Environmental factors influencing recreational trail condition
by Wendi Ann Urie

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University
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Abstract:
Trail systems in national and state forests and parks weave their way through many different bedrock types, slope gradients, aspects, soil and habitat types. Management of these trail systems requires knowledge of how humans affect the environment at landscape scales in addition to randomly selected sample plots and other micro-environments. Research concerning the impact of human use on soils and vegetation has traditionally focused on site-specific impacts and these results are difficult to extrapolate to entire landscapes. This study explained 50% of the variability in trail condition along two existing trails in the Gallatin National Forest of Montana with a series of landscape scale variables. Information on three environmental controls (soil water content, trail slope and understory vegetation cover) and cross-sectional area were measured at 130 sites spaced at 100 m intervals along the trail. Six terrain variables were computed with the Topographic Analysis Programs for the Environmental Sciences - Grid version (TAPES-G) and a 1:24,000 scale DEM. Trail slope explained 25% and soil water content 11% of the variability in trail cross-sectional area and both were positively correlated to trail condition. Regional slope was negatively correlated to trail slope and explained another 5% of the variability in trail cross-sectional area. The regression coefficients for trail slope varied in size when the trail was divided into four landscape units. A steady-state wetness index was also computed at 100 m intervals along the trail, but this index explained only 10% of the variability in measured soil water content.

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Master of Science

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Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

October 1994

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APPROVAL

of a thesis submitted by

Wendi Ann Urie

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ACKNOWLEDGMENTS

Funding for this study was provided by the Department of Earth Sciences, the Yellowstone Center for Mountain Environments and the Gallatin National Forest. John Wilson provided guidance and support as my advisor and edited numerous thesis drafts. Andrew Marcus assisted with field methods, statistical consulting and editing of drafts. Kathy Hansen provided input on vegetation data collection and draft editing. Jon Wraith invested many hours converting the TDR to an easily transportable system and also helped with soil physics and draft editing. William Locke, professor of geology at M.S.U. helped broaden my understanding of the influences of geology and also assisted me in my statistical inquiry. Damian Spangrud and Lou Glassey provided much needed computer assistance and guidance. Lastly, Barb Urie and Mike Cimonetti were my dedicated field assistants.

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ABSTRACT

Trail systems in national and state forests and parks weave their way through many different bedrock types, slope gradients, aspects, soil and habitat types. Management of these trail systems requires knowledge of how humans affect the environment at landscape scales in addition to randomly selected sample plots and other micro-environments. Research concerning the impact of human use on soils and vegetation has traditionally focused on site-specific impacts and these results are difficult to extrapolate to entire landscapes. This study explained 50% of the variability in trail condition along two existing trails in the Gallatin National Forest of Montana with a series of landscape scale variables. Information on three environmental controls (soil water content, trail slope and understory vegetation cover) and cross-sectional area were measured at 130 sites spaced at 100 m intervals along the trail. Six terrain variables were computed with the Topographic Analysis Programs for the Environmental Sciences - Grid version (TAPES-G) and a 1:24,000 scale DEM. Trail slope explained 25% and soil water content 11% of the variability in trail cross-sectional area and both were positively correlated to trail condition. Regional slope was negatively correlated to trail slope and explained another 5% of the variability in trail cross-sectional area. The regression coefficients for trail slope varied in size when the trail was divided into four landscape units. A steady-state wetness index was also computed at 100 m intervals along the trail, but this index explained only 10% of the variability in measured soil water content.

CHAPTER ONE

INTRODUCTION

Balancing the interest in preserving natural areas with a desire for multiple use of landscapes involves many trade-offs. Some researchers, for example, argue that any disturbance by humans should not be tolerated in wilderness and other natural areas, whereas others have suggested that these areas should be open for humans to enjoy and appreciate. The challenge for resource managers is to manage access and levels of use in ways that are sustainable; thus causing as little damage to surrounding areas as possible. Strategically located and properly constructed and maintained trail systems offer the best chance of achieving this objective. Recreation trails provide access for hikers, horses and, in some cases, bicyclists and motorcyclists and thereby limit any damage to a narrow corridor of soils, vegetation and animals.

Land managers require tools to easily make appropriate trail design and maintenance decisions for a variety of landscapes. Trail systems in national and state forests and parks weave their way through many different bedrock types, slope gradients, aspects, soils and habitat types. Management of these trail systems requires knowledge of how humans affect the environment at landscape scales in addition to knowledge of how human activities affect randomly selected sample plots and other micro-environments. Research concerning the impact of human use on the soils, natural vegetation and wildlife has traditionally focused on site-specific impacts and these results are difficult to extrapolate to entire landscapes (Helgath

1975; Kuss and Morgan 1980; Cole 1987; Seney 1991; Wilson and Seney 1994).

Land managers require knowledge concerning the relationship of trail conditions to common terrain and soil attributes and also the ability to estimate these attributes quickly and easily. This study first attempts to determine the terrain and soil variables which influence trail condition and secondly attempts to explore modeling methods to derive these variables.

Most of the modeling solutions proposed to date have utilized micro-scale process descriptions in hillslope or catchment-scale models with only limited success (Goodrich and Woolhiser 1991; Moore et al. 1993a). Moore et al. (1993a) recently proposed an alternative index approach that is based on simplified representations of the underlying physics of the processes but includes the key factors that modulate system behavior (such as topography). These models are based on, and are able to operate with, what Nix (1981) termed "minimum data sets". This approach sacrifices some physical sophistication to allow improved estimates of spatial patterns in landscapes (Moore et al. 1991). The method is also able to operate at different levels of sophistication depending on the availability of possible input data and the spatial resolution of that data. Moore et al. (1993a) used the distribution of soil water content in a landscape, a major factor determining the biophysical behavior of landscapes, to illustrate the basic approach. Soil water content data is not readily available to managers. A modeling approach to determining soil water content could provide land managers with this information.

The challenge now is to demonstrate the applicability of these methods to recreational trail management issues. The objectives of this project are to: 1) measure trail condition at specified intervals along the trail system; 2) measure selected environmental factors at

specified intervals along the trail system; 3) determine the relationship between erosion and other environmental factors; and 4) explore the potential for using terrain analysis techniques to predict the spatial distribution of soil water content within the study area.

This work builds on previous and current efforts in terrain analysis (Moore et al. 1991, 1993), soil erosion modeling (Moore et al. 1992; Moore and Wilson 1992, 1994), and field-based trail studies (Seney 1991; Wilson and Seney 1994). The validation of these models would help forest and park managers with the early identification of potential problem areas on current trails and lands slated for new trails.

Literature Review

Many researchers have examined the effects of types of trail use, construction and levels of use on vegetation and/or soils at specific sites (e.g., Dale and Weaver 1973; Dawson et al. 1974; Helgath 1975; Bryan 1977; Cole 1978; 1988; Bratton et al. 1979; Grabherr 1982). These studies fall into two categories: those which study the effects of trail use on vegetation and those which focus on the effects on soil compaction and erosion. Many studies have found that some species are more vulnerable to trampling than others (Burden and Randerson 1972; Grabherr 1982; Cole 1988). Dale and Weaver (1974) studied the effects of different user types on vegetation finding that damage generally increased from hikers to motorcycles to horses. Cole (1988) experimented with both use intensities and resistant/nonresistant habitat types to analyze the vulnerability of various habitats and their recovery potentials. These studies have consistently found that both resistant and non-resistant vegetation is removed quickly from trails; thus on trails with prolonged use, accelerated soil erosion and

soil compaction are the dominant impacts on the trail (Cole 1988).

Soil Erosion Impacts

Rates of soil erosion depend on climate, soil and topographic factors. Bryan (1977) linked rates of trail erosion to soil properties such as texture, homogeneity, morphology, stability and organic content. Helgath (1975) and Burde and Renfro (1986) emphasized a combination of soil, climatic and topographic factors, including landform, trail grade and vegetative habitat type. Dale and Weaver (1974), Helgath (1975), Cole (1983) and Kuss (1987) identified use intensity as a major factor controlling soil erosion. The rate of change decreased with higher use intensities. Wilson and Seney (1994) found that 70 percent of the trail erosion observed in their plot experiments could be statistically explained by regression terms combining soil texture, slope and user treatment. Horse travel produced more sediment than hiker, off-road bicycle or motorcycle traffic for all conditions and was found especially damaging on pre-wetted sites. Weaver and Dale (1978) also examined impacts by user type and found the results were slope dependent with motorcycle damage greatest going up the slope and hiker and horse damage greatest coming down the slope. McQuaid-Cook (1978) compared hikers and horses and found that horses caused more erosion on slopes but had considerably less impact than hikers on level sites.

Trail slope and soil water content were mentioned by several researchers to be controlling factors in trail erosion. Helgath (1975) found that trial grade is significantly correlated to area loss in subalpine fir (*Abies lasiocarpa*), ponderosa pine (*Pinus ponderosa*) - blue bunch wheat grass (*Agropyron spicatum*), and Douglas-fir (*Pseudotsuga menziesii*)

habitat types. Bratton et. al. (1979) employed factor analysis and found trail slope to be significantly correlated to percent rutting, percent exposed rock and percent exposed roots. Burde and Renfro (1986) found trail slope to be significantly correlated to trail cross-sectional area loss, trail depth and width of loose rock. Wilson and Seney (1994) correlated trail slope to sediment yield from 2 ft. by 2 ft. plots along the New World Gulch trail. They also found increased sediment yield on prewetted sample plots.

Overall, a large number and variety of contributing factors have been linked to observed and predicted erosion rates on trails, as evidenced by the studies noted above. Many of these variables are especially site specific in nature including: soil texture, soil organic content, vegetative habitat type, and geomorphic landform.

Helgath (1975) and Summer (1980, 1986), for example, both divided their study areas into landform units. Helgath (1975) classified each study site as either alluvial erosional, alluvial depositional, glacial erosional or glacial depositional. She found that the glacial depositional, glacial erosional and alluvial depositional units all suffered similar mean area losses and that the alluvial erosional units experienced higher losses than any of the other units. Summer (1980, 1986) utilized more specific landform categories and classified her study sites by one of the following categories: outcrop, talus slope, terrace, floodplain, moraine/outwash, moraine, colluvial slope, alluvial-colluvial fan, or alpine colluvial fan. After three seasons of monitoring, Summer (1986) found that the mean change in depth of trail was highest on the 10° colluvial slope and on the 13° - 18° side slopes of the moraines. Colluvial fans and colluvial slopes of 5° also experienced changes in depth of trail. Both Helgath and Summer invested considerable time and energy classifying these landforms in the field. Many

landform types may be present in a given area thus it is difficult to extrapolate results from these studies to areas with different geomorphic landforms.

Soil Compaction Impacts

Soil compaction also contributes to trail deterioration in many instances by decreasing the permeability of the soil and increasing ponding and overland flow down the trail. Several researchers have linked rates of soil compaction to soil properties and use patterns similar to the soil erosion studies (Dotzenko et. al 1967; Dawson et. al. 1974; Kuss 1983: McQuaid-cook 1977; Summer 1980; Weaver and Dale 1978). Weaver and Dale (1978) found compaction increased with slope, use intensity and level of horse use. Dawson et. al. (1974) found that north-facing slopes experienced significantly less compaction due to use than south-facing slopes. Dotzenko et. al. (1967) found that organic content of the soil, soil texture, and soil moisture were inversely correlated and that use intensity was positively correlated to soil compaction. McQuaid-Cook's (1977) study combined many of the above attributes and found that the rate of soil compaction depended on terrain, use intensity, type of user (horse versus hiker), soil type and soil water content.

None of the above studies sought to quantify the contributions of trail erosion and compaction to overall trail deterioration. In this study erosion was assumed to represent the dominant process controlling trail deterioration and no analysis was done to compare soil erosion and soil compaction rates at given sites.

Trail Erosion Modeling

Applying the results of these site specific studies to larger landscapes is problematic

(Helgath 1975; Kuss and Morgan 1980, 1984; Cole 1987; Wilson et al. 1994), although Helgath (1975) and Kuss and Morgan (1980, 1984) have proposed methodologies to anticipate and cope with the challenges of extending site specific results to broader areas. Helgath (1975) suggested an index system based on "biophysical" units. These units divide landforms and vegetation habitats into homogeneous environments. Each unit has a specific potential for deterioration attached to it. Managers could strive to avoid units where erosive potential is high (Helgath 1975). Kuss and Morgan (1980, 1984) proposed the use of the Universal Soil Loss Equation (USLE) to estimate the carrying capacity of hiking trails. The equation, as modified by Kuss and Morgan, is written as T = RKLSC. The maximum rate of soil erosion that will permit the productivity of the land to be sustained economically and indefinitely is represented by T and calculated in terms of rainfall (R), soil erodibility (K), slope gradient (S), slope length (L), and type and extent of vegetational cover (C). Kuss and Morgan (1980, 1984) argued that this modified USLE model would help the land manager to determine when the conditions warranted measures to prevent further erosion.

The Helgath and Kuss/Morgan models both have significant deficiencies. Helgath's model is a framework for classifying potential erodibility using landforms and vegetation. Dividing the landscape into homogeneous biophysical units which represent all possible environments would require extensive field work and study thus defeating the purpose of developing the model. This approach of sequentially dividing a landscape into smaller units which are assumed to be homogeneous, predicting the response of each element and then aggregating the response to allow the spatially-variable environmental response to be predicted has been tried in hydrology for over 20 years. The field evidence gathered in the

past decade indicates that this approach has been only partially successful such that many hydrologic processes cannot be treated in this way (Goodrich and Woolhiser 1991; Moore et al. 1993a). Hence, Helgath's (1975) biophysical units provide only a framework for further study rather than a quantitative method which simulates the environmental processes operating in landscapes.

The modified USLE approach proposed by Kuss and Morgan (1980, 1984) suffers from many of the same problems even though their approach does provide a quantitative model which utilizes site-specific information to predict environmental impacts across landscapes. There are six main problems: (1) the division of landscapes into small homogeneous units in order to simulate the processes operating across landscapes; (2) the need for field and laboratory studies to compile the spatially-variable soils and vegetation data required as inputs for the model; (3) the cost and difficulty of relating the vegetation information collected for these landscapes to the vegetative cover factor tables and nomographs prepared for the agricultural (Wischmeier and Smith 1978) and rangeland (Dissmeyer and Foster 1980) versions of the USLE; (4) the extrapolation of USLE model results to highly compacted and non-vegetated trails; (5) the failure of the model to predict gully erosion as well as sheet and rill erosion given that some trial systems will collect runoff and serve as ephemeral channel systems (Cole 1987); and (6) the failure of the USLE to account for the effects of slope convergence and divergence on the spatial patterns of runoff and accelerated soil erosion by water (Moore et al. 1993a). These problems are serious because the USLE is a statistical model and its application to environments and conditions outside of those for which it was developed and validated is fraught with difficulties (Wischmeier 1976; Wilson 1986).

