



Soil and terrain attributes for evaluation of leaching in a Montana farm field  
by Melissa Ann Landon

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils  
Montana State University

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Abstract:

Degradation of water quality from agricultural sources is a critical concern for both surface and ground waters in the United States. Nutrient (nitrate) management on the farm can reduce agricultural non-point pollution. Practical and operational solutions to ground water contamination problems will require consideration of contrasting environmental differences within fields. One difficulty in designing leaching models is that when a model successfully simulates a particular profile, it may not be representative of the overall field situation due to spatial and/or temporal variability.

The objectives of this study were to: 1) characterize the spatial variability of nitrate and bromide leaching; 2) test the leaching prediction capabilities of several soil, soil water, and terrain attributes that singly, or in combination, represent the spatial distribution of soils and microclimate in a farm field under uniform application of nitrogen and bromide; and 3) determine if a topographically-derived wetness index is correlated with field-measured soil water content. Nitrogen was applied by the farmer in the course of normal field management and potassium bromide was uniformly applied to small areas at 70 selected sites. Soil samples were collected at each site to a maximum depth of 180 cm every spring and fall for three years (two cropped, one fallow).

Small spatial variability in soil water (to 25 cm, 100 cm and 150 cm depths) was measured. It is possible that the thick, permeable, loess-derived soils capture and retain precipitation from rainfall and melting snow without significant lateral distribution in the landscape. The observed variability in solute concentrations was also small and less than reported in other field studies. The spatial variability of bromide increased over time indicating that movement (leaching) differences may be expressed slowly. Paired t-tests and correlation analyses indicated that the spatial behavior patterns of nitrogen and bromide were similar in only two of five time periods.

Three types of leaching indices were calculated for both nitrogen and bromide. Stepwise multiple regression analysis occasionally showed some promise, but the results were not consistent. None of the three index types produced results more reliable or consistent than the other two. Exclusion of sites within an ephemeral stream channel also did not produce substantially or consistently better results. Overall, nitrogen leaching indices produced slightly stronger relationships with the environmental factors than bromide indices.

Correlation analysis indicated that wetness indices at two scales (2 m and 10 m) were moderately correlated to one another and to the thickness of the mollic horizon. Neither the wetness indices or thickness of mollic horizon were correlated to either season average measured water content or average measured water content from June of each year.

These results reiterate the difficulties that are encountered in trying to understand (predict) the interrelationships between environment, nitrogen leaching, and potential contamination of ground water.

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A thesis submitted in partial fulfillment  
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MONTANA STATE UNIVERSITY  
Bozeman, Montana

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5/16/95  
Date

Jeffrey S. Jacobson  
Chairperson, Graduate Committee

Approved for the Major Department

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Jeffrey S. Jacobson  
Head, Major Department

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## ABSTRACT

Degradation of water quality from agricultural sources is a critical concern for both surface and ground waters in the United States. Nutrient (nitrate) management on the farm can reduce agricultural non-point pollution. Practical and operational solutions to ground water contamination problems will require consideration of contrasting environmental differences within fields. One difficulty in designing leaching models is that when a model successfully simulates a particular profile, it may not be representative of the overall field situation due to spatial and/or temporal variability.

The objectives of this study were to: 1) characterize the spatial variability of nitrate and bromide leaching; 2) test the leaching prediction capabilities of several soil, soil water, and terrain attributes that singly, or in combination, represent the spatial distribution of soils and microclimate in a farm field under uniform application of nitrogen and bromide; and 3) determine if a topographically-derived wetness index is correlated with field-measured soil water content. Nitrogen was applied by the farmer in the course of normal field management and potassium bromide was uniformly applied to small areas at 70 selected sites. Soil samples were collected at each site to a maximum depth of 180 cm every spring and fall for three years (two cropped, one fallow).

Small spatial variability in soil water (to 25 cm, 100 cm and 150 cm depths) was measured. It is possible that the thick, permeable, loess-derived soils capture and retain precipitation from rainfall and melting snow without significant lateral distribution in the landscape. The observed variability in solute concentrations was also small and less than reported in other field studies. The spatial variability of bromide increased over time indicating that movement (leaching) differences may be expressed slowly. Paired t-tests and correlation analyses indicated that the spatial behavior patterns of nitrogen and bromide were similar in only two of five time periods.

Three types of leaching indices were calculated for both nitrogen and bromide. Stepwise multiple regression analysis occasionally showed some promise, but the results were not consistent. None of the three index types produced results more reliable or consistent than the other two. Exclusion of sites within an ephemeral stream channel also did not produce substantially or consistently better results. Overall, nitrogen leaching indices produced slightly stronger relationships with the environmental factors than bromide indices.

Correlation analysis indicated that wetness indices at two scales (2 m and 10 m) were moderately correlated to one another and to the thickness of the mollic horizon. Neither the wetness indices or thickness of mollic horizon were correlated to either season average measured water content or average measured water content from June of each year.

These results reiterate the difficulties that are encountered in trying to understand (predict) the interrelationships between environment, nitrogen leaching, and potential contamination of ground water.

## CHAPTER 1

### SITE-SPECIFIC FARMING, NITRATE LEACHING, AND GROUND WATER QUALITY

#### Background

##### Nitrate Leaching and Ground Water Quality

Ground water is the source of public drinking water for nearly 75 million people in the United States. Private wells supply water to an additional 30 million individuals. Evidence indicates that contaminants from agricultural production are now found in underground water supplies (National Resource Council, 1989). Major water quality problems of concern to agriculture are nutrients, pesticides, and sediments. Nutrients and pesticides in water supplies can be a health concern when levels reach established critical levels.

Non-point sources of pollution have been difficult to identify and regulate (Bauder et al., 1991), but nitrogen (N) has received the most attention as a threat to water quality. Nitrite is the most toxic form of N, but children, young animals, and cattle convert nitrates into nitrites in their stomachs and can develop methemoglobinemia. In 1962, the U.S. Public Health Service set an upper limit on nitrate in drinking water at 10 mg  $\text{NO}_3\text{-N}$  per liter (45 ppm nitrate) (McCool and Renard, 1990). In 1991, Bauder et al. found in a study of private well water quality

in Montana that 1 in every 20 samples had nitrate-N concentrations greater than the U.S. EPA standard of 10 parts per million. Fifty percent of the high nitrate samples were attributed to point-source contamination. The other 50% may be the result of long-term summer fallowing.

Nitrates in ground water originate from several non-point sources, including geological substrate, septic tanks, improper use of animal manures, cultivation (especially fallowing), precipitation (acid rain), mineralization of organic N, and fertilizers (Power and Schepers, 1989). Most nitrate-related environmental impacts occur at local or regional scales rather than the national scale, and they usually mimic spatial distribution of the sources (National Research Council, 1978). Conditions conducive to ground water contamination by fertilizer include shallow ground water, coarse-textured soils, low organic matter levels, high soil permeability, and excess water (precipitation, irrigation) (Follett et al., 1991).

Since the late 1960's, there has been a three-fold increase in applications of N to Montana soils (Jacobsen and Johnson, 1991). Under native prairie vegetation, annual N inputs were typically measured in tens of  $\text{kg ha}^{-1}$ . Today, inputs of several hundred  $\text{kg N ha}^{-1}$  are common with many grain crops (National Research Council, 1978). However, most plants apparently cannot remove all of the  $\text{NO}_3\text{-N}$  present in soil solution. Numerous field studies have shown that less than 50% of the N input into grain crops is removed in the harvested crop. Therefore, 100  $\text{kg N ha}^{-1}$  or more is either stored in the soil or lost into the environment (National Research Council, 1978).

Nitrate is the end product of the reactions converting other forms of N in soil. It is stable and remains in soil once it has been introduced, except when removed by plant uptake, denitrification, or leaching. The quantity of N available to plants is a function of the amounts applied as manure and fertilizer and mineralized from soil organic matter. Only a small fraction (usually <1%) of the total N in surface soils is present as nitrate, but this fraction can undergo rapid changes depending on both environmental conditions and external sources. Moisture and temperature are major factors affecting the amount of nitrate in soil, and the nitrate concentrations vary seasonally, often in a complicated and unpredictable fashion (National Research Council, 1978). The amount of N released from organic sources, and to some extent, the amount of fertilizer-derived N existing in the soil after addition of ammonium ( $\text{NH}_4^+$ ) or nitrate ( $\text{NO}_3^-$ ) depends on the factors affecting N mineralization, immobilization, and losses from the soil. Nitrogen fertilizers applied in any form are converted to nitrate through nitrification. During the growing season, nitrate is absorbed rapidly by plant roots, probably by a combination of active (metabolic) and passive (water flow) mechanisms.

Nitrate losses from soil are typically measured utilizing ceramic cups, lysimeters, collecting water from field drainage, or sampling soil rather than water, or estimated by computer modeling (Addiscott et al., 1991). The rate of nitrate leaching from the soil depends on a wide variety of factors. Nitrate leaching from soil is affected by: plant cover (Hill, 1991), rainfall or irrigation (Thomas, 1970), temperature (National Research Council, 1978), soil texture and organic matter

content (Bergstrom and Johansson, 1991), soil depth, structure and parent material (Hill, 1991), ground water level and drainage (Hill, 1991), crop strains, tillage (National Research Council (1978), and forms of N (Hill, 1991).

Nitrate distribution in a soil system is a function of the water balance of the soil system in that rainfall and irrigation move nitrate downward, while evaporation moves nitrate back towards the surface. However, the evaporative process is usually important only in the upper 30 cm of the soil profile (Thomas, 1970). Temperature is a factor because water drains more slowly through cold soils. Freezing essentially stops downward nitrate movement (National Research Council, 1978). Soil texture and organic matter content can have a major influence on leaching (Bergstrom and Johansson, 1991). Light and sandy soils tend to retain less water than heavy clay soils and, therefore, allow more free movement of water and soluble ions following rainfall. Shallow soils are also usually well drained and are associated with rapid leaching. Soils rich in organic matter are usually also rich in organic N. This provides suitable material for the bacterial formation of nitrate and subsequent nitrate leaching. Tillage stimulates ammonification and nitrification, and most row cropping practices leave the land bare at least part of the year (National Research Council, 1978). A vegetation-free period and high rainfall can lead to an increased downward movement of nitrate into aquifers (Hill, 1991).

#### Spatial Variability of Soil and Water Properties

Most of the soil and environmental parameters which influence the transport of dissolved nitrates through natural fields vary substantially at different locations, even

at short separation distances, and many are not normally distributed (Addiscott and Wagenet, 1985). Spatial and temporal variability in soil properties with depth in the soil profile and across landscape positions results in diverse patterns of water and solute distribution in the landscape. Beckett (1987) points out that the temporal variability of soil nutrient status may equal or exceed spatial variability.

Hall and Olson (1991) state that two categories of variability, systematic and random, exist in most landscape studies. Placement in either category may depend on the level or scale of observation. Soil profile depth, water content, and soil physical and chemical properties vary with landscape position (Daniels et al., 1985; Brubaker et al., 1993). This systematic variation of soil properties with landscape position may affect solute transport under natural rainfall conditions (Afyuni et al., 1994).

Bouma and Finke (1993) alternatively suggest that soil variability may be attributed to natural soil resource variability or management-induced variability. Soil resource variability can be expressed in terms of static and dynamic properties. Static properties are those that, for example, relate to variation in relatively stable soil properties such as soil texture or organic matter content. Dynamic properties are those that exhibit differences at short distances; for example, water, solute, air, and temperature regimes.

Soil textural and structural properties, antecedent soil water content distributions, and the rate and amount of infiltrating water affect leaching and movement of water and solutes (Anderson and Bouma, 1977a;1977b). Even when the water application rate is relatively uniform over the entire soil surface, such as with

rainfall (Jury et al., 1982) or sprinkler irrigation (Van de Pol et al., 1977; Butters, 1987), the resulting vertical water velocities within the soil are not spatially uniform. Lateral movement can cause substantial variations in solute concentration across a field of agricultural size (Jury and Nielsen, 1989).

Soil hydraulic properties vary across landscape positions due to changes in soil profile characteristics (Bathke and Cassel, 1991). Nielsen et al. (1994) state that the soil hydraulic conductivity at water saturation is 10 million times greater than that exhibited at air-dryness or, stated another way, a seven percent change in soil water content yields a corresponding 10-fold change in hydraulic conductivity. Therefore, small differences in soil water content across a seemingly uniform field soil lead to large differences in the rate of movement of water (and its dissolved constituents) through the soil.

### Site-Specific Farming

Concerns for agricultural sustainability and for protection of surface and ground water from agricultural chemicals has resulted in increased interest in precision or site-specific farming. The modern implementation of site-specific crop management is often thought of in terms of the integration of two complementary technologies: GPS and GIS. GPS, the satellite-controlled Global Positioning System, provides the location coordinates for recording data and controlling devices in the field. GIS (Geographic Information Systems) maintain geographically correct linkages between GPS-generated data from the field and desktop mapping and decision support applications (Brown and Saufferer, 1991).

In order for a computer simulation model of field-scale leaching to have practical application in this context, computer programs capable of identifying best combinations of management practices for a given soil, climate, and water regime must be developed. Precise guidance of equipment (relative to a previously defined position) is now possible due to the 24-hour availability of NAVSTAR GPS satellites and receivers capable of determining position in real time with a resolution of one centimeter (Larson et al., 1991). In addition to these guidance systems, field implementation of these management practices benefit from: 1) mechanisms (i.e., sensors on field equipment) to detect differences within a field with respect to important soil properties (texture, organic matter, bulk density, water content, temperature, nutrient status, etc.); and 2) servo-mechanisms controlled by an on-board computer to alter settings on planters, tillage tools, sprayers, fertilizer spreaders, cultivators, and other machinery while moving through the field.

Within such a system, a farmer could maintain or enhance crop yield, optimize fertilizer and other inputs, maximize net return, and also potentially control ground water contamination or other environmental problems (Power and Schepers, 1989). Preliminary field experiment results from a soil specific anhydrous ammonia management system in Minnesota indicate variable benefits, with a maximum of \$17 ha<sup>-1</sup>, when comparing soil specific management to conventional soil management (Robert, 1991). In 1991, Macy realized a \$5.67 ha<sup>-1</sup> savings on a 54 ha field in Wayne County, Indiana utilizing spatially variable control of fertilizer and seed.

Carr et al. (1991) used yield and fertility trials in 1987-88 at five locations to demonstrate that fertilizing by soil is profitable under dryland systems in Montana.

#### On-Farm, Field-Scale Information Systems

Many technologies necessary to implement site-specific crop management practices are currently being developed as separate and narrowly focused, dedicated applications. Brown and Saufferer (1991) state that unless these "closed subsystems" can be networked into a whole-farm, integrated management information system, their potential value will be greatly limited.

There is a growing demand for simple techniques applicable for day-to-day land management decisions, but which also incorporate environmental protection considerations. To that end, integrated technological systems including on-farm, field-scale information systems and site-specific farming provide opportunities for "farming soils, not fields" (Carr et al., 1991). Implementation of integrated agricultural management practices can have two major consequences: 1) effects on the environment including ground water quality; and 2) effects on economic return from the agricultural enterprise (Power and Schepers, 1989).

#### Field-Scale Solute Transport Models

Approaches used to model the transport of a mobile solute such as nitrate through soil can be divided into two groups: deterministic models and stochastic models (Tables 1 and 2) (Addiscott and Wagenet, 1985). Predictive models are designed for estimating the effects of changing inputs or transfer rates on pool sizes,

leaching losses, and related issues (Winteringham, 1984). Knowledge of two aspects is needed for a complete description of leaching: 1) the position of the chemical's peak concentration in the soil profile (i.e., solute center of mass); and 2) the shape of the leaching band (Smith et al., 1984).

Deterministic models develop a description of transport based on mass conservation and flux laws, and rely on differential equations to predict values of the water and solute variables as functions of position and time. In contrast, stochastic models describe the variables as random functions, which depend on the distribution of soil property values, to predict concentration averages and variances. These statistics are used to calculate the probability of having a given value appear at a given depth or time (Jury and Nielsen, 1989).

Deterministic models require detailed measurements of transport and rate coefficients for predicting nitrate movement through soil. The deterministic piston flow model provides only a rough estimate of nitrate movement, but can be applied using only minimal information about soil properties (Jury and Nielsen, 1989). However, the spatial variability of water and solute transport parameters in natural field soils has made it difficult to apply detailed deterministic models to field-scale solute transport. In 1985, Jury reviewed field-scale solute transport experiments and reported coefficients of variation of 60-200% for apparent solute velocity. Jury (1982) and Jury et al. (1986) proposed a stochastic, non-mechanistic solute transport model using a transfer function to represent solute transport and reactions implicitly.

Table 1. Review of leaching models (after Addiscott and Wagenet, 1985).

| DETERMINISTIC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>● presume system or process operates such that occurrence of given set of events leads to uniquely-defined outcome</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| MECHANISTIC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | FUNCTIONAL                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| <ul style="list-style-type: none"> <li>● define rates of change</li> <li>● usually based on rate parameters</li> <li>● driven by time</li> <li>● incorporate fundamental process mechanisms</li> <li>● based on convection-dispersion equation</li> <li>● serve primarily as research tools</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | <ul style="list-style-type: none"> <li>● define changes</li> <li>● usually based on capacity parameters (less spatially variable than rates)</li> <li>● driven by rainfall, evaporation, irrigation</li> <li>● incorporate simplified treatments of solute and water flow</li> <li>● no claim to fundamentality</li> <li>● require less input data and computer expertise</li> <li>● input data obtainable independently of test data</li> <li>● more widely used as management guides</li> </ul>                                                                                                                                                                                      |
| <p><u>Analytical Solution</u></p> <ul style="list-style-type: none"> <li>● assume steady-state solute movement, steady-state one-dimensional water flow, homogeneous soil</li> <li>● general form, flexible incorporation of processes</li> <li>● widely usable if experiments simulated meet required boundary conditions</li> <li>● mainly restricted to controlled, homogenous, de-structured lab columns</li> <li>● main value is validating conceptual framework</li> <li>● Problems:               <ol style="list-style-type: none"> <li>1. constraints of boundary conditions required rarely represent field conditions</li> <li>2. some constants needed must be obtained by fitting model to test data</li> <li>3. subject to problem of variability</li> </ol> </li> </ul> | <p><u>Partially Analytical</u></p> <ul style="list-style-type: none"> <li>● assume piston flow, compute solute peak position, impose effects of dispersion and diffusion around peak</li> <li>● displacement calculated using water content at field capacity, not rates of movement</li> <li>● potential use as both research and management tools, but with limitations in each case</li> <li>● Problems:               <ol style="list-style-type: none"> <li>1. cannot handle heterogeneous profiles or those which contain solute at depth at beginning of leaching period</li> <li>2. do not address immobile water associated with intra-aggregate pores</li> </ol> </li> </ul> |

Table 1 continued. Review of leaching models.

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <u>Numerical Solution</u> <ul style="list-style-type: none"> <li>● most widely used</li> <li>● solid mathematical basis</li> <li>● solve convective-dispersion equation for non-steady-state, transient water and solute conditions</li> <li>● use finite difference and finite element methods</li> <li>● flexible in range of initial and boundary conditions for water and solute</li> <li>● avoid site specificity by appropriate use of soil physical and chemical data</li> <li>● Problems:               <ol style="list-style-type: none"> <li>1. susceptible to problems of variability</li> <li>2. modeled solute and water fluxes tested against measured water content in previous validation exercises</li> <li>3. predictions misleading unless inputs well characterized in terms of variability</li> </ol> </li> </ul> | <u>Layer &amp; Other Simple Approaches</u> <ul style="list-style-type: none"> <li>● useful for management purposes</li> <li>● mathematically simple</li> <li>● modest input requirements</li> <li>● no prior fitting procedures required</li> </ul><br><u>Chromatographic</u> <ul style="list-style-type: none"> <li>● relevant to exchanged/adsorbed solutes</li> </ul><br><u>Layer</u> <ul style="list-style-type: none"> <li>● offshoots of chromatographic approach</li> <li>● divide soil into horizontal layers</li> <li>● accommodate mobile and immobile water phases</li> <li>● handle non-uniform initial solute distributions and multiple solute pulses</li> <li>● Problem arises if inputs fail to simulate important variability in real leaching</li> </ul><br><u>Mass balance or conservation</u> <ul style="list-style-type: none"> <li>● several equations required</li> <li>● computer program needed</li> </ul> |
| <p style="text-align: center;"><b>STOCHASTIC</b></p> <ul style="list-style-type: none"> <li>● presuppose the outcome to be uncertain</li> <li>● allow solute and water movement to vary spatially with soil properties</li> <li>● mainly used in research due to shortage of suitable field studies for validation</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| <p style="text-align: center;"><b>MECHANISTIC</b></p> <ul style="list-style-type: none"> <li>● use randomly-distributed input values to produce a distribution of output values</li> <li>● useful for assessing impact of variability</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | <p style="text-align: center;"><b>NON-MECHANISTIC</b></p> <ul style="list-style-type: none"> <li>● use transfer or probability density functions</li> <li>● consider soil to be composed of twisted capillaries of different lengths within which water moves by piston flow</li> <li>● simulate spatially-variable field processes with minimum input data</li> <li>● unknown if satisfactory in vertically inhomogeneous soils or if give accurate estimates of flux as well as concentration</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                          |

Table 2. Models for solute leaching in soils (after Addiscott and Wagenet (1985) and Pennell et al. (1990)).

| DETERMINISTIC                                                                                                                                                                                                           |                                                                                                                                                                                   |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| MECHANISTIC                                                                                                                                                                                                             | FUNCTIONAL                                                                                                                                                                        |
| <u>Analytical Flow Solution</u>                                                                                                                                                                                         | <u>Partially Analytical</u>                                                                                                                                                       |
| Nielsen & Biggar (1962)<br>Nielsen et al. (1973)<br>Biggar & Nielsen (1976)<br>Van Genuchten & Wierenga (1976)                                                                                                          | DeSmedt & Wierenga (1978)-Piston flow<br>Scotter (1978)-Soil voids<br>Rose et al. (1982 a,b)-Mass conservation<br>Nofziger & Hornsby (1987)-CMLS<br>Steenhuis et al. (1987)-MOUSE |
| <u>Numerical Flow Solution</u>                                                                                                                                                                                          | <u>Layer &amp; Other Simple Approaches</u>                                                                                                                                        |
| Bresler & Laufer (1974)<br>Tillotson & Wagenet (1982)<br>Carsel et al. (1984)-PRZM<br>Parker & VanGenuchten (1984)-CXTFIT<br>Wagenet & Hutson (1987)-LEACHM<br>Knisel et al. (1989)-GLEAMS<br>Sharma & Taniguchi (1991) | <u>Chromatographic Approach</u><br>Levin (1964)<br>Frissel & Poelstra (1967)<br>Thomas et al. (1978)                                                                              |
| <u>Preferential Flow</u><br>Beven (1981); Beven & Germann (1981)<br>Bouma et al. (1981)<br>Trudgill et al. (1983)                                                                                                       | <u>Layer</u><br>Terkeltoub & Babcock (1971)<br>Burns (1972, 1974, 1975)<br>Addiscott (1977)-mobile/immobile water<br>Nichols et al. (1982)<br>Addiscott (1982)                    |
|                                                                                                                                                                                                                         | <u>Mass Conservation</u><br>Bresler (1967)<br>Tanji et al. (1972)                                                                                                                 |
| STOCHASTIC                                                                                                                                                                                                              |                                                                                                                                                                                   |
| MECHANISTIC                                                                                                                                                                                                             | NON-MECHANISTIC                                                                                                                                                                   |
| Biggar & Niesen (1976)<br>Dagan & Bressler (1979)<br>Bresler & Dagan (1979, 1981)<br>Amoozegar-Fard et al. (1982)                                                                                                       | <u>Probability Density/Transfer Functions</u><br>Raats (1978)<br>Jury (1982), Jury et al. (1982, 1986)<br>White et al. (1986)<br>Kachanoski et al. (1992)<br>Destouni (1993)      |
| <u>Scaling Theory</u><br>Bresler et al. (1979)<br>Wagenet & Rao (1983)                                                                                                                                                  |                                                                                                                                                                                   |

The solute transport properties of a volume of soil between the soil surface and outflow surface (i.e., some specified depth where solute is monitored) is represented by a solute travel time probability density function (Jury and Nielsen, 1989). Jury and Nielsen (1989) indicate that the advantages of this approach for solute transport in the field are: 1) the formulation of transport is general enough to encompass all linear solute transport paths; and 2) the transfer function may be calibrated without measuring the soil water transport properties directly.

Amoozegar-Fard et al. (1982) used an alternative stochastic, mechanistic transport model for spatially-variable field soils. The Monte Carlo model assumes that a specific process model (such as the convection-dispersion model) is valid at a specific location, but that the model parameters have a distribution of values over the field. Simulations are run by drawing values for the parameters randomly from their probability distributions. The field-averaged solute concentration and its variance is calculated from the set of individual outcomes using the random values of the parameters (Jury and Nielsen, 1989).

Afyuni et al. (1994) state that predictive models for solute transport in soil must consider the landscape if they are to accurately reflect the process as it occurs in nature. The empirical, predictive approach utilized in this project incorporates consideration of presumed topographical controls on soil water through the use of terrain attributes relating to water flow in and across the landscape.

### Scope and Purpose

The work presented in this thesis is part of a larger effort to examine the possibility of integrating site-specific information about leaching into an on-farm, field-scale information system. Integrating soil survey, terrain, and microclimate attributes and image analysis along with information regarding leaching potential into a GIS format may provide new opportunities for applying leaching potential models to variable soil landscapes. Subsequent identification of areas susceptible to leaching, or management zones which consider leaching susceptibility as an important factor, would provide a basis for more selective N fertilizer application. Site-specific applications of N fertilizer may improve profitability, and at the same time, reduce the possibility of ground water contamination. This approach is currently being attempted on a regional level. Wylie et al. (1994) are developing and validating methods of linking the Nitrate Leaching and Economic Analysis Package (NLEAP) (Schaffer et al., 1991) to a GIS framework to identify and map regional nitrate-nitrogen leaching distributions under irrigated agriculture in the western U.S. The NLEAP model uses farm management, soil, and climate information to estimate nitrate leaching indices. The overall purpose of the work presented here was to investigate the relationships between field-scale nitrate leaching and soil, soil water, and topographic characteristics in a cultivated Montana farm field.

### Objectives

Two projects relating to field-scale leaching are described in this thesis. The first project, discussed in Chapter 2, encompassed two objectives: 1) to characterize and describe the spatial and temporal variability of nitrate and bromide leaching in a 20-ha Montana farm field of moderate relief (43 m); and 2) to test the leaching prediction capabilities of several soil, soil water, and terrain attributes that singly, or in combination, represent the spatial distribution of soils and microclimate attributes in this farm field under uniform application of N and bromide. Chapter 3 describes the second project to determine if a topographically-derived wetness index calculated at two grid scales (2 m and 10 m) is correlated to field-measured soil water content (collected over three field seasons including two cropped and one unusually wet, fallow year).

## CHAPTER 2

### DESCRIPTION AND PREDICTION OF FIELD-SCALE LEACHING

#### Introduction

The degradation of water quality from agricultural sources is a critical concern for both surface and ground waters in the U.S. (Crowder and Young, 1988).

Pollution prevention practices are more cost effective than after-the-fact clean-up practices. Reclaiming contaminated ground water is impossible or uneconomical in many instances (McCool and Renard, 1990). There is evidence that nitrates already accumulated deep in the soil profile will raise ground water contamination levels even if corrective agricultural practices are adopted immediately (Winteringham, 1984).

More than 50% of Montanans (95% in rural areas) depend on ground water as a source of drinking water (Jacobsen and Johnson, 1991; Algard et al., 1994) and legislation has been enacted to protect this resource. The Montana Agricultural Chemical Ground Water Protection Act, which took effect on January 1, 1990, encourages proper management of agricultural chemicals to prevent, minimize, or mitigate their presence in ground water (Hart and Jacobsen, 1994).

The links between agricultural land use and ground water quality are not as well understood as those for surface water. Most agricultural pollution is non-point in nature. Estimating the potential for ground water contamination by agricultural

chemicals is complicated by complex geological, hydrological, and biological processes (Crowder and Young, 1988).

In the 1980's, soil N was identified as the single most important factor contributing to problems of "increased productivity with simultaneous resource protection" (Winteringham, 1984). Nitrogen fertilizers are the most frequently cited cause for nitrate accumulation in ground water, although other sources can collectively contribute hundreds of kilograms of  $\text{NO}_3\text{-N ha}^{-1}$  each year (Power and Schepers, 1989). Nitrate is a mobile form of soil N and can reach ground and surface water by several mechanisms including surface erosion, runoff, local re-absorption of volatilized N compounds, or leaching transport mechanisms.

In agricultural landscapes, ground water contamination occurs in areas where surplus soil water leaches excess nitrates or other soluble compounds below the crop root zone and potentially to ground water. Although nitrate is taken up rapidly by growing plants, this removal mechanism only occurs within the crop root zone. The nitrates may be derived from fertilizers, legumes, manure, or natural soil sources. Failure to match crop nutrient needs with soil water nutrient supply may lead to the presence of excess nitrates in the soil system when: 1) residual (surplus) nitrates from over-fertilized areas are present; or 2) lack of plant-available N decreases water use and promotes percolation beyond the root zone.

Nutrient management on the farm can reduce agricultural non-point pollution. Use of known best management practices (BMPs) has been demonstrated to be highly effective in controlling leaching of nitrates (Power and Schepers, 1989). However,

the control of nitrate leaching is complicated. Reduction of surface runoff and its constituents through implementation of soil conservation practices may increase percolation of water through the soil root zone and subsequently recharge of ground water aquifers, thereby potentially increasing the leaching of nitrates, pesticides, fecal coliform bacteria, and phosphorus to ground water. Because fertilizers are the predominant N source in agricultural systems, the most effective adjustments in management practices needed to control ground water degradation will involve fertilizer practices (Crowder and Young, 1988).

Changes can be made in fertilizer practices to enhance fertilizer use efficiency and thereby reduce potential for nitrate leaching. The general relationship between N fertilizer application rates and crop yields is qualitatively well known. The growth of a crop in a given location and efficiency of the crop's use of available N, however, depend on soil properties, weather and climate, and cultivation and management practices. The complex interaction of these factors makes it extremely difficult to predict exact fertilizer needs for a specific crop at a specific location, or alternatively, to determine the amount of residual N lost to the environment (National Resource Council, Commission on Natural Resources, 1978). Synchronizing the amount and timing of N fertilizer and other nutrient applications with the crop's requirement is probably the most cost-effective and efficient method to control pollution in surface and ground water (Crowder and Young, 1988; Addiscott et al., 1991). Consequently, uniform fertilizer management is a potential source of ground water contamination. Uniform management creates inefficiencies by over-treating and under-treating

portions of fields. This can increase field management cost, waste energy, decrease net return, and potentially contribute to both surface and ground water pollution (Burrough, 1993). The spatial variation of soil properties, terrain, and microclimate causes uneven patterns in soil fertility and crop growth. This variation decreases fertilizer use efficiency when applied uniformly at the field scale (Miller et al., 1988; Bhatti et al., 1991; Larson and Robert, 1991; Mulla, 1993). Soil spatial variability within fields has been identified by soil testing and crop yield differences. Detailed soil surveys or crop-free aerial photographs show that individual fields often include several soil types (Robert and Rust, 1982).

Recent technologies in geographic soil information systems, remote sensing techniques, simulation modeling techniques, and computerized field applicators offer new opportunities for "farming soils, not fields" by applying fertilizer selectively to take account of the variation in fertility and leaching capacity of the soil (Carr et al., 1991; Larson and Robert, 1991; Burrough, 1993). If the spatial variation of soil fertility and leaching potential over a field could be mapped, fertilizer applications could be adjusted based on management zones, thereby reducing excess fertilizer application. A Global Positioning System (GPS) receiver and a small computer with a digital map of management zones in the cab of a tractor is required. This allows the amount of fertilizer released from application equipment to be adjusted according to each management zone as the tractor progresses through a field (McEachern et al., 1990; Petersen, 1991). The cost savings in fertilizer inputs and reduction in ground water pollution may be sufficient to justify the capital and time expenditure.

Practical and operational (field-usable) solutions to ground water contamination problems will require consideration of contrasting environmental differences within fields. Many mathematical expressions and models have been developed to predict the downward leaching rate and depth-concentration profile of solutes. One difficulty in designing leaching process models is that when the model successfully simulates a particular soil profile, it may not be representative of the overall field situation due to spatial and/or temporal variability. Additionally, water infiltrating down the soil profile can bypass uniform displacement mechanisms by entering structural or biological voids in the soil (Winteringham, 1984; White, 1985).

New techniques and models as well as additional data may be needed to predict field-scale leaching (Mulla, 1990; 1991; 1993). Model and data requirements to achieve this goal must be reasonable if the model is to be used for farm planning. Many studies attempting to relate soil properties or crop parameters to landscape position have used general landscape mapping units (hilltops, midslopes, footslopes) to characterize soil position rather than specific topographic attributes (Walker et al., 1968; Stone et al., 1985; Brubaker et al., 1993, 1994; Er-Raji and Cihacek, 1994). Two types of topographic attributes are significant with respect to characterizing the spatial variability of the landscape: 1) primary attributes (including slope and aspect) which are calculated directly from digital elevation models (DEM); and 2) secondary attributes or compound topographic indices which may help describe or characterize spatial variability of specific processes occurring in the landscape, such as soil water distribution (Moore et al., 1993a; 1993b).

