THESIS

CHANNEL INITIATION IN THE SEMIARID COLORADO FRONT RANGE

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JAMESON E. HENKLE ENTITLED CHANNEL INITIATION IN THE SEMIARID COLORADO FRONT RANGE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

CHANNEL INITIATION IN THE SEMIARID COLORADO FRONT RANGE

The channel head, defined as the upstream boundary of concentrated water flow and sediment transport between definable banks, represents the transition from hillslope processes to fluvial processes. The ability to delineate the location along a slope at which channels initiate is important for understanding hydrologic and geomorphic processes governing headwater streams. Studies demonstrating an inverse relationship between either contributing drainage area (A) and local valley slope (θ) or basin length (L) and θ for channel heads come primarily from regions with humid climates. Seventy-eight channel heads were mapped in the headwaters of the Cache la Poudre River and the North St. Vrain Creek in the semiarid Colorado Front Range. Multiple field sites were chosen along both rivers to account for variability due to aspect and elevation. Surface topographic parameters were measured in the field and analyzed to test the hypothesis that surface processes control channel initiation in this region. Although simple linear regressions indicate a poor inverse relationship between A and L and no relationship between L and θ, multiple regressions indicate that surface topographic parameters explain over half the variability in the location of channel heads. This suggests that surface processes exert an influence on channel initiation, but do not explain as much of the variability as observed in previous studies from wetter regions. A threshold of erosion necessary to initiate a channel was observed at approximately 10,000 m^2 for *A*, although values as high as 600,000 m^2 were mapped for some channel heads. Variation within the study area correlated with elevation, which is a proxy for differences in volume and type of precipitation; sites at lower elevation with less precipitation, but more intense convective rainfall, tend to have smaller contributing area and basin length. Aspect did not influence surface topographic parameters. Field-mapped channel head locations plot at or downslope from the inflection point of a regional slope-area curve generated from 10 m DEMs, although some extend well downslope. Most actual drainage areas for channel initiation are thus an order of magnitude larger, and plot in a significantly different portion of the slope-area graph, than would result from the widespread practice of assuming channel heads are located at the gradient reversal in such curves.

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1. Introduction

Fluvial processes begin in the headwaters of river networks at the location of the channel head. Headwater streams are an essential part of the channel network that supplies the initial load of water and sediment into the fluvial system. Internal and external factors governing headwater processes influence downstream form and process. Because understanding headwater streams will aid in better understanding fluvial processes and landscape evolution, studying the dominant controls governing channel heads and predicting the location of channel initiation points has gained increasing interest in recent years. Prediction of channel initiation points on a given hillslope will further increase our understanding of headwater streams and the role they play in channel network extension and landscape evolution (Dunne, 1986).

The ability to delineate the location along a slope at which channels initiate is important for understanding hydrologic and geomorphic processes and for managing headwater streams (Jaeger et al., 2007). Headwater streams play a critical role in: transporting sediment from hillslopes into downstream channel networks (Milliman and Syvitski, 1992); processing nitrogen and other nutrients (Freeman et al., 2007); providing diverse habitat and refuges for varied aquatic and riparian organisms (Gomi et al., 2002; Meyer and Wallace, 2001); and supplying water to lower elevations in arid and semiarid regions. Despite these recognized vital functions, the dynamics of headwater streams remain poorly understood relative to downstream portions of channel networks. This lack of understanding is particularly problematic in arid and semiarid mountainous channel networks, where water is commonly diverted very close to the head of the channel network, creating downstream disruptions in physical and ecological processes that are also poorly understood (Rader and Belish, 1999).

First-order streams rarely initiate at the same location as valley networks. Instead, they can initiate tens to hundreds of meters down-valley of the drainage divide (Dietrich and Dunne, 1993). The channel head is the location where a channel initiates downslope from the drainage divide (Figure 1). The *channel head* is defined as the upstream boundary of concentrated water flow and sediment transport between definable banks (Anderson et al., 1997; Dietrich and Dunne, 1993; Montgomery and Dietrich, 1988; Montgomery and Dietrich, 1989). Currently, a universally accepted

Figure 1: Field photograph of channel head in a forested landscape (left) and above treeline in an alpine environment (right). Note the 1 m white staff for scale.

criterion for well-defined banks does not exist. Banks can be identified by signs of sediment transport such as: wash marks, small bedforms, and armored surfaces (Dietrich and Dunne, 1993). Criteria for defining channel initiation in this study will be further described in the methods section.

The channel head is a morphological feature independent of flow. The location of the channel head does not necessarily coincide with the location of the *stream head*, where perennial flow occurs. Channel segments of intermittent and ephemeral flow are commonly present above the stream head and below the channel head.

The channel head represents the transition from the unchanneled hillslope hollow to the channel network (Figure 2). Because a tight coupling of valley hillslope

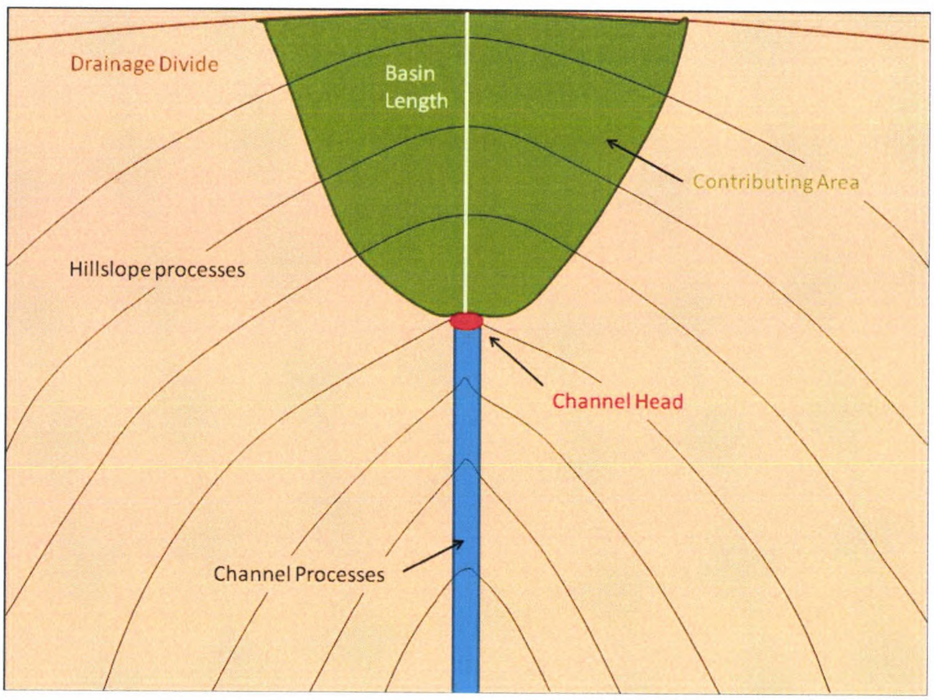

Figure 2: Schematic hillslope displaying surface topographic parameters contributing area and basin length, and showing location of channel head.

processes and the channel network exists, understanding the factors controlling channel initiation is essential for understanding the evolution of both hillslope and drainage networks (Montgomery and Dietrich, 1989). The morphology of the fluvial landscape is controlled by the density and structure of the valley network, which drains water and sediment from the land (Dietrich and Dunne, 1993). Drainage density, a common characteristic used in describing channel networks, is the total stream length divided by the drainage area (Figure 3). To constrain drainage density more accurately for a drainage basin, it is critical to have a spatially defined location for channel initiation.

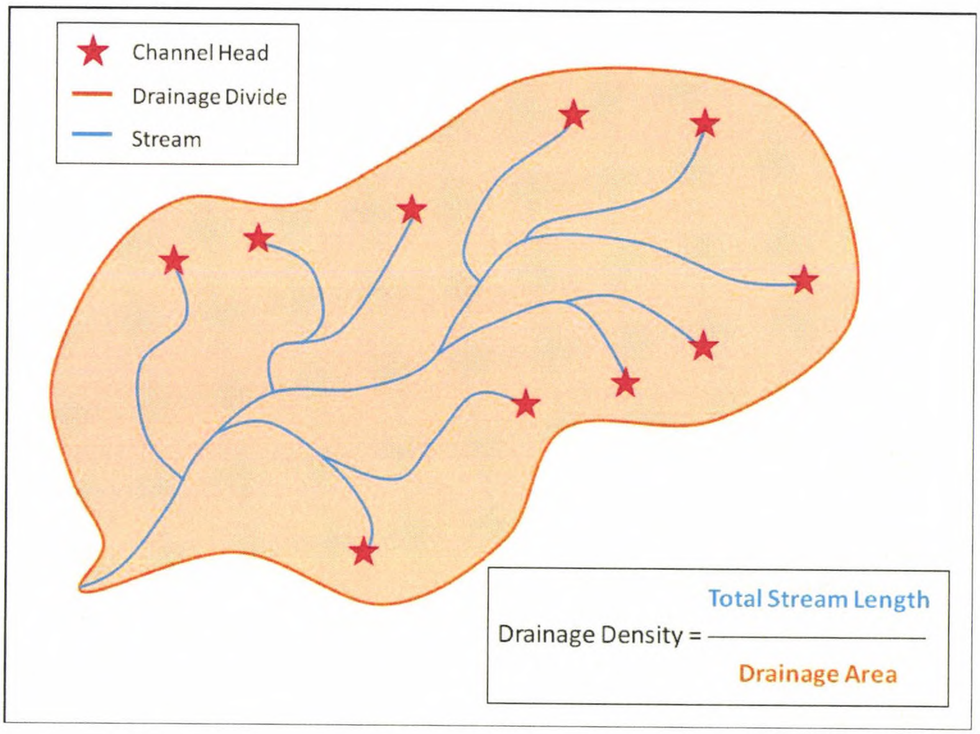

Figure 3: Idealized drainage basin illustrating drainage density and displaying locations of channel heads on first-order headwater streams.

1.1. Previous work on channel head form and process

G.K. Gilbert observed an apparent finite extent to landscape dissection (Gilbert and Dutton, 1877). Horton (1945) then recognized the importance of channel initiation in understanding channel networks and basin development. He proposed that stream development on a fresh slope continues until source basin length reaches some critical distance, x_c, required for erosion. The location where overland flow can institute erosion is the channel head. Horton also recognized groundwater influences on the location of the channel head, such that the distance to the drainage divide is reduced by subsurface flow. He concluded that the channel end point, or channel head, is where groundwater flow is no longer effective.

Montgomery and Dietrich (1988) have shown that empirically defined topographic parameters associated with channel initiation points controlling landscape dissection are limited by an erosional threshold. Their work indicates that critical contributing area decreases with increasing values of local valley gradient at the channel head. Research focusing on the quantification of channel initiation in the field has been conducted primarily in humid regions. Montgomery and Dietrich (1989) mapped channel initiation points in the Tennessee Valley area of Marin County, California, and developed empirical equations relating source basin length (L), local valley slope (θ), and contributing drainage area (A):

$$L = \lambda \tan \theta^{-0.83}, \text{ where } \lambda = 67 \text{ m} \quad (1)$$

$$A = \lambda \tan \theta^{-1.65}, \text{ where } \lambda = 1978 \text{ m}^2 \quad (2)$$

$$A = 0.46\, L^{1.99} \quad (3)$$

$$L = 1.48\, A^{0.50} \qquad (4)$$

They noted an inverse relationship for the regression between both source-basin length and contributing drainage area against slope over a wide range of gradients (Figure 4). Multiple investigations support an erosional threshold theory to landscape dissection (Dietrich et al., 1992; Montgomery, 2001; Montgomery and Dietrich, 1992; Montgomery and Foufoula-Georgiou, 1993; Prosser and Abernethy, 1996), although these relationships vary between steep gradients controlled by landsliding and Hortonian overland flow, versus shallower gradients controlled by seepage erosion and saturation overland flow (Montgomery and Dietrich, 1989).

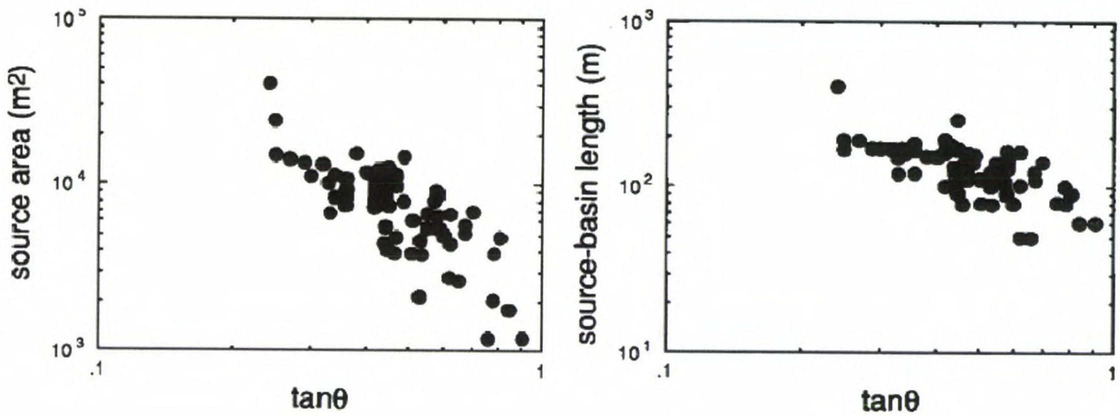

Figure 4: Inverse relationship of source area (R^2=0.75) and source-basin length (R^2=0.47) against local valley slope for channel initiation points in the Tennessee Valley, California (Montgomery and Dietrich, 1989).

Climate has been recognized to affect the temporal and spatial variability of hydrologic processes controlling channel initiation points. Precipitation patterns will produce daily and seasonal variation in wetness and saturation (Wilcox et al., 1997), affecting whether Hortonian versus saturation overland flow is produced in different environments. Initial soil moisture conditions also affect the hydrologic response to a given storm event (Zehe and Blöschl, 2004). Connected flow paths on the surface and subsurface increase the convergence of water, producing sufficient flows to initiate a channel. Runoff increases significantly when hillslopes and channel networks become connected due to large storms (Tromp-van Meerveld and McDonnell, 2006).

Dietrich et al. (1993; 1992) produced a digital terrain model to predict the location of channel initiation points by graphically characterizing landscapes using digital elevation data. They divided the landscape into process domains by sediment transport and channel initiation mechanisms. Process domains define specific areas where particular geomorphic processes govern habitat attributes and dynamics (Montgomery, 1999). The contributing area-slope relationship was used to quantitatively analyze spatial variation in dominance of different erosional processes using process thresholds (Dietrich et al., 1992; Montgomery and Dietrich, 1994). Montgomery (2001) used DEMs to analyze the relationship between slope distributions, local topography, and process domains for two mountain ranges in the humid Oregon coast. Prosser and Abernathy (1996) adapted the digital terrain model of Dietrich et al. (1993) to compare values of shear stress generated by Hortonian overland flow and saturation overland flow. These studies further support an inverse contributing area-slope relationship, indicating that erosional thresholds are directly related to surface topographic controls.

Some subsequent studies have supported the inverse relationship between contributing area and slope (Roth and La Barbera, 1997; Roth et al., 1996), whereas others indicate these relationships do not always hold for a given environment (Adams and Spotila, 2005; Bischetti et al., 1998; Jaeger et al., 2007) due to varying bedrock lithology or weathering affecting the downslope transport of water. The importance of fractured bedrock has been recognized in both field and lab studies to affect the lateral mobility of water downslope (Anderson et al., 1997; Jaeger et al., 2007; McDonnell, 2003). Infiltration rates will vary with depth to bedrock and fracture properties. These studies support the argument that bedrock topography exerts a greater control on channel initiation points than surface topography (Freer et al., 1997). Given the conflicting findings from various studies on channel initiation, there is evidence that subsurface processes may be more important than surface processes on channel head formation for certain environments. Relationships between surface topographic parameters may be weak in drier regions with seasonal snowmelt infiltration compared to those in more humid regions, for example, because of diminished surface runoff in the drier regions.

A relationship among valley slope and contributing area derived from digital elevation models has been observed by multiple researchers. Geomorphic processes have been shown to affect the relationship between slope and area (Dietrich et al., 1993; Montgomery and Dietrich, 1994; Tarboton et al., 1992). An inflection from positive to negative in the slope-area relationship that has been observed in multiple studies (Ijjasz-Vasquez and Bras, 1995; Montgomery and Foufoula-Georgiou, 1993; Tarboton et al., 1991) has been interpreted to indicate the transition where unstable channel-forming processes yield to stable diffusive processes based on the assumption that instability leads to channelization (Tarboton et al., 1992). In some profiles, multiple inflections have been interpreted as reflecting boundaries of geomorphic processes such as debris flows and landslides (Tucker and Bras, 1998). Recent studies have predicted channel head locations based on the slope-area relationship in the absence of actual field data on channel head locations (Hancock and Evans, 2006; Tarolli and Dalla Fontana, 2009).

Asymmetrical valley morphology has been recognized in mountainous regions. Asymmetry occurs in all climates and is caused by differences in local climatic regimes, and particularly moisture retention and associated characteristics of soils, vegetation, and downslope flow paths of water, on opposing sides of the valley (Wohl, 2000). Aspect-related sources of variability are particularly likely to exist in semiarid regions. Semiarid regions typically display lower gradients on north-facing slopes where residence time for snowfall is greater than drier south-facing slopes (Leopold et al., 1995; Wohl and Pearthree, 1991). Local variation in vegetation composition and structure have been observed due to angle and aspect (Holland and Steyn, 1975). Aspect-related differences in surface and subsurface properties that influence the location of channel heads can thus create smaller-scale variability in regional area-slope and length-slope relationships for semiarid drainages.

1.2. Application to the Colorado Front Range

There are no current field-tested criterion for predicting the location and spatial extent of channel initiation points in the semiarid Colorado Front Range. There is also no existing theory for predicting a threshold ratio of contributing area to gradient and basin length to gradient for channel initiation. Consequently, I use field data to assess the feasibility of predicting channel head locations from surface topographic parameters contributing area, basin length, and local slope (Figure 2). Because no theory exists for predicting channel initiation in dryland environments, acquisition of even limited field data will provide a significant improvement over application of various theoretical models to the problem of defining channel network extension and channel initiation points (Montgomery and Foufoula-Georgiou, 1993). If a relationship is found to exist, the quantification of spatial controls on headwater streams will facilitate prediction of channel characteristics using remote data obtained from DEMs. Lack of a consistent relationship will provide insight to the importance of subsurface controls or other factors that obscure slope-area controls on channel initiation in arid and semiarid regions.

1.3. Objectives

Building on previous research conducted in more humid climates, I seek to investigate whether a quantifiable relationship exists for locating channel heads based on surface topographic parameters in the semiarid Colorado Front Range. The overarching fundamental research question driving this work is; are channel initiation points controlled by surface processes? I also seek to determine the sources of variability in the data collected. Will these sources of variability reveal the importance of other geomorphic processes governing channel initiation? The results and findings of this project will then be compared to work previously completed in wetter areas to evaluate the similarities and differences regarding channel initiation across regions and climates.

A field-based data collection project aimed at quantifying the spatial extent of channel initiation points included the following tasks to address the objectives listed above;

1) map the spatial extent and location of channel initiation points,
2) measure and quantify i) local slope of channel head, ii) geometry of channel head, and iii) soil composition and thickness,
3) classify channel heads as; abrupt, gradational, or zonational;
4) evaluate whether location and extent of channel initiation points have a consistent relationship to surface topographic parameters (contributing area, basin length, local slope) and whether these relationships are affected by aspect and elevation,
5) conduct statistical analysis to test significance of relationships developed, and
6) analyze and compare the location and extent of channel initiation points in the Front Range to studies from more humid regions.