Soil Water Modeling

The results from the site-specific and plot-scale trail studies conducted by Helgath (1975), Bryan (1977), McQuaid-Cook (1978), Weaver and Dale (1978), Bratton et al. (1979), Fish et al. (1981), Wilson and Seney (1994) and others during the past two decades in a variety of geographic settings and landscapes point to a strong connection between soil water distribution and erosion potential. These results also provide a strong rationale for the application and testing of the modeling techniques described above given the cost and difficulty of collecting spatially-variable weather, soil and vegetation information in mountain environments.

Moore et al. (1993a) recently proposed a modeling approach in which a series of indices or equations are used to represent the spatial distribution of soil water content in a landscape. This method for modeling at a landscape scale holds promise as possible methods to extend previous site specific trail studies to landscape scales.

The soil water index relies on a series of equations which apply first a spatially-variable topographic term, and then terms for soil properties, infiltration rates and evapotranspiration to predict the spatial distribution of soil water content. This approach assumes that water distribution in mountainous or hilly terrain is controlled by vertical and horizontal water divergence and convergence, infiltration recharge and evapotranspiration. The latter two terms are affected by solar insolation and vegetation canopy which vary strongly with exposure in semi-arid areas, while the divergence/convergence term is dependent on hillslope position (Moore et al. 1990). Burt and Butcher (1986), Moore et al. (1988), and Wood et

dependent on hillslope position (Moore et al. 1990). Burt and Butcher (1986), Moore et al. (1988), and Wood et al. (1990) achieved good results using only the topographic attributes to characterize soil water distribution. This approach avoids the difficulties associated with the direct measurement or estimation of the spatial variability of the soil water and evapotranspiration terms.

This model offers an additional advantage to recreational managers in that it relies on attributes which can be stored as separate data layers in a geographic information system (GIS). A GIS has many management applications because it allows the user to input, store, analyze and output the large volumes of spatially-referenced data. These data are required for modeling and managing the landscape processes which influence the erodibility of recreation trail systems.

Description of Study Area

The study area includes two trails in the Gallatin National Forest south of Bozeman, Montana (Figure 1). The two trails have a combined length of 13 km. They traverse a landscape with variable geology, terrain and soils whose ownership is split between the Montana Department of State Lands and Gallatin National Forest.

The first trail, New World Gulch Trail, originates in Bear Canyon, 12 km southeast of Bozeman, at study site number 1 and ascends southward to a divide near site number 59 (Figure 2). The trail then traverses a ridge between sites 59-71 and descends to the shore of Mystic Lake at site 76. Sites 77-99 follow the shoreline of the lake (Figure 2). The New World Gulch Trail is underlain by limestone, sandstone and shale bedrock of the Mowry,

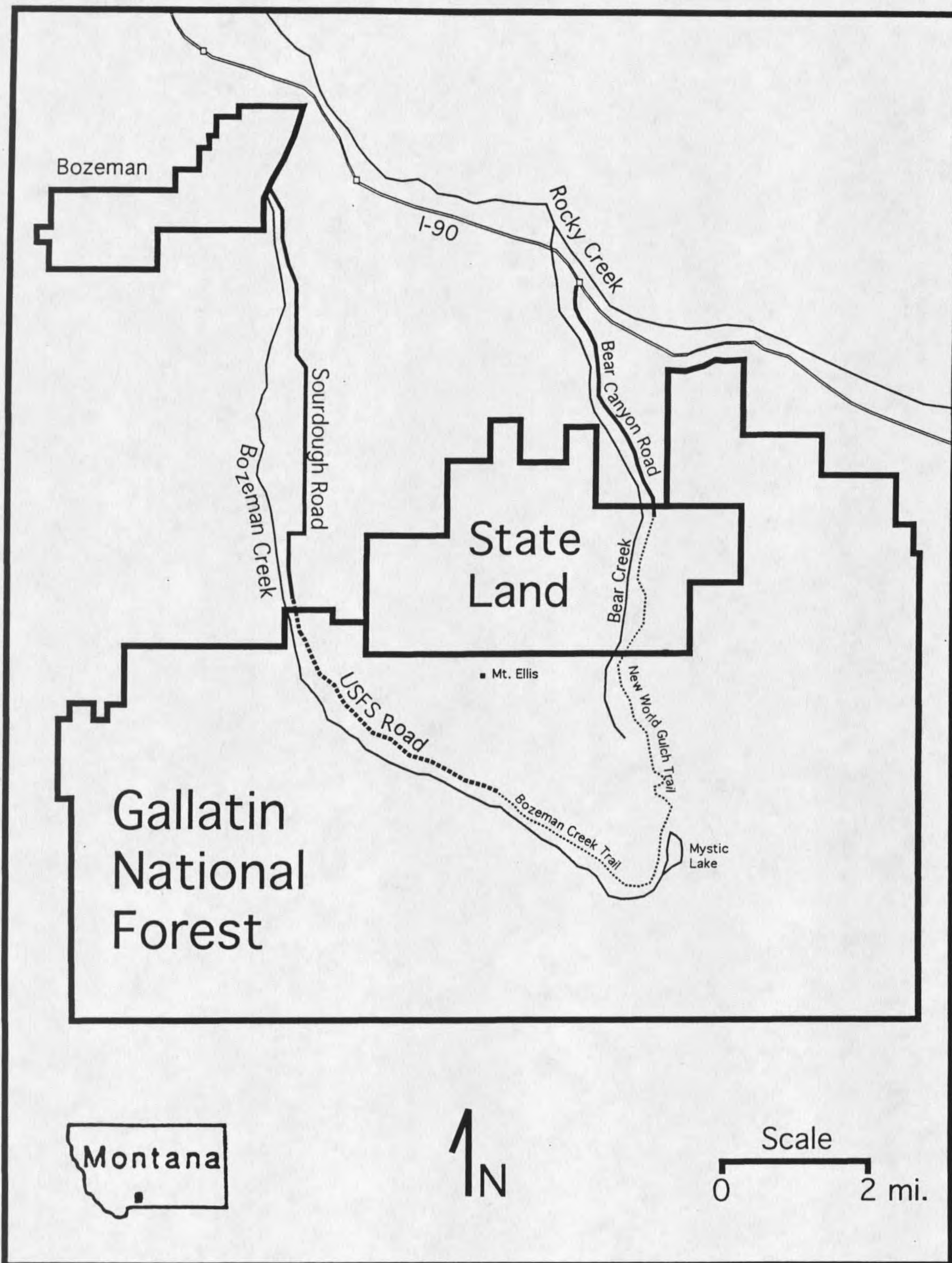

Figure 1. Study area location map.

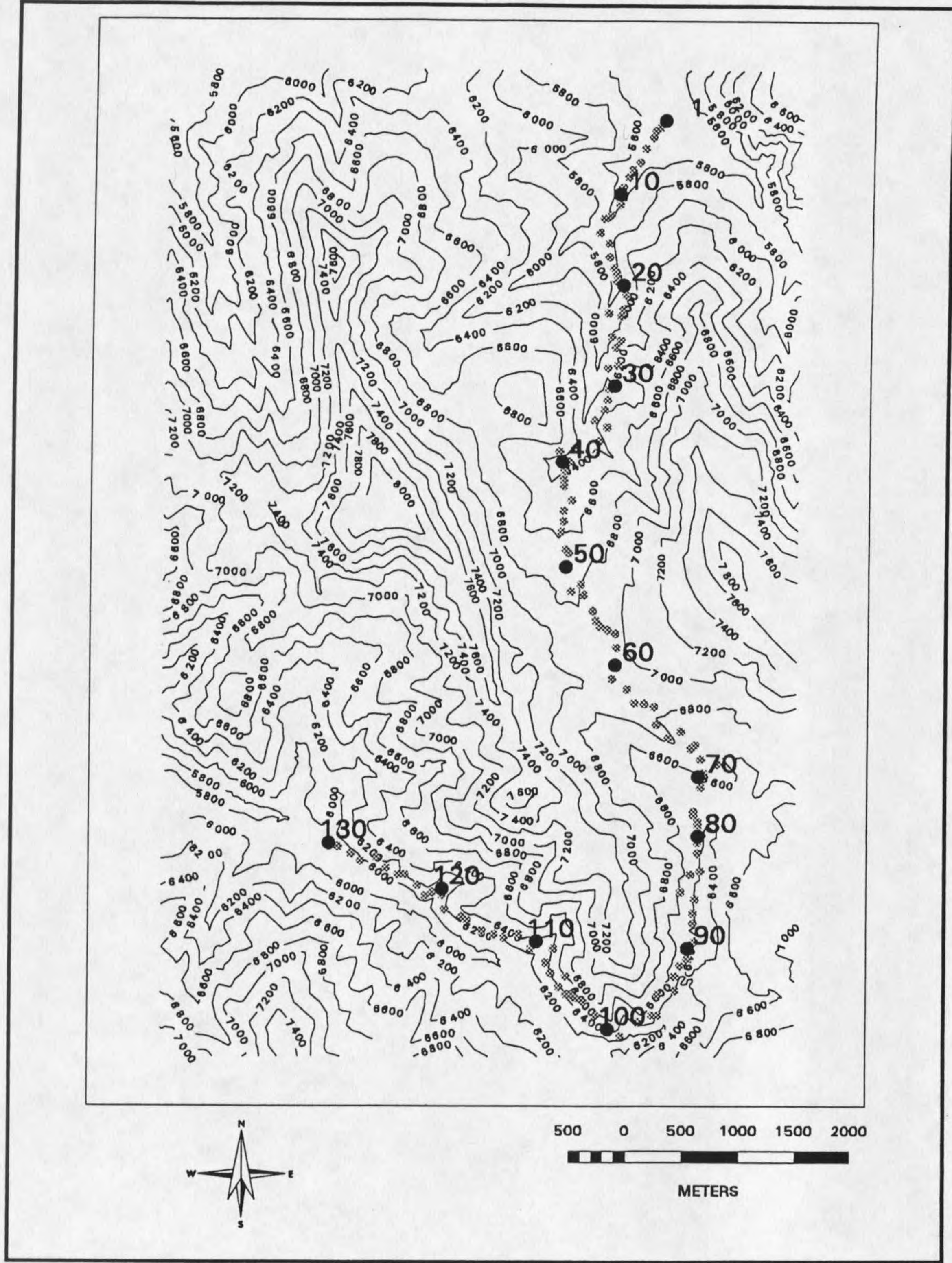

Figure 2. Study area elevation and trail location map.

Thermopolis, Kootenai and Jurassic formations (Roberts 1964). The resultant soils are fine- to medium-textured with subsoil clay accumulations. These soils are moderately well-drained (Davis and Shovic 1984). The elevation along the trail varies between 1658 m (5440 ft) and 2121 m (6960 ft). Sites 1-58 have predominately north to northeast facing aspects. As the trail traverses the ridge and descends to the lake from sites 59-76 the aspect changes from northeast to southwest. Along Mystic Lake sites 77-99 have east to south east aspects.

Lodgepole pine (*Pinus contorta*) is the dominant vegetation type with Subalpine fir (*Abies lasiocarpa*), Engleman spruce (*Picea engelmanii*) and Douglas fir (*Pseudotsuga menziesii*) also present. The understory consists of thick mat shrubs such as blue huckleberry (*Vaccinium globulare*), twinflower (*Linnaea borealis*) and grouse whortleberry (*Vaccinium scoparium*). Perennial bunch grasses such as Idaho fescue (*Festuca idahoensis*) and mat shrubs such as blue huckleberry (*Vaccinium globulare*), twinflower (*Festuca idahoensis*), bluebunch wheatgrass (*Agropyron spicatum*), bearded wheat grass (*Agropyron caninum*) and mountain brome (*Bromus carinatus*) populate the open meadows (Seney 1991).

The second (unnamed) trail leaves a USDA-Forest Service road 6 km from the Bozeman Creek trailhead, near study site number 130, and parallels Bozeman Creek to its source at Mystic Lake near study site number 100 (Figure 1). This trail is underlain by folded and faulted limestone of the Madison formation with some sandstone and shale interbedding. Soils are variable with medium-textured soils formed from weathered limestone and sandstone and fine-textured soils weathered from shales. Most of the soils along this trail are well-drained due to the steep slope perpendicular to the trail. The elevation along the trail varies between 1830 m (5973 ft) and 2020 m (6626 ft) with a predominately southwest aspect.

Vegetation consists of open Douglas fir (*Pseudotsuga menziesii*) forest with an understory of Idaho fescue (*Festuca idahoensis*) and bluebunch wheatgrass (*Agropyron caninum*).

Climate in this region is characteristic of the Northern Rocky Mountains. Precipitation is heaviest in the spring with heavy snowfalls common in March and April followed by spring rainstorms in May and June. The average snowfalls for March and April were 41.57 cm and 33.66 cm respectively, at the Montana State University Climate Station (National Atmospheric Administration 1993). Rainfall averaged 7.37 cm in May and 7.24 cm in June at the same station (National Atmospheric Administration 1993). Actual rain and snowfall averages for the study area may be greater and snow accumulations may remain on the ground longer due to the higher elevation . This climate regime controls the timing of peak erosion periods. It would be expected to have large erosion events mostly in the spring and early summer in this area. Precipitation increases again in September and October. Precipitation averages 4.59 cm in September and 3.75 cm in October thus potentially indicating another runoff period (National Atmospheric Administration 1993). Soils, though, at this time of year are drier and can absorb more moisture before saturation is reached and ponding and overland flow begin.

A variety of trail users are found on these trails. The New World Gulch Trail is utilized by hikers, mountain bikers, motorcyclists and horses during the summer and by skiers (cross-country and back-country) and to a limited extent snowmobilers in the winter. The unnamed trail in Bozeman Creek is heavily utilized by mountain bikers in the summer and also sees some horse and hiker use. Due to the steepness of the terrain, winter use is limited. No motorized vehicles are permitted in this portion of the study area. Neither the U. S. Forest

Service nor the Department of State Lands has annual data on the numbers of users traveling the trails.

CHAPTER TWO

METHODS

The goals of the study were approached using several different methods. Field data, collected during two summer field sessions, produced data on soil erosion and compaction, soil water content, local slope and vegetation cover. Data gained from map interpretation of geological and topographic maps included geology, regional slope, aspect, specific catchment area, plan and profile curvature. The above data were then synthesized using several statistical methods. Finally, terrain modeling techniques were utilized in an attempt to predict steady-state soil wetness indices.