The integration of soil survey (soil attributes and boundaries), terrain (three-dimensional topography), microclimate (precipitation and transpiration), and image analysis (precise pest and crop performance mapping) into a GIS format would add detail to soil management areas within an on-farm GIS (He et al., 1992; Mausbach et al., 1993; Robert, 1993; Wilson et al., 1994). Management areas could then be identified based, in part, on their leaching susceptibility. Fertilizers could then be precisely applied within a field with GPS receivers guiding application equipment. More selective N fertilizer application practices based on soil, terrain, microclimate, and imagery information may reduce or avoid ground water contamination, and improve profitability.

### Objectives

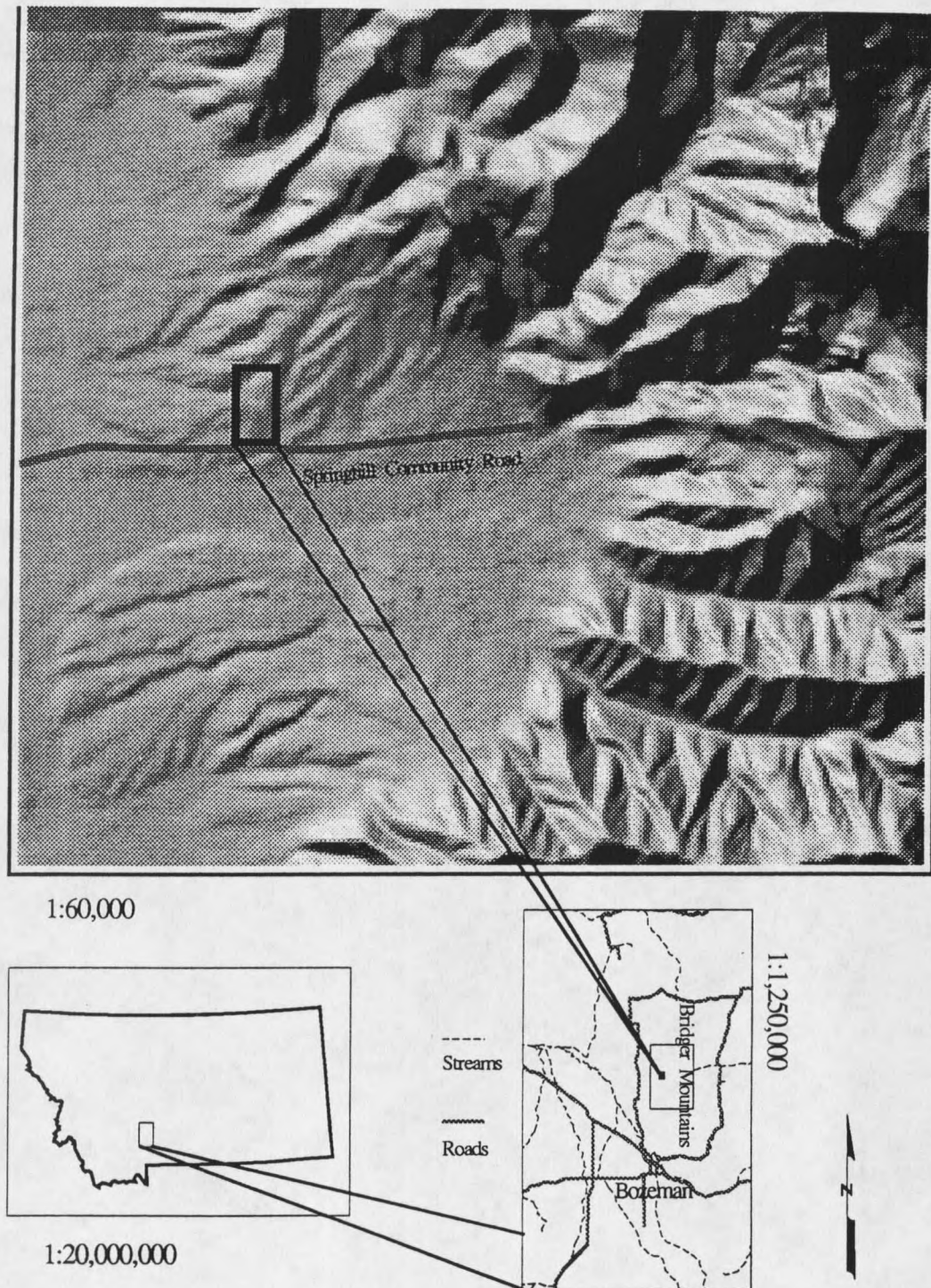
This study encompassed two objectives: 1) to characterize and describe the spatial and temporal variability of nitrate and bromide leaching; and 2) to test the leaching prediction capabilities of several soil, water, and terrain attributes that singly, or in combination, represent the spatial distribution of soil and climatic indices in a farm field under uniform application of N and bromide. The results could potentially provide a tool to be used by farmers in making land management decisions for ground water protection.

### Description of Study Area

The study area consisted of a 20 ha (50 acre) portion of a farm field located at the base of the Bridger Mountains (2700-2950 m) in the Gallatin Valley near the community of Springhill, Montana (T1N, R6E, Section 18; 45°50'40" 111°2'12") (Figure 1). It is bounded on the south by a gravel county road and on the east by a gravel driveway/road. In general, it has a southerly aspect, moderately strong relief (43 m), and an average elevation of 1509 m (Figures 2 and 3). A small intermittent stream runs through the field in a south-south-westerly direction (see bottom half of Figures 2 and 3). The field has been dryland farmed by the Wright family with a grain-fallow rotation for approximately 50 years.

The underlying geologic materials are soft tertiary valley fill sediments, alluvium, and loess derived from Devonian to Cambrian rocks (Veseth and Montagne, 1980). The soils in this field are dominated by: 1) Fine-silty, mixed Typic Argiborolls (Farland silt loam) formed in loess and stratified alluvium on terraces and valley footslopes; and 2) Coarse-silty, mixed Typic Ustochrepts (Brodyk silt loam) associated with the Farland silt loam. Some Fine, mixed Argic Cryoborolls (Bridger variant clay loam) formed in very thick loam or clay loam unconsolidated deposits from a variety of igneous, metamorphic, and sedimentary rock deposited as alluvium or glacial till in intermountain valleys were also present (National Cooperative Soil Survey, 1994).

Figure 1. Location map (Spangrud, 1995).



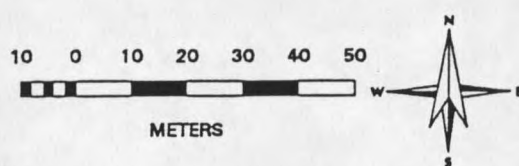
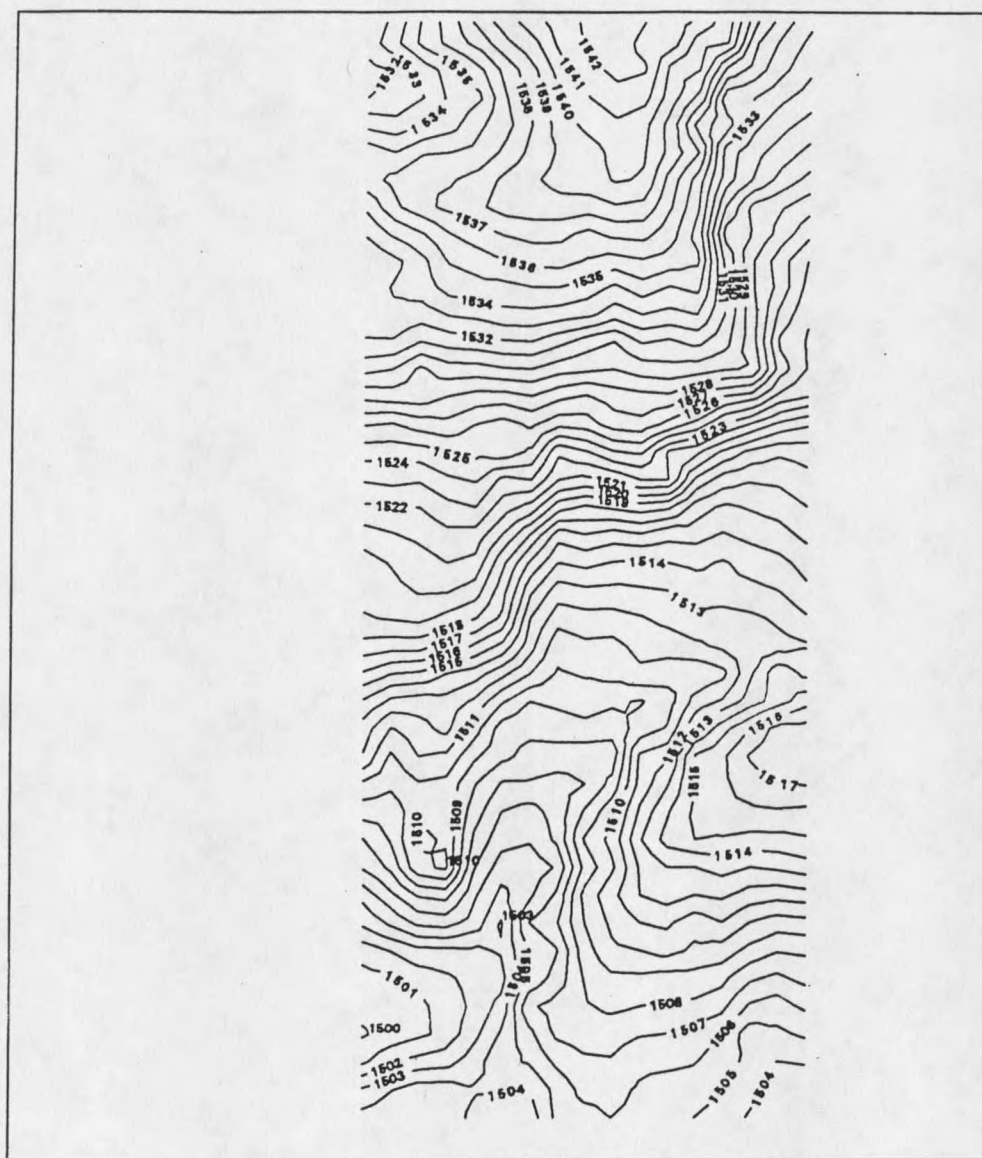
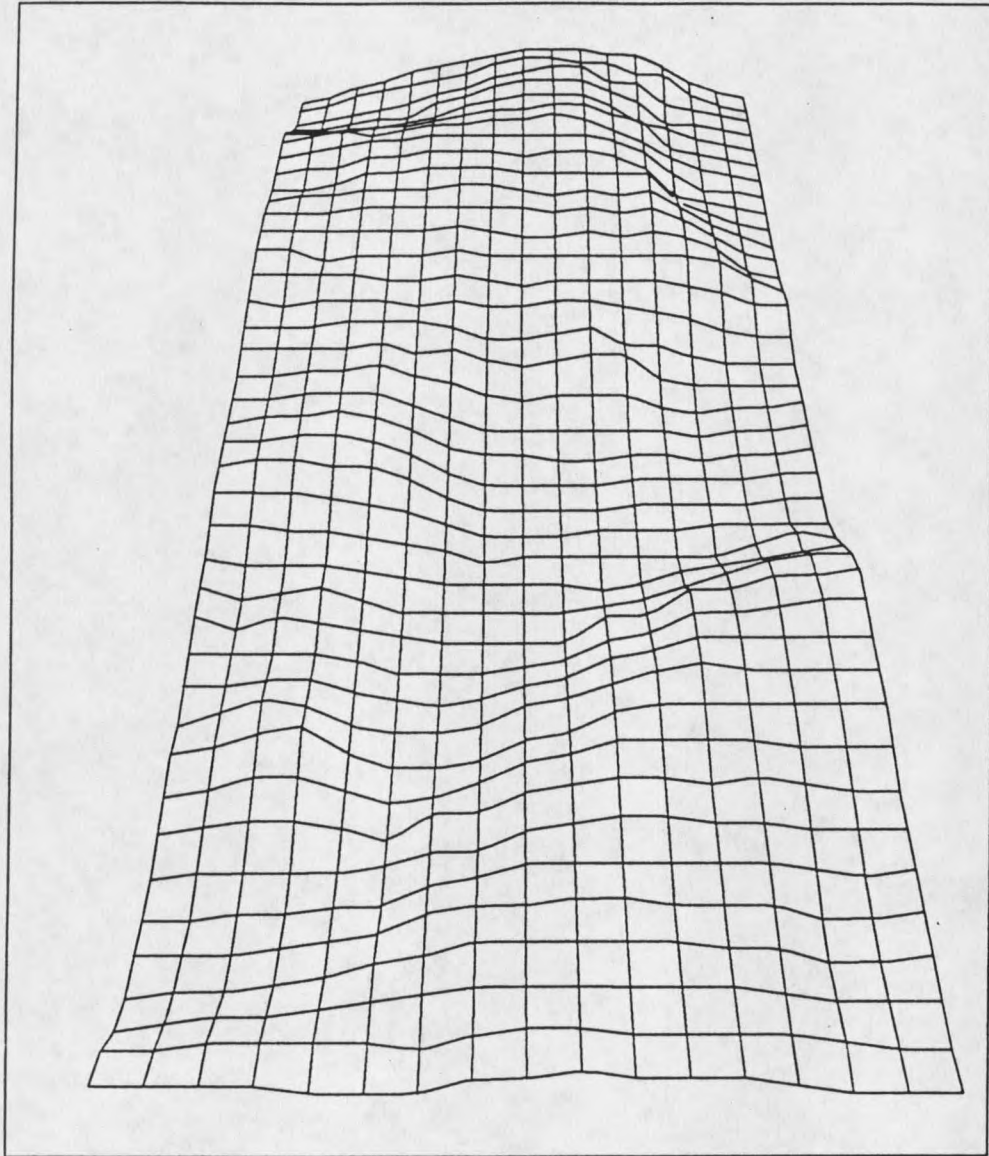


Figure 3. Interpolated 10 m elevation lattice (Spangrud, 1995).



1 mesh cell = 5 by 5 meters



Farland silt loams, were found on nearly level to gently sloping terraces and footslopes of stream valleys (4-8% and 8-15%), are deep, well-drained soils that formed in stratified alluvium of mixed mineralogy. Brodyk silt loams consist of very deep, well-drained soils formed in loess on dissected stream terraces with slopes ranging from 8 to 15% and were found in association with Farland silt loams. Bridger variant clay loam, which was found on a steep slope (15-35%), consists of deep, well-drained soils formed in colluvium and residuum from limestone and shale. All three soil series exhibit medium to slow/moderately slow runoff and moderate permeability (National Cooperative Soil Survey, 1975;1978;1992).

The climate at Gallatin Field (45°47'N 111°09'W, 1353 m) located approximately 14 km southwest of the study area in the Gallatin Valley is cool, semi-arid, with long cold winters (Ruffner, 1985). However, the study site experiences cooler and wetter conditions due to its location next to the base of the Bridger Mountains. The study site experiences a mean annual air temperature of about 6.7 °C (44 °F) (Caprio et al., 1994). Most of the precipitation falls as snow and spring rain. The study area receives mean annual precipitation of about 41 to 76 cm (16 - 18 inches) and mean annual snowfall of about 127 to 254 cm (50 - 100 inches) (Caprio et al., 1994).

### Material and Methods

The following sections describe field management during the course of this study, field data collection, sample analysis, generation of terrain attributes, data preparation, and the statistical methods used for data analysis.

### Field Management

The timeline followed in this study is summarized in Table 3 and additional details are discussed below by year.

1992. Initial soil samples were collected and described during installation of seventy neutron access tubes. Additional soil samples were collected for neutron probe calibration. Potassium bromide (KBr) solution was then surface applied as a tracer to test plots adjacent to each neutron access tube. The KBr solution was prepared from pellets and applied using a CO<sub>2</sub> pressured backpack unit equipped with a fan spray nozzle. A constant volume of 0.5 liters KBr solution (50.37 g KBr L<sup>-1</sup>) was placed in a plastic 2-liter soda bottle and delivered across each plot as evenly as possible. The KBr solution was sprayed inside a 1.5 m by 1.5 m quadrat for an application rate of 150 kg ha<sup>-1</sup> (133.9 lbs ac<sup>-1</sup>). Grain yield was sampled both by hand and by plot combine around each sample site.

1993. Barley stubble remained in the field over the winter of 1992-1993 and the field remained fallow until early October when it was seeded with winter wheat (Triticum aestivum L.). In July, Roundup solution was sprayed on each KBr test plot and around each neutron access tube to prevent uptake of nitrogen and bromide by weeds. Roundup was applied using a CO<sub>2</sub> pressured backpack unit equipped with a spray nozzle. In late September, KBr solution was re-applied to test plots adjacent to each neutron access tube and soil samples were again collected. The KBr solution

Table 3. Springhill project timeline.

---

FALL 1991

Sep GPS data collected and sample grid of 70 sites established

SPRING 1992

May 14-20 Initial soil samples collected, field descriptions of soil profiles recorded, and neutron access tubes installed

May 15 Field sprayed with Roundup herbicide

Jun 1 Field seeded at ~ 67-101 kg ha<sup>-1</sup> barley (*Hordeum vulgare* L.) and fertilized at ~ 56-22-28-22 kg ha<sup>-1</sup> (50-20-25-20 lbs ac<sup>-1</sup>) N-P-K-S

Jun 5 Surface application of bromide (KBr) solution on test plots at 150 kg ha<sup>-1</sup> (~ 133.9 lbs ac<sup>-1</sup>)

FALL 1992

Sep 29/Oct 1 Grain yield and plant biomass samples collected

Oct. 19-20 Field harvested

Oct. 21-23 Soil samples collected

SPRING 1993

May 1 Neutron access tube locations resurveyed

May 25/Jun 4 Soil samples collected

Jul 1 1% Roundup herbicide solution sprayed around each access tube and on each bromide test plot

Jul 1-2 Field tilled and sprayed with Roundup

Jul 14 Field tilled

Aug 3-4 Field tilled

FALL 1993

Sep 23 Surface application of bromide (KBr) solution on test plots at 337.5 kg ha<sup>-1</sup> (~ 301.3 lbs ac<sup>-1</sup>)

Sep 28-29 Soil samples collected

Sep 30/ Oct 1 & 5 Riser sections of neutron access tubes removed from field and lower section sealed below ground level

Oct 10-11 Field fertilized at ~ 90-34-34 kg ha<sup>-1</sup> (80-30-30 lbs ac<sup>-1</sup>) N-P-K

Oct 18 Field seeded at ~ 101 kg ha<sup>-1</sup> (90 lbs) winter wheat(*Triticum aestivum* L.) and FarGo applied at rate of ~ 14.5 kg ha<sup>-1</sup> (12.94 lbs ac<sup>-1</sup>)

Oct 22-23 Neutron access tubes relocated with hand-held metal detector

SPRING 1994

Apr 16-17 Riser sections of neutron access tubes replaced

Apr 15-20 Field tilled

Apr 18-19 Soil samples collected

May 2 Field reseeded at ~ 84 kg ha<sup>-1</sup> (75 lbs ac<sup>-1</sup>) barley (*Hordeum vulgare* L.)

FALL 1994

Aug 20-24 Field harvested

Sept 1 Field tilled

Sept 1-3,6 Soil samples collected

Oct 12 Neutron access tubes removed from field

---

was sprayed inside a 1 m by 1 m quadrat for an application rate of  $337.5 \text{ kg ha}^{-1}$  ( $301.3 \text{ lbs ac}^{-1}$ ). After planting, two sample points were not able to be reestablished (#20 and #48).

1994. Neutron access riser tubes were replaced in mid-April while the field was being tilled to prepare for planting barley (Hordeum vulgare L.) due to the failure of the winter wheat. The field was re-seeded after re-installation of the neutron access tube risers and the equipment paths that were followed to avoid crushing the neutron access tubes led to non-uniform seeding and the occurrence of weeds around the tube sites and across the bromide test plots. Therefore, plant samples were not collected for either grain yield determination or plant biomass and uptake.

#### Preparation of GPS Survey and Sample Grid

Elevation data were collected at 6,284 different locations in Fall 1991 with an Ashtech Sensor GPS receiver mounted on a pickup truck and an Ashtech P-12 GPS receiver operating in kinematic mode at a fixed reference location (Figure 4). This survey was performed by Dr. David Tyler from the Dept. of Surveying Engineering at the University of Maine-Orono. The data collected included longitude and latitude in state plane meters (NAD 1983) and elevation values in meters above sea level. A permanent sampling grid consisting of 70 sample points was established in the field (Figure 5). A 5.1-cm (2-inch) PVC neutron access tube was installed at each sample point to 200 cm below the soil surface using a truck-mounted hydraulic soil sampler and 5.1-cm (2-inch) diameter bit. Each neutron probe access tube consisted of two

Figure 4. GPS collection pattern (Spangrud, 1995).

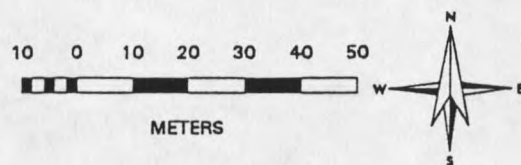
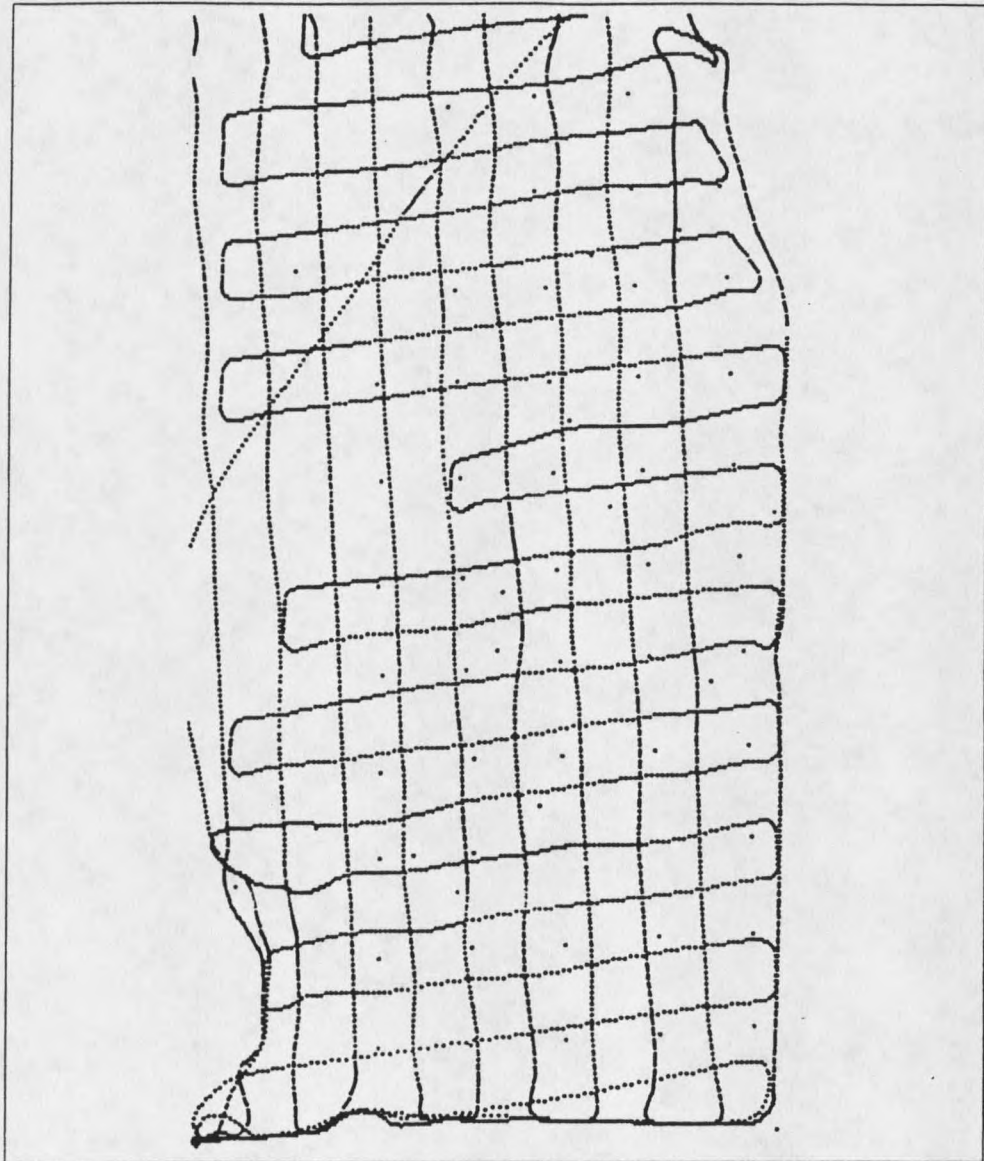
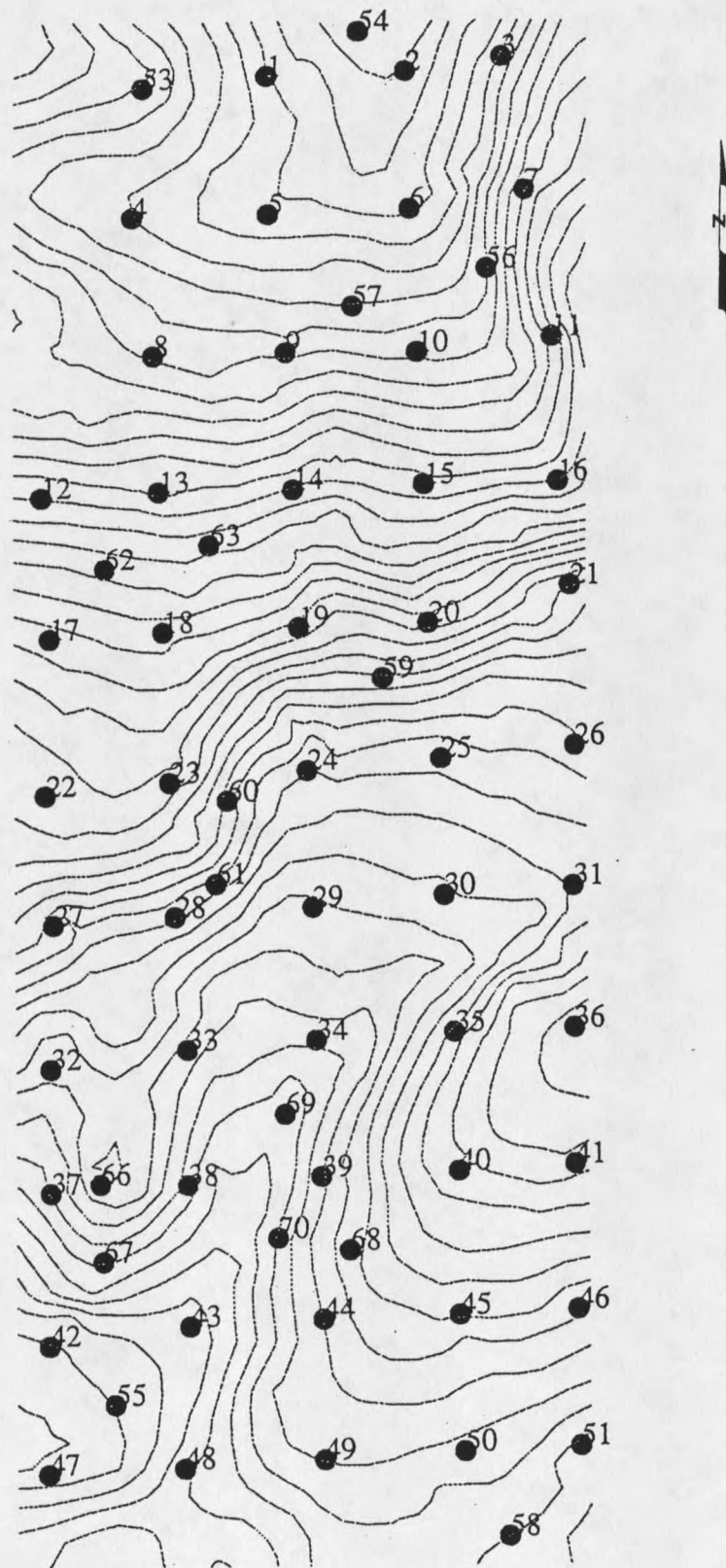


Figure 5. Permanent sampling grid (Spangrud, 1995).



sections. The lower section was installed with the top edge at least 20.3 cm (8 inches) below ground level. Two 1.3 cm (0.5-inch) holes were drilled in the lower section 3.8 cm (1.5 inches) below the top of the tube and covered with electrical tape. The purpose of these holes was to facilitate extraction of the tubes at a future date. A 22.9 cm (9-inch) piece of rebar was buried on the north side of each lower section tube to aid in relocation. A riser section of the same diameter was fitted over the lower section through the use of a collar or sleeve to extend the tube assembly above ground level for neutron probe access. The riser section was sealed with a 5.1 cm (2-inch) solid rubber stopper (Size 11-1/2) between neutron probe data collections.

The locations and elevations of the neutron access tubes were resurveyed in May 1993 by Mr. Brian Autio and his students from the Dept. of Civil and Agricultural Engineering at Montana State University utilizing an HP-48 data collector with a Topcon GTS-303 total station.

### Soil Sampling

Initial soil samples were collected and described in May 1992. Field descriptions and measurements of the mollic epipedon, Bt, Bk, and 2C horizons, color, texture, and percent clay were obtained from the cores removed for neutron access tube installation. The cores were then divided into 15 cm and 30 cm increments to depths of 30 cm and 210 cm, respectively, for laboratory analysis. Soil samples were collected in lined, paper sample bags and placed in coolers in the field for transportation back to Montana State University where they were air-dried, ground, and screened through a 2-mm sieve prior to analysis. Soil testing performed

on these initial samples included pH (1:2 solid:solution ratio), EC (1:2 dS m<sup>-1</sup>), OM (%) determined by the Walkley-Black method, extractable Olsen P (mg kg<sup>-1</sup>), and extractable K (mg kg<sup>-1</sup>) for 0-15 cm, and extractable NO<sub>3</sub>-N (mg kg<sup>-1</sup>) for each depth increment to 210 cm. All soil and plant analyses were performed by the Montana State University Soil Analytical Lab.

Soil samples were subsequently collected each spring and fall for three years from the KBr test plot to a maximum depth of 180 cm (in the increments listed above) with a hydraulic soil sampler utilizing a 3.4-cm (1.34 inch) diameter bit. The samples were handled and processed as described above before analysis for both nitrate-N and bromide (mg kg<sup>-1</sup>).

The soil samples were analyzed for NO<sub>3</sub>-N via a colorimetric cadmium reduction method after a 1:5 soil to solution calcium hydroxide extraction. The procedure used for analysis of soil bromide was developed at MSU by Dennis Hengel (Appendix A).

#### Generation of Terrain Attributes

The terrain attribute data were generated by Damian Spangrud. The following description is paraphrased from his unpublished thesis, and a more detailed description of the procedure may be obtained there (Spangrud, 1995). All of the GPS elevation data were converted to a regular, rectangular 10 m DEM grid using ANUDEM (Hutchinson, 1989). ANUDEM uses a series of partial, thin-plate splines with drainage enforcement to create grid-based DEMs from irregular point or contour data.

The interpolated 10 m elevation lattice data (Figure 3) were then entered into the grid version of the Terrain Analysis Programs for the Environmental Sciences program (TAPES) (Moore, 1992) to calculate terrain attributes for each 100 m<sup>2</sup> cell in the study area. Five of the twelve primary terrain attributes generated were used in the current study: slope, aspect, profile (down-slope) curvature, plan (across-slope) curvature, specific catchment area (area draining to a cell divided by the width of that cell). Additionally, one secondary or compound topographic attribute (steady-state, relative wetness index) was calculated with the WET program (Moore, 1992).

TAPES-G allows different attribute prediction algorithms to be used based on user preference for topographically important variables such as slope and specific catchment area. Slope was calculated using the FD (finite difference) approach rather than the D8 (approximate) approach. Specific catchment areas can be calculated in TAPES-G using either the D8, Rho8 (a stochastic version of the more common D8 algorithm), or FRho8 algorithms. The FRho8 algorithm was utilized in this study because it allows flow to be : 1) routed to any of the eight neighboring cells on a slope-weighted basis; and 2) distributed to multiple cells in upland areas above the channel head. Modeling of upland non-stream areas was important to this project because there is no defined stream channel system over most of the study area.

The steady-state wetness index was calculated with the WET program and is derived from two primary TAPES-G attributes, specific catchment area and slope as follows:

$$w = \ln(A_s / \tan \beta) \quad (1)$$

where  $w$  indicates the wetness index,  $A_s$  is the specific catchment area ( $m^2 m^{-1}$ ), and  $\beta$  is the slope angle (degrees). Two important assumptions are incorporated into this wetness index: 1) that the direction of subsurface flow (dictated by the gradient of the piezometric head) is parallel to the gradient of the surface topography; and 2) that steady-state conditions apply. Equation (1) provides a relative index where the value increases with increasing specific catchment area and decreasing slope gradient.

