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

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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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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Date 11-1-94

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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,

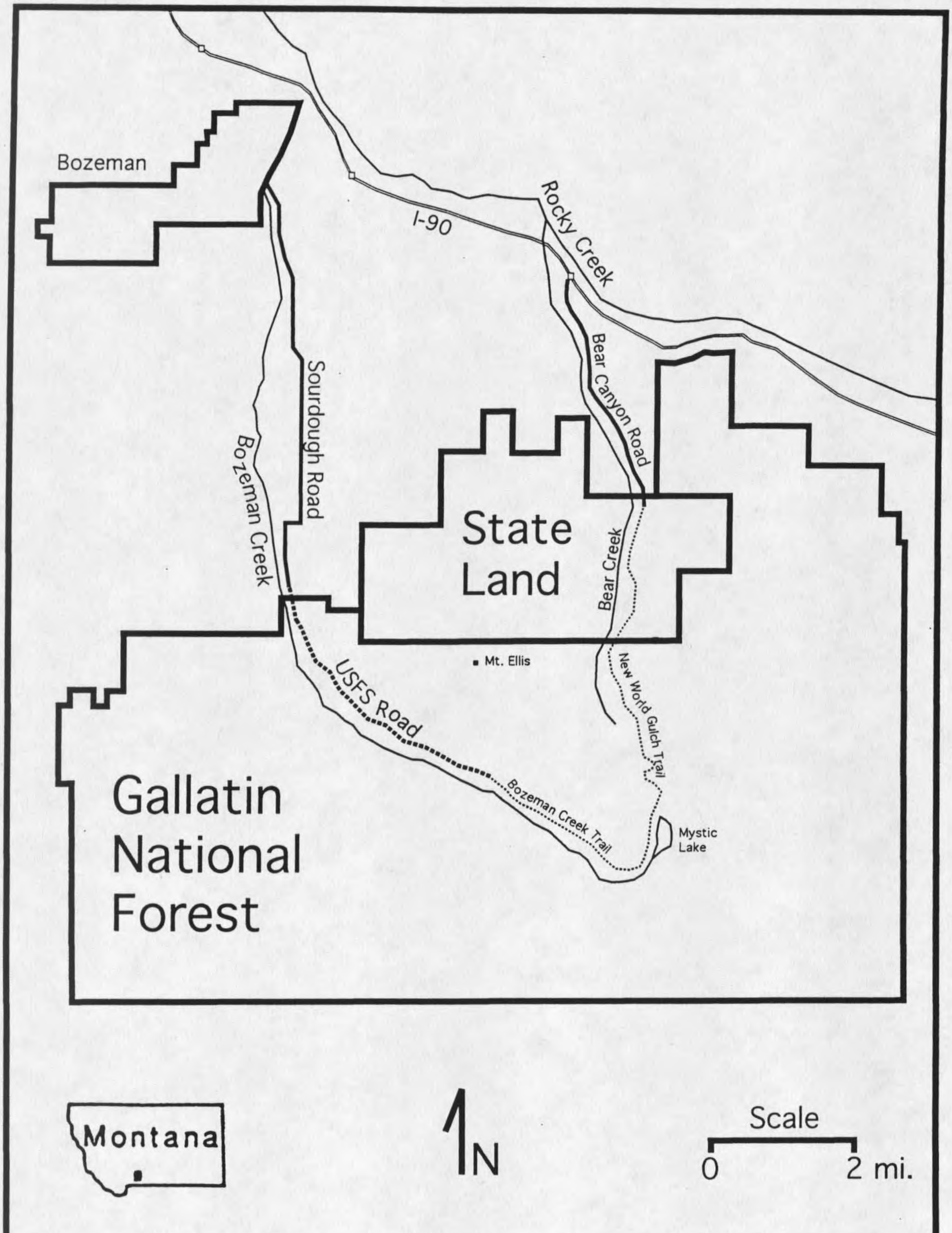

Figure 1. Study area location map.