Field Data

Data was collected at approximately 100 m intervals along the two trails so that a variety of landscapes in two drainage basins could be sampled. A randomly chosen number was used to locate the first stake 11 m from the New World Gulch trailhead. Pacing was employed to place stakes at intervals of about 100 m along the New World Gulch trail to Mystic Lake and then along the unnamed trail to its terminus at Bozeman Creek Road (Figure 1 and 2). The stakes were painted orange to make them easier to find on successive field days.

The sampling sites were mapped using a Magellan Nav5000 Pro Global Positioning System (GPS) receiver. The Magellan receivers utilize a series of satellites maintained by the

U.S. Department of Defense to calculate X, Y locations in terms of latitude/ longitude or Universal Transverse Mercator (UTM) meters. The accuracy varies between 5 and 30 m depending on the number of satellites in view when readings are taken. The GPS was used in two dimensional mode utilizing three of four possible satellites due to the often dense tree cover and location of parts of the trails in ravines. This approach limited accuracy to approximately 30 m. The readings were recorded in a field note book and taken back to the office for processing. The X, Y coordinates were entered into a spreadsheet for tabular analysis and later transferred to an ASCII text file. This file was then imported into ARC/INFO and three maps were produced (Figure 3). The first two maps show different sections of the New World Gulch trail and the third map shows the sampling site locations on the unnamed trail along Bozeman Creek. The latter map was rotated relative to the first two maps to fit on the same map page.

Soil Erosion and Compaction

The existing trail condition was documented at each stake (i.e., 100 m intervals) during the 1992 summer field season to assess the current status of the trail system. Two trail attributes were measured: 1) the width of the disturbed zone, and 2) the depth of the trail at 10 cm intervals across this width. This information was then used to compute the quantities of soil eroded or compacted at these locations along the trail.

The most commonly used method for estimating soil erosion and compaction on trails involves measuring the cross-sectional area between the tread surface and a taut line stretched between two fixed points on either edge of the trail (Cole 1987). The procedures described

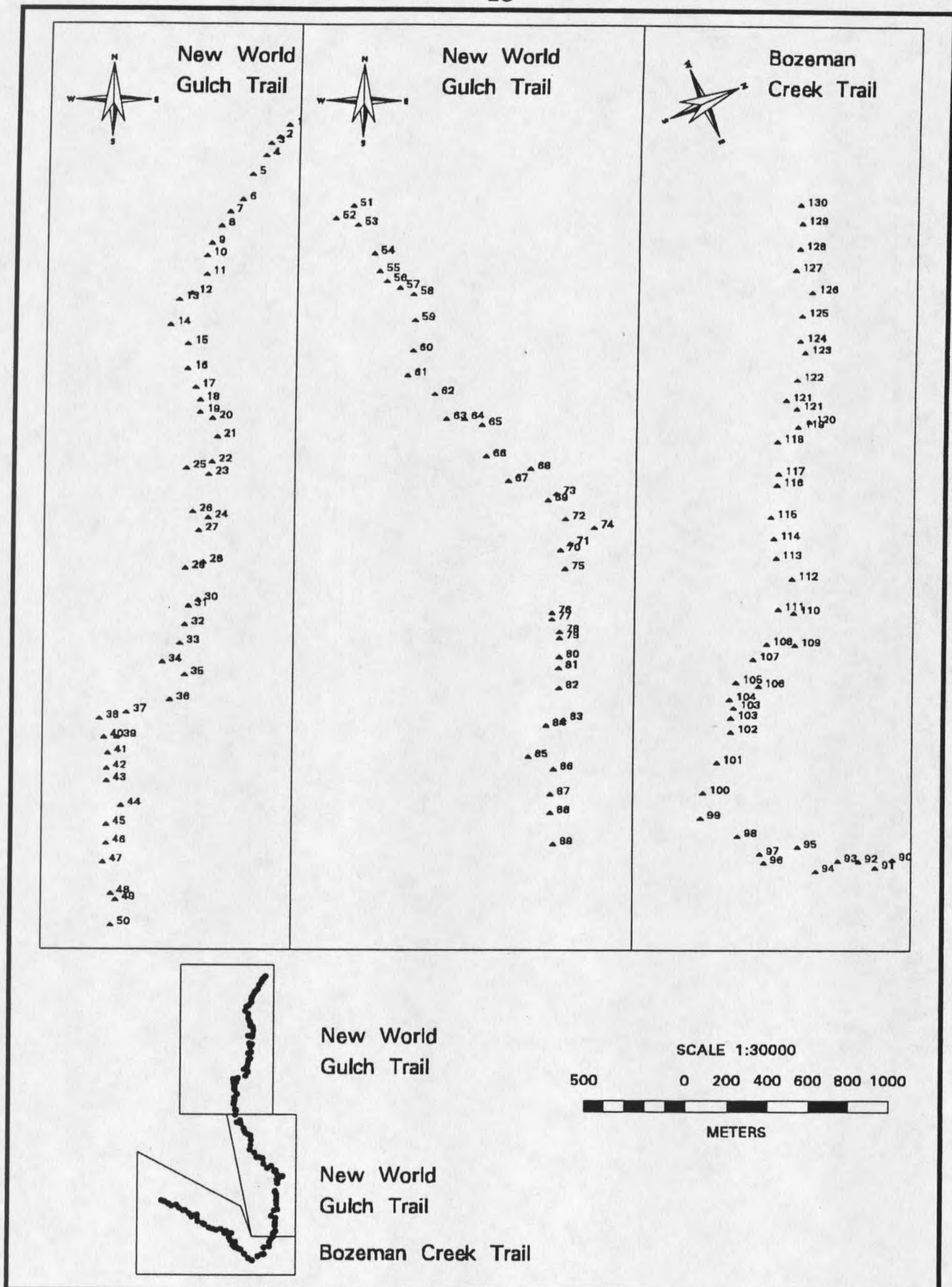

Figure 3. Map of sample site locations by trail.

and used by Ketchledge and Leonard (1970), Leonard and Whitney (1977) and Cole (1987) were areas along the trail. The modified method utilized two rebar poles with copper wire strung between them placed at the edge of the bare soil on either side of the trail. A string level was placed on the copper wire to ensure it was level at each site. The length of the wire was adjusted to accommodate varying trail widths at different sites. Colored tape was used to mark off 10 cm intervals along the wire. A plumb bob, which slid along the length of the wire, measured the distance from the taut wire to the ground surface at each of the markers.

Cole's (1987) formula for converting the above measurements to cross-sectional measurements is:

$$A_1 = [(V_1 + 2V_2 + \ldots + 2V_n + V_{n+1})/2] \times L \qquad (1)$$

where A_1 is the cross-sectional area under the copper wire, V_1 through V_{n+1} are vertical distances from the wire to the trail surface at 10 cm intervals beginning at the left rebar stake and ending within 10 cm of the right rebar stake, and L is the 10 cm interval (Figure 4). Equation 1 assumes that the wire is fixed at a constant height on the rebar pole for each measurement. The height of the wire, however, was not fixed to minimize any problems incurred with vegetation interfering with the height measurements. The formula was thus modified to calculate the cross-sectional area of soil loss below an estimated original soil horizon as follows:

$$\text{If} \quad V_1 < V_{n+1} \quad A_2 = A_1 - (V_1 \times W) - 1/2[(V_{n+1} - V_1)W] \qquad (2)$$

$$\text{Else} \quad A_2 = A_1 - (V_{n+1} \times W) - 1/2[(V_1 - V_{n+1})W]$$

where A_2 is the cross-sectional area of soil loss and W is the width of the bare soil on the trail (Figure 5).

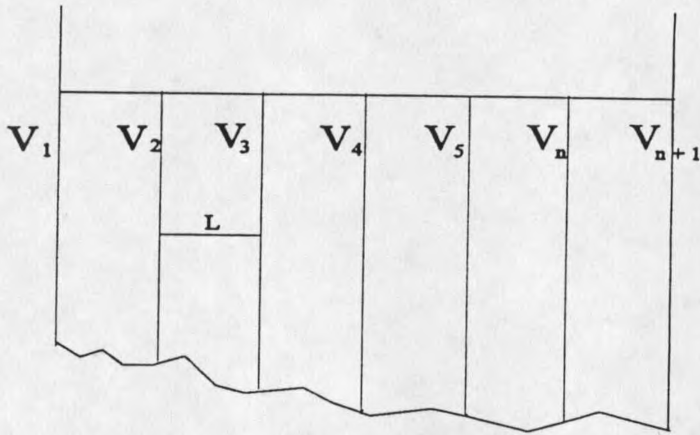

Figure 4. Measurements taken to calculate cross-sectional area, A_1

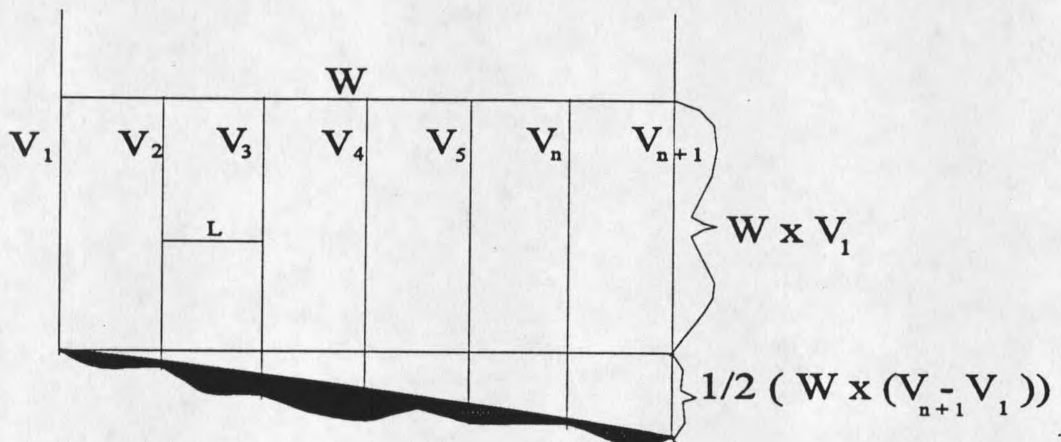

Figure 5. Calculations used to determine the area of the shaded region, A_2.

The new formula subtracts the area between the estimated former soil horizon and the copper wire from Cole's formula to calculate only the estimated cross-sectional area of soil loss. Equation 2 incorporates two options to allow for tilting in either direction. Several of the sample sites include two or more profiles because the trail braids into two or more sections. The cross-sectional areas of the individual braids were summed at these sites. Values recorded in the field were entered into a spreadsheet and the above formulae were implemented.

Soil Water Content

Soil water content was measured for the top 20 cm of the soil profile at each stake along the trail system in the late spring and fall of 1992 and late spring of 1993. Measurements were made at four sites that were chosen randomly (each time) within a 3 m^2 area centered on the stake and according to my ability to locate a position where the probe would insert 20 cm into the ground.

A Tektronix time domain reflectometry (TDR) cable tester, on loan from Dr. Jon M. Wraith in the Department of Plant, Soil and Environmental Sciences, was used for these measurements (Figure 6). The TDR was connected to a laptop computer for the spring 1992 measurements and a Campbell Scientific 21X electronic datalogger for the fall, 1992 and spring, 1993 measurements. The datalogger used a slightly different algorithm than the laptop to analyze the TDR output and convert it to volummetric soil water content. The TDR was mounted on an aluminum backpack frame for portability.

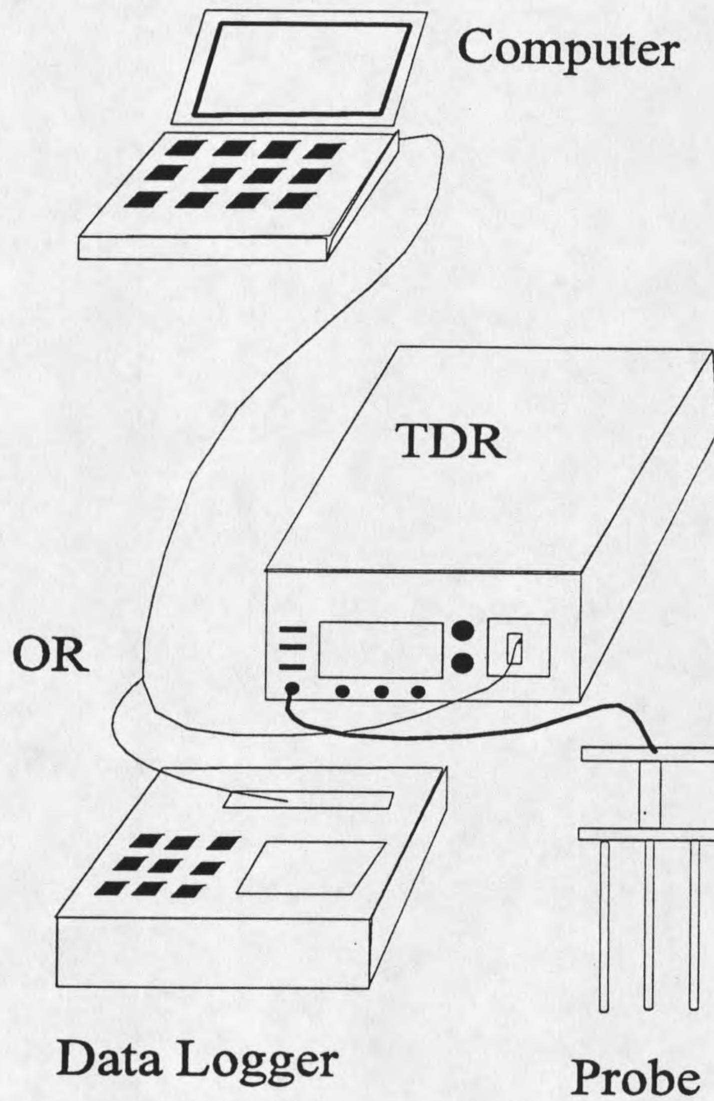

Figure 6. Textronix Time Domain Reflectometer (TDR) cable tester, Campell Scientific 21X electronic datalogger and laptop computer.