Larger indices indicate cells with low slope and large drainage areas relative to other cells in the study area. Therefore, hilltops (flat areas with low specific catchment area) exhibit moderate values, valleys (high specific catchment area and low slope) where water concentrates exhibit high values, and steep hillslopes (high slope) where water drains more freely exhibit low values (Moore et al., 1993a; 1993b).

The terrain attributes calculated by TAPES-G were then imported into ARC/INFO (Environmental Systems Research Institute, Inc., Redlands, CA 92373) and a point-in-polygon overlay of the 67 sample point coordinates and the grid was performed to determine cells in which the sample points were located. The terrain attributes for each cell containing a sample point were then extracted from ARC/INFO as an ASCII file for further analysis.

Three sample points (#52, #64, #65) were removed from analysis when the DEM coverage was clipped to a rectangular area. Subsequently, two of these sample points (#64 and #65) were independently lost due to the construction of a new house on the west side of the field during the study.

### Soil Water Content

Neutron probe (Gardner, 1986) data was collected in 25-cm intervals between 25 and 200 cm depth at each sample point using a CPN Hydroprobe moisture meter. Measurements were taken throughout the growing season for three years as follows: 1) approximately 10-day intervals from 6-8-92 to 11-12-92; 2) approximately 15-day intervals from 5-18-93 to 9-24-93; and 3) approximately 10-12-day intervals from 4-21-94 to 8-17-94. Water which periodically accumulated in the bottom of some neutron access tubes was removed as necessary via a suction apparatus. This problem was more prevalent in the spring and probably resulted from rain entering the tubes due to cap removal or loss between data collections.

Wet and dry calibration soil samples and corresponding neutron probe readings were collected in May 1992 and September 1992, respectively at 11 locations across a range of topographic positions. The resulting probe calibration equation is:

$$Y = 0.20X - 0.013 \quad (2)$$

where Y is the predicted volumetric water content ( $\theta_v$ ) and X is the neutron probe count ratio (measured count  $\div$  standard count). This regression yielded an  $R^2$  value of 0.65 which was somewhat lower than expected.

Equipment problems resulted in standard count readings varying from about 8000 to 10,000 on different days of data collection. A standard count of approximately 10,000 is expected, thus, all count ratios collected on monitoring dates with a standard reading of less than 10,000 were adjusted to a 10,000 standard count

before further calculations were made. The count ratios recorded at each depth for all sites for each monitoring date were then transformed to depth equivalent of water (cm) by:

$$D_e = \theta_v D \quad (3)$$

where  $\theta_v$  is the measured volume water content and  $D$  is the corresponding measurement depth interval in centimeters.

From this transformed data, the average total water content (cm of water) in the soil profile was calculated over each growing season for each site for three different total profile depths (25 cm, 100 cm, and 150 cm).

#### Grain Yield and Plant Uptake Measurements

Barley grain yield and plant biomass samples were collected in September 1992. Grain yield was determined by hand clipping and plot combine methods. Hand collected grain samples were obtained from the northeast side of each neutron access tube sample point by clipping barley heads from an area 1 m in length across 4 rows (25.4 cm (10 inches) apart) giving a sampling cell of 1.02 m<sup>2</sup>. These grain samples were threshed and grain yield (kg m<sup>-2</sup>) was determined by weighing each grain sample on a toploading balance.

Separate barley grain yield samples were collected from the four quadrants around each sample point using a plot combine which employed a 1.2 m header giving a sampling cell of 0.006 ha. Barley grain yield for the plot combine samples was determined by weighing each of the samples on a large capacity beam balance in

the field. An average yield ( $\text{kg m}^{-2}$ ) for each sample point was then calculated by averaging the four sample cells surrounding a sample point.

A small sub-sample of barley grain was taken at the time of Fall 1992 harvest for test weight and protein determination. Percent protein was determined by the Montana State University Cereal Quality Laboratory using infrared reflectometry techniques.

A  $0.305 \text{ m} \times 0.254 \text{ m}$  (12"  $\times$  10") area (sampling cell of  $0.077 \text{ m}^2$ ) of barley was also clipped at ground level and collected from the KBr test plot for determination of plant uptake. The samples were weighed on a toploading balance to determine plant biomass ( $\text{g m}^{-2}$ ), ground, and then analyzed for N and bromide.

The Kjeldahl procedure was used for analyzing the plant tissue for total N (%) (Bremner and Mulvaney, 1982). The procedure for bromide (%) analysis of plant tissue was adapted by Dennis Hengel at MSU from the bromide selective-ion electrode method reported by Abdalla and Lear (1975) (Appendix A).

Barley grain yield and plant biomass samples were not collected in Fall 1994 due to variable seeding rates around neutron access tubes.

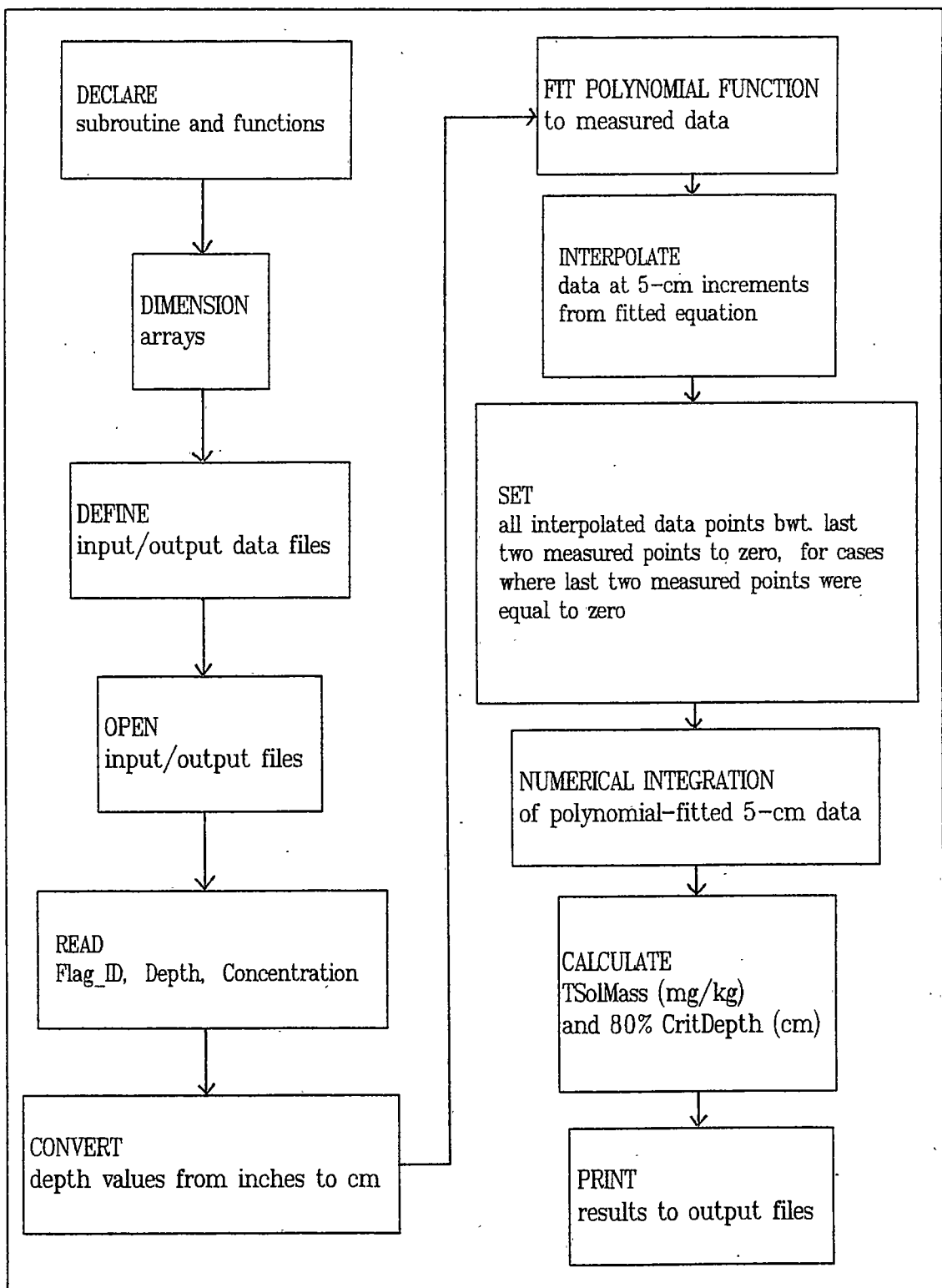
#### Computations for Leaching Characterization

A minimum of two leaching indices were generated for both N and bromide for each sampling period. Where appropriate, four additional indices were generated. The two primary indices were generated using a BASIC program written with the assistance of Dr. Jon M. Wraith in the Dept. of Plant, Soil, and Environmental Sciences at Montana State University.

The LEACHIND.BAS program was created to generate the two primary leaching indices (Figure 6; Figure 14 in Appendix B). This program calculates the total solute mass and a "critical depth" of solute within the soil profile from smoothed data. The program begins by fitting an  $n-1$  order polynomial function to the measured solute concentration by depth data at each site and then interpolating data at 5-cm depth increments from the fitted equation. The next step is numerical integration of the fitted, interpolated data at each site using Newton's forward (2<sup>nd</sup> order), Bessel's (3<sup>rd</sup> order), and Newton's backward integration (2<sup>nd</sup> order) procedures. Each of these procedures is based on finite difference approximations to the integral. Lastly, the program calculates two leaching indices for each site: 1) the total solute load (ie. solute mass) in the soil profile to a depth of 180 cm; and 2) a depth marking the boundary above which 80% of the total solute load is found (ie. critical depth). The program was rerun twice to also calculate a critical depth for 25% and 50% (i.e., center of mass) of the total solute load. Field sites that were not sampled at a particular time period were treated as missing values. Additionally, two secondary leaching indices were calculated from the solute mass and critical depth values, i.e., positive or negative change in these values from one sampling date to the next were calculated for each applicable time period.

Where applicable, two other leaching indices were calculated based on conservation of mass estimates. For each applicable time period, a mass balance leaching index was calculated at two depths, 60 and 90 cm. Sixty centimeters was selected because it is the common rooting depth of barley (Sims, 1994). The ninety

Figure 6. LEACHIND.BAS flowchart.



centimeter depth was chosen for comparison as it is the greatest depth to which most sites were sampled in any one time period.

Three sources of N exist during the growing season. One comes from residual N in the soil, the second comes from mineralization and nitrification of organic matter, and the third is from fertilizer applied. The additions and removals from the system included in the mass balance calculations for both nitrogen and bromide during each time period are listed in Table 4. Denitrification as a nitrate removal reaction through biological transformation from soil was considered negligible in this study area and was not included in the mass balance calculations. Denitrification primarily occurs under low oxygen conditions and is most likely to take place in moist soils with high water holding capacity or inside aggregates which are water saturated (Broadbent and Clark, 1965).

The only input factor not accounted for was the possible reintroduction of N or bromide onto the soil surface with decaying plant biomass. Quantitative information on N or bromide release from plant residue was not available, and therefore, was not included as an addition in the calculations.

The mass balance calculations were performed on a pounds per acre basis. Bulk density values were not available, so all data were transformed to  $\text{lbs ac}^{-1}$  units via the weight of an acre furrow slice. It is customary to consider that an average acre furrow slice (6.67 inches) has a bulk density of  $1.3 \text{ g cm}^{-3}$  and weighs about 2,000,000 pounds or 1,000 tons (Brady, 1990). Due to using this uniform transformation across the range of topographic sites and with depth, some information about variability was not incorporated. The soils were sampled in 15 cm (6-inch)

increments, therefore  $(6 \div 6.67 \text{ inches}) \times (2,000,000 \text{ lbs of soil})$  yields 1,799,100 lbs per 6-inch acre furrow slice. This corresponds to an assumed uniform bulk density of  $1.32 \text{ g cm}^{-3}$ .

Table 4. Mass balance worksheet factors.

|                             | 1992           |      | 1993   |      | 1994   |      |
|-----------------------------|----------------|------|--------|------|--------|------|
|                             | Spring         | Fall | Spring | Fall | Spring | Fall |
| Nitrogen                    |                |      |        |      |        |      |
| Soil                        | + <sup>3</sup> | +    | +      | +    | +      | +    |
| Fertilizer                  |                | +    |        |      | +      |      |
| Mineralization <sup>1</sup> |                | +    | +      | +    | +      | +    |
| Plant Uptake <sup>2</sup>   |                | -    |        |      |        | -    |
| Bromide                     |                |      |        |      |        |      |
| Soil                        |                | +    | +      | +    | +      | +    |
| Plant Uptake <sup>2</sup>   |                | -    |        |      |        | -    |

<sup>1</sup> Nitrogen mineralization assumed to be 30 lbs/ac/yr/% organic matter. Values pro-rated for time interval between sampling dates.

<sup>2</sup> Rooting depth for barley at 60 cm (Sims, 1994).

<sup>3</sup> "+" represent addition; "-" represents removal.

A benchmark soil in Gallatin Valley, the Amsterdam series, a Fine-Silty, Mixed Typic Cryoboroll, is similar to the soils present at the study site. Bulk density values (1/3 bar) for this soil range from  $1.40 \text{ g cm}^{-3}$  in the surface horizon (0 - 16 cm) to  $1.25 \text{ g cm}^{-3}$  at the greatest depth measured (135 - 180 cm) (benchmark soil samples at MSU). The assumed bulk density used in the data transformations is, therefore, equivalent to the average bulk density found in the Amsterdam series.

For each time period, an equation was developed to set N or bromide leaching (i.e., % of solute unrecoverable) equal to the sum of other appropriate terms listed in Table 4. For example, in Fall 1992 the percent unrecoverable N was calculated as:

$$[(\text{Unrecoverable N}) \div (\text{N Present in System})] * 100 \quad (4)$$

or:

$$[(\text{N Present in System} - \text{N Recovered in Plant and Soil Samples}) \div \text{N Present in System}] * 100 \quad (5)$$

or specifically:

$$[(\text{SP92 N level} + \text{Fertilizer} + \text{Mineralization} - \text{F92 Plant Uptake} - \text{F92 N level}) \div (\text{SP92 N level} + \text{Fertilizer} + \text{Mineralization})] * 100 \quad (6)$$

The results from the mass balance calculations indicate the percent of solute unrecoverable at the current sampling date across a common sampling depth of 60 or 90 cm in the soil profile relative to what was present at the previous sampling date. Mass balance indices were not calculated for the last time period, Spring 1994 to Fall 1994, as barley samples were not collected for determination of plant uptake due to non-uniform seeding and occurrence of weeds on the test plots. Negative percentages (results) were treated as missing values.

### Statistical Analysis

All edaphic, terrain, soil water, and yield variables along with the leaching and mass balance indices were stored for each of the 67 sample points in database files. Tables 43 and 44 in Appendix C present complete lists of the initial baseline values for the measured soil and both measured and predicted terrain variables, respectively.

These data were exported to SAS (SAS Institute, Inc., 1988) as ASCII data files to create permanent SAS data files to facilitate correlation and regression analyses.

Correlation analysis was performed to estimate correlation coefficients for each pair of independent variables, dependent variables (N and bromide) and the dependent and independent variable combinations. Paired t-tests were performed between the solute mass and mass balance indices for N and bromide for each time period using MSUSTAT (Lund, 1993).

Stepwise multiple regression analysis was used to separate those environmental factors (edaphic, terrain, soil water, and yield) which correlated best with N and bromide leaching. The dependent variables (leaching indices) for each time period were considered one at a time in each regression procedure. The exact number of independent variables utilized in any one regression procedure differed based on the presence or absence of a crop and other relevant factors for each sampling period. The F level for entry or deletion of an independent variable was set to 0.05. Statistical significance of the overall equation was determined by an F-test. The t-test was used to test the significance of each independent variable. The models were also evaluated for over- or under-specification using Mallow's Cp value. Plots of regression residuals were examined to determine the presence of outliers.

## Results and Discussion

### Leaching Behavior

Nitrogen. Table 5 lists the values of average N solute mass in the soil profiles integrated to a depth of 180 cm from the LEACHIND.BAS program which are graphically depicted in Figure 7. In S92 at the beginning of field monitoring, an average of 459.1 mg kg<sup>-1</sup> was present in each soil profile. The distribution of the N was such that 80% of the N mass was present within the top 103 cm, 50% within 60 cm, and 25% within 34 cm of the soil surface (Table 6; Figure 8). This amount and distribution was then considered as "time zero" or baseline for subsequent N calculations.

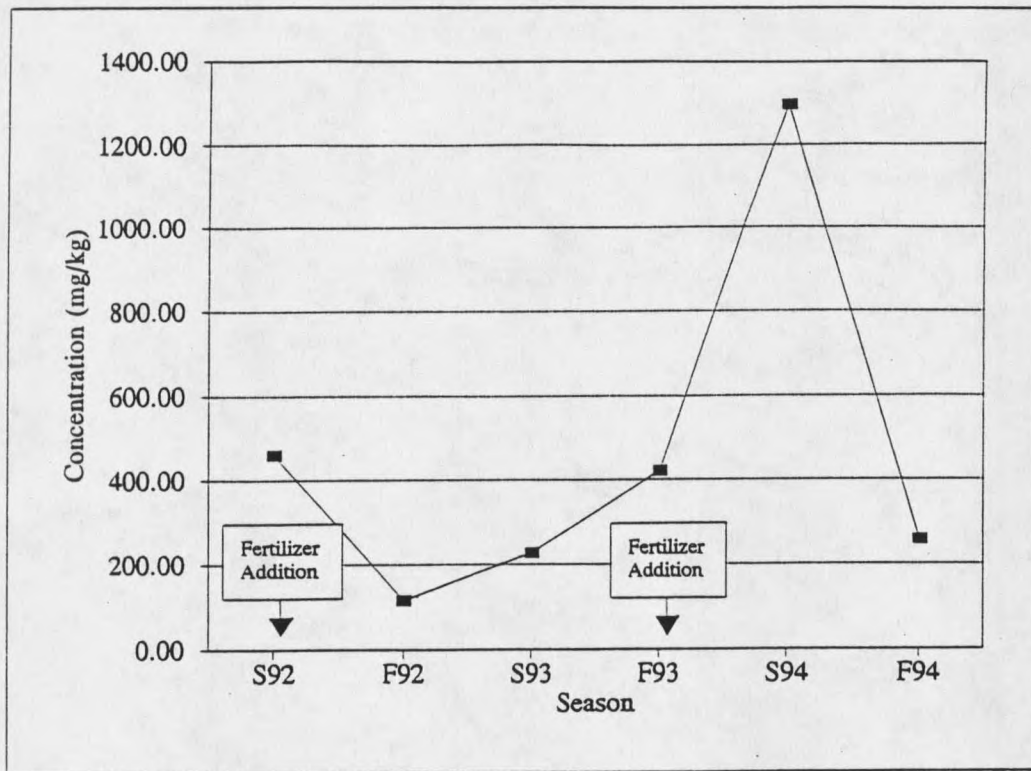
Table 5. Summary statistics for nitrogen solute mass<sup>1</sup> (mg kg<sup>-1</sup>).

| Variable                                                    | S92    | F92   | S93   | F93    | S94    | F94    |
|-------------------------------------------------------------|--------|-------|-------|--------|--------|--------|
| n                                                           | 67     | 65    | 66    | 67     | 65     | 64     |
| Min                                                         | 41.0   | 17.0  | 32.7  | 68.3   | 218.2  | 2.3    |
| Max                                                         | 1873.1 | 523.9 | 776.5 | 1345.5 | 4179.3 | 1127.4 |
| Mean                                                        | 459.1  | 115.7 | 227.1 | 421.6  | 1297.4 | 258.0  |
| S.D.                                                        | 332.0  | 100.9 | 147.3 | 244.8  | 753.6  | 255.3  |
| C.V.                                                        | 0.72   | 0.87  | 0.65  | 0.58   | 0.58   | 0.99   |
| SE <sub><math>\bar{x}</math></sub> <sup>2</sup>             | 40.57  | 12.52 | 18.13 | 29.90  | 93.47  | 31.92  |
| SE <sub><math>\bar{x}</math></sub> / $\bar{x}$ <sup>3</sup> | 0.09   | 0.11  | 0.08  | 0.07   | 0.07   | 0.12   |

<sup>1</sup> To a depth of 180 cm.

<sup>2</sup> Standard Error of the mean.

<sup>3</sup> Standard Error of the mean as a proportion of the mean.

Figure 7. Average nitrogen solute mass ( $\text{mg kg}^{-1}$ ).

From S92 to F92 a barley crop was present in the field. Analysis of soil samples collected after barley harvest showed that the average N solute mass decreased from 459.1 to 115.7  $\text{mg kg}^{-1}$  (Table 5; Figure 7). However, since N fertilizer was added to the field with barley seeding in the spring after the soil samples had been collected, the maximum N concentration was not captured. Therefore, the decrease shown is less than that experienced in the field. The N unrecoverable in the plant or soil samples (Table 7; Figure 9) was 56.4% to 60 cm and 46.6% to 90 cm depth (roughly similar to the percent unrecoverable for bromide during the same time period). However, the critical depths for the remaining N decreased for all three levels, although by differing amounts. The critical depths containing both 80% and 25% of total solute decreased by similar amounts from

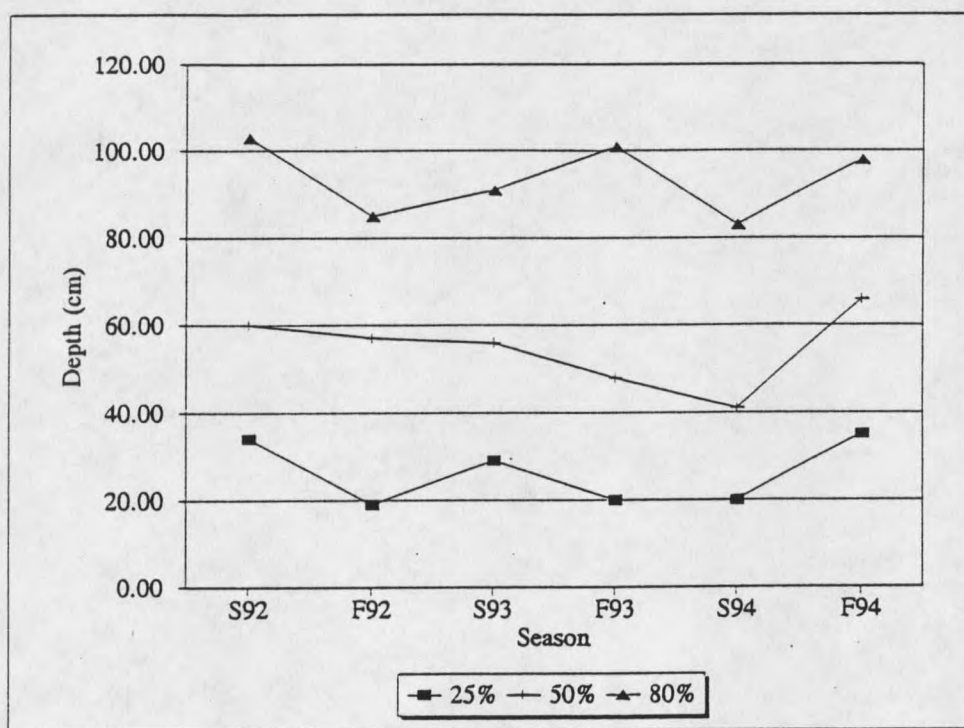
Table 6. Average nitrogen critical depth (cm).

| Sample               | S92<br>n = 67 |     |      | F92<br>n = 65 |     |      | S93<br>n = 66 |     |      | F93<br>n = 67 |     |      | S94<br>n = 65 |     |      | F94<br>n = 64 |    |      |
|----------------------|---------------|-----|------|---------------|-----|------|---------------|-----|------|---------------|-----|------|---------------|-----|------|---------------|----|------|
| PTSL*                | 25            | 50  | 80   | 25            | 50  | 80   | 25            | 50  | 80   | 25            | 50  | 80   | 25            | 50  | 80   | 25            | 50 | 80   |
|                      | %             |     |      | %             |     |      | %             |     |      | %             |     |      | %             |     |      | %             |    |      |
| Min                  | 10            | 25  | 40   | 5             | 5   | 10   | 5             | 10  | 20   | 5             | 15  | 40   | 5             | 10  | 15   | 5             | 5  | 5    |
| Max                  | 80            | 105 | 150  | 105           | 115 | 150  | 75            | 145 | 155  | 85            | 115 | 150  | 100           | 110 | 135  | 11            | 13 | 15   |
| Mean                 | 34            | 60  | 103  | 19            | 57  | 85   | 29            | 56  | 91   | 20            | 48  | 101  | 20            | 41  | 83   | 35            | 66 | 98   |
| S.D.                 |               |     | 23   |               |     | 49   |               |     | 34   |               |     | 29   |               |     | 27   |               |    | 42   |
| C.V.                 |               |     | 22   |               |     | 58   |               |     | 37   |               |     | 29   |               |     | 35   |               |    | 43   |
| SE $\bar{x}$         |               |     | 2.83 |               |     | 6.07 |               |     | 4.22 |               |     | 3.51 |               |     | 3.31 |               |    | 5.29 |
| SE $\bar{x}/\bar{X}$ |               |     | 0.03 |               |     | 0.07 |               |     | 0.05 |               |     | 0.03 |               |     | 0.04 |               |    | 0.05 |

\* PTSL = percent of total solute load

103 to 85 cm and 34 to 19 cm respectively, but a much smaller change in the critical depth at 50% was observed, decreasing only slightly from 60 to 57 cm (Table 6; Figure 8). Although N fertilizer was applied to the field at the time of barley planting in S92, plant uptake and N mineralization in surface layers of the soil probably led to the observed decreases in the critical depth values at all levels.

Figure 8. Average nitrogen critical depth (cm).



Over the fallow winter months from F92 to S93, average total N mass increased to 227.1 mg kg<sup>-1</sup>. In conjunction, the nearly parallel line segments for F92-S93 in Figure 9 indicate that the percent of N unrecoverable at both 60 and 90 cm both increased by virtually the same increment, 22.9 and 22.6%, to 79.3 and 69.2% respectively. Although the 50% critical depth did not change (57 to 56 cm), the

critical depth for both the 25% and 80% levels both increased from 19 to 29 cm and 85 to 91 cm, respectively (Table 6; Figure 8).

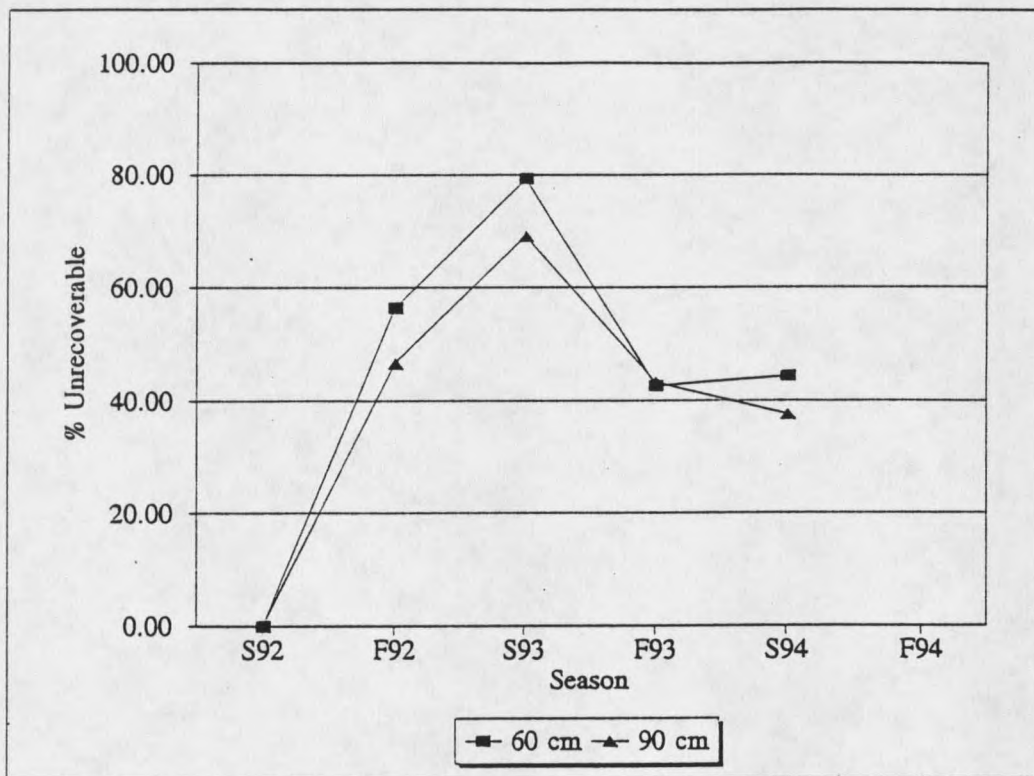
Table 7. Summary statistics for nitrogen balance (% unrecoverable).

| Variable             | F92   |       | S93   |       | F93   |       | S94   |       |
|----------------------|-------|-------|-------|-------|-------|-------|-------|-------|
|                      | 60 cm | 90 cm | 60 cm | 90 cm | 60 cm | 90 cm | 60 cm | 90 cm |
| n                    | 62    | 47    | 60    | 40    | 50    | 42    | 58    | 54    |
| Min                  | 25.8  | 9.8   | 18.8  | 9.8   | 0.9   | 0.9   | 0.2   | 0.2   |
| Max                  | 78.5  | 99.9  | 92.4  | 89.5  | 87.8  | 83.1  | 82.4  | 78.4  |
| Mean                 | 56.4  | 46.6  | 79.3  | 69.2  | 42.6  | 43.2  | 44.3  | 37.6  |
| S.D.                 | 12.3  | 15.6  | 12.8  | 18.2  | 23.1  | 20.8  | 17.1  | 17.4  |
| C.V.                 | 0.22  | 0.33  | 0.16  | 0.26  | 0.54  | 0.48  | 0.39  | 0.46  |
| SE $\bar{x}$         | 1.56  | 2.28  | 1.65  | 2.88  | 3.26  | 3.21  | 2.25  | 2.36  |
| SE $\bar{x}/\bar{X}$ | 0.05  | 0.10  | 0.04  | 0.10  | 0.17  | 0.20  | 0.10  | 0.13  |

During the summer fallow period from S93 to F93, the average N mass increased from 227.1 to 421.6 mg kg<sup>-1</sup> (Table 5; Figure 7). This was expected due to increased mineralization of N from organic matter and increased breakdown or decay of crop residue during the warm months. This increase was larger than that observed for F92 to S93. Simultaneously, the N balance for both 60 and 90 cm decreased substantially, converging on nearly the same percentage, 42.6% and 43.2%, respectively (Figure 9). The N distribution data presented in Figure 8 concurs with both the N solute mass and mass balance data. The data show that 25% and 50% of the N in the profiles was closer to the surface by the F92 sampling. The critical depth decreased at both levels by virtually the same amount, 9 and 8 cm respectively. The fact that the percent unrecoverable and critical depth both decreased makes sense

in light of N mineralization in surface mollic horizons. However, the critical depth for the 80% level increased from 91 to 101 cm. The N present in the lower profile moved downward with summer precipitation. The summer of 1993 was the coolest and wettest on record (Montana Climate Center, 1995).

Figure 9. Average nitrogen balance (% unrecoverable).



After soil sampling in F93, N fertilizer was applied to the field prior to planting of winter wheat. Subsequently, the S94 sampling revealed a large increase in average N mass in the profiles to 1297.4 mg kg<sup>-1</sup> (Table 5; Figure 7). Figure 9 shows that some of the N, residual and applied, moved partially downward through the profile over the winter months. The percent of unrecoverable N slightly increased in the top 60 cm and slightly decreased in the top 90 cm. This information along

with the S94 critical depths in Figure 8 indicate that applied and residual N in the profiles moved downward relative to the distribution in F93. The critical depth for the 80% level decreased by almost 20 to 83 cm while the critical depth decreased by 7 to 41 cm for the 50% level and remained the same for the 25% level at 20 cm.

After S94 soil sampling, the field was reseeded with barley due to the failure of the winter wheat. The percent N unrecoverable was not calculated for F94 since plant biomass samples were not collected to monitor plant uptake of N or bromide. Soil analysis revealed that the average N mass in the profiles decreased sharply from 1297.4 mg kg<sup>-1</sup> in S92 to 258.0 mg kg<sup>-1</sup> after harvest in F94 (Table 5; Figure 7). Although N uptake by barley plants undoubtedly occurred, Table 6 and Figure 8 indicate that the average critical depth of the N increased by 15 cm at the 25% and 80% levels, while the 50% critical depth level increased more dramatically by 25 cm. This is the opposite trend seen in the S92 - F92 cropped period where critical depths decreased. The S92 sampling followed a fallow period and much more N was present in the soil profiles (4179.3 mg kg<sup>-1</sup>). It appears that excess N not taken up by the barley crop leached downward.

Bromide. In field experiments, bromide ion has been widely used as a proxy or tracer to indicate how nitrate moves in soils. Bromide ion is a suitable tracer for solute transport in many soil systems for three reasons: 1) its natural background concentration in most waters and soils is very low, thus movement of small amounts can be detected (Kung, 1990; Onken et al., 1977; Agus and Cassel, 1992); 2) it can be easily analyzed (Onken, et al., 1975); and 3) it is nonreactive (Kung, 1990).

