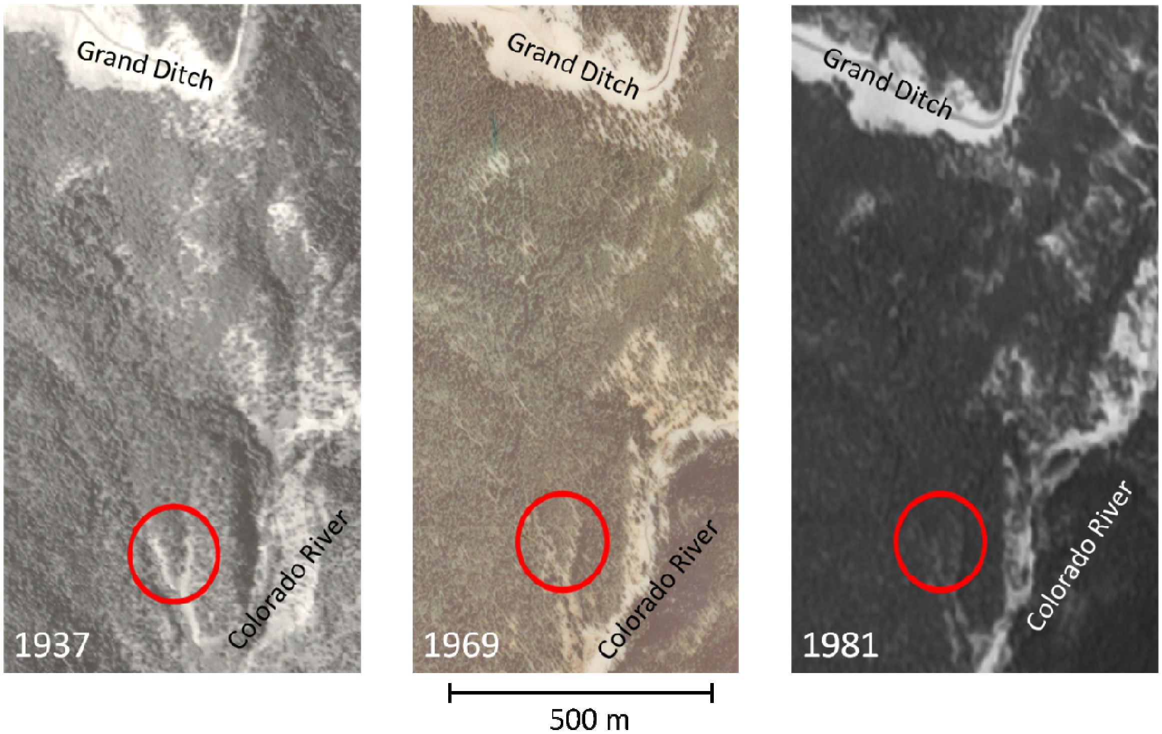
Crater Creek





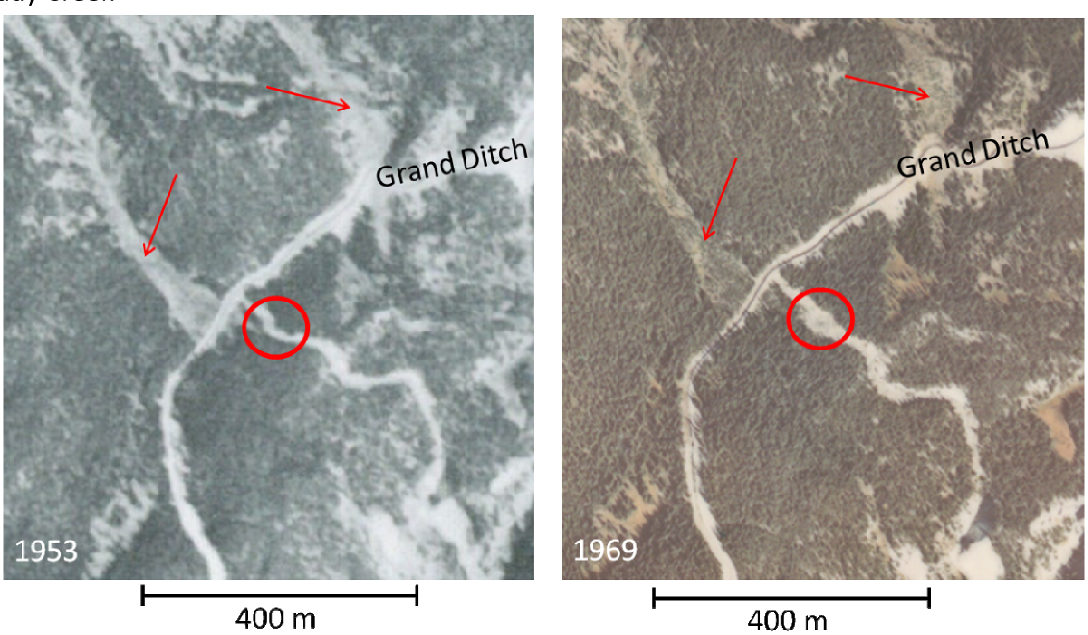
area between the 1953

Sawmill Creek



37, 1969, and
a disturbance

Lady Creek



ıve the
Creek

Across from Specimen Creek

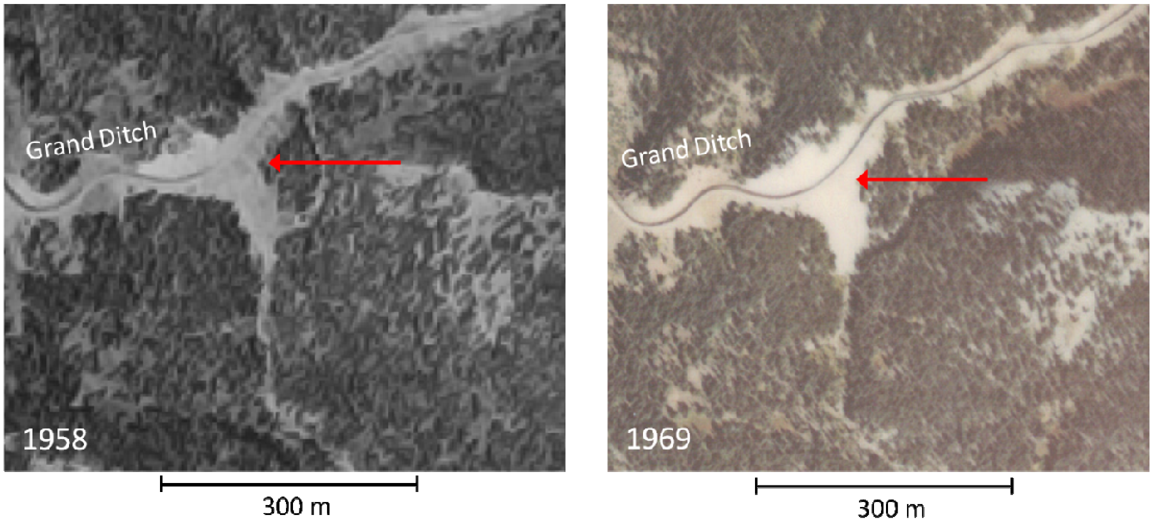


Figure 21: Aerial photographs of the tributary across from Specimen Creek from 1958, and 1969. Loss of trees marked by the red arrows indicates a disturbance between 1958 and 1969 (scale 1:10,000).

Big Dutch Creek

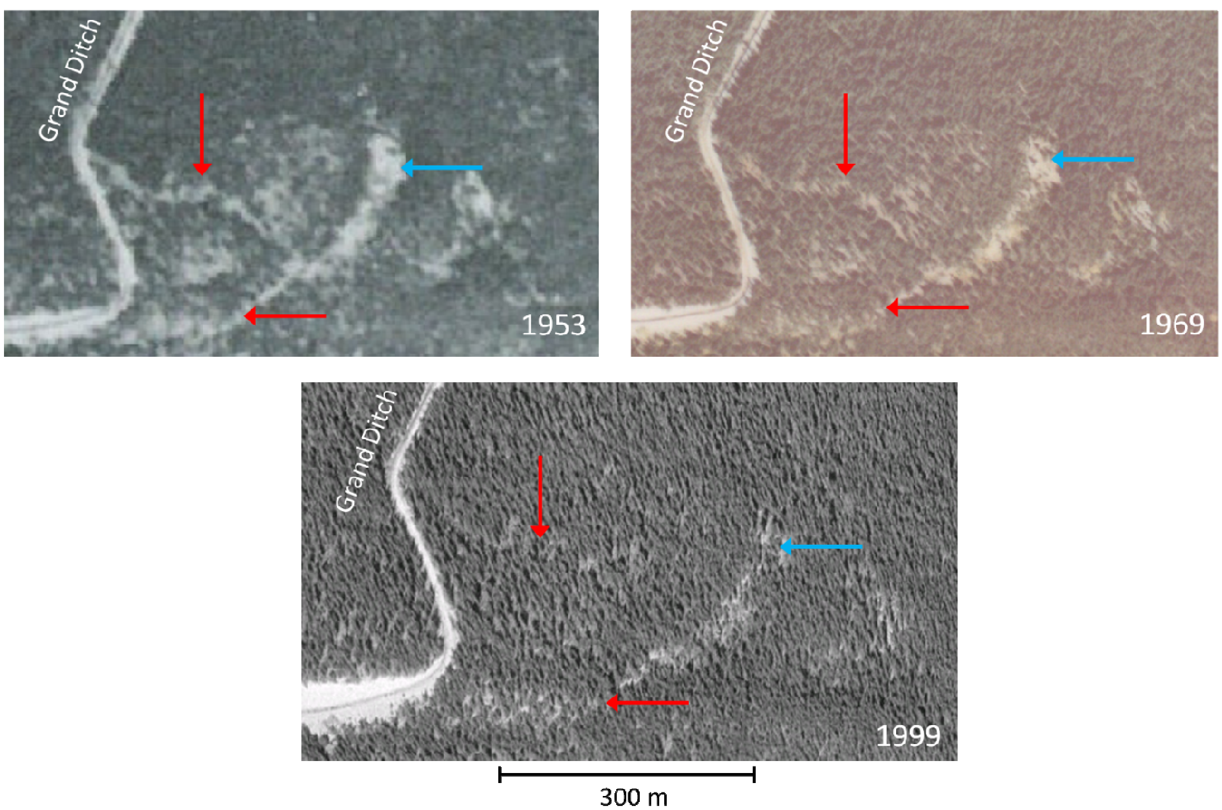


Figure 22: Aerial photographs of Big Dutch Creek below the Grand Ditch from 1953, 1969, and 1999. Gradual recovery of trees in paths indicated by the arrows indicate disturbance before 1953. The blue arrow signifies a disturbance that does not appear to be related to the Grand Ditch (scale 1:10,000).

Appendix B: Raw Tree Core Ring Widths

Table 7: Measured tree core ring widths presented in the Tucson format for tree ring dating. From left to right, each row contains the starting year for ring widths divided by decade followed by the up to ten ring width measurements in millimeters from that decade in chronologic order. The '999' measurement value indicates the end of the series.