The TDR measures the apparent bulk dielectric permittivity of the soil. The dielectric constant of soil is strongly dependent on soil water content and nearly independent of soil density, texture and salt content. Water, as a very poor insulator, greatly reduces the soil's effectiveness as an insulator thus causing TDR to be a very direct measure of soil water content (Topp et al., 1980). A wide frequency current flows from the TDR through a coaxial cable into 20 cm prongs inserted into the soil and returns to the TDR. A waveform is output to the datalogger and converted to a bulk apparent dielectric constant using equations developed by Topp et al. (1980) based on the time necessary for the current to travel through the system (Baker and Allmaras, 1990). A jig consisting of two 5 cm square wooden blocks was used to maintain the position of the prongs during insertion into the soil. Several attempts were often required to fully insert the probe in particularly rocky or shallow soil. The probe was left in the soil while three replicate readings were taken. Each TDR waveform analyzed was the mean of 8 waveforms sampled by the cable tester. The volummetric soil water content was then recorded from the datalogger or computer to a field notebook.

Trail Slope

The slope along the trail was also measured at each sample site. An aluminum pole 1 m long was placed parallel to the trail. A Brunton compass was placed on the pole and the slope in degrees was read. The slope curvature and position of the sampling site relative to the top, middle, and bottom of the slope of the trail was also recorded.

Understory Vegetation

The understory vegetation communities located adjacent to the trail system were characterized at 100 m intervals. Techniques outlined by Bonham (1989) were used to estimate percent cover of forbs, shrubs and grasses. Strip quadrants measuring 10 cm x 30 cm were located lengthwise next to the trail edge, 1 m from the edge and 2 m from the edge along both sides of the trail at each study site. Percent cover was estimated for each quadrant, and dominant plant species and canopy type were also recorded. A mean percent cover value was calculated by computing the mean percent cover for the six plots at each site. In several cases the sum of the values for percent cover of forbs, grasses and shrubs exceeded 100% due to the fact that many forb species were understories of taller shrubs, thus both covered similar areas of ground and were counted twice.

Map Interpretation

Two types of map interpretation were conducted. First, data on underlying geology along the trail were gathered from a 1:24,000 scale geologic map of the area. Second, terrain attributes were computed using a digital elevation model produced from a 1:24,000 scale topographic map.

Geology

Information on the geology underlying the trail was obtained from the Geologic Map of the Mystic Lake Quadrangle, Montana (Roberts, 1964). A 1:24,000 scale mylar plot of the GPS points was overlaid on the map and geological map unit was noted at each stake.

The GPS points had an error of up to 30 m and there was an unknown error associated with the geologic map and it was often difficult to determine exactly which geologic unit a site belonged to. Map units were divided into resistant and non-resistant geology categories because of these potential errors. Units dominated by limestone, sandstone, dolomite and conglomerates were classified as resistant; and shales and areas of alluvium deposits were classified as non-resistant. Some map units were composed of both resistant and non-resistant rocks and were therefore classified based on whether they formed ridges (resistant) or gullies (non-resistant) where the trail crossed them on the topographic map.

Terrain Attributes

Terrain attributes were obtained with the help of computerized methods. A digital elevation model (DEM) was constructed from the 1:24,000 scale topographic map and the Topographic Analysis Programs for the Environmental Sciences - Grid version (TAPES-G) (Moore et. al. 1993a) were used to compute five terrain attributes at each stake location.

Digital Elevation Model Construction A 30 m x 30 m DEM was constructed for the 1:24,000-scale Mount Ellis quadrangle using the ARC/INFO Geographic Information System Software. TAPES-G requires a regular grid DEM as input and the 30 m DEM coverages prepared by the United States Geological Survey (USGS) have not been extended to cover this part of the United States yet. A mylar copy of the contour lines used by the USGS to produce the 1:24,000 scale Mount Ellis quadrangle was scanned using a Houston Instruments LDS 4000 plus scanner. Scanning errors were manually corrected and elevation attributes were added to the data file. The coverage was then converted to an ASCII file with X, Y and

Z coordinates.

The ASCII file was used with the program ANUDEM (Hutchinson, 1989) to develop the regular grid 30 m DEM. ANUDEM utilizes a finite difference scheme and spot heights, contour and stream line data to interpolate regular grid DEMs. The drainage enforcement option, which automatically removes spurious pits and maintains the fidelity of the drainage network, was used in this study.

TAPES-G Analysis The 30 m DEM was used with the TAPES-G to calculate slope, aspect, specific catchment area, profile and plan curvature for each cell in the DEM. These topographic attributes are computed using the grid-elevation values directly with a second order finite difference scheme, or by fitting a bivariate interpolation function z = f(x,y) to those values and then estimating the derivatives of the function. The mathematics have been simplified using the following notation:

$$f_x = \frac{dz}{dx},\ f_y = \frac{dz}{dy},\ f_{xx} = \frac{d^2z}{dx^2},\ f_{yy} = \frac{d^2z}{dy^2},\ f_{xy} = \frac{d^2z}{dxdy} \qquad (3)$$

and

$$p = f_x^2 + f_y^2,\ \ q = p + 1 \qquad (4)$$

where z [= f(x,y)] is the elevation at coordinates x, y in the horizontal plane, f_x and f_y are the first derivatives in the x and y directions, and f_{xx}, f_{yy} and f_{xy} are the second derivatives (Moore et. al. 1993b). The functions used to compute regional slope, aspect, plan and profile curvature are recorded in Table 1.

Specific catchment area was estimated in TAPES-G with the FRho8 algorithm in upland areas above defined channels and the Rho8 algorithm below points of channel initiation

(Moore et. al. 1993b). A channel initiation threshold of 49.5 ha (550 cells) was used to delineate channels. Drainage from a node to multiple nearest neighbors is determined on a slope-weighted basis in upland areas above defined channels. The algorithm uses the flow dispersion formula in Table 1 to calculate the fraction of catchment area passed to neighbor i in order to determine the proportion of flow or upslope contributing area assigned to multiple downslope nearest neighbors. This permits the modeling of flow dispersion in upland areas (Moore et. al. 1993b).

Table 1. Functions used by TAPES-G model (Moore et. al. 1993b).

Attribute	Function	
Regional Slope (β)	$\beta = \arctan\left(p^{.5}\right)$	(5)
Aspect (ψ)	$\psi = 180 - \arctan\left[\frac{f_y}{f_x}\right] + 90\left[\frac{f_x}{\lvert f_x \rvert}\right]$	(6)
Profile Curvature (κ)	$\kappa_p = \frac{f_{xx} f_x^2 + 2 f_{xy} f_x f_y + f_{yy} f_y^2}{p q^{\frac{3}{2}}}$	(7)
Plan Curvature (κ)	$\kappa_p = \frac{f_{xx} f_y^2 + 2 f_{xy} f_x f_y + f_{yy} f_x^2}{p^{\frac{3}{2}}}$	(8)
Flow Dispersion (F)	$F_i = \frac{\mathrm{Max}\left(0, \mathrm{Slope}_i^{1.1}\right)}{\sum \left[\mathrm{Max}\left(0, \mathrm{Slope}_j^{1.1}\right)\right]}$	(9)

TAPES-G outputs a file containing X, Y coordinates , elevations and computed terrain attributes (Table 1). The program TAPESOUT, written by Robert Snyder in the MSU Geographic Information and Analysis Center, creates ASCII compatible files containing X, Y coordinates and a user specified terrain attribute which can be imported into ARC/INFO using the ASCIIGRID command. This program was run for each of the attributes. An Arc Macro Language (AML) program, written by Damian Spangrud, was then run using the TAPESOUT coverages and the sampling sites coverage to obtain terrain attributes for each sample stake.

Statistical Analysis

Two statistical tests were used to asses the impact of the measured variables on trail soil erosion and compaction. First, a covariance matrix was constructed to determine which variables were independent of each other. Secondly, multiple regression was employed to identify interactions between the independent variables and soil erosion/ compaction.

The SAS (Freund and Littel, 1986) statistical software package was used to develop the covariance matrix and regression models. Multiple regression models were constructed with eight continuous variables and two sets of indicator variables (Table 2). The indicator variable geology divided the data set into resistant and non-resistant geology. The second series of indicator variables divided the sampling sites into four subsets based on aspect. Sites 1-58 comprise the first subset and have predominately north to northeast-facing aspects. The second subset is composed of sites 59-76 with aspects ranging from northeast to southwest-facing. The third subset includes sites 77-99 along Mystic Lake with chiefly east to southeast-

facing aspects. Lastly, sites 100-130 made up the fourth subset with predominately southwest-facing aspects. These indicator variables allow for the inclusion of non-ratio scale variables in the analysis. The result is a multiple regression equation with nine independent variables, one or more indicator variables and nine or more cross-product variables that represent the interactions between geology and aspect and the other independent variables.

Table 2. Independent variables used in regression models.

Continuous Variables	Units
Trail Slope	degrees
Soil Water Content	decimal percent
Understory Vegetation Cover	percent
Regional Slope	degrees
Elevation	feet
Specific Catchment Area	m^2m^{-1}
Profile Curvature	m
Plan Curvature	m
Indicator Variable	**Value**
Geologic Unit (resistant, non-resistant)	0 or 1 resistant or non-resistant geology
Aspect	0 or 1 depending on presence/absence of stakes in one of four aspect classes

The multiple regression models were developed using step-wise regression with forward selection and backward elimination of non-significant variables until all significant variables are included in the equation. A significance threshold of .05 was used for both forward selection and backward elimination. The SAS procedure RSQUARE was also utilized to compare the generated regression model with other competing regression models and determine if the most appropriate model was used (Freund and Littell, 1986).

Soil Water Modeling

A terrain attribute not directly estimated by TAPES-G but important to this study is soil wetness. This attribute was calculated using the steady-state soil wetness index of Moore et. al. (1993a) and selected TAPES terrain attributes as inputs.

The steady-state wetness equation proposed by Moore et. al. (1993a) can be written:

$$X_i = \ln(A_{si}/\tan\beta_i) \quad (10)$$

where X_i is steady-state wetness, A_{si} is the specific catchment area ($m^2\ m^{-1}$) and β_i is the regional slope gradient in degrees. The value of the index increases with increasing specific catchment area and decreasing slope gradient. High values are computed on flat areas and in valleys where water concentrates and low values are obtained on steep hillslopes where water is free to drain (Moore et. al. 1993a). This index was calculated in SAS using the slope and specific catchment area attributes generated by TAPES-G. Regression analysis was employed using the SAS program to compare variation in the independent variable, predicted steady-state wetness, to the variation in the dependent variable, measured soil water content.

CHAPTER THREE

RESULTS

Several approaches to synthesizing data were utilized. First, the spatial pattern of the trail cross-sectional area was investigated graphically. The relationships between environmental controls and trail condition were then explored through multiple regression analysis. Finally, bivariate regression analysis was used to evaluate the steady-state wetness index.

Spatial Pattern of Trail Erosion and Compaction

Cross-sectional areas over the length of the trail range 864 cm^2 to 22,942 cm^2 with a mean of 4,819 cm^2 and a standard deviation of 4,102 cm^2. A histogram of the measured cross-sectional areas was created to assess the spatial distribution of soil erosion and compaction along the trails (Figure 7). The graph shows that the sites with high cross-sectional areas occur along the first 6 km of the New World Gulch Trail, between study sites #1 and #60. Some sites have lower cross-sectional area values indicating much variability in trail condition along this portion of the trail. The condition of the last 7 km of trail is much more uniform. Most of these sites have less erosion and compaction than sites along the first 6 km of trail. Regression analysis was employed to investigate whether this variability in trail cross-sectional area can be explained by the variability in the other environ-

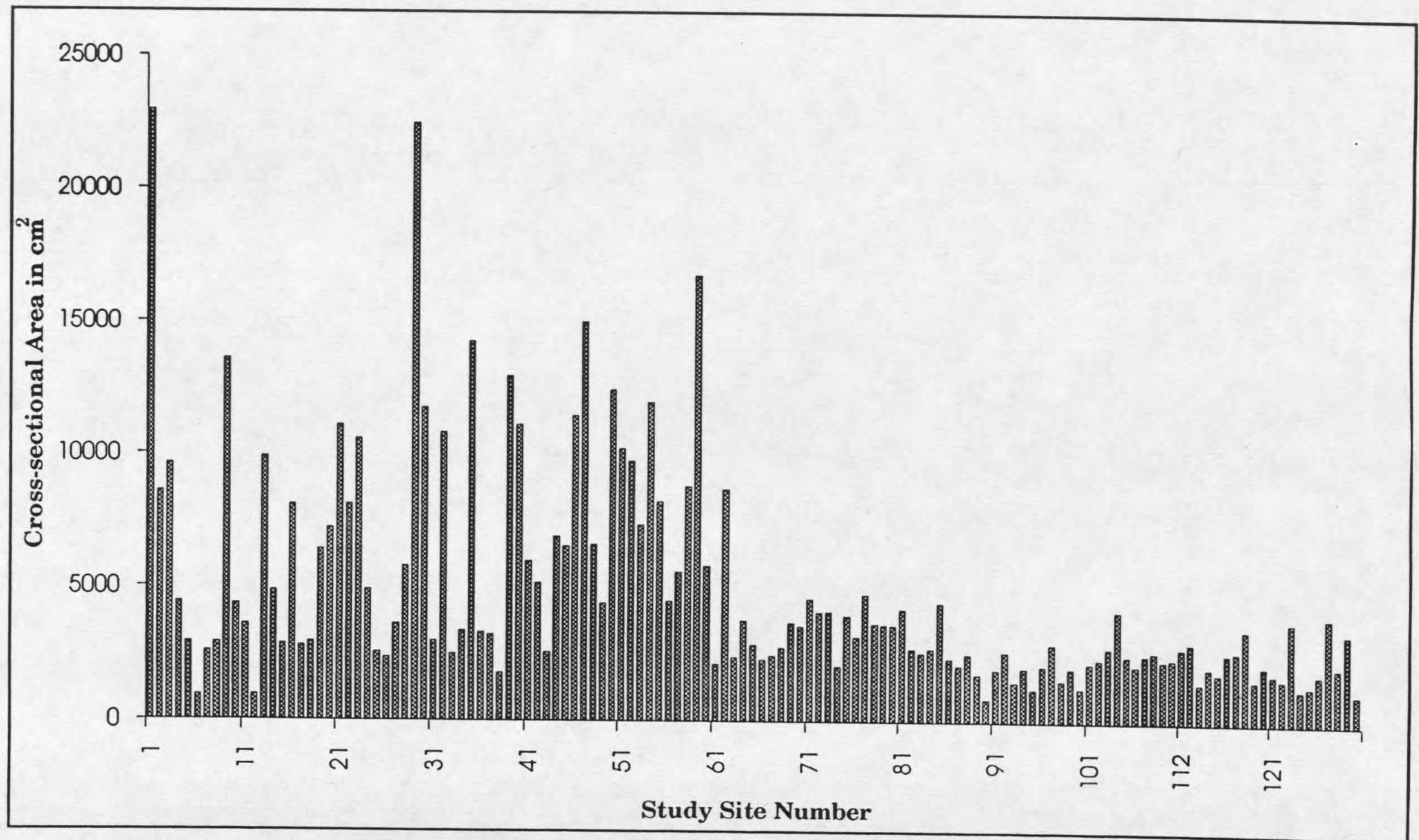

Figure 7. Spatial distribution of trail cross-sectional area.