Several studies have shown that nitrate and bromide behave similarly in the subsoil (Smith and Davis, 1974; Onken et al., 1977). However, bromide cannot be used to determine quantitative movement of nitrate (Onken et al., 1977), because it is not subject to processes involved in the soil N cycle. In other words, bromide is a biologically conserved tracer and cannot be used to determine "specific questions regarding the fate of fertilizer N in a soil-plant system" (Silvertooth et al., 1992). Silvertooth et al. (1992) also indicate, however, that the concentration profile of bromide can "infer solute movement patterns and present a worst-case scenario regarding potentials for nitrate leaching loss."

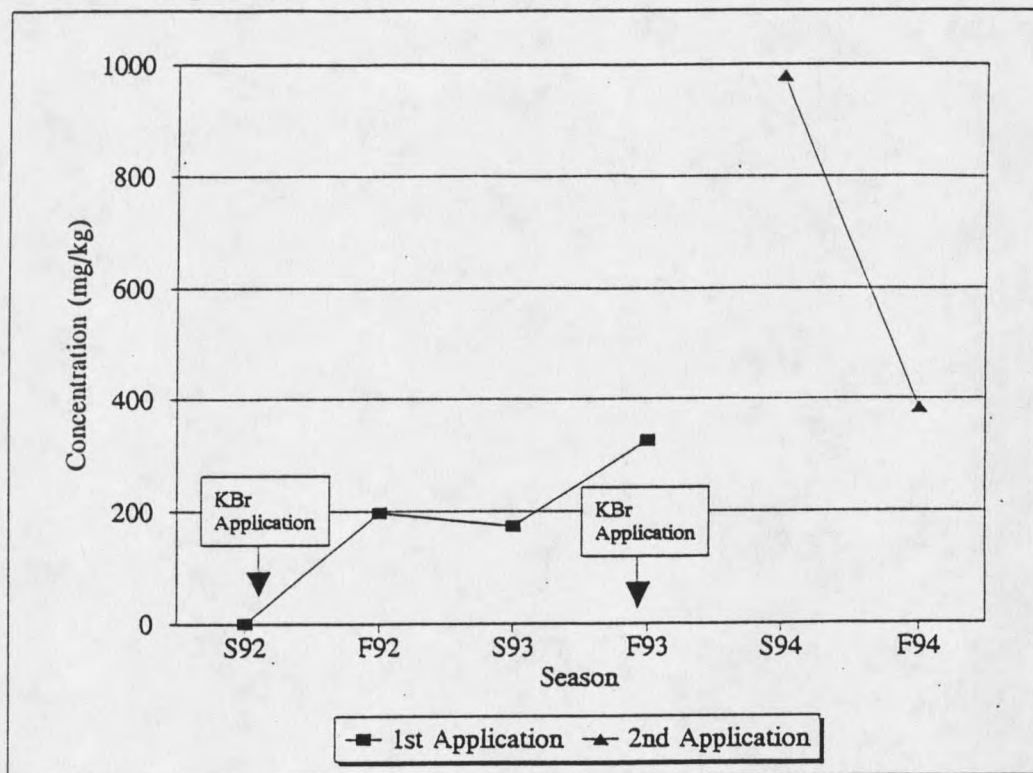
In laboratory column studies without root systems, bromide has been shown to be a good tracer for the movement of nonreactive solutes and its breakthrough patterns can be well described by a convection-dispersion model (Clothier and Elrick, 1985; Jardine et al., 1988). However, the uptake of bromide ions from the root zone and reintroduction back to the soil surface can significantly change the character of a bromide pulse under certain conditions and with specific plants (Kung, 1990; Wraith and Inskeep, 1994). Therefore, the dependability of using the bromide front to indicate the velocity of solute movement in a field soil with active roots, and whether the bromide breakthrough curve (BTC) can represent the fate of some contaminants that can be degraded in plants needs to be addressed (Kung, 1990).

Table 8 lists the summary statistics for bromide solute mass in the soil profile integrated to a depth of 180 cm for each sampling. Figure 10 graphically depicts the change in average bromide solute mass over time listed in Table 8.

Table 8. Summary statistics for bromide solute mass (mg kg<sup>-1</sup>).

| Variable             | S92 | F92   | S93    | F93    | S94    | F94    |
|----------------------|-----|-------|--------|--------|--------|--------|
| n                    | 67  | 65    | 66     | 67     | 65     | 64     |
| Min                  | 0   | 31.1  | 0.0    | 0.0    | 51.3   | 8.4    |
| Max                  | 0   | 644.7 | 1189.1 | 3145.0 | 2631.3 | 1413.0 |
| Mean                 | 0   | 197.6 | 173.2  | 325.5  | 980.2  | 383.3  |
| S.D.                 |     | 137.1 | 238.8  | 702.2  | 542.9  | 276.2  |
| C.V.                 |     | 0.69  | 1.38   | 2.16   | 0.55   | 0.72   |
| SE $\bar{x}$         |     | 17.00 | 29.39  | 85.78  | 67.34  | 34.53  |
| SE $\bar{x}/\bar{X}$ |     | 0.09  | 0.17   | 0.26   | 0.07   | 0.09   |

As expected, average bromide total solute mass increased between S92 and F92 from zero to 197.6 mg kg<sup>-1</sup> due to the addition of KBr solution (150 kg ha<sup>-1</sup> or 133.9 lbs ac<sup>-1</sup>) after the S92 soil sampling. However, by F92, 53.1% of the surface-applied bromide was unrecoverable to 60-cm depth and 39.3% was unrecoverable to 90-cm depth after accounting for uptake of bromide by the barley crop present within the bromide test plot during the 1992 growing season (Table 9; Figure 11). Although these data appear to provide strong evidence for bromide leaching during the first growing season, it is also possible that some plants adjacent to the bromide test plot took up some of the applied bromide. It is also possible that lateral movement of bromide occurred due to concentration gradients. Table 10 and Figure 12 indicate that 50% of the bromide in the soil was within the top 19 cm and 80% was present in the top 46 cm. In other words, over half of the bromide applied is unrecoverable in the top 60 cm, however, 80% of the remaining bromide is present in the top 46 cm of the soil profile.

Figure 10. Average bromide solute mass ( $\text{mg kg}^{-1}$ ).

Although Figure 10 (Table 8) indicates that the average total solute mass of bromide in the soil profiles decreased only slightly from 197.6 to 173.2  $\text{mg kg}^{-1}$  during the F92 to S93 period, Figure 11 (Table 9) reveals that amount of bromide unrecoverable increased at nearly the same rate from 53.1 to 86.4% to 60 cm and from 39.3 to 68.9% to 90 cm. Table 10 and Figure 12 show that the depth to which the soil must be sampled to recover 25 and 50% of the remaining bromide increased at nearly the same rate from 8 to 58 cm and 19 to 72 cm, respectively. The critical depth for 80% increased at a slightly lower rate from 46 to 87 cm. These results indicate that the bromide remaining in the profiles after the F92 barley harvest moved significantly downward, but remained within 180 cm of the soil surface.

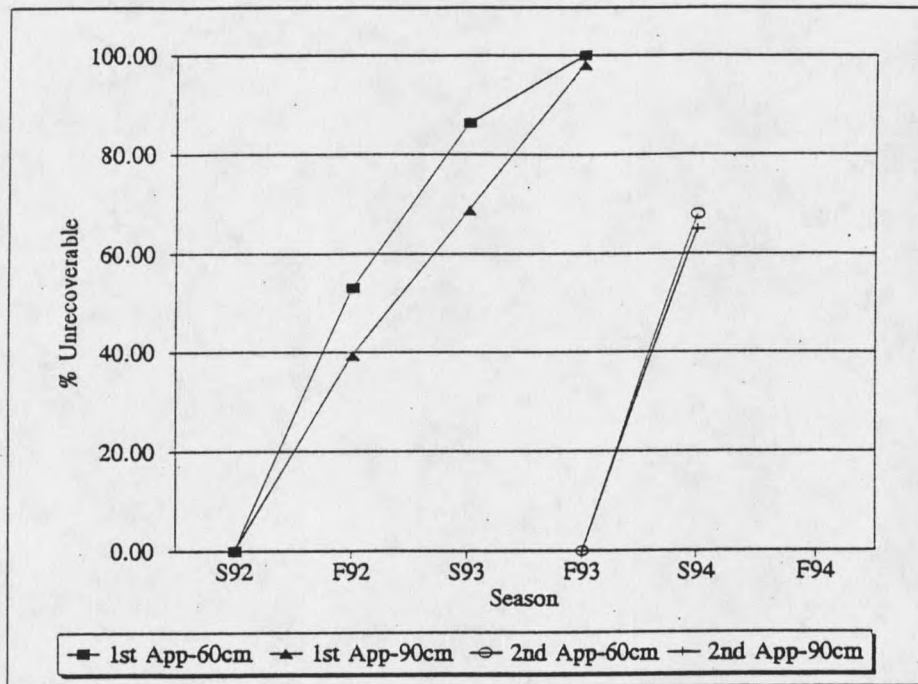
Additionally, 11 sites were identified from the S93 sampling where the bromide had moved sufficiently down the profile such that the solute was deeper than sampling depth of 180 cm. At the other sites, only a small amount of bromide was leached from the sampled soil volume, but significant downward movement of the remaining bromide was observed during this winter fallow period.

Table 9. Summary statistics for bromide balance (% unrecoverable).

| Variable             | F92   |       | S93   |       | F93   |       | S94   |       |
|----------------------|-------|-------|-------|-------|-------|-------|-------|-------|
|                      | 60 cm | 90 cm | 60 cm | 90 cm | 60 cm | 90 cm | 60 cm | 90 cm |
| n                    | 62    | 47    | 56    | 32    | 60    | 52    | 64    | 62    |
| Min                  | 13.0  | 0.9   | 43.4  | 2.3   | 100.0 | 0.0   | 23.8  | 19.7  |
| Max                  | 82.4  | 75.0  | 100.0 | 100.0 | 100.0 | 100.0 | 98.7  | 98.4  |
| Mean                 | 53.1  | 39.3  | 86.4  | 68.9  | 100.0 | 98.1  | 68.1  | 65.1  |
| S.D.                 | 16.7  | 18.5  | 14.9  | 28.2  | 0     | 13.9  | 17    | 17.9  |
| C.V.                 | 0.31  | 0.47  | 0.17  | 0.41  | 0     | 0.14  | 0.25  | 0.27  |
| SE $\bar{x}$         | 2.12  | 2.70  | 1.99  | 4.99  | 0     | 1.92  | 2.12  | 2.27  |
| SE $\bar{x}/\bar{X}$ | 0.04  | 0.07  | 0.02  | 0.07  | 0     | 0.02  | 0.03  | 0.03  |

Between S93 and F93 the field was fallow and significant downward movement of bromide was again observed, but was accompanied by an increase in average solute mass. Figure 10 (Table 8) indicates that the average solute mass almost doubled from 173.2 to 325.5 mg kg<sup>-1</sup>. Although 42 sites contained no bromide within the sampling depth of 180 cm, ten values from the F93 sampling were greater than 1000 mg kg<sup>-1</sup> and two of those ten values were greater than 3000 mg kg<sup>-1</sup>. These high values skewed the mean value for bromide solute mass.

Figure 11. Average bromide balance (% unrecoverable).



The second application of KBr was surface applied on the test plot immediately prior to the F93 soil sampling. By F93, most of the bromide left in the soil profiles resided at the deeper depths sampled. Therefore, prior to calculating the F93 leaching indices, the bromide concentration values reported by the Soil Analytical Lab were adjusted by subtracting out the known amount of bromide just applied on the surface in an attempt to reveal an actual decrease in bromide solute mass from the first KBr application. After this adjustment, some sites still displayed surface concentration values of bromide greater than zero. This is very likely due to bromide redistribution to the soil surface as a result of a mechanism by which bromide is taken up by plants and later redistributed to the soil surface as observed in barley and canola (Wraith and Inskeep, 1994). Kung (1990) speculated that this might occur

Table 10. Average bromide critical depth (cm).

|                      | F92<br>n = 65 |     |      | S93 <sup>1</sup><br>n = 55 |     |      | F93 <sup>2</sup><br>n = 25 |     |      | S94<br>n = 65 |    |      | F94<br>n = 64 |    |      |
|----------------------|---------------|-----|------|----------------------------|-----|------|----------------------------|-----|------|---------------|----|------|---------------|----|------|
| PTSL <sup>3</sup>    | 25            | 50  | 80   | 25                         | 50  | 80   | 25                         | 50  | 80   | 25            | 50 | 80   | 25            | 50 | 80   |
|                      | %             |     |      | %                          |     |      | %                          |     |      | %             |    |      | %             |    |      |
| Min                  | 5             | 5   | 10   | 5                          | 5   | 10   | 40                         | 50  | 65   | 5             | 10 | 15   | 5             | 5  | 5    |
| Max                  | 60            | 130 | 145  | 120                        | 135 | 150  | 155                        | 160 | 165  | 45            | 80 | 120  | 10            | 12 | 15   |
| Mean                 | 8             | 19  | 46   | 58                         | 72  | 87   | 122                        | 132 | 144  | 19            | 31 | 58   | 18            | 44 | 80   |
| S.D.                 |               |     | 35   |                            |     | 34   |                            |     | 23   |               |    | 25   |               |    | 37   |
| C.V.                 |               |     | 76   |                            |     | 39   |                            |     | 16   |               |    | 43   |               |    | 46   |
| SE $\bar{x}$         |               |     | 4.38 |                            |     | 5.59 |                            |     | 8.72 |               |    | 3.06 |               |    | 4.63 |
| SE $\bar{x}/\bar{X}$ |               |     | 0.09 |                            |     | 0.08 |                            |     | 0.16 |               |    | 0.05 |               |    | 0.06 |

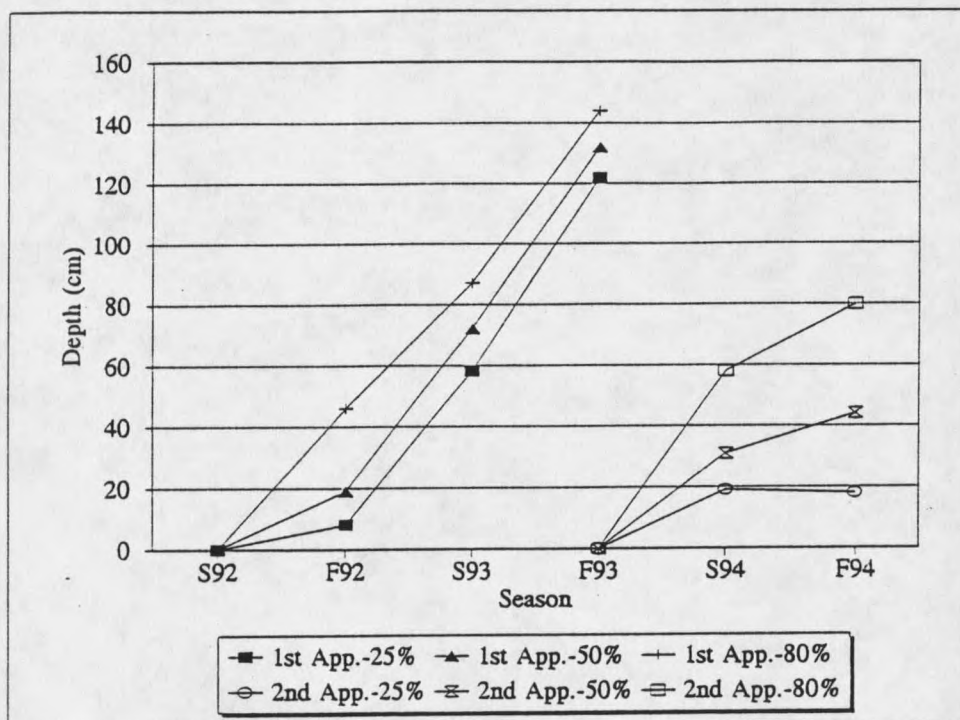
<sup>1</sup> In S93, bromide deeper than 180 cm at 11 sites.

<sup>2</sup> In F93, bromide deeper than 180 cm at 42 sites.

<sup>3</sup> Percent total solute load.

when dead leaves decay. Owens et al. (1985) showed that, in a field study, as much as 30% of applied bromide can be taken up by grass and reintroduced into the soil surface after the grass has decayed.

Figure 12. Average bromide critical depth (cm).



However, since the total increase in bromide mass is larger than can be accounted for by this mechanism, it is probable that some measurement or calculation error may be involved. The expected overall decrease of bromide solute mass is supported by the data in Figure 11 (Table 9) showing that the percent of unrecoverable bromide to both 60 and 90 cm increased, converging toward a value of 100.0% (98.1% to 90 cm depth). In addition, 42 sites (compared to 11 in S93) were identified where the bromide was no longer present within the sampling depth of 180

cm. At the other 25 sites, the critical depth of the bromide remaining in the profiles increased almost linearly from 58 to 122 cm, 72 to 132 cm, and 73 to 144 cm at the 25, 50, and 80% levels respectively (Table 10; Figure 12). These data indicate only very small amounts of bromide present in the 0 - 90 cm portion and a significant amount of bromide now located between 90 and 180 cm.

As mentioned above, a second application of  $337.5 \text{ kg ha}^{-1}$  (or  $301.3 \text{ lbs ac}^{-1}$ ) KBr was surface applied in F93. This application is reflected in the large increase in average total mass of bromide solute to  $980.2 \text{ mg kg}^{-1}$  in the S94 sampling (Table 8; Figure 10). Over the F93 to S94 winter period, winter wheat (which ultimately failed in S94) was present in the field. By the S94 sampling, nearly 70% of the bromide was unrecoverable (68.1% to 60 cm and 65.1% to 90 cm) (Table 9; Figure 11). This is a much larger first period increase in percent unrecoverable than observed following the first KBr application in S92. These data indicate that either more leaching or lateral water flow occurred because the field was effectively fallow and/or there was some plant uptake by the winter wheat crop during this period. The critical depths for recovery of 25, 50, and 80% of the bromide were 19, 31, and 58 cm respectively Table 10; Figure 12). These changes in critical depths during a winter period are greater than those observed for the summer cropped period from S92 to F92 directly following the first KBr application. It is interesting to note, however, that the distances between the critical depth at each level are virtually identical; 11-12 cm between the 25 and 50% levels, and 27 cm between the 50 and 80% levels. Therefore, although different amounts of solute were present in the soil profiles, the relative distribution is the same.

From S94 to F94, average bromide mass in the soil profiles sharply decreased by nearly two-thirds from 980.2 to 383.3 mg kg<sup>-1</sup> (Table 8; Figure 10). Two types of losses were possible during this period, leaching and plant uptake and the data reflect a large decrease in bromide solute mass. The percent of bromide unrecoverable was not calculated for F94 because no plant samples were collected as discussed earlier (p. 38). The rate of increase in critical depth (Table 10; Figure 12) at all three levels is less (-1 vs. 8 cm at 25% level; 13 vs. 19 cm at 50% level; and 22 vs. 46 cm at 80% level) than that measured during the 1992 growing season following the first application of KBr. However, the 1994 growing season was the driest of the three included in this study which may explain the slower downward movement.

Nitrogen Behavior vs. Bromide Behavior. Paired t-tests were performed between N and bromide mass by season to determine whether the spatial patterns were similar. Table 11 shows that the t-test result was highly significant on three of the five sampling dates (F92, S94, and F94) indicating that spatial patterns of N and bromide variability were different. In S93 following a winter fallow period, the t-test was not significant at the 5% level, but was significant at the 10% level ( $P = 0.0724$ ) indicating some differences in spatial behavior patterns. After two fallow periods in F93, the t-test was highly insignificant ( $P = 0.3064$ ) indicating that N and bromide behavior was more similar during the summer of 1993. Pearson's and Spearman Rank correlation coefficient values (Table 11) varied from  $|r| = 0.3023$  to 0.4040 at the 5% level of significance. Although the relationship between N and

bromide solute mass is relatively weak based on r-values, it is definitely notable that a significant relationship is present for three of the five time periods.

Table 11. Comparison of nitrogen and bromide solute mass by season.

| Sampling Date | n  | Paired t-test | Pearson's Correlation | Spearman Rank Correlation |
|---------------|----|---------------|-----------------------|---------------------------|
|               |    | P-value       | r-value<br>P-value    | r-value<br>P-value        |
| Fall 1992     | 65 | 0.0000        | -0.1455<br>0.2496     | -0.1835<br>0.1435         |
| Spring 1993   | 66 | 0.0724        | 0.3023<br>0.0136      | 0.2592<br>0.0356          |
| Fall 1993     | 67 | 0.3064        | -0.0873<br>0.4821     | 0.1025<br>0.4094          |
| Spring 1994   | 65 | 0.0000        | 0.3347<br>0.0064      | 0.2469<br>0.0474          |
| Fall 1994     | 64 | 0.0010        | 0.4040<br>0.0000      | 0.4037<br>0.0000          |

Statistical comparisons of the N and bromide mass balance estimates were also performed by season (Table 12). The t-test results to 60 cm depth were highly significant on three of the four sampling dates (S93, F93, and S94). In F92 following a cropped period, the results were not significant to 60 cm depth ( $P = 0.2432$ ). The t-test to 90 cm depth was highly significant on half of the sampling dates (F93 and S94). Although, the t-test to 90 cm depth for F92 was not significant at the 5% level, but was significant at the 10% level ( $P = 0.0681$ ). However, at the S93 sampling date (following a winter fallow period) the results to 90 cm depth were not significant ( $P = 0.7223$ ) indicating a higher degree of similarity in N and bromide behavior over

the winter 92-93 fallow period. Review of the Pearson's and Spearman Rank correlation data (Table 12) again reveals mostly weak relationships between N and bromide mass balance figures. The only significant (5% level) r-values obtained occur for the Spearman Rank correlation in F93 to both 60 and 90 cm depths.

Table 12. Comparison of nitrogen and bromide mass balance by season.

|                  |    | Paired<br>t-test | Pearson's<br>Correlation | Spearman Rank<br>Correlation |
|------------------|----|------------------|--------------------------|------------------------------|
| Sampling<br>Date | n  | P-value          | r-value<br>P-value       | r-value<br>P-value           |
| <u>60 cm</u>     |    |                  |                          |                              |
| Fall 1992        | 61 | 0.2432           | -0.0097<br>0.9408        | 0.0370<br>0.7769             |
| Spring 1993      | 56 | 0.0021           | 0.2551<br>0.0578         | 0.1774<br>0.1908             |
| Fall 1993        | 48 | 0.0000           | 0.0000<br>1.0000         | 0.5445<br>0.0000             |
| Spring 1994      | 58 | 0.0000           | 0.0322<br>0.8105         | 0.0553<br>0.6802             |
| <u>90 cm</u>     |    |                  |                          |                              |
| Fall 1992        | 46 | 0.0681           | 0.0626<br>0.6792         | 0.0735<br>0.6276             |
| Spring 1993      | 32 | 0.7223           | 0.0492<br>0.7892         | -0.1194<br>0.5152            |
| Fall 1993        | 40 | 0.0000           | 0.0606<br>0.7103         | 0.5051<br>0.0000             |
| Spring 1994      | 54 | 0.0000           | -0.0202<br>0.8847        | -0.0156<br>0.9111            |

The data presented in Tables 11 and 12 are not surprising in that one would not expect N and bromide to behave similarly in the field. Bromide is a non-reactive,

biologically conserved substance. Once bromide is applied on the surface, it is either taken up by plants or moves through the profile with soil water. The original amount applied may be tracked as no new sources of bromide exist in the soil. In contrast, N is not only taken up by plants, but is also involved in N cycling interactions.

Additionally, a new source of N exists via mineralization near the soil surface.

These complexities make tracking fertilizer N applied difficult.

Conclusion. Evaluation of N and bromide behavior through examination of three indices (solute mass, critical depth, and mass balance) show that leaching of both N and bromide did occur in this field. In general, the data seem to make sense in light of N and bromide applications and the environmental factors involved in each time period. It is interesting to note that greater variation in critical depth values for N was not observed across the five sampling periods. Nitrogen has a source for addition of new material via mineralization near the surface, while bromide does not. Paired t-tests between N and bromide solute mass and % unrecoverable yielded mixed results regarding the similarity of spatial behavior patterns. The solute mass comparisons seem to indicate that N and bromide behaved most similarly when the field was fallow from S93 to F93. However, the mass balance comparisons (% unrecoverable) indicate greatest similarity during the S92 to F92 cropped period and over the following winter fallow period from F92 to S93.

#### Environmental Controls

Data representing environmental factors that potentially explain nitrate leaching were gathered at each of the 67 sites. These data were grouped into measured

edaphic, water, and biotic (plant), and both measured (x coordinate, y coordinate, and elevation) and computed topographic categories. Tables 13 through 16 present the sample numbers, minimum and maximum values, means, and standard deviations of the edaphic, topographic, water, and biotic factors, respectively.

Table 13. Summary statistics for edaphic controls.

|      | pH<br>(1:2) | EC<br>(1:2)<br>(dS m <sup>-1</sup> ) | OM<br>(%) | K<br>(mg kg <sup>-1</sup> ) | Olsen<br>P<br>(mg kg <sup>-1</sup> ) | Thickness<br>of Mollic<br>Horizon<br>(cm) | Depth<br>to<br>CaCO <sub>3</sub><br>(cm) |
|------|-------------|--------------------------------------|-----------|-----------------------------|--------------------------------------|-------------------------------------------|------------------------------------------|
| n    | 67          | 67                                   | 67        | 67                          | 67                                   | 67                                        | 67                                       |
| Min  | 5.6         | 0.04                                 | 1.08      | 166                         | 0.0                                  | 10                                        | 10                                       |
| Max  | 8.3         | 0.23                                 | 5.55      | 844                         | 93.1                                 | 126                                       | >180                                     |
| Mean | 6.3         | 0.07                                 | 3.47      | 318                         | 43.6                                 | 45                                        |                                          |
| S.D. | 0.6         | 0.03                                 | 0.91      | 121                         | 19.0                                 | 27                                        |                                          |
| C.V. | 0.09        | 0.43                                 | 0.26      | 0.38                        | 0.44                                 | 0.60                                      |                                          |

Table 14. Summary statistics for topographic controls.

|      | Elev<br>(m) | Slope<br>(%) | Aspect<br>(deg) | Spec:<br>Catch:<br>Area<br>(m <sup>2</sup> m <sup>-1</sup> ) | Wetness<br>Index | Plan<br>Curv.<br>(m m <sup>-1</sup> ) | Profile<br>Curv.<br>(m m <sup>-1</sup> ) |
|------|-------------|--------------|-----------------|--------------------------------------------------------------|------------------|---------------------------------------|------------------------------------------|
| n    | 67          | 67           | 67              | 67                                                           | 67               | 67                                    | 67                                       |
| Min  | 1489.85     | 1.503        | 64.295          | 10.8                                                         | 4.533            | -18.245                               | -1.844                                   |
| Max  | 1532.08     | 23.259       | 332.319         | 8717.5                                                       | 13.271           | 28.838                                | 1.187                                    |
| Mean | 1508.89     | 10.054       | 191.228         | 592.2                                                        | 6.940            | 0.463                                 | 0.081                                    |
| S.D. | 12.10       | 5.187        | 57.170          | 1849.3                                                       | 1.771            | 8.474                                 | 0.471                                    |
| C.V. | 0.01        | 0.52         | 0.003           | 3.12                                                         | 0.25             | 18.30                                 | 5.81                                     |

Table 15. Summary statistics for soil water controls: average total water (cm).

|                      | 1992     |           |           | 1993     |           |           | 1994     |           |           |
|----------------------|----------|-----------|-----------|----------|-----------|-----------|----------|-----------|-----------|
|                      | 25<br>cm | 100<br>cm | 150<br>cm | 25<br>cm | 100<br>cm | 150<br>cm | 25<br>cm | 100<br>cm | 150<br>cm |
| n                    | 67       | 65        | 64        | 65       | 61        | 57        | 65       | 61        | 43        |
| Min                  | 5.64     | 14.41     | 25.90     | 6.79     | 22.56     | 23.35     | 5.52     | 19.14     | 29.07     |
| Max                  | 7.88     | 25.50     | 55.98     | 9.39     | 29.19     | 40.00     | 8.14     | 25.15     | 34.58     |
| Mean                 | 6.77     | 18.24     | 32.78     | 8.36     | 26.02     | 36.89     | 6.55     | 21.49     | 32.42     |
| S.D.                 | 0.59     | 1.71      | 3.88      | 0.61     | 1.23      | 2.81      | 0.54     | 1.17      | 1.31      |
| C.V.                 | 0.09     | 0.09      | 0.12      | 0.07     | 0.05      | 0.08      | 0.08     | 0.05      | 0.04      |
| SE $\bar{x}$         | 0.07     | 0.43      | 0.95      | 0.19     | 0.93      | 0.18      | 0.18     | 0.77      | 1.92      |
| SE $\bar{x}/\bar{X}$ | 0.01     | 0.02      | 0.03      | 0.02     | 0.04      | 0.05      | 0.03     | 0.04      | 0.09      |

Table 16. Summary statistics for biotic controls: Fall 1992 barley yield and plant uptake.

|      | Grain<br>Hand<br>Collection<br>(kg m <sup>-2</sup> ) | Yield<br>Plot<br>Combine<br>(kg m <sup>-2</sup> ) | Plant<br>Biomass<br>(g) | Plant<br>Nitrogen<br>(%) | Plant<br>Bromide<br>(%) |
|------|------------------------------------------------------|---------------------------------------------------|-------------------------|--------------------------|-------------------------|
| n    | 67                                                   | 66                                                | 67                      | 67                       | 67                      |
| Min  | 0.078228                                             | 0.035879                                          | 59.15                   | 0.44                     | 0.28                    |
| Max  | 0.580837                                             | 0.415944                                          | 175.52                  | 1.81                     | 2.02                    |
| Mean | 0.336014                                             | 0.278093                                          | 100.65                  | 0.90                     | 0.74                    |
| S.D. | 0.080379                                             | 0.067889                                          | 19.92                   | 0.27                     | 0.29                    |
| C.V. | 0.24                                                 | 0.24                                              | 0.20                    | 0.30                     | 0.39                    |

### Observed Spatial and Temporal Variability

Agus and Cassel (1992) state that a common field experience is that substantial variability exists in both the depth of solute movement and its concentration even when extreme care is taken to apply the chemical uniformly over the soil surface.

However, results from the current study indicate only modest spatial variability in both soil water content and solute measurements.

Soil Water. Table 15 lists descriptive statistics for average total water content (cm) measured to three depths during each growing season. The consistent small coefficient of variation values (CV) (0.04 - 0.12) and standard error ratios ( $SE_{\bar{x}}/\bar{X}$ ) (0.01 - 0.09) for each depth within each growing season indicate the lack of substantial spatial variability in water content across the 70 sites or with depth.

The lack of spatial variability in water content is surprising in that the study area exhibits topographic relief which should theoretically translate into redistribution of water across the landscape. However, in three field seasons spent collecting neutron probe data (including the wet, fallow 1993 season), no evidence of surface runoff was observed other than in the ephemeral stream channel. A possible explanation of this lack of spatial variability in water content is the possibility that the downward component of water movement overwhelms any tendency towards lateral subsurface flow in these deep, permeable agricultural soils (Wraith, 1994). The data in Table 15 appear to support this explanation. The season averages for 1993 were not substantially higher than those for 1992 or 1994 to any depth indicating that water is lost quickly or moves rapidly in this environment or that most values were near field capacity, especially below the zone of substantial root uptake.

Undoubtedly some temporal variability of water content was not incorporated by calculating season averages for use in multiple regression. Difference and correlation comparisons of the season averages to the water content measured in June

(wettest date near the beginning of each season) of each corresponding year were performed to evaluate differences and to determine whether the season averages retained similar patterns of variability.

Average differences between the season averages and June data to each of the three depths are shown in Table 17. In 1992, the differences between the season average water content values and those measured in June were all negative. Specifically, the season average total water content values to 25, 100, and 150 cm for each site were on average 3.19, 13.24, and 11.83 cm, respectively, drier than the measured total water content at the same site in June. The CV values were 0.11, 0.11, and 0.28 for the three depths. In 1993, small positive and negative differences occurred between the season averages and values for June. The season average total water content values to the three depths were on average 0.18 and 0.15 cm wetter to the 25 and 50 cm depths, respectively, and 0.09 cm drier to the 150 cm depth than the measured water content values in June. The CV values of the differences were 1.40, 1.78, and 10.28, respectively. In 1994, the differences were again all negative and the CV values were 0.87, 0.29, and 0.42 respectively for the three depths. The season average total water content values were on average 1.09, 2.70, and 2.91 cm drier than those measured at the corresponding site in June.

Table 18 shows that both the Pearson's and Spearman Rank correlation coefficients between the season average and June data were fairly high. The correlations were executed on a data set which included all sites (Stream Channel In = SCI) and on a smaller subset which excluded the sites lying within the ephemeral

stream channel (Stream Channel Out = SCO). The sites considered to be in the stream channel were 30, 31, 34, 42, 43, 47, 55, and 69. These sites receive additional water from outside the study area via a culvert located on the east side of the field (Figures 2 and 5). The r-values obtained for the SCO data set were slightly higher than for the SCI data set.