4.1: Crater Creek, Fir, 428049 E, 4476217 N

1963	98	94	106	76	77	81	61			
1970	70	88	63	74	63	64	71	66	62	74
1980	75	72	77	60	60	47	51	49	64	57
1990	50	66	56	77	53	70	85	59	45	59
2000	51	63	48	46	41	57	60	47	58	61
2010	71	999								

4.2: Crater Creek, Fir, 428049 E, 4476217 N

1984	99	98	83	98	94	94				
1990	110	148	88	82	58	81	86	84	63	73
2000	61	48	43	61	46	55	83	56	71	67
2010	999									

6.1: unassociated, Fir, 428199 E, 4476698 N

1878	95	61								
1880	47	67	52	38	51	46	43	47	35	28
1890	46	35	31	44	47	51	51	55	62	58
1900	51	58	73	47	79	59	66	85	93	72
1910	74	77	63	62	91	91	86	82	70	85
1920	91	91	106	83	71	64	54	55	68	54
1930	71	56	57	80	71	59	75	73	84	69
1940	60	62	60	61	45	48	47	64	66	65
1950	69	64	64	79	63	71	92	99	108	94
1960	71	74	65	60	74	80	84	84	69	108
1970	127	138	124	102	107	99	89	94	128	138
1980	157	162	181	191	152	128	119	137	174	145
1990	92	114	108	128	180	157	155	157	143	123
2000	178	162	122	142	189	164	111	156	999	

6.2: unassociated, Pine, 428199 E, 4476698 N

1827	280	160	148							
1830	98	110	84	64	67	54	60	39	48	74
1840	96	122	112	94	59	40	45	58	96	74
1850	59	76	82	52	55	38	21	20	22	20
1860	28	88	98	94	66	44	43	37	41	52
1870	43	37	33	48	111	221	238	387	354	240
1880	268	115	99	96	91	136	103	121	76	146
1890	183	151	68	80	100	93	99	72	80	101
1900	114	84	92	98	62	90	101	80	94	80
1910	92	110	109	81	94	98	99	103	80	49
1920	81	61	59	84	113	112	124	136	128	106
1930	74	71	68	48	51	65	70	65	62	62
1940	67	72	63	64	74	58	47	52	53	63
1950	40	38	32	34	24	22	29	29	34	45
1960	43	45	47	50	36	32	29	28	28	27
1970	29	30	39	30	32	37	38	38	26	30
1980	36	43	43	48	62	79	67	87	70	59
1990	53	54	82	100	100	95	119	103	146	117
2000	76	69	55	87	69	86	154	131	999	

7.1: Ellen's Tributary, Fir, 428388 E, 4477749 N

1955	39	43	44	45	27					
1960	33	26	28	33	26	34	69	32	40	34
1970	35	37	42	20	26	39	28	33	31	20
1980	18	26	46	56	33	44	38	51	67	57

1990	58	45	51	43	41	43	59	38	71	64
2000	42	53	52	72	62	53	38	61	51	54
2010	61	999								

7.2: Ellen's Tributary, Fir, 428400 E, 4477751 N

1961	90	77	63	43	41	42	31	72	84	
1970	62	51	39	33	42	39	43	53	87	74
1980	61	47	58	40	41	48	70	66	60	55
1990	89	90	117	104	84	84	59	49	38	57
2000	58	49	41	72	78	82	86	83	62	56
2010	999									

8.1: Little Yellow, Pine, 428252 E, 4478554 N

1977	48	68	101							
1980	125	91	158	195	227	210	176	191	239	230
1990	230	218	213	265	203	226	242	229	234	263
2000	221	210	163	143	145	138	94	84	97	86
2010	49	999								

8.2: Little Yellow, Pine, 428252 E, 4478554 N

1979	205									
1980	140	152	181	190	218	238	191	296	289	356
1990	345	366	364	339	287	326	299	293	302	312
2000	305	309	232	256	255	301	253	247	254	262
2010	298	248	999							

10.1: Lady Creek, Pine, 428404 E, 4478638 N

1975	362	153	264	231	195					
1980	130	276	263	210	220	185	201	133	195	158
1990	155	174	184	141	159	199	190	181	232	224
2000	204	200	188	148	154	155	158	123	137	108
2010	999									

10.2: Lady Creek, Pine, 428404 E, 4478638 N

1973	116	136	152	191	258	183	249			
1980	203	286	205	205	211	215	259	235	235	225
1990	262	236	267	250	228	269	165	277	299	206
2000	255	222	214	167	206	175	150	145	136	143
2010	160	999								

10.3: Lady Creek, Fir, 428483 E, 4478877 N

1974	42	36	52	83	118	135				
1980	95	141	135	179	174	167	163	138	154	160
1990	161	183	190	233	234	261	234	255	190	241
2000	202	236	183	261	191	191	253	179	213	191
2010	999									

10.4: Lady Creek, Pine, 428483 E, 4478877 N

1973	579	435	137	84	113	118	169			
1980	191	393	318	298	372	843	540	344	354	231
1990	233	209	268	202	170	202	225	251	260	230
2000	211	149	154	162	327	241	257	239	266	297
2010	250	999								

10.4b: Lady Creek, Pine, 428483 E, 4478877 N

1970	212	168	166	271	130	193	88	94	138	133
1980	178	292	355	355	295	343	258	277	220	180
1990	211	188	251	202	180	247	206	261	275	223
2000	232	168	167	225	394	280	298	284	270	256
2010	226	999								

12.1: Lady Creek, Spruce, 428729 E, 4479203 N

1979	98									
1980	49	70	77	104	206	186	189	196	158	142
1990	176	179	218	225	232	219	277	155	215	321

2000	425	360	352	314	383	379	348	330	328	375
2010	381	999								

12.2: Lady Creek, Spruce, 428729 E, 4479203 N

1987	106	102	115							
1990	110	164	132	107	235	215	255	201	278	314
2000	328	313	280	157	213	187	193	193	168	175
2010	195	999								

12.3: Lady Creek, Spruce, 428729 E, 4479203 N

1979	23									
1980	18	19	17	63	106	130	116	83	85	65
1990	113	114	101	149	177	126	189	106	187	285
2000	277	249	268	205	236	231	134	181	239	255
2010	236	239	999							

12.4: Lady Creek, Fir, 428729 E, 4479203 N

1988	141	117								
1990	110	177	179	142	143	191	211	224	262	292
2000	245	265	211	220	262	232	240	257	253	243
2010	222	212	999							

12.5: Lady Creek, Fir, 428729 E, 4479203 N

1981	174	178	229	286	271	254	179	165	180	
1990	206	211	140	141	175	171	125	175	216	186
2000	201	176	140	133	169	127	100	86	72	48
2010	43	46	999							

14.1: Specimen Creek, Spruce, 428774 E, 4479284 N

1976	252	241	169	157						
1980	160	200	154	136	218	189	174	159	151	193
1990	179	165	159	182	190	181	186	200	205	173
2000	213	195	184	152	148	140	144	133	142	144
2010	132	999								

14.2: Specimen Creek, Spruce, 428774 E, 4479284 N

1966	75	67	73	98						
1970	95	60	74	86	64	79	64	97	118	119
1980	167	130	126	178	173	205	202	196	181	193
1990	160	175	177	191	180	239	260	306	229	259
2000	213	185	129	194	133	132	146	195	209	204
2010	999									

18.1: Miscellaneous West, Fir, 427885 E, 4477462 N

1959	34									
1960	40	63	42	39	52	56	52	39	51	39
1970	46	55	46	32	49	51	49	27	39	37
1980	27	23	26	39	37	42	41	57	55	45
1990	53	59	56	52	47	65	55	33	35	34
2000	39	44	42	48	47	45	52	71	66	92
2010	99	48	999							

18.2: Miscellaneous West, Spruce, 427885 E, 4477462 N

1946	30	34	46	38						
1950	39	43	40	43	54	42	42	44	34	56
1960	56	57	62	54	52	39	27	40	38	32
1970	33	52	51	28	42	49	46	26	20	22
1980	22	24	25	29	60	65	100	95	72	66
1990	73	80	70	74	56	69	83	110	100	95
2000	91	76	54	89	83	73	106	87	104	119
2010	999									

23.1: Specimen Creek, Fir, 427833 E, 4479969 N

1972	85	78	75	69	64	78	53	43		
1980	49	53	68	47	42	64	72	56	69	54

1990	60	52	42	55	39	55	49	71	55	71
2000	85	86	86	68	61	50	47	38	45	55
2010	66	63	999							

23.2: Specimen Creek, Spruce, 427833 E, 4479969 N

1973	53	78	81	70	54	65	70			
1980	88	74	61	54	82	86	64	120	98	110
1990	119	116	125	130	179	177	209	231	227	187
2000	137	111	120	122	117	117	192	190	181	188
2010	199	999								

24.1: Lady Creek, Pine, 428568 E, 4479611 N

1979	273									
1980	245	369	438	307	258	238	246	205	222	247
1990	239	235	243	224	211	223	210	179	182	164
2000	183	215	225	198	216	264	215	206	167	132
2010	102	117	999							

24.2: Lady Creek, Pine, 428568 E, 4479611 N

1975	171	116	83	83	61					
1980	96	109	146	131	153	141	140	127	105	100
1990	118	126	128	130	95	102	112	102	148	115
2000	116	95	81	112	114	94	77	64	66	132
2010	77	999								

32.1: Little Yellow, Pine, 428036 E, 4478050 N

1979	407									
1980	361	339	321	361	323	305	274	220	264	324
1990	314	325	182	164	208	306	276	365	435	331
2000	251	155	162	257	234	211	179	158	150	191
2010	208	204	999							

32.2: Little Yellow, Fir, 428036 E, 4478050 N

1973	317	400	290	219	238	238	244			
1980	296	394	369	323	321	327	333	327	415	457
1990	360	381	317	262	295	295	263	271	279	245
2000	247	225	179	197	182	185	148	181	139	177
2010	160	160	999							

33.1: Little Yellow, Pine, 428090 E, 4478190 N

1974	56	53	53	69	47	88				
1980	77	86	123	107	146	189	181	209	197	192
1990	170	138	176	113	113	151	151	163	166	170
2000	179	190	179	198	188	163	150	138	167	218
2010	149	999								

33.2: Little Yellow, Pine, 428090 E, 4478190 N

1977	72	64	81							
1980	61	86	100	131	166	204	214	225	189	202
1990	205	194	197	105	120	128	126	147	146	142
2000	220	196	183	207	207	186	182	141	142	201
2010	159	999								

33.3: Little Yellow, Pine, 428084 E, 4478195 N

1986	39	31	45	53						
1990	55	97	67	65	81	66	105	104	163	225
2000	254	242	289	233	235	195	161	111	129	137
2010	130	999								

33.4: Little Yellow, Pine, 428084 E, 4478195 N

1981	45	37	63	83	69	62	62	73	70	
1990	82	103	72	84	91	81	124	109	140	239
2000	272	247	305	245	237	193	155	115	127	130
2010	145	999								

33.5: Little Yellow, Spruce, 428100 E, 4478217 N

1968	48	59								
1970	54	81	82	80	80	68	49	48	79	70
1980	59	76	80	61	75	82	78	80	94	65
1990	57	63	78	70	67	54	86	60	89	89
2000	110	94	58	66	109	99	86	72	86	127
2010	152	999								

33.6: Little Yellow, Spruce, 428100 E, 4478217 N

1970	78	94	97	92	85	59	46	63	87	76
1980	63	55	68	69	73	86	82	73	97	59
1990	47	59	72	77	77	50	88	50	87	86
2000	96	90	61	58	101	83	96	74	82	118
2010	141	999								

33.7: Little Yellow, Spruce, 428094 E, 4478187 N

1983	102	172	160	169	143	165	149			
1990	169	188	205	173	174	184	203	231	206	214
2000	201	218	259	309	277	227	234	253	202	229
2010	227	999								

33.8: Little Yellow, Spruce, 428094 E, 4478187 N

1984	140	182	230	176	164	155				
1990	222	244	233	176	167	191	226	258	211	187
2000	237	216	209	225	244	212	233	244	271	294
2010	324	999								

Appendix C: Adjusted Tree Core Ring Widths

Table 8: Adjusted tree core ring widths presented in the Tucson format for tree ring dating. Ring widths have been adjusted through normalization and two stages of detrending (negative exponential and cubic spline). Values represent a relative ring width as compared to the mean of the series, in which 1000 is the mean value. From left to right, each row contains the starting year for ring widths divided by decade followed by the up to ten relative ring width measurements in from that decade in chronologic order. The '999' measurement value indicates the end of the series.