-mental factors.

Soil Water Measurements

The soil water content of the top 20 cm of soil was measured on three different dates at each stake. In order to utilize the soil water measurements in a regression analysis a method for synthesizing these three different measurement periods was necessary (Table 3). First, data on the precipitation events prior to these measurements were investigated to explore the temporal variability of soil water content.

Table 3. Soil water measurements (in percent).

Date of Measurement	Minimum	Maximum	Mean	Coefficient of Variation
July 1992	6.0	58.0	18.3	55.2%
September 1992	3.1	46.5	16.4	48.2%
June 1993	11.4	57.9	28.9	34.3%

Table 4 shows the previous precipitation recorded at the Montana State University Climate Station located in Bozeman, MT, 20 km northwest of the study area. Rainfall on the study area may be somewhat different than the values recorded in the valley due to the effect of the surrounding mountains on precipitation patterns. The values recorded at the MSU Climate Station should, though, approximate the rainfall on the study area. It rained several times prior to the June 1993 measurements, including the three days immediately preceding the field measurements. Approximately 8 cm of precipitation was reported in each of the two months preceding these measurements. The two months prior to the July 1992 measurements were wetter than the corresponding period preceding the June 1993 measurements. During

the week immediately prior to the measurements, though, only 0.18 cm of precipitation was recorded in July 1992 compared with 0.89 cm for the week prior to the June 1993 measurements. The higher soil water levels in June 1993 demonstrate the impact of recent rainfall on soil water measurements. The September 1992 mean precipitation was less than that measured in July 1992 or June 1993, as expected, given the timing (end of summer) and lesser amount of precipitation in the preceding two months (Table 4). This data indicates that soil water content is both spatially and temporally variable. The ranks of these three moisture periods were used to determine if similar sites were always wet relative to the other sites and if similar sites were also dry relative to the other sites.

Table 4. Precipitation history, at MSU, Bozeman, MT, previous to soil water content measurements in centimeters (National Oceanic and Atmospheric Administration 1992, 1993).

Time Period	July 1992 Precipitation	September 1992 Precipitation	June 1993 Precipitation
Previous Day	0.00	0.00	0.23
Previous Three Days	0.00	0.36	0.53
Previous Week	0.18	1.59	0.89
Previous Two Weeks	1.65	2.28	2.63
Previous Month	13.49	2.29	8.41
Previous Two Months	21.00	6.66	16.49

The mean soil water content values for each stake were ranked from high to low for the three measurement periods and the Spearman's Rank Coefficient was calculated for each pair of measurements to examine the spatial variability in soil water measurements. Spearman's Rank is a non-parametric statistical method to compare the correlation between two sets of ranked data. The results are bounded by -1 and 1 where 1 indicates perfect

positive correlation of ranks, -1 indicates perfect negative correlation of the ranks and 0 indicates no correlation. The results (Table 5) show positive correlation between all data sets. The Z values are greater than 4.0 indicating there is greater than a 99% chance that the results are statistically significant. It can be concluded that the different measurement periods produced similarly ranked outcomes. Thus the three soil water content data sets were averaged to form one data set representing a hiking season mean soil water content in the study area.

Table 5. Spearman's rank coefficient and corresponding Z values for each soil water content measurement pair.

	July 1992 versus September 1992	July 1992 versus June 1993	September 1992 versus June 1993
Spear man's Rank	0.676	0.749	0.610
Z value	6.377	7.066	5.755

Regression Analysis

Regression analysis was used to explore how much of the variability in trail cross-sectional area (Figure 7) could be explained by the variability in selected environmental factors. Several iterations were needed to identify the preferred regression model.

Development of Correlation Matrix

The correlation matrix (Table 6) includes cross-sectional area and the continuous variables listed in Table 2. This matrix shows two results: (1) the environmental factors that are related to cross-sectional area (column 1) and (2) how the environmental factors are

Table 6. Pearson's correlation coefficients.

Variable	Cross-Sect. Area	Elev.	Aspect	Reg. Slope	Prof. Curv.	Plan Curv.	Spec. Catch. Area	Trail Slope	Soil Water Content	Veg. Cover
Cross-Sectional Area	-									
Elevation	-0.04	-								
Aspect	0.18[1]	-0.23[1]	-							
Regional Slope	-0.38[2]	-0.03	-0.01	-						
Profile Curvature	-0.14	-0.20[1]	0.12	-0.11	-					
Plan Curvature	0.03	-0.03	0.04	-0.14	0.39[2]	-				
Specific Catchment Area	0.07	-0.32[2]	-0.23[1]	-0.20[1]	0.16	0.26[2]	-			
Trail Slope	0.49[2]	-0.07	-0.12	-0.10	-0.09	0.05	0.17[1]	-		
Soil Water Content	0.35[2]	0.17	0.04	-0.50[2]	-0.04	0.04	-0.03	0.03	-	
Vegetation Cover	0.05	-0.02	0.10	-0.20[1]	-0.01	-0.14	0.00	0.00	0.31[2]	-

[1]Significant at 0.05 level.
[2]Significant at 0.01 level.

related to one another. This last set of correlations is important because regression analysis assumes independence of variables.

Inspection of column 1 of Table 6 reveals the significant relationships between variation in cross-sectional area and several environmental factors. Aspect is significant at the 0.05 level and regional slope, trail slope and soil water content are significant at the 0.01 level. Aspect, trail slope and soil water content are all positively correlated to cross-sectional area. Thus as aspect, trail slope or soil water content increase trail cross-sectional area increases. Regional slope is negatively correlated to cross-sectional area and thus trail cross-sectional area decreases as regional slope increases. The Pearson's correlation coefficients can be squared and this statistic (R^2) can be used to describe how much variation in cross-sectional area is statistically explained by these other variables. Hence, trail slope explains approximately 24% of the variability in cross-sectional area, regional slope and soil water content explain 14% and 12%, respectively, and aspect explains only 3% of the variability. Scattergrams were used to determine that these relationships were approximately linear.

The inclusion of aspect in the above analysis is both problematic and misleading given that the measurement of aspect in degrees produces non-linear results. The difference, for example, between 1° and 359° is only 2° rather than 358°. This poses a problem for applying regression analysis to the data since standard regression analysis assumes interval or ratio data. The inclusion of indicator variables in the regression analysis is one way to solve this problem.

The remainder of Table 6 indicates which variables are correlated to one another. Multiple regression assumes that independent variables are not correlated with one another and the presence of significant multicollinearity will allow substitution of terms in competing regression models. Hence, the fact that soil water content and regional slope are negatively correlated at the 0.01 significance level means that we would not expect soil water content and regional slope to appear simultaneously in the same regression model. The same is true of specific catchment area given that this term is significantly correlated with five other variables. The specific catchment area term may not appear in the regression models because a larger proportion of the variability in the cross-sectional area of the trail is accounted for by the variability in the other variables to which specific catchment area is related.

Table 7 summarizes the means, standard deviations, and minimum/maximum values computed for the continuous environmental control variables along the trail. The trail covers 466 m of relief and shows great variability in terms of vegetation cover, trail and regional slopes, specific catchment areas, and soil water content. The computation of 0% regional slopes at several stakes indicates flat areas and explains why aspects were not computed in three instances. A greater variability of trail slopes compared to regional slopes was expected and reflects the scale and style of measurement given trail slopes were measured over several meters along the trail and regional slopes were measured with a 30 m DEM. Overall, these data indicate that the study area is composed of a trail system that traverses a large number and variety of geomorphic conditions.

Inclusion of Indicator Variables

The above discussion only encompasses the continuous variables listed in Table 2.

Regression analysis also allows for indicator variables where the values consist of zeros and ones. This method was used to include resistant/non-resistant geology and four aspect classes in the analysis.

Table 7. Environment control summary data.

Variable	Minimum	Maximum	Mean	Standard Deviation	Median
Cross-sectional Area(m^2)	864.0	22942.0	481.0	4102.0	3173.0
Elevation (m)	1658.0	2121.0	1926.0	120.0	1952.0
Regional slope (%)	0.0	26.3	11.2	7.3	9.4
Profile curvature (m)	-2.6	6.0	0.15	0.99	0.03
Plan curvature (m)	-5.9	12.3	-0.1	2.4	0.0
Specific catchment Area (m^2 m^1)	33.0	531670.0	14550.0	73230.0	225.0
Trail slope (%)	0.0	40.4	10.3	8.3	8.3
Soil water content (%)	6.5	52.4	19.5	8.9	17.3
Vegetation cover (%)	0.0	102.0	64.0	20.0	65.0

Table 8 divides the trail data into resistant and non-resistant geology and records the means and difference of means t-test results for each variable. The cross-sectional areas reported for non-resistant geology are larger (5630 cm versus 4080 cm) and statistically different (0.03) at the 0.05 significance level than those measured in resistant materials. However, elevation, regional slope, soil water content and understory vegetation cover also varied between resistant and non-resistant geology. Lower elevations, soil water contents and vegetation covers and steeper regional slopes were associated with resistant geology and higher elevations, soil water contents and vegetation covers and gentler regional slopes were associated with non-resistant geology. These relationships were also statistically significant

at the 0.05 significance level. This multicollinearity between geology and some of the continuous variables explains why the addition of geology had little or no impact on the regression results.

Table 8. Environmental control means by resistant/non-resistant geology and t-test results.

Variable	Resistant Geology (Geol = 0)	Non-Resistant Geology (Geol = 1)	Mann-Whitney Test Z	Prob> | Z |
Cross-sectional Area	4080.0	5630.0	2.59	0.01
Elevation	1906.0	1949.0	2.86	0.00
Aspect	179.0	218.0		
Regional slope	12.7	9.7	-2.43	0.01
Profile curvature	0.1	0.2	0.09	0.93
Plan curvature	-0.2	0.1	0.54	0.59
Specific catchment area	17660.0	11139.0	0.69	0.49
Trail slope	8.8	11.7	1.87	0.06
Soil water content	18.1	21.0	2.31	0.02
Vegetation cover	59.8	67.6	2.32	0.02
Number of stakes	68	62		

The division of landscapes into similar aspects was found to be one method to incorporate the effect of aspect on trail condition without the difficulties associated with the measurement of aspect in degrees as discussed earlier. A careful review of Figure 2 would seem to indicate that the trail traverses four very different aspects in this instance. These aspect classes were added as indicator variables and used to assess the impact of aspect on the erosional status of the trail. Visual examination of the map (Figure 2) and the characteristics (Appendix 1) were used to assign stakes to the four aspects (Table 9).

Table 9. Environmental control means by aspect class.

Variable	Stakes 1-58	59-76	77-99	100-130
Cross-sectional area	7153.0	4381	2589	2362
Elevation	1875.0	2061.0	1968.0	1915.0
Minimum	1659.0	1973.0	1923.0	1818.0
Maximum	2123.0	2123.0	2019.0	2020.0
Aspect				
N	9	0	0	0
NE	4	5	0	0
E	1	3	12	0
SE	2	2	8	3
S	1	2	2	5
SW	1	5	0	17
W	19	1	0	6
NW	19	0	0	0
None	2	0	1	0
Regional slope	7.6	6.7	13.4	19.2
Profile curvature	0.3	0.4	-0.1	0.0
Plan curvature	-0.1	0.9	-0.5	-0.3
Specific catchment area	30733.0	610.0	2401.0	1379.0
Trail slope	11.8	11.6	7.6	8.3
Soil water content	22.7	24.1	17.3	12.4
Vegetation cover	66.1	66.7	58.0	60.9
Number of stakes	58	18	23	31

Stakes 1-58 delineate the first unit. These stakes ascend the bottom of a drainage to the top of the highest ridge. The trail itself crosses the stream channel in several places and many of the stakes were located in digital elevation model cells with high specific catchment areas (i.e. large numbers of cells draining to them). These stakes had predominately north-facing to west-facing aspects. Stakes 59-76 delineated the portion of New World Gulch trail that descends from the top of the ridge to the northern end of Mystic Lake. The position of these stakes near the ridge line accounts for the low specific catchment areas. Aspect is more

variable along this portion of the trail with most of the sites facing northeast/east/southeast or southeast/south/southwest (Table 9).

Stakes 77-99 skirted the western boundary of Mystic Lake and delineated the third aspect. These stakes have mostly southeast or east aspects and higher regional slopes and lower trail slopes than the first two trail sections. The final group of stakes (100-130) traverse the steep hillslopes that make up the northern boundary of the Bozeman Creek drainage. This position accounts for the south and southeast-facing aspects and lower elevations compared with the second and third trail sections.

Multiple Regression Analysis

The Pearson's correlation matrix indicated that regional slope, trail slope and soil water content were correlated with trail cross-sectional area. No single variable explained more than 25% of the variability in cross-sectional area thus multiple regression analysis was employed to determine the combined influence of these variables. The stepwise regression results reported here utilized the continuous variables summarized in Table 7 and three indicator variables delineating four different aspects (Table 10).

Table 10. Indicator variables used to describe aspects.

Indicator Variable	Aspects Stakes 1-58	 59-76	 77-99	 100-130
Aspect1	0	1	0	0
Aspect2	0	0	1	0
Aspect3	0	0	0	1

The first column of regression results in Table 11 indicates that the model included five terms and the third and fourth columns indicate that the variability in these terms combined to explain 50% of the variability in cross-sectional area. The three trail slope terms combined to explain 35% of the variability compared to soil water content and regional slope which explained an additional 11% and 5%, respectively.

Table 11. Multiple regression results.