Table 17. Differences between soil water season averages and June data.

|      | 1992     |           |           | 1993     |           |           | 1994     |           |           |
|------|----------|-----------|-----------|----------|-----------|-----------|----------|-----------|-----------|
|      | 25<br>cm | 100<br>cm | 150<br>cm | 25<br>cm | 100<br>cm | 150<br>cm | 25<br>cm | 100<br>cm | 150<br>cm |
| n    | 64       | 65        | 56        | 64       | 60        | 50        | 56       | 50        | 41        |
| Mean | -3.19    | -13.24    | -11.83    | 0.18     | 0.15      | -0.09     | -1.09    | -2.70     | -2.91     |
| S.D. | 0.34     | 1.48      | 3.26      | 0.25     | 0.27      | 0.97      | 0.95     | 0.78      | 1.22      |
| C.V. | 0.11     | 0.11      | 0.28      | 1.40     | 1.78      | 10.26     | 0.87     | 0.29      | 0.42      |

The high r-values from Pearson's correlations indicate that the general pattern of relationships of water content between sample sites is relatively strongly reflected in the season averages. The high Spearman Rank correlation coefficients indicate a high degree of similarity between the ranking of the season averages and June data from wettest to driest. However, paired t-tests between the season average water data and the June data were highly significant ( $P = 0.0000$ ) for each combination for both SCI and SCO; with one exception. The P-value for the season average-June pair to 150 cm in 1993 was 0.4984 (SCI) and 0.9176 (SCO). These results indicate that the spatial patterns of variability of the season average water data were significantly different from the June data except to a depth of 150 cm in the wettest year, 1993.

The data presented in Table 17 show that the soil water season averages differed from the June data by the largest margins in 1992. However, the variation of these differences were relatively small (as indicated by the CV data), with the exception of the values for 150 cm in 1993 ( $CV > 10$ ). The data presented in Table 18 reveal that the soil water season averages are highly correlated to the measurements taken in June of each corresponding year. The lower r-values obtained for the 100 and 150 cm depths in 1992 concur with the larger differences shown in Table 17. Finally, the paired t-test results indicate that with the exception of the 150 cm depth increment in 1993, the season average and June values do not share similar patterns of variability. Therefore, although the season average water values share a general relationship with the June data, their distribution across the landscape differs.

Table 18. Correlations for total soil water between season averages and June data.

|               | Stream Channel In |           |          | Stream Channel Out |           |          |
|---------------|-------------------|-----------|----------|--------------------|-----------|----------|
|               | n                 | Pearson's | Spearman | n                  | Pearson's | Spearman |
|               |                   | r         | r        |                    | r         | r        |
| <u>25 cm</u>  |                   |           |          |                    |           |          |
| 1992          | 64                | 0.8520    | 0.8436   | 57                 | 0.9029    | 0.9050   |
| 1993          | 64                | 0.9132    | 0.8851   | 56                 | 0.9399    | 0.9243   |
| 1994          | 65                | 0.6722    | 0.7248   | 57                 | 0.7499    | 0.7548   |
| <u>100 cm</u> |                   |           |          |                    |           |          |
| 1992          | 65                | 0.6337    | 0.8154   | 58                 | 0.7387    | 0.8519   |
| 1993          | 60                | 0.9755    | 0.9648   | 54                 | 0.9750    | 0.9666   |
| 1994          | 58                | 0.8006    | 0.7590   | 53                 | 0.8000    | 0.7637   |
| <u>150 cm</u> |                   |           |          |                    |           |          |
| 1992          | 56                | 0.4903    | 0.7437   | 53                 | 0.4760    | 0.7912   |
| 1993          | 50                | 0.8759    | 0.9492   | 47                 | 0.9408    | 0.9564   |
| 1994          | 41                | 0.7455    | 0.7546   | 39                 | 0.7568    | 0.7623   |

Solutes. The spatial variability of resident solute mass concentrations of nitrate and bromide in the soil profiles at each sampling date are listed in Tables 5 and 8, respectively. These tables show small CV and  $SE_{\bar{x}}/\bar{X}$  values for N at any sampling date and small CV and  $SE_{\bar{x}}/\bar{X}$  values for bromide that increase with time after application.

The observed variability in N and bromide was in general less than that reported in other controlled field studies. Silvertooth et al. (1992) examined N and bromide movement in an irrigated cotton production system in southern Arizona. They indicate that their data "reinforce the presence of substantial variability associated with the measurements of both nitrate and bromide at any date or depth of sampling." CV values and  $SE_{\bar{x}}/\bar{X}$  ratios calculated from their reported mean nitrate concentrations ( $\text{mg kg}^{-1}$ ) vary from 0.12 to 1.39, and 12 to 40% through time, respectively. Table 5 shows that the CV values observed for mean N solute mass in the soil profiles in the current study display a narrower range, from 0.58 to 0.99. The  $SE_{\bar{x}}/\bar{X}$  ratios observed here were substantially less, 7 to 12%, than those by Silvertooth et al. (1992). The corresponding  $SE_{\bar{x}}/\bar{X}$  ratios for N unrecoverable (%) in the current study also display narrow ranges: 4 to 17% to 60 cm depth; and 10 to 20% to 90 cm depth (Table 6). However, irrigated conditions present in the Silvertooth et al. (1992) study are more conducive to non-uniform flow. Irrigation might well increase variability compared to rain-fed conditions due to preferential flow of solutes under saturated or near-saturated conditions during and/or after irrigation.

In addition, CV values calculated from the mean bromide concentration data ( $\text{mg kg}^{-1}$ ) reported by Silvertooth et al. (1992) varied from 0.25 to 2.24, while  $\text{SE}_{\bar{x}}/\bar{X}$  ratios varied from 16 to 49% through time. In another study, Agus and Cassel (1992) examined field-scale bromide transport under three tillage treatments in the Atlantic Coastal Plain of North Carolina. The CV values and  $\text{SE}_{\bar{x}}/\bar{X}$  ratios calculated from their reported mean bromide concentration ( $\text{mg kg}^{-1}$ ) data varied from 0.33 to 2.39 and 16 to 18%, respectively, under the three tillage treatments on one sampling date. Table 8 indicates that the CV values for mean bromide solute mass ( $\text{mg kg}^{-1}$ ) varied from 0.55 to 2.16 in this field. The corresponding  $\text{SE}_{\bar{x}}/\bar{X}$  ratios varied from 9% to a high of 26%. Both CV and  $\text{SE}_{\bar{x}}/\bar{X}$  ratio values increased as time elapsed from the KBr applications in S92 and F93. The highest values occurred in F93 just prior to the second surface application of KBr. This increase over time in spatial variability indicates that movement differences are expressed slowly. Thus, the observed  $\text{SE}_{\bar{x}}/\bar{X}$  ratios for mean bromide solute mass in this study are not only substantially lower than those reported by Silvertooth et al. (1992), but in three of the five time periods, the ratios are also much less than those observed by Agus and Cassel (1992). The CV values for bromide in this study display narrower ranges than those in either of these 1992 studies.

Silvertooth et al. (1992) also calculated mass balance estimates for bromide recovery (%) across five sampling dates. The  $\text{SE}_{\bar{x}}/\bar{X}$  ratios calculated from their reported data vary from 8 to 32%, with all but one value being greater than 10%. In contrast, the  $\text{SE}_{\bar{x}}/\bar{X}$  ratios calculated for bromide unrecoverable (%) in the current

study are substantially lower and varied from only 2 to 4% to 60 cm depth and 2 to 7% to 90 cm depth across the sampling periods. The CV values from their study ranged from 0.20 to 0.78 as compared to 0.17 - 0.31 to 60 cm and 0.14 - 0.47 to 90 cm in the current study.

In 1985, Bruce et al. examined the redistribution of bromide by rainfall infiltration. They concluded that observed differences in bromide transport between soil profiles in a drainageway and those occurring on slopes at various sites on a sandy loam landscape were due to differences in soil characteristics and rainfall infiltration. The Bt horizons of soil profiles located in the drainageway not only had higher hydraulic conductivities than slope sites, but they also had significantly smaller maximum clay contents which occurred approximately 0.5 m deeper than in slope sites. They state that "these and other differences in physical characteristics of the soil profiles in addition to effect of landscape position produced the observed differences in bromide movement among sites" (Bruce et al., 1985). Although the soil and terrain characteristics do vary across the landscape in this farm field (Tables 44 and 45, Appendix C), there appears to be very little hydrologic variability as expressed in measured water content (Table 15).

Bathke et al. (1992) reported that solute transport varied across landscape positions due to changes in soil profile characteristics. Bromide moved deeper in profiles with lower clay contents and higher hydraulic conductivities. They state that lateral bromide movement "was greatest at headslope sites where water drainage pathways have developed over a long period of time" due to a "decrease in

macroporosity and increase in clay content at the residual soil material boundary in the B horizon" (Bathke et al., 1992) Solute leaching was only indirectly analyzed by classes of landscape position in the current study via computed terrain attributes.

These comparisons provide strong evidence that the spatial variability in N and bromide solute concentrations observed in this field which experiences a drier climate is substantially less than observed in other controlled field studies. Additionally, the increase in spatial variability over time for bromide indicates that movement differences are expressed slowly in this field.

#### Multiple Regression Analysis

The Pearson's correlation matrices for pairwise comparison of the N and bromide leaching indices with the independent variables indicated that no single variable consistently explained a substantial portion of the variability in leaching as measured by any leaching index. Multiple regression analysis was employed to determine the combined influence of these variables. The stepwise regression results included continuous variables summarized in Tables 13-16 and one indicator variable delineating two different soil profile types. This indicator variable, *limedep1*, was set to a value of 1 if depth to  $\text{CaCO}_3 \leq 100$  cm and alternatively set to zero if depth to  $\text{CaCO}_3 > 100$  cm. Interaction variables were then defined as the product of each environmental variable and *limedep1*. This provided a way to distinguish whether the depth to  $\text{CaCO}_3$  had any effect on leaching of N and bromide. If a soil, terrain, or water attribute is present in a regression equation as a simple variable, this indicates that the attribute contributes to the model for soil profiles where the depth to  $\text{CaCO}_3$

is greater than 100 cm. If an interaction variable appears in a regression equation, it would indicate that the attribute is important and contributes to the model only for those profiles where the depth to  $\text{CaCO}_3 \leq 100$  cm.

Three approaches to prediction of leaching were attempted for each solute, nitrate-N and bromide, during each time period (where appropriate) as outlined in Table 19. The first approach examined whether the solute mass or critical depth level measured at the end of the current time period could be explained as a function of not only soil, terrain, soil water, and yield variables effective during that time period, but also by the past solute mass and critical depth levels from the previous sampling date. The second approach examined whether, alternatively, the increase or decrease in the solute mass or critical depth from one sampling date to the next could be explained as a function of the soil, terrain, soil water, and yield variables effective during that time period. This second approach was utilized because N dynamics in the soil are complicated, and perhaps examining the change in solute mass over time would be more instructive relative to the amount of leaching or N movement than trying to predict levels of N solute mass at a particular point in time. This approach was only used for time periods in which no new N or bromide was applied. Lastly, the third approach attempted to determine the predictive capabilities of effective soil, terrain, and soil water variables with respect to the amount of leaching (% unrecoverable) which occurred over the current time period as estimated by the mass balance calculations. Yield variables were not included in the stepwise regression model statements for this third approach, because plant uptake (related to yield) was

previously accounted for in the mass balance calculations. Tables 20 and 21 contain abbreviations for the soil water, soil, plant, terrain variables used in multiple regressions.

Table 19. Regression approaches to prediction of field-scale leaching.

| Dependent Leaching Index Variable | Independent Variables |         |            |                                   |                                     |
|-----------------------------------|-----------------------|---------|------------|-----------------------------------|-------------------------------------|
|                                   | Soil                  | Terrain | Soil Water | Plant Uptake & Yield <sup>1</sup> | SM and CD from previous time period |
| Solute Mass                       | ✓                     | ✓       | ✓          | ✓                                 | ✓                                   |
| Critical Depth                    | ✓                     | ✓       | ✓          | ✓                                 | ✓                                   |
| SM-Difference                     | ✓                     | ✓       | ✓          | ✓                                 |                                     |
| CD-Difference                     | ✓                     | ✓       | ✓          | ✓                                 |                                     |
| Balance - 60 cm                   | ✓                     | ✓       | ✓          |                                   |                                     |
| Balance - 90 cm                   | ✓                     | ✓       | ✓          |                                   |                                     |

<sup>1</sup> Included only when applicable (i.e., Fall 1992).

The critical depth at 80%, rather than at 25 or 50%, was chosen for inclusion in the multiple regression analysis because: 1) for bromide, the almost linear increase in critical depth was nearly the same for all three levels calculated (Figure 12); and 2) for N, the changes in critical depth over time nearly paralleled one another at each of the three levels (Figure 8).

Table 20. Abbreviations for soil water variables.

| Depth  | 1992    | 1993    | 1994    |
|--------|---------|---------|---------|
| 25 cm  | TW2592  | TW2593  | TW2594  |
| 100 cm | TW10092 | TW10093 | TW10094 |
| 150 cm | TW15092 | TW15093 | TW15094 |

The baseline soil potassium and phosphorous values listed in Table 43 (Appendix C) and summarized in Table 13 were not included as edaphic controls, or variables, in the multiple regressions. Values for these nutrient levels were not available for any time period after baseline values were obtained from initial soil samples. N-P-K fertilizer was applied to the field in both S92 and F93 after soil sampling as indicated in Table 3 and potassium and phosphorous levels were not subsequently re-tested after either addition. Aspect was also not utilized as a variable in the multiple regressions. Although aspect has a significant effect on evapotranspiration and soil water content, the sites in this field exhibit mostly southerly aspects.

Each approach was executed on a data set which included all sites (Stream Channel In = SCI;  $n = 67$ ) and on a smaller subset which excluded the sites lying within the ephemeral stream channel (Stream Channel Out = SCO;  $n = 59$ ). As discussed earlier, the ephemeral stream sites receive additional water from outside the study area via a culvert located on the east side of the field (Figure 2). Several of these stream sites have higher specific catchment areas (SCA) (Table 44, Appendix C), and thus wetness indices (WI), due to this outside influence which are not quantifiable, because a DEM was not created for any area outside of the study area boundaries. In other words, the SCA and WI values for these sites are biased (underestimated) even though they are already higher than the values computed for other sample locations. The sites considered to be in the stream channel were 30, 31, 34, 42, 43, 47, 55, and 69 (Figure 5).

Table 21. Abbreviations for soil, plant, and terrain attributes.

| Attribute                    | Abbreviation |
|------------------------------|--------------|
| <u>Soil</u>                  |              |
| pH                           | pH           |
| Electrical Conductivity      | EC           |
| Organic Matter               | OM           |
| Thickness of Mollic Epipedon | Mollic       |
| <u>Plant - Fall 1992</u>     |              |
| Nitrogen                     | Pl-Nit       |
| Bromide                      | Pl-Br        |
| Grain Yield - hand sampled   | GY-Hand      |
| Grain Yield - plot combine   | GY-Avg       |
| <u>Terrain</u>               |              |
| Elevation                    | Elev         |
| Slope                        | Slope        |
| Specific Catchment Area      | SCA          |
| Wetness Index                | WI           |
| Plan Curvature               | PlanC        |
| Profile Curvature            | ProC         |

Nitrogen. Table 22 contains the multiple regression results for N solute mass present in the soil profiles at the beginning of the field monitoring period in S92. The significant terms are listed in step order from Proc Reg in SAS which lists the terms in order of decreasing partial  $r^2$  values. These are the variables that were each statistically significant at greater than the 95% probability level and explained the greatest amount of variation in N solute mass. Interaction variables are marked with

an asterisk. The results were dependent upon inclusion (SCI) or exclusion (SCO) of the sites located in the ephemeral stream channel.

Table 22. Multiple regression results for nitrogen solute mass in Spring 1992.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 59) |                    |               |             |       |          |
| Intercept                   | 7276.7             |               |             |       |          |
| pH                          | 230.3              | 0.20          | 0.20        | 14.56 | 0.0003   |
| WI                          |                    | 0.25          | 0.46        | 26.36 | 0.0001   |
| pH 1*                       | -68.4              | 0.07          | 0.53        | 8.33  | 0.0055   |
| SCA 1*                      | 3.3                | 0.07          | 0.60        | 8.86  | 0.0043   |
| PlanC 1*                    | -27.3              | 0.03          | 0.63        | 4.82  | 0.0325   |
| Elev                        | -5.4               | 0.04          | 0.67        | 6.25  | 0.0156   |
| PlanC                       | 13.9               | 0.03          | 0.70        | 4.57  | 0.0373   |
| (WI)                        |                    | (0.01)        | 0.68        | 1.92  | 0.1717   |
| Slope                       | -8.8               | 0.02          | 0.71        | 4.10  | 0.0480   |
| Stream Channel In (n = 67)  |                    |               |             |       |          |
| Intercept                   | 9607.4             |               |             |       |          |
| Mollic                      | 6.2                | 0.26          | 0.26        | 22.44 | 0.0001   |
| Elev                        | -6.4               | 0.09          | 0.35        | 9.21  | 0.0035   |
| EC                          | 2211.5             | 0.07          | 0.42        | 7.66  | 0.0074   |
| SCA 1*                      | 3.5                | 0.05          | 0.47        | 6.32  | 0.0146   |
| Mollic 1*                   | -8.2               | 0.07          | 0.55        | 9.74  | 0.0028   |
| PlanC 1*                    | -16.8              | 0.03          | 0.58        | 4.59  | 0.0361   |

\* Interaction Variable: variable \* limedep1

The first column indicates that the model for SCO included seven terms and the third and fourth columns indicate that the variability in these terms combined to explain 71% of the variability in N solute mass. The wetness index (WI) was

removed from the model after the addition of plan curvature (PlanC). Pairwise correlation shows that these two variables are related by an r-value of 0.66. For SCI, the number of significant terms dropped to six and the variability in these terms combined to explain 58% of the variability in N solute mass.

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

$$Y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \epsilon_i \quad (7)$$

where  $Y_i$  is the leaching index,  $x_1$  might represent specific catchment area (SCA),  $x_2$ , might represent limedep1 (whose value may be 0 or 1 depending on the location of  $\text{CaCO}_3$  in the soil profile),  $\beta_0$  is the intercept,  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  represent the parameter estimates for these two terms and their interaction (ie.  $x_1 x_2$ ) and  $\epsilon_i$  represents error.

The resulting response function would read:

$$E(Y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 \quad (8)$$

The exact meaning of the significant regression terms is best interpreted by examining the nature of the response function for each lime unit or profile type separately. The regression results for SCO summarized in Table 22 can be written in equation form as:

$$E(Y) = 7276.7 + 230.3x_1 - 68.4x_1x_6 + 3.3x_2x_6 - 27.3x_3x_6 - 5.4x_4 + 13.9x_5 - 8.8x_5 \quad (9)$$

where  $Y$  is N solute mass in the soil profile,  $x_1$  is the pH,  $x_2$  is SCA,  $x_3$  is PlanC,  $x_4$  is elevation,  $x_5$  is slope, and  $x_6$  is limedep1.

Since limedep1 is equal to 1 for sites where  $\text{CaCO}_3 \leq 100$  cm from the soil surface, the  $x_6$  is equal to 1, and the response function reads:

$$E(Y) = 7276.7 + 162.2x_1 + 3.3x_2x_6 - 13.4x_3 - 5.4x_4 - 8.8x_5 \quad (10)$$

or:

$$E(Y) = 7276.7 + 162.2(\text{pH}) + 3.3(\text{SCA}) - 13.4(\text{PlanC}) - 5.4(\text{Elev}) - 8.8(\text{Slope}) \quad (11)$$

indicating that predicted N solute mass in the soil profile (to a depth of 180 cm) increases with increasing pH and SCA and decreasing PlanC, elevation, and slope.

The same general pattern is true for other types of sites where  $\text{CaCO}_3 > 100$  cm from the soil surface, although the absence of interaction terms changes the final response function. For these sites,  $x_6$  (limedep1) is equal to zero, so that the response function reduces to:

$$E(Y) = 7276.7 + 230.3x_1 + 13.9x_3 - 5.4x_4 - 8.8x_5 \quad (12)$$

or:

$$E(Y) = 7276.7 + 230.3(\text{pH}) + 13.9(\text{PlanC}) - 5.4(\text{Elev}) - 8.8(\text{Slope}) \quad (13)$$

where predicted N solute mass increases with increasing pH and PlanC and decreasing elevation and slope.

The regression models for SCO and SCI in Table 22 explained 58 to 71 % of the variation in N solute mass in the soil profile at the beginning of the field monitoring period in S92. Twenty-nine to 42 % of the variation remains unexplained.

No model was generated (SCO or SCI) for the critical depth of the N solute mass in S92. In F92, prediction of N solute mass, critical depth, or changes in these indices was not attempted. Nitrogen fertilizer was added to the field after the S92 sampling and, therefore, cannot be accounted for in a model. However, the mass balance indices incorporate the N fertilizer addition. Although no model was generated for the 90 cm depth, the results for N balance to 60 cm in F92 are shown in Table 23. The model for SCO ( $R^2 = 0.17$ ) indicates that % N unrecoverable increases with decreasing pH and SCA. Sites with low SCA typically occur on hilltops and near the tops of slopes. The model for SCI ( $R^2 = 0.32$ ) indicates that % N unrecoverable increases at sites with lower SCA and more organic matter (OM). An additional term appears in the model for soil profiles where  $\text{CaCO}_3 \leq 100$  cm; the % N unrecoverable also increases as average total soil water to 150 cm depth (TW15092) increases.

In S93, the N solute mass and mass balance indices produced the strongest relationships (Table 24). The SCO model ( $R^2 = 0.50$ ) indicates that N solute mass increases with increasing values of SCA, depth of the mollic horizon (Mollic), and prior amount of N solute mass present in the profile in Fall 92 (NF92SM). The model for SCI ( $R^2 = 0.36$ ) indicates that N solute mass increases with increasing values of Mollic, NF92SM, and TW15092.

Table 23. Multiple regression results for nitrogen balance to 60 cm in Fall 1992.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 57) |                    |               |             |      |          |
| Intercept                   | 97.4               |               |             |      |          |
| pH                          | -6.1               | 0.10          | 0.10        | 5.93 | 0.0182   |
| SCA                         | -0.01              | 0.07          | 0.17        | 4.44 | 0.0398   |
| Stream Channel In (n = 60)  |                    |               |             |      |          |
| Intercept                   | 31.8               |               |             |      |          |
| SCA                         | -0.003             | 0.13          | 0.13        | 9.07 | 0.0038   |
| OM                          | 6.5                | 0.12          | 0.25        | 9.65 | 0.0029   |
| TW15092 · 1*                | 0.2                | 0.07          | 0.32        | 6.13 | 0.0162   |

\* Interaction variable: variable \* limedep1

Table 24. Multiple regression results for nitrogen solute mass in Spring 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 57) |                    |               |             |       |          |
| Intercept                   | 56.0               |               |             |       |          |
| SCA                         | 0.2                | 0.32          | 0.32        | 25.54 | 0.0001   |
| Mollic                      | 2.0                | 0.12          | 0.44        | 11.19 | 0.0015   |
| NF92SM                      | 0.6                | 0.06          | 0.50        | 6.73  | 0.0122   |
| Stream Channel In (n = 65)  |                    |               |             |       |          |
| Intercept                   | -111.8             |               |             |       |          |
| Mollic                      | 2.4                | 0.23          | 0.23        | 18.54 | 0.0001   |
| NF92SM                      | 0.5                | 0.07          | 0.30        | 6.52  | 0.0131   |
| TW15092                     | 5.0                | 0.06          | 0.36        | 5.55  | 0.0217   |

NF92SM = N solute mass in soil profile in Fall 92.

The N mass balance results for S93 are listed in Table 25. In the top 60 cm, the SCO model ( $R^2 = 0.47$ ) indicates that % N unrecoverable increases as SCA decreases and PlanC increases. No model was generated to 60 cm for SCI because none of the independent variables were significant. The SCO model to 90 cm ( $R^2 = 0.55$ ) indicates that % N unrecoverable increases as SCA and pH decrease and PlanC increases. One additional term appears in the model for sites where  $\text{CaCO}_3 \leq 100$  cm; the % N unrecoverable increases as Mollic increases. The model generated for SCI to 90 cm ( $R^2 = 0.14$ ) is only applicable to sites where  $\text{CaCO}_3 \leq 100$  cm. At these sites, the model indicates that % N unrecoverable increases at sites with higher wetness index (WI) values.

In F93, the models yielding the largest  $R^2$  values were those for N solute mass and critical depth. Table 26 shows that the SCO model for N solute mass ( $R^2 = 0.24$ ) contains only one term, the prior amount of N solute mass present in the soil profile in S93 (NS93SM). More N solute mass was present at sites which had a higher amount of N solute mass in S93. The SCI model ( $R^2 = 0.41$ ) contains three different terms. The NS93SM term was the first term entered in the model, but subsequently removed from the final model. This model indicates larger amounts of N solute mass at sites which have thicker mollic horizons, more water present to 150 cm, and are located at lower elevations.

Table 25. Multiple regression results for nitrogen balance in Spring 1993.

| Variable                          | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out                |                    |               |             |       |          |
| 60 cm (n = 51)                    |                    |               |             |       |          |
| Intercept                         | 84.3               |               |             |       |          |
| SCA                               | -0.03              | 0.29          | 0.29        | 19.80 | 0.0001   |
| PlanC                             | 0.8                | 0.18          | 0.47        | 16.17 | 0.0002   |
| 90 cm (n = 34)                    |                    |               |             |       |          |
| Intercept                         | 131.6              |               |             |       |          |
| SCA                               | -0.03              | 0.24          | 0.24        | 10.24 | 0.0031   |
| pH                                | -9.7               | 0.16          | 0.40        | 8.44  | 0.0067   |
| PlanC                             | 0.8                | 0.08          | 0.48        | 4.73  | 0.0376   |
| Mollic 1*                         | 0.2                | 0.07          | 0.55        | 4.29  | 0.0472   |
| Stream Channel In                 |                    |               |             |       |          |
| 60 cm (n = 58) -- NOT SIGNIFICANT |                    |               |             |       |          |
| 90 cm (n = 38)                    |                    |               |             |       |          |
| Intercept                         | 61.6               |               |             |       |          |
| WI 1*                             | 2.2                | 0.14          | 0.14        | 6.02  | 0.0191   |

\* Interaction Variable: variable \* limedep1

The SCO model for N critical depth ( $R^2 = 0.16$ ) indicates that as slope decreased, the critical depth of the N solute mass increased or moved deeper (Table 27). The SCI model ( $R^2 = 0.34$ ) indicates that N critical depth increased at sites with more water present to 150 cm depth and lower pH values. An additional term appears in the model for sites where  $\text{CaCO}_3 \leq 100$  cm. At these sites, N critical depth increases as PlanC decreases.

Table 26. Multiple Regression results for nitrogen solute mass in Fall 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 56) |                    |               |             |       |          |
| Intercept                   | 247.0              |               |             |       |          |
| NS93SM                      | 0.8                | 0.24          | 0.24        | 17.23 | 0.0001   |
| Stream Channel In (n = 64)  |                    |               |             |       |          |
| Intercept                   | 7990.3             |               |             |       |          |
| NS93SM                      |                    | 0.25          | 0.25        | 20.64 | 0.0001   |
| Mollic                      | 4.6                | 0.09          | 0.34        | 8.51  | 0.0049   |
| TW15093                     | 10.9               | 0.04          | 0.38        | 4.14  | 0.0462   |
| (NS93SM)                    |                    | (0.04)        | 0.34        | 3.90  | 0.0529   |
| Elev                        | -5.4               | 0.06          | 0.41        | 6.62  | 0.0126   |

NS93SM = N Solute Mass in soil profile in Spring 1993.

Table 27. Multiple regression results for nitrogen critical depth in Fall 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 56) |                    |               |             |       |          |
| Intercept                   | 128.1              |               |             |       |          |
| Slope                       | -2.2               | 0.16          | 0.16        | 10.56 | 0.0020   |
| Stream Channel In (n = 64)  |                    |               |             |       |          |
| Intercept                   | 113.4              |               |             |       |          |
| TW15093                     | 1.7                | 0.21          | 0.21        | 16.46 | 0.0001   |
| PlanC 1*                    | -2.2               | 0.08          | 0.29        | 7.32  | 0.0088   |
| pH                          | -13.1              | 0.05          | 0.34        | 4.42  | 0.0398   |

\* Interaction Variable: variable \* limedep1

The three models generated for % N unrecoverable in F93 (Table 50, Appendix D), contained only one term for both SCO ( $R^2 = 0.11$ ) and SCI ( $R^2 = 0.08$ ). The models indicate that % N unrecoverable increases as SCA decreases.

In S94, prediction of N solute mass, critical depth, or changes in these indices was not attempted. Nitrogen fertilizer was again added to the field after the F93 sampling and cannot be accounted for in a model. The N mass balance model to 60 cm for SCO ( $R^2 = 0.27$ ) indicates that % N unrecoverable increases as OM content and electrical conductivity (EC) decrease (Table 28). For sites where  $\text{CaCO}_3 \leq 100$  cm, one more term is added to the model. At these sites, % N unrecoverable also increases as SCA decreases. The SCI model to 60 cm ( $R^2 = 0.18$ ) shows that % N unrecoverable increases with decreasing ProC. Another term is again added for sites where  $\text{CaCO}_3 \leq 100$  cm such that % N unrecoverable increases as EC decreases.

The models for SCO ( $R^2 = 0.23$ ) and SCI ( $R^2 = 0.25$ ) to 90 cm contain the same terms, but each term accounts for differing amounts of variability in each model (Table 28). Both models indicate the % N unrecoverable increases as ProC decreases. For sites where  $\text{CaCO}_3 \leq 100$  cm, % N unrecoverable is larger where SCA is smaller.

Crop yield or plant uptake factors were not available for F94 and therefore, N balance indices were not computed for this time period. However, prediction of N solute mass and critical depth was attempted without values for these factors. The models generated for N solute mass were identical for SCO and SCI ( $R^2 = 0.27$ ). The models indicate that N solute mass increased at sites that contained more N solute

mass in the prior S94 sampling and have thinner mollic epipedons. No model was generated for the change in solute mass from S94 for F94.

Table 28. Multiple regression results for nitrogen balance in Spring 1994.

| Variable           | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|--------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out |                    |               |             |      |          |
| 60 cm (n = 49)     |                    |               |             |      |          |
| Intercept          | 79.4               |               |             |      |          |
| SCA 1*             | -0.1               | 0.11          | 0.11        | 5.66 | 0.0214   |
| OM                 | -6.5               | 0.08          | 0.19        | 4.61 | 0.0371   |
| EC                 | -129.1             | 0.07          | 0.27        | 4.70 | 0.0347   |
| 90 cm (n = 47)     |                    |               |             |      |          |
| Intercept          | 42.9               |               |             |      |          |
| SCA 1*             | -0.1               | 0.13          | 0.13        | 6.98 | 0.0113   |
| ProC               | -10.6              | 0.09          | 0.23        | 5.24 | 0.0269   |
| Stream Channel In  |                    |               |             |      |          |
| 60 cm (n = 56)     |                    |               |             |      |          |
| Intercept          | 50.3               |               |             |      |          |
| ProC               | -16.1              | 0.09          | 0.09        | 5.51 | 0.0226   |
| EC 1*              | -133.1             | 0.09          | 0.18        | 5.61 | 0.0216   |
| 90 cm (n = 52)     |                    |               |             |      |          |
| Intercept          | 42.5               |               |             |      |          |
| ProC               | -14.8              | 0.15          | 0.15        | 8.81 | 0.0046   |
| SCA 1*             | -0.1               | 0.10          | 0.25        | 6.86 | 0.0117   |

\* Interaction Variable: variable \* limedep1

The models generated for F94 N critical depth (Table 29) and the change in N critical depth (Table 30) were the same for SCO and SCI with the exception of model  $R^2$  and partial  $r^2$  values. The SCI models yielded slightly higher model  $R^2$  values in

each case. Table 29 indicates that N critical depth increased at sites with thinner mollic epipedons and lower slopes. Table 30 indicates that the change in N critical depth was greater (N moved deeper in profile) at sites with thicker mollic epipedons, more OM, and lower pH values.