4.1: Crater Creek, Fir, 428049 E, 4476217 N

1963	1015	1019	1199	894	939	1021	792			
1970	934	1201	878	1051	909	937	1053	991	941	1135
1980	1162	1128	1219	960	970	767	839	811	1064	951
1990	836	1106	940	1296	895	1188	1452	1015	780	1031
2000	898	1116	854	821	732	1017	1067	831	1020	1065
2010	1230	999								

4.2: Crater Creek, Fir, 428049 E, 4476217 N

1984	934	945	818	988	970	994				
1990	1194	1652	1013	974	713	1029	1129	1140	883	1055
2000	906	731	669	966	739	894	1363	928	1187	1130
2010	999									

6.1: unassociated, Fir, 428199 E, 4476698 N

1878	1517	1005								
1880	801	1183	953	723	1007	941	908	1020	777	631
1890	1045	795	699	976	1020	1077	1044	1088	1184	1067
1900	905	992	1205	749	1218	882	958	1201	1283	972
1910	980	1003	809	786	1142	1133	1066	1014	866	1055
1920	1136	1147	1353	1076	936	860	740	768	966	779
1930	1038	829	853	1208	1080	905	1159	1137	1318	1092
1940	957	996	969	989	729	776	754	1017	1034	1003
1950	1045	951	932	1127	880	972	1234	1304	1399	1199
1960	892	916	790	716	863	910	930	904	720	1092
1970	1244	1311	1144	914	932	838	733	754	1000	1052
1980	1171	1186	1305	1362	1075	901	835	960	1218	1015
1990	643	796	752	888	1243	1079	1060	1069	969	830
2000	1197	1086	816	947	1258	1090	736	1034	999	

6.2: unassociated, Pine, 428199 E, 4476698 N

1827	1732	1062	1057							
1830	756	917	757	622	699	602	709	485	623	994
1840	1329	1735	1634	1407	906	631	729	964	1641	1304
1850	1073	1430	1598	1050	1147	814	459	440	481	429
1860	581	1749	1849	1672	1099	682	616	486	493	570
1870	429	337	276	369	793	1482	1517	2379	2129	1432
1880	1606	699	615	613	600	928	728	887	579	1154
1890	1502	1288	602	735	951	913	1000	745	846	1087
1900	1244	928	1025	1099	698	1015	1139	901	1057	897
1910	1028	1226	1212	900	1043	1087	1098	1143	888	543
1920	896	672	648	919	1234	1224	1363	1510	1443	1220
1930	873	861	850	618	677	888	984	940	921	946
1940	1051	1161	1046	1096	1310	1063	895	1029	1092	1353
1950	896	887	777	855	624	588	792	807	959	1285
1960	1242	1314	1389	1497	1093	986	904	882	887	857
1970	917	940	1203	906	941	1052	1040	995	649	710
1980	806	908	856	901	1099	1325	1066	1319	1013	817
1990	705	690	1010	1190	1154	1066	1305	1107	1543	1219
2000	781	700	550	856	667	815	1431	1193	999	

7.1: Ellen's Tributary, Fir, 428388 E, 4477749 N

1955	1013	1128	1166	1206	732					
1960	905	720	782	928	735	967	1972	921	1160	994
1970	1033	1101	1260	603	787	1180	843	984	911	577

1980	506	710	1216	1431	815	1051	879	1145	1463	1215
1990	1211	922	1028	855	804	833	1129	719	1329	1187
2000	773	969	945	1302	1117	952	681	1090	909	959
2010	1081	999								

7.2: Ellen's Tributary, Fir, 428400 E, 4477751 N

1961	1388	1220	1027	721	706	741	558	1321	1567	
1970	1173	976	753	639	813	751	819	997	1611	1348
1980	1092	826	1000	674	675	771	1096	1008	895	804
1990	1278	1275	1644	1457	1180	1187	841	706	553	836
2000	856	726	609	1068	1155	1212	1269	1224	914	825
2010	999									

8.1: Little Yellow, Pine, 428252 E, 4478554 N

1977	561	683	889							
1980	982	647	1030	1177	1283	1121	895	932	1128	1056
1990	1034	966	935	1160	891	1000	1087	1050	1104	1285
2000	1127	1128	929	872	955	991	744	741	966	984
2010	659	999								

8.2: Little Yellow, Pine, 428252 E, 4478554 N

1979	1201									
1980	768	783	878	870	945	981	751	1114	1047	1247
1990	1176	1220	1194	1099	925	1048	962	947	983	1026
2000	1015	1042	794	889	899	1079	921	914	955	1002
2010	1159	981	999							

10.1: Lady Creek, Pine, 428404 E, 4478638 N

1975	1344	600	1087	994	872					
1980	601	1315	1286	1051	1124	963	1063	712	1055	861
1990	849	956	1012	775	873	1093	1044	997	1285	1251
2000	1153	1150	1103	889	950	984	1036	834	962	787
2010	999									

10.2: Lady Creek, Pine, 428404 E, 4478638 N

1973	726	808	860	1033	1340	916	1205			
1980	954	1310	918	900	911	915	1088	977	969	922
1990	1069	962	1089	1023	939	1118	694	1184	1302	917
2000	1165	1045	1041	843	1081	958	858	869	855	946
2010	1115	999								

10.3: Lady Creek, Fir, 428483 E, 4478877 N

1974	728	546	698	994	1272	1322				
1980	852	1168	1040	1292	1184	1078	1003	813	871	872
1990	848	933	941	1125	1105	1209	1068	1151	852	1076
2000	901	1054	820	1177	869	877	1176	844	1020	930
2010	999									

10.4: Lady Creek, Pine, 428483 E, 4478877 N

1973	2006	1511	476	291	389	401	565			
1980	627	1266	1007	931	1153	2613	1687	1092	1150	772
1990	804	745	989	770	669	817	933	1062	1118	1001
2000	925	655	675	705	1410	1027	1081	992	1089	1199
2010	997	999								

10.4b: Lady Creek, Pine, 428483 E, 4478877 N

1970	1263	981	950	1520	713	1035	460	477	680	634
1980	822	1308	1549	1515	1239	1425	1066	1144	910	748
1990	881	789	1059	855	764	1048	873	1103	1157	932
2000	962	690	678	902	1560	1095	1152	1086	1023	961
2010	841	999								

12.1: Lady Creek, Spruce, 428729 E, 4479203 N

1979	1311									
1980	575	728	718	878	1587	1318	1243	1204	912	774

1990	908	878	1018	1002	987	891	1079	579	770	1105
2000	1408	1151	1090	944	1120	1081	970	901	877	984
2010	982	999								

12.2: Lady Creek, Spruce, 428729 E, 4479203 N

1987	939	828	860							
1990	761	1053	791	601	1243	1079	1221	926	1240	1368
2000	1407	1332	1191	672	923	823	867	887	793	849
2010	976	999								

12.3: Lady Creek, Spruce, 428729 E, 4479203 N

1979	987									
1980	601	511	377	1178	1703	1825	1445	929	864	604
1990	968	905	746	1029	1148	770	1093	583	981	1434
2000	1343	1171	1228	920	1041	1005	577	771	1010	1070
2010	985	993	999							

12.4: Lady Creek, Fir, 428729 E, 4479203 N

1988	1071	837								
1990	743	1131	1084	817	783	998	1056	1077	1216	1314
2000	1074	1137	889	914	1076	945	971	1036	1018	978
2010	895	856	999							

12.5: Lady Creek, Fir, 428729 E, 4479203 N

1981	788	810	1049	1320	1264	1199	857	801	888	
1990	1033	1077	727	746	944	942	705	1014	1292	1155
2000	1303	1201	1013	1029	1410	1152	996	948	887	666
2010	678	831	999							

14.1: Specimen Creek, Spruce, 428774 E, 4479284 N

1976	1258	1224	874	825						
1980	854	1081	842	750	1210	1055	974	892	847	1082
1990	1001	921	885	1011	1054	1005	1035	1117	1153	983
2000	1226	1140	1096	925	922	893	942	894	980	1021
2010	962	999								

14.2: Specimen Creek, Spruce, 428774 E, 4479284 N

1966	1165	992	1032	1325						
1970	1228	742	874	969	686	803	616	881	1012	963
1980	1278	942	867	1166	1082	1230	1167	1095	981	1018
1990	824	882	876	930	865	1137	1230	1445	1085	1238
2000	1030	909	645	990	692	701	792	1080	1183	1182
2010	999									

18.1: Miscellaneous West, Fir, 427885 E, 4477462 N

1959	744									
1960	872	1368	910	844	1125	1214	1131	853	1124	867
1970	1034	1251	1060	748	1163	1228	1197	668	976	932
1980	682	580	651	966	902	1006	964	1316	1248	1005
1990	1168	1287	1212	1119	1008	1389	1172	700	738	709
2000	800	884	822	912	862	795	883	1158	1033	1384
2010	1433	670	999							

18.2: Miscellaneous West, Spruce, 427885 E, 4477462 N

1946	833	915	1201	964						
1950	963	1035	941	990	1220	933	920	953	730	1195
1960	1193	1217	1332	1173	1146	875	618	936	908	781
1970	822	1318	1314	731	1107	1298	1217	682	516	552
1980	532	554	547	599	1167	1193	1735	1566	1134	997
1990	1063	1126	956	984	726	874	1029	1338	1196	1119
2000	1056	870	610	990	908	785	1119	901	1056	1184
2010	999									

23.1: Specimen Creek, Fir, 427833 E, 4479969 N

1972	970	1008	1064	1048	1022	1291	901	745		

1980	859	937	1209	837	749	1139	1279	992	1219	951
1990	1052	907	727	944	663	925	814	1167	895	1146
2000	1366	1381	1385	1102	998	827	787	644	771	952
2010	1154	1113	999							

23.2: Specimen Creek, Spruce, 427833 E, 4479969 N

918	1289	1283	1067	794	923	960				
1166	946	751	639	928	929	658	1173	909	969	110
996	923	949	944	1249	1192	1366	1475	1423	1158	187
840	676	727	734	699	693	1126	1103	1040	1068	188
1119	999									

24.1: Lady Creek, Pine, 428568 E, 4479611 N

1979	852									
1980	787	1219	1490	1075	931	884	940	804	893	1017
1990	1006	1010	1065	1000	959	1030	985	852	879	803
2000	908	1083	1152	1033	1151	1442	1209	1196	1004	824
2010	662	789	999							

24.2: Lady Creek, Pine, 428568 E, 4479611 N

1975	1518	1025	730	725	529					
1980	825	927	1229	1094	1269	1164	1154	1047	867	829
1990	983	1056	1081	1108	818	888	988	912	1344	1063
2000	1092	913	795	1124	1170	988	829	705	744	1523
2010	909	999								

32.1: Little Yellow, Pine, 428036 E, 4478050 N

1979	1135									
1980	1031	992	962	1107	1014	978	897	734	896	1117
1990	1098	1151	653	595	762	1133	1034	1387	1684	1309
2000	1018	646	695	1136	1066	992	868	790	773	1014
2010	1138	1150	999							

32.2: Little Yellow, Fir, 428036 E, 4478050 N

1973	1101	1366	975	725	775	763	769			
1980	918	1203	1111	962	948	960	975	958	1223	1359
1990	1086	1171	997	847	982	1015	937	1003	1075	984
2000	1037	988	823	948	918	977	818	1048	843	1124
2010	1065	1117	999							

33.1: Little Yellow, Pine, 428090 E, 4478190 N

1974	1100	918	817	953	586	996				
1980	796	817	1082	877	1123	1375	1255	1393	1272	1209
1990	1050	841	1061	676	671	892	887	953	966	986
2000	1035	1096	1032	1141	1085	943	871	804	978	1282
2010	882	999								

33.2: Little Yellow, Pine, 428090 E, 4478190 N

1977	921	739	849							
1980	584	758	816	997	1187	1382	1385	1404	1146	1199
1990	1200	1125	1138	605	692	738	726	846	838	812
2000	1253	1113	1037	1172	1172	1055	1036	806	816	1161
2010	924	999								

33.3: Little Yellow, Pine, 428084 E, 4478195 N

1986	1183	780	955	963						
1990	865	1335	814	703	786	578	836	758	1098	1413
2000	1504	1365	1572	1235	1226	1012	837	582	687	744
2010	723	999								