Variable	Parameter Estimate	Partial R2	ModeledR^2	F	Prob>F
Intercept	1926.2				
Trail Slope	284.2	0.25	0.25	41.46	0.0001
Soil Water Content	113.5	0.11	0.36	22.52	0.0001
Trail Slope 2[1]	-249.2	0.05	0.40	9.56	0.0025
Trail Slope 1[2]	-198.9	0.05	0.45	10.46	0.0016
Regional Slope	-141.3	0.05	0.50	11.54	0.0009

1 Interaction variable trail slope * aspect2

2 Interaction variable trail slope * aspect1

The derivation of the response functions that apply to different sections of trail may help to illustrate the significance and meaning of the five regression terms further. The basic equation used for a first order regression model with one interaction term is:

$$Yi = \beta_0 + \beta_1 x_1 + \beta x_2 x_2 + \beta_3 x_1 x_2 + \varepsilon_i \quad (11)$$

where Y_i is the trail cross-sectional area, x_1 might represent trail slope, x_2 might represent aspect 2 (stakes 59-77), and β_1, β_2 and β_3 represent the parameter estimates for these two terms and their interaction (i.e., x_1x_2). The resulting response function would read:

$$E(Y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 \quad (12)$$

The exact meaning of the significant regression terms is best interpreted by examining the

nature of the response function for each aspect separately. The regression results summarized in Table 11 can be written in equation form as:

$$E(Y) = 1926 + 284x_1 + 114x_2 - 199x_1x_3 - 249x_1x_4 - 141x_5 \quad (13)$$

where Y is trail cross-sectional area, x_1 is trail slope in percent, x_2 is soil water content in percent, x_3 is aspectl = 1 (stakes 59-76), x_4 is aspect2 = 1 (stakes 77-99), and x_5 is regional slope in degrees.

For stakes 1 through 58 and 100 through 130, x_3 and x_4 both equal 0, so that the response function reads:

$$E(Y) = 1926 + 284x_1 + 114x_2 - 141x_5 \quad (14)$$

Predicted cross-sectional areas increase with increasing trail slopes, increasing soil water contents and decreasing regional slopes. The same general pattern is true for the other two trail sections although the presence of the interaction terms changes the rate of change for the relationship between trail slope and cross-sectional area. Hence, the equation for stakes 59-76 reads:

$$E(Y)= 1926 +(284-249)x_1+ 114x_2 - 141x_5 \quad (15)$$

and the equation for stakes 77-99 reads:

$$E(Y)= 1926 +(284 - 199)x_1 + 114x_2 - 141x_5 \quad (16)$$

The parameter estimates for the trail slope variable (x_1) are reduced in both instances indicating that unit changes in trail slope have much less impact on trail cross-sectional area along these middle portions of the trail.

The negative parameter estimate for the regional slope term is surprising given that most other studies have found a positive correlation between slope and trail deterioration.

Its appearance in this study can be traced to the magnitude of the surrounding landforms and the orientation of the trail relative to the steepest slopes (Table 9). The means reported in Table 9 indicate how cross-sectional areas decreased and the regional slopes increased from the first through the fourth aspects. The likelihood that this pattern would be repeated along other trails will be examined in the next chapter.

The regression model explained 50% of the variation in trail cross-sectional area. One-half of the variation remains unexplained. Investigation of the regression residuals helped to pinpoint areas where the model did not fit the data well. Figure 8 graphs the residuals spatially along the trail. The sites with high negative residuals included sites #6,12,38,43,61 and 101. These sites could be divided into two categories. Stakes #6,43 and 61 are located in meadows and stakes 12 and 38 occur next to stream banks. Stake 101 belongs to neither of these categories. The division of stakes with high residuals into these two categories was not substantiated by further investigation of the residuals. Study sites #41, 42, 72, 73, 74 and 75 are also located in meadows but none of these sites have residuals greater than 100 cm^2 and thus the model worked well at these sites. Other sites located along stream banks included stake #2, 5, 18, 44 and 76. These sites have small residuals (i.e., less than 150 cm^2). Site #101 has very little in common with the other sites with high residuals.

A second look at the residuals revealed three areas where the residuals were spatially similar. Sites 5-18 had mostly large negative residuals (Figure 8). This indicates the model over-estimated the trail cross-sectional areas for this section. The presence of waterbars along the trail or soil variations (e.g. alluvium from the creek creating coarse soils) may be responsible for these high residuals. Waterbars located above study sites would decrease the

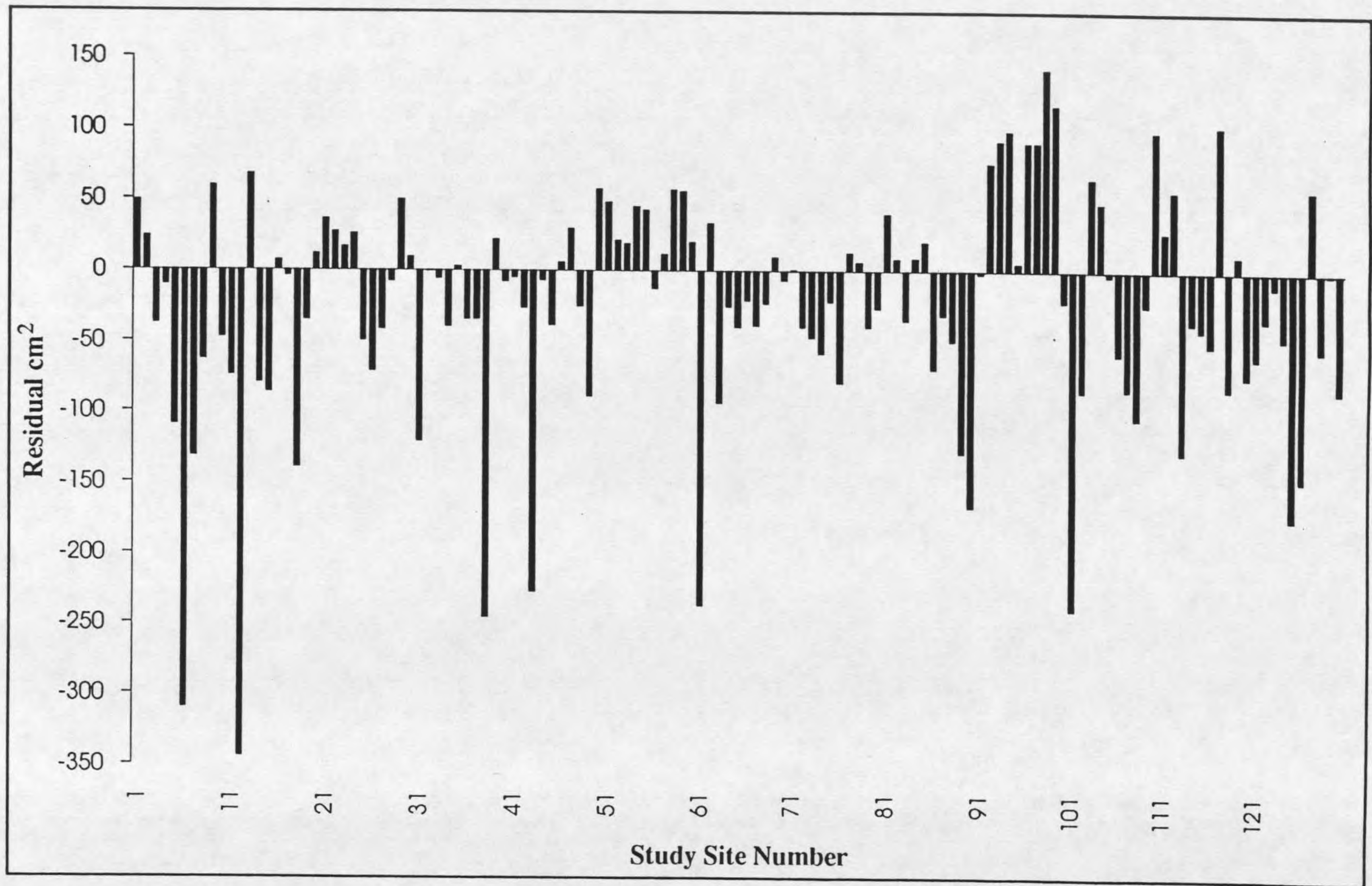

Figure 8. Spatial distribution of residuals.

amount of erosion at a site. Coarse gravels cause soils to be less erodible thus the combination of these two factors may make this portion of the trail less erodible than the model would expect. A second area where residuals are similar is for sites 51-60 (Figure 8). Here the model has underestimated trail cross-sectional erosion. This section of trail follows an old logging road where a wide path of trees has been cleared. This allows for greater widening and thus greater cross-sectional area of the trail. Lastly the section of trail from site 92 to 99 has underestimated trail cross-sectional areas (Figure 8). This section lies along Mystic Lake and the lake could be a contributing factor in this result. Mystic Lake was, at one time, dammed to create a larger water supply for Bozeman. The lake shore was at that time much closer to the trail and may have influenced the soil moisture conditions during that period and contributed to trail deterioration (i.e. greater trail cross-sectional areas). This portion of trail along the lake may also gain more use due to fishermen walking repeatedly back and forth along its length causing increased erosion and compaction.

Soil Water Modeling

The fourth objective of this study was to explore the potential for using terrain analysis techniques to predict the spatial distribution of soil water content. Soil water content was time consuming and expensive to measure, thus, attributes from the TAPES-G program and models developed by Moore et. al. (1993a) were utilized in an effort to find an easier method to assess soil water content.

Multiple regression was used to compare the variability in the measured mean soil water content and the steady-state wetness index across aspect units. The dependent variable

was measured soil water content and the independent variables included the modeled wetness index and geomorphic indicator variables. The regression results are shown in Table 12. The R^2 value of 0.10 indicates that the variability in modeled soil water content explained only 10% of the variability in measured soil water content.

Table 12. Results of measured versus modeled soil water content (SWC) bivariate regression.

Variable	Parameter Estimate	Partial R2	Modeled R2	F	Prob>F
Intercept	12.17				
Modeled SWCl[1]	0.64	0.06	0.06	7.97	0.006
Modeled SWC	0.74	0.04	0.10	6.37	0.013

1. Interaction variable modeled soil water content * aspectl.

CHAPTER FOUR

DISCUSSION

This study examined the relationships between trail condition and landscape scale variables that have been frequently cited by previous studies (Dale and Weaver 1973, Dawson et. al. 1974, Helgath 1975, Bryan 1977, Bratton et. al. 1979, Burde and Renfro 1986, Wilson and Seney 1994). Many of these studies examined these relationships in small study areas with less than 100 sites (e.g., Helgath 1975; Summer 1980, 1986; Wilson and Seney 1994). This study sought to combine landscape scale variables with randomly selected sample plots at approximately 100 m intervals along 11 km of trail to better depict the relationships between these variables and trail condition.

The environmental controls of trail slope and soil water content were found by this study to be positively correlated with trail cross-sectional area along the entire trail, such that increases in trail slope or soil water were accompanied by cross-sectional area increases. Trails often provide a channel for channelized flow. Increased trail slope created higher velocities of water flow and thus increased the erosive power of the water (Cole 1988). Increased soil water content provides for more compactable soils due to increased lubrication between the particles and also creates more erodible soils because water will pond on the surface and initiate overland flow causing erosion on the trail surface in areas of saturated soils (Hillel 1980).

The degree to which trail slope affected the variability in trail cross-sectional area varied from one aspect to another. The regression coefficient for trail slope in the response functions for the first and last sections of the trail (sites 1-58 and 100-130) was much larger than for the middle sections of trail. Unit changes in trail slope at either end of the trail have a much larger impact on predicted cross-sectional areas than for the middle sections of trail. This result implies that the variability in trail slope on northeast to southwest facing aspects is not as correlated to trail cross-sectional area as for the other two sections of trail. Neither of these sections exhibit especially low mean trail slopes (11.6 % and 7.6% respectively) compared to the mean trail slope for the first aspect unit (11.8%) and the last aspect unit (8.3%). Thus it appears that the aspect units may encompass more than just aspect.

Classes of aspects could also mirror the variability in trail topographic position and landform size. Aspect unit one is located in a drainage where the trail ascends approximately directly up the drainage and traverses the lower portions of landforms over 1000 m in height (Figure 2). Aspect unit two follows a ridge and descends a short distance down the ridge. Here the trail is at or very near (less than 100 m) the top of the landform (Figure 2). The third aspect unit follows the contour of the lake. Although the trail here is located at the base of a landform, the landforms are quite small with most slopes only reaching a maximum of 500 m. The last aspect unit is located in the drainage of Bozeman Creek. The trail is located on the lower portion of the steep western slopes of Mt. Ellis (Figure 2). For the middle two sections of trail the combination of small landform sizes (sites 77-99) or high topographic position of the trail relative to hilltops and ridges (sites 59-76) makes the trail slope less a factor in trail cross-sectional area since water's erosional force is less on features where the

uphill slope is short. The first and last sections of trail are located near the bottom of long slopes where water's erosional powers would be greater than for the middle two sections of trail thus trail slope is more important on these landforms. It appears then that the aspect classes used in this study may embody more than just the aspect variable but also topographic position and landform size.

These results match those obtained in earlier studies given that (1) others found the division of landscapes into landform units helped explain trail condition (Helgath, 1975, Summer 1980, 1986) and (2) others found trail slope and soil water content affected erosional status (Helgath 1975; Bratton et. al. 1979; Burde and Renfro 1986; Wilson and Seney 1994). The landform units utilized in this study are more generalized than either Helgath's (1975) or Summer's (1980, 1986) but may still embody similar meaning. These units were derived by using the position of the stakes relative to the main ridges and the Mystic Lake shoreline to divide the trail into four sections. These terrain divisions were obtained from topographic map interpretation and could be implemented in other landscapes by dividing landscapes first into broad aspect categories and then further dividing the classes by topographic position and landform size.

Regional slope was also found to significantly influence trail cross-sectional area. Regional slope was found to be inversely related to cross-sectional area so that for every percent increase in regional slope trail cross-sectional area decreases by 141 cm^2. The negative correlation may be a consequence of the particular route travelled by these trails. The largest regional slopes are found at sites 110-130 where trail cross-sectional areas were very low. The trail between stakes 100 -130 traverses, at right angles to the maximum

gradient, a series of steep slopes. This combination produced low trail slopes, low cross-sectional areas but steep regional slopes.

Fifty-percent of trail cross-sectional area variability was accounted for by the study but the other fifty percent remains unexplained. Several factors may have contributed to the unexplained variance including: (1) the accuracy of the global positioning system, (2) the scale of the DEM and geologic map, (3) variables not measured by the study and (4) the contribution of compaction to the measured trail cross-sectional area.

The Magellan Nav5000 Pro Global Positioning System used to map the study site locations had an accuracy of 5 to 30 m. The terrain variables were computed from a 30 m DEM of the study area. Placement of the stakes to within 30 m of their true position coupled with the accuracy of the 1:24,000-scale topographic maps and subsequent interpolation provided numerous opportunities for the incorrect assignment of points to cells during the point to grid cell overlays performed in ARC/INFO. These problems may be unavoidable given the fact that a distance of 30 m is represented by 1.25 mm on a 1:24,000-scale map. Manual location of the trail on the topographic map in the field would not have produced a better result.