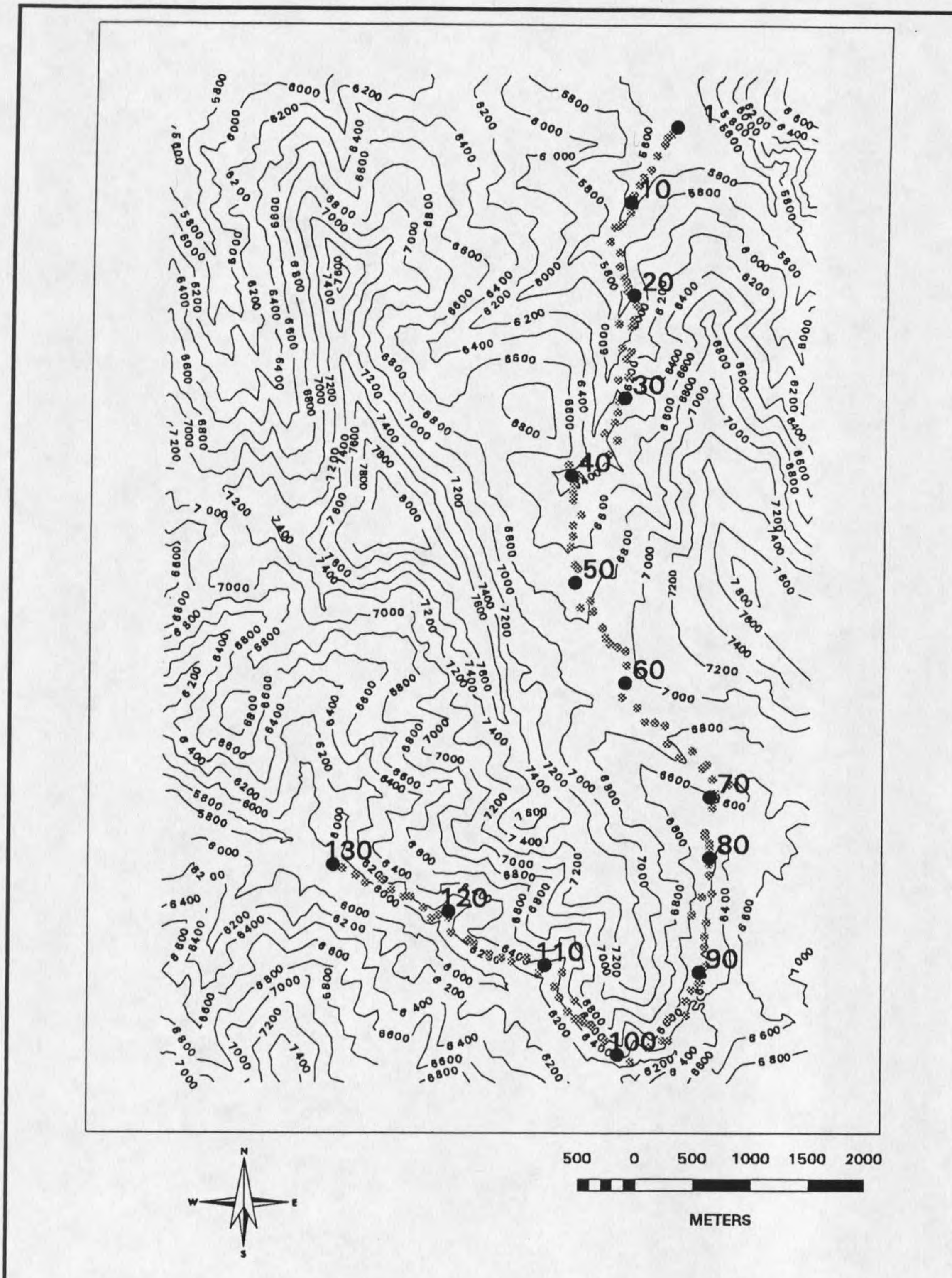

Figure 2. Study area elevation and trail location map.

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