33.4: Little Yellow, Pine, 428084 E, 4478195 N

1981	1069	783	1202	1442	1100	913	846	927	827	
1990	903	1057	689	749	756	627	897	739	893	1443
2000	1567	1370	1644	1296	1242	1010	816	613	688	718
2010	821	999								

33.5: Little Yellow, Spruce, 428100 E, 4478217 N

1968	774	936								
1970	843	1245	1244	1199	1188	1001	716	697	1139	1003
1980	840	1076	1126	855	1047	1141	1082	1109	1301	899
1990	787	868	1070	954	905	721	1131	776	1129	1106
2000	1336	1115	671	742	1190	1047	880	712	821	1169
2010	1350	999								

33.6: Little Yellow, Spruce, 428100 E, 4478217 N

1970	931	1141	1199	1159	1092	772	613	852	1194	1055
1980	883	778	967	986	1046	1235	1180	1053	1401	853
1990	679	850	1032	1096	1086	697	1210	676	1156	1120
2000	1223	1120	740	685	1158	923	1033	770	824	1145
2010	1322	999								

33.7: Little Yellow, Spruce, 428094 E, 4478187 N

1983	741	1206	1083	1106	906	1013	887			
1990	976	1054	1117	917	898	925	995	1105	963	979
2000	901	959	1120	1318	1168	948	970	1043	829	936
2010	925	999								

33.8: Little Yellow, Spruce, 428094 E, 4478187 N

1984	811	1033	1280	961	880	817				
1990	1151	1245	1172	873	817	922	1076	1211	977	853
2000	1064	954	906	957	1016	863	927	946	1025	1083
2010	1164	999								

Appendix D: Raw Tree Slab Ring Widths

Table 9: Measured tree slab ring widths presented in the Tucson format for tree ring dating. From left to right, each row contains the sample ID, the starting year for ring widths divided by decade, and the up to ten ring width measurements in millimeters from that decade in chronologic order. The '999' measurement value indicates the end of the series.

Sample 2A: Miscellaneous East, Pine, 428113 E, 4474848 N

1874	57	52	83	97	88	95				
1880	112	74	91	104	133	114	116	135	122	109
1890	110	114	173	165	120	143	108	125	92	91
1900	107	120	108	70	114	150	115	85	114	130
1910	91	76	93	88	71	58	89	87	97	102
1920	56	78	97	97	94	102	105	105	82	70
1930	72	53	43	68	80	103	89	60	61	45
1940	55	63	71	65	64	73	56	58	36	42
1950	32	55	63	98	147	107	104	93	87	70
1960	104	91	88	76	67	53	49	65	59	54
1970	62	32	26	18	17	18	23	25	22	34
1980	26	26	21	23	20	29	25	38	30	24
1990	18	16	19	21	20	15	17	16	16	24
2000	19	20	16	15	12	14	19	17	17	18
2010	21	999								

Sample 2B: Miscellaneous East, Pine, 428176 E, 4474848 N

1904	224	263	152	124	161	170				
1910	149	166	191	156	156	134	176	181	188	137
1920	141	158	110	156	95	146	105	94	102	140
1930	91	103	118	122	112	108	111	103	82	87
1940	93	70	57	70	73	81	72	59	68	69
1950	55	58	65	71	59	66	78	91	102	116
1960	115	128	106	87	98	96	104	96	84	92
1970	96	80	71	73	55	49	37	43	52	52
1980	59	47	42	52	42	47	54	51	53	57
1990	52	64	42	33	42	42	61	40	44	26
2000	33	42	44	42	39	38	32	30	29	32
2010	27	999								

Sample 2C: Miscellaneous East, Pine, 428218 E, 4474860 N

1945	240	276	215	149	159					
1950	126	160	151	139	124	143	178	159	147	140
1960	148	142	149	121	120	106	111	115	110	122
1970	95	102	105	104	103	112	139	127	132	86
1980	96	130	103	103	148	164	138	158	144	148
1990	127	136	121	92	98	86	87	78	69	82
2000	76	116	119	103	100	94	78	82	98	105
2010	79	999								

Sample 2D: Miscellaneous East, Pine, 428213 E, 4474854 N

1908	154	148								
1910	104	95	108	88	81	71	111	195	166	191
1920	183	193	174	136	153	149	197	157	150	164
1930	145	110	125	120	97	134	127	107	126	93
1940	73	96	92	74	80	57	74	68	59	44
1950	57	39	50	64	85	126	105	102	139	122
1960	111	93	77	90	74	65	96	47	56	49
1970	34	35	35	40	40	47	38	27	31	25
1980	24	23	27	24	32	27	19	23	22	14
1990	13	9	7	8	8	6	7	8	7	12
2000	12	7	999							

Sample 3A: Miscellaneous East, Pine, 427981 E, 4475822 N

1927	163	169	162							
1930	123	133	120	139	180	115	98	96	169	67

1940	51	42	51	35	60	87	47	77	89	311
1950	299	282	171	166	124	159	122	133	132	99
1960	86	119	111	101	90	104	133	115	148	104
1970	98	129	147	131	106	74	98	88	94	83
1980	93	104	98	80	79	85	67	83	85	62
1990	69	66	51	46	53	43	32	25	30	33
2000	18	15	19	24	29	25	21	15	17	14
2010	21	999								

Sample 4A: Crater Creek, Fir, 427946 E, 4475996 N

1883	132	105	168	96	106	112	114			
1890	67	104	57	36	48	43	53	52	55	35
1900	47	37	34	37	34	33	29	35	41	21
1910	29	16	19	14	14	13	21	20	16	14
1920	15	13	18	13	13	12	11	8	10	10
1930	18	11	14	14	15	9	16	17	18	17
1940	11	13	15	12	13	19	7	6	7	6
1950	8	8	11	16	10	17	17	14	12	12
1960	23	18	18	22	27	25	32	26	21	22
1970	23	22	21	14	14	2	17	25	15	23
1980	16	12	8	13	6	7	11	16	12	14
1990	42	36	49	39	41	75	47	30	27	28
2000	36	31	27	21	15	8	10	14	10	10
2010	10	999								

Sample 4B: Crater Creek, Fir, 427945 E, 4475985 N

1910	161	66	88	209	175	135	116	107	83	101
1920	68	97	145	134	99	98	103	99	57	42
1930	21	26	26	29	24	30	27	31	29	45
1940	31	32	32	39	37	27	33	38	52	45
1950	40	29	37	27	23	18	23	32	22	35
1960	31	37	50	71	79	94	90	61	56	46
1970	36	52	59	58	126	115	211	250	232	254
1980	175	151	146	173	138	137	106	107	95	88
1990	87	86	116	92	78	87	88	123	121	117
2000	94	57	70	85	101	67	70	70	57	49
2010	55	999								

Sample 7A: Ellen's Tributary, Fir, 428391 E, 4477737 N

1924	144	137	185	183	187	179				
1930	202	214	190	176	145	144	142	166	136	115
1940	95	118	120	129	105	83	96	101	81	82
1950	76	66	53	63	49	46	57	88	77	62
1960	68	60	55	60	66	62	55	63	62	60
1970	48	44	45	49	38	34	30	33	37	43
1980	42	52	39	40	39	21	36	30	23	31
1990	43	44	42	28	43	47	43	40	25	34
2000	36	27	52	54	47	46	999			

Sample 7B: Ellen's Tributary, Pine, 428382 E, 4477726 N

1946	300	319	283	304						
1950	255	318	235	223	186	225	214	188	170	250
1960	224	293	235	231	239	221	229	163	152	153
1970	133	137	186	198	116	64	56	74	77	78
1980	72	101	110	96	95	93	83	63	46	53
1990	45	38	55	55	59	50	53	53	72	46
2000	56	54	37	42	28	52	39	47	42	46
2010	39	999								

Sample 7C: Ellen's Tributary, Fir, 428342 E, 4477698 N

1949	116									
1950	105	108	95	86	97	84	94	69	70	67
1960	78	79	65	68	67	74	68	69	74	63
1970	85	83	81	79	73	66	81	94	89	80
1980	79	64	74	62	71	68	73	80	87	143

1990	137	125	128	90	60	50	48	51	55	50
2000	34	26	27	30	18	33	27	23	16	19
2010	25	999								

Sample 8A: Little Yellow, Pine, 428222 E, 4478539 N

1950	86	79	81	108	118	122	109	143	123	146
1960	162	185	146	148	139	167	193	191	207	226
1970	209	214	229	181	232	206	199	155	182	176
1980	178	161	148	163	129	101	118	117	116	133
1990	109	98	102	122	100	96	106	82	89	72
2000	75	62	112	151	178	122	100	120	94	168
2010	116	999								

Sample 9A: Lady Creek, Fir, 428150 E, 4478283 N

1929	88									
1930	94	92	112	110	129	121	86	115	145	104
1940	122	101	85	108	99	104	96	104	98	113
1950	107	104	89	83	80	79	68	68	62	79
1960	62	64	115	160	219	230	184	208	181	163
1970	124	119	108	95	97	102	87	79	87	80
1980	65	78	76	83	80	69	69	60	87	54
1990	63	49	56	52	61	52	47	45	68	53
2000	52	50	55	51	60	66	62	64	68	70
2010	59	999								

Sample 9B: Little Yellow, Spruce, 428166 E, 4478322 N

1953	111	107	121	141	168	145	139			
1960	238	216	233	233	281	310	265	273	263	236
1970	288	264	219	223	115	166	263	258	335	234
1980	257	256	323	254	203	202	192	138	164	154
1990	136	118	129	96	104	112	98	94	97	116
2000	129	112	109	96	87	115	107	97	103	82
2010	90	80	999							

Sample 10B: Lady Creek, Fir, 428495 E, 4478893 N

1954	143	84	151	133	108	101				
1960	105	411	547	451	408	550	423	549	576	533
1970	489	533	431	411	408	256	359	440	88	138
1980	174	297	304	222	158	104	110	117	131	135
1990	111	88	116	149	151	149	175	148	184	140
2000	157	129	130	112	165	129	102	132	121	153
2010	153	999								

Sample 14A: Specimen Creek, Fir, 428774 E, 4479284 N

1920	209	217	178	169	167	139	128	104	132	116
1930	111	111	94	119	142	126	123	126	108	114
1940	90	102	83	83	68	73	75	76	42	60
1950	58	73	85	75	70	75	82	72	62	64
1960	61	53	53	52	49	56	97	93	99	116
1970	108	120	97	78	60	33	24	23	32	51
1980	51	58	54	61	59	66	45	22	24	22
1990	24	27	18	19	11	22	12	14	14	18
2000	14	22	33	34	23	22	20	25	21	22
2010	42	999								

Sample 14B: Specimen Creek, Fir, 428813 E, 4479351 N

1945	201	224	326	398	368					
1950	296	179	156	157	175	134	180	189	188	153
1960	127	97	147	154	230	124	70	65	56	106
1970	60	46	72	84	135	147	95	106	106	85
1980	82	94	121	129	130	116	115	172	109	75
1990	82	57	44	59	70	47	63	62	94	94
2000	104	73	54	39	31	44	33	32	30	34
2010	26	999								

Sample 15A: Miscellaneous West, Fir, 427706 E, 4476992 N

1968	99	90								
1970	86	88	155	113	131	135	135	144	128	116
1980	93	69	53	63	88	175	161	178	171	217
1990	208	177	75	68	115	161	187	184	270	219
2000	284	283	272	257	266	319	360	277	269	252
2010	168	999								

Sample 15B: Miscellaneous West, Fir, 427688 E, 4476998 N

1908	86	99								
1910	89	103	98	105	93	76	95	114	109	82
1920	90	77	84	82	66	65	82	76	87	131
1930	99	93	77	82	69	97	96	99	108	106
1940	87	62	57	52	62	52	57	56	48	41
1950	45	38	43	42	49	43	38	51	32	36
1960	29	38	37	39	46	37	44	39	35	40
1970	27	23	33	36	26	26	26	24	29	27
1980	35	31	32	31	36	36	30	30	31	30
1990	37	29	78	71	34	47	43	51	54	63
2000	54	73	76	44	26	27	23	18	17	17
2010	16	999								