The scale of the geologic and topographic maps may also help to explain the modest success (R^2). Geology at the 130 stakes along the trail was classified as resistant or non-resistant. The level of accuracy of the GPS derived stake locations and the complexity of the geology along certain sections of the trail may have contributed to the misassignment of resistant/non-resistant classifications at some stakes. Many formations such as the Frontier Formation include resistant sandstones and limestones along with non-resistant shales. The

Frontier Formation is comprised chiefly of non-resistant materials but a ridge is located where the trail crosses this formation. One of the layers of the formation is resistant and is exposed at these sites. This example was easily recognized and accounted for but other, less prominent examples, may not have been identified.

Similarly, the use of a 1:24,000-scale topographic map may have obscured some of the fine-scale topographic features. Some terrain features affecting regional slopes may not have been captured at the 30 m^2 scale. For example, smaller drainages may not be represented at this scale. Study site #3 is located on a short (15 m) steep hill. The TAPES-G model generated a regional slope of only 6.1% for this site. This reflects the overall average slope for that 900 m^2 area of which the hill is only a small portion. A larger scale DEM that divided the landscape into smaller cell sizes may have captured these micro-relief changes.

At least four other factors, which were not measured, may also have contributed to the final result. Bratton et. al. (1979) found that trail slope, regional slope, elevation and trail orientation relative to regional slope orientation were correlated with trail erosion. This study includes all but the last factor. Trail orientation could have been determined when the trail slope was measured and compared to aspect (i.e. the path of maximum descent) at each of the stakes (similar to Bratton and his colleagues). This term may have replaced regional slope in the final regression equation and increased the final regression R^2.

A second factor, which may have helped the analysis, is information about over story vegetation. The type and density of over story vegetation, such as trees, greatly affects the timing and amount of precipitation the soil receives. In heavily forested areas trees intercept much of the precipitation. This moisture is either lost to evapotranspiration or eventually falls

to the soil below. Once moisture does reach the soil, though, it is less likely to be lost to evapotranspiration in forested areas than in more open areas (Cole 1988). Trees also play a role in the prevention of soil erosion. Roots help bind the soil and hold it in place (Helgath 1976). Documenting the combined influences of over story on soil and water supply may have improved the regression model developed in this study.

The presence of trail maintenance measures such as water bars was also not assessed by this study. Properly placed water bars on an existing trail could greatly influence the degree of erosion at a given study site. Water bars serve as diversion devices to divert water from the trail and limit its erosive powers. Sites located on a steep trail grade with water bars upslope of them should experience less erosion than those without water bars. Data concerning location of study sites relative to water diversion devices may add to the predicted variability of trail cross-sectional area.

The final factor concerns the dependent variable. Trail cross-sectional areas may be attributable to two causes: soil compaction and/or soil erosion. Previous studies have sought to link rates of soil compaction to soil properties and use (Dotzenko et. al. 1967; Dawson et. al. 1974; McQuaid-Cook 1977; Weaver and Dale 1978; Summer 1980; Kuss 1983) but none have sought to quantify the contributions of both trail erosion and compaction to overall trial deterioration. The linking of the two types of studies provides another opportunity for further study.

This study does show that the most successful trails will be located on relatively dry and gentle slopes. Planning a trail to match gentle slopes may be easier than finding dry areas. Trail design techniques such as switchbacks can be utilized to create gently sloping trails.

Approximately $10,000 worth of equipment and 16 field days was required to collect 3 sets of soil water measurements at 130 stake locations in this study. This large investment of time and resources may not be feasible for many land managers. The fourth and final objective of the study sought to examine the potential for using terrain analysis techniques to predict the spatial distribution of soil water content within the study area. Results of the regression analysis show very poor correlation between measured and predicted soil water content. Two potential causes for this poor correlation have been observed; the division of the landscape into uniform 900 m^2 cells and the assumption that a steady-state soil water equilibrium is achieved in the field.

Band et. al (1991) found models that use *a priori* knowledge of terrain to divide an area into discrete landscape units instead of more conventional grid cells improves the predictions of hydroecologic simulation models. Band et. al. (1991) utilized FOREST-BGC, a forest ecosystem process model, to simulate forest evapotranspiration and net primary productivity. Parameters such as air temperature, vapor pressure deficit, solar radiation, leaf area index and available soil water capacity were used. The soil water capacity parameter was of particular interest to this study. These factors form micro-environments that follow spatial patterns. In water limited ecosystems such as western Montana the spatial pattern of these micro-environments is controlled by local slope, exposure and landscape position. Hillslope facets, therefore, were chosen as the basic unit instead of uniform cells (pixels).

The selection of hillslope facets is problematic. Ideally, terrain should be divided into facets in which the variability in solar radiation, vegetation cover and soil water is minimal. Band et. al. (1991) tested many hillslope scales and found that in mountain environments the

high variance in these factors over small areas limits the efficiency of the hillslope partition strategy. This is a particular problem for the study area used here where solar radiation, vegetation cover and soil water change dramatically over short distances. For example at site 35 the aspect is southerly on a 22% slope. Consequently soil water content is low (12%) and vegetation cover sparse (42.5%). Site 37, 200 m away, has a northeast aspect on a 3.5% slope with much higher soil water content (25%). Very small units are needed with either hillslope or cell unit partitioning. Developing large numbers of small hillslope units would require extensive knowledge of the landscape making the technique difficult and time consuming to implement.

The assumption that a steady-state equilibrium could be reached in the hydrologic system may represent a second reason for failure. The values generated by the steady state wetness index calculated in this study assume this equilibrium has been reached in all areas. In reality the hydrologic process is much more variable with equilibria being achieved and destroyed throughout time and space (Barling et. al. 1994). The steady state soil water index also assumes: (1) uniform infiltration capacity; (2) uniform losses to ground water; (3) uniform soil transmissivity; and (4) coincidence between the surface and subsurface areas draining to each unit length of contour. None of these assumptions were validated for this study area and they may have further limited the power of the steady-state wetness index.

There is also the possibility that the measured soil water contents (which represent several snapshots of soil water content through time) may not represent the long-term steady-state or quasi-dynamic soil water content. A quasi-dynamic soil water index was proposed by Barling et. al. (1994) to account for changing states of equilibrium in the system.

The index has a shortcoming in that it requires the user to specify drainage times and soil properties not measured by this study. Future work is warranted to determine whether or not this index is feasible to use and to determine if it more closely models the soil water content measured in the field.

Conclusions

The time and financial constraints on land and recreation managers have forced them to consider easy to implement and cost effective methods to design recreation trail systems and maintain existing systems. The findings of this study may help managers anticipate in advance areas to avoid in order to create trails with minimum impact on their surroundings. The three major findings of this study are: (1) trail cross-sectional area increases with increasing trail slope; (2) trail cross-sectional area increases with increasing soil water content: and (3) the division of landscapes into landform units helps to explain trail condition.

Future research is needed to address several of the shortcomings of this study. The use of improved digital data in the form of a larger scale DEM and/or more accurate GPS locations may greatly improve the correlations found in the regression analysis. Further studies are also warranted to (1) differentiate soil compaction and trail erosion, and (2) investigate the addition of variables such as trail orientation, water bar location and overstory vegetation characteristics to the regression analysis. Trail deterioration is caused by both soil erosion and compaction. This study focused on variables linked to soil erosion and future research examining the spatial variability in soil compaction rates is needed to assess this impact of human use on the natural environment.

Land and recreation managers seek to minimize the impact of human use on natural areas while also minimizing the cost and time involved in creating and managing recreation areas. Strategically locating and constructing trail systems such that they minimize damage to the natural environment requires time and money. This study attempted to utilize field data along with available digital data and terrain models to identify and explain areas of severe trail deterioration. The ability to locate these areas without costly field work and equipment may improve the location, construction and maintenance of trail systems. Further research utilizing larger scale DEMs, better GPS and other soil wetness models is necessary to refine the methods introduced in this study.

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APPENDICES

APPENDIX A

FIELD MEASUREMENTS AND TERRAIN ESTIMATES

Field Measurements and Terrain Estimates.

Stake Number	Cross-Sectional Area	Trail Slope	Soil Water	Percent Cover	Regional Slope	Profile Curvature	Plan Curvature	Aspect	Ele-vation	Specific Catchment Area	Geology
1	22942	14.0	29.9	94.2	4.85	-2.102	-1.741	350	5440	46.2	1
2	8600	1.5	44.1	70.8	7.76	0.564	-0.656	329	5454	170.4	0
3	9618	18.5	23.5	77.5	6.11	-0.830	4.526	26	5461	531669.9	0
4	4414	3.5	12.6	45.0	1.44	0.190	-0.234	49	5480	530688.9	0
5	2893	2.5	25.6	60.0	0.00	0.000	0.000	1000	5480	2156.4	0
6	909	2.5	15.4	81.7	8.41	0.232	-1.109	324	5520	129.0	0
7	2557	6.0	15.1	59.2	4.89	1.327	-1.654	350	5520	181.5	1
8	2870	2.5	16.5	69.2	2.48	1.496	0.013	296	5520	1430.7	1
9	13562	6.0	9.8	57.5	3.68	-0.048	2.415	344	5551	3897.3	0
10	4342	1.5	38.0	58.3	4.06	1.753	3.969	320	5560	5037.3	0
11	3573	7.0	14.9	60.0	6.15	0.695	0.000	270	5600	979.8	1
12	937	2.0	13.8	75.0	2.27	1.145	-5.067	313	5600	834.9	1
13	9884	2.0	14.3	69.2	9.43	0.999	0.394	135	5613	375.0	0
14	4857	12.0	14.2	49.2	5.95	1.327	-0.060	91	5640	100.8	1
15	2841	7.5	16.3	84.2	15.72	0.249	-1.958	262	5720	117.9	1
16	8112	9.0	27.4	61.7	14.06	-0.094	-1.766	288	5720	159.3	1
17	2761	2.0	18.4	86.7	15.09	0.201	0.683	264	5760	262.2	1

Stake Number	Cross-Sectional Area	Trail Slope	Soil Water	Percent Cover	Regional Slope	Profile Curvature	Plan Curvature	Aspect	Ele-vation	Specific Catchment Area	Geology
18	2921	6.5	19.9	65.0	2.93	6.011	12.286	215	5760	272058.6	1
19	6433	12.0	13.2	74.2	5.55	2.538	-1.054	64	5757	269076.6	1
20	7234	10.5	14.6	68.3	17.40	-0.042	2.109	287	5810	1881.9	0
21	11073	11.5	13.8	52.5	15.44	0.017	0.410	300	5920	549.3	0
22	8122	9.0	12.5	38.3	13.74	-0.044	1.775	284	5960	352.2	0
23	10567	15.0	10.4	36.7	13.74	0.080	-1.902	284	6000	115.2	0
24	4893	4.5	12.8	75.0	14.06	0.007	-2.135	288	6120	95.1	0
25	2538	1.0	17.2	64.2	4.06	1.624	-3.352	305	5840	1581.3	0
26	2339	4.0	17.4	48.3	13.33	0.000	0.000	270	6000	207.9	0
27	3606	5.0	22.8	70.0	13.44	0.045	-0.984	277	6080	214.2	0
28	5780	7.5	25.7	68.3	16.67	0.303	0.000	270	6160	168.3	0
29	22483	15.5	23.8	58.3	8.33	1.471	-2.560	323	6120	45.9	1
30	11733	15.5	19.0	70.0	9.43	0.706	1.200	45	6213	191.4	0
31	2972	3.5	34.0	65.0	6.67	0.943	-4.210	0	6252	84.9	0
32	10805	13.0	29.4	48.3	6.67	-2.560	0.000	0	6320	1406.4	0
33	2477	0.5	17.0	63.3	10.41	-0.603	-2.613	341	6400	309.0	0
34	3335	5.0	17.3	40.0	12.19	-0.225	0.119	294	6373	243.0	1
35	14244	22.0	12.6	42.5	7.23	0.465	-2.083	293	6456	224.7	1
36	3284	3.5	17.3	61.7	8.50	2.836	5.531	259	6320	23553.6	0

Stake Number	Cross-Sectional Area	Trail Slope	Soil Water	Percent Cover	Regional Slope	Profile Curvature	Plan Curvature	Aspect	Ele-vation	Specific Catchment Area	Geology
37	3200	3.5	25.5	65.8	15.91	-0.060	-0.215	115	6380	132.6	0
38	1778	6.0	35.8	90.0	20.07	-0.148	-3.785	185	6480	71.7	0
39	12935	4.5	52.4	63.3	0.00	0.000	0.000	1000	6360	379.5	0
40	11107	15.5	20.2	54.2	0.82	0.540	0.000	0	6360	819.6	0
41	5975	4.5	25.1	101.7	5.11	0.209	1.799	327	6400	333.6	0
42	5144	5.5	24.2	99.2	6.30	-0.005	-0.171	304	6423	964.5	0
43	2545	7.5	26.1	95.0	2.06	-1.188	-3.275	317	6440	463.8	1
44	6915	2.0	45.8	82.5	4.86	0.312	-0.856	304	6490	1735.5	1
45	6558	9.0	29.5	101.7	4.83	-0.649	1.138	328	6511	25137.6	1
46	11447	13.0	26.2	41.7	4.81	-2.369	-3.659	2	6560	68.4	1
47	14992	14.0	19.6	60.0	4.69	-2.321	0.000	0	6600	62475.0	1
48	6622	7.0	33.3	73.3	6.33	0.541	1.044	322	6650	749.4	1
49	4379	6.5	34.5	0.0	5.59	-0.698	1.106	334	6670	862.5	1
50	12428	4.5	16.4	65.0	5.15	-0.390	1.541	320	6705	1025.4	1
51	10216	1.5	30.8	58.3	6.16	-0.478	-2.643	291	6800	260.1	1
52	9736	5.0	32.6	80.8	3.25	-0.272	3.329	323	6751	32671.2	1
53	7352	6.5	18.2	88.3	8.98	-1.189	-1.839	284	6840	154.8	1
54	11948	4.0	27.4	74.2	3.26	1.869	0.000	270	6880	297.0	1
55	8232	2.5	19.6	72.5	4.79	0.028	-0.205	259	6894	1061.7	1