1.4. Hypotheses

Previous work indicates an inverse relationship between both contributing area and basin length with local slope in humid regions (Figure 4). Erosional thresholds are likely to vary between sites dominated by Hortonian overland flow and those dominated by saturation overland flow. In cold arid and semiarid climates, the landscape is much drier and a larger portion of precipitation may infiltrate during snowmelt. With sufficient infiltration, the potential for subsurface parameters to control channel initiation exists. However, I propose that infiltration and subsurface controls are not critical in channel initiation in cold dryland regions.

H1: A consistent relationship between contributing area (*A*), basin length (*L*), and slope (θ) exists for the semiarid study area.

This relationship is based on a threshold of erosion that must be exceeded at some point downslope from the drainage divide in order for channel initiation to occur. The alternative hypothesis (H1a) is that a consistent relationship between *A*, *L*, and θ does not exist, presumably because of subsurface influences on the location of channel heads.

A quantitative theory for channel initiation on steep terrain involving the influence of topographic parameters on the location of the channel head specifies that contributing area should vary as a function of slope (Montgomery and Dietrich, 1988). For a given slope, the magnitude of contributing area should also increase with aridity to produce some combination of runoff and local slope at the channel head (Montgomery and Dietrich, 1988). Therefore,

H2: Larger values of surface topographic parameters, contributing area and basin length, relative to a given slope can be expected in the Colorado Front Range than in more humid areas.

Values of contributing area and basin length are expected to increase linearly with mean annual precipitation. Alternatively, subsurface processes sufficiently concentrate runoff and surface topographic parameters do not differ significantly between the semiarid study area and the wetter sites of other studies (H2a).

Aspect, along with elevation, controls the dominant species and relative abundances of vegetation on a given slope, directly affecting soil characteristics and hillslope processes. Aspect controls the residence time for snow. Aspect also influences the morphology of the landscape through runoff processes, which are closely linked to vegetation and precipitation effects. Given the morphological and ecological differences between north-facing and south-facing slopes,

> H3: The area-slope and length-slope relationships, if present, will also vary as a function of aspect.

Alternatively, runoff processes do not differ substantially enough between north- and south-facing slopes to create statistically significant differences in surface topographic relationships (H3a).

Elevational differences in precipitation patterns, ecological processes, and morphological processes have been recognized for mountainous regions.

> H4: Elevation will affect surface topographic parameters contributing area and basin length.

Area and length should decrease with elevation in response to increased mean annual precipitation. This relationship is expected to have a threshold value, presumably where dominant precipitation patterns move from convective rainfall to snowmelt at 2300 m. Alternatively, climatic, lithologic, and vegetative differences due to elevational zonation will not affect channel initiation points (H4a).

2. Field area and methods

2.1. Field area

The Colorado Front Range is a continental mountain range that is part of the Rocky Mountains. The Front Range is east of the Continental Divide in northern Colorado (Figure 5). Tectonic deformation of Paleozoic and Mesozoic sedimentary rocks and underlying Precambrian rocks occurred approximately 80-35 million years ago during the Laramide Orogeny, resulting in uplift of the mountains to their current elevation (Bradley, 1987). This episode of deformation caused large regional joints to develop. These joints are spatially heterogeneous and have been linked with differences in valley morphology (Ehlen and Wohl, 2002) and development of landscape features such as strath terraces (Wohl, 2008). Fractured bedrock can affect how sensitive an area may be to weathering, erosion, and infiltration. Later erosion of the overlying sedimentary rocks left granites, gneiss, and schist composing the rocks seen on the surface of the Front Range today (Tweto, 1979). Sites chosen for this study consist of a mélange of undifferentiated coarse-grained igneous and metamorphic rocks.

The Front Range exhibits a strong elevational zonation related to differences in glacial history, climate, and bedrock geology (Caine, 1984). Some headwater landscapes above 2300 m are influenced by Quaternary alpine glaciation (Madole et al., 1998). This elevation also marks a transition in dominant hydrologic runoff processes. Above 2300 m, low-magnitude snowmelt flows dominate the hydrograph, while below 2300 m large-magnitude convective rainfall storms occur (Jarrett, 1990). Peak discharge per unit drainage area is also heavily influenced by an elevational transition in runoff processes.

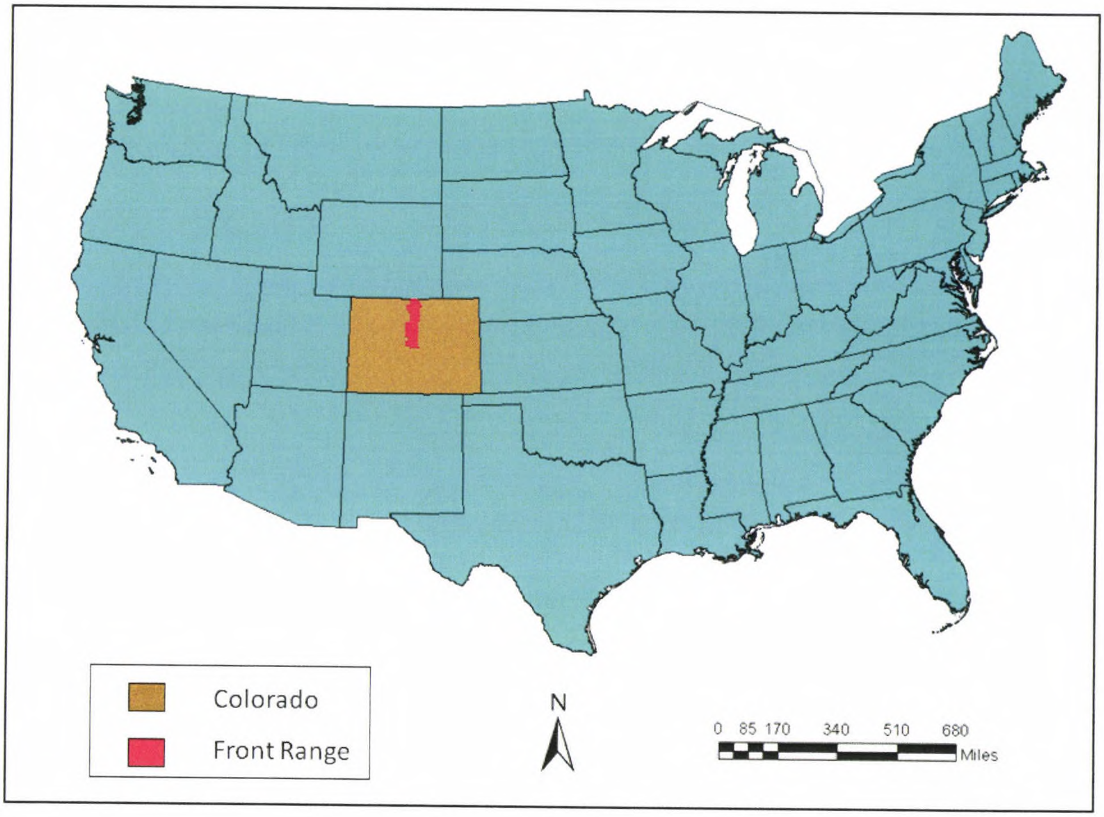

Figure 5: Map of the United States showing Colorado and location of the northern Colorado Front Range (Latitude 4032' North, Longitude 10529'West).

Jarrett (1990) calculated maximum peak flows for snowmelt precipitation patterns above 2300 m to have unit discharges of less than 2.2 $m^3/s*km^2$, while maximum peak flows for rainfall below 2300 m have unit discharges of greater than 22 $m^3/s*km^2$. Higher elevations experience a greater magnitude of mean annual precipitation than do lower elevations. A positive relationship for average annual precipitation with increasing elevation exists for the Colorado Front Range (PRISM, 2006).

Due to the influence of elevational zonation in climate and precipitation patterns, plant communities also vary with elevation. They can be divided into four distinct ecosystems: Lower Montane, Upper Montane, Subalpine, and Alpine Tundra (Veblen and Lorenz, 1991). Lower Montane (1830-2350 m) and Upper Montane (2440-2740 m) are divided at the transitional elevation between snowmelt and rainfall runoff processes. Plant communities of both are composed of predominantly coniferous tree and shrub species and shift from Ponderosa pine (*Pinus ponderosa*) in the Lower Montane to Lodgepole pine (*Pinus contorta*) in Upper Montane, which also includes willow species (*Salix* spp.) in the riparian zone. The subalpline (2840-3350 m) ecosystem is immediately below treeline and contains Engelmann spruce (*Picea engelmannii*) and Subalpine fir (*Abies lasiocarpa*) with more shrub species including willows (*Salix*), birches (*Betula*), sedges (*Cyperaceae*) and forbs. Alpine Tundra (>3450 m) ecosystems support grasses and herbaceous plant species.

Aspect and elevation also heavily influence soil development and erosion. Large differences in soil properties and profiles have been associated with microclimatic differences due to slope orientation (Birkeland, 1999). Jobbagy and Jackson (2000) studied soil profiles in the Sierra Nevada Range along a vertical profile gradient and found significant compositional differences related to elevation; similar differences likely exist in the Front Range. Soils reflect the bioclimatic continuum found from low to high elevations (Birkeland, 2003). Surface erosion and sediment transport rates also vary with elevation (Caine, 1984). Differences in soil composition and thickness are thus expected across varying spatial scales within the study area.

Extensive land use changes have altered the cover of the Colorado Front Range during the past two centuries. These human-induced changes have directly impacted riverine and riparian systems. Colorado Front Range rivers have been substantially modified due to beaver trapping, mining, timber harvest , flow regulation, development, and recreation (Wohl, 2001). Northern Colorado drainage basins were most heavily affected by 19th-century deforestation that likely altered channel head locations, although the specific study sites have had stable forest cover for over a century.

For this study, channel initiation points were studied in the headwater streams feeding two major river systems draining the Colorado Front Range. The Cache La Poudre River and North St Vrain Creek are both located in northern Colorado (Figure 6). Sites within these watersheds were chosen because of access to hillslopes not disturbed by timber harvest or road building within the past century. Selected sites also exhibit varying elevation and aspects. Other characteristics of these watersheds (e.g., underlying lithology, elevation-related trends in climate and vegetation) are representative of the range of conditions present in the Front Range.

2.2. Methods

Bedrock lithology, elevation-related gradients in climate and vegetation, and land use history are assumed to be effectively constant throughout the study area. Thus, the two main sources of variation between study sites identified *a priori* are aspect and elevation. Multiple field areas were mapped for both the Cache la Poudre River and North St. Vrain Creek watersheds at different elevations and varying orientations of hillslopes to test the significance of aspect and elevation as influences on channel head location.

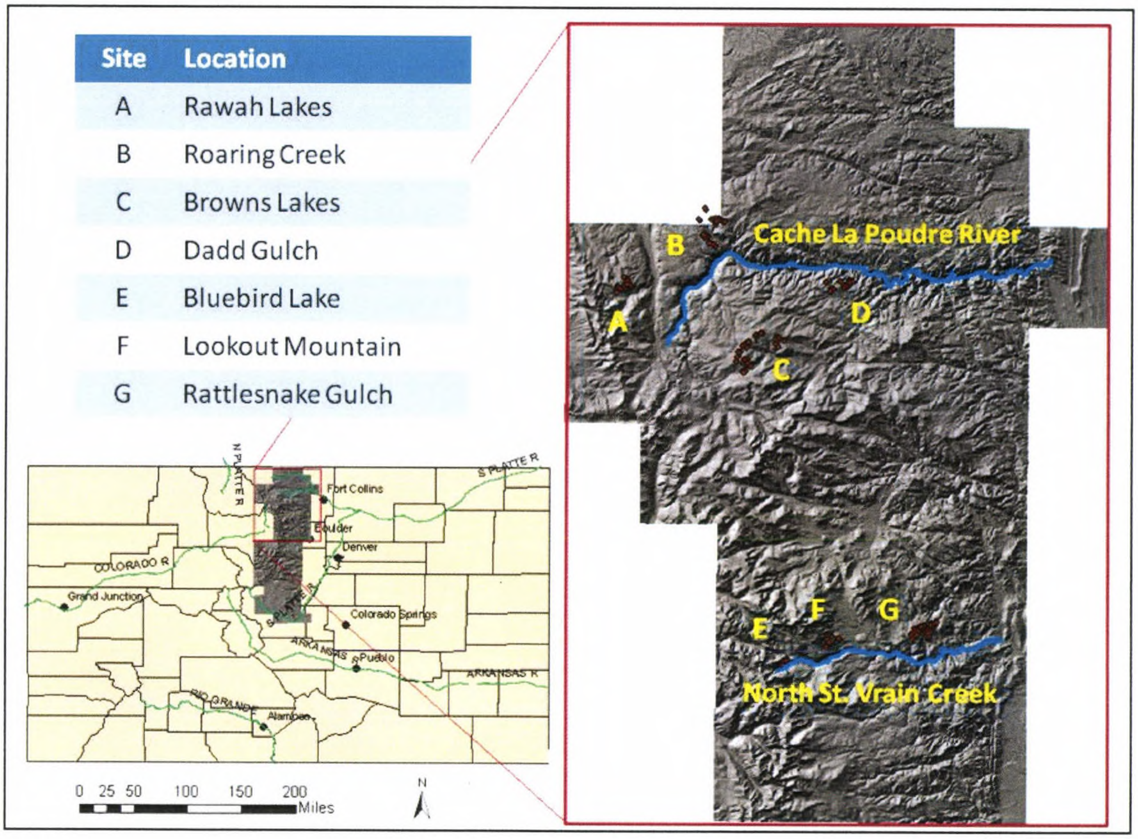

Figure 6: Map of Colorado with digital elevation model inset of northern Colorado Front Range showing locations of headwater streams mapped for the Cache La Poudre River and North St. Vrain Creek.

Channel heads within the Cache la Poudre basin were mapped at middle and high elevations. In the North St Vrain Creek basin, channel heads were mapped at low, middle, and high elevations. Low elevations are specified at 1500-2300 m, middle elevations at 2300-3400 m, and high elevations >3400 m; these divisions reflect differences in hydroclimatology and vegetation. A summary of specific field sites within each basin and total data points is located in Table 1. Because of the specific geologic history of the Front Range, two types of topography exist at high-elevation sites; steep, largely unvegetated slopes of bedrock and talus, and gently undulating surfaces of much lower relief covered with alpine vegetation. The Bluebird Lake and Rawah Lakes sites represent the steep, high-elevation sites and the Browns Lake sites represent the low relief, high-elevation sites (Table 1).

Table 1: Field sites

Watershed	Elevation	Area	Data points
North St. Vrain	Low (1500-2300 m)	Rattlesnake Gulch	25
	Middle (2300-3400 m)	Lookout Mountain	3
	High (>3400 m)	Bluebird Lake	5
Cache La Poudre	Middle (2300-3400 m)	Dadd Gulch	9
	Middle (2300-3400 m)	Roaring Creek	12
	High (>3400 m)	Browns Lake	17
	High (>3400 m)	Rawah Lakes	7

Analysis of United States Geological Survey (USGS) 7.5′ topographic maps of the various field areas pinpointed targets for potential channel heads at the location of blue lines and within hollows. Field work consisted of exploration of the landscape for first-order streams. Once found, headwater streams were followed upslope until an identifiable channel head based on consistent criterion was found. Channel heads were defined as the furthest point upslope with continuous concentrated flow of water and sediment. Channel heads are commonly located at an observable change in hollow topography. At the channel head, the hollow typically converges from a gently sloping U-shaped gradient into one containing a steeper, sharper, V-shaped slope into the channel (Figure 1). The channel immediately downstream of the channel head has banks that show an observable, pronounced, sharp break in slope.

At each channel initiation point, multiple field variables were recorded. Channel heads were mapped using a global positioning system (GPS) device that typically had approximately 5 m of horizontal resolution and 7.5′ quad maps. Coordinates were recorded in NAD 1983 UTM projection in degrees and minutes that were later converted to decimal degrees for further analysis in GIS. The drainage divide for each channel head was assumed to be located perpendicularly upslope to topography. Wherever physically possible, coordinates for the drainage divide were also recorded with the GPS unit to check this assumption.

Channel heads were identified as abrupt, gradational, or as a channel initiation zone. Abrupt channel heads have a single, well-defined surface expression (Figure 1). The width and depth of abrupt channel heads were measured using a metric tape. Gradational channel heads do not have one specified location but develop over several meters. Geometry was not measured for this type of channel head. Zonational channel initiation occurs when multiple channel heads initiate adjacent to each other in an area approximately smaller than 20 m^2 (Figure 7). These small channels then converge downslope within a distance of less than 30 m.

Local slope was defined as the gradient immediately upslope of the channel head. Local slope was measured with a metric tape, stadia rod, staff, and hand level. The tape was placed on the ground upslope of the channel head for a distance of approximately 10-20 m that was feasible for measurement based on line of sight through vegetation or other obstructions. A 1 m staff was located at the upper-most point of the channel head. A 2 m stadia rod was placed at the upslope end of the tape. A

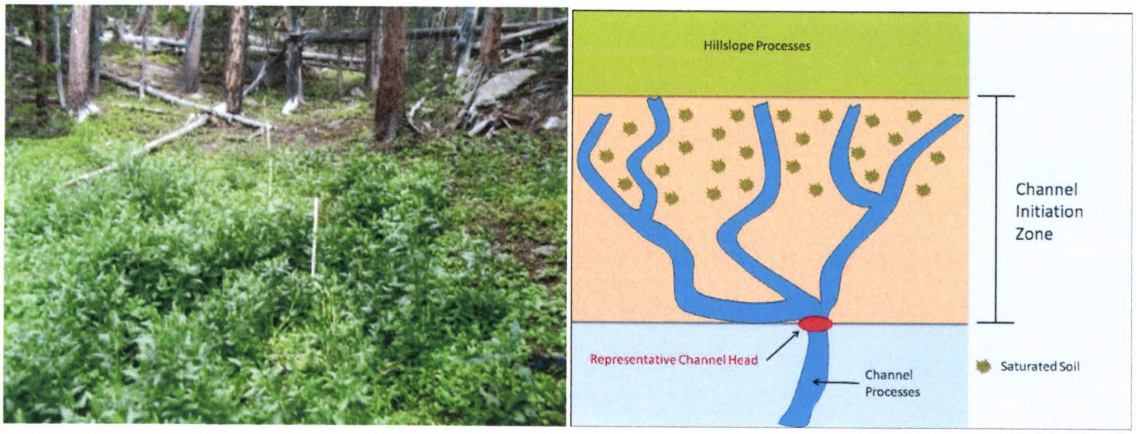

Figure 7: Field photo of channel initiation zone (left) and schematic diagram (right). Note 1 m white staff for scale.

hand level was used to record the angle between the top of the staff and a point along the stadia rod. Various distances upslope and heights of the stadia rod were recorded because obstructions such as trees and thick brush impeded a clear view for the measurement. Trigonometry was used in the office to solve for local slope based on parameters recorded in the field.

Soil depth and composition were recorded at each channel head. A hole was dug with a trowel adjacent to each channel head until a layer of gravels and boulders was reached. The vertical distance into the soil column on top of the gravels and boulders for soil thickness was then recorded. The composition of the colluvium was identified by the major and minor grain sizes. A crude grain size field identification criterion was used as follows: sand has grains that are visible by the naked eye; silt has grains that stain black when rubbed between the fingers; clay has grains that cause fingers to adhere together when the sediment is rubbed between them.