Sample 15C: Miscellaneous West, Spruce, 427693 E, 4476992 N

1897	67	42	46							
1900	43	40	38	41	37	27	37	43	41	28
1910	39	35	36	38	28	44	33	40	28	40
1920	26	23	23	33	54	56	47	47	54	72
1930	66	55	53	50	44	51	99	86	78	59
1940	54	58	46	37	36	42	33	53	40	42
1950	49	49	35	36	54	53	52	40	33	23
1960	33	42	42	45	48	43	33	30	34	30
1970	23	39	44	40	34	23	18	22	14	19
1980	9	16	33	15	22	43	45	51	41	52
1990	71	60	50	37	45	39	38	40	52	61
2000	54	46	62	62	67	62	68	102	113	120
2010	94	999								

Sample 17A: Miscellaneous West, Pine, 427829 E, 447350 N

1927	117	104	102							
1930	97	89	72	76	88	68	76	71	60	61
1940	76	59	44	45	35	41	41	55	45	52
1950	42	51	43	69	55	46	37	59	115	114
1960	92	83	92	88	73	72	60	66	58	66
1970	31	24	24	20	25	31	28	33	32	36
1980	37	39	37	46	52	35	56	54	55	47
1990	41	39	45	47	57	46	37	51	43	48
2000	53	53	37	35	31	38	36	33	33	41
2010	43	999								

Sample 17B: Miscellaneous West, Pine, 427829 E, 447350 N

1920	55	105	84	62	63	54	42	49	57	46
1930	32	34	24	29	20	25	32	30	29	26
1940	22	19	25	20	21	16	15	17	14	16
1950	14	20	16	22	18	10	11	16	25	17
1960	12	12	14	19	23	17	22	25	30	57
1970	74	77	84	75	62	58	53	56	43	35
1980	39	29	26	20	15	13	15	13	14	17
1990	17	16	24	20	21	28	30	38	37	24
2000	21	11	9	8	13	11	9	11	12	12
2010	11	999								

Sample 17C: Miscellaneous West, Pine, 427829 E, 447350 N

1896	45	60	64	63						
1900	63	51	64	57	68	62	72	76	55	61
1910	81	56	63	86	94	72	85	73	55	62

1920	68	63	63	61	84	79	77	75	75	65
1930	43	41	33	50	46	43	43	31	39	55
1940	44	55	59	47	54	58	41	48	48	52
1950	41	44	38	43	67	48	52	42	49	70
1960	55	28	35	38	42	42	55	69	136	146
1970	159	147	138	132	111	113	88	87	67	78
1980	96	84	85	85	85	67	101	96	90	96
1990	88	63	58	79	86	86	72	71	86	82
2000	80	112	109	113	80	68	89	76	78	84
2010	59	999								

Sample 17D: Miscellaneous West, Pine, 427829 E, 447350 N

1900	93	86	61	98	103	64	66	90	94	70
1910	59	58	57	53	50	73	61	73	71	56
1920	60	51	49	64	53	61	52	52	54	44
1930	45	59	49	52	38	51	52	62	68	70
1940	69	70	74	69	81	68	68	63	51	60
1950	51	65	50	64	47	63	62	52	76	77
1960	74	84	72	70	69	68	47	61	65	49
1970	53	49	39	48	58	45	48	51	61	50
1980	47	50	56	38	58	44	66	60	51	44
1990	47	38	41	43	43	52	49	53	47	66
2000	53	58	59	57	41	43	21	24	32	38
2010	37	999								

Sample 18A: Miscellaneous West, Pine, 427870 E, 4477470 N

1942	173	165	161	177	103	118	125	124		
1950	160	179	187	113	129	138	207	111	95	112
1960	135	233	197	165	210	161	164	183	226	152
1970	214	187	155	167	129	117	136	154	128	140
1980	121	125	181	175	143	148	131	109	102	110
1990	120	100	98	97	125	96	95	64	66	147
2000	70	77	86	102	116	90	82	75	64	120
2010	93	999								

Sample 18B: Miscellaneous West, Pine, 427881 E, 4477470 N

1903	272	238	244	264	241	270	267			
1910	226	216	246	274	167	224	206	202	222	166
1920	150	146	168	140	149	118	144	156	167	141
1930	152	108	106	105	69	81	83	82	204	119
1940	118	104	104	87	74	80	103	85	82	79
1950	74	88	54	33	38	41	33	40	29	31
1960	33	40	43	57	66	58	60	61	55	59
1970	49	45	38	41	37	45	40	32	55	48
1980	36	39	47	41	43	46	51	51	44	33
1990	42	44	47	41	43	46	38	35	49	46
2000	52	43	31	38	42	45	39	35	30	29
2010	31	999								

Sample 19A: Big Dutch Creek, Fir, 427568 E, 4475672 N

1918	160	184								
1920	181	107	108	107	135	157	162	130	133	149
1930	119	107	124	113	125	119	145	127	137	161
1940	129	109	106	112	107	132	105	111	85	106
1950	86	27	20	37	30	19	46	49	50	47
1960	41	33	44	55	55	73	56	51	49	36
1970	38	34	27	45	37	47	44	37	26	32
1980	32	39	38	54	44	36	38	32	29	18
1990	25	23	21	16	22	21	29	28	40	40
2000	38	44	49	42	43	42	36	34	56	36
2010	33	999								

Sample 19B: Big Dutch Creek, Fir, 427575 E, 4475664 N

1888	22	20								
1890	21	16	21	19	17	30	34	28	32	33

1900	37	36	38	36	44	43	40	26	43	52
1910	35	42	45	50	45	48	58	57	69	58
1920	54	60	54	40	38	42	32	30	29	44
1930	29	16	26	19	14	12	11	12	14	15
1940	13	18	17	15	18	16	19	17	16	15
1950	14	13	17	13	20	33	23	12	12	11
1960	12	20	23	32	36	39	39	39	41	71
1970	62	54	60	49	44	32	28	22	19	21
1980	16	18	24	21	22	20	20	21	17	17
1990	16	12	14	13	8	6	6	4	9	8
2000	11	8	9	10	11	17	18	16	19	21
2010	21	999								

Sample 19C: Big Dutch Creek, Fir, 427575 E, 4475664 N

1863	28	16	11	11	11	19	20			
1870	21	14	20	14	16	18	22	24	12	14
1880	18	15	16	16	14	17	23	18	14	15
1890	52	36	28	31	21	17	16	13	23	21
1900	18	25	28	20	16	12	18	26	38	40
1910	38	40	47	33	43	51	31	17	15	24
1920	15	14	19	25	25	34	32	29	27	25
1930	26	14	20	14	12	15	14	16	11	12
1940	9	9	10	6	17	15	17	23	27	20
1950	21	17	17	20	29	22	22	43	32	26
1960	24	24	13	18	22	34	32	27	37	30
1970	23	35	25	22	40	45	55	39	31	38
1980	29	25	24	38	32	36	33	37	40	31
1990	29	27	23	18	16	12	10	9	8	7
2000	7	6	7	5	7	5	10	7	6	4
2010	5	999								

Sample 19D: Big Dutch Creek, Spruce, 427542 E, 4475703 N

1902	60	43	52	37	70	68	72	72		
1910	73	57	54	56	70	65	55	66	52	55
1920	71	66	60	42	43	50	65	71	67	67
1930	54	58	53	61	51	51	80	73	65	66
1940	72	80	65	66	69	74	71	76	60	43
1950	42	51	52	52	35	44	55	63	37	47
1960	34	54	46	48	47	46	66	61	64	81
1970	76	61	69	71	62	65	54	45	66	64
1980	48	63	37	59	111	101	175	109	67	66
1990	78	49	52	35	57	54	62	59	84	57
2000	54	42	42	40	28	29	29	35	36	22
2010	28	999								

Sample 19E: Big Dutch Creek, Fir, 427520 E, 4475721 N

1934	40	38	24	22	23	28				
1940	24	39	48	49	54	55	44	60	58	69
1950	33	60	76	40	47	65	42	32	28	32
1960	36	48	45	52	42	48	39	26	15	13
1970	23	14	27	43	74	137	119	87	54	28
1980	29	24	20	18	17	21	18	14	12	6
1990	4	5	6	7	5	8	7	5	4	5
2000	5	4	5	7	5	4	9	6	8	7
2010	10	999								

Sample 20A: Sawmill Creek, Spruce, 427997 E, 4478321 N

1891	84	64	103	97	95	111	98	196	229	
1900	268	268	235	131	168	266	270	229	289	367
1910	380	281	398	368	432	494	409	278	372	347
1920	271	259	287	314	293	486	512	612	524	581
1930	530	463	457	471	469	374	380	307	315	447
1940	403	342	287	269	294	250	225	210	198	262
1950	229	236	207	199	165	177	172	172	148	151
1960	105	112	76	74	74	97	81	79	97	99

1970	67	75	57	62	56	58	55	59	53	67
1980	72	67	66	62	46	52	46	49	35	35
1990	36	35	33	31	25	29	32	35	37	32
2000	32	32	31	25	23	20	15	22	16	20
2010	20	27	999							

Sample 23A: Specimen Creek, Fir, 428832 E, 4479972 N

1980	78	106	97	103	105	132	109	98	108	73
1990	120	122	97	63	98	95	175	154	165	140
2000	138	136	104	86	142	206	358	284	245	316
2010	215	999								

Sample 25A: Lulu Creek, Spruce, 428155 E, 4478460 N

1919	255									
1920	285	273	346	280	266	255	231	224	178	182
1930	177	165	155	234	215	224	216	201	239	227
1940	237	227	260	233	245	249	230	221	168	168
1950	154	196	177	200	166	161	187	134	73	89
1960	84	91	72	104	104	99	77	85	89	102
1970	126	105	114	107	119	113	111	96	103	101
1980	104	113	128	126	113	124	113	131	135	142
1990	146	144	142	144	158	124	123	116	80	113
2000	145	138	143	131	139	132	139	151	137	73
2010	80	999								

Sample 25B: Lulu Creek, Spruce, 428155 E, 4478460 N

1867	199	221	213							
1870	245	162	65	71	73	88	154	141	189	160
1880	179	230	187	207	213	214	170	188	195	210
1890	213	151	195	156	219	201	209	264	181	140
1900	199	236	166	182	181	173	179	180	159	186
1910	171	185	214	198	206	155	155	155	156	140
1920	125	130	122	150	164	171	166	147	161	156
1930	143	133	120	121	67	53	81	76	62	62
1940	70	81	83	80	67	73	58	60	59	61
1950	66	122	108	99	88	68	68	61	74	84
1960	79	67	90	87	103	95	95	76	81	62
1970	76	66	51	52	50	35	22	25	23	16
1980	18	22	18	20	27	25	25	25	23	19
1990	25	21	16	23	30	24	34	16	25	24
2000	16	19	23	20	25	74	28	96	62	41
2010	31	999								

Sample 25C: Lulu Creek, Spruce, 428191 E, 4478511 N

1888	71	45								
1890	81	76	74	60	107	132	129	76	87	127
1900	154	102	134	144	126	171	214	202	277	276
1910	173	76	61	67	66	54	62	114	127	176
1920	194	166	191	188	166	127	114	106	88	72
1930	74	123	149	171	132	137	131	153	159	139
1940	144	147	125	134	133	142	135	138	127	81
1950	69	125	175	198	163	132	104	159	205	179
1960	148	167	137	146	149	155	133	122	110	101
1970	127	146	119	133	137	108	97	130	125	98
1980	114	116	99	91	84	64	66	69	59	79
1990	60	46	45	54	31	39	32	38	43	29
2000	22	25	22	18	22	18	35	35	27	37
2010	31	999								

Sample 28A: Little Yellow, Spruce, 428172 E, 4478337 N

1927	60	66	52							
1930	48	50	43	40	26	31	31	28	25	30
1940	29	40	42	56	64	67	55	88	87	88
1950	61	67	64	71	94	82	63	57	57	56
1960	53	46	49	54	67	53	71	64	83	76