Table 29. Multiple regression results for nitrogen critical depth in Fall 1994.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 52) |                    |               |             |       |          |
| Intercept                   | 164.4              |               |             |       |          |
| Mollic                      | -0.7               | 0.16          | 0.16        | 9.52  | 0.0033   |
| Slope                       | -3.1               | 0.14          | 0.30        | 10.11 | 0.0026   |
| Stream Channel In (n = 57)  |                    |               |             |       |          |
| Intercept                   | 165.2              |               |             |       |          |
| Mollic                      | -0.9               | 0.28          | 0.28        | 21.02 | 0.0001   |
| Slope                       | -2.6               | 0.10          | 0.38        | 8.34  | 0.0056   |

Table 30. Multiple regression results for change in nitrogen critical depth in Fall 1994.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 52) |                    |               |             |       |          |
| Intercept                   | -194.4             |               |             |       |          |
| OM                          | 21.8               | 0.12          | 0.12        | 6.66  | 0.0128   |
| Mollic                      | 32.5               | 0.14          | 0.26        | 9.26  | 0.0038   |
| pH                          | -0.8               | 0.08          | 0.34        | 5.91  | 0.0188   |
| Stream Channel In (n = 57)  |                    |               |             |       |          |
| Intercept                   | -176.2             |               |             |       |          |
| Mollic                      | 20.1               | 0.14          | 0.14        | 8.90  | 0.0043   |
| OM                          | 29.8               | 0.15          | 0.29        | 11.78 | 0.0012   |
| pH                          | -1.0               | 0.07          | 0.36        | 5.84  | 0.0192   |

Bromide. Although bromide (KBr) was added to the field after the S92 sampling, prediction of the change in bromide solute mass and critical depth indices was attempted. The changes were calculated as the differences from zero since no bromide was present in the soil profiles prior to the S92. Therefore, these differences reflect the amount of bromide present in the profiles in F92. Table 31 shows that the models for change in bromide solute mass are very similar for SCO ( $R^2 = 0.29$ ) and SCI ( $R^2 = 0.31$ ). The models are only applicable for sites where  $\text{CaCO}_3 \leq 100$  cm. These results indicate that sites with smaller PlanC values and more water present in the profiles experienced greater changes in bromide solute mass. In other words, more bromide remained in the soil profile, therefore, less bromide leaching occurred at these sites.

Table 31. Multiple regression results for change in bromide solute mass from Spring 1992-Fall 1992.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 57) |                    |               |             |       |          |
| Intercept                   | 137.0              |               |             |       |          |
| PlanC 1*                    | -10.5              | 0.19          | 0.19        | 13.00 | 0.0007   |
| TW2592 1*                   | 13.5               | 0.10          | 0.29        | 8.03  | 0.0065   |
| Stream Channel In (n = 65)  |                    |               |             |       |          |
| Intercept                   | 134.0              |               |             |       |          |
| TW15092 1*                  | 2.5                | 0.21          | 0.21        | 16.31 | 0.0001   |
| PlanC 1*                    | -9.8               | 0.11          | 0.31        | 9.89  | 0.0026   |

\* Interaction variable: variable \* limedep1

The F92 bromide mass balance indices do incorporate the bromide application in S92 (Table 32). All four models generated for % bromide unrecoverable to 60 and 90 cm were very similar for both SCO ( $R^2 = 0.15 - 0.16$ ) and SCI ( $R^2 = 0.16 - 0.24$ ) and are applicable only for sites where  $\text{CaCO}_3 \leq 100$  cm. Each model indicates a positive relationship between % bromide unrecoverable and PlanC. One additional term is incorporated into the model for SCI to 90 cm. This model indicates an inverse relationship with EC.

Table 32. Multiple regression results for bromide balance in Fall 1992.

| Variable           | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|--------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out |                    |               |             |       |          |
| 60 cm (n = 53)     |                    |               |             |       |          |
| Intercept          | 54.1               |               |             |       |          |
| PlanC 1*           | 1.4                | 0.16          | 0.16        | 10.07 | 0.0026   |
| 90 cm (n = 40)     |                    |               |             |       |          |
| Intercept          | 40.1               |               |             |       |          |
| PlanC 1*           | 1.3                | 0.15          | 0.15        | 6.70  | 0.0214   |
| Stream Channel In  |                    |               |             |       |          |
| 60 cm (n = 60)     |                    |               |             |       |          |
| Intercept          | 54.8               |               |             |       |          |
| PlanC 1*           | 1.4                | 0.16          | 0.16        | 11.46 | 0.0013   |
| 90 cm (n = 45)     |                    |               |             |       |          |
| Intercept          | 46.1               |               |             |       |          |
| PlanC 1*           | 1.1                | 0.16          | 0.16        | 7.95  | 0.0072   |
| EC 1*              | -135.1             | 0.08          | 0.24        | 4.51  | 0.0397   |

\* Interaction Variable: variable \* limedep1

The S93 results for bromide solute mass, critical depth, and the changes in these indices were either poor or no models were generated at all (Tables 52 - 54, Appendix D). Table 33 list the models for bromide balance in S93. The models are virtually identical for SCO ( $R^2 = 0.36$ ) and SCI ( $R^2 = 0.31$ ). Both indicate that % bromide unrecoverable increases at higher elevations. Additionally, both models indicate that for sites where  $\text{CaCO}_3 \leq 100$  cm, % bromide unrecoverable also increases at sites with thinner mollic epipedons.

Table 33. Multiple regression results for bromide balance in Spring 1993.

| Variable                          | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out                |                    |               |             |      |          |
| 60 cm (n = 48)                    |                    |               |             |      |          |
| Intercept                         | 87.8               |               |             |      |          |
| SCA                               | -0.01              | 0.08          | 0.08        | 4.27 | 0.0444   |
| 90 cm (n = 28)                    |                    |               |             |      |          |
| Intercept                         | -1256.0            |               |             |      |          |
| Mollic 1*                         | -0.9               | 0.24          | 0.24        | 8.46 | 0.0073   |
| Elev                              | 0.9                | 0.12          | 0.36        | 4.72 | 0.0395   |
| Stream Channel In                 |                    |               |             |      |          |
| 60 cm (n = 55) -- NOT SIGNIFICANT |                    |               |             |      |          |
| 90 cm (n = 31)                    |                    |               |             |      |          |
| Intercept                         | -1162.8            |               |             |      |          |
| Mollic 1*                         | -0.8               | 0.20          | 0.20        | 7.28 | 0.0115   |
| Elev                              | 0.8                | 0.11          | 0.31        | 4.50 | 0.0429   |

\* Interaction Variable: variable \* limedep1

In F93, no models were generated for the change in critical depth or % bromide unrecoverable to either 60 or 90 cm. Models for bromide solute mass ( $R^2 = 0.13 - 0.15$ ) and the change in solute mass ( $R^2 = 0.14 - 0.21$ ) (Table 55, Appendix D) were very similar for both SCO and SCI. Each model indicates a positive relationship between the solute mass index and pH value. The models for bromide critical depth yielded fairly high  $R^2$  values and were very similar for SCO and SCI. The sample numbers are low because the regressions were run only for sites where bromide was still present within the top 180 cm. In both cases, pH was the first significant term added to the model, but was removed from the final model. For SCO ( $R^2 = 0.65$ ), bromide critical depth increases as both ProC (convex) and EC decrease (Table 34). For SCI ( $R^2 = 0.72$ ), one new term is added to the model such that bromide critical depth is inversely related to not only ProC and EC, but also to SCA.

As discussed earlier, a second treatment of bromide was surface applied in F93 just prior to soil sampling. In S94, regression results for change in bromide solute mass for SCO ( $R^2 = 0.17$ ) indicate greater differences (ie. more bromide still present in profile; less leaching occurred) at sites with higher SCA and lower PlanC values (Table 57, Appendix D). No model was generated for SCI data set. The same model ( $R^2 = 0.13$ ) was generated for change in critical depth for both SCO and SCI (Table 58, Appendix D). This model shows that greater downward changes in critical depth occur at sites with smaller ProC values.

Table 34. Multiple regression results for bromide critical depth in Fall 1993 (for sites where solute present at < 180 cm).

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 22) |                    |               |             |       |          |
| Intercept                   | 185.4              |               |             |       |          |
| pH                          |                    | 0.27          | 0.27        | 7.43  | 0.0130   |
| ProC                        | -37.6              | 0.29          | 0.56        | 12.45 | 0.0022   |
| EC                          | -595.4             | 0.09          | 0.65        | 4.87  | 0.0407   |
| (pH)                        |                    | (0.004)       | 0.65        | 0.18  | 0.6723   |
| Stream Channel In (n = 24)  |                    |               |             |       |          |
| Intercept                   | 192.1              |               |             |       |          |
| pH                          |                    | 0.27          | 0.27        | 8.11  | 0.0094   |
| ProC                        | -33.7              | 0.28          | 0.55        | 12.93 | 0.0017   |
| EC                          | -605.4             | 0.10          | 0.65        | 5.94  | 0.0289   |
| (pH)                        |                    | (0.006)       | 0.64        | 0.16  | 0.6933   |
| SCA                         | -0.2               | 0.07          | 0.72        | 5.19  | 0.0338   |

The S94 model for bromide mass balance to 60 cm for SCO ( $R^2 = 0.09$ ) indicates that % bromide unrecoverable increases at sites with higher slopes (Table 59, Appendix D). No model was generated for SCI. The model for % bromide unrecoverable to 90 cm was the same for SCO and SCI with an  $R^2$  of 0.08. It shows a positive relationship with EC.

Finally, in F94, no models were generated for bromide critical depth or change in bromide solute mass. Table 35 lists the results for bromide solute mass in F94. Once again, the models for SCO ( $R^2 = 0.21$ ) and SCI ( $R^2 = 0.25$ ) are almost identical. Both models are applicable only for sites where  $\text{CaCO}_3 \leq 100$  cm and indicate a positive relationship with OM content and an inverse relationship with

slope. The models for change in critical depth for F94 yielded the same  $R^2$  value (0.08) and indicated an inverse relationship with slope for SCO and an inverse relationship with the thickness of the mollic epipedon for SCI (Table 60, Appendix D).

Table 35. Multiple regression results for bromide solute mass Fall 1994.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 52) |                    |               |             |       |          |
| Intercept                   | 342.1              |               |             |       |          |
| OM 1*                       | 111.7              | 0.13          | 0.13        | 7.77  | 0.0075   |
| Slope 1*                    | -20.1              | 0.07          | 0.21        | 4.68  | 0.0354   |
| Stream Channel In (n = 57)  |                    |               |             |       |          |
| Intercept                   | 298.7              |               |             |       |          |
| OM 1*                       | 121.9              | 0.19          | 0.19        | 12.73 | 0.0008   |
| Slope 1*                    | -19.0              | 0.06          | 0.25        | 4.29  | 0.0431   |

\* Interaction variable: variable \* limedep1

Discussion. Results for regressions not discussed are listed in Tables 45-60 in Appendix D. Tables 22 - 35 discussed above (and those in Appendix D) illustrate that the attempt to predict nitrate or bromide leaching occasionally showed some promise, but consistency was a problem. Model  $R^2$  values obtained were typically low and no consistent patterns or groupings of significant independent variables were identified for either N or bromide. When model  $R^2$  values were high (i.e., F93 critical depth; Table 34), the relationship between the leaching index and significant terms do not appear to make explicit sense or be physically reasonable. Although the

change in solute mass and critical depth indices provide the most direct method of characterizing leaching, none of the three approaches to multiple regression analysis produced results that were more consistent or stronger than the other two. No consistent trends were observed in the presence of outliers on scatterplots. Based on Mallow's  $C_p$  values, some models are over-specified and some are under-specified with respect to the number of significant terms included in the model. Nitrogen appears to, on average, show stronger relationships to the soil, soil water, and terrain variables than bromide. One reason for this trend may be related to N cycling and mineralization.

Relationships between conventional soil morphology and edaphic properties directly relevant to land management under irrigated or dryland systems are often weak (McKenzie and MacLeod, 1989). This study, therefore, utilized a combination of conventional soil morphological characteristics (thickness of mollic horizon and depth to  $\text{CaCO}_3$ ) and soil properties measured analytically in the lab (i.e., pH, OM, EC, etc.). Soil textures were not utilized in this study as one of the independent soil variables. Clay percentages estimated from the initial soil cores removed from the field were listed as 26% (with only three exceptions).

Bruce et al. (1985) state that variability in topography and soil characteristics from place to place on the landscape affecting infiltration and soil water transport frequently does not permit ready description of solute distribution in fields. Differences in environmental attribute correlations and model development can occur due to physiographic setting, scale of analysis, computation methods, and other

reasons (data structure, quality and error) (Gessler, et al., 1993). In this field, small differences in leaching across a range of topographic sites were observed. In light of the paucity of spatial variability of water and solute observed, prediction of leaching differences is statistically difficult where variability across the landscape is negligible. This level of variability might be below the minimum detection level for prediction.

It is probable that the overall results might not be different if another model for solute leaching had been used. These results illustrate fundamental questions associated with appropriate sampling in space and time. Soil-landscape processes operate across a range of spatial and temporal scales (Kachanoski, 1988). This complexity causes soil properties to exhibit different and complex scales of variation (Burrough, 1993). Therefore, "expectations for deciphering the relationship between pattern and process should vary in different physiographic domains" (Gessler et al., 1993). The scale of the predicted variable must match scale of the process of interest, ie. field-scale leaching, with respect to both time and space. If the chosen scale is below the scale of the process, there may be too much "noise" in the data to identify pertinent relationships. If the chosen scale is above the scale of the process, it is possible to miss important information.

With respect to space, the coarse 10 m DEM grid used for generation of terrain attributes was originally chosen for applicability in site-specific farming. Ten meters may be the smallest operational unit manageable by a farmer or within which equipment may be regulated on-the-go in a field (Nielsen, 1994). However, digital terrain attributes are scale dependent and computed attributes may be meaningless or

the processes of interest may be masked if scale effects are not considered (Moore et al., 1991; 1993c).

Terrain attributes computed from digital terrain models can be measures of the hydrologic processes based on surface form at the hillslope scale: 1) water redistribution through lateral flow; and 2) sediment transport through runoff. Neither process may have occurred in this field to any significant degree during the duration of the study. Alternatively, geomorphic attributes are measures of broader scale regional processes. Aeolian deposition produces a progressive fining or thinning of loess at greater distances away from mountains. The Springhill study site is located near the base of the Bridger Mountains and possesses a thick loess cap. It is possible that the thick, permeable, loess-derived soils capture and retain precipitation from rainfall and melting snow without significant lateral redistribution in the landscape. No surface runoff, or evidence thereof, was observed in three field seasons, except at the ephemeral stream sites in Spring 1994.

Water and solute transport in soils are intimately related to soil property and water balance relationships (Bathke et al., 1992). Additionally, Afyuni et al. (1994) state that the vertical and lateral anisotropic nature of soils plus any downslope hydraulic gradient enhances lateral as well as vertical chemical transport. However, Jury et al. (1982) showed in a field test that the distribution of relative water uptake by wheat in the root zone had a greater effect on solute concentration distributions than the soil water content.

Only very small differences in solute movement were observed across a range of topographic positions and soil properties in this study. The results presented here seemingly indicate no connection between soil or terrain variables and leaching in the short term. It is possible that leaching in this environment is driven by pulses of water or events that were not monitored with this sampling scheme. Neutron probe data were by necessity never collected while it was raining, and usually around 48 hours later. The water data indicate that water is lost quickly in this environment or that most values measured were near field capacity, especially below the zone of substantial root uptake. Additionally, it is possible that lateral water flow rarely occurs in this field and that the time scale of observation of leaching in this study may not have been sufficient to expose any real differences in solute movement relating to water balance in the soil. The increase in the spatial variability of bromide over time seems to support this in that it indicates that movement differences are expressed slowly in this field.

Finally, the presence of gopher holes around many of the neutron access tubes may have contributed to measurement error with respect to soil moisture readings and solute concentrations (if soil core passed through underground tunnel).

### Conclusions

An attempt was made to identify and quantify, by multiple stepwise regression, the environmental factors that regulate water flow and leaching within a dryland farming system in southwest Montana. The factors considered included edaphic, topographic, soil water, and biotic characteristics. The observed variability in

measured water content across the soil landscape was small. The data indicate that nitrate and bromide leaching did occur. Due to the minimal lateral redistribution of water in this field, removal or loss of nitrate and bromide not accounted for by plant uptake are attributed to leaching. However, the observed variability in nitrate and bromide leaching was also small and less than reported in other field studies.

Nitrate and bromide exhibited statistically significant differences in spatial behavior patterns in all but a couple of time periods. The uniformity of the water and solute data across a range of topographic positions made prediction of leaching "differences" statistically difficult. Differences in leaching across the deep, permeable soil landscape were not satisfactorily explained with the combination of soil, water, and terrain attributes (10 m scale) in this farm field. Multiple regression analyses occasionally showed some promise, but were not consistent. Overall, the nitrate indices produced slightly stronger relationships to the environmental factors than bromide.

These results reiterate the difficulties that are encountered in trying to predict (understand) the interrelationships between environment, N leaching, and potential contamination of ground water. In order to prevent ground water contamination, it is important not only to identify and evaluate the characteristics of soils and the landscape critical to water and solute distribution, but also those which account for the variability of observed field-scale leaching.

## CHAPTER 3

### RELATIONSHIP BETWEEN MEASURED SOIL WATER CONTENT AND A TOPOGRAPHICALLY-DERIVED WETNESS INDEX

#### Introduction

Qualitative and quantitative models of soil-landscape relationships have been developed by numerous researchers (Aandahl, 1948; Troeh, 1964; Walker et al., 1968; Speight, 1974; Webster, 1977; Dikau, 1989; Odeh et al., 1991; Moore et al., 1988b, 1993a; 1993b). Several researchers have asserted that topographic features specifically influence surface runoff, subsurface water movement, the development of zones of surface saturation, and the distribution of soil water content (Zaslavsky and Rogowski, 1969; Anderson and Burt, 1978; Beven and Kirkby, 1979; Zaslavsky and Sinai, 1981a-d; Sinai et al., 1981; O'Loughlin, 1981, 1986; Hanna et al., 1982, 1983; Burt and Butcher, 1985; Moore and Burch, 1986).

Most topographic attributes are defined at points within a catchment on the landscape. However, maps of these landscape parameters or topographic attributes are easily derived from a digital elevation model (DEM) within a GIS framework (Moore et al., 1988a). In 1989, Dikau stated that the most important quantifiable landform attributes which can be computed from a DEM are slope, plan curvature, and profile curvature. However, Odeh et al. (1991) added upslope distance and area

attributes and reported that these five attributes accounted for the greatest majority of the soil variability in their study area (Spangrud, 1995). Moore et al. (1993a) have related soil variability to compound topographic attributes such as wetness, stream power, and sediment transport capacity indices. They have proposed to expand their model to more heterogeneous landscapes through the inclusion of geology, climate, and radiation variables (Spangrud, 1995).

Jones (1986; 1987) discusses the usefulness of the wetness index as an indicator of the spatial distribution of soil water content and soil water drainage. He states four assumptions or limitations involved in its use: 1) a spatially uniform infiltration capacity; 2) a spatially and temporally uniform transmissivity; 3) a constant subsurface leakage to ground water; and 4) coincident surface and subsurface drainage areas (Moore et al., 1988a). Burt and Butcher (1985) also state that "care must be exercised in applying a static index, like the wetness index, to predict the distribution of a dynamic process like soil water content that shows hysteric effects, especially when threshold changes occur in the area of saturation" (Moore et al., 1991).

Beven and Kirkby (1979) related the topographic structure of a catchment and the average soil water storage to the saturated area (Moore et al., 1988a).

O'Loughlin (1986) derived a slightly different form of wetness index that is capable of handling spatially variable transmissivities. However, both authors relate their wetness index to the spatial distribution and size of zones of saturation or variable source areas for runoff generation (Moore et al., 1991). Moore and Nieber (1989)

suggest that "a threshold concept could possibly be used to also relate the potential for ground water recharge and non-point source pollution to a wetness index because significant percolation of soil water to ground water occurs only when the soil water content exceeds field capacity."

Burt and Butcher (1985) found that the product of a wetness index and plan curvature produced the best correlations with surface soil water distributions.

Alternatively, Moore et al. (1988a) indicate that a linear relationship involving a wetness index and aspect yielded the best results. Moore et al. (1988b) also reported a strong correlation between the distribution of a wetness index and the distribution of surface soil water in a small fallow catchment.

Moore's steady-state wetness index is an analytically-derived, compound topographic attribute (Moore et al., 1991). It is calculated from two primary attributes, specific catchment area and slope, and is described as:

$$w = \ln(A_s / \tan \beta) \quad (14)$$

where  $w$  indicates the wetness index,  $A_s$  is the specific catchment area ( $\text{m}^2 \text{m}^{-1}$ ), and  $\beta$  is the slope angle (degrees). Two important assumptions are incorporated into this wetness index: 1) that the direction of subsurface flow (dictated by the gradient of the piezometric head) is parallel to the gradient of the surface topography; and 2) that steady-state conditions apply. The wetness index values are indices relative only to the total area analyzed with the DEM. The value of this index increases with increasing specific catchment area and decreasing slope gradient. Larger indices

indicate those cells in the study area having low slope and large drainage areas relative to other cells in the study area. Therefore, hilltops (flat areas with low specific catchment area) exhibit moderate values, valleys (high specific catchment area and low slope) where water concentrates exhibit high values, and steep hillslopes (high slope) where water drains more freely exhibit low values (Moore et al., 1993a; 1993b).

Moore et al. (1993a) hypothesized that "the spatial distribution of topographic attributes that characterize water flow paths also captures the spatial variability of soil attributes at the meso-scale" ( $10^4$  to  $2 \times 10^5$  m). They state that the wetness index has been used to characterize the spatial distribution of zones of surface saturation and soil water content in landscapes (Moore et al., 1988a; 1993d) and appears to be useful for mapping forest soils (Skidmore et al., 1991). Moore et al. (1993b) show that the wetness index is correlated with several soil properties such as silt percentage ( $r = 0.61$ ), organic matter content ( $r = 0.57$ ), phosphorous ( $r = 0.53$ ), and A horizon depth ( $r = 0.55$ ) in the soil surface of a small toposequence in Colorado. They reported that: 1) thick A horizons on steep slopes are associated with high values of wetness index and plan curvature (ie. concave areas where water concentrates) and; 2) the wetness index appears to characterize similar patterns of overland and subsurface flow convergence.

Gessler et al. (1993) found that the wetness index calculated from TAPES-G was a useful predictor for some diagnostic morphologic properties because it "combines contextual and site information via the upslope catchment area and slope

respectively." Bell et al. (1994) calculated a similar wetness index, defined as:

$$WI = \log (A/S) \quad (15)$$

where A is the specific catchment area ( $m^2 m^{-1}$ ) and S is the slope gradient (%).

They reported that this wetness index correlated with A-horizon depth ( $r = 0.57$ ) and depth to carbonates ( $r = 0.59$ ) in a 20-ha study site located in west-central Minnesota currently in a mixture of grasses under CRP (Bell et al., 1994).

### Objectives

The objective of this study was to test whether Moore's compound, quantitative, topographically-derived wetness index calculated from a DEM at two different grid scales (2 m and 10 m) is correlated to field-measured soil water content.

### Materials and Methods

#### Study Site

The analysis was conducted on data from the study site described in Chapter 2 (p. 22): a 20-ha cultivated field of moderate relief (43 m) in southwestern Montana.

#### Depth of Mollic Horizon

The depth of the mollic horizon (cm) at each site was measured and recorded from soil cores removed in Spring 1992 for installation of neutron access tubes (Chapter 2).

### Generation of Wetness Indices

The wetness indices at the 10 m scale were generated as described earlier in Chapter 2 (p. 33) utilizing ANUDEM (Hutchinson, 1989) and the grid version of the Terrain Analysis Programs for the Environmental Sciences (TAPES-G) (Moore, 1992). Slope was calculated using the finite difference approach and specific catchment areas were calculated using the FRho8 algorithm. These procedures were repeated using a 2 m regular rectangular grid to produce the second set of wetness indices. The 10 m scale was originally chosen for its possible applicability to site-specific farming (Nielsen, 1994). For this analysis, a scale of 2 m was chosen for comparison as it more closely represents the physical sphere of influence of the neutron probe in the field when taking measurements.

### Soil Water Content

Collection of field-measured soil water content and calculations of average total water in the profiles at the 70 sites is described in Chapter 2 (p. 36). For purposes of this analysis, average total water content values to 25, 100, and 150 cm in the soil profiles were also calculated for a sampling date in June of each year. The June dates were June 22, June 25, and June 24 for 1992-1994, respectively. These June dates were selected for comparison since they represent the "wettest" time of year sampled, and therefore come closest to satisfying the assumption of steady-state conditions in wetness index calculations in TAPES-G (Moore, 1992).

### Statistical Analysis

As stated earlier in Chapter 2, three sample points (#52, #64, #65) were removed from analysis due to clipping the DEM coverage to a rectangular area. The wetness index, depth of mollic horizon, and soil water variables were imported into a spreadsheet for calculation of some summary statistics (CV,  $SE_x$ , and  $SE_x/X$ ). The data were then exported to two ASCII files: one containing a full data set ( $n = 67$ ) referred to as Stream Channel In (SCI), the other excluding the sites in the stream channel ( $n = 59$ ) referred to as Stream Channel Out (SCO). These files were subsequently used as input files for statistical analysis. Additional summary statistics were obtained from the SUMSTAT procedure in MSUSTAT (Lund, 1991).

Paired t-tests were performed between the season average water values and the June water data using MSUSTAT. Correlation analyses were performed (MSUSTAT) utilizing the NPCORR procedure to estimate Pearson's correlation coefficients and P-values for pairwise comparison of the wetness indices (2 m and 10 m grids) with the soil water variables (season averages and June data) to 25, 100, and 150 cm depths. Correlation analyses were also performed between the wetness indices and thickness of the mollic epipedon. All correlations were calculated for both SCI and SCO. The ephemeral stream sites removed for the SCO data set were 30, 31, 34, 42, 43, 47, 55, and 69. As discussed in Chapter 2, although these sites have wetness index values higher than for other sites, they are biased (underestimated) due to the influence of water imported from outside the study area and DEM boundaries.

## Results and Discussion

### Wetness Indices

Table 36 lists the summary statistics for the wetness indices. The minimum, maximum, mean, standard deviation (SD), and coefficient of variation (CV) values for the wetness indices are very similar at each scale for SCI. Although the minimum values remain the same for SCO, the maximum values are lower at both scales. There is also a greater difference in the standard deviation values between the two scales for SCO. Table 61 in Appendix E contains a complete listing of the wetness index values for each site at the 2 m and 10 m scales. These values are graphed in a scatterplot Figure 13 for visual comparison.

Table 36. Summary statistics for wetness indices.

|      | Stream Channel In<br>(n = 67) |        | Stream Channel Out<br>(n = 59) |        |
|------|-------------------------------|--------|--------------------------------|--------|
|      | 2 m                           | 10 m   | 2 m                            | 10 m   |
| Min  | 3.833                         | 4.533  | 3.833                          | 4.533  |
| Max  | 13.223                        | 13.271 | 11.702                         | 10.470 |
| Mean | 6.648                         | 6.940  | 6.371                          | 6.552  |
| S.D. | 1.769                         | 1.771  | 1.486                          | 1.132  |
| C.V. | 0.263                         | 0.255  | 0.233                          | 0.173  |

S.D. = standard deviation.

C.V. = coefficient of variation.

Figure 13. Scatterplot of wetness index values at 2 m and 10 m scales.

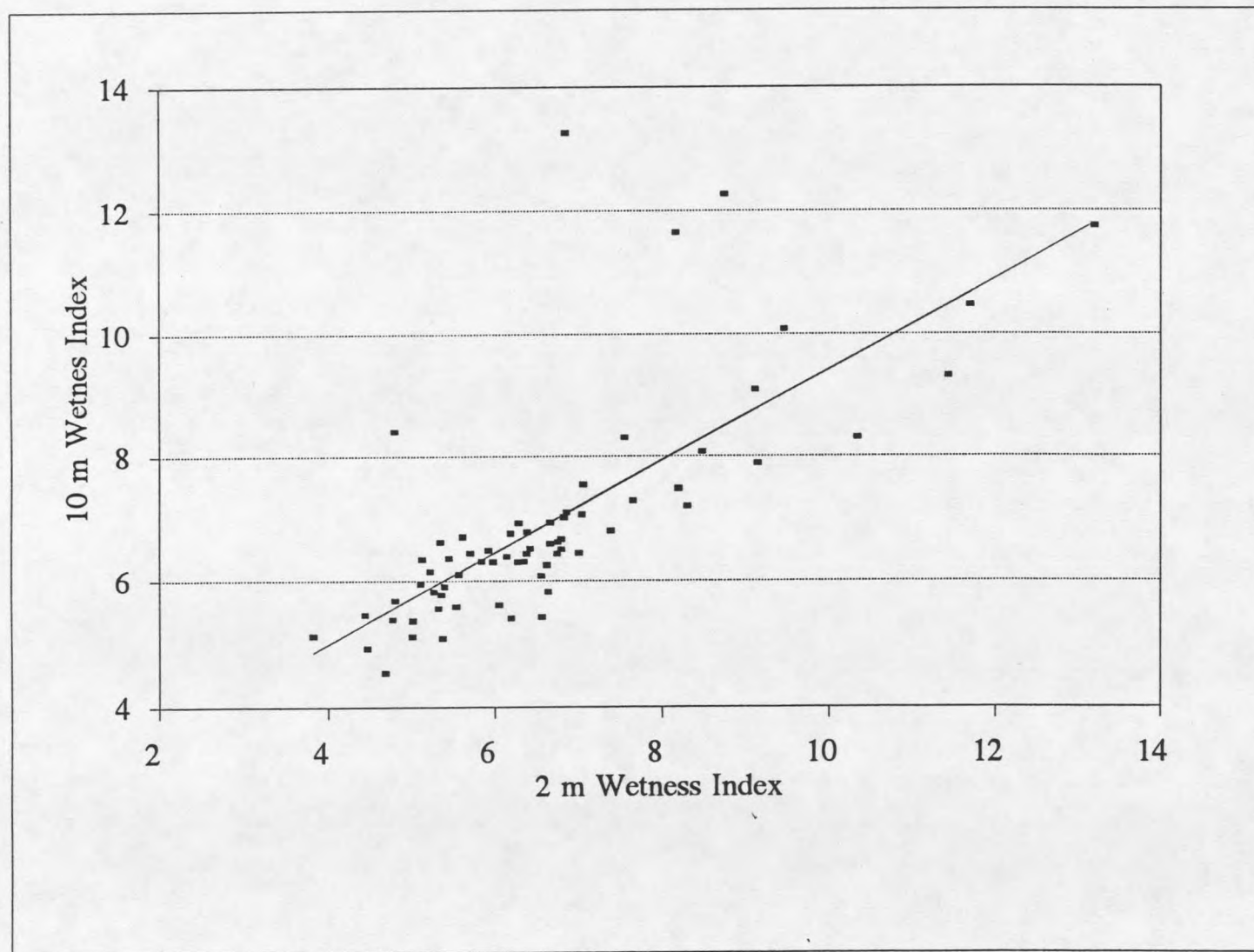


Table 37 lists the results of both Pearson's correlation and Spearman rank correlation analysis of the wetness indices. Both Figure 13 and Table 37 indicate that the 2 m and 10 m wetness index values are only fairly well correlated to one another. Pearson's correlation analysis yielded an r-value of 0.74 for the SCI data set ( $R^2 = 0.54$ ; Figure 13). A slightly larger  $R^2$  of 0.71 was obtained for the SCO data set, which removed three of the four outliers in Figure 13. Spearman's rank correlation analysis revealed an opposite trend. The value of r decreased from 0.81 for SCI to 0.79 for SCO. All r-values were significant at the 5% level.

Table 37. Correlation analyses of wetness indices at 2 m and 10 m scales.

| Correlation Procedure | Stream Channel In<br>(n = 67) |         | Stream Channel Out<br>(n = 59) |         |
|-----------------------|-------------------------------|---------|--------------------------------|---------|
|                       | r                             | P-value | r                              | P-value |
| Pearson's             | 0.7377                        | 0.0000  | 0.8441                         | 0.0000  |
| Spearman Rank         | 0.8102                        | 0.0000  | 0.7923                         | 0.0000  |

Paired t-tests between the wetness indices were significant at the 10% level ( $P = 0.067$  for SCI;  $P = 0.091$  for SCO) indicating that the 2 m and 10 m values do not share similar patterns of spatial variability.

#### Soil Water Content

Table 38 lists the summary statistics for the average total water in the soil profiles in the upper 25, 100, and 150 cm depths during the growing seasons from 1992 to 1994. As discussed in Chapter 2, the data reveal minimal differences in soil water measured to the three depths across the landscape as evidenced by the small coefficient of variation (CV) values (0.04 - 0.12) and  $SE_{\bar{x}}/\bar{X}$  ratios (0.01 - 0.09).

Table 38. Summary statistics for season average total water (SCI).

|                                   | 1992     |           |           | 1993     |           |           | 1994     |           |           |
|-----------------------------------|----------|-----------|-----------|----------|-----------|-----------|----------|-----------|-----------|
|                                   | 25<br>cm | 100<br>cm | 150<br>cm | 25<br>cm | 100<br>cm | 150<br>cm | 25<br>cm | 100<br>cm | 150<br>cm |
| n                                 | 67       | 65        | 64        | 65       | 61        | 57        | 65       | 61        | 43        |
| Min                               | 5.64     | 14.41     | 25.90     | 6.79     | 22.56     | 23.35     | 5.52     | 19.14     | 29.07     |
| Max                               | 7.88     | 25.50     | 55.98     | 9.39     | 29.19     | 40.00     | 8.14     | 25.15     | 34.58     |
| Mean                              | 6.77     | 18.24     | 32.78     | 8.36     | 26.02     | 36.89     | 6.55     | 21.49     | 32.42     |
| S.D.                              | 0.59     | 1.71      | 3.88      | 0.61     | 1.23      | 2.81      | 0.54     | 1.17      | 1.31      |
| C.V.                              | 0.09     | 0.09      | 0.12      | 0.07     | 0.05      | 0.08      | 0.08     | 0.05      | 0.04      |
| SE $\bar{x}$ <sup>1</sup>         | 0.07     | 0.43      | 0.95      | 0.19     | 0.93      | 1.65      | 0.18     | 0.77      | 1.92      |
| SE $\bar{x}/\bar{X}$ <sup>2</sup> | 0.01     | 0.02      | 0.03      | 0.02     | 0.04      | 0.05      | 0.03     | 0.04      | 0.09      |

<sup>1</sup> Standard error of the mean.