The azimuth (for slope aspect) was recorded directly downslope of the channel head at each data point mapped. Each data point collected was photo-documented using a digital camera in the field. Photos were taken of the channel head using the staff for scale. Photos were also taken looking both upslope and downslope of the data point.

GPS coordinates were analyzed using Geographical Information System (GIS) software. Channel initiation points and drainage divide points were projected on a 10 m digital elevation model (DEM) of the Colorado Front Range and used to solve multiple parameters. Contributing area, elevation, and x-y coordinate attributes were created using ArcGIS. Values for contributing area were pulled directly from GIS for most of the field area. Basin length and basin slope were calculated in Excel. Coordinates of both the drainage divide and the channel head allowed for basin slope to be calculated. The difference in elevation between the drainage divide and the channel head, along with basin slope, allowed for calculation of basin length using simple trigonometry. Approximately 90% of data points were covered by the DEM. The USGS online program StreamStats was used to calculate contributing area, basin length, and basin slope for the remaining 10% of the sites. StreamStats was also used in a sensitivity analysis for points within the DEM coverage. Specifically StreamStats was used to solve parameters for five channel heads not covered by the 10 m DEM used in ArcGIS as well as a check on the accuracy of ArcGIS in calculating topographic parameters. Extreme values and a sample of 1-2 channel heads were selected from each field area and solved for contributing area. Results from both analyses were within a margin of error equal to 10%.

Mean annual precipitation data were downloaded off the PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate Group website through Oregon State University. A base map displaying mean annual precipitation contours was created using ArcGIS. Average precipitation data were calculated from 1971-2000. Mean annual precipitation was solved for all data points.

All field data were input and organized using Excel. A text file of the complete dataset was created for statistical analysis. Statistical software R was used to explore the dataset. All data were analyzed using histograms, qq plots, and boxplots. A log transformation of the data was completed to meet the assumptions of normality about the residuals. Collinearity among variables was tested using Spearmans rank correlation coefficient and satisfied the criteria of noncollinearity between values of 0.8 and -0.8.

Simple linear regressions were run on contributing area, basin length, local slope, elevation, basin slope, aspect, width to depth ratio, soil type, soil thickness, and mean annual precipitation. Following the precedents established by previous investigators, contributing area and basin length were each used as the response variable with local slope as the independent variable. Linear regressions were run on all possible combinations of parameters, allowing each variable to be both the dependent and independent variable.

Multiple linear regressions were run on the variables stated previously. Contributing area, basin length, and local slope were used as the response variable. Models were developed using stepwise, backward, and forward model selection.

Models were selected based on lowest AIC values. AIC, or Akaike's information criterion, is a measure of the goodness of fit for statistical models.

All regressions were run using both the full dataset and subsets. Variability due to aspect was tested by creating north- and south-facing aspect subsets. Aspect was divided into north (271-90 compass degrees, where north equals 0 degrees) and south (91-270 compass degrees). Variability due to elevation was tested by creating low, middle, and high elevation subsets.

Multiple slope-area curves were developed for the data set by splitting the data into elevation regions and major drainage basins (Poudre vs North St. Vrain). Splitting the data resulted in relatively small data subsets, however, so a single slope-area curve was used for the study area. ArcGIS was used to delineate basins from the 10 m DEM around data points collected in the field. Fifty-five of 78 data points were captured and analyzed. Elevation data allowed for the generation of slopes for each pixel within the delineated basin. Flow accumulation for corresponding pixels was solved giving the contributing area. The average slope was plotted against the binned average area and plotted on a log scale. Slope breaks in the average slope function that can be interpreted as the location of channel heads were visually identified and compared to the field-mapped location of channel heads.

2.3. Limitations to this analysis

Previous studies indicate that bedrock characteristics, including susceptibility to weathering and fracture density, can influence downslope movement of water and the location of channel heads (Anderson et al., 1997; Jaeger et al., 2007). Lithology throughout the study area is relatively consistent, but fracture density does vary spatially (Ehlen and Wohl, 2002). However, because fracture density can vary substantially over distances as small as tens of meters, and large bedrock exposures were not common in the immediate vicinity of channel heads or upslope contributing areas, I did not characterize fracture density.

A second basic limitation to the results reported here is that they represent a 'snapshot' in time. The study area is subject to stand-killing wildfires and intense convective precipitation that triggers landslides and debris flows, and can reconfigure channel head locations, at recurrence intervals that vary from circa 20 years to more than 100 years, partly as a function of elevation and forest composition (Moody and Martin, 2001). I chose study sites that had not been subject to this type of landscape disturbance for several decades, but the history of such disturbance over decades to centuries can create another source of spatial variability in the location of channel heads that is not directly addressed in this study.

3. Results

3.1. Surface topographic controls on channel initiation

Simple linear regressions were run to explore whether a quantifiable relationship exists between either contributing area or basin length and local slope. A logarithmic transformation provided a normal distribution about the mean and satisfied the assumptions of normality for the residuals (Figure 8). Using the logarithm of

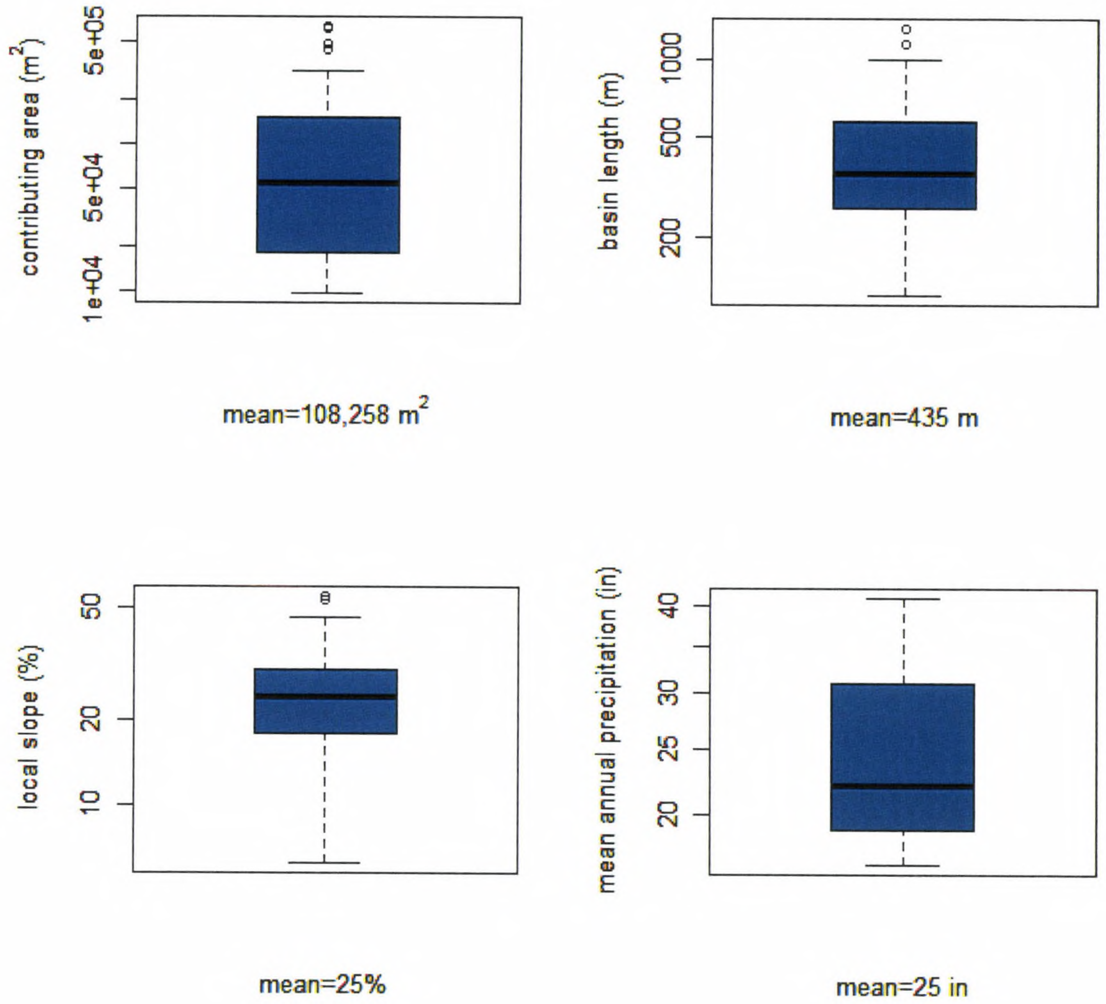

Figure 8: Boxplots (box and whiskers plots) of significant continuous variables used for statistical analysis. The top and bottom of each box represent the upper and lower quartile with the band between them representing the median. The ends of the whiskers are 1.5 times the interquartile range, a measure of statistical dispersion equal to the difference between the first and third quartiles. The dots located outside the whiskers are considered extreme values.

contributing area (A) as the dependent variable regressed against the logarithm of local slope (θ), a weak inverse relationship over a wide range of slopes is observed (Figure 9) and yields the equation:

$$A = \lambda \tan \theta^{-0.923}, \text{ where } \lambda = 1.0 * 10^6 \quad (5)$$

with an adjusted R^2 value of 0.11 and a p-value of 0.002. Using the logarithm of basin length (L) as the dependent variable regressed against local slope (θ), a significant relationship is not observed (Figure 9) with an adjusted R^2 value of <0.01 and a p-value of 0.599.

For contributing area regressed on local slope (Figure 9), 3 data points on the lower left half of the graph were re-examined for potential outliers. No physical basis for

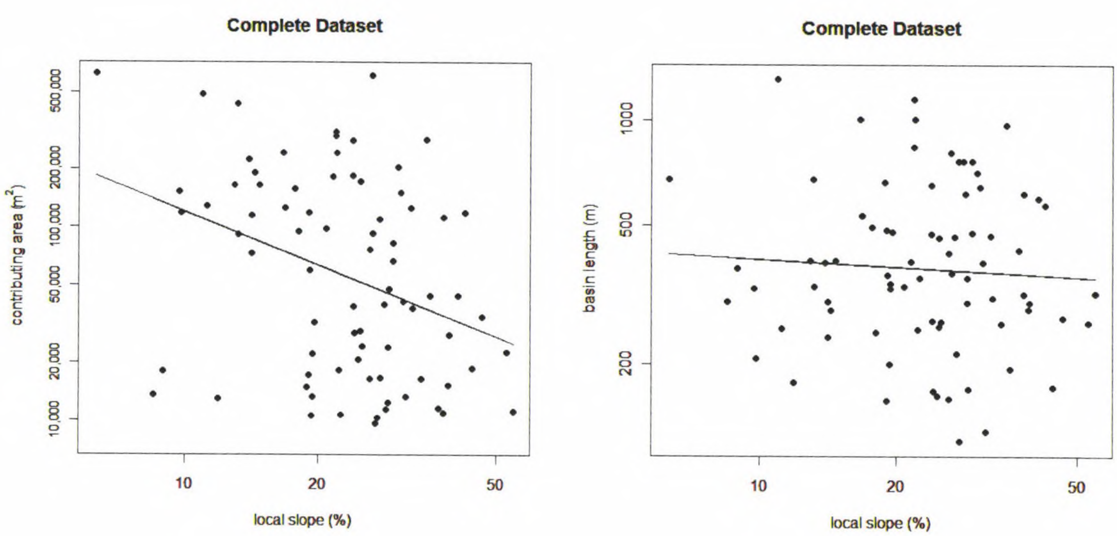

Figure 9: Plot of contributing area (R^2=0.11) and basin length (R^2=<0.01) each regressed on local slope. For area-slope graph, note the 3 data points on the bottom left of graph. These data were re-examined and kept due to lack of any physical explanation to remove them.

removing these points was found and the data were therefore left in. At slopes greater than approximately 19%, there seems to be no trend in the data. This is interpreted as being a threshold slope for channel initiation. Above a 19% local valley slope, there is no predictable value for contributing area.

Contributing area is weakly related to local slope, while basin length is unrelated to local slope. This suggests that it is appropriate to reject hypothesis H1 that a consistent relationship based on surface topographic parameters exists in favor of the alternative that subsurface controls likely influence channel initiation.

Multiple regressions were run to explore the possibility of supplementary surface metrics influencing channel initiation. A logarithmic transformation of continuous variables including; contributing area, basin length, local slope, and mean annual precipitation was conducted and provided normal bell-shaped distributions about the mean (Figure 8). Data were divided into low, middle, and high elevation bands as well as north-facing and south-facing aspects for use as categorical variables in multiple regression (Figure 10). A model was produced for both contributing area and basin length as the dependent variable and yields an equation with the following significant predictors in order of highest explanatory power of the model:

$$\text{contributing area} = \text{basin length} + \text{local slope} + \text{elevation} + \text{mean annual precipitation} \quad (6)$$

with an adjusted R^2 value of 0.53 and a p-value of <0.001;

$$\text{basin length} = \text{elevation} + \text{contributing area} + \text{mean annual precipitation} + \text{local slope} \quad (7)$$

with an adjusted R^2 value of 0.64 and a p-value of <0.001.

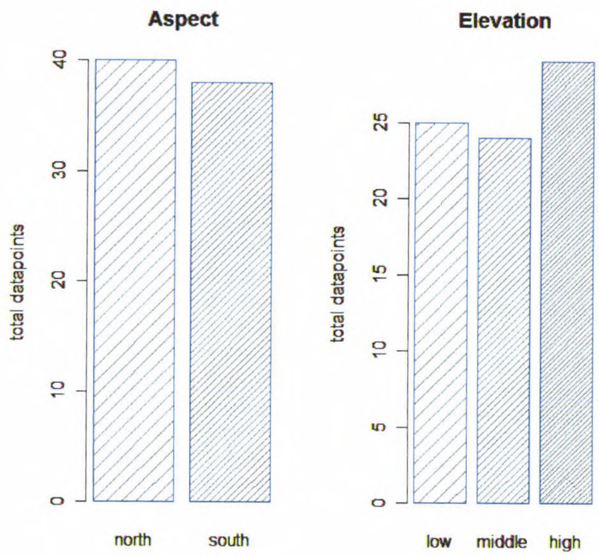

Figure 10: Bar graphs of categorical variables displaying the number of observations for each group with categories.

Models were selected based on lowest AIC values. When analysis of variance is run on the linear model for contributing area, mean annual precipitation is insignificant. Similarly, when analysis of variance is run on basin length, local slope is insignificant. The full model compared to the reduced model, where each removes the insignificant predictor, gives a lower AIC value for the full model. All predictors are significant in the linear model when elevation is split into three groups even though analysis of variance displays insignificance. This discrepancy is due to how the class variable is treated between the linear model and analysis of variance. R^2 values for each response variable decrease significantly when reduced. Although the low relative importance of a single predictor in the model evaluated individually would appear to be insignificant, it greatly increases the explanatory power of the final model. Therefore the full model was chosen for interpretation.

The relative importance of independent variables was evaluated by comparing individual R^2 values of each predictor in the model. Elevation was treated as a class variable. High elevation was set to 0 and coefficients and p-values are provided for both low and middle elevations. For each model, individual R^2 values normalized to sum 100%, coefficients, and p-values are presented in Tables 2 and 3.

Table 2: Linear model for contributing area as dependent variable

Predictor variable	Relative importance	Coefficient	P-value
Basin length	0.569	1.61	<0.001
Local slope	0.195	-0.87	<0.001
Mean annual precipitation	0.045	1.01	0.057
Elevation	0.191		
low		1.13	0.004
middle		1.22	<0.001

Table 3: Linear model for basin length as dependent variable

Predictor variable	Relative importance	Coefficient	P-value
Contributing area	0.417	0.256	<0.001
Local slope	0.021	0.220	0.016
Mean annual precipitation	0.117	-0.373	0.078
Elevation	0.445		
low		-0.834	<0.001
middle		-0.570	<0.001

These models account for over half the variability within the data. In contrast to the simple linear regression, the multiple regression results support the hypothesis (H1) that surface topographic parameters are the dominant controls, although the models do not have sufficiently high explanatory power to reject the alternative that subsurface controls influence channel initiation. In summary, the combined results suggest that, although surface topographic parameters alone do not control channel initiation, they do exert an influence sufficient to explain about half of the variability between sites. The remaining significant variables, precipitation and elevation, are closely related to one another and could reflect differences in either surface or subsurface processes between sites. A Spearmans rank correlation coefficient test was run on elevation and mean annual precipitation. Although these variables are related, they were not found to be collinear.

3.2. Values of contributing area and basin length

Values for contributing area observed in the Front Range have a minimum threshold of approximately 10,000 m^2 and a maximum near approximately 600,000 m^2 (Figure 11). The mean value equals 108,258 m^2. A minimum value for basin length was observed at 120 m and maximum value of 1300 m. The mean value equals 435 m. Values of contributing area conducted in more humid regions range from 100 m^2 to 4,000 m^2. Basin length has been found in other studies to range from 25 m to 400 m. Contributing area and basin length have a positive relationship with each other (Figure 12). A significant relationship is observed when contributing area is regressed on basin

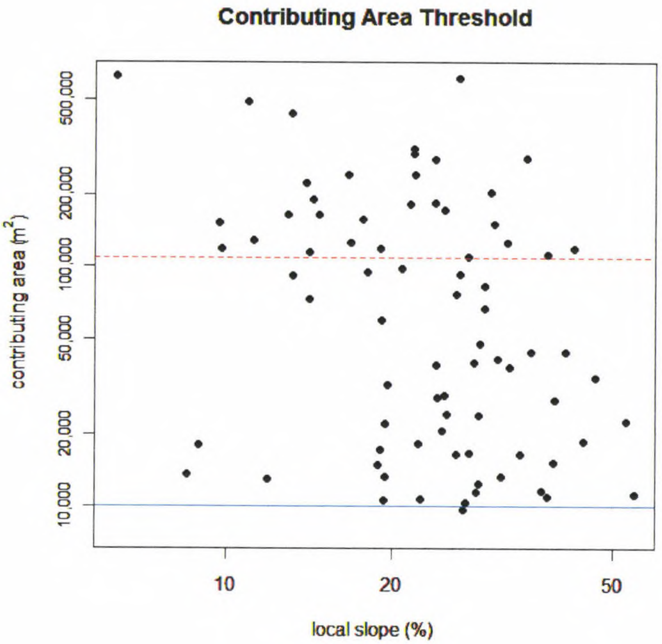

Figure 11: Graph displaying threshold value of contributing area (solid blue line) at approximately 10,000 m^2. The mean value is equal to 108,258 m (dotted red line).

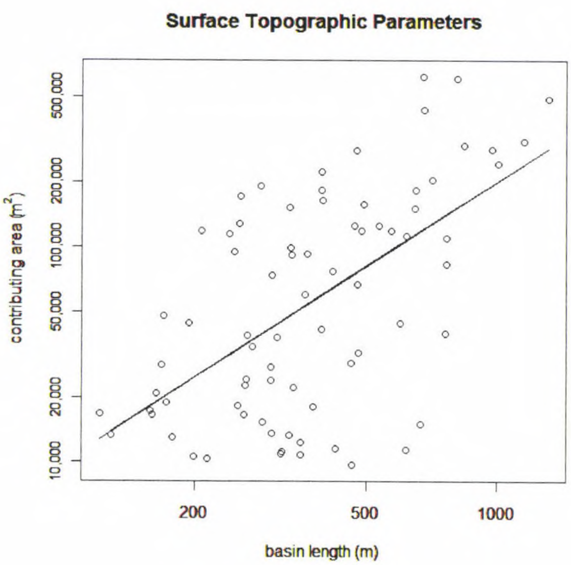

Figure 12: Contributing area regressed on local slope displaying a positive linear relationship between surface topographic parameters. R^2=0.42 and p-value <0.001.

length (R^2 = 0.42, p-value <0.001). These findings support hypothesis (H2) that values of contributing area and basin length are larger for semiarid regions compared to values for more humid regions.