1970	85	85	106	98	88	85	106	101	103	152
1980	148	199	260	255	231	186	189	185	120	83
1990	80	75	75	60	55	58	57	62	65	50
2000	56	48	52	49	59	41	42	64	43	60
2010	61	999								

Sample 30A: Little Yellow, Fir, 428157 E, 4476799 N

1934	112	129	139	140	131	98				
1940	86	87	79	67	72	61	62	58	79	71
1950	89	91	100	106	100	90	90	95	85	96
1960	98	123	118	117	155	123	123	55	164	95
1970	91	108	119	137	174	155	112	95	75	90
1980	95	96	96	61	69	76	63	67	65	71
1990	62	78	67	58	51	54	51	52	41	33
2000	46	41	40	41	45	32	42	43	52	52
2010	37	999								

Sample 30B: Little Yellow, Fir, 428141 E, 4476815 N

1934	102	95	79	63	57	58				
1940	55	47	65	66	57	55	47	55	56	59
1950	46	47	52	43	48	38	54	46	44	45
1960	38	33	29	25	18	11	9	15	18	17
1970	12	15	11	13	16	29	33	48	50	48
1980	45	50	53	51	41	65	49	48	48	54
1990	53	47	39	50	27	25	13	9	10	10
2000	13	9	15	11	10	10	9	7	6	8
2010	7	999								

Sample 30C: Little Yellow, Fir, 428121 E, 4476830 N

1892	79	77	90	77	106	131	106	116		
1900	93	236	197	191	218	170	182	181	214	248
1910	289	288	270	289	275	249	260	269	358	294
1920	199	234	217	179	182	141	130	184	186	183
1930	191	131	148	136	136	140	138	102	102	30
1940	70	49	65	100	120	129	117	87	74	82
1950	91	85	71	67	76	86	69	63	59	66
1960	67	60	67	49	57	53	85	61	53	75
1970	59	77	87	64	61	54	70	56	40	50
1980	45	51	60	46	43	45	74	67	65	43
1990	51	40	38	35	45	47	52	44	65	55
2000	65	74	79	56	58	44	47	44	53	41
2010	39	999								

Appendix E: Adjusted Tree Slab Ring Widths

Table 10: Adjusted tree slab ring widths presented in the Tucson format for tree ring dating. Ring widths have been adjusted through normalization and two stages of detrending (negative exponential and cubic spline). Values represent a relative ring width as compared to the mean of the series, in which 1000 is the mean value. From left to right, each row contains the sample ID, the starting year for ring widths divided by decade, and the up to ten relative ring width measurements in from that decade in chronologic order. The '999' measurement value indicates the end of the series.

Sample 2A: Miscellaneous East, Pine, 428113 E, 4474848 N

1874	836	710	1061	1167	1002	1029				
1880	1159	735	871	962	1193	996	991	1131	1006	888
1890	889	916	1388	1326	970	1166	890	1044	780	783
1900	934	1063	972	640	1058	1414	1102	829	1133	1316
1910	939	799	994	955	781	646	1000	984	1104	1167
1920	644	901	1127	1135	1110	1218	1272	1294	1031	899
1930	945	711	589	951	1141	1496	1317	903	932	696
1940	858	988	1114	1016	993	1119	844	857	519	589
1950	435	725	807	1223	1797	1290	1246	1116	1053	860
1960	1307	1178	1182	1066	987	825	810	1147	1116	1099
1970	1363	761	669	500	508	574	778	889	817	1309
1980	1031	1057	872	971	858	1262	1105	1707	1372	1120
1990	858	780	946	1066	1035	789	908	866	876	1326
2000	1059	1123	905	853	686	804	1096	987	994	1064
2010	1259	999								

Sample 2B: Miscellaneous East, Pine, 428176 E, 4474848 N

1904	1136	1367	810	676	898	968				
1910	865	981	1149	954	971	848	1135	1189	1261	939
1920	989	1136	811	1179	737	1162	857	787	875	1231
1930	820	952	1119	1189	1123	1117	1185	1137	936	1027
1940	1134	880	737	927	986	1109	995	818	941	947
1950	744	770	843	897	724	787	904	1027	1125	1256
1960	1229	1358	1123	925	1052	1046	1156	1094	986	1117
1970	1210	1051	974	1048	826	770	606	733	917	946
1980	1102	899	818	1029	842	951	1103	1050	1100	1193
1990	1100	1370	911	726	939	955	1412	944	1060	640
2000	830	1081	1159	1135	1083	1086	943	912	910	1038
2010	906	999								

Sample 2C: Miscellaneous East, Pine, 428218 E, 4474860 N

1945	1044	1287	1070	787	887					
1950	737	977	957	910	835	987	1256	1145	1080	1048
1960	1129	1103	1179	975	984	883	938	984	951	1063
1970	832	895	921	910	897	968	1192	1079	1111	717
1980	792	1062	834	827	1181	1305	1099	1264	1163	1212
1990	1058	1157	1054	822	899	810	839	770	694	839
2000	789	1219	1264	1105	1083	1028	861	913	1100	1189
2010	903	999								

Sample 2D: Miscellaneous East, Pine, 428213 E, 4474854 N

1908	1387	1292								
1910	881	782	863	682	608	517	784	1339	1112	1254
1920	1183	1235	1108	866	978	961	1288	1045	1021	1146
1930	1044	818	963	960	808	1163	1150	1012	1246	962
1940	789	1082	1077	897	998	727	958	887	769	569
1950	727	487	611	763	990	1439	1183	1141	1556	1378
1960	1276	1097	939	1142	984	911	1425	743	947	889
1970	663	735	792	976	1053	1336	1167	897	1113	970
1980	1005	1036	1303	1237	1750	1556	1143	1429	1394	893
1990	824	562	428	479	472	355	424	514	503	1049
2000	1494	1924	999							

Sample 3A: Miscellaneous East, Pine, 427981 E, 4475822 N

1927	289	53	2899							
1930	202	50	2167	1941	210	146	2938	1903	1651	0
1940	893	0	752	913	622	0	1029	1453	763	0
1950	443	134	4107	2459	229	86	1791	2324	178	30
1960	1321	0	1884	1780	162	16	1478	1710	213	49
1970	1590	0	2057	2328	205	16	1663	1162	1543	0
1980	1486	0	1703	1635	1367	0	1435	1603	1319	0
1990	1498	0	1603	1318	1269	0	1686	1477	1190	0
2000	788	0	770	1052	1434	0	2023	1895	1742	0
2010	2138	0	999							

Sample 4A: Crater Creek, Fir, 427946 E, 4475996 N

1883	895	777	1357	846	1017	1170	1296			
1890	827	1394	827	564	809	777	1024	1070	1203	812
1900	1155	962	934	1073	1041	1066	990	1262	1564	848
1910	1240	724	909	707	744	724	1223	1214	1010	917
1920	1015	907	1291	955	974	914	848	622	780	780
1930	1400	852	1080	1076	1149	688	1224	1305	1391	1327
1940	870	1044	1225	997	1099	1630	607	523	609	516
1950	674	655	869	1213	725	1177	1123	883	723	693
1960	1276	963	934	1113	1341	1227	1565	1275	1041	1108
1970	1184	1162	1141	784	806	118	1024	1528	923	1415
1980	974	715	462	718	314	344	504	683	477	520
1990	1465	1189	1548	1192	1227	2223	1398	906	838	902
2000	1216	1111	1037	875	686	407	573	919	768	927
2010	1166	999								

Sample 4B: Crater Creek, Fir, 427945 E, 4475985 N

1910	1149	481	655	1590	1364	1081	956	910	730	920
1920	643	954	1490	1446	1128	1187	1336	1383	864	693
1930	379	512	559	677	604	809	771	929	903	1442
1940	1014	1061	1070	1309	1243	907	1107	1272	1738	1503
1950	1335	965	1224	882	737	560	688	911	591	878
1960	723	799	997	1307	1343	1477	1309	822	699	532
1970	386	516	544	498	1014	873	1524	1737	1567	1686
1980	1154	998	976	1177	962	983	786	822	758	728
1990	746	764	1065	872	761	873	907	1301	1315	1309
2000	1085	680	864	1088	1345	930	1017	1068	916	832
2010	991	999								

Sample 7A: Ellen's Tributary, Fir, 428391 E, 4477737 N

1924	766	736	1003	1003	1039	1010				
1930	1162	1258	1146	1093	930	957	979	1191	1017	898
1940	776	1008	1073	1209	1031	854	1036	1141	957	1012
1950	976	880	731	895	714	685	865	1357	1205	985
1960	1097	984	917	1018	1142	1096	995	1170	1183	1179
1970	973	921	972	1093	874	804	729	821	940	1113
1980	1106	1392	1059	1101	1086	590	1016	849	650	872
1990	1202	1220	1153	761	1155	1247	1127	1034	636	851
2000	884	650	1226	1247	1063	1019	999			

Sample 7B: Ellen's Tributary, Pine, 428382 E, 4477726 N

1946	1005	1095	995	1095						
1950	940	1200	907	880	749	924	894	799	735	1100
1960	1004	1342	1103	1116	1193	1144	1235	919	899	951
1970	871	948	1361	1536	955	559	517	722	790	839
1980	810	1186	1346	1225	1264	1290	1200	949	720	859
1990	753	654	969	990	1082	933	1005	1022	1411	917
2000	1137	1117	780	904	615	1167	896	1108	1018	1152
2010	1012	999								

Sample 7C: Ellen's Tributary, Fir, 428342 E, 4477698 N

1949	1103									
1950	1031	1097	998	934	1089	974	1124	850	885	868
1960	1031	1062	886	936	927	1027	944	954	1018	860

1970	1149	1111	1073	1034	945	844	1023	1173	1097	975
1980	951	762	870	721	816	775	826	903	984	1633
1990	1592	1492	1585	1167	822	728	749	857	1002	992
2000	737	619	709	870	579	1183	1085	1042	825	1129
2010	1739	999								

Sample 8A: Little Yellow, Pine, 428222 E, 4478539 N

1950	1062	891	841	1039	1059	1027	865	1075	879	995
1960	1058	1161	883	866	789	922	1040	1008	1075	1159
1970	1064	1086	1165	927	1201	1084	1068	852	1029	1026
1980	1073	1007	962	1103	909	742	903	931	959	1139
1990	965	894	956	1169	976	950	1057	820	887	712
2000	731	593	1048	1381	1590	1065	853	1002	768	1344
2010	909	999								

Sample 9A: Lady Creek, Fir, 428150 E, 4478283 N

1929	848									
1930	898	871	1053	1028	1200	1123	798	1070	1355	978
1940	1158	968	824	1060	984	1047	978	1071	1019	1185
1950	1128	1099	939	870	828	802	673	652	574	703
1960	529	524	906	1218	1623	1673	1326	1500	1318	1208
1970	943	934	879	806	859	946	846	805	930	896
1980	761	954	969	1102	1104	988	1023	920	1376	880
1990	1054	840	979	925	1099	946	859	824	1243	964
2000	938	893	970	887	1027	1112	1029	1046	1095	1112
2010	926	999								

Sample 9B: Little Yellow, Spruce, 428166 E, 4478322 N

1953	977	840	859	915	1007	810	728			
1960	1179	1018	1052	1015	1188	1279	1074	1092	1043	931
1970	1134	1041	866	885	459	666	1063	1053	1384	982
1980	1101	1125	1463	1192	992	1032	1029	778	974	965
1990	898	821	943	736	832	931	843	833	883	1080
2000	1225	1084	1073	961	886	1190	1126	1039	1124	913
2010	1022	927	999							

Sample 10B: Lady Creek, Fir, 428495 E, 4478893 N

1954	1441	613	869	635	442	363				
1960	339	1208	1490	1154	995	1293	970	1241	1298	1209
1970	1128	1261	1055	1049	1094	726	1083	1418	304	513
1980	695	1278	1408	1106	845	595	669	750	879	938
1990	792	640	852	1099	1114	1096	1283	1081	1340	1018
2000	1140	937	945	815	1204	944	749	973	897	1143
2010	1154	999								