<sup>2</sup> Standard error of the mean as proportion of the mean.

This lack of spatial variability is also evidenced in the summary statistics for total soil water present to the three depths on a sampling date in June of each year (Table 39). The CV values are again small and exhibit a narrower range from 0.05 to 0.09.

As discussed in Chapter 2 (pp. 67-69), both the Pearson's and Spearman Rank correlation coefficients between the season average and June data were fairly high regardless of inclusion or exclusion of ephemeral stream sites. Paired t-tests between the season average water data and the June data yielded P values of 0.0000 for each combination for both SCI and SCO; with one exception. The spatial pattern of season average water data was most similar to the pattern of June data to 150 cm in 1993 ( $P = 0.50$  for SCI and  $P = 0.92$  for SCO).

Table 39. Summary statistics for total water in June (SCI).

|      | 1992 - June 22 |           |           | 1993 - June 25 |           |           | 1994 - June 24 |           |           |
|------|----------------|-----------|-----------|----------------|-----------|-----------|----------------|-----------|-----------|
|      | 25<br>cm       | 100<br>cm | 150<br>cm | 25<br>cm       | 100<br>cm | 150<br>cm | 25<br>cm       | 100<br>cm | 150<br>cm |
| n    | 64             | 65        | 56        | 64             | 61        | 50        | 65             | 58        | 42        |
| Min  | 8.79           | 22.31     | 35.62     | 6.67           | 21.18     | 30.36     | 5.79           | 20.49     | 28.89     |
| Max  | 11.30          | 35.30     | 50.21     | 9.44           | 29.03     | 40.39     | 10.06          | 27.75     | 37.88     |
| Mean | 9.99           | 31.48     | 44.98     | 8.18           | 25.77     | 37.45     | 7.54           | 24.27     | 35.24     |
| S.D. | 0.66           | 1.76      | 2.32      | 0.62           | 1.31      | 1.96      | 0.71           | 1.29      | 1.84      |
| C.V. | 0.07           | 0.06      | 0.05      | 0.08           | 0.05      | 0.05      | 0.09           | 0.05      | 0.05      |

### Correlation Analysis

Pearson's correlation matrices for the soil water variables and the 2 m and 10 m wetness indices are shown in Tables 40 (SCI) and 41 (SCO). From these matrices it can be seen that some correlation coefficients were positive, some were negative. Overall, the r-values were very low indicating that the topographically-generated wetness indices do not relate well to field-measured water content (season average or June date).

The correlations for the season average total soil water variables reveal no pattern with respect to positive or negative values for certain depths for either the 2 m or 10 m wetness index. The range of r-values for SCI were very similar for the 2 m ( $|r| = 0.01 - 0.16$ ) and 10 m ( $|r| = 0.03 - 0.17$ ) scales (Table 40). Removing the sites in the ephemeral stream channel (SCO) did not substantially improve the correlations. At 2 m,  $|r| = 0.02 - 0.19$ ; and for the 10 m index,  $|r| = 0.02 - 0.21$  (Table 41).

Table 40. Pearson's correlation analyses between wetness indices and soil water variables (SCI).

| Total Soil<br>Water Attribute | n  | 2 m           |         | 10 m          |         |
|-------------------------------|----|---------------|---------|---------------|---------|
|                               |    | Wetness Index |         | Wetness Index |         |
|                               |    | r             | P-value | r             | P-value |
| <u>1992 Season Average</u>    |    |               |         |               |         |
| 25 cm                         | 67 | -0.0604       | 0.6275  | -0.0292       | 0.8145  |
| 100 cm                        | 65 | 0.0899        | 0.4761  | 0.1734        | 0.1673  |
| 150 cm                        | 64 | -0.1041       | 0.4130  | -0.1416       | 0.2642  |
| <u>1993 Season Average</u>    |    |               |         |               |         |
| 25 cm                         | 65 | -0.0681       | 0.5897  | -0.1042       | 0.4087  |
| 100 cm                        | 61 | -0.0254       | 0.8459  | -0.0789       | 0.5454  |
| 150 cm                        | 57 | 0.0653        | 0.9615  | 0.1166        | 0.3878  |
| <u>1994 Season Average</u>    |    |               |         |               |         |
| 25 cm                         | 65 | -0.0155       | 0.9023  | -0.0755       | 0.5502  |
| 100 cm                        | 61 | -0.0109       | 0.9334  | 0.0311        | 0.8119  |
| 150 cm                        | 43 | 0.1595        | 0.3070  | -0.0351       | 0.8232  |
| <u>1992 - June 22</u>         |    |               |         |               |         |
| 25 cm                         | 64 | -0.0280       | 0.8259  | -0.1002       | 0.4307  |
| 100 cm                        | 65 | 0.0941        | 0.4560  | 0.0369        | 0.7705  |
| 150 cm                        | 56 | -0.0815       | 0.5505  | -0.1436       | 0.2910  |
| <u>1993 - June 25</u>         |    |               |         |               |         |
| 25 cm                         | 64 | -0.0780       | 0.5403  | -0.0910       | 0.4745  |
| 100 cm                        | 61 | -0.2350       | 0.0683  | -0.2605       | 0.0426  |
| 150 cm                        | 50 | -0.0980       | 0.4986  | -0.1400       | 0.3320  |
| <u>1994 - June 24</u>         |    |               |         |               |         |
| 25 cm                         | 65 | 0.2993        | 0.0154  | 0.1499        | 0.0154  |
| 100 cm                        | 58 | 0.1844        | 0.1659  | 0.0815        | 0.5432  |
| 150 cm                        | 42 | 0.2394        | 0.1268  | 0.0758        | 0.6333  |

Table 41. Pearson's correlation analyses between wetness indices and soil water variables (SCO).

| Total Soil<br>Water Attribute | n  | 2 m           |         | 10 m          |         |
|-------------------------------|----|---------------|---------|---------------|---------|
|                               |    | Wetness Index |         | Wetness Index |         |
|                               |    | r             | P-value | r             | P-value |
| <u>1992 Season Average</u>    |    |               |         |               |         |
| 25 cm                         | 59 | -0.0434       | 0.7439  | -0.0957       | 0.4711  |
| 100 cm                        | 58 | 0.0798        | 0.5514  | 0.0250        | 0.8521  |
| 150 cm                        | 58 | -0.0160       | 0.9049  | -0.0441       | 0.7421  |
| <u>1993 Season Average</u>    |    |               |         |               |         |
| 25 cm                         | 57 | 0.0766        | 0.5714  | 0.0557        | 0.6808  |
| 100 cm                        | 55 | 0.1507        | 0.2720  | 0.1216        | 0.3766  |
| 150 cm                        | 53 | 0.1321        | 0.3457  | 0.1943        | 0.1633  |
| <u>1994 Season Average</u>    |    |               |         |               |         |
| 25 cm                         | 57 | 0.0517        | 0.7026  | 0.0357        | 0.7918  |
| 100 cm                        | 54 | 0.1833        | 0.1846  | 0.2084        | 0.1305  |
| 150 cm                        | 41 | 0.1905        | 0.2329  | 0.0219        | 0.8916  |
| <u>1992 - June 22</u>         |    |               |         |               |         |
| 25 cm                         | 57 | 0.0792        | 0.5584  | 0.0426        | 0.9749  |
| 100 cm                        | 58 | 0.1412        | 0.2904  | 0.1222        | 0.3610  |
| 150 cm                        | 53 | 0.0810        | 0.5644  | -0.0191       | 0.8919  |
| <u>1993 - June 25</u>         |    |               |         |               |         |
| 25 cm                         | 56 | 0.0427        | 0.7544  | -0.0487       | 0.9716  |
| 100 cm                        | 54 | 0.1604        | 0.2465  | 0.1042        | 0.4535  |
| 150 cm                        | 47 | 0.1164        | 0.4360  | -0.0831       | 0.9558  |
| <u>1994 - June 24</u>         |    |               |         |               |         |
| 25 cm                         | 57 | 0.1988        | 0.1382  | 0.1538        | 0.2533  |
| 100 cm                        | 53 | 0.2975        | 0.0305  | 0.2097        | 0.1318  |
| 150 cm                        | 40 | 0.2399        | 0.1359  | 0.0785        | 0.6300  |

The second approach involving total soil water present on June sampling dates did yield a few correlations slightly higher than for the season average soil water variables. The range of  $r$ -values for the SCI data set were  $|r| = 0.03 - 0.30$  for the 2 m wetness index and  $|r| = 0.04 - 0.26$  for the 10 m index (Table 40). Removing the sites in the ephemeral stream channel (SCO) yielded the following correlations: At 2 m,  $|r| = 0.04 - 0.30$ ; and for the 10 m index,  $|r| = 0.02 - 0.21$  (Table 41).

Table 42 shows that the wetness indices moderately correlate with the thickness of the mollic horizon for both SCI ( $|r| = 0.42 - 0.62$ ) and SCO ( $|r| = 0.36 - 0.41$ ). All  $r$ -values were significant at the 5% level. Thicker mollic horizons tend to develop in the landscape at locations where either: 1) large scale events have historically placed more water; or 2) more water is present more often due to microtopographic effects. However, correlation analyses between soil water variables and the thickness of the mollic horizon yielded low  $r$ -values of  $|r| = 0.03 - 0.23$  for SCI and  $|r| = 0.01 - 0.29$  for SCO (not shown). Additionally, most soil water variables exhibited an inverse relationship to the thickness of the mollic horizon.

### Conclusions

Data from this cultivated farm field in southwestern Montana indicate that the wetness indices at the two scales, 2 m and 10 m, are highly correlated to one another and fairly well correlated to the thickness of mollic horizon. Neither of the wetness indices or the thickness of mollic horizon correlated well with season average or June

soil water variables. Season averages for total water are highly correlated to June total water data. The inclusion or exclusion of sites located in the ephemeral stream channel did not have a substantial effect on the results of any data analysis procedure.

Table 42. Correlation (Pearson's and Spearman Rank) analyses between wetness indices and thickness of mollic horizon.

| Correlation Procedure | Stream Channel In<br>(n = 67) |         | Stream Channel Out<br>(n = 59) |         |
|-----------------------|-------------------------------|---------|--------------------------------|---------|
|                       | r                             | P-value | r                              | P-value |
| <u>Pearson's</u>      |                               |         |                                |         |
| 2 m                   | 0.4210                        | 0.0000  | 0.3590                         | 0.0052  |
| 10 m                  | 0.6239                        | 0.0000  | 0.3746                         | 0.0035  |
| <u>Spearman Rank</u>  |                               |         |                                |         |
| 2 m                   | 0.4857                        | 0.0000  | 0.4109                         | 0.0012  |
| 10 m                  | 0.4784                        | 0.0000  | 0.4023                         | 0.0016  |

Based on a knowledge of soil genesis it might be expected that the depth of the mollic horizon would be correlated to the distribution of water across the landscape over a long period of time. This may be reflected in the calculation of the wetness index in that the depth of the mollic horizon in this field is moderately correlated with both the 2 m and 10 m wetness indices. Wilson et al. (1994) showed that a combination of image and terrain attributes including the wetness index could predict the thickness of the mollic horizon for this study area. However, these data indicate that over three field seasons, including one wet, fallow year (1993), the depth of the mollic horizon and wetness indices are poorly correlated with measured soil water content. Moore's "wetness index" does not appear to be a good indicator of the

distribution of soil water and the potential location of zones of saturation in this catchment. The two basic assumptions incorporated into the calculation of the wetness index are not met in the soil-landscape environment of the study field. The assumption that a piezometric head dictates the direction of subsurface flow parallel to the gradient of subsurface topography indicates either the presence of a water table or an impeding layer in the soil profile and lateral redistribution of water. Secondly, the assumption of steady-state conditions is clearly not met in this field possessing deep, permeable agricultural soils.

The data presented in Table 38 show that the total soil water in 1993 is not much higher than in the other two years. This perhaps indicates that water is redistributed to field capacity very quickly in this landscape with deep loess soils. The distribution of mollic thickness may be more related to near surface processes of water distribution as a function of time rather than those in the entire soil profile.

## CHAPTER 4

### SUMMARY

The research presented in this thesis is part of larger effort to examine the possibility of integrating site-specific information about leaching into an on-farm, field-scale information system. Integrating soil survey, terrain, and microclimate attributes and image analysis along with information regarding leaching potential into a GIS format may provide new opportunities for applying leaching potential models to variable soil landscapes. Subsequent identification of areas susceptible to leaching, or management zones which consider leaching susceptibility as an important factor, would provide a basis for more selective N fertilizer application. Site-specific applications of N fertilizer may improve profitability, and at the same time, reduce the possibility of ground water contamination.

A 20-ha portion of a farm field in southwestern Montana possessing considerable topographic relief and substantial variation in both soil and terrain attributes was selected for this study in an effort to characterize differences in leaching across the landscape. It was assumed that these soil and topographic variations would lead to differential infiltration and redistribution of water which, in turn, would translate into differential leaching of nitrate and bromide. However, the Springhill site has deep, loess-derived, permeable soils which apparently capture and

retain precipitation from rainfall and melting snow without significant lateral redistribution in the landscape. It appears that the downward component of water movement overwhelms any tendency towards lateral subsurface flow.

The spatial variability of both the temporal and spatial variability of measured water content was small. Neutron probe data was by necessity collected around 48 hours after any significant rainfall. Either water is lost quickly (moves rapidly) in this environment or most soil water content values measured were near field-capacity, especially below the zone of substantial root uptake. The spatial variability of nitrate and bromide was also small. The variability of bromide did, however, increase with time from surface application. This possibly indicates that differences in solute movement are expressed very slowly in this rainfed field.

Leaching was characterized through three approaches: 1) total solute mass and critical depth at a particular point in time; 2) change in total solute mass and critical depth with time; and 3) percent of solute unrecoverable with time (based on mass balance estimates). Nitrate and bromide exhibited statistically different spatial behavior patterns under field conditions except in a couple time periods. None of the three approaches yielded stronger or more consistent relationships with the soil, soil water, or terrain attributes.

Additionally, Moore's "wetness" index does not appear to be a good indicator of the distribution of soil water and the potential location of zones of saturation in this catchment. However, neither of the two basic assumptions incorporated in the calculation of this index were met at the Springhill site. Based on a knowledge of soil

genesis it might be expected that the depth of the mollic horizon would be related to the distribution of water across the landscape over a long period of time. But, over a three year period, the thickness of the mollic horizon exhibited only a weak inverse relationship to measured soil water content.

This study raises fundamental questions regarding spatial and temporal scales of the interrelationships between environment, nitrogen leaching, and potential contamination of ground water.

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APPENDICES

APPENDIX A

PROCEDURES FOR PLANT TISSUE AND SOIL BROMIDE ANALYSIS

Soil Bromide Extraction Technique

1. Make eluant solution consisting of 2 liter mixed solution of 0.1908 g/L  $\text{NaCO}_3$  and 0.1428 g/L  $\text{NaHCO}_3$
2. Add 20 ml eluant solution to 10 g prepared soil (air-dried and ground)
3. Shake soil/solution mixture for one hour
4. Filter soil/solution mixture through Whatman glass filter
5. Filter solution from #4 through Supor-450 0.45um membrane filter
6. Analyze filtered solution on ion chromatograph

Plant Tissue Analysis for Bromide (Br<sup>-</sup>)

1. Make standard solutions
2. Create standard curve
3. Calibrate bromide electrode prior to each run
4. Add 25 ml  $\text{DDH}_2\text{O}$  with ISA to 1 gm dry plant tissue
5. Shake for 30 minutes (setting #7)
6. Homogenize for 3 minutes (setting 3.5)
7. Centrifuge at 10,000 rpm for 6 minutes
8. Filter through double thickness #1 Whatman paper
9. Calibrate bromide electrode and take millivolt (mv) readings (stir solution with magnetic stirrer)

**APPENDIX B**  
**LEACHIND.BAS OUTLINE AND PROGRAM**

LEACHIND.BAS  
Leaching Index Generation Program  
Written by Dr. J.M. Wraith and M.A. Landon

DECLARE subroutine and functions

DIMENSION arrays

DEFINE in and out file names

OPEN in and out files

READ flag\_id, depth (inches), and concentration (mg/kg) values for each flag\_id (assign a value of 999 for missing (non-measured) depth and concentration values) from data files

CONVERT depth values from inches to centimeters

FIT Polynomial Function (N-1 degree) to measured data at each flag\_id, and INTERPOLATE data at 5-cm depth increments from the fitted equation at each flag\_id

SET all interpolated data points between last two measured points to zero, for cases where last two measured points were equal to zero

NUMERICAL INTEGRATION of the N-1 polynomial-fitted (i.e. 5-cm increment) data at each flag\_id using Newton's Forward Integration (2nd order) Function, Bessel's Integration (3rd order) Function, and Newton's Backward Integration (2nd order) Function for equally-spaced depth values

CALCULATE total solute load (TSolMass, mg/kg) and depth at which 80% of the total load is above (CritDepth, cm) at each flag\_id

PRINT resultant data to out files

**\*NOTE:** Need to convert data to volume basis rather than mass basis in order to validly integrate and plot concentration vs. depth. Not a problem if just want to calculate CritDepth.

Figure 14. LEACHIND.BAS program.

```

'*****
',
',
',           LEACHIND.BAS
',
',           July 27, 1994
',           Leaching Index Generation Program
',           Written by Dr. Jon Wraith and Melissa Landon
',
',Depth array contains the measurement depths (cm)
',Conc array contains the measured solute concentration profile
',NumPts array contains the number of points per site location
',MaxDepth array contains the maximum depth measured at each site location
',TSolMass array contains the total solute mass
',CritDepth array contains the depth at which 80% of solute is below
',DepthCon array contains the fitted solute concentration profile
',ID is the site location identification number
',Depth is the soil depth at the midpoint of the soil core increment
',Conc is the solute concentration for the soil depth increment
',N is a number of points counter
',
'*****
DECLARE SUB PolInt (XA!(), YA!(), N!, X!, Y!, DY!)
DECLARE FUNCTION BESSINT3! (DeltX!, FMIN1!, F0!, F1!, F2!)
DECLARE FUNCTION NBACKINT2! (DeltX!, FMIN2!, FMIN1!, F0!)
DECLARE FUNCTION NFORINT2! (DeltX!, F0!, F1!, F2!)

DIM Depth(70, 7), Conc(70, 7), PredConc(70, 40)
DIM NumPts(70), MaxDepth(70), PredConcError(70, 40)
DIM TSolMass(70), CritDepth(70), DepthCon(70, 36)

CLS
'Infil$ = "c:\melissa\brdats93"
INPUT "Enter file name (no extension)"; Infil$

Infile$ = Infil$ + ".csv"
Outfile1$ = Infil$ + ".tst"
Outfile2$ = Infil$ + ".sum"
Outfile3$ = Infil$ + ".fit"

OPEN Infile$ FOR INPUT AS #1
OPEN Outfile1$ FOR OUTPUT AS #2
OPEN Outfile2$ FOR OUTPUT AS #3
OPEN Outfile3$ FOR OUTPUT AS #4

```

Figure 14 continued. LEACHIND.BAS program.

```

FOR ID = 1 TO 70
  N = 0
  FOR Depth% = 1 TO 7
    INPUT #1, ID
    INPUT #1, D$
    INPUT #1, c$
    IF D$ = "" THEN
      Depth(ID, Depth%) = 999
      Conc(ID, Depth%) = 999
    ELSE
      Depth(ID, Depth%) = VAL(D$)
      Conc(ID, Depth%) = VAL(c$)
    END IF

    IF Depth(ID, Depth%) = 999 THEN
      NumPts(ID) = N
      IF Depth% = 7 THEN EXIT FOR
      FOR D = Depth% + 1 TO 7
        INPUT #1, ID      'read data pts., & just assign 999's
        INPUT #1, D$
        INPUT #1, c$
        Depth(ID, D) = 999
        Conc(ID, D) = 999
      NEXT D
      EXIT FOR          'go to next tube ID
    ELSE
      N = N + 1
      IF N = 1 THEN
        TotalDepth = Depth(ID, Depth%)
        Depth(ID, Depth%) = Depth(ID, Depth%) / 2
      ELSEIF N > 1 THEN
        lastDepth = TotalDepth
        TotalDepth = Depth(ID, Depth%)
        Depth(ID, Depth%) = lastDepth + (TotalDepth - lastDepth) / 2
      END IF
    END IF
  NEXT Depth%
  NumPts(ID) = N
NEXT ID

```

Figure 14 continued. LEACHIND.BAS program.

```

'convert depth midpoints to cm
FOR ID = 1 TO 70
  FOR Depth% = 1 TO 7
    IF Depth(ID, Depth%) = 999 THEN
      MaxDepth(ID) = Depth(ID, Depth% - 1)
      EXIT FOR
    ELSE
      Depth(ID, Depth%) = Depth(ID, Depth%) * 2.54      'convert to cm
    END IF
    MaxDepth(ID) = Depth(ID, Depth%)
  NEXT Depth%
NEXT ID

'test file input and manipulation routines
FOR ID = 1 TO 70
  FOR Depth% = 1 TO 7
    PRINT #2, USING "##   ##.##   ##.####   ##.##"; ID; Depth(ID,
Depth%); Conc(ID, Depth%); MaxDepth(ID)
  NEXT Depth%
NEXT ID
CLOSE #2
'END

*****

'Fit function to measured data, and interpolate data at 5-cm
'depth increments from the fitted equation.

FOR ID = 1 TO 70      'tubes
  N1% = NumPts(ID)
  IF N1% = 0 THEN GOTO 222 'skip over PolInt sub (N will be zero)

  FOR D = 1 TO NumPts(ID) 'load depth and conc. values into temporary arrays
    Dpth(D) = Depth(ID, D)
    Cnc(D) = Conc(ID, D)
  NEXT D

  CALL Spline(Dpth(), Cnc(), N1%, 1E+31, 1E+31, DerivSpln())

  FOR D = 0 TO INT(MaxDepth(ID) / 5) 'no. depths in 5 cm increments
    PredConc(ID, D) = 0 'initialize to zero
    Dpth1 = D * 5 'depth in cm
  
```

Figure 14 continued. LEACHIND.BAS program.

```

      CALL Splint(Dpth(), Cnc(), DerivSplint(), N1%, Dpth1, PC)
      CALL PolInt(Dpth(), Cnc(), NumPts(ID), Dpth1, PC, PCerror)
      PredConc(ID, D) = PC
      PredConcError(ID, D) = PCerror
NEXT D

222      'if no data for this tube, don't go to PolInt sub

NEXT ID

*****
'Set all interpolated data points between last 2 measured pts. = zero, for
'cases where last 2 measured points = 0.

FOR ID = 1 TO 70
  IF NumPts(ID) = 0 THEN GOTO 333
  IF (Conc(ID, NumPts(ID) - 1) = 0 AND Conc(ID, NumPts(ID)) = 0) THEN
    D1 = Depth(ID, NumPts(ID) - 1) 'depth in cm of second-from-bottom
    D2 = INT(D1 / 5)
    D3 = D1 / 5
    IF D2 < D3 THEN D2 = D2 + 1
    FOR D4 = D2 TO INT(MaxDepth(ID) / 5)
      PredConc(ID, D4) = 0 'set all to zero
    NEXT D4
  END IF
333      'if no data for a tube, go to next tube
NEXT ID

*****
'Numerical integration of the spline-fitted (i.e. 5-cm depth increment) data
'to calculate total solute load and depth at which 80% of total load is above.

'NOTE: need to convert data to volume basis rather than mass basis in order to
'  validly integrate, if want to plot Concentration vs. Depth.
'  Not a problem if just want Critical Depth.

```

Figure 14 continued. LEACHIND.BAS program.

```

DeltX = 5      'depth increment in cm
FOR ID = 1 TO 70
    TSolMass(ID) = 0      'initialize
    FOR D = 1 TO INT(MaxDepth(ID) / 5) + 1      'skip depth zero (sometimes
extreme)
        IF D = 1 THEN
            Cnc = NFORINT2(DeltX, PredConc(ID, D), PredConc(ID, D + 1),
PredConc(ID, D + 2))
        ELSEIF D < 35 THEN      'Bessel's requires 2 points "ahead of"
            Cnc = BESSINT3(DeltX, PredConc(ID, D - 1), PredConc(ID, D),
PredConc(ID, D + 1), PredConc(ID, D + 2))
        ELSE
            Cnc = NBACKINT2(DeltX, PredConc(ID, D - 2), PredConc(ID, D - 1),
PredConc(ID, D))
        END IF
        DepthCon(ID, D) = Cnc
        TSolMass(ID) = TSolMass(ID) + Cnc
    NEXT D

    'Determine depth at which 80% of solute load is above
    SumConc = 0
    FOR D = 1 TO INT(MaxDepth(ID) / 5) + 1
        IF TSolMass(ID) = 0 THEN
            CritDepth(ID) = 0
            EXIT FOR
        END IF
        SumConc = SumConc + DepthCon(ID, D)
        IF SumConc >= .8 * TSolMass(ID) THEN
            CritDepth(ID) = D * 5
            EXIT FOR
        END IF
    NEXT D
NEXT ID

```

Figure 14 continued. LEACHIND.BAS program.

```

*****
'Print out Resultant Data to Outfiles

PRINT #3, "ID TSolMass CritDepth"
PRINT #4, "ID Depth Conc"
FOR ID = 1 TO 70
  PRINT #3, USING "## #####.## ##.##"; ID; TSolMass(ID); CritDepth(ID)
  FOR Depth% = 1 TO 36
    D = Depth% * 5
    PRINT #4, USING "## ###.## ##.##"; ID; D; DepthCon(ID, Depth%)
  NEXT Depth%
NEXT ID

CLOSE
END

*****
,
'BESSEL'S INTEGRATION (3rd Order) FUNCTION:
,
, Calculates Finite Difference Approx. to Integral for 3rd Order
, Approximation (Order Polynomial) based on Bessel's formula.
, Assumes: K=0, Equally-spaced X-Values.
,
, ARGUMENTS PASSED IN are:
, DELTX = delta-x increment (may use 1 if delta-x = delta-y)
, FMIN1,F0,F1,F2 are Y=F(X) points to use for 3rd order
, approx.
, RETURNS the value of the integral from F0 to F1.
,

FUNCTION BESSINT3 (DeltX, FMIN1, F0, F1, F2)
  BESSINT3 = DeltX * (13 * F0 + 13 * F1 - F2 - FMIN1) / 24
END FUNCTION

```

Figure 14 continued. LEACHIND.BAS program.

```

'*****
,
'NEWTON'S BACKWARD INTEGRATION (2nd order) FUNCTION:
,
' Calculates Finite Difference Approx. to Integral for 2nd Order
' Approximation (Order Polynomial) based on Newton's Backward formula.
' Assumes: K=0, Equally-spaced X-Values.
,
' ARGUMENTS PASSED IN are:
' DELTX = delta-x increment (may use 1 if delta-x = delta-y)
' FMIN2,FMIN1,F0 are Y=F(X) points to use for 2nd order
' approx.
' RETURNS the value of the integral from FMIN1 to F0.
,
FUNCTION NBAKINT2 (DeltX, FMIN2, FMIN1, F0)
  NBAKINT2 = DeltX * (8 * FMIN1 + 5 * F0 - FMIN2) / 12
END FUNCTION

'*****
,
'NEWTON'S FORWARD INTEGRATION (2nd Order) FUNCTION:
,
' Calculates Finite Difference Approx. to Integral for 2nd Order
' Approximation (Order Polynomial) based on Newton's Forward formula.
' Assumes: K=0, Equally-spaced X-Values.
,
' ARGUMENTS PASSED IN are:
' DELTX = delta-x increment (may use 1 if delta-x = delta-y)
' F0, F1, F2 are Y=F(X) points to use for 2nd order
' approx.
' RETURNS the value of the integral from F0 TO F1.
,
FUNCTION NFORINT2 (DeltX, F0, F1, F2)
  NFORINT2 = DeltX * (8 * F1 + 5 * F0 - F2) / 12
END FUNCTION

SUB PolInt (XA(), YA(), N, X, Y, DY)
  'Given arrays XA and YA, each of length N, and given a value X, this
  'routine returns a value Y, and an error estimate DY. IF P(X) is the
  'polynomial of degree N - 1 such that P(XAi) = YAi, i = 1,...,N, then
  'the returned value Y = P(X).

```

Figure 14 continued. LEACHIND.BAS program.

```

DIM c(N), D(N)
NS = 1
DIF = ABS(X - XA(1))
FOR I = 1 TO N      'Find the index NS of closest table entry.
    DIFT = ABS(X - XA(I))
    IF DIFT < DIF THEN
        NS = I
        DIF = DIFT
    END IF
    c(I) = YA(I)      'Initialize the tableau of C's and D's.
    D(I) = YA(I)
NEXT I
Y = YA(NS)          'This is the initial approximation to Y.
NS = NS - 1
FOR M = 1 TO N - 1  'For each column of the tableau,
    FOR I = 1 TO N - M 'loop over the current C's and D's and update.
        HO = XA(I) - X
        HP = XA(I + M) - X
        W = c(I + 1) - D(I)
        DEN = HO - HP
        IF DEN = 0! THEN PRINT "Abnormal exit": EXIT SUB
        DEN = W / DEN      'This error can occur only if two input XA's
        D(I) = HP * DEN    'are (to within roundoff) identical.
        c(I) = HO * DEN    'The C's and D's are updated.
    NEXT I
    IF 2 * NS < N - M THEN 'After each column in the tableau is completed,
        DY = c(NS + 1)    'decide the correction, C or D, to add to
    ELSE                    'accumulating value of Y, ie. which path to take
        DY = D(NS)        'through the tableau, forking up or down. Done
        NS = NS - 1        'in such a way as to take the most "straight"
    END IF                  'line route through the tableau to its apex,
    Y = Y + DY              'updating NS accordingly to keep track of
NEXT M                      'location. This route keeps the partial
ERASE D, c                  'approximations centered on the target X. The
END SUB                      'last DY added is thus the error indication.

```

APPENDIX C

INITIAL VALUES FOR SOIL AND TERRAIN ATTRIBUTES

Table 43. Initial soil test values.

| Flag ID | pH (1:2) | EC (1:2) (dS m <sup>-1</sup> ) | OM (%) | K (mg kg <sup>-1</sup> ) | Olsen P (mg kg <sup>-1</sup> ) | Thickness of Mollic Horizon (cm) | Depth to CaCO <sub>3</sub> (cm) |
|---------|----------|--------------------------------|--------|--------------------------|--------------------------------|----------------------------------|---------------------------------|
| 1       | 5.8      | 0.06                           | 3.52   | 310                      | 37.9                           | 15                               | 57                              |
| 2       | 6.0      | 0.06                           | 2.33   | 222                      | 27.2                           | 15                               | 62                              |
| 3       | 5.7      | 0.05                           | 2.90   | 268                      | *                              | 19                               | 76                              |
| 4       | 6.3      | 0.07                           | 3.14   | 266                      | 28.7                           | 49                               | 64                              |
| 5       | 6.2      | 0.08                           | 3.44   | 388                      | 44.7                           | 63                               | 85                              |
| 6       | 6.0      | 0.05                           | 2.85   | 238                      | 30.2                           | 18                               | 51                              |
| 7       | 5.9      | 0.06                           | 4.00   | 386                      | 64.8                           | 20                               | 131                             |
| 8       | 6.1      | 0.06                           | 3.66   | 326                      | 51.6                           | 33                               | 85                              |
| 9       | 5.8      | 0.06                           | 3.08   | 324                      | 48.8                           | 30                               | >180                            |
| 10      | 5.8      | 0.06                           | 3.47   | 302                      | 52.2                           | 43                               | 107                             |
| 11      | 7.1      | 0.23                           | 2.09   | 222                      | 24.7                           | 66                               | >180                            |
| 12      | 6.0      | 0.05                           | 2.65   | 274                      | 51.0                           | 27                               | 79                              |
| 13      | 5.9      | 0.04                           | 3.21   | 260                      | 35.9                           | 37                               | 86                              |
| 14      | 6.1      | 0.05                           | 3.55   | 286                      | 37.0                           | 53                               | 88                              |
| 15      | 6.0      | 0.05                           | 3.24   | 294                      | 36.8                           | 34                               | 67                              |
| 16      | 6.0      | 0.06                           | 2.31   | 210                      | 27.0                           | 16                               | 48                              |
| 17      | 5.9      | 0.07                           | 3.79   | 392                      | 62.1                           | 22                               | 77                              |
| 18      | 5.9      | 0.06                           | 3.93   | 352                      | 51.0                           | 25                               | 67                              |
| 19      | 6.5      | 0.09                           | 2.77   | 238                      | 25.4                           | 80                               | 99                              |
| 20      | 8.2      | 0.12                           | 1.69   | 174                      | 23.3                           | 15                               | 27                              |
| 21      | 6.4      | 0.09                           | 2.43   | 302                      | 55.0                           | 55                               | >180                            |
| 22      | 5.8      | 0.08                           | 4.84   | 490                      | 63.8                           | 52                               | 107                             |
| 23      | 6.5      | 0.05                           | 2.00   | 184                      | 27.7                           | 16                               | 46                              |
| 24      | 5.8      | 0.06                           | 3.58   | 392                      | 52.9                           | 76                               | >180                            |
| 25      | 6.0      | 0.06                           | 4.32   | 466                      | 55.2                           | 114                              | >180                            |
| 26      | 6.0      | 0.05                           | 3.37   | 314                      | 27.2                           | 53                               | >180                            |
| 27      | 5.9      | 0.04                           | 3.26   | 278                      | 32.0                           | 41                               | 87                              |
| 28      | 6.0      | 0.05                           | 3.21   | 242                      | 33.8                           | 15                               | 48                              |

\* Value not available.