A slope-area curve was produced representing all elevations including both watersheds (Figure 13). The curve was divided into four regions, following previous work (Ijjasz-Vasquez and Bras, 1995; Tucker and Bras, 1998; McNamara et al., 2006; Tarolli and Dalla Fontana, (2009). Region I, with a positive slope-area gradient, has been interpreted to represent hillslopes where sediment is transported by soil creep. Region II, with a negative slope-area gradient, has been interpreted to represent unchanneled valleys where channels initiate. Region III, where the slope-area gradient decreases,

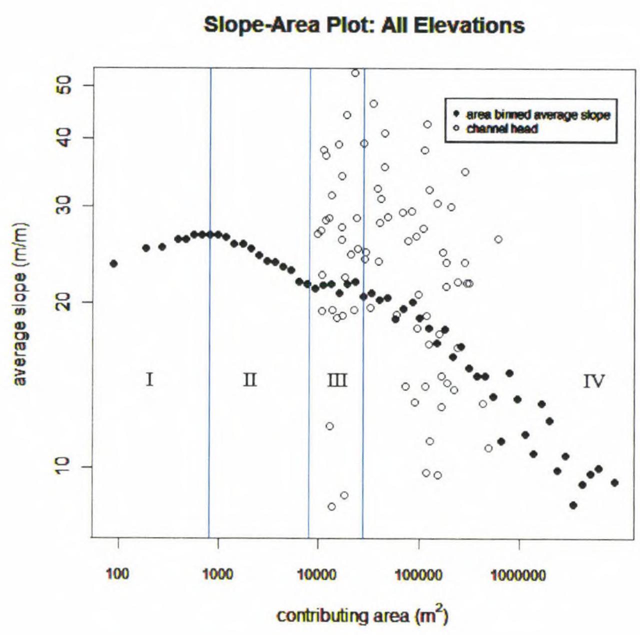

Figure 13: Slope-area plot. Blue lines signify transitions between regions denoted by inflections in the curve. See text for explanations of four regions.

represents a transition zone, and the higher negative slope-area gradient of region IV represents alluvial channels. Based on past interpretations, channel heads should thus plot at the boundary between regions I and II (e.g., Tarolli and Dalla Fontana, 2009; Yetemen et al., 2010). Field-mapped channel head locations from the Colorado Front Range plot at the threshold between regions II and III, although some extend well into region IV. Most actual drainage areas for channel initiation are thus an order of magnitude larger, and plot in a significantly different portion of the slope-area graph, than would be expected based on past work.

3.3. Aspect-related variances

Simple linear regressions on both contributing area and basin length against local slope were rerun as multiple regressions and evaluated statistically grouped by aspect to observe whether any significant differences occur in relation to aspect. The data were divided into a north-facing group and a south-facing group (Figure 10).

Graphical analysis indicated a possible difference in the relationship between north-facing and south-facing slopes for contributing area regressed on local slope (Figure 14). The null hypothesis that the slopes of the lines are equal to each other was evaluated using a t-test. The t-test failed to reject the null hypothesis, indicating that there is no statistically significant difference between the relationships for each line. Basin length was also tested using t-tests and failed to produce any significant results, as is readily observed graphically (Figure 14). The means for both contributing area and basin length grouped by aspect were tested for a significant difference using a t-test and

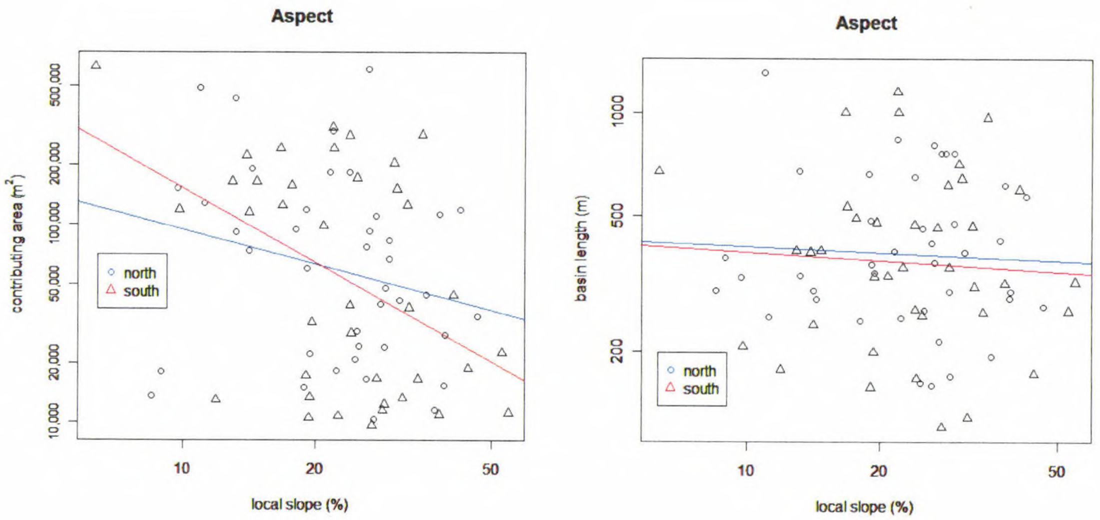

Figure 14: Contributing area and basin length regressed on local slope grouped by aspect. Summary statistics for regression lines are located in Table 4.

failed to produce significant results in both cases (Figure 15). The assumption of equal variance was met between groups for both area and length. Summary statistics for the regressions of contributing area and basin length grouped by aspect are presented in Table 4. The lack of significant results produced by categorizing the data by aspect indicates that there is no statistical evidence that the surface topographic parameters of contributing area and basin length vary as a function of aspect. The data thus should be analyzed as a complete dataset when making interpretations from the models produced. There is no interaction present between aspect and local slope.

Hypothesis (H3), which states that the area-slope and length-slope relationships vary as a function of aspect, is rejected. The location of channel heads downslope from the drainage divide does not vary as a function of aspect.

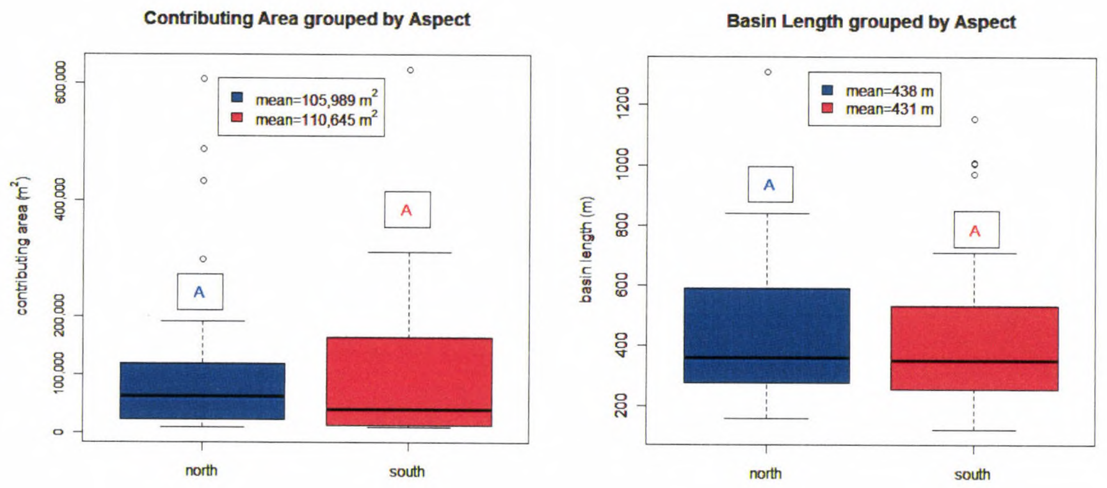

Figure 15: Boxplots of contributing area and basin length grouped by aspect. Similar letters show no significant differences between means.

Table 4: Summary statistics for contributing area and basin length regressed on local slope grouped by aspect

Predictor:	Elevation:	Adjusted R^2 value:	P-value:
Contributing Area	north-facing	0.03	0.14
	south-facing	0.17	0.006
Basin Length	north-facing	<0.01	0.74
	south-facing	<0.01	0.70

3.4. Elevation-related variances

Simple linear regressions on both contributing area and basin length against local slope were run grouped by elevation independently of aspect and rerun as multiple regressions to observe whether any significant differences in the relationship occur due to elevation. The data were divided into low, middle, and high elevation groups (Figure 10).

The graph of contributing area regressed on local slope grouped by elevation indicates a similar relationship between low and middle elevations with a possible difference for high elevation (Figure 16). The null hypothesis that the slopes of the lines are equal was tested using simple t-tests that yielded no significant results. Basin length displays similar slopes but appears to have different y-intercepts for each elevation (Figure 16). The null hypothesis that the intercepts are equal was tested using an F-test comparing the full model to the reduced model. The test produced significant results at the 0.001 level.

Box plots of contributing area and basin length grouped by elevation show significantly different results in median and mean values (Figure 17). The variance among groups was tested. The low elevation group has unequal variance in relation to the middle and high elevation groups for both area and length. A nonparametric t-test was conducted between groups with unequal variance. The mean values of contributing area for middle and high elevations are not statistically different from each other, but are significantly different than the mean for low elevation when tested with a t-test. A t-test also indicates significantly different means between low, middle, and high elevations for basin length. Summary statistics for the regressions of both contributing area and basin length are presented in Table 5.

Hypothesis (H4) is accepted in that surface topographic parameters contributing area and basin length vary as a function of elevation. The area-slope and length slope relationships show no significant difference when grouped by elevation.

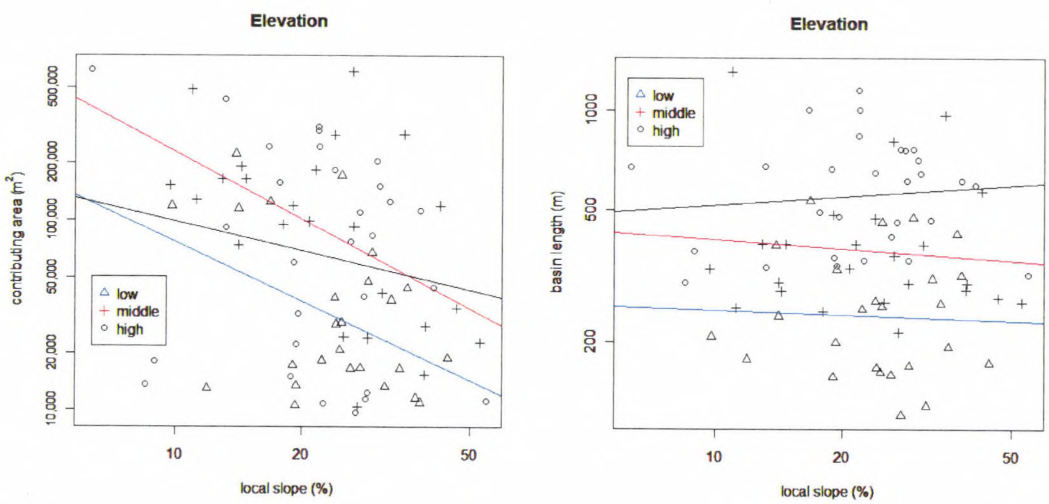

Figure 16: Contributing area and basin length regressed on local slope grouped by elevation. Summary statistics for lines located in Table 5.

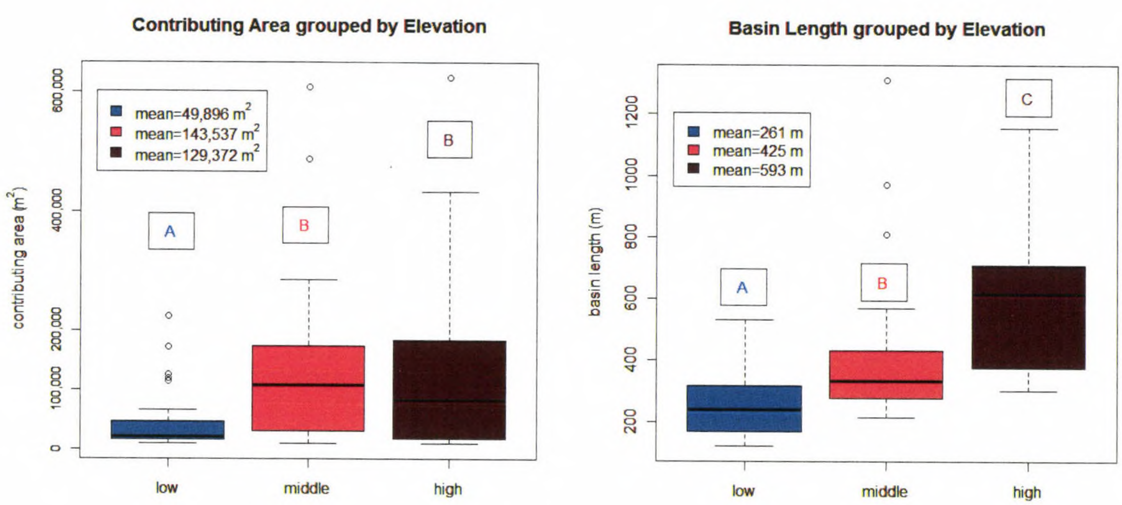

Figure 17: Box plot of contributing area and basin length grouped by elevation. Different letters show significantly different means between groups.

Table 5: Summary statistics for contributing area and basin length regressed on local slope grouped by elevation			
Predictor:	Elevation:	Adjusted R^2 value:	P-value:
Contributing Area	low	0.14	0.035
	middle	0.24	0.009
	high	<0.01	0.321
Basin Length	low	<0.01	0.846
	middle	<0.01	0.656
	high	<0.01	0.592

3.5. Alternative Variables

A variety of alternative variables including basin slope, channel type, width to depth ratio, soil type, and soil depth were explored to test the influence of each on channel initiation. These variables were used in simple linear regressions run against local slope. No significant relationships resulted from any of these regressions. They were included in model selection and again proved not to be significant. Therefore these parameters were left out of the final multiple regression models developed. These data are included in the appendices.

4. Discussion

4.1. Surface topographic controls on channel initiation

Simple linear regressions of both contributing area and basin length on local slope suggest that these surface topographic parameters shown to exert a large control in more humid regions do not exert as strong an influence on channel initiation in the semiarid Colorado Front Range. Montgomery and Dietrich (1989) observed an R^2 value of 0.75 for contributing area and an R^2 value of 0.47 for basin length. These values are much higher than an adjusted R^2 value of 0.11 for contributing area and an adjusted R^2 value of -0.01 for basin length. A much greater amount of the variability is unaccounted for by the simple least squares models developed for the Front Range. Although the R^2 values are low, an inverse relationship is still present for contributing area. This trend follows the inverse area-slope relationship observed by previous researchers (Montgomery and Dietrich, 1989; Roth and La Barbera, 1997; Roth et al., 1996).

Multiple regression results provide a strong caveat on interpreting the linear regression results, in that they highlight the importance of topographic parameters. Models developed for both contributing area and basin length yielded the same significant predictors; local slope, mean annual precipitation, elevation, and contributing area or basin length, depending on which was the response variable. Local slope was present in both models. The gradient directly upslope of the channel head is important for overcoming the threshold of erosion necessary to initiate a channel. Mean annual precipitation increases with elevation. Both these variables were significant in the models and show that the amount of water delivered to the channel head is an important control. Although precipitation and elevation are related, they proved to be uncorrelated. Both contributing area and basin length were significant predictors for the regression run on the opposite variable. I interpret this to mean that they are related, as seen in the regression of contributing area on basin length (Figure 12), and are both important factors in channel initiation.

A potential double threshold can be interpreted from the data presented here. A minimum threshold value of 10,000 m^2 appears to be necessary to initiate a channel at any slope (Figure 11). Above ~19% there is no predictable value for contributing area (Figure 9), suggesting that slope-area relations break down above this threshold slope, perhaps because local features such as bedrock surface constrictions exert greater influence on channel initiation. Multiple regression analysis contributes to an explanation of the variability within the data.

The multiple regression models developed here increase our explanation for surface controls on channel initiation but do not provide a complete understanding of primary drivers. It is likely that subsurface properties account for some of the variability in the models, although subsurface parameters were not measured as part of this study. Large regional jointing and shallow subsurface flow are hypothesized to be the two largest influencing subsurface properties.

I interpret these results to indicate that neither surface nor subsurface topographic parameters and processes are the dominant control on channel initiation. Instead, a complex system of both surface and subsurface controls is likely to interact to create the present morphology of headwater streams in the Front Range.

The data presented here are collected from two watersheds in the Colorado Front Range and are assumed to be representative of the region as a whole. These results likely can also be applied to other regions with similar climate, lithology, and geomorphology. These data can improve current theoretical models by providing a field test of these models and by exploring additional parameters beyond area and length that may influence the location of channel initiation. Precipitation, elevation, and slope were shown to be significant and should be considered when developing landscape evolution and channel network growth models.

4.2. Values of contributing area and basin length

Montgomery and Dietrich (1989) observed values of contributing area ranging from 100 m^2 to 4,000 m^2 and values of basin length ranging from 50 m to 400 m for the Tennessee Valley in California. Montgomery and Dietrich (1992) collected data from a variety of small drainage basins, putting finite limits on landscape dissection on both contributing area and basin length. They observed a minimum and maximum threshold value for surface contributing area ranging from 500 m^2 to 4,000 m^2. They also observed a minimum and maximum threshold value for basin length ranging from 25 m to 200 m. The values observed by these researchers are much less than minimum values observed for the Front Range. Contributing area in the Front Range is similar to Montgomery and Dietrich data in that it exhibits a minimum threshold value to initiate a channel. A maximum value was not observed, with extreme values of contributing area over 600,000 m^2. Neither minimum nor maximum threshold values for basin length were observed in the Front Range data.

The Colorado Front Range displays much larger values of contributing area and basin length than studies in humid regions. Hillslope processes on different soil types and thicknesses could affect these values. Substantial bedrock jointing at the Front Range sites also can potentially direct water laterally downward into the ground, necessitating a greater volume of water to initiate a channel. The larger minimum values of both contributing area and basin length in the semiarid Front Range relative to those in more humid regions likely reflect fundamental differences associated with hydroclimatic contrasts between regions. The diverse climates produce different infiltration rates, peak discharges, vegetation cover, and soil properties.

Findings in central New Mexico based on digital elevation models indicate that channel initiation occurs at approximately 600 m^2 at low elevations and 1000 m^2 at middle elevations (Yetemen et al., 2010). This area is similar in elevation and climate to the northern Colorado Front Range and the threshold for channel initiation increases with elevation, similar to the Front Range. The similar trends in area and length with elevation support the assertion that results from the Front Range field sites can also provide insight into channel initiation patterns in other semiarid regions.

Channel initiation has been interpreted to occur at the inflection in the slope-area relationship from positive to negative (Tarolli and Dalla Fontana, 2009). The data presented here indicate that this is not necessarily the case. Channel heads in the Front Range plot beginning in region III and extend well into region IV (Figure 13), in contrast to studies based solely or primarily on assumptions that have not been verified with field data, which plot channel heads in regions I and II (e.g., Tarolli and Dalla Fontana, 2009). The Front Range data indicate that assumptions about the locations of channel heads in relation to inflections in slope-area plots need to be verified with field data, particularly for semiarid regions with substantial subsurface flow.