Sample 14A: Specimen Creek, Fir, 428774 E, 4479284 N

1920	1087	1182	1017	1011	1047	911	876	741	977	890
1930	880	907	791	1029	1262	1152	1159	1224	1085	1185
1940	970	1140	962	997	845	936	990	1028	580	843
1950	825	1046	1225	1084	1012	1083	1181	1032	883	904
1960	853	732	722	698	649	732	1255	1198	1276	1508
1970	1426	1623	1353	1130	906	521	397	398	580	966
1980	1009	1202	1174	1397	1429	1700	1239	650	762	752
1990	881	1062	755	844	513	1064	595	704	706	899
2000	688	1056	1541	1541	1011	937	825	1000	812	824
2010	1525	999								

Sample 14B: Specimen Creek, Fir, 428813 E, 4479351 N

1945	639	752	1154	1488	1455					
1950	1239	794	733	781	920	743	1051	1162	1214	1038
1960	904	723	1146	1255	1956	1099	644	618	547	1055
1970	604	466	728	845	1347	1453	931	1030	1022	814
1980	782	894	1151	1232	1253	1133	1144	1752	1142	812
1990	919	662	530	736	904	628	871	888	1397	1456
2000	1688	1249	980	756	645	988	805	853	881	1109

2010	953	999								

Sample 15A: Miscellaneous West, Fir, 427706 E, 4476992 N

1968	1044	910								
1970	838	830	1422	1012	1151	1168	1155	1221	1079	973
1980	775	570	432	505	690	1336	1194	1281	1192	1466
1990	1360	1120	458	400	650	871	967	909	1276	992
2000	1235	1187	1103	1013	1021	1198	1328	1006	965	894
2010	590	999								

Sample 15B: Miscellaneous West, Fir, 427688 E, 4476998 N

1908	897	1036								
1910	935	1087	1039	1119	997	820	1031	1246	1200	909
1920	1004	863	945	925	745	733	922	852	973	1463
1930	1107	1043	868	932	793	1131	1139	1201	1346	1363
1940	1160	861	826	787	983	863	990	1017	910	810
1950	925	809	946	953	1142	1028	930	1275	816	934
1960	765	1018	1006	1076	1289	1055	1277	1154	1057	1233
1970	850	738	1076	1190	869	874	874	804	962	882
1980	1121	970	974	916	1029	993	798	768	764	712
1990	847	642	1677	1491	701	957	871	1033	1103	1308
2000	1150	1611	1757	1078	682	767	714	618	652	739
2010	801	999								

Sample 15C: Miscellaneous West, Spruce, 427693 E, 4476992 N

1897	1378	891	1008							
1900	973	934	916	1018	944	707	992	1177	1142	792
1910	1117	1012	1046	1107	814	1273	945	1129	776	1082
1920	684	585	563	776	1217	1211	976	940	1043	1348
1930	1203	980	926	861	749	863	1672	1458	1336	1026
1940	958	1053	857	708	707	846	680	1117	860	919
1950	1090	1107	802	836	1270	1263	1256	980	820	580
1960	844	1090	1106	1205	1310	1198	941	877	1021	926
1970	730	1274	1479	1384	1209	839	669	828	529	712
1980	331	572	1137	495	692	1287	1282	1387	1068	1303
1990	1717	1405	1137	818	967	812	765	776	968	1087
2000	917	743	950	899	918	803	833	1181	1240	1251
2010	933	999								

Sample 17A: Miscellaneous West, Pine, 427829 E, 447350 N

1927	1036	984	1029							
1930	1041	1014	870	971	1186	965	1133	1109	979	1037
1940	1340	1075	823	860	677	797	795	1057	851	962
1950	757	892	729	1132	873	708	553	861	1645	1611
1960	1295	1173	1317	1286	1098	1124	978	1130	1048	1264
1970	630	517	547	479	625	800	739	882	858	961
1980	976	1011	940	1143	1263	832	1304	1235	1239	1046
1990	904	854	981	1022	1239	1003	811	1126	959	1084
2000	1214	1234	877	846	764	955	922	861	876	1108
2010	1182	999								

Sample 17B: Miscellaneous West, Pine, 427829 E, 447350 N

1920	588	1263	1131	930	1046	988	841	1069	1348	1174
1930	877	996	748	957	696	914	1225	1201	1212	1135
1940	1002	903	1240	1034	1131	897	872	1022	866	1012
1950	900	1298	1039	1417	1139	616	651	900	1324	841
1960	550	507	542	674	748	508	606	639	717	1285
1970	1592	1601	1709	1513	1256	1194	1121	1229	989	850
1980	1008	802	772	639	515	478	587	538	607	764
1990	785	753	1144	962	1017	1368	1483	1912	1909	1280
2000	1166	640	552	519	894	805	703	919	1077	1163
2010	1158	999								

Sample 17C: Miscellaneous West, Pine, 427829 E, 447350 N

1896	811	1059	1107	1069						

1900	1049	834	1028	900	1056	948	1084	1128	806	883
1910	1160	794	886	1202	1308	1001	1183	1020	772	877
1920	970	908	919	902	1262	1209	1205	1205	1240	1109
1930	758	746	620	967	913	874	891	652	830	1179
1940	949	1191	1281	1023	1178	1269	899	1055	1056	1144
1950	900	961	823	921	1412	992	1049	823	927	1273
1960	956	463	548	560	582	547	674	799	1495	1536
1970	1615	1455	1344	1274	1071	1095	862	863	676	800
1980	1002	893	919	934	949	759	1159	1115	1056	1138
1990	1052	758	701	956	1041	1039	867	851	1026	974
2000	947	1323	1288	1340	954	817	1081	933	970	1059
2010	754	999								

Sample 17D: Miscellaneous West, Pine, 427829 E, 447350 N

1900	1051	994	722	1187	1278	814	861	1204	1290	986
1910	853	859	865	822	791	1176	1000	1217	1203	964
1920	1049	905	881	1164	974	1131	970	975	1014	825
1930	840	1093	899	941	677	893	894	1046	1127	1141
1940	1109	1112	1165	1080	1264	1060	1061	985	799	942
1950	802	1022	785	1002	733	979	959	801	1167	1181
1960	1136	1296	1120	1101	1100	1103	776	1028	1118	860
1970	949	894	723	903	1105	866	932	997	1198	986
1980	930	992	1112	756	1155	877	1317	1199	1021	883
1990	945	765	826	866	866	1048	989	1074	958	1359
2000	1107	1234	1284	1276	948	1030	522	621	862	1067
2010	1085	999								

Sample 18A: Miscellaneous West, Pine, 427870 E, 4477470 N

1942	1147	1102	1084	1200	702	808	857	850		
1950	1094	1219	1267	761	861	912	1353	716	604	701
1960	832	1413	1178	976	1231	938	953	1064	1318	893
1970	1269	1123	945	1035	814	751	889	1024	866	964
1980	848	892	1316	1298	1085	1151	1045	893	859	953
1990	1068	914	919	933	1230	965	974	668	699	1577
2000	759	843	948	1131	1292	1007	921	845	722	1356
2010	1052	999								

Sample 18B: Miscellaneous West, Pine, 427881 E, 4477470 N

1903	988	883	924	1020	952	1090	1103			
1910	957	938	1097	1257	790	1093	1038	1052	1196	926
1920	866	872	1037	893	980	800	1006	1121	1235	1073
1930	1189	868	875	888	597	716	749	755	1917	1145
1940	1167	1060	1096	951	841	948	1276	1104	1120	1137
1950	1124	1413	916	590	712	801	668	832	614	664
1960	709	858	918	1209	1391	1216	1256	1278	1156	1248
1970	1046	970	827	902	821	1007	901	724	1249	1093
1980	821	890	1072	935	980	1047	1161	1161	1003	753
1990	960	1007	1079	944	994	1068	887	823	1162	1102
2000	1261	1058	776	969	1092	1196	1062	977	860	854
2010	939	999								

Sample 19A: Big Dutch Creek, Fir, 427568 E, 4475672 N

1918	1059	1235								
1920	1231	737	753	753	959	1125	1169	945	974	1099
1930	883	800	933	856	954	917	1131	1005	1104	1326
1940	1091	951	959	1054	1054	1367	1149	1291	1055	1409
1950	1227	413	328	646	553	367	924	1013	1057	1009
1960	890	721	966	1211	1216	1624	1256	1157	1127	840
1970	901	819	661	1118	934	1205	1147	981	701	878
1980	893	1109	1102	1600	1334	1119	1211	1045	967	611
1990	858	792	721	543	734	684	918	860	1190	1154
2000	1065	1201	1307	1097	1104	1062	899	839	1368	871
2010	792	999								

Sample 19B: Big Dutch Creek, Fir, 427575 E, 4475664 N

1888	1310	1098								
1890	1070	761	935	795	670	1117	1199	939	1023	1009
1900	1085	1015	1033	945	1118	1059	957	605	974	1148
1910	755	886	931	1017	903	954	1147	1128	1375	1172
1920	1114	1272	1185	914	910	1060	856	854	883	1439
1930	1023	610	1073	849	676	624	613	710	873	976
1940	875	1243	1194	1064	1282	1137	1339	1183	1093	1000
1950	906	811	1017	742	1084	1692	1112	546	511	438
1960	446	694	746	975	1036	1068	1023	989	1014	1730
1970	1505	1320	1492	1253	1167	888	818	680	624	735
1980	597	717	1021	955	1070	1041	1114	1255	1090	1171
1990	1182	950	1184	1167	756	590	605	407	909	790
2000	1048	728	775	812	839	1216	1211	1014	1138	1193
2010	1136	999								

Sample 19C: Big Dutch Creek, Fir, 427575 E, 4475664 N

1863	1633	941	651	655	657	1136	1196			
1870	1254	835	1189	830	944	1056	1282	1389	688	795
1880	1008	827	866	847	725	858	1133	865	657	690
1890	2349	1606	1240	1367	925	748	702	568	997	900
1900	760	1035	1133	789	614	446	648	908	1289	1324
1910	1233	1282	1497	1052	1381	1662	1030	579	524	861
1920	552	529	735	990	1014	1415	1370	1282	1238	1194
1930	1297	732	1098	807	725	947	920	1087	766	849
1940	640	636	695	406	1113	944	1025	1328	1493	1061
1950	1071	834	805	915	1285	947	922	1762	1285	1025
1960	930	915	487	661	791	1196	1100	907	1215	964
1970	723	1079	756	653	1169	1300	1575	1113	885	1089
1980	837	729	709	1142	981	1131	1069	1242	1402	1143
1990	1134	1128	1035	879	853	704	648	647	640	624
2000	697	667	868	693	1084	868	1957	1560	1547	1219
2010	1861	999								

Sample 19D: Big Dutch Creek, Spruce, 427542 E, 4475703 N

1902	1078	761	907	637	1188	1141	1196	1188		
1910	1198	933	883	916	1147	1068	907	1093	865	919
1920	1190	1110	1012	709	725	841	1089	1183	1109	1102
1930	882	939	851	970	803	796	1237	1121	993	1005
1940	1097	1222	1000	1025	1085	1183	1158	1268	1026	755
1950	756	941	982	1003	687	875	1104	1272	748	947
1960	680	1066	894	916	878	839	1176	1062	1090	1351
1970	1244	982	1093	1108	954	986	807	662	954	908
1980	668	860	496	778	1446	1306	2261	1418	884	887
1990	1074	694	759	528	889	872	1039	1029	1529	1087
2000	1083	890	944	956	715	794	854	1114	1246	834
2010	1172	999								

Sample 19E: Big Dutch Creek, Fir, 427520 E, 4475721 N

1934	1444	1279	758	654	646	745				
1940	607	941	1109	1090	1163	1154	904	1215	1164	1380
1950	661	1211	1551	829	991	1399	923	717	639	742
1960	844	1134	1068	1236	996	1131	910	598	339	287
1970	496	295	556	872	1493	2782	2470	1876	1228	681
1980	764	692	638	641	681	955	935	836	828	480
1990	370	533	731	964	765	1334	1247	930	760	953
2000	940	733	886	1194	821	633	1380	897	1173	1016
2010	1450	999								