Table 43 continued. Initial soil test values.

| Flag ID | pH (1:2) | EC (1:2) (dS m <sup>-1</sup> ) | OM (%) | K (mg kg <sup>-1</sup> ) | Olsen P (mg kg <sup>-1</sup> ) | Thickness of Mollic Horizon (cm) | Depth to CaCO <sub>3</sub> (cm) |
|---------|----------|--------------------------------|--------|--------------------------|--------------------------------|----------------------------------|---------------------------------|
| 29      | 5.9      | 0.09                           | 4.92   | 662                      | 71.6                           | 62                               | > 180                           |
| 30      | 6.0      | 0.07                           | 4.83   | 564                      | 57.2                           | 80                               | > 180                           |
| 31      | 7.1      | 0.04                           | 1.08   | 166                      | 8.1                            | 24                               | > 180                           |
| 32      | 6.0      | 0.06                           | 4.18   | 522                      | 59.0                           | 48                               | > 180                           |
| 33      | 7.6      | 0.11                           | 2.57   | 320                      | 69.3                           | 60                               | > 180                           |
| 34      | 6.4      | 0.07                           | 3.93   | 410                      | 35.6                           | 53                               | > 180                           |
| 35      | 6.3      | 0.09                           | 3.55   | 270                      | 32.1                           | 28                               | 112                             |
| 36      | 6.2      | 0.09                           | 4.04   | 324                      | 32.4                           | 35                               | 67                              |
| 37      | 7.8      | 0.13                           | 3.41   | 230                      | 64.7                           | 29                               | 46                              |
| 38      | 5.8      | 0.06                           | 4.29   | 388                      | 48.9                           | 42                               | > 180                           |
| 39      | 6.5      | 0.08                           | 4.47   | 248                      | 34.6                           | 18                               | 69                              |
| 40      | 6.3      | 0.04                           | 2.82   | 236                      | 26.1                           | 19                               | 50                              |
| 41      | 6.1      | 0.05                           | 4.05   | 300                      | 33.0                           | 26                               | 110                             |
| 42      | 6.4      | 0.07                           | 2.68   | 326                      | 38.3                           | 50                               | 126                             |
| 43      | 6.1      | 0.08                           | 4.25   | 450                      | 69.3                           | 109                              | > 180                           |
| 44      | 6.4      | 0.06                           | 3.41   | 224                      | 28.3                           | 26                               | 56                              |
| 45      | 6.2      | 0.05                           | 3.43   | 172                      | 17.8                           | 20                               | 79                              |
| 46      | 6.3      | 0.06                           | 4.27   | 340                      | 37.1                           | 60                               | 112                             |
| 47      | 6.3      | 0.10                           | 5.55   | 844                      | 92.1                           | 117                              | > 180                           |
| 48      | 5.8      | 0.08                           | 5.55   | 388                      | 58.3                           | 50                               | > 180                           |
| 49      | 6.2      | 0.07                           | 3.96   | 304                      | 37.1                           | 20                               | 84                              |
| 50      | 6.6      | 0.11                           | 4.38   | 286                      | 48.3                           | 23                               | 94                              |
| 51      | 6.2      | 0.06                           | 4.45   | 344                      | 52.8                           | 69                               | 149                             |
| 53      | 5.6      | 0.08                           | 4.95   | 466                      | 81.5                           | 58                               | > 180                           |
| 54      | 5.9      | 0.09                           | 2.61   | 306                      | 27.7                           | 34                               | 74                              |
| 55      | 6.4      | 0.07                           | 4.35   | 502                      | 93.1                           | 126                              | > 180                           |
| 56      | 6.2      | 0.05                           | 2.91   | 226                      | 32.2                           | 52                               | > 180                           |
| 57      | 6.1      | 0.05                           | 3.95   | 294                      | 63.1                           | 54                               | 118                             |
| 58      | 6.0      | 0.12                           | 3.98   | 218                      | 35.8                           | 36                               | 64                              |

Table 43 continued. Initial soil test values.

| Flag ID | pH (1:2) | EC (1:2) (dS m <sup>-1</sup> ) | OM (%) | K (mg kg <sup>-1</sup> ) | Olsen P (mg kg <sup>-1</sup> ) | Thickness of Mollic Horizon (cm) | Depth to CaCO <sub>3</sub> (cm) |
|---------|----------|--------------------------------|--------|--------------------------|--------------------------------|----------------------------------|---------------------------------|
| 59      | 8.2      | 0.11                           | 3.09   | 292                      | 70.1                           | 118                              | > 180                           |
| 60      | 6.2      | 0.04                           | 2.78   | 272                      | 52.2                           | 40                               | > 180                           |
| 61      | 6.6      | 0.04                           | 1.80   | 170                      | 15.8                           | 14                               | 51                              |
| 62      | 5.9      | 0.06                           | 3.89   | 318                      | 57.2                           | 51                               | 95                              |
| 63      | 6.0      | 0.06                           | 3.09   | 250                      | 32.2                           | 48                               | 83                              |
| 66      | 8.1      | 0.16                           | 2.20   | 216                      | 25.9                           | 10                               | 10                              |
| 67      | 8.3      | 0.11                           | 2.28   | 188                      | 22.0                           | 31                               | 70                              |
| 68      | 6.3      | 0.05                           | 3.29   | 208                      | 27.4                           | 45                               | 59                              |
| 69      | 6.2      | 0.09                           | 4.18   | 454                      | 64.2                           | 64                               | > 180                           |
| 70      | 5.8      | 0.05                           | 4.00   | 182                      | 63.3                           | 43                               | > 180                           |

Table 44. Measured and calculated terrain attributes.

| Flag ID | X Coordinate (UTM m) | Y Coordinate (UTM m) | Elevation (m) | Slope (%) | Aspect (deg) | Specific Catchment Area (m <sup>2</sup> m <sup>-1</sup> ) | Wetness Index | Plan Curvature (m m <sup>-1</sup> ) | Profile Curvature (m m <sup>-1</sup> ) |
|---------|----------------------|----------------------|---------------|-----------|--------------|-----------------------------------------------------------|---------------|-------------------------------------|----------------------------------------|
| 1       | 498364.8             | 5076876.0            | 1529.03       | 11.340    | 254.922      | 63.2                                                      | 6.323         | 1.893                               | -0.191                                 |
| 2       | 498420.3             | 5076878.0            | 1531.08       | 10.378    | 129.134      | 22.0                                                      | 5.357         | 1.786                               | -0.025                                 |
| 3       | 498458.8             | 5076884.0            | 1527.35       | 18.160    | 117.553      | 109.0                                                     | 6.397         | 0.216                               | -0.323                                 |
| 4       | 498311.3             | 5076820.0            | 1527.11       | 3.578     | 303.024      | 13.9                                                      | 5.962         | -17.896                             | -0.030                                 |
| 5       | 498365.6             | 5076821.0            | 1528.81       | 2.549     | 244.440      | 14.6                                                      | 6.350         | -17.695                             | 0.071                                  |
| 6       | 498422.4             | 5076823.0            | 1529.62       | 5.447     | 133.512      | 12.7                                                      | 5.452         | -18.245                             | -0.524                                 |
| 7       | 498468.5             | 5076830.0            | 1522.20       | 13.552    | 117.227      | 59.6                                                      | 6.086         | -4.776                              | 0.406                                  |
| 8       | 498319.8             | 5076764.0            | 1525.02       | 4.622     | 211.283      | 35.2                                                      | 6.635         | -7.771                              | -0.310                                 |
| 9       | 498372.7             | 5076765.0            | 1525.50       | 7.406     | 177.678      | 50.5                                                      | 6.525         | -4.740                              | 0.051                                  |
| 10      | 498425.4             | 5076765.0            | 1525.18       | 8.146     | 159.897      | 54.1                                                      | 6.498         | 1.404                               | 0.273                                  |
| 11      | 498479.7             | 5076771.0            | 1518.77       | 20.865    | 64.295       | 55.6                                                      | 5.585         | 3.103                               | 0.753                                  |
| 12      | 498274.0             | 5076707.0            | 1519.17       | 11.710    | 187.853      | 73.5                                                      | 6.442         | 3.113                               | 0.446                                  |
| 13      | 498321.8             | 5076709.0            | 1519.32       | 6.757     | 177.455      | 128.2                                                     | 7.548         | 5.343                               | 0.982                                  |
| 14      | 498375.5             | 5076710.0            | 1519.29       | 13.425    | 162.442      | 73.8                                                      | 6.309         | -2.749                              | -0.332                                 |
| 15      | 498428.0             | 5076712.0            | 1519.12       | 10.842    | 194.421      | 86.4                                                      | 6.681         | 2.220                               | 0.255                                  |
| 16      | 498482.1             | 5076713.0            | 1518.67       | 12.864    | 138.940      | 21.4                                                      | 5.114         | -9.174                              | -0.302                                 |
| 17      | 498277.2             | 5076650.0            | 1513.10       | 8.416     | 194.449      | 149.7                                                     | 7.484         | 0.296                               | 0.045                                  |

Table 44 continued. Measured and calculated terrain attributes.

| Flag ID | X Coordinate (UTM m) | Y Coordinate (UTM m) | Elevation (m) | Slope (%) | Aspect (deg) | Specific Catchment Area (m <sup>2</sup> m <sup>-1</sup> ) | Wetness Index | Plan Curvature (m m <sup>-1</sup> ) | Profile Curvature (m m <sup>-1</sup> ) |
|---------|----------------------|----------------------|---------------|-----------|--------------|-----------------------------------------------------------|---------------|-------------------------------------|----------------------------------------|
| 18      | 498323.4             | 5076653.0            | 1513.99       | 7.760     | 177.045      | 91.7                                                      | 7.075         | -0.963                              | -0.015                                 |
| 19      | 498377.7             | 5076654.0            | 1513.68       | 16.494    | 147.755      | 56.3                                                      | 5.833         | -3.385                              | 0.104                                  |
| 20      | 498429.5             | 5076656.0            | 1512.59       | 14.378    | 153.791      | 90.7                                                      | 6.447         | 4.940                               | 1.086                                  |
| 21      | 498486.7             | 5076671.0            | 1510.89       | 23.359    | 166.886      | 86.6                                                      | 5.915         | -0.289                              | 0.644                                  |
| 22      | 498275.3             | 5076587.0            | 1509.61       | 4.314     | 225.939      | 175.4                                                     | 8.310         | 1.490                               | 0.155                                  |
| 23      | 498325.9             | 5076592.0            | 1510.07       | 6.642     | 154.592      | 54.9                                                      | 6.717         | 3.061                               | -0.113                                 |
| 24      | 498380.9             | 5076597.0            | 1503.58       | 11.312    | 163.568      | 997.5                                                     | 9.085         | 21.572                              | 1.187                                  |
| 25      | 498434.3             | 5076601.0            | 1503.82       | 9.774     | 187.052      | 143.7                                                     | 7.293         | 3.710                               | 0.589                                  |
| 26      | 498488.6             | 5076606.0            | 1505.52       | 5.450     | 213.398      | 174.1                                                     | 8.069         | -0.831                              | -0.084                                 |
| 27      | 498278.3             | 5076535.0            | 1505.86       | 17.913    | 175.197      | 112.5                                                     | 6.443         | 4.503                               | -0.200                                 |
| 28      | 498327.8             | 5076538.0            | 1504.79       | 15.523    | 154.838      | 50.5                                                      | 5.785         | -2.135                              | 0.079                                  |
| 29      | 498383.0             | 5076542.0            | 1500.12       | 5.615     | 193.913      | 1978.1                                                    | 10.470        | 3.395                               | 0.188                                  |
| 30      | 498435.4             | 5076546.0            | 1501.20       | 3.501     | 178.363      | 387.4                                                     | 9.311         | 2.070                               | -0.032                                 |
| 31      | 498487.7             | 5076550.0            | 1502.34       | 4.117     | 204.386      | 167.3                                                     | 8.310         | -1.097                              | -0.284                                 |
| 32      | 498276.9             | 5076477.0            | 1499.91       | 8.840     | 135.917      | 236.5                                                     | 7.892         | 5.741                               | 0.427                                  |
| 33      | 498332.4             | 5076485.0            | 1499.55       | 11.577    | 109.687      | 87.9                                                      | 6.632         | -6.451                              | -0.268                                 |
| 34      | 498384.0             | 5076488.0            | 1498.05       | 7.338     | 192.995      | 46.3                                                      | 6.447         | -1.521                              | -0.187                                 |

Table 44 continued. Measured and calculated terrain attributes.

| Flag ID | X Coordinate (UTM m) | Y Coordinate (UTM m) | Elevation (m) | Slope (%) | Aspect (deg) | Specific Catchment Area (m <sup>2</sup> m <sup>-1</sup> ) | Wetness Index | Plan Curvature (m m <sup>-1</sup> ) | Profile Curvature (m m <sup>-1</sup> ) |
|---------|----------------------|----------------------|---------------|-----------|--------------|-----------------------------------------------------------|---------------|-------------------------------------|----------------------------------------|
| 35      | 498439.1             | 5076491.0            | 1501.82       | 18.674    | 313.481      | 48.6                                                      | 5.562         | 2.759                               | 0.422                                  |
| 36      | 498487.8             | 5076493.0            | 1505.92       | 10.333    | 332.319      | 22.5                                                      | 5.383         | 0.526                               | -0.437                                 |
| 37      | 498276.5             | 5076428.0            | 1497.02       | 7.510     | 233.664      | 337.6                                                     | 8.411         | 7.622                               | 0.067                                  |
| 38      | 498332.2             | 5076431.0            | 1496.48       | 16.015    | 102.257      | 35.5                                                      | 5.401         | 1.517                               | 0.180                                  |
| 39      | 498385.8             | 5076434.0            | 1496.95       | 15.076    | 286.572      | 51.2                                                      | 5.828         | -0.990                              | 0.231                                  |
| 40      | 498440.5             | 5076436.0            | 1504.34       | 6.323     | 247.694      | 18.7                                                      | 5.689         | -6.720                              | -0.005                                 |
| 41      | 498487.8             | 5076438.0            | 1505.57       | 4.851     | 171.703      | 13.4                                                      | 5.621         | -15.593                             | -0.900                                 |
| 42      | 498275.8             | 5076367.0            | 1491.86       | 13.844    | 184.557      | 31.4                                                      | 5.424         | -3.292                              | 0.968                                  |
| 43      | 498332.9             | 5076374.0            | 1493.11       | 6.668     | 169.196      | 7653.2                                                    | 11.651        | 7.300                               | 0.649                                  |
| 44      | 498386.3             | 5076377.0            | 1497.96       | 9.237     | 258.447      | 43.4                                                      | 6.152         | 0.267                               | -0.084                                 |
| 45      | 498440.5             | 5076378.0            | 1500.69       | 7.301     | 179.215      | 53.8                                                      | 6.602         | 4.121                               | 0.416                                  |
| 46      | 498488.7             | 5076380.0            | 1499.68       | 10.159    | 155.579      | 105.6                                                     | 6.946         | 0.139                               | 0.154                                  |
| 47      | 498275.3             | 5076316.0            | 1489.85       | 1.503     | 273.814      | 8717.5                                                    | 13.271        | 25.310                              | 0.040                                  |
| 48      | 498330.4             | 5076318.0            | 1493.40       | 10.533    | 295.592      | 58.6                                                      | 6.321         | 3.658                               | -0.192                                 |
| 49      | 498386.4             | 5076321.0            | 1497.29       | 3.970     | 196.837      | 22.0                                                      | 6.317         | -5.900                              | 0.004                                  |
| 50      | 498442.3             | 5076324.0            | 1497.44       | 5.582     | 149.300      | 74.7                                                      | 7.199         | -1.121                              | -0.027                                 |
| 51      | 498489.3             | 5076326.0            | 1495.69       | 10.958    | 157.179      | 132.8                                                     | 7.100         | 1.270                               | 0.207                                  |

Table 44 continued. Measured and calculated terrain attributes.

| Flag ID | X Coordinate (UTM m) | Y Coordinate (UTM m) | Elevation (m) | Slope (%) | Aspect (deg) | Specific Catchment Area (m <sup>2</sup> m <sup>-1</sup> ) | Wetness Index | Plan Curvature (m m <sup>-1</sup> ) | Profile Curvature (m m <sup>-1</sup> ) |
|---------|----------------------|----------------------|---------------|-----------|--------------|-----------------------------------------------------------|---------------|-------------------------------------|----------------------------------------|
| 53      | 498315.3             | 5076872.0            | 1523.68       | 3.762     | 265.426      | 895.5                                                     | 10.078        | 27.339                              | 0.201                                  |
| 54      | 498401.4             | 5076894.0            | 1532.08       | 2.616     | 225.000      | 22.7                                                      | 6.766         | -3.344                              | -0.172                                 |
| 55      | 498302.4             | 5076343.0            | 1491.16       | 3.835     | 247.782      | 8189.6                                                    | 12.272        | 3.382                               | 0.050                                  |
| 56      | 498453.1             | 5076799.0            | 1524.93       | 20.976    | 87.131       | 33.6                                                      | 5.076         | 0.780                               | -0.772                                 |
| 57      | 498399.6             | 5076784.0            | 1526.70       | 7.748     | 198.435      | 52.3                                                      | 6.515         | 1.846                               | 0.651                                  |
| 58      | 498459.9             | 5076290.0            | 1495.31       | 4.893     | 158.416      | 44.1                                                      | 6.804         | -3.887                              | 0.040                                  |
| 59      | 498411.4             | 5076634.0            | 1509.99       | 12.806    | 193.548      | 132.1                                                     | 6.939         | -0.334                              | 0.012                                  |
| 60      | 498348.9             | 5076585.0            | 1505.79       | 20.373    | 119.396      | 106.7                                                     | 6.261         | 1.882                               | 0.345                                  |
| 61      | 498344.3             | 5076551.0            | 1504.95       | 18.112    | 143.984      | 30.1                                                      | 5.113         | -3.847                              | -0.079                                 |
| 62      | 498299.8             | 5076678.0            | 1516.34       | 9.949     | 188.089      | 112.3                                                     | 7.029         | -0.155                              | 0.084                                  |
| 63      | 498342.2             | 5076688.0            | 1517.59       | 11.575    | 171.555      | 103.1                                                     | 6.792         | -0.065                              | -0.061                                 |
| 66      | 498296.8             | 5076431.0            | 1499.96       | 11.611    | 257.819      | 10.8                                                      | 4.533         | -7.047                              | -1.844                                 |
| 67      | 498297.9             | 5076400.0            | 1497.12       | 12.572    | 197.354      | 17.2                                                      | 4.919         | -7.638                              | -0.009                                 |
| 68      | 498397.1             | 5076404.0            | 1498.89       | 10.078    | 283.485      | 59.1                                                      | 6.374         | 1.773                               | -0.245                                 |
| 69      | 498371.3             | 5076459.0            | 1495.53       | 5.092     | 172.666      | 6417.3                                                    | 11.744        | 28.838                              | 0.908                                  |
| 70      | 498368.2             | 5076409.0            | 1496.37       | 15.099    | 290.956      | 68.2                                                      | 6.113         | 0.473                               | 0.086                                  |

APPENDIX D

MULTIPLE REGRESSION RESULTS

Table 45. Multiple regression results for nitrogen critical depth in Spring 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 57) |                    |               |             |      |          |
| Intercept                   | 160.0              |               |             |      |          |
| TW2592                      | -20.3              | 0.09          | 0.09        | 5.32 | 0.0249   |
| TW15092                     | 1.9                | 0.11          | 0.20        | 7.86 | 0.0070   |
| Stream Channel In (n = 65)  |                    |               |             |      |          |
| Intercept                   | 110.7              |               |             |      |          |
| TW15092                     | 1.9                | 0.13          | 0.13        | 9.37 | 0.0032   |
| TW2592                      | -13.2              | 0.07          | 0.20        | 5.85 | 0.0185   |

Table 46. Multiple regression results for change in nitrogen solute mass from Fall 1992-Spring 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 57) |                    |               |             |       |          |
| Intercept                   | 24.0               |               |             |       |          |
| SCA                         | 0.2                | 0.26          | 0.26        | 19.24 | 0.0001   |
| Mollic                      | 1.8                | 0.09          | 0.34        | 7.12  | 0.0100   |
| Stream Channel In (n = 65)  |                    |               |             |       |          |
| Intercept                   | -59.0              |               |             |       |          |
| OM                          | 49.4               | 0.11          | 0.11        | 7.52  | 0.0079   |

Table 47. Multiple regression results for change in nitrogen critical depth from Fall 1992-Spring 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 57) |                    |               |             |      |          |
| Intercept                   | -38.1              |               |             |      |          |
| Slope                       | 4.6                | 0.13          | 0.13        | 8.39 | 0.0054   |
| Stream Channel In (n = 65)  |                    |               |             |      |          |
| Intercept                   | -33.7              |               |             |      |          |
| Slope                       | 4.1                | 0.12          | 0.12        | 8.43 | 0.0051   |

Table 48. Multiple regression results for change in nitrogen solute mass from Spring 1993-Fall 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 56) |                    |               |             |      |          |
| NOT SIGNIFICANT             |                    |               |             |      |          |
| Stream Channel In (n = 64)  |                    |               |             |      |          |
| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
| Intercept                   | 114.0              |               |             |      |          |
| Mollic                      | 2.0                | 0.06          | 0.06        | 4.28 | 0.0443   |

Table 49. Multiple regression results for change in nitrogen critical depth from Spring 1993-Fall 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 56) |                    |               |             |      |          |
| Intercept                   | -38.7              |               |             |      |          |
| OM                          | 21.2               | 0.11          | 0.11        | 6.98 | 0.0108   |
| Mollic                      | -0.6               | 0.09          | 0.20        | 5.88 | 0.0188   |
| Stream Channel In (n = 64)  |                    |               |             |      |          |
| Intercept                   | -143.4             |               |             |      |          |
| TW2593                      | 18.4               | 0.08          | 0.08        | 5.13 | 0.0271   |

Table 50. Multiple regression results for nitrogen balance in Fall 1993.

| Variable                          | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out                |                    |               |             |      |          |
| 60 cm (n = 44)                    |                    |               |             |      |          |
| Intercept                         | 48.5               |               |             |      |          |
| SCA 1*                            | -0.1               | 0.11          | 0.11        | 5.10 | 0.0292   |
| 90 cm (n = 37)                    |                    |               |             |      |          |
| Intercept                         | 48.2               |               |             |      |          |
| SCA 1*                            | -0.1               | 0.11          | 0.11        | 4.56 | 0.0397   |
| Stream Channel In                 |                    |               |             |      |          |
| 60 cm (n = 48)                    |                    |               |             |      |          |
| Intercept                         | 47.0               |               |             |      |          |
| SCA 1*                            | -0.1               | 0.08          | 0.08        | 4.14 | 0.0476   |
| 90 cm (n = 40) -- NOT SIGNIFICANT |                    |               |             |      |          |

\* Interaction Variable: variable \* limedep1

Table 51. Multiple regression results for nitrogen solute mass in Fall 1994.

| Variable                    | Parameter Estimate | Partial R <sup>2</sup> | Model R <sup>2</sup> | F     | Prob > F |
|-----------------------------|--------------------|------------------------|----------------------|-------|----------|
| Stream Channel Out (N = 52) |                    |                        |                      |       |          |
| Intercept                   | 194.6              |                        |                      |       |          |
| NS94SM                      | 0.2                | 0.20                   | 0.20                 | 12.56 | 0.0009   |
| Mollic                      | -3.2               | 0.07                   | 0.27                 | 5.08  | 0.0287   |
| Stream Channel In (N = 57)  |                    |                        |                      |       |          |
| Intercept                   | 173.5              |                        |                      |       |          |
| NS94SM                      | 0.2                | 0.20                   | 0.20                 | 13.71 | 0.0005   |
| Mollic                      | -2.5               | 0.07                   | 0.27                 | 5.34  | 0.0247   |

NS94SM = N solute mass in soil profile in Spring 1994.

Table 52. Multiple regression results for bromide solute mass in Spring 1993.

| Variable                    | Parameter Estimate | Partial R <sup>2</sup> | Model R <sup>2</sup> | F    | Prob > F |
|-----------------------------|--------------------|------------------------|----------------------|------|----------|
| Stream Channel Out (N = 57) |                    |                        |                      |      |          |
| NOT SIGNIFICANT             |                    |                        |                      |      |          |
| Stream Channel In (N = 65)  |                    |                        |                      |      |          |
| Intercept                   | 119.4              |                        |                      |      |          |
| Mollic 1*                   | 3.5                | 0.08                   | 0.08                 | 5.17 | 0.0264   |

\* Interaction Variable: variable \* limedep1

Table 53. Multiple regression results for bromide critical depth in Spring 1993 (for sites where solute present at < 180 cm).

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 49) |                    |               |             |      |          |
| NOT SIGNIFICANT             |                    |               |             |      |          |
| Stream Channel In (n = 54)  |                    |               |             |      |          |
| Intercept                   | -1119.9            |               |             |      |          |
| Elev                        | 0.8                | 0.08          | 0.08        | 4.32 | 0.0425   |

Table 54. Multiple regression results for change in bromide critical depth from Fall 1992-Spring 1993 (for sites where solute present at < 180 cm).

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 49) |                    |               |             |      |          |
| Intercept                   | 24.6               |               |             |      |          |
| Mollic                      | 0.5                | 0.08          | 0.08        | 4.13 | 0.0478   |
| Stream Channel In (n = 54)  |                    |               |             |      |          |
| Intercept                   | 46.2               |               |             |      |          |
| SCA                         | -0.01              | 0.09          | 0.09        | 5.02 | 0.0293   |

Table 55. Multiple regression results for bromide solute mass in Fall 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 56) |                    |               |             |      |          |
| Intercept                   | -2396.6            |               |             |      |          |
| pH                          | 441.7              | 0.15          | 0.15        | 9.37 | 0.0034   |
| Stream Channel In (n = 64)  |                    |               |             |      |          |
| Intercept                   | -2309.4            |               |             |      |          |
| pH                          | 420.9              | 0.13          | 0.13        | 9.71 | 0.0028   |

Table 56. Multiple regression results for change in bromide solute mass from Spring 1993-Fall 1993.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F     | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Stream Channel Out (n = 56) |                    |               |             |       |          |
| Intercept                   | -2413.2            |               |             |       |          |
| pH                          | 515.3              | 0.15          | 0.15        | 9.41  | 0.0034   |
| PlanC                       | 39.1               | 0.06          | 0.21        | 4.23  | 0.0446   |
| Stream Channel In (n = 64)  |                    |               |             |       |          |
| Intercept                   | -2705.5            |               |             |       |          |
| pH                          | 456.5              | 0.14          | 0.14        | 10.20 | 0.0022   |

Table 57. Multiple regression results for change in bromide solute mass from Fall 1993-Spring 1994.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 55) |                    |               |             |      |          |
| Intercept                   | 895.8              |               |             |      |          |
| SCA                         | 0.8                | 0.08          | 0.08        | 4.80 | 0.0329   |
| PlanC                       | -25.8              | 0.09          | 0.17        | 5.77 | 0.0199   |
| Stream Channel In (n = 63)  |                    |               |             |      |          |
| NOT SIGNIFICANT             |                    |               |             |      |          |

Table 58. Multiple regression results for change in bromide critical depth from Fall 1993-Spring 1994.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 55) |                    |               |             |      |          |
| Intercept                   | 56.6               |               |             |      |          |
| ProC 1*                     | -27.8              | 0.13          | 0.13        | 7.88 | 0.0070   |
| Stream Channel In (n = 63)  |                    |               |             |      |          |
| Intercept                   | 55.8               |               |             |      |          |
| ProC 1*                     | -28.1              | 0.13          | 0.13        | 8.80 | 0.0043   |

\* Interaction Variable: variable \* limedép1

Table 59. Multiple regression results for bromide balance in Spring 1994.

| Variable                          | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out                |                    |               |             |      |          |
| 60 cm (n = 55)                    |                    |               |             |      |          |
| Intercept                         | 56.9               |               |             |      |          |
| Slope                             | 1.0                | 0.09          | 0.09        | 5.00 | 0.0296   |
| 90 cm (n = 55)                    |                    |               |             |      |          |
| Intercept                         | 53.0               |               |             |      |          |
| EC                                | 156.2              | 0.08          | 0.08        | 4.71 | 0.0345   |
| Stream Channel In                 |                    |               |             |      |          |
| 60 cm (n = 62) -- NOT SIGNIFICANT |                    |               |             |      |          |
| 90 cm (n = 60)                    |                    |               |             |      |          |
| Intercept                         | 52.8               |               |             |      |          |
| EC                                | 160.7              | 0.08          | 0.08        | 5.42 | 0.0234   |

Table 60. Multiple regression results for change in bromide critical depth from Spring 1994-Fall 1994.

| Variable                    | Parameter Estimate | Partial $r^2$ | Model $R^2$ | F    | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Stream Channel Out (n = 52) |                    |               |             |      |          |
| Intercept                   | 51.5               |               |             |      |          |
| Slope                       | -2.4               | 0.08          | 0.08        | 4.46 | 0.0397   |
| Stream Channel In (n = 57)  |                    |               |             |      |          |
| Intercept                   | 41.4               |               |             |      |          |
| Mollic                      | -0.4               | 0.08          | 0.08        | 4.68 | 0.0348   |

APPENDIX E  
WETNESS INDEX VALUES

Table 61. Wetness index values.

| Site ID | 10 m Wetness Index | 2 m Wetness Index | Site ID | 10 m Wetness Index | 2 m Wetness Index |
|---------|--------------------|-------------------|---------|--------------------|-------------------|
| 1       | 6.323              | 6.352             | 36      | 5.383              | 4.786             |
| 2       | 5.357              | 5.027             | 37      | 8.411              | 4.811             |
| 3       | 6.397              | 6.146             | 38      | 5.401              | 6.197             |
| 4       | 5.962              | 5.125             | 39      | 5.828              | 5.283             |
| 5       | 6.350              | 5.141             | 40      | 5.689              | 4.815             |
| 6       | 5.452              | 4.451             | 41      | 5.621              | 6.058             |
| 7       | 6.086              | 6.560             | 42      | 5.424              | 6.570             |
| 8       | 6.635              | 6.755             | 43      | 11.651             | 8.180             |
| 9       | 6.525              | 6.428             | 44      | 6.152              | 5.239             |
| 10      | 6.498              | 5.926             | 45      | 6.602              | 6.665             |
| 11      | 5.585              | 5.545             | 46      | 6.946              | 6.665             |
| 12      | 6.442              | 6.750             | 47      | 13.271             | 6.853             |
| 13      | 7.548              | 7.067             | 48      | 6.321              | 5.847             |
| 14      | 6.309              | 6.280             | 49      | 6.317              | 5.979             |
| 15      | 6.681              | 6.801             | 50      | 7.199              | 8.312             |
| 16      | 5.114              | 3.833             | 51      | 7.100              | 6.864             |
| 17      | 7.484              | 8.209             | 53      | 10.078             | 9.477             |
| 18      | 7.075              | 7.047             | 54      | 6.766              | 6.189             |
| 19      | 5.833              | 6.642             | 55      | 12.272             | 8.761             |
| 20      | 6.447              | 5.708             | 56      | 5.076              | 5.384             |
| 21      | 5.915              | 5.411             | 57      | 6.515              | 6.799             |
| 22      | 8.310              | 10.349            | 58      | 6.804              | 7.396             |
| 23      | 6.717              | 5.620             | 59      | 6.939              | 6.288             |
| 24      | 9.085              | 9.133             | 60      | 6.261              | 6.631             |
| 25      | 7.293              | 7.656             | 61      | 5.113              | 5.021             |
| 26      | 8.069              | 8.490             | 62      | 7.029              | 6.832             |
| 27      | 6.443              | 6.379             | 63      | 6.792              | 6.390             |
| 28      | 5.785              | 5.372             | 66      | 4.533              | 4.699             |
| 29      | 10.470             | 11.702            | 67      | 4.919              | 4.481             |
| 30      | 9.311              | 11.438            | 68      | 6.374              | 5.465             |
| 31      | 8.310              | 7.560             | 69      | 11.744             | 13.223            |
| 32      | 7.892              | 9.159             | 70      | 6.113              | 5.576             |
| 33      | 6.632              | 5.357             |         |                    |                   |
| 34      | 6.447              | 7.008             |         |                    |                   |
| 35      | 5.562              | 5.337             |         |                    |                   |

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