Stake Number	Cross-Sectional Area	Trail Slope	Soil Water	Percent Cover	Regional Slope	Profile Curvature	Plan Curvature	Aspect	Ele-vation	Specific Catchment Area	Geology
56	4471	2.0	24.7	62.5	4.88	-0.012	0.093	258	6905	934.5	1
57	5577	0.5	29.8	67.5	4.56	-0.116	0.052	273	6934	709.8	1
58	8801	0.5	19.7	69.2	4.32	0.051	-0.091	269	6960	654.9	1
59	16767	11.5	39.3	75.8	4.80	-0.351	0.000	270	6960	302.1	1
60	5806	3.0	29.3	69.2	7.56	0.830	2.303	245	6920	982.5	1
61	2110	2.5	44.5	100.8	1.59	0.496	-2.957	79	6929	67.2	1
62	8710	3.5	31.7	60.8	1.71	1.049	2.478	206	6920	294.3	1
63	2369	2.5	21.0	55.8	0.58	-0.386	0.000	90	6880	3207.3	0
64	3755	5.0	22.8	35.8	3.89	-0.247	1.804	156	6863	2844.9	0
65	2830	5.5	14.5	80.0	3.07	1.603	2.491	161	6840	1151.4	0
66	2272	4.5	11.2	45.0	7.90	-2.152	-1.248	32	6840	32.7	0
67	2433	4.5	15.1	55.8	6.67	0.945	-4.183	90	6813	41.4	0
68	2733	1.0	18.6	71.7	5.79	0.767	-0.587	58	6730	116.1	0
69	3668	5.0	17.4	31.7	9.43	1.607	5.002	45	6720	105.6	0
70	3538	8.5	16.9	48.3	9.43	1.284	5.893	225	6560	271.8	1
71	4569	10.5	20.7	44.2	9.43	1.569	5.107	225	6600	162.3	1
72	4075	13.0	24.5	94.2	6.90	-0.427	-4.989	165	6747	35.1	1
73	4089	17.5	24.1	84.2	9.43	0.107	0.295	45	6699	188.1	1
74	2047	2.5	27.2	100.0	15.19	0.041	0.544	29	6680	66.9	1

Stake Number	Cross-Sectional Area	Trail Slope	Soil Water	Percent Cover	Regional Slope	Profile Curvature	Plan Curvature	Aspect	Ele-vation	Specific Catchment Area	Geology
75	3945	13.0	23.3	70.0	12.24	0.505	6.676	213	6480	366.6	1
76	3146	6.0	30.8	76.7	4.81	-0.550	1.349	125	6470	748.8	1
77	4746	19.0	15.8	50.0	5.59	-0.101	1.051	107	6764	696.0	1
78	3650	0.5	17.3	55.0	3.47	-0.560	2.365	115	6433	1248.9	1
79	3610	3.5	31.5	96.7	4.66	-0.556	1.773	75	6431	603.3	1
80	3580	5.0	20.3	81.7	0.00	0.000	0.000	1000	6440	16350.9	0
81	4183	1.0	21.2	55.0	13.33	0.000	0.000	90	6440	79.8	0
82	2708	6.0	13.4	88.3	9.43	-1.284	-5.893	135	6440	40.5	0
83	2563	7.0	14.4	45.8	3.75	0.894	2.793	105	6384	6770.4	1
84	2701	8.0	17.5	77.5	13.74	-0.080	-1.332	76	6520	68.4	1
85	4430	8.5	26.4	69.2	13.52	0.034	0.977	99	6560	475.5	0
86	2337	7.0	21.7	58.3	6.03	0.826	-0.265	92	6400	3589.5	0
87	2091	7.0	20.1	86.7	13.33	0.000	0.000	90	6440	125.4	1
88	2510	8.0	28.9	83.3	13.67	-0.556	-4.048	125	6460	48.6	0
89	1770	1.5	22.0	45.8	3.17	0.105	-2.448	118	6400	22714.5	0
90	864	2.0	18.9	85.0	13.33	0.000	0.000	90	6440	224.7	0
91	1931	2.5	15.8	37.5	13.44	-0.337	-2.955	120	6440	190.2	0
92	2606	1.0	13.1	24.2	20.07	-0.007	-1.619	95	6500	220.2	0
93	1487	2.5	14.2	26.7	25.22	0.211	1.707	98	6493	911.4	0

Stake Number	Cross-Sectional Area	Trail Slope	Soil Water	Percent Cover	Regional Slope	Profile Curvature	Plan Curvature	Aspect	Ele-vation	Specific Catchment Area	Geology
94	1999	1.0	12.5	51.7	23.86	-0.069	-1.824	115	6450	153.6	0
95	1232	1.5	13.0	80.0	16.49	0.138	1.422	147	6620	359.1	0
96	2086	1.0	12.5	57.5	22.67	0.169	0.334	107	6410	128.7	0
97	2902	3.5	11.5	24.2	22.36	-0.197	-1.689	117	6490	74.7	0
98	1551	1.0	8.5	30.0	25.50	0.060	-0.486	191	6430	105.3	0
99	2004	1.5	7.0	24.2	22.24	-0.167	-2.242	167	6307	63.6	1
100	1272	3.5	7.0	66.7	20.62	0.172	-0.465	194	6400	101.4	1
101	2198	15.0	10.5	41.7	23.15	0.121	0.602	210	6520	145.5	1
102	2342	8.5	16.5	7.5	26.32	0.027	-0.085	226	6550	159.3	0
103	2760	2.5	10.5	38.3	24.04	-0.097	-1.138	236	6490	183.3	1
104	4150	5.5	8.0	69.2	24.04	-0.097	-1.138	236	6490	183.3	1
105	2466	2.5	9.5	63.3	12.02	1.059	0.949	236	6413	269.4	1
106	2104	5.0	10.5	78.3	16.02	-0.135	-1.280	236	6400	146.1	1
107	2504	9.5	12.5	65.0	24.78	0.061	0.577	228	6627	163.5	1
108	2627	8.0	12.0	83.3	13.52	0.093	-1.423	261	6400	127.5	1
109	2300	4.0	7.5	55.0	13.52	-0.046	-0.933	279	6360	194.4	1
110	2358	1.5	6.5	66.7	23.86	0.266	0.400	282	6410	174.9	0
112	2771	1.0	15.5	51.7	15.37	0.155	-1.344	193	6360	179.7	1
113	2966	0.5	9.5	68.3	13.89	-0.003	-3.456	143	6280	180.9	0

Stake Number	Cross-Sectional Area	Trail Slope	Soil Water	Percent Cover	Regional Slope	Profile Curvature	Plan Curvature	Aspect	Ele-vation	Specific Catchment Area	Geology
114	1497	5.0	10.5	47.5	15.44	0.060	-0.724	210	6440	168.6	0
115	2039	5.5	10.5	39.2	21.73	0.274	1.341	212	6240	150.6	0
116	1850	5.0	6.5	55.0	17.95	0.028	-0.547	201	6227	248.1	0
117	2574	6.5	9.5	81.7	16.42	-0.147	-2.750	203	6240	97.5	0
118	2658	0.0	10.4	38.3	22.36	-0.212	-1.590	207	6300	99.6	0
119	3492	12.0	18.4	70.0	25.90	-0.100	-1.035	215	6300	79.2	0
120	1629	1.5	13.5	75.8	19.51	0.255	-0.807	250	6150	92.4	0
121	2135	4.5	14.9	33.3	15.10	0.218	0.615	276	6080	168.6	0
121.5	1829	0.5	14.3	39.2	5.98	-1.969	6.446	248	6080	37690.5	0
122	1655	3.5	13.3	84.2	20.88	0.019	0.420	151	6090	114.9	0
123	3791	7.5	13.0	35.0	20.88	0.019	0.420	151	6090	114.9	0
124	1300	3.5	13.5	67.5	23.21	-0.126	-0.078	201	6130	237.0	0
125	1434	8.5	10.3	94.2	24.10	-0.151	-1.347	206	6190	86.4	0
126	1851	7.0	13.3	63.3	16.57	0.041	-1.523	230	6110	81.9	0
127	3981	1.0	18.4	93.3	20.00	0.133	-0.370	180	6133	116.1	1
128	2137	4.5	16.1	72.5	18.86	-0.095	0.491	225	6190	237.0	1
129	3392	2.5	25.8	75.0	18.86	0.229	0.000	225	5960	197.4	1
130	1156	2.0	16.3	66.7	18.67	0.007	-0.632	217	5973	249.9	1

APPENDIX B

MODELED STEADY-STATE WETNESS INDEX

Modeled Steady-State Wetness Index

Stake Number	Steady-State Wetness
1	6.86
2	7.70
3	15.98
4	17.42
5	-999
6	7.34
7	8.22
8	10.96
9	11.57
10	11.73
11	9.68
12	10.51
13	8.29
14	7.44
15	6.62
16	7.03
17	7.46
18	16.04
19	15.39
20	9.29
21	8.18
22	7.85
23	6.73
24	6.52

Stake Number	Steady-State Wetness
25	10.57
26	7.35
27	7.14
28	6.92
29	6.31
30	7.62
31	7.15
32	9.96
33	8.00
34	7.67
35	8.04
36	12.53
37	6.73
38	5.88
39	-999
40	11.51
41	8.78
42	9.64
43	10.02
44	10.48
45	13.16
46	7.26
47	14.10
48	9.38
49	9.64
50	9.90

Stake Number	Steady-State Wetness
51	8.35
52	13.82
53	7.45
54	9.12
55	10.01
56	9.86
57	9.68
58	9.63
59	8.75
60	9.47
61	8.35
62	9.75
63	13.22
64	11.20
65	10.53
66	6.03
67	6.43
68	7.60
69	7.02
70	7.97
71	7.45
72	6.23
73	7.60
74	6.09
75	8.01
76	9.65

Stake Number	Steady-State Wetness
77	9.43
78	10.49
79	9.47
80	-999
81	6.39
82	6.06
83	12.10
84	6.21
85	8.17
86	11.00
87	6.85
88	5.87
89	13.48
90	7.43
91	7.26
92	7.00
93	8.19
94	6.47
95	7.69
96	6.34
97	5.81
98	6.02
99	5.66
100	6.20
101	6.44
102	6.41

Stake Number	Steady-State Wetness
103	6.64
104	6.64
105	7.71
106	6.82
107	6.49
108	6.85
109	7.27
110	6.60
112	7.06
113	7.17
114	7.00
115	7.64
116	7.23
117	6.39
118	6.10
119	5.72
120	6.16
121	7.02
121.5	13.35
122	6.31
123	6.31
124	6.93
125	5.88
126	6.20
127	6.36
128	7.14

Stake Number	Steady-State Wetness
129	6.95
130	7.20

APPENDIX C

MOISTURE DATA

Moisture Data

Stake Number	June 1993	July 1992	September 1992
1	0.337	0.31	0.250
2	0.419	0.44	0.465
3	0.296	0.18	0.230
4	0.178	0.09	0.111
5	0.232	0.36	0.178
6	0.216	0.13	0.117
7	0.206	0.1	0.148
8	0.217	0.09	0.187
9	0.119	0.12	0.054
10	0.405	0.45	0.285
11	0.221	0.11	0.117
12	0.162	0.14	0.114
13	0.215	0.06	0.154
14	0.156	0.07	0.201
15	0.145	0.17	0.173
16	0.223	0.36	0.240
17	0.202	0.18	0.170
18	0.164	0.21	0.223
19	0.165	0.1	0.132
20	0.165	0.13	0.144
21	0.195	0.12	0.098
22	0.166	0.12	0.089
23	0.153	0.1	0.060
24	0.156	0.11	0.119
25	0.157	0.14	0.220
26	0.272	0.12	0.131
27	0.290	0.17	0.224

Stake Number	June 1993	July 1992	September 1992
28	0.314	0.18	0.276
29	0.356	0.18	0.180
30	0.256	0.17	0.143
31	0.382	0.36	0.278
32	0.365	0.24	0.277
33	0.275	0.12	0.115
34	0.235	0.13	0.154
35	0.182	0.11	0.087
36	0.266	0.12	0.133
37	0.342	0.21	0.213
38	0.403	0.37	0.302
39	0.572	0.58	0.419
40	0.247	0.18	0.179
41	0.324	0.18	0.248
42	0.304	0.17	0.253
43	0.356	0.18	0.247
44	0.535	0.51	0.329
45	0.343	0.29	0.252
46	0.317	0.19	0.278
47	0.293	0.13	0.166
48	0.461	0.37	0.166
49	0.228	0.42	0.387
50	0.209	0.18	0.103
51	0.405	0.34	0.179
52	0.409	0.32	0.250
53	0.245	0.18	0.121
54	0.360	0.28	0.182
55	0.320	0.17	0.099

Stake Number	June 1993	July 1992	September 1992
56	0.382	0.21	0.150
57	0.438	0.26	0.196
58	0.315	0.14	0.136
59	0.499	0.4	0.281
60	0.376	0.33	0.172
61	0.579	0.46	0.297
62	0.359	0.22	0.371
63	0.302	0.22	0.108
64	0.294	0.25	0.141
65	0.164	0.21	0.062
66	0.151	0.14	0.045
67	0.241	0.14	0.072
68	0.295	0.16	0.102
69	0.249	0.18	0.094
70	0.266	0.21	0.031
71	0.264	0.26	0.097
72	0.306	0.2	0.228
73	0.337	0.17	0.217
74	0.377	0.22	0.218
75	0.356	0.18	0.163
76	0.341	0.32	0.264
77	0.252	0.15	0.073
78	0.249	0.16	0.109
79	0.387	0.3	0.259
80	0.290	0.19	0.129
81	0.314	0.21	0.112
82	0.212	0.14	0.050
83	0.114	0.14	0.180

Stake Number	June 1993	July 1992	September 1992
84	0.278	0.15	0.096
85	0.400	0.21	0.181
86	0.283	0.17	0.200
87	0.283	0.12	0.201
88	0.350	0.33	0.188
89	0.272	0.24	0.149
90	0.268	0.14	0.159
91		0.16	0.157
92		0.14	0.122
93		0.15	0.133
94		0.13	0.120
95		0.13	0.130
96		0.14	0.110
97		0.11	0.120
98		0.07	0.100
99		0.06	0.080
100		0.07	0.070
101		0.11	0.100
102		0.18	0.150
103		0.1	0.110
104		0.07	0.090
105		0.1	0.090
106		0.1	0.110
107		0.12	0.130
108		0.12	0.120
109		0.07	0.080
110		0.07	0.060
112		0.16	0.150

Stake Number	June 1993	July 1992	September 1992
113		0.1	0.090
114		0.1	0.110
115		0.11	0.100
116		0.06	0.070
117		0.1	0.090
118		0.11	0.098
119		0.13	0.239
120		0.11	0.159
121			0.149
121		0.12	0.166
122		0.12	0.147
123		0.12	0.140
124		0.12	0.150
125		0.12	0.085
126		0.11	0.155
127		0.15	0.218
128		0.13	0.192
129		0.24	0.276
130		0.12	0.205

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