4.3. Aspect

Surface topographic parameters contributing area and basin length were not found to differ significantly in their relationships with local slope when grouped by aspect (Figure 14). Aspect was also found not to be significant in model selection. Aspect does not interact with local slope or any other variables to produce statistically significant differences in area and length. Although it has been well documented that aspect can produce microclimates affecting dominant vegetation type and soil characteristics, this analysis does not show that it is an influential control on channel initiation. Soil depth and soil type were also found not to be significant in the model selection analysis. Differences in soil properties have been correlated with differences in vegetation relative to a given aspect. A lack of both an aspect interaction and a soil interaction in the final model is interpreted to indicate that the factors associated with aspect do not significantly affect channel initiation. These would include variables not measured in the field such as vegetation, residence time for snow, microclimate, and soil properties (i.e., infiltration rates). Surface and subsurface controls that dominate channel initiation thus do not appear to be affected by the orientation of the slope.

4.4. Elevation

Elevational zonation in the semiarid Colorado Front Range influences climate. Precipitation increases with elevation and a transition from convective rainfall to snowmelt hillslope processes occurs at approximately 2300 m. Field sites were chosen to represent low, middle, and high elevation bands and data were grouped accordingly and tested for differences between elevations.

Contributing area regressed on local slope grouped by elevation proved not to be significant with a t-test, but graphical analysis indicates a potentially different relationship for high elevation than lower elevations (Figure 16). High elevation sites are located above treeline and many channel heads occupied mountain cirques not present at lower elevations. The morphology of the landscape was notably different at higher elevations than at lower elevations, and it is quite possible that with more data from higher elevations the slopes of the lines could be statistically significantly different. This would support the interpretation that the relationship between contributing area and local slope is different at higher elevations than it is at low and middle elevations.

The mean values for middle and high elevation sites are statistically significantly different than the mean value for low elevation sites (Figure 17). Middle elevation sites start at approximately the transition from convective rainfall to snowmelt runoff processes. Middle and high elevations do not have significantly different means. This is interpreted to reflect a threshold value for mean contributing area at elevations above 2300 m. Sites above 2300 m have statistically significantly larger values for contributing area than do those below 2300 m.

Basin length regressed on local slope grouped by elevation displayed significant differences in the y-intercepts (Figure 16) and means (Figure 17). The mean values also increase linearly with elevation. This observation is counter-intuitive given the fact that precipitation increases with elevation. For a greater amount of precipitation, the threshold of erosion should be overcome over a shorter distance, decreasing the length to the drainage divide. Instead, an increase in basin length was observed. This is interpreted to reflect the volume of large floods at different elevations. At low elevations, convective rainfall storms create short duration, intense rainfalls generating high discharge peak floods. These floods are predominantly surface runoff and may initiate channels closer to the drainage divide. At higher elevations, lower peak discharges due to snowmelt delay the delivery of water via surface runoff and may allow for more water to enter the subsurface, creating greater basin lengths for channel initiation.

4.5. Additional observations

Channel initiation points were observed in the field to be controlled by boulder or wood constrictions at the location of the channel head (Figure 18). Fifty-two of the 78 points mapped and used for analysis contained a stabilizing constriction. Channel heads were mapped in areas with minimal recent disturbances from land use (e.g., timber harvest) or stand-clearing forest fires. This period of relative land cover stability allowed channel heads to migrate upslope or downslope to an equilibrium position.

Sixty-seven percent of channel initiation points were observed to have boulder constrictions causing stable channel heads. The upslope erosion of headwater streams that are actively eroding on a given slope can be halted when intersecting a large subsurface topographic constriction such as a boulders or tree roots. The constriction limits channel head migration until a flood can move these large particles or initiate

Figure 18: Field photograph of boulder constriction indicating stability of channel head. Channel is an ephemeral headwater steam. Note 1 m staff for scale.

channel incision above the channel head. There was no evidence in the field of debris-flow processes depositing these boulders at their current location. Instead, these boulders are interpreted to result from weathering of *in situ* bedrock or from weathered bedrock with minimal downslope transport. (The data in Figure 9 were also plotted using different symbols for constricted and unconstricted channel heads, but no new trends were detected as a result of this differentiation of the data. These alternate figures are in Appendix D).

The apparent importance of channel constrictions in triggering the formation of channel heads has implications for landscape evolution models. If local, site-specific controls such as boulder constrictions are responsible for much of the scatter in the slope-area relationship (Figure 9), this may obscure trends across multiple sites or regions, making it more appropriate to conceptualize channel initiation in terms of thresholds rather than linear correlations between topographic parameters.

Although each field site was visited only once, precluding definitive evaluation of perennial versus ephemeral flow at each channel head, the stream head was observed to be present at the channel head for many bedrock-constricted channel initiation points (Figure 19). Bedrock topography or some other subsurface parameter forces shallow subsurface flow to the surface at the location of the channel head. For these conditions, channel heads are stable due to return flow from the subsurface that incises a channel at a point downslope from the drainage divide.

Figure 19: Field photograph displaying discharge of subsurface flow at channel head influenced by bedrock topography. Channel is a perennial headwater stream. Note 1 m staff for scale.

In multiple locations across the field sites, the presence of preferential subsurface flow was suggested by abrupt channel heads at springs. Piping is the development of preferential subsurface drainage associated with lateral and vertical differences in porosity and permeability (Parker, 1963). Piping is likely to explain some of the variability in channel head location that was not accounted for by surface topographic parameters (Figure 20). The existence of piping and springs further indicates the importance of groundwater flow and complex flow paths, and the interactions among surface and subsurface processes leading to channel initiation.

Figure 20: Field photograph of piping feature showing significance of subsurface flow.

5.1. Conclusion

Channel initiation in the semiarid Colorado Front Range is governed by both surface and subsurface controls. Surface topographic parameters including contributing area, basin length, and local slope influence channel initiation but do not exert as strong an influence as they have been documented to exert in more humid regions. Bedrock topography and subsurface properties also appear to strongly influence channel initiation, although they were not directly measured in this study.

Over a wide range of slopes, the semiarid climate of the Colorado Front Range exhibited larger values of contributing area and basin length relative to local slope than regions with a wetter climate. A threshold value for contributing area was observed at approximately 10,000 m^2. These findings highlight the importance of regional variability for geomorphic processes due to differences in climate, vegetation, and lithology.

Aspect was found to have no effect on channel initiation in the Front Range. Data collected on a variety of different slopes representing both north- and south-facing orientation indicated no significantly different relationships based on aspect.

Elevation was observed to affect channel initiation. Basin length increases linearly with increasing elevation. Peak discharges are lower at higher elevations, presumably due to snowmelt runoff processes, and higher at lower elevations, likely as a result of convective rainfall. The transition from rainfall to snowmelt alters the volume and rate of infiltration, and downslope pathways of runoff, making it necessary for more area and length to overcome the threshold of erosion necessary for channel initiation.

Subsurface flow appears to be a prominent feature of the hillslopes studied.

Water infiltrates into the ground and is directed back to the surface through bedrock topography. The importance of bedrock topography is displayed through both the lack of highly correlated relationships between surface topographic parameters and observations in the field of the prominence of subsurface flow.

The data collected and analyzed in this study are assumed to be representative of the Colorado Front Range. Similar results in both the Cache la Poudre and North St. Vrain watersheds in the Front Range support the ability to extrapolate from these data to a broader geographic region or to other sites with similar regional climate and lithology. The fact that field data indicate larger initial values of both area and length (i) than demonstrated for wetter regions, (ii) than assumed based on inflection points in regional slope-area curves, and (iii) with elevation, provide corrections to existing widely used assumptions, and these corrections can be applied to theoretical models. These data will aid in improving current methods of developing drainage basins using remote data by more accurately depicting drainage density. Current practices of mapping the spatial extent of channel initiation points using digital elevation models underestimate contributing area, as mapped in the field for this study, by approximately an order of magnitude. The results from this study thus allow for more accurate representation of drainage basin characteristics and aid in comparisons across drainage basins.

5.1. Future work

To fully understand channel initiation in the semiarid Colorado Front Range would necessitate increased knowledge of subsurface processes influencing channel initiation. Detailed mapping of bedrock topography and subsurface flow paths would allow for better estimating how water is relayed to the channel head. A study of subsurface processes would need to be conducted at low, middle, and high elevation bands and on both north- and south-facing slopes to account for variability potentially present in the subsurface in relation to aspect and elevation.

Mapping perennial flow for headwater streams would allow further analysis of the relative importance of surface and subsurface flow. Channel heads that coincide with the stream head and are fed by subsurface flow year-round could be placed in one category, while ephemeral channels with seasonally dry channel heads fed by storms could be placed in another. An analysis of these two distinct channel types at the channel head would increase our understanding of how both surface and subsurface processes affect channel initiation. Channel heads were not revisited to confirm whether those observed to be fed by subsurface flow were in fact perennial streams. Many channel heads mapped were ephemeral streams. Values of contributing area and basin length for perennial channels in the Front Range therefore may be larger than those documented in this study.

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7. Appendices

7.1. Appendix A: Raw Data

Legend for continuous variables		
Header	Variable	Units
CA	Contributing area	m^2
Slope	Local slope	m/m
Basinslope	Basin slope	m/m
W.D	Width to depth	m/m
SoilDepth	Soil Depth	cm
Length	Basin length	m
MAP	mean annual precipitation	in

Point	Identifier	Watershed	Elevation
CG	Coulson Gulch	North St. Vrain	low
RG	Rattlsnake Gulch	North St. Vrain	low
BG	Bear Gulch	North St. Vrain	low
SL	Sunset Lake	North St. Vrain	low
HP	Horsetooth Peak	North St. Vrain	middle
LM	Lookout Mountain	North St. Vrain	middle
RC	Roaring Creek	Cache la Poudre	middle
DG	Dadd Gulch	Cache la Poudre	middle
BL	Browns Lake	Cache la Poudre	high
OL	Ouzel Lake	North St. Vrain	high
TL	Thunder Lake	North St. Vrain	high
CL	Comanche Lake	Cache la Poudre	high
RF	Rawah Forest	Cache la Poudre	high

Number	Point	LAT	LONG	Elev	Elevation	CA	Slope	Basinslope
1	CG2	40.246	-105.409	low	2332	11000	38.1	29.9
2	CG3	40.242	-105.409	low	2329	18800	44.3	33.1
3	CG4	40.242	-105.408	low	2338	16600	26.1	28.6
4	CG5	40.250	-105.408	low	2366	13000	11.9	14.7
5	CG6	40.234	-105.410	low	2292	13300	31.5	12.5
6	CG8	40.236	-105.407	low	2243	16600	34.1	25.3
7	CG9	40.237	-105.408	low	2243	47600	28.7	25.7

8	CG10	40.240	-105.407	low	2258	44100	35.5	33.3
10	RG2	40.247	-105.404	low	2357	16700	27.5	15.9
11	RG3	40.248	-105.402	low	2347	17300	19.0	19.2
12	RG4	40.249	-105.401	low	2344	10600	19.3	17.2
13	RG5	40.252	-105.402	low	2351	13400	19.4	15.5
14	RG6	40.253	-105.405	low	2340	28300	24.1	22.9
15	RG7	40.253	-105.399	low	2291	20800	24.6	18.0
16	RG8	40.253	-105.398	low	2297	38900	23.9	20.1
17	CG11	40.248	-105.416	low	2390	38000	32.5	23.2
18	CG12	40.247	-105.420	low	2453	18300	22.3	19.2
19	CG13	40.244	-105.420	low	2451	115300	14.1	16.8
20	BG1	40.240	-105.430	low	2424	172600	24.8	24.2
21	BG2	40.239	-105.430	low	2485	28900	24.8	22.6
22	BG3	40.238	-105.434	low	2509	119200	9.8	13.1
23	BG4	40.236	-105.431	low	2450	224200	13.9	13.3
24	SL1	40.250	-105.417	low	2390	11600	37.2	29.2
25	SL2	40.250	-105.416	low	2384	67100	29.3	27.9
26	SL3	40.248	-105.425	low	2510	125200	16.8	12.6
27	HP1	40.231	-105.552	middle	2846	34500	46.4	38.2
28	LM1	40.235	-105.565	middle	2926	284898	34.8	36.5
29	LM2A	40.223	-105.573	middle	3006	608600	26.3	20.5
36	RC1	40.725	-105.759	middle	2926	164900	12.9	18.0
37	RC2	40.725	-105.759	middle	2926	164900	14.7	18.0
38	RC4	40.730	-105.770	middle	2979	22700	52.8	28.1
39	RC5	40.735	-105.771	middle	2900	119500	42.5	26.6
40	RC6	40.736	-105.776	middle	3011	10400	27.1	21.5
41	RC7	40.739	-105.777	middle	2976	23900	28.6	25.9
42	RC8	40.756	-105.786	middle	3060	128463	11.2	12.9
43	RC9	40.770	-105.775	middle	3048	98420	20.8	24.4
44	RC11	40.758	-105.764	middle	3036	183112	21.5	32.7
45	RC14	40.759	-105.756	middle	3109	92462	26.5	20.9
46	RC15	40.753	-105.760	middle	3119	94793	18.0	25.5
47	RC16	40.756	-105.751	middle	3123	191141	14.3	21.1
48	DG1	40.684	-105.542	middle	2351	281600	23.8	20.5
49	DG2	40.683	-105.542	middle	2401	15300	39.1	30.4
50	DG3	40.680	-105.544	middle	2472	118500	19.0	18.0
51	DG4	40.677	-105.549	middle	2473	27700	39.2	32.0
52	DG5	40.677	-105.551	middle	2456	152800	9.7	23.2
53	DG7	40.674	-105.569	middle	2581	24300	25.1	20.7
54	DG8	40.673	-105.571	middle	2586	41200	31.0	15.7
55	DG9	40.680	-105.579	middle	2569	487300	10.9	10.5

56	DG11	40.683	-105.557	middle	2440	73500	14.1	15.0
57	BL1	40.599	-105.656	high	3165	310900	21.8	12.5
58	BL2	40.603	-105.660	high	3218	242850	21.9	18.5
59	BL3	40.603	-105.660	high	3218	242850	16.6	18.5
60	BL4	40.611	-105.692	high	3342	11200	54.6	23.8
30	OL1	40.201	-105.635	high	3081	44000	41.0	38.9
31	OL2	40.204	-105.643	high	3350	125800	32.2	54.5
33	OL4	40.196	-105.647	high	3263	22200	19.4	39.3
34	OL5	40.201	-105.634	high	3077	112500	38.2	38.2
35	TL1	40.210	-105.614	high	2983	32100	19.6	50.0
61	BL5	40.615	-105.682	high	3425	10800	22.5	14.3
62	CL2	40.599	-105.706	high	3283	151400	30.5	21.1
63	CL3	40.598	-105.708	high	3279	9700	26.8	20.5
64	CL4	40.597	-105.708	high	3247	11500	28.4	17.9
65	CL5	40.592	-105.717	high	3376	12400	28.6	12.8
66	CL6	40.586	-105.721	high	3472	110500	27.4	17.8
67	CL7	40.586	-105.721	high	3474	39600	28.1	17.6
68	CL8	40.586	-105.722	high	3489	15000	18.8	17.8
69	CL9	40.582	-105.705	high	3429	297400	21.8	13.2
70	CL10	40.583	-105.706	high	3425	18000	8.9	16.6
71	CL11	40.575	-105.700	high	3222	184200	23.8	41.8
72	CL12	40.567	-105.709	high	3375	59600	19.1	13.4
73	CL13	40.567	-105.709	high	3373	91500	13.2	15.9
74	RF1	40.665	-105.920	high	3105	83300	29.4	58.0
75	RF2	40.671	-105.915	high	3235	625500	6.3	32.0
76	RF3	40.669	-105.913	high	3245	205500	30.1	22.3
77	RF5	40.683	-105.909	high	3330	158200	17.6	10.6
78	RF6	40.681	-105.902	high	3247	13700	8.5	28.2
79	RF7	40.679	-105.903	high	3280	433000	13.1	16.5
80	RF8	40.674	-105.898	high	3253	76600	26.0	22.2

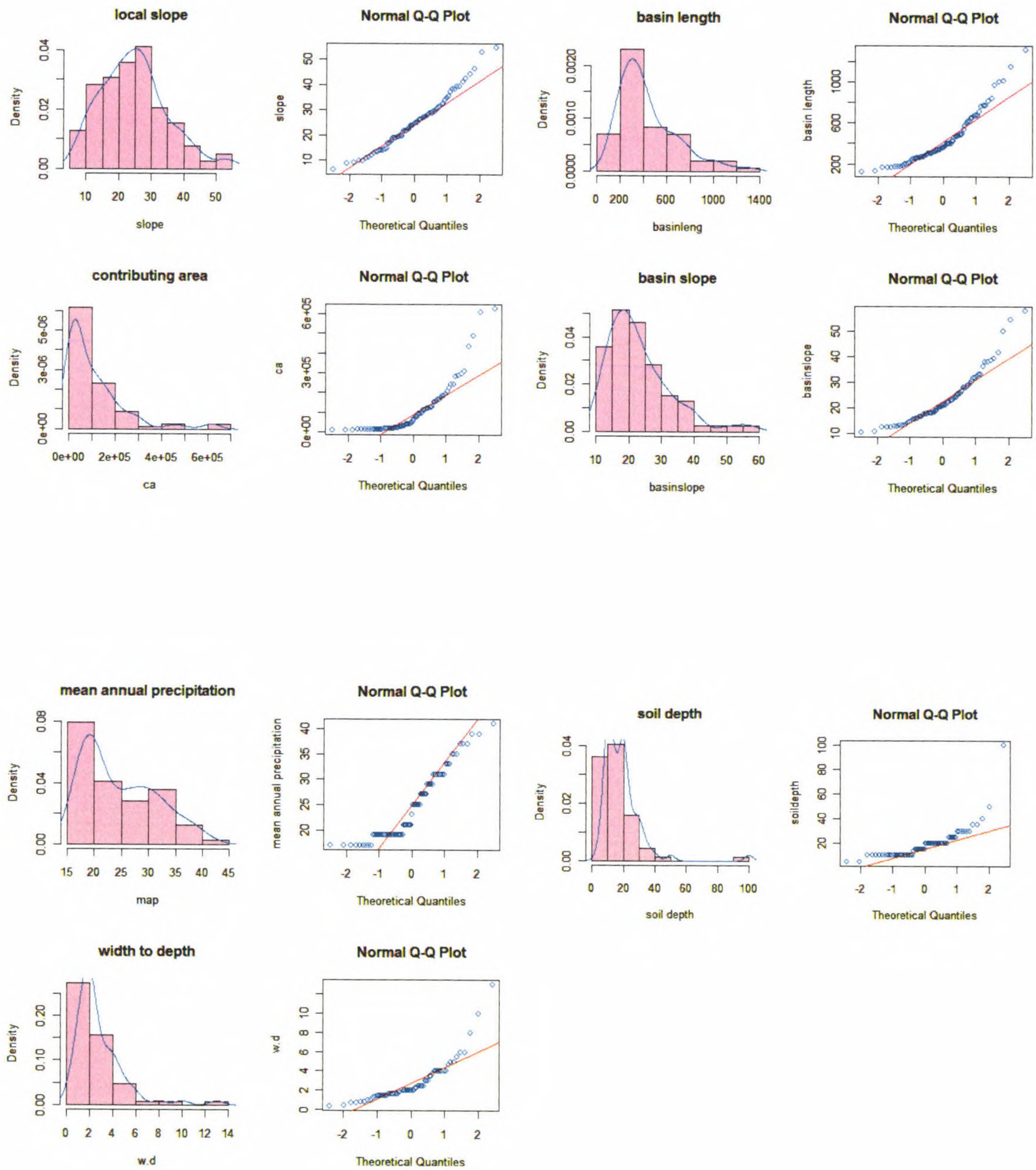
Number	Point	Aspect	Type	W.D	Soil type	Soildepth	Length	MAP
1	CG2	south	abrupt	5.5	siltsand	10	316	19
2	CG3	south	abrupt	1.3	siltsand	10	172	19
3	CG4	north	abrupt	0.5	siltsand	10	159	19
4	CG5	south	abrupt	1.5	siltsand	25	177	19
5	CG6	south	abrupt	1.7	sand	10	128	19
6	CG8	south	abrupt	5.0	siltsand	15	260	19
7	CG9	north	abrupt	2.5	siltsand	15	169	19