Sample 20A: Sawmill Creek, Spruce, 427997 E, 4478321 N

1891	1410	846	1125	905	775	805	640	1167	1256	
1900	1365	1277	1054	556	676	1018	986	801	970	1187
1910	1188	852	1175	1060	1219	1368	1114	745	981	900
1920	691	648	703	753	688	1118	1158	1367	1161	1285
1930	1175	1035	1035	1086	1106	905	947	790	839	1236
1940	1159	1026	900	882	1010	901	850	833	823	1144

1950	1050	1137	1050	1065	933	1059	1091	1158	1060	1152
1960	853	969	699	723	764	1056	927	947	1214	1291
1970	908	1054	828	929	863	918	892	979	901	1167
1980	1287	1233	1253	1219	939	1104	1018	1130	842	877
1990	938	946	924	895	743	884	1000	1117	1207	1068
2000	1092	1119	1112	922	875	787	613	940	722	965
2010	1049	1578	999							

Sample 23A: Specimen Creek, Fir, 428832 E, 4479972 N

1980	908	1172	1027	1052	1042	1279	1037	919	1000	669
1990	1087	1091	855	545	829	781	1394	1183	1217	988
2000	928	868	627	488	757	1030	1679	1251	1016	1236
2010	795	999								

Sample 25A: Lulu Creek, Spruce, 428155 E, 4478460 N

1919	899									
1920	1034	1018	1327	1104	1078	1061	985	976	791	821
1930	807	757	713	1076	986	1022	981	909	1077	1021
1940	1066	1024	1181	1069	1140	1180	1114	1099	860	889
1950	844	1116	1050	1240	1078	1098	1343	1013	581	744
1960	735	829	679	1009	1032	998	783	868	908	1035
1970	1268	1046	1122	1040	1142	1069	1035	882	931	898
1980	909	971	1081	1046	922	996	895	1023	1042	1085
1990	1106	1085	1066	1080	1185	932	928	878	608	863
2000	1112	1065	1111	1027	1103	1061	1136	1257	1164	634
2010	711	999								

Sample 25B: Lulu Creek, Spruce, 428155 E, 4478460 N

1867	1150	1304	1284							
1870	1507	1015	413	455	469	562	973	877	1153	955
1880	1046	1315	1048	1140	1154	1144	898	984	1013	1083
1890	1093	772	994	794	1113	1022	1064	1348	928	721
1900	1031	1231	871	962	964	928	967	979	871	1027
1910	952	1039	1214	1136	1198	915	929	944	966	881
1920	799	845	806	1008	1123	1197	1191	1085	1228	1235
1930	1180	1149	1088	1154	673	560	899	882	749	775
1940	900	1065	1110	1082	911	993	786	806	783	799
1950	851	1549	1353	1226	1079	828	823	735	889	1008
1960	950	809	1097	1075	1298	1229	1270	1058	1183	957
1970	1248	1162	969	1074	1129	868	601	753	763	583
1980	717	950	837	990	1408	1358	1399	1422	1313	1074
1990	1381	1118	812	1100	1341	997	1308	569	821	729
2000	451	499	568	469	562	1619	605	2085	1378	952
2010	768	999								

Sample 25C: Lulu Creek, Spruce, 428191 E, 4478511 N

1888	1212	689								
1890	1125	967	869	654	1090	1264	1167	653	712	995
1900	1160	742	945	990	849	1135	1409	1329	1833	1851
1910	1182	531	435	488	488	404	466	857	953	1316
1920	1446	1236	1425	1408	1251	965	873	818	682	559
1930	574	951	1145	1306	1002	1033	983	1143	1183	1032
1940	1068	1090	926	993	985	1050	995	1014	927	587
1950	495	886	1225	1370	1116	895	700	1065	1369	1195
1960	991	1124	930	1002	1035	1092	951	887	813	759
1970	971	1136	944	1076	1133	915	843	1162	1153	936
1980	1130	1199	1070	1033	1005	809	884	982	894	1278
1990	1038	852	894	1150	708	954	836	1058	1270	905
2000	721	855	779	655	817	677	1325	1331	1028	1410
2010	1182	999								

Sample 28A: Little Yellow, Spruce, 428172 E, 4478337 N

1927	1199	1357	1101							
1930	1047	1123	992	944	625	752	753	674	591	690
1940	644	852	855	1088	1189	1193	942	1458	1402	1388

1950	948	1030	979	1085	1440	1264	979	894	901	889
1960	842	727	765	827	1000	764	983	846	1043	904
1970	955	901	1059	923	782	714	843	764	744	1054
1980	992	1301	1674	1635	1491	1223	1280	1304	889	652
1990	671	674	727	628	622	710	752	881	990	812
2000	965	872	989	970	1208	864	907	1411	966	1371
2010	1418	999								

Sample 30A: Little Yellow, Fir, 428157 E, 4476799 N

1934	908	1088	1221	1282	1253	979				
1940	896	944	890	779	859	741	761	714	968	861
1950	1062	1064	1143	1183	1088	955	931	957	835	920
1960	917	1125	1058	1032	1348	1058	1049	466	1386	802
1970	770	918	1019	1187	1532	1393	1033	903	736	916
1980	1003	1054	1097	727	856	983	848	938	947	1075
1990	975	1274	1137	1022	933	1025	1003	1057	859	711
2000	1015	924	917	953	1058	759	1004	1034	1258	1265
2010	905	999								

Sample 30B: Little Yellow, Fir, 428141 E, 4476815 N

1934	1212	1183	1030	858	810	857				
1940	842	744	1061	1109	985	976	856	1028	1076	1166
1950	936	988	1131	971	1128	933	1391	1249	1264	1374
1960	1237	1148	1077	988	753	481	407	688	823	762
1970	519	617	425	469	538	906	962	1312	1290	1177
1980	1058	1136	1173	1108	882	1396	1059	1053	1078	1252
1990	1280	1195	1053	1447	846	855	489	374	463	517
2000	753	587	1107	923	963	1117	1186	1114	1196	2119
2010	2751	999								

Sample 30C: Little Yellow, Fir, 428121 E, 4476830 N

1892	1297	1048	1048	785	963	1073	792	797		
1900	592	1401	1098	1005	1090	811	833	797	911	1025
1910	1166	1140	1055	1120	1063	965	1015	1065	1443	1214
1920	845	1027	987	846	896	724	697	1029	1087	1119
1930	1224	880	1044	1008	1060	1146	1187	920	963	295
1940	714	515	701	1101	1347	1473	1361	1031	893	1009
1950	1143	1089	929	894	1035	1194	976	907	863	979
1960	1006	911	1025	755	883	824	1327	956	834	1187
1970	941	1239	1417	1057	1023	922	1216	990	719	913
1980	833	955	1135	877	824	866	1428	1296	1259	833
1990	986	770	726	663	843	870	952	797	1168	984
2000	1162	1330	1434	1032	1091	848	931	899	1121	900
2010	892	999								

Appendix F: Ring Width Series Comparison

Table 11: Comparison of 20th century ring width series at, from left to right, Milner Pass (MP), Onahu Creek (OC), Cameron Pass (CP), and the Colorado Headwaters (CH).

Date	MP	OC	CP	CH
1900	1262	1024	1093	1075
1901	1210	1094	1005	960
1902	809	1004	825	1115
1903	1098	1048	982	924
1904	863	1043	1116	958
1905	923	1097	1048	948
1906	688	972	746	1049
1907	883	1051	1003	1051
1908	950	1038	1024	1170
1909	1117	998	1033	934
1910	1004	1017	954	1004
1911	963	1178	948	1115
1912	1034	1233	1041	1011
1913	949	1112	1170	843
1914	1055	1177	1099	1093
1915	897	1127	978	1110
1916	941	1178	1042	1082
1917	1027	1179	1051	1078
1918	1021	1115	1002	877
1919	1139	994	984	799
1920	770	969	869	1016
1921	937	1095	1012	910
1922	959	1054	950	1000
1923	945	1138	929	997
1924	873	1153	1018	1085
1925	905	1147	1008	1042
1926	815	1099	967	1051
1927	1046	1096	1014	1139
1928	1158	1169	1204	1204
1929	1313	1080	1093	999
1930	1169	1017	917	956
1931	1141	1031	1074	845
1932	1107	1045	1057	851
1933	1098	941	1121	913
1934	933	873	883	879
1935	1025	894	947	896
1936	1012	836	947	1072
1937	963	973	852	1038
1938	1052	890	943	1120
1939	1275	955	1036	1019
1940	1130	1008	1032	1004
1941	1025	1071	917	1078
1942	980	970	1070	1008
1943	970	1114	1017	1042
1944	1018	1060	898	1020
1945	1017	1195	798	920
1946	984	1106	991	827
1947	1091	1211	928	987
1948	994	975	876	1109
1949	1088	1150	884	1106
1950	1044	988	1073	968
1951	1374	1137	1192	958
1952	1211	1159	1043	883
1953	1365	1205	1064	991
1954	1204	1129	944	908
1955	1191	1141	1076	876
1956	1105	1081	1033	1019
1957	1158	1119	1008	1058
1958	1078	964	1018	1074
1959	1088	876	847	1031
1960	1100	868	982	1021
1961	1058	892	997	1154
1962	1032	897	1030	1071
1963	1280	1009	1049	1028
1964	1411	961	1067	958
1965	1199	969	1076	979
1966	1319	973	1198	1045
1967	930	1039	963	873
1968	947	904	968	994
1969	876	812	901	1023
1970	944	906	915	1038
1971	955	880	924	1098
1972	986	915	999	1047
1973	960	980	1048	1021
1974	1128	1095	1072	1030
1975	1188	1167	1021	963
1976	1070	969	970	900
1977	1129	951	958	832
1978	1163	1127	1032	906
1979	1175	1001	988	871
1980	1094	945	945	900
1981	1016	1104	858	948
1982	932	1074	1015	985
1983	972	1060	1031	1036
1984	1086	1262	1020	1094
1985	968	1238	965	1156
1986	1019	1485	1054	1046
1987	1232	1295	1055	1033

Appendix G: Scar Heights

Table 12: Top and bottom heights of tree scars relatively to the modern bankfull surface of the Colorado River. Distance from the bankfull surface, approximate compass direction in which scars face, and UTM coordinates of scars are included.

Sample ID	Site	E (UTM)	N (UTM)	Scar Top (m)	Scar Bot. (m)	River Dist. (m)	Dir.
19-A	BD	427568	4475672	2	1.57	2.7	N
19-B	BD	427575	4475664	0.62	0.44	3.3	S
19-C	BD	427575	4475664	0.32	0.12	3.3	S
19-D	BD	427542	4475703	2.2	2.09	12	N
4-A	CC	427946	4475996	1.7	1.54	9.8	N
4-B	CC	427945	4475985	2.3	2.07	9.9	N
7-A	ET	428391	4477737	5.5	5.2	21	N
7-B	ET	428382	4477726	3.45	3.25	5	N
26-A	GD	428178	4478456	2	1.65	3	E
27-A	GD	428170	4478385	1.95	1.47	12.7	E
10-B	LC	428495	4478893	2.8	2.43	15.2	E
25-A	LU	428155	4478460	0.95	0.75	18.7	W
25-B	LU	428155	4478460	2.8	0.95	20	W
25-C	LU	428191	4478511	2.35	1.7	18.7	E
28-A	LY	428172	4478337	1.6	1.27	10	W
8-A	LY	428222	4478539	2.27	2.17	26	W
9-A	LY	428150	4478283	2	1.65	1.5	E
9-B	LY	428166	4478322	1.62	1.48	5	E
18-A	MW	427870	4477470	2.6	2.36	21	N
18-B	MW	427881	4477470	1.68	1.53	20.6	N
14-A	SC	428774	4479284	2.05	1.85	22	E
14-B	SC	428813	4479351	1.16	0.77	14.2	E
20-A	SM	427997	4478321	2.3	1.97	3.3	W