8	CG10	north	abrupt	3.0	siltsand	10	193	19
10	RG2	south	abrupt	1.5	sand	10	120	19
11	RG3	south	abrupt	6.0	sand	10	157	19
12	RG4	south	abrupt	1.7	sand	10	199	19
13	RG5	south	abrupt	8.0	sand	10	330	19
14	RG6	south	abrupt	3.5	sand	15	167	19
15	RG7	north	abrupt	1.5	siltsand	15	162	19
16	RG8	south	abrupt	0.4	siltsand	10	265	19
17	CG11	south	abrupt	1.8	sand	10	309	19
18	CG12	north	abrupt	13.0	sand	10	251	19
19	CG13	south	abrupt	2.0	siltsand	20	239	19
20	BG1	south	abrupt	4.0	siltsand	20	255	19
21	BG2	north	abrupt	4.0	siltsand	NA	459	21
22	BG3	south	abrupt	4.0	sand	25	207	21
23	BG4	south	abrupt	4.7	sand	35	391	21
24	SL1	north	abrupt	1.7	sand	20	424	19
25	SL2	north	abrupt	2.5	sand	15	475	19
26	SL3	south	grad	NA	sand	25	533	19
27	HP1	north	grad	NA	sand	NA	271	27
28	LM1	south	zone	NA	sand	NA	971	31
29	LM2A	north	abrupt	1.5	sand	NA	809	33
36	RC1	south	abrupt	0.8	clay	30	395	21
37	RC2	south	abrupt	2.5	clay	35	395	21
38	RC4	south	abrupt	NA	sand	14	262	23
39	RC5	north	abrupt	1.5	siltsand	20	569	25
40	RC6	north	abrupt	2.5	sand	10	214	25
41	RC7	north	abrupt	NA	sand	NA	299	25
42	RC8	north	abrupt	4.0	clay	20	253	27
43	RC9	south	abrupt	3.5	clay	NA	333	29
44	RC11	north	abrupt	2.0	sand	10	393	29
45	RC14	north	abrupt	4.0	sand	20	363	31
46	RC15	north	zone	NA	siltsand	20	246	29
47	RC16	north	abrupt	4.0	clay	20	284	29
48	DG1	south	abrupt	1.7	siltsand	40	471	17
49	DG2	north	abrupt	2.0	sand	15	287	17
50	DG3	north	abrupt	5.0	sand	20	485	17
51	DG4	north	abrupt	1.5	sand	15	299	17
52	DG5	north	abrupt	1.9	siltsand	50	330	17
53	DG7	north	grad	NA	sand	30	263	17
54	DG8	north	grad	NA	sand	25	391	17
55	DG9	north	abrupt	1.7	sand	10	1312	17

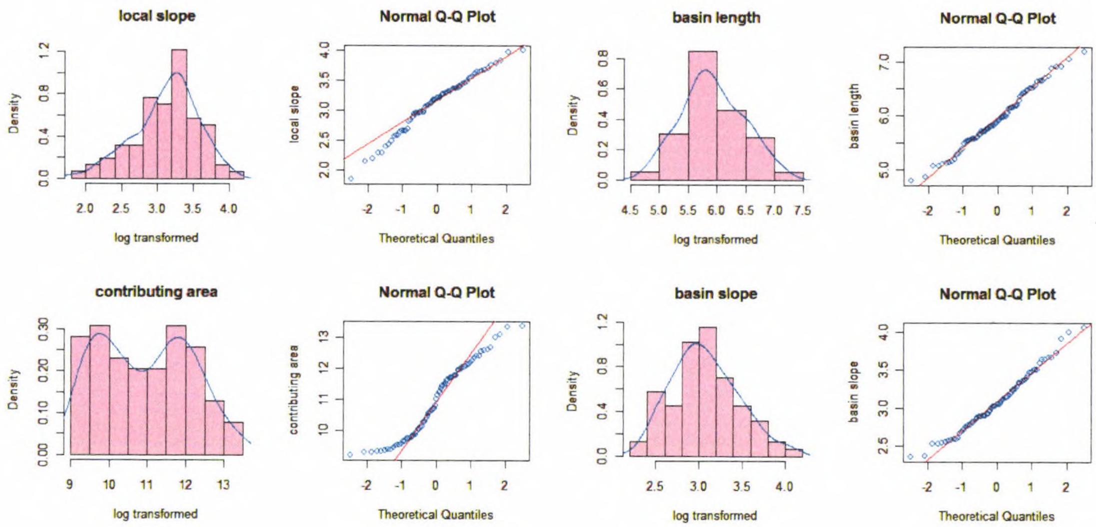
56	DG11	north	abrupt	4.0	sand	10	302	17
57	BL1	south	abrupt	3.0	siltsand	25	1154	21
58	BL2	south	abrupt	1.7	sand	10	1007	21
59	BL3	south	abrupt	2.3	clay	10	1005	21
60	BL4	south	abrupt	NA	NA	NA	319	25
30	OL1	south	abrupt	10.0	sand	20	596	37
31	OL2	south	abrupt	NA	NA	NA	466	39
33	OL4	north	abrupt	2.0	sand	30	339	41
34	OL5	north	abrupt	2.0	sand	20	616	37
35	TL1	south	abrupt	2.0	sand	20	478	35
61	BL5	south	abrupt	2.0	sand	10	352	25
62	CL2	south	abrupt	0.8	sand	5	644	25
63	CL3	south	abrupt	6.0	sand	15	462	27
64	CL4	south	zone	NA	clay	10	616	27
65	CL5	south	abrupt	2.0	sand	10	352	29
66	CL6	north	abrupt	1.0	clay	20	764	31
67	CL7	north	abrupt	3.0	sand	10	761	31
68	CL8	north	abrupt	1.0	sand	20	665	31
69	CL9	north	zone	NA	sand	15	841	27
70	CL10	north	abrupt	1.7	sand	10	376	27
71	CL11	north	zone	NA	siltsand	30	650	25
72	CL12	north	abrupt	3.8	sand	5	359	31
73	CL13	north	abrupt	2.0	siltsand	20	334	31
74	RF1	north	abrupt	2.3	sand	20	765	39
75	RF2	south	abrupt	0.7	sand	30	675	37
76	RF3	south	abrupt	2.0	sand	20	709	35
77	RF5	south	abrupt	2.5	NA	NA	492	35
78	RF6	north	abrupt	0.7	sand	100	301	33
79	RF7	north	abrupt	1.4	siltsand	20	677	33
80	RF8	north	grad	NA	sand	30	417	31

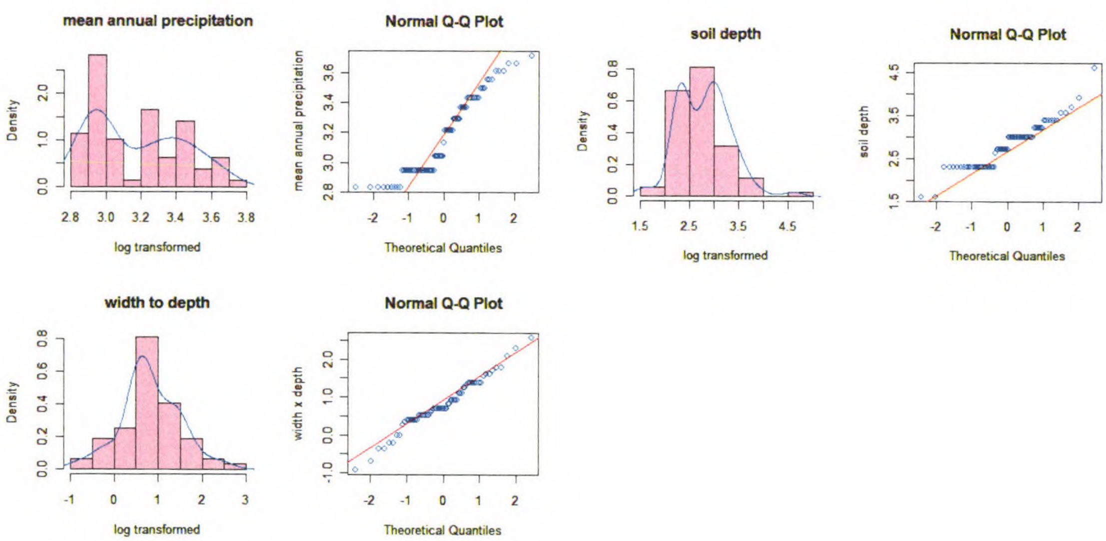
7.2. Appendix B: Variables and statistical analyses not included in thesis

Histograms and qqplots of continuous variables before log transformation

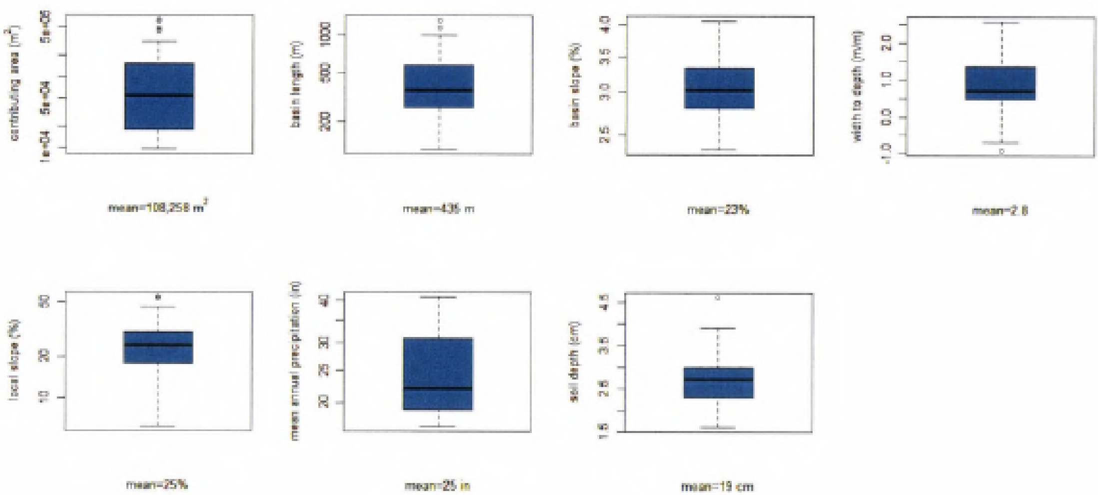


Histograms and qqplots of continuous variables after log transformation



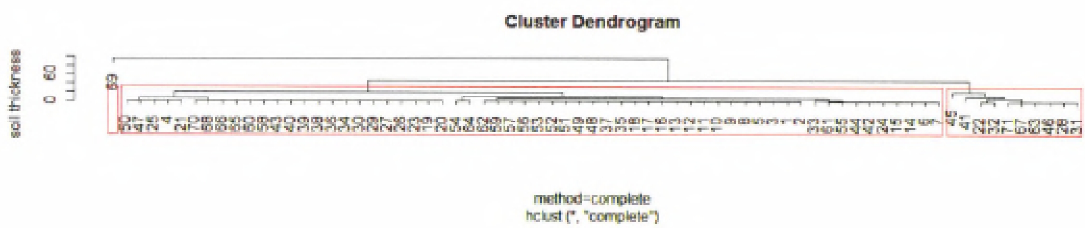


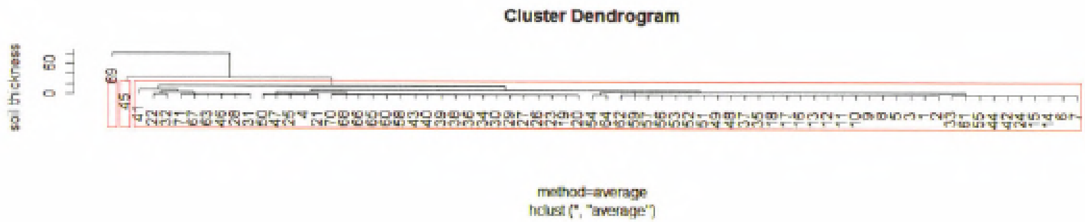
Boxplots of all continuous variables on log scale



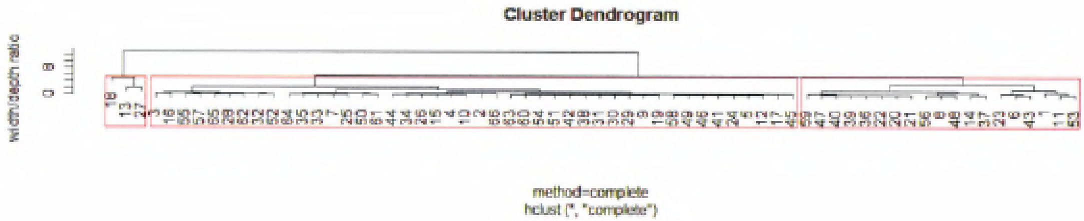
Cluster anlysis

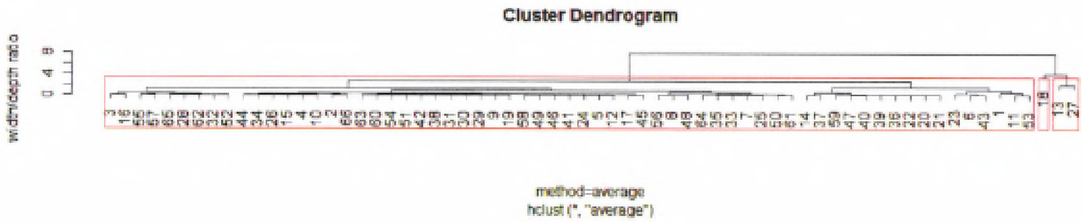
Soil Depth



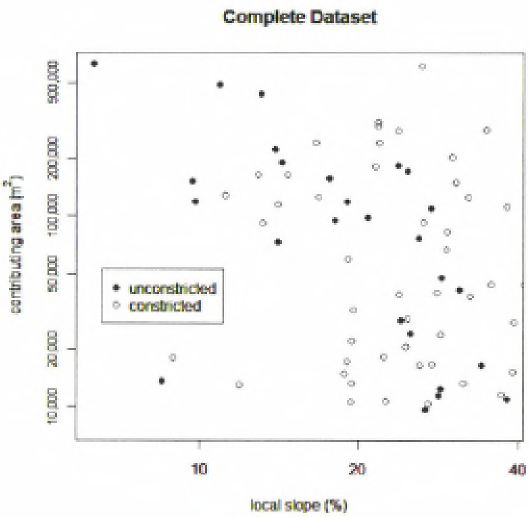


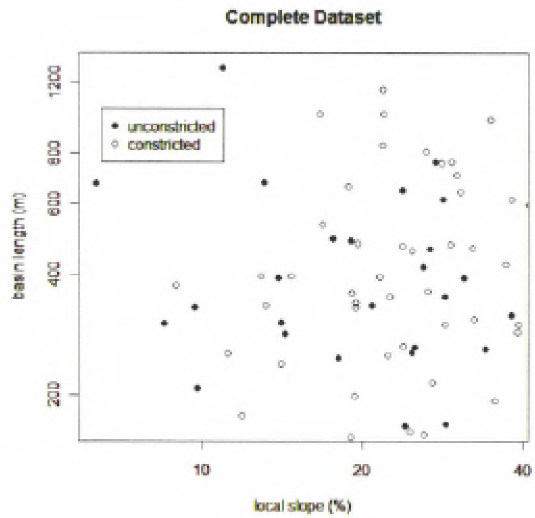
Width to depth ratio



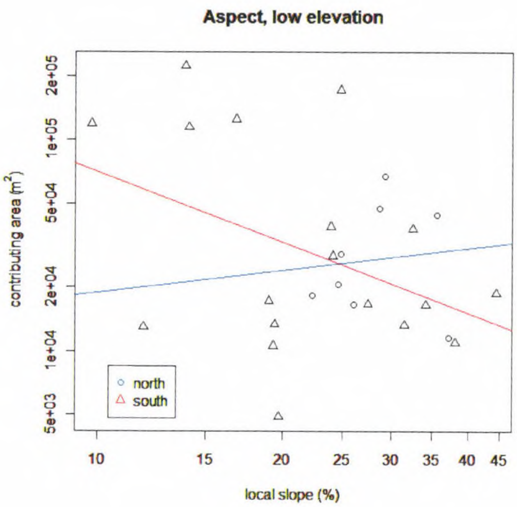


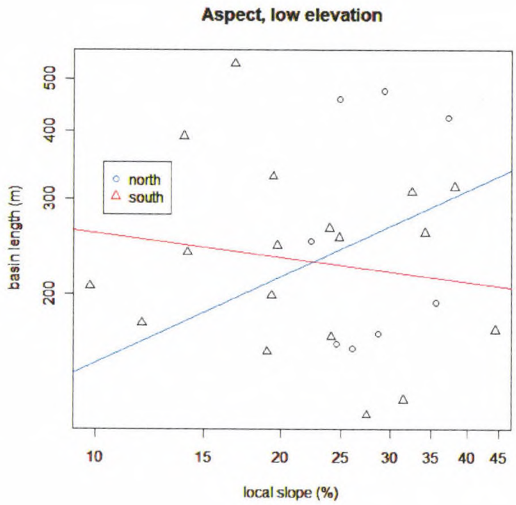
Area and length regressed on local slope: data divided between restricted and unrestricted:



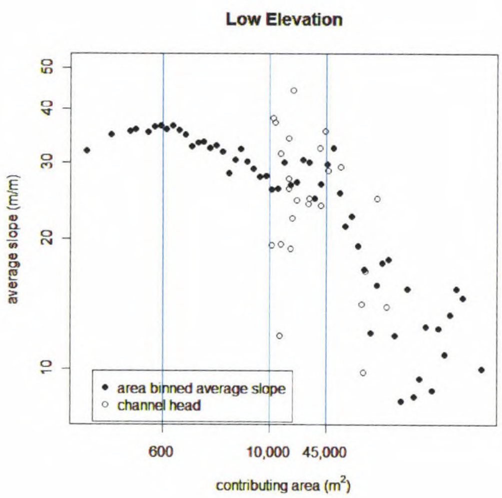


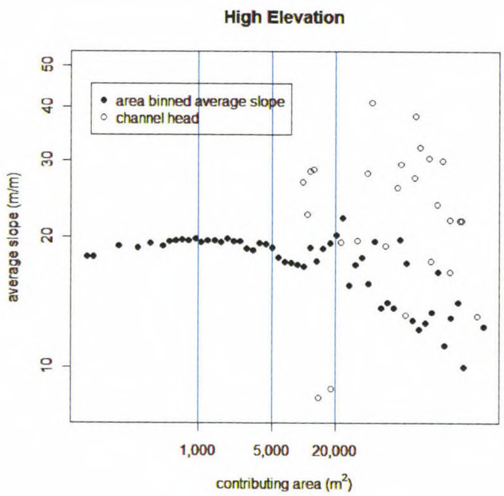
Contributing area and basin length split by aspect for low elevation data

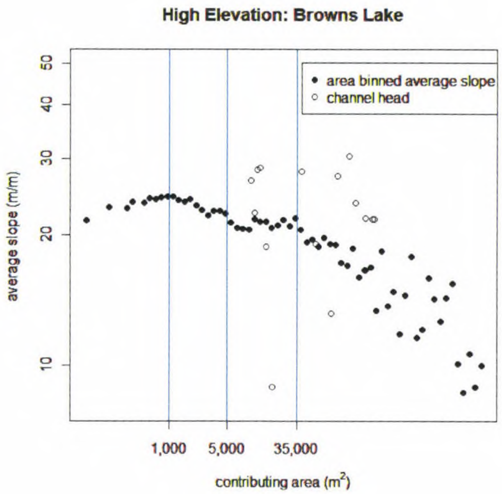


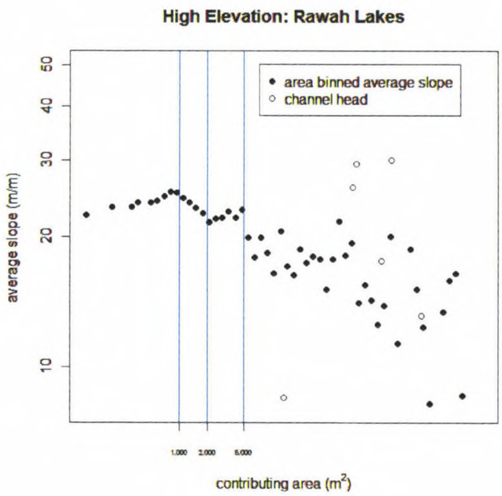


Additional slope-area plots





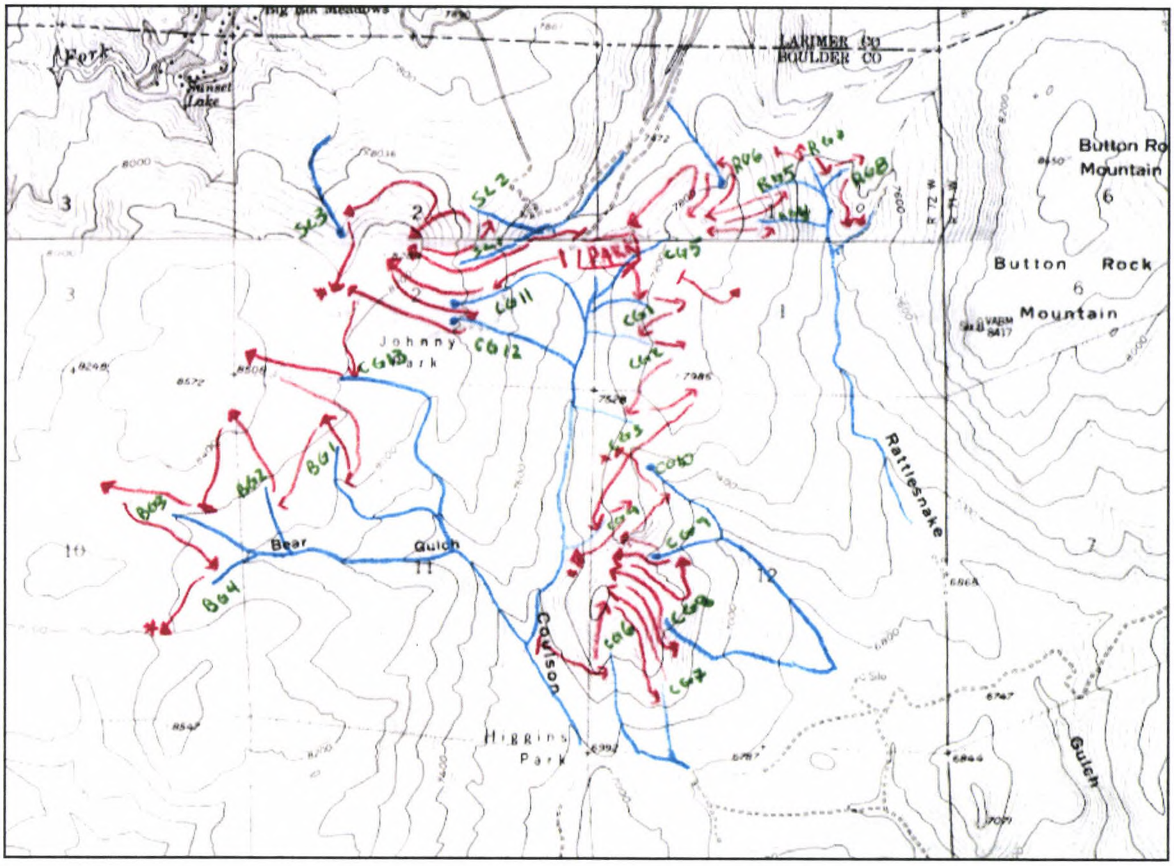




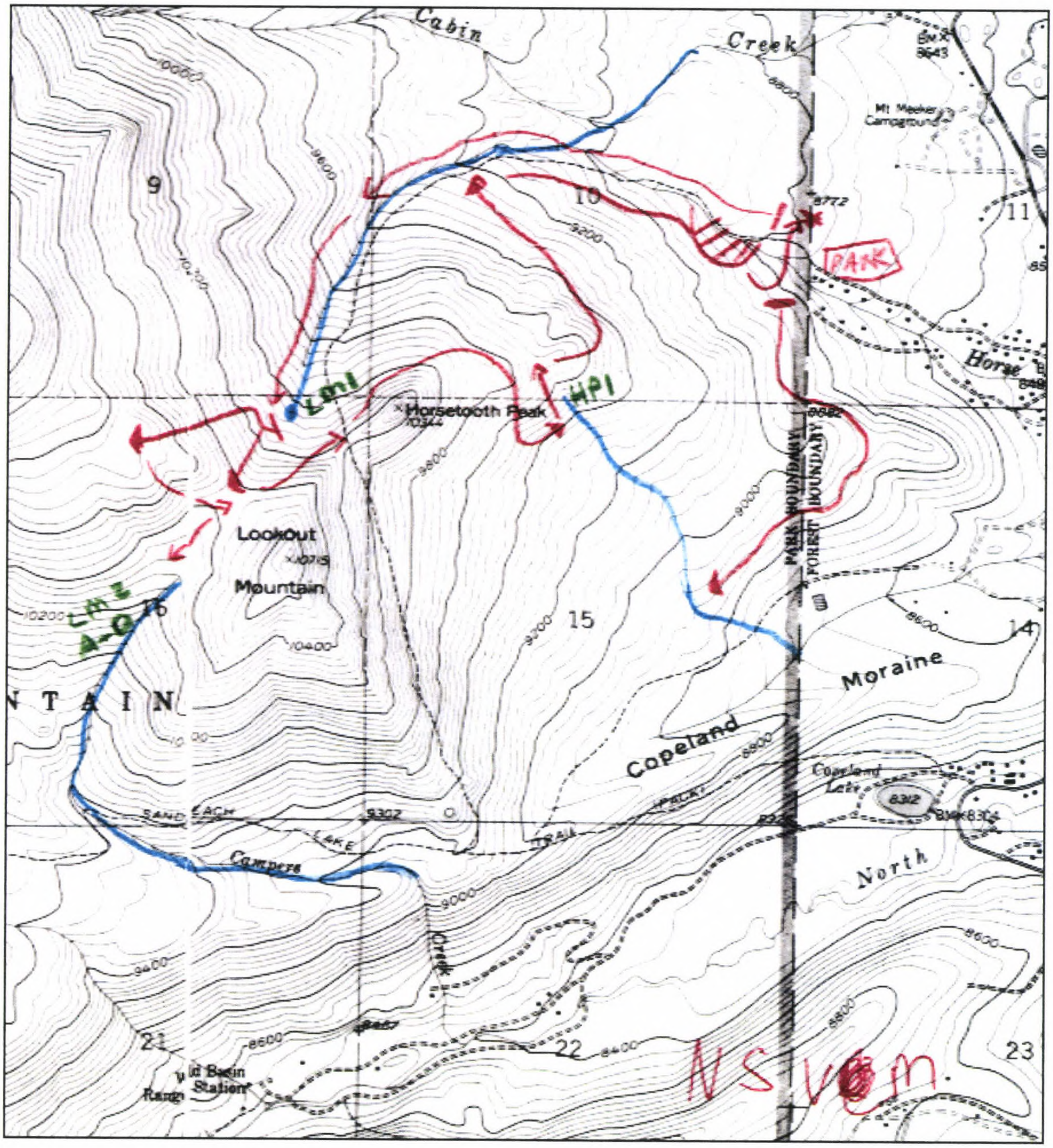
7.3. Appendix C: Topographic Maps

United States Geological Survey (USGS) topographic quadrangles for field areas	
Field Area	USGS 7.5' Quad
Rattlesnake Gulch	Panorama Peak Raymond
Lookout Mountain	Allens Park
Bluebird Lake	Isolation Peak
Dadd Gulch	Rustic
Roaring Creek	Kinikinik Boston Peak Deadman South Bald Mountain
Browns Lake	Comanche Peak
Rawah Lakes	Rawah Lakes

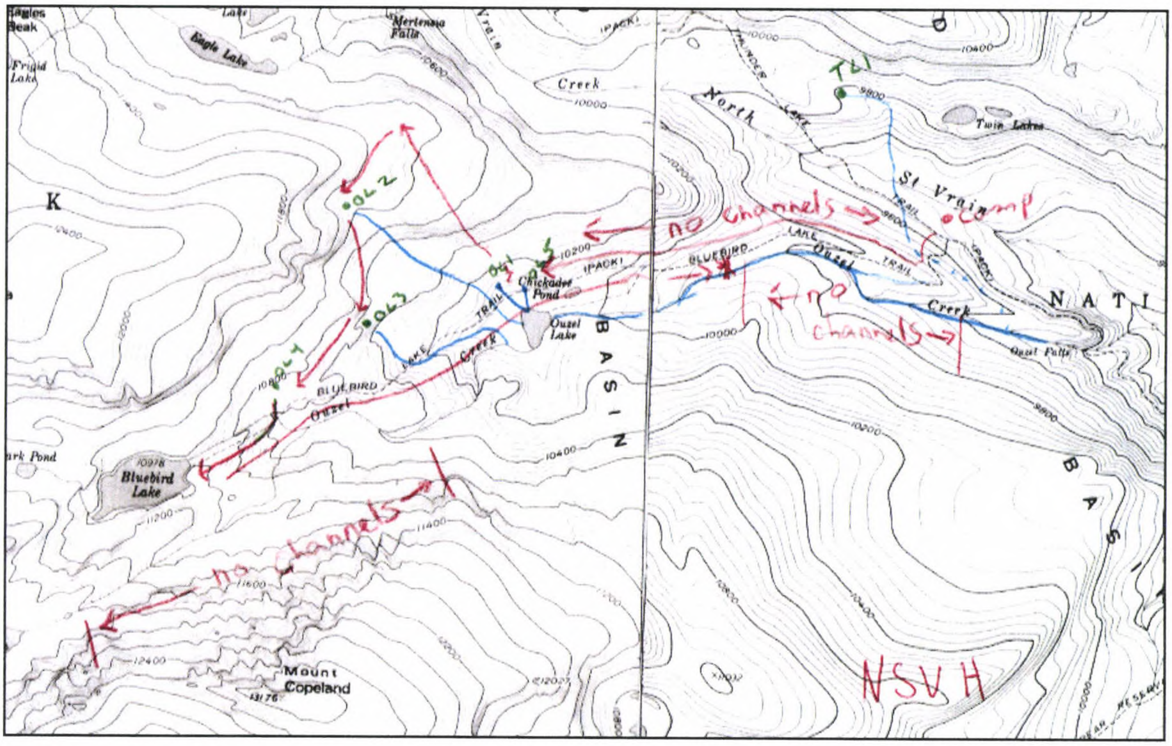
Rattlesnake Gulch



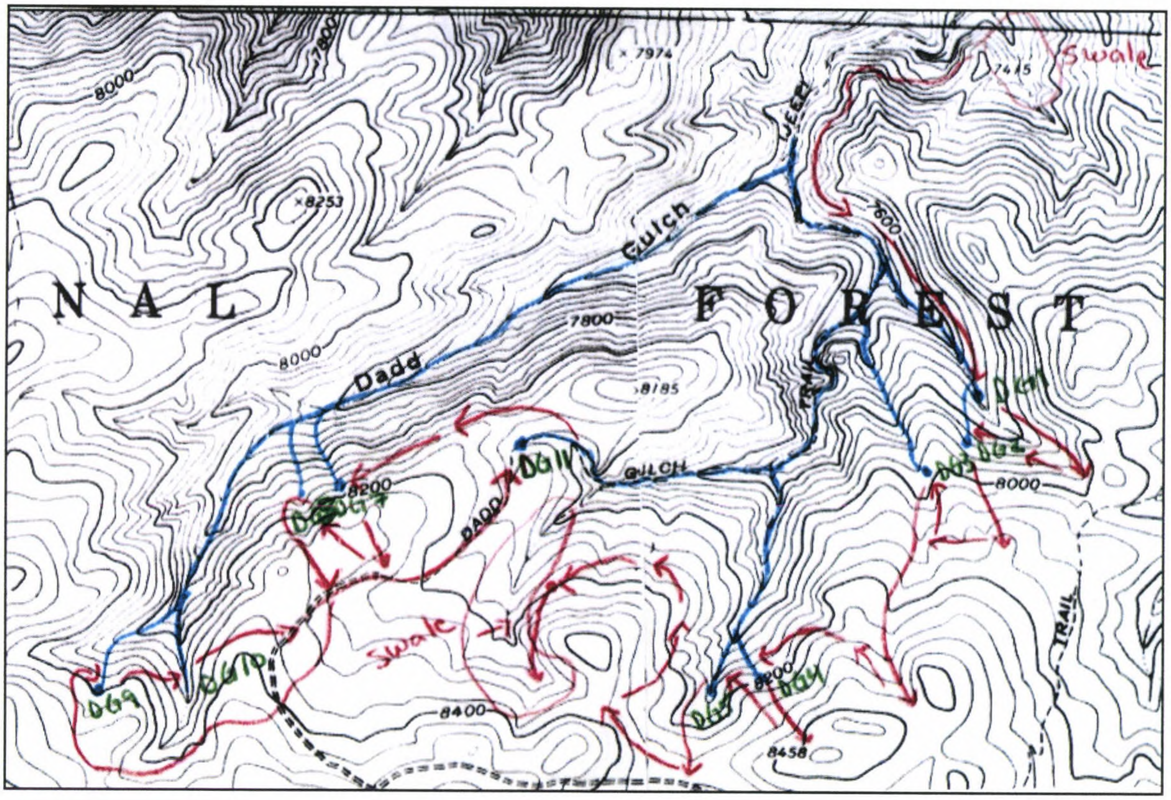
Lookout Mountain



Bluebird Lake

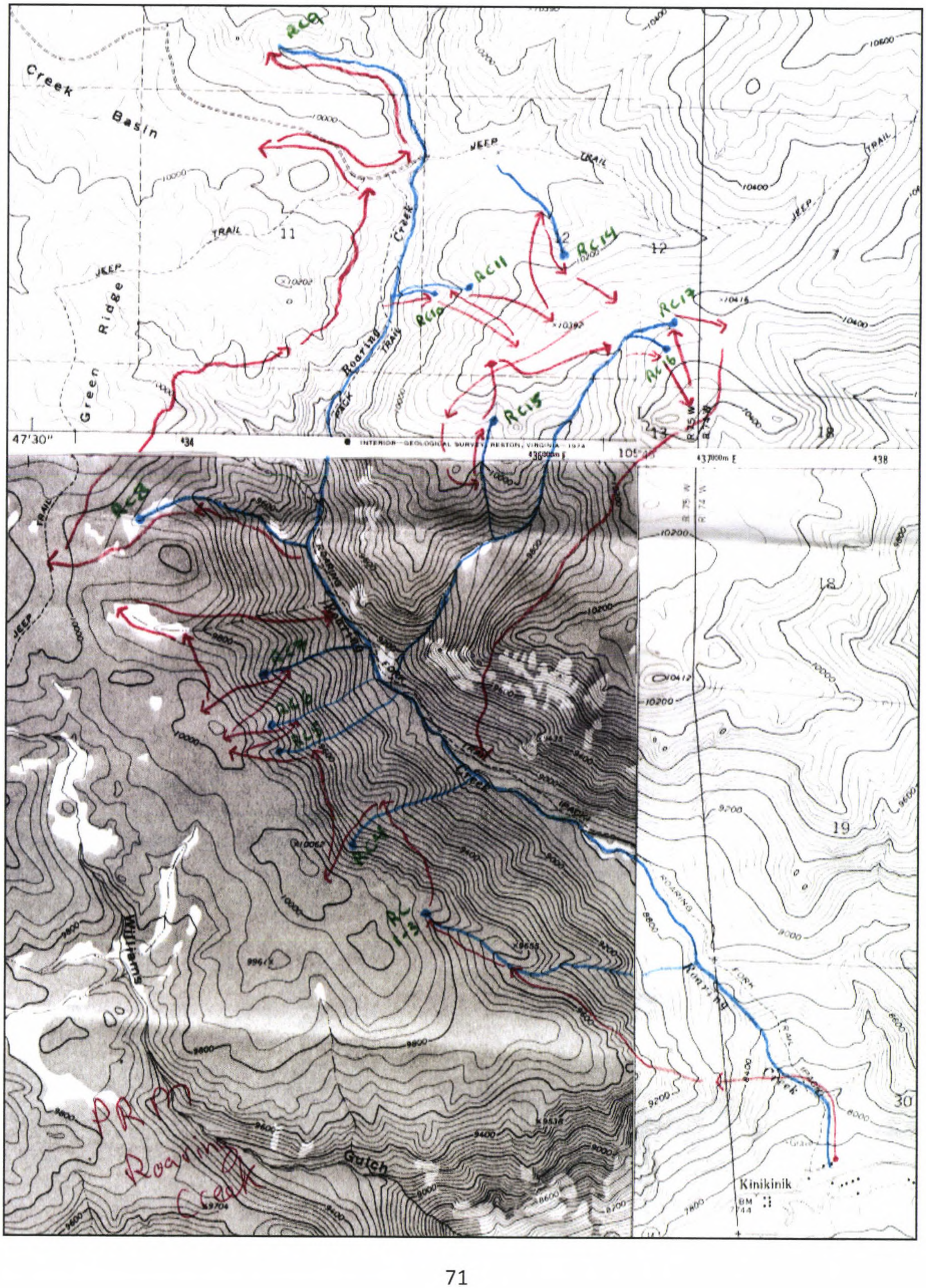


Dadd Gulch

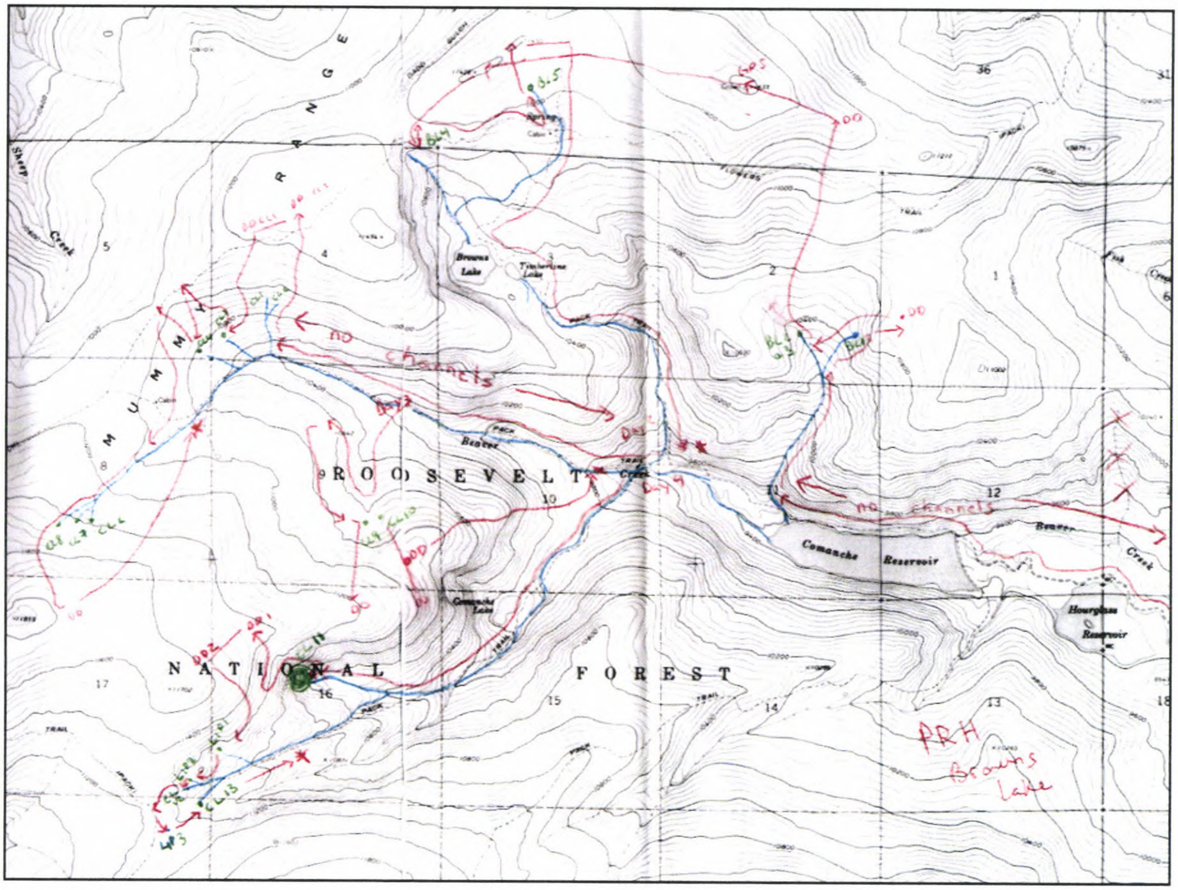


NAL
FOREST
Dadd
Gulch
DADD
GULCH
JEEP
TRAIL
TRAIL
Swale
Swale
8000
8000
8000
7800
8200
8200
8400
×7974
×8253
8185
8458
7415
DG1
DG2
DG4
DG7
DG9
DG10
DG11

Roaring Creek

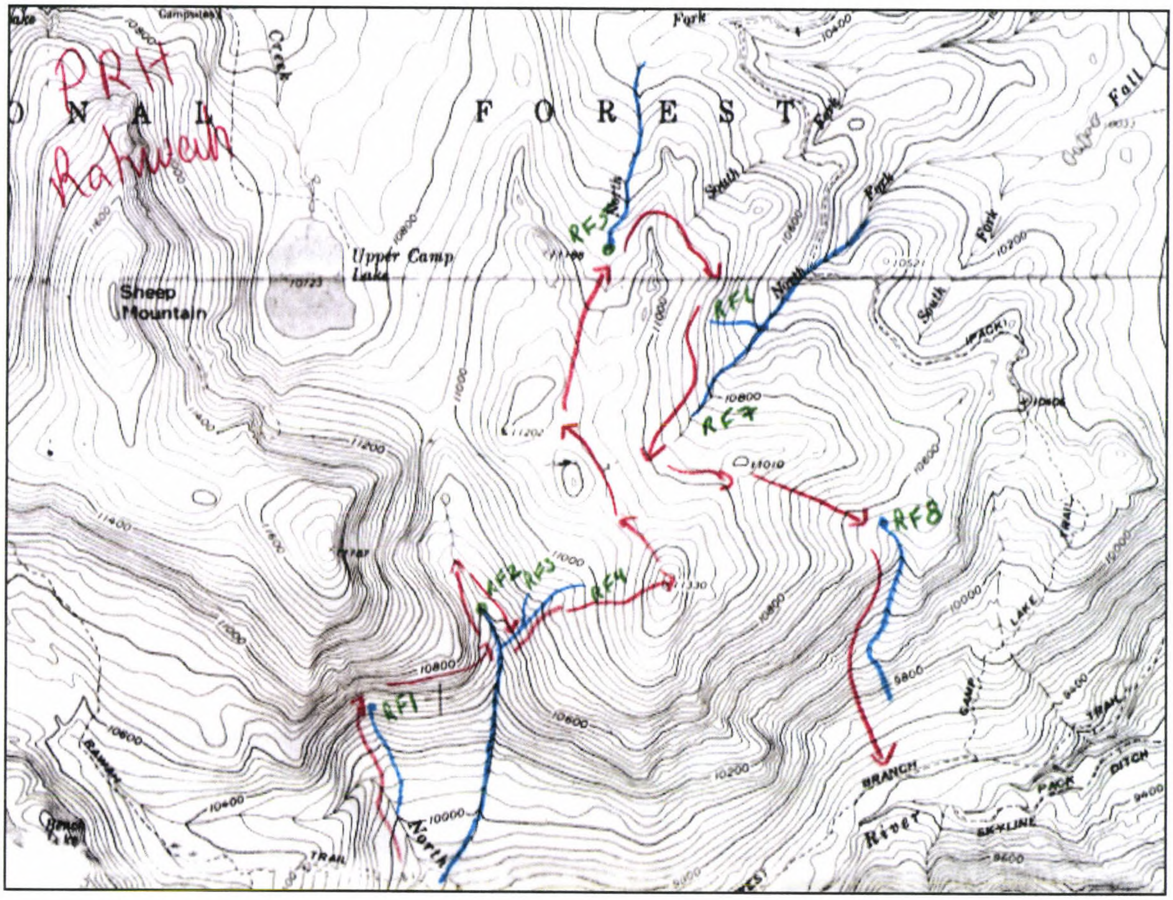


Browns Lake



M U M M Y
R A N G E
Browns Lake
Timberline Lake
R O O S E V E L T
N A T I O N A L
F O R E S T
Beaver
Comanche Reservoir
Hourglass Reservoir
Comanche Lake
no channels
no channels
PRH
Browns Lake

Rawah Lakes

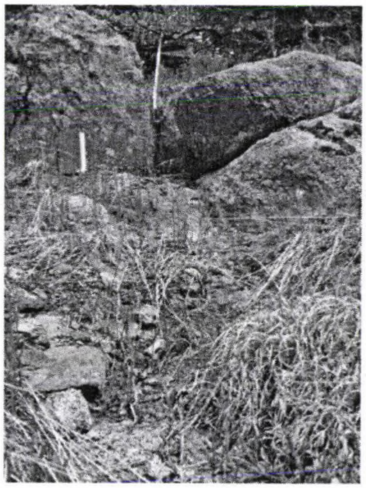

PRH
Rahweih
F O R E S T
Sheep Mountain
Upper Camp Lake
RF1
RF2
RF3
RF4
RF5
RF6
RF7
RF8
BRANCH
River
North
South Fork
North Fork
Creek
Fork
TRAIL
SKYLINE
DITCH

7.4. Appendix D: Field Photographs (All photographs of channel heads are taken looking upslope).

CG2:

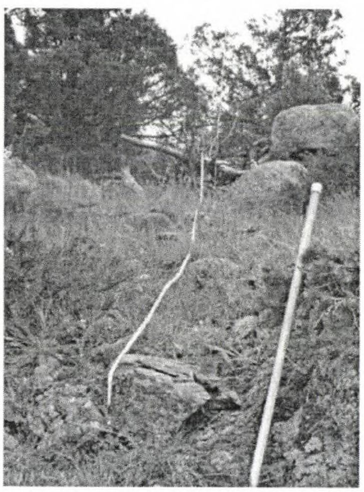
CG3:

CG4:



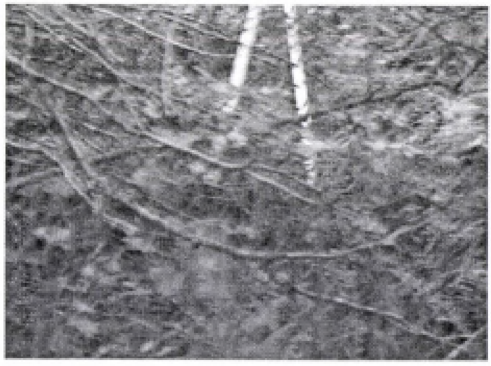
CG5:

CG6:



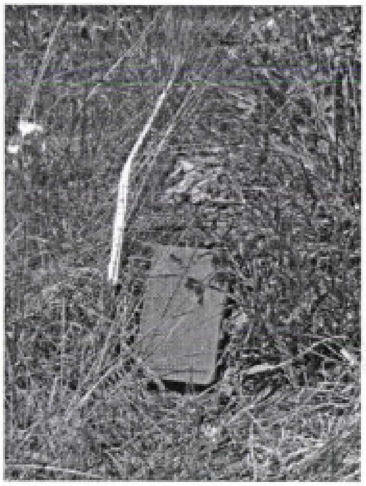
CG8:

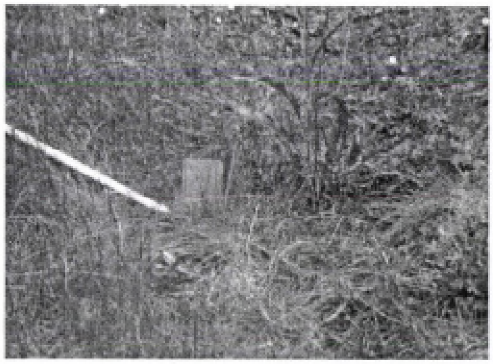
CG9:



RG2:

RG3:





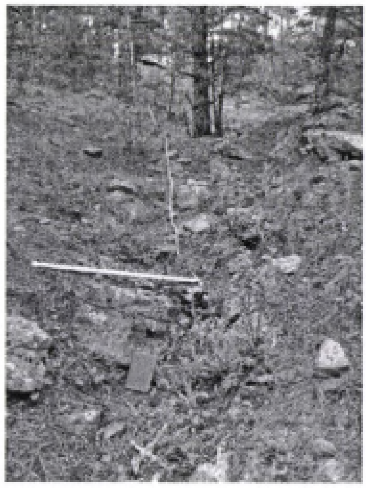
RG4:

RG5:

CG10:

RG6:

RG8:



CG11:

CG12:

CG13:

RG7:

BG1:

BG3:

BG4:

SL1:

SL2:

BG2:

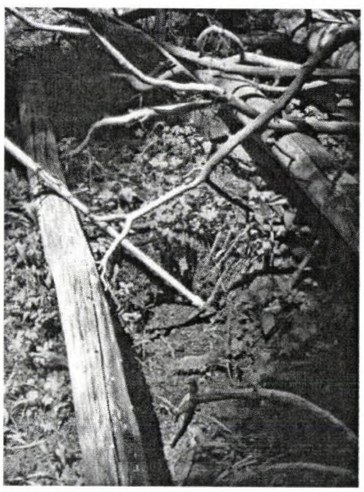
SL3:

LM1:

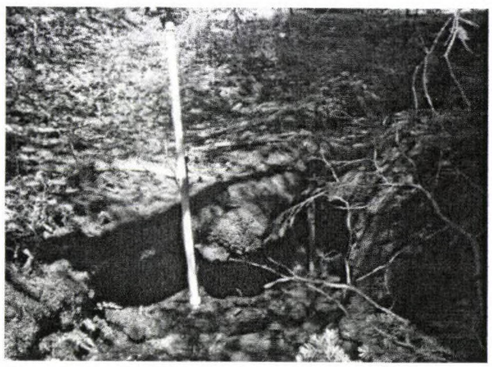
LM2A:

RC1:

RC2:



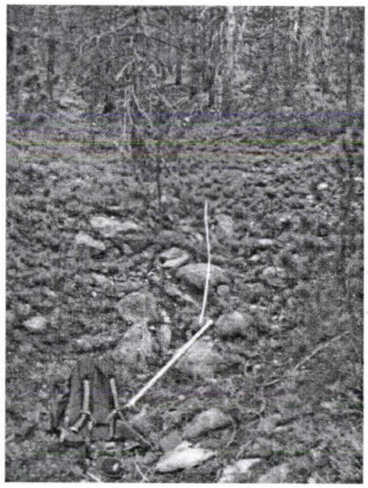
HP1:



RC4:

RC6:

RC7:



RC8:

RC9:

RC5:

RC11:

RC15:

RC16:

DG1:

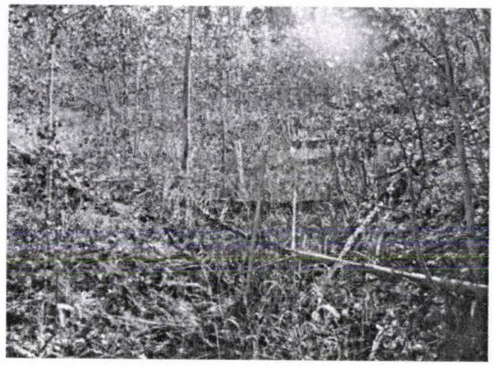
DG2:

RC14:

DG3:

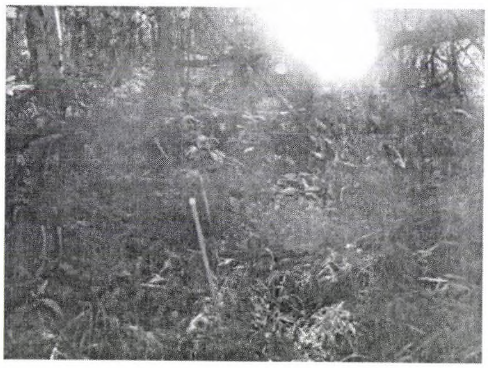
DG5:

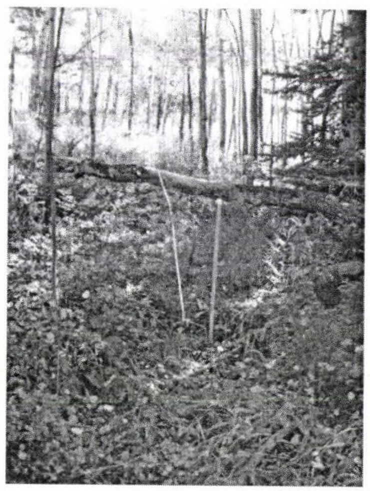
DG7:



DG8:

DG9:





DG4:

DG11:

BL2:

BL4:

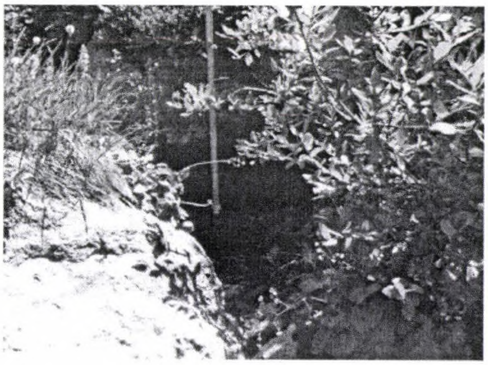
no photograph

BL1:

BL3:

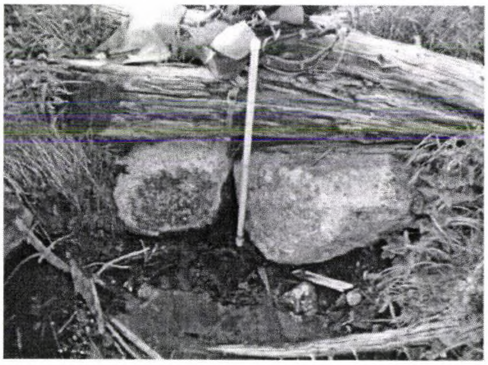
OL1:

OL2:



OL5:

TL1:

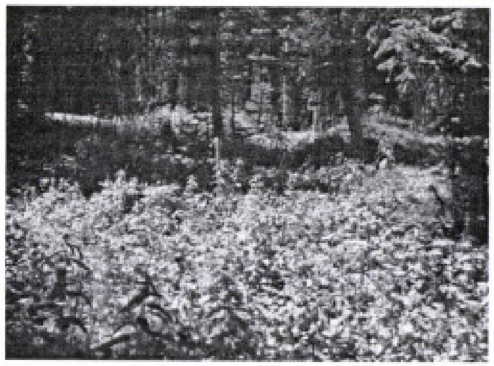


BL5:

CL2:

OL4:

CL3:

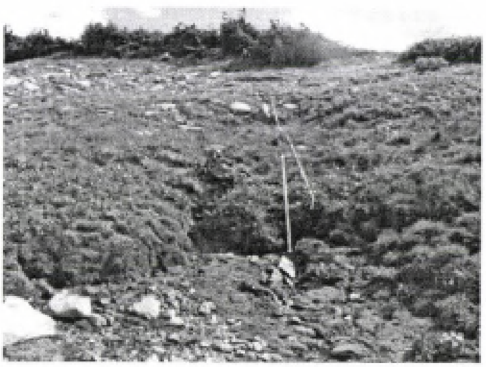


CL5:

no photograph

CL6:

CL7:



CL8:

CL4:

CL9:

CL11:

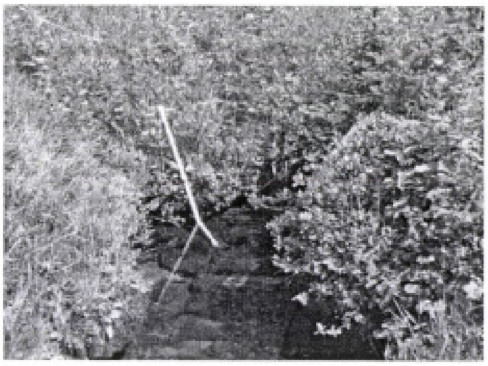
CL12:

CL13:

RF1:

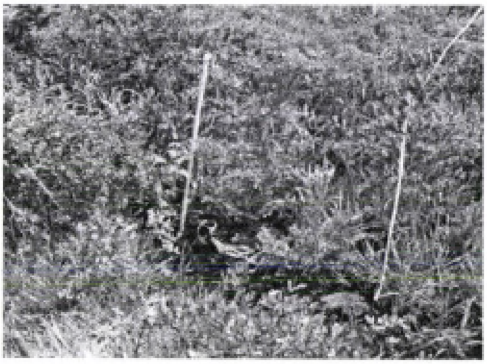
CL10:

RF2:



RF5:

RF6:



RF7:

RF8:

